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Water, Health, and Social Technologies: One Million Cisterns Programme Case Study

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ORIGINAL RESEARCH

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ABSTRACT

Background: This paper focuses on the impacts of climate change on vulnerable ecosystems and its implications for the health and well-being of populations. It specifically examines the semi-arid region of Brazil, where the introduction of a social climate adaptation tool, cisterns, has brought about significant positive changes. Cisterns, a low-cost climate adaptation technology, can be replicated globally, reducing the negative health impacts of frequent droughts, especially for vulnerable groups in remote rural areas.

Objective: We analyze the impact of the "One Million Cisterns Program" (P1MC) on health by synthesizing the literature and modeling its interactions with climatic and environmental factors with the *Driving Force–Pressure–State–Exposure–Effect–Action* (DPSEEA) framework.

Methods: Our case study employs a multidisciplinary approach, focusing on two key objectives: (i) synthesizing the literature on the implementation of the P1MC and its association with health outcomes, using search criteria that specifically target articles linking the program to health impacts; and (ii) developing a conceptual framework to model the relationship between climatic and environmental factors, adaptive ecosystems,

KEYWORDS:
climate adaptation technology, cisterns, semi-arid regions, water scarcity, health

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and health outcomes. The DPSEEA framework evaluates the structural connections between climate change and human health.

Findings: The study found a significant gap in the literature concerning the relationship between P1MC and health outcomes. Cisterns target the pressure/state linkages related to contextual factors and health effects, addressing the root causes of drought-related health issues. This framework also provides a foundation for collaboration among health, environmental, and policy sectors to address shared challenges, such as water security and health outcomes.

Conclusion: We offer a multidisciplinary analytical framework that can be used to explore various perspectives—environmental, social, and health-related—with experts and stakeholders to develop and improve adaptive social technology strategies for living in the era of climate change. This framework also facilitates the implementation of qualitative and quantitative well-being and health assessments.

1. BACKGROUND

The Brazilian semi-arid expanse ranks among the largest and most densely populated in the world [1]. In 2021, the Federal Government released the latest demarcation, revealing a notable augmentation in the domain's municipal coverage and territorial stretch [2]. Currently, the semi-arid domain constitutes 15.5% of the national territory, encompassing approximately 1,427 municipalities and accommodating 30.3 million people (equivalent to 14.6% of the total Brazilian population and 54.7% of the Northeastern region's inhabitants).

In addition to water scarcity and prolonged droughts exacerbated by climate change, which hinders access to water for consumption and food production, the semi-arid region harbors the largest proportion of the rural Brazilian population facing poverty and extreme poverty. Approximately 47% of the region's population experienced severe food insecurity immediately following the COVID-19 pandemic, with socioeconomic, gender, and racial inequities becoming further pronounced [3].

The population of the semi-arid region is racially, ethnically, and culturally diverse, featuring the Black population and indigenous and *quilombola* communities in the area. These social groups understand nature from different perspectives than the so-called Westerners. Traditional communities comprehend land, water, and animals through their cosmologies, avoiding accepting the earth only as an economic resource [4]. Most of this population engage in subsistence farming and livestock activities [5]. Nevertheless, despite their cultural and identity richness, they are particularly exposed to stigmas, harmful environmental stressors, and to socially deprived areas, which increase their vulnerability to extreme weather events due to climate change [6].

In the semi-arid region, resource conservation is crucial. It involves storing water for drinking, agriculture, and livestock, as well as preserving food and seeds. The NGO *Articulação do Semiárido* (*ASA*) was formed to improve coexistence in the Brazilian semi-arid region. The ASA is a network of civil society organizations that works for the social, economic, political, and cultural development of the semi-arid region of Brazil, bringing together hundreds of entities, including other NGOs, rural workers' unions, farmers' associations, cooperatives, environmental organizations, pastoral groups, churches, and others [7].

As communities engage with the ASA association and construct cisterns, they learn the power of collective action in asserting their rights, fostering community engagement, and promoting full citizenship. We present a detailed cultural and territorial perspective in the supplementary material SM1. By mobilizing society, the program advocates for effective and inclusive policies that uphold rural populations' rights to clean water [8]. The participatory design of the One Million Cisterns Program (P1MC) also offers valuable lessons for other public policies seeking to strengthen ties between government initiatives and the everyday realities of rural populations. Its emphasis

on community protagonism, local knowledge, and co-management mechanisms exemplifies how adaptation strategies can be shaped from the ground up. This approach fosters technical solutions, marginalized groups' political and social empowerment, and encourages a broader culture of citizenship beyond water access.

Over the past two decades, potable water access in the semi-arid region has evolved from emergency relief to a government-endorsed policy with national budget allocations. The National Council for Food and Nutritional Security (Consea) has rightly recognized P1MC cisterns as a lifeline for water and food security in the region [8]. The provision of potable water is essential for food security and other human rights. The region's water scarcity results from limited rainfall and social factors like unequal income distribution and ownership [9, 10]. Traditional drought mitigation measures, such as large reservoirs, have been ineffective and politically manipulated, exacerbating water inequality [10].

The program actively encourages communities to shape and implement initiatives suited to their needs, emphasizing their empowerment and the program's participatory approach. Social and community participation is integral to the program, beginning with the establishment of municipal committees responsible for oversight and coordination. These committees, comprising various social organizations, provide legitimate channels for community input and ensure accountability in program implementation [8].

According to the Brazilian Government, 1,146,210 cisterns were constructed by 2022. During periods of increased funding for the cisterns program,[1] such as between 2013 and 2015, over 100,000 cisterns were built annually. However, the program has experienced substantial budget cuts since then, with only 5,946 cisterns constructed in 2022, as illustrated in Figure 1.

The P1MC improved water access in Brazil's semi-arid region, particularly as climate change exacerbates water scarcity and its associated socioeconomic and health challenges [13, 14]. Integrating longitudinal cohort data can offer an opportunity to rigorously evaluate the program's impact on key health outcomes [15]. As climate change drives extreme weather events globally, the P1MC policy becomes even more critical for addressing immediate water access and mitigating broader public health and social vulnerabilities. This evidence-based approach can inform scalable climate adaptation strategies worldwide, particularly in regions facing similar environmental and economic pressures.

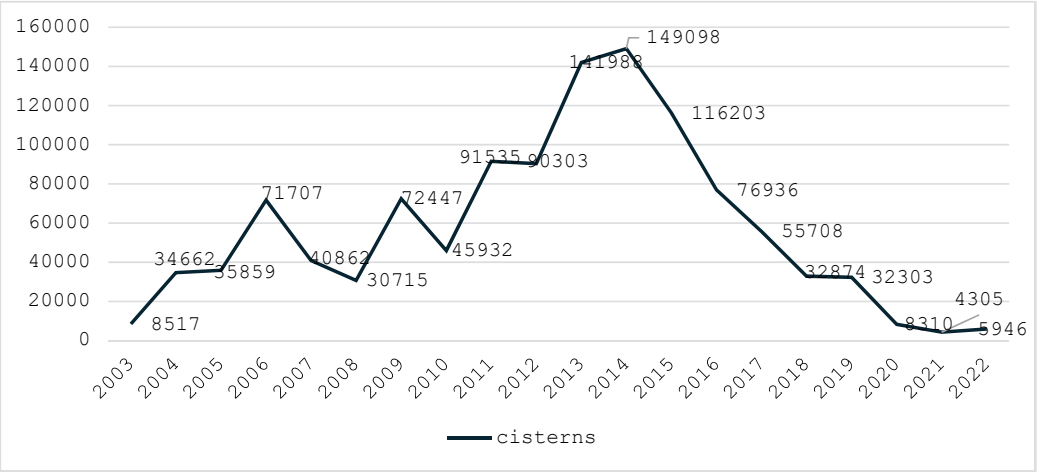

Figure 1 Total number of cisterns built since 2003 in Brazil.
Source: Brazil, 2023 [12].

1 It is important to note that P1MC was developed as a third-sector initiative and incorporated into a government policy in 2013. The institutional aspects related to this process are explored by Arsky (2020) [11]. See also: https://asabrasil.org.br/asa/.

Finally, this study analyzes the documented impact of P1MC in Brazil's semi-arid region regarding human health. We synthesized existing literature and employed a conceptual framework to identify potential health consequences from climate-induced ecosystem changes and policy-driven adaptation to drought. The *Driving Force–Pressure–State–Exposure–Effect–Action* (DPSEEA) model enabled us to trace and understand the context of this specific study on the P1MC public policy and its effects on the health and well-being of the population in the Brazilian semi-arid region, providing a perspective and a guide for future studies and steps involving this topic. Additionally, we present the cohort of 130 million Brazilians [15] as a significant, purposeful, and strategic resource for future research, providing a robust data foundation to explore the associations between social and environmental programs and various health outcomes.

2. METHODS

2.1 LITERATURE SEARCH

We searched using web resources such as *Web of Knowledge, Google Scholar, Scielo, Scopus*, and *ScienceDirect*, combining terms related to the environmental and health fields. Health-related terms included "health," "water-related diseases," "mortality," and "epidemiology"; environmental terms included "Brazilian semi-arid region" and "drought," and our exposure term was the "One Million Cisterns Program." Additional complimentary terms included "qualitative methods," "statistical methods," and "literature review." We identified approximately 39 studies (scientific articles) describing the P1MC, and only eight of them associate it with health outcomes. It is important to highlight that this intervention was designed exclusively for the Brazilian semi-arid region due to its unique characteristics linked to natural/climatic issues and the social vulnerability of its population. An official map of the boundaries of the semi-arid region is presented in Figure 4 in the supplementary material.

2.2 THE DPSEEA FRAMEWORK

Different approaches and conceptual models from various fields can be used to analyze and manage environmental impacts on human health. Hambling, Weinstein, and Slaney [16] evaluated 11 frameworks for developing environmental health indicators for climate change and indicated that the DPSEEA is the most comprehensive model due to conceptual clarity and scope, flexibility, balance between environmental and health issues, and usability. The framework's multidisciplinary approach, conciseness, and ease of communication for decision-making are also cited as advantages.

The DPSEEA framework, initially developed by the World Health Organization [17, 18], has proven its adaptability in various contexts. Morris *et al.* [19] further enhanced this framework to account for the complex impact of contextual factors on the environment–health relationship. This adaptability is evident in its application in diverse contexts, such as the dynamics of human health and the water environment [20], the implications of changes between natural ecosystems and associations with health services [21], and the association between natural ecosystems, green spaces, climate adaptation and mitigation tools, and health effects [22].

Applying the DPSEEA framework in the Brazilian semi-arid region exemplifies a comprehensive approach to integrating climate change and adaptation strategies with public health and ecosystem management. The framework facilitates a structured analysis of the complex interdependencies among environmental changes, societal responses, and health outcomes, highlighting the influences of regional and global environmental drivers [18, 20–22]. Additionally, it supports the creation and identification of indicators to aid the monitoring and evaluation of social policies.

The DPSEEA framework is applied systematically to understand the pathway from environmental determinants to health outcomes. First, driving forces such as socioeconomic and demographic factors are identified using literature reviews or data analysis. Pressures like emissions or waste can then be assessed through quantitative data collection. The state of the environment is

evaluated using environmental quality monitoring and spatial analysis. Exposure is measured through modeling or surveys to determine how populations encounter environmental hazards. Effects on health are assessed using epidemiological studies and statistical analysis to establish the relationship between exposures and health outcomes. Finally, policy analysis and stakeholder evaluations identify actions to mitigate these effects. Various applications have been conducted, such as a study on managing healthcare waste [23] and another on drought, leptospirosis, and scorpionism [24].

3. FINDINGS

3.1 LITERATURE FINDINGS

Despite the importance of the P1MC, there is a significant gap in our understanding of its effects on human health. Our literature search found only eight articles describing cistern implementation through P1MC linking to health outcomes. Luna et al. [25] and Marcynuk et al. [26] found a substantial reduction in diarrheal episodes among households with cisterns compared to those without cisterns. Luna et al. [25] observed a 73% decrease in diarrhea cases, especially in individuals aged 1 to 59, with a more substantial protective effect seen among males (76%). Marcynuk et al. [26] reported a markedly lower 30-day prevalence of acute diarrhea in households with cisterns, particularly among children under five. Both studies noted limitations, including potential selection bias and a lack of mechanisms to improve rainwater quality, suggesting room for improvement in program implementation.

Cisterns have been shown to lower the prevalence of parasitic infections and diarrheal disease, as Fonseca et al. [27] found that children from households with cisterns had a lower prevalence of *G. duodenalis* infections (4.8%) than those relying on unsanitary water sources such as rivers and springs (16.7%). The study emphasizes the importance of water access in reducing parasitic diseases, though it also highlights the need for further complementary sanitation interventions to mitigate health risks. In a groundbreaking study, Da Mata et al. [28] demonstrated that access to cisterns during early pregnancy increased birth weight by an average of 1.73 g per week.

Studies have also pointed out the broader perception of P1MC's impact on health and welfare. Passador and Passador [14] traced the evolution of public policies in Brazil's Northeast, showing that cisterns significantly improved the quality of life for families by enhancing health, leisure, income, and gender equality. Similarly, Gomes and Heller [13] found that the program reduced the time spent fetching water by nearly 90%, although challenges related to water quality and socioeconomic conditions persisted. Finally, Fagundes et al. [29] highlighted cisterns' positive impact on food security and agricultural production. Despite facing high rates of excess weight, cardiovascular risks, and food insecurity, 75% of families involved in the study reported improvements in food security due to the water provided by cisterns. Table 1 summarizes the main aspects of the research discussed.

3.2 THE CONCEPTUAL FRAMEWORK ANALYSIS

Figure 2 illustrates the conceptual framework of the P1MC within the DPSEEA model, climate change is the primary driver exerting various pressures on the ecosystem. These include changes in temperature and precipitation patterns, which are particularly impactful in Brazil's semi-arid regions. The pressures in this scenario are multifaceted. The increased frequency and intensity of droughts strain water resources and agricultural productivity. Desertification exacerbates land degradation, reducing arable land and affecting biodiversity [24, 31]. Increased demand for water due to economic development adds pressure to existing water supplies. Economic development drives land-use changes, potentially leading to increased pollution and habitat loss [32].

The state of the adaptative ecosystem in the Brazilian semi-arid region is shaped by its inherent capacity to adapt to environmental stresses. This adaptability is reflected through several specific functions and attributes critical for both ecological balance and human well-being. Firstly, the ecosystem supports essential services such as drinking water and food production, notably through drought-resistant crops and effective livestock management practices adapted to arid

REFERENCE AND LOCATION	DATA AND METHODS	HEALTH OUTCOME	MAIN CONTRIBUTION	MAIN RESULTS
Luna *et al*. [25]. 21 municipalities of Pernambuco state	Data was gathered from over 60 days and included 1,765 individuals Longitudinal prospective study, nested in a cross-sectional study comparing two groups (households with and without water tanks)	Occurrence of diarrheal episodes	The findings of this study point to the importance of access to drinking water for the reduction of disease	Among the 949 individuals with water tanks, there was a reduction in the risk of the occurrence of episodes of diarrhea by 73% compared with the 816 individuals without water tanks (RR = 0.27; $p < 0.001$)
Marcynuk *et al.* [26]. Agreste Central Region of Pernambuco state	Logistic regression using a face-to-face survey with 3,679 people from 774 households.	Determine the 30-day prevalence of diarrhea	This indicates that using cisterns for drinking water is associated with a decreased occurrence of diarrhea in this study population. Further research should be conducted to account for additional risk factors and preventative factors	People from households with a cistern had a significantly lower 30-day period prevalence of diarrhea (prevalence = 11.0%; 95% CI 9.5–12.4) than people from households without a cistern (prevalence = 18.2%; 95% CI 16.4–20.0)
Silva, Heller and Carneiro* [30]. Two municipalities in the Médio Vale do Jequitinhonha, Minas Gerais: Berilo and Chapada do Norte	Quasi-experimental, using survey-based analysis with 664 children under five years old	Occurrence of diarrhea in the last 72 h	The authors highlight the need to improve the sanitary practices of the rural population so that personal and household hygiene and hygiene concerning consumed water are incorporated into routine habits	The total prevalence of diarrhea was 5% but no significant difference between the groups
Fonseca et al. [27]. Berilo and Chapada do Norte (Minas Gerais state)	Quasi-experimental study cohort with 664 children	The prevalence of *G. duodenalis* in children under 5 years	The study suggests the necessity of complementing physical interventions with personal and domestic hygiene actions to further reduce parasite infections, which mainly affect underprivileged populations	They showed a higher risk of *G. duodenalis* infection in children who did not have access to rainwater cisterns when compared to children who did (OR 1.72; 95% CI 1.14–2.59)
Da Mata et al. [28]. All semi-arid regions	Administrative data from P1MC, CadÚnico, and SINASC. Fixed effects panel regression models	Birth weight	The paper studies how in utero exposure to a large-scale climate adaptation program affects birth outcomes	Access to cisterns during early pregnancy increased birth weight, particularly for more educated mothers. We show that each additional week of in utero exposure to cisterns is associated with a positive effect on an average birth weight of about 1.7 g.
Passador and Passador [14]. Municipality of Juazeiro, Bahia	34 interviews with benefited families	Beneficiaries' perception of improved health	Families reported that water-related illnesses, such as diarrhea, vomiting, and cramps, were quite common in families when they consumed poor-quality water of dubious origin. However, since using water collected in the cistern, such diseases occur very sporadically	Using cisterns positively influences the quality of life of these families in terms of health, free time, income, and gender issues
Gomes and Heller [13]. 63 municipalities of Minas Gerais	Survey-based analysis with 623 beneficiaries	Beneficiaries' perception of improved health	Emphasize that public water supply policies in semi-arid rural areas must associate technical issues with management elements that consider local social, climatic, and economic specificities	Improvements in the perception of the health of the benefited families and a reduction in the time spent searching for drinking water, but the challenges remain significant in precariousness and socioeconomic conditions and those related to an adequate supply of water in quantity and quality
Fagundes et al.* [29]. Alagoas state	Survey-based analysis with 29 families	Food and nutritional security	This study highlights the importance of water access programs for food production within public policies to guarantee FNS	Food Insecurity Scale showed that food insecurity occurs in 75% of these families However, focus groups showed that families positively perceive Boardwalk Cisterns for their food security. They believe that agricultural production has improved, offering a wider range of foods and improving food security

Table 1 Summary of articles describing cisterns' impact on health outcomes in the Brazilian semi-arid region.

Source: Authors' own. *Not focused on the P1MC.

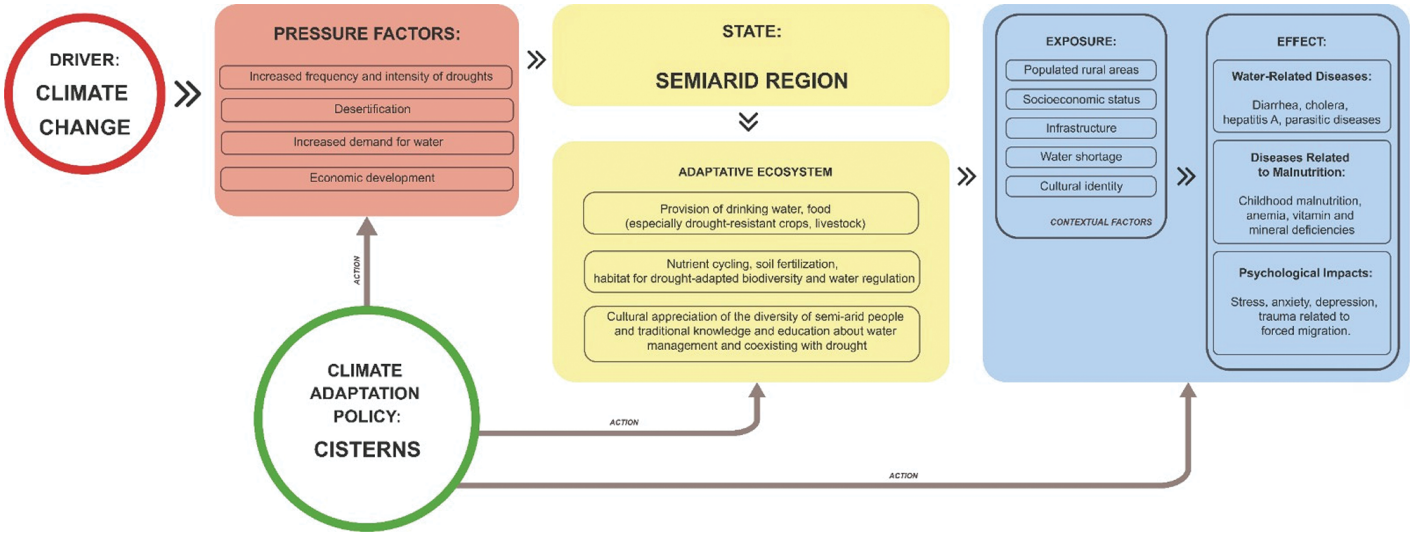

Figure 2 The conceptual analysis of the P1MC based on the DPSEEA framework.
Source: Authors' own elaboration.

conditions [33, 34]. These agricultural practices are vital for local food security. They are interlinked with maintaining nutrient cycling and soil fertility, crucial for sustaining agriculture in nutrient-poor soils prevalent in semi-arid areas.

The cultural values embedded within these communities, manifested in traditional knowledge systems related to water management and sustainable living, are components of the ecosystem state. These practices include ancient techniques for water conservation, such as the construction and use of dams, weirs, and cisterns, as well as soil preservation methods that have been passed down through generations. These cultural practices are not just survival strategies but are also key to maintaining the ecological balance and enhancing the resilience of the community and the ecosystem to climatic adversities [35–37].

Regarding the contextual factors, the convergence of limited infrastructure, socioeconomic disparities, cultural practices, and acute water shortages creates a multifaceted exposure that critically impacts community health and resilience. Infrastructure deficiencies—from inadequate water supply systems to poor healthcare access—intersect with economic inequalities, further stratifying communities based on their ability to adapt to environmental pressures. Lower income groups often lack the resources to implement effective water conservation techniques or access emergent agricultural technologies essential for survival in arid conditions [38, 39].

Culturally, the deeply ingrained traditional knowledge of water management and land use shapes community responses to these environmental challenges [39]. However, the effectiveness of combining traditional practices with modern adaptation strategies varies significantly across different communities, influenced by both cultural acceptance and the practicality of integrating new solutions into established lifestyles. For instance, traditional rainwater harvesting methods might be enhanced by modern cisterns, yet acceptance varies based on perceived benefits and the alignment with cultural values regarding land and water stewardship.

Furthermore, the challenge of water scarcity is a catalyst that exacerbates existing infrastructural and socioeconomic vulnerabilities, directly influencing public health outcomes through increased incidences of waterborne diseases and conditions linked to poor nutrition and sanitation. The resultant decline in crop yields exacerbates food scarcity, leading to an upsurge in malnutrition-related illnesses. This situation is particularly dire for vulnerable populations, such as children and the elderly, who face increased risks of anemia, vitamin deficiencies, and other diet-related health issues [29].

As droughts become more severe, water scarcity leads to an increased use of potentially contaminated water sources. This rise in water contamination contributes directly to increased

waterborne diseases such as diarrhea, cholera, and various parasitic infections, as populations resort to less reliable water sources for daily use [28, 29, 32].

The psychological impact of these environmental stresses also becomes profound. The persistent threats of water scarcity, food insecurity, and economic instability cultivate a pervasive sense of uncertainty and stress among communities. This psychological burden can lead to increased incidences of anxiety, depression, and other mental health disorders, compounding the community's health challenges [40].

Finally, implementing cisterns as a social technology significantly counters the pressures of increased drought frequency and desertification in a scenario of intensification of climate extreme events, by providing a stable and sustainable water supply. This technology directly mitigates water scarcity by capturing and storing rainwater during rainy seasons for use during droughts. Water availability supports the adaptive ecosystem, allowing for sustainable human consumption during dry periods. The strategic placement of cisterns influences various exposure variables and contextual factors that affect the local populations. When enhancing water security, cisterns alleviate socioeconomic disparities by equipping even the most economically disadvantaged communities with the means to collect and store water. This addresses infrastructure gaps and aligns with traditional water management practices, ensuring cultural integration and acceptance.

4. DISCUSSION

The studies on the P1MC demonstrate significant health improvements in Brazil's semi-arid region, specifically a reduction in diarrheal episodes in households with cisterns, improved birth weights, and enhanced food security among participating families, who report positive impacts on agricultural productivity [25, 26, 28, 29]. These outcomes are directly linked to increased access to clean water, underscoring the importance of water security as a determinant of health. Although there is still little evidence, these findings have global relevance, particularly for regions facing similar climate-induced water scarcity challenges, such as Sub-Saharan Africa and South Asia. Implementing cisterns mitigates the health risks associated with waterborne diseases, undernutrition, and poor maternal and child health by providing a stable, local water supply.

Applying P1MC as a climate adaptation technology demonstrates its potential scalability and relevance for global health interventions in drought-prone regions. Given the increasing frequency of climate-related extreme weather events, integrating water security solutions like cisterns into public health policy is critical.

The need for studies evaluating the health impacts of the P1MC represents a significant gap in the literature, particularly given the growing relevance of water security in the face of climate change. It highlights the urgent need for a comprehensive research agenda focused on evaluating the health outcomes of P1MC. Health impacts are profoundly affected by the use of cisterns [28]. Reliable access to clean water can decrease the incidence of waterborne diseases, rampant during water scarcity periods when populations might otherwise rely on contaminated sources [26]. Additionally, irrigating crops using stored rainwater can mitigate the effects of malnutrition by increasing food availability, even during unyielding droughts [41]. This dual benefit of cisterns—improving both water and food security—significantly enhances communities' overall health and resilience.

The application of the DPSEEA framework also facilitates the identification of indicators to support assessments of climate change and adaptive strategies in the Brazilian semi-arid region. This exercise, which does not aim to exhaust the number of indicators, will differ from other applications by adding a qualitative dimension, broadening the scope of information, and including the experiences, perceptions, and perspectives of people who have first-hand experience of the limitations and adaptations in a semi-arid environment affected by climate change. We understand that incorporating social participation during the knowledge production process is an important strategy for better connecting with problems and solutions and expanding the potential applicability of results. Klenk et al. [42] demonstrate how climate change and health research have included local knowledge, though still with limitations, such as focusing on people's perceptions.

In our framework, we identify quantitative indicators such as rates of temperature increase, precipitation, duration and frequency of droughts, water reserves, sociodemographic data and mortality rates, and diseases. In addition, we listed some qualitative indicators that will help capture the complexity of human experience in this environment. These include changes in hygiene practices, perceptions of water quality, and reports of psychological stress. By activating these subjective components, different methodologies will be required in the analyses, such as focus groups, interviews, and participant observation. Table 2 lists the indicators by framework level and provides a preliminary list of recommended actions that should be validated and complemented through collaboration with participants living in the semi-arid region in the next stages of this study.

In the Brazilian semi-arid region, inconsistent rainfall patterns mean families may struggle to maintain and refill cisterns during extended dry spells, potentially limiting the reservoirs' ability to

LEVEL	DETERMINANTS OR DRIVERS	INDICATORS	ACTIONS
Driver	Climate change	Increase in rate of temperature	Development and monitoring of a heat-health action plan for the semi-arid region
Pressure factors	Increased frequency and intensity of droughts	1. Precipitation level 2. Drought duration and frequency 3. Water reservoir levels	Monitoring to prevent deforestation Environmental education on how to avoid soil pollution Support for family farming Social cash transfer program
	Desertification	1. Decline vegetation area between time intervals 2. Decrease in soil organic matter content between time intervals	
	Increased demand for water	1. Number of water trucks	
	Economic development	1. GDP 2. Poverty rate 3. HDI	
State	Semi-arid region	1. Region	
Exposure	Populated rural areas	1. Population in drought areas 2. Rate of migration 3. Number of children, adults and elderly (cohort data)	Educational policy for youth in the territories Sustainable economic development policies P1MC improvements Health promotion actions and educational materials to preserve technology
	Socioeconomic status	1. Income rates 2. Education rates 3. Access to healthcare 4. Age 5. Gender 6. Race-color (cohort data)	
	Infrastructure	1. Water coverage and sources	
	Water shortage	1. Number of houses without cisterns 2. Time to access water	
	Cultural identity	1. Changes in hygiene practices 2. Building capacity in managing cistern water	
	Water quality	1. Perception of water quality by beneficiaries 2. Water indicators (pH level, turbidity, etc.) 3. Frequency of water quality tests	

(Contd.)

LEVEL	DETERMINANTS OR DRIVERS	INDICATORS	ACTIONS
Effects	Water-related diseases: Diarrhea, cholera, hepatitis A, parasitic diseases	1. Disease rates 2. Mortality 3. Hospitalization	Health surveillance and promotion programs Improvements of PHC
	Diseases related to malnutrition: Childhood malnutrition, anemia, vitamin and mineral deficiencies	1. Malnutrition disease rates 2. Morbidity and mortality caused by these diseases 3. Food diversity index (cohort data)	
	Psychological impacts: stress, anxiety, depression, and trauma related to forced migration	1. Disease rates 2. Behavior changes 3. Testimonies on psychological distress (cohort data)	
	Health and well-being	1. Perception of life satisfaction 2. HDI	

Table 2 Qualitative indicators supporting action on P1MC.
Source: Authors' own.

provide clean water consistently. This is further complicated by the economic constraints many households face, as maintaining and managing these cisterns often requires additional financial and logistical resources that low-income families may not readily have. The costs associated with water treatment, maintenance, and sometimes even purchasing water during drought can undermine such programs' long-term sustainability.

Similar challenges have been addressed in other settings through innovative approaches that help families maintain water security despite variable rainfall [43]. For example, in Sub-Saharan Africa and South Asia, rainwater harvesting systems are often supplemented by community-managed water storage facilities or water delivery programs during dry periods [44, 45]. In Ethiopia's Tigray region, water-sharing cooperatives allow multiple households to pool resources for the upkeep and maintenance of water storage facilities, thus reducing individual economic burdens [46]. Additionally, financial support mechanisms, such as subsidies or microloans for water infrastructure maintenance, have been implemented in parts of India to enable low-income families to manage their cisterns effectively [47].

Similar solutions could be adopted to overcome the limitations of rainfall variability in the P1MC. Introducing community-managed water reserves or establishing contingency funds to help families maintain and refill cisterns during droughts would increase the program's resilience. Furthermore, government policies that subsidize water treatment supplies or offer financial aid to low-income families could reduce the economic strain and ensure sustained access to water even in times of scarcity. By learning from these global examples, the P1MC can be strengthened to withstand the challenges posed by climate-induced water scarcity.

4.1 THE ROLE OF COHORT DATA ON THE ASSESSMENT OF CLIMATE CHANGE IMPACT AND THE DEVELOPMENT OF CLIMATE ADAPTATION STRATEGIES

To assess the impact of climate and climate adaptation strategies on health, we propose utilizing the Center for Data and Knowledge Integration for Health (CIDACS) 100 Million Brazilian Cohort as a sizable, secure database with immense potential for studies on climate change, adaptation policies, and their various effects on human health. The 100 Million Brazilian Cohort represents a groundbreaking initiative in public health research in Brazil, developed in response to the scattered yet high-quality social and health databases available in the country [15]. This cohort was established to integrate these databases and assess the impact of various social protection policies on health outcomes. The overarching goal is to improve the understanding of how these

policies influence the social determinants of health overall and within specific subgroups of interest over time. From 2001 to 2018, the cohort's baseline amassed data on 131.7 million low-income individuals from over 35 million families [15]. This population predominantly comprises children and young adults, with a larger proportion of females than the general Brazilian population. The 100 Million Brazilian Cohort provides a unique opportunity to advance the study of climate adaptation policies in the Brazilian semi-arid region. This vast cohort offers several key advantages that can be leveraged to understand and enhance the effectiveness of interventions aimed at mitigating the impacts of climate change in this vulnerable area. We can enumerate some key points as:

1. *Comprehensive and longitudinal data:* The cohort's integration of health and social data from various government sectors enables the exploration of the social determinants of health and their interplay with environmental factors. The longitudinal nature of the data is especially valuable, with follow-ups beginning in 2001 and continuing through the period following the implementation of numerous social policies in 2003. It enables analysis of the lasting effects of climate adaptation strategies, such as the introduction of water-saving technologies like cisterns, on health outcomes over time.
2. *Sub-population analyses:* Given the cohort's large size, researchers can study less common health outcomes and their variations across different sub-populations, including those most affected by climate change, such as rural, indigenous, and isolated communities. This capability is critical in the semi-arid region, where diverse ethnic and socioeconomic groups may experience the effects of climate change differently.
3. *Detailed interaction studies:* The cohort allows for examining detailed interactions among various factors, such as age, gender, and race, as well as the effects of combined social and climate-related policies. It can help to elucidate how different demographic groups respond to climate adaptation measures and which strategies are most effective in improving health outcomes in the context of ongoing environmental changes.
4. *High data quality and reduced bias:* Using administrative data minimizes recall bias often associated with self-reported data, enhancing the reliability of studies on service usage and health outcomes. The linkage techniques and continuous quality checks ensure the accuracy of data, which is crucial for forming robust inferences about the effectiveness of climate adaptation interventions.
5. *Focus on vulnerable populations:* Since the cohort includes a significant representation of the poorer segments of the population, it is well-suited to explore the impacts of climate adaptation policies on those most vulnerable to climate change. This focus is particularly relevant in the semi-arid region, where economic challenges and limited access to resources compound the effects of environmental stressors.

With that, researchers can better understand the complex dynamics at play in the semi-arid region of Brazil. This understanding can inform the development of more effective and targeted climate adaptation policies, guiding policy decisions at various local and national levels. For instance, insights from this data could lead to the implementation of water-saving technologies in areas most affected by drought. This approach ensures that climate adaptation strategies are grounded in empirical evidence, thereby maximizing their potential impact on improving health and quality of life in one of Brazil's most climate-vulnerable regions.

5. CONCLUSIONS

As a core component of the P1MC, the cisterns stand out as a culturally resonant adaptation tool that embodies the intersection of environmental necessity and local cultural practices. As evidence suggests, cisterns have influenced the health and well-being of local populations, proving crucial in drought by providing necessary water reserves. To this end, it is important to highlight that ASA's engagement has the potential to support the implementation of the social technology of cisterns in other territorial contexts.

However, while cisterns are vital resources, their effectiveness is limited by several factors, including rainfall variability and families' economic capabilities to maintain and refill these reservoirs during prolonged dry spells [28]. Maintenance issues further complicate their functionality, affecting their long-term viability as a sustainable water source. These limitations emphasize the need for comprehensive policies that not only support the installation of cisterns but also ensure their maintenance and the continuous training of communities to manage their water resources efficiently.

Harnessing the comprehensive and detailed data from the 100 million Brazilian Cohort will enable us to understand the dynamics within Brazil's semi-arid region and inform the development of evidence-based climate adaptation strategies that focus on health outcomes. Integrating this extensive dataset with records from P1MC and *CadÚnico* provides insights into the effectiveness of interventions, such as cistern installation, which directly correlate with improved health outcomes and an enhanced quality of life for vulnerable populations. Cisterns have proven critical during periods of severe drought, highlighting the direct impact of targeted adaptation policies. Furthermore, the ability to track health outcomes such as infant mortality and diseases related to water quality provides a clear indicator of success and areas for improvement in current policies. Continuing to leverage this cohort data, policy decisions can be better informed at all levels, ensuring that adaptation strategies not only address the immediate needs of these communities but also contribute to sustainable development and resilience in one of the region's most vulnerable to the adverse effects of climate change.

As we move forward, policymakers must consider both the successes and the limitations of current strategies, adapting and evolving policies to better meet the needs of Brazil's semi-arid population. A holistic approach will ensure that the benefits of such programs as the P1MC are maximized, contributing to the sustainability and health of vulnerable communities in the face of ongoing climate challenges. Finally, when producing a contextualized study, it is crucial to emphasize that achieving listening and understanding of life beyond data, engaging both the community and policymakers, is essential to enhance a public policy like P1MC and improve the health of communities needing support to thrive in their contexts.

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The authors have no competing interests to declare.

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