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The One Million Cisterns Programme—a viability assessment of community rainwater management in Brazil

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This research investigated the governance of the national community-based rainwater harvesting initiative, known as One Million Cisterns (P1MC), within the local context of the Brazilian Amazon rainforest. The initiative aimed to empower communities by providing water collection infrastructures and involved over 3,000 civil society organisations and various local and national bodies. Our study observed that while some communities thrived, others faced challenges in adopting and maintaining the cisterns. Focusing on communities near the city of Belém, Pará, within a specific Protected Extractivist Reserve Areas (RESEX), we explored the factors behind success and failure in managing rainwater systems. By applying Ostrom's Institutional Analysis and Development Framework (IADF) and Beer's Viable System Model (VSM), we assessed local institutional arrangements and community self-organisation. Through questionnaires and interviews with 109 end-users between 2018 and 2022, we identified two distinct organisational structures and their associated pathologies. The combined use of IADF and VSM provided valuable insights into the structural and institutional dynamics affecting system adoption, maintenance, and governance. Our findings emphasise the importance of a comprehensive framework integrating these analytical tools for designing effective social programmes in Brazil. This study contributes to the ongoing discourse on sustainable development and resource management in the Amazon region, highlighting the significance of tailored governance structures and community engagement in addressing complex environmental challenges.

KEYWORDS

viable system model, institutional analysis and development framework, rainwater harvesting, governance, civil society

1 Introduction

Over the past three decades, ensuring access to clean water has been a central priority for the United Nations (UN). By 2011, 41 countries were experiencing severe water stress, and 40% of the global population faced significant challenges in accessing clean and secure water sources (UNDP, 2011). In response to these pressing issues, the UN established the Sustainable Development Goals (SDGs), with Goal 6 specifically dedicated to ensuring availability and sustainable management of water and sanitation for all (UN, 2015). This initiative built upon the UN Millennium Development Goal 7, which committed member states to providing a safe and reliable water supply as a fundamental element of environmental sustainability (UN, 2000, 2012). By 2015, the progress report for the SDGs indicated an increase in global access to safe drinking water, rising from 70 to 75% of the population (UN, 2022). Despite these advancements, UNDP forecasts that by 2050, one in four people will face recurring water shortages, with 8 out of 10 of those lacking access to clean water residing in rural areas (UNDP, 2022). Recent projections suggest that at the current rate of progress, 81% of the global population will have access to safely managed drinking water by 2030, leaving approximately 1.6 billion people without a reliable water supply (UN-Water, 2021; WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP), 2022; Michielin, 2023).

Within this context, rainwater harvesting systems have emerged internationally as a successful strategy for improving access to clean water, particularly in regions facing severe water scarcity. These systems collect and store rainwater for various uses, including drinking, irrigation, and sanitation, offering a sustainable solution for communities lacking reliable water sources. Rainwater harvesting has been implemented across diverse geographic and climatic conditions, demonstrating its versatility and effectiveness. For instance, in India, extensive rainwater harvesting projects have been carried out to combat water scarcity and recharge groundwater aquifers, which have led to significant improvements in water availability and quality (Kumar and Singh, 2018). Similarly, in Kenya, rainwater harvesting systems have been used to enhance water security for rural communities, improving both water access and agricultural productivity (Gichuki et al., 2018). In Australia, large-scale rainwater harvesting initiatives have been integrated into urban water management strategies, contributing to water conservation efforts and reducing reliance on centralised water supply systems (McDonald and Brown, 2019). These examples highlight how rainwater harvesting can be effectively employed as part of broader water management strategies to address water scarcity and improve community resilience.

In the context of the UNDP-SDG framework, Brazil made significant strides from 2002 to 2015, lifting 28 million people out of poverty and elevating 36 million to the middle class through extensive social investments (Oliveira, 2015). Despite these successes, 16.2 million Brazilians continue to live in extreme social vulnerability, as reported by the Brazilian Institute of Geography and Statistics (IBGE, 2010). During this period, the "Brazil Without Misery Plan" was implemented, which sought to incorporate the most marginalised populations into the country's economic and social development through the expansion of existing initiatives and the creation of new social programmes, including the One Million Cisterns (P1MC) project.

Despite these determined efforts and notable achievements, the Amazon region in Brazil remains one of the most challenging areas for the maintenance and expansion of social programmes. This challenge is largely due to logistical complexities and the widely dispersed communities that rely heavily on rivers for transportation. Consequently, there are significant barriers to delivering essential services such as electricity and clean water. For example, high local rates of waterborne diseases underscore the persistent lack of clean water in the region (Joventino et al., 2010; Silva et al., 2012), often exacerbated by untreated water supply systems (Gnadlinger, 1999, 2000, 2007) and the use of water unfit for human consumption (Veloso, 2012). Additionally, inadequate or non-existent sewage treatment facilities and open-air dumps further contribute to the region's water and sanitation challenges (Souza et al., 2011). The local Municipal Sanitation and Management Plan of Belém highlights that while 91% of municipalities in the Amazon have water supply systems, 100% fail to meet the minimum water quality standards for human consumption as defined by the Ministry of Health (Prefeitura de Belém, 2020). This issue is compounded by widespread infrastructure deficiencies and water quality problems that severely impact public health in the region (Silva and Costa, 2017; Costa and Almeida, 2018; Santos and Campos, 2019).

The persistence of these challenges can be traced to various factors, including heavy metal pollution from mining activities (Fenzl and Mathis, 2004), increased levels of iron from local groundwater deposits (Veloso and Lopes, 2014), and the direct release of untreated domestic, commercial, and industrial wastewater into rivers (Gregorio and Mendes, 2009; Souza et al., 2016). Recent studies have also revealed that many riverside communities lack adequate waste management knowledge (Miranda et al., 2019), which exacerbates water contamination and contributes to the negative effects of COVID-19 on water resources and public health (Urban and Kondo, 2020). Additionally, ongoing research highlights further issues such as the negative impacts of mining activities, heavy metal contamination, and the consequences of damming Amazon rivers, which affect water quality, fisheries, and the overall health of river ecosystems (Santos et al., 2020; Queiroz et al., 2022).

Given the complexity and persistence of these issues, it is crucial to explore effective governance models for community-based water initiatives. This study investigates the governance of the national community-based rainwater harvesting initiative, One Million Cisterns (P1MC), within the local context of the Brazilian Amazon rainforest. By examining the implementation, management, and outcomes of the P1MC project, this research aims to enhance understanding of how such initiatives can be effectively governed to improve water security and public health in remote and logistically complex regions.

The findings from this study can significantly impact water governance strategies in Brazil and other regions with similar challenges. By providing insights into successful governance models and identifying potential barriers, this research can inform policymakers, practitioners, and community leaders about best practises for implementing and sustaining community-based water initiatives. Furthermore, the study's outcomes may serve as a foundation for future research on adaptive governance approaches for water management in diverse socio-environmental contexts. These results could contribute to achieving the broader goals of the UN SDGs, particularly in enhancing water security and improving the quality of life for vulnerable populations in rural isolated areas.

2 Brazilian context of rain water collection systems

To solve the limited access to clean water in "off-grid" rural areas in Brazil, since 1999 the federal government explored technical solutions not just for clean water but to fight desertification in the semi-arid states of the east of the country, developing rainwater collectors and cisterns. This initial design—devised as a solution that fits all—was adopted as the reference for a national programme called One Million Cisterns (P1MC) with the ambitious objective of delivering One Million Cisterns in all the isolated rural areas of the country. The cisterns (see Figure 1), which had slight regional variations, were constructed using concrete, with inner walls and floor were coated with a long-lasting cement plaster, and buried in the ground up to approximately two-thirds of their total height (Drynet, 2015).

The P1MC was designed as a multi-agency initiative with support from multiple national and international funds and NGOs to design, train, and facilitate social mobilisation around the adoption of shared rainwater collectors in local programmes devised as a family and community-oriented initiative, involving 3,000 civil society organisations and local governments nationwide (RRH: Rural and Remote Health, 2018; Future Policy, 2022; Aragon, 2004). For its implementation, the programme required the development of institutional arrangements where the construction of the cisterns of common use (mostly family-based units)—following the initial design—was imposed. For this purpose, the beneficiary communities had to engage in collective action to establish rules of access and define roles for the construction and upkeep of the system, similar to those described by Ostrom (1990, 2002), Ostrom and Gardner (1993), and Janssen and Anderies (2013).

The implementation of the One Million Cisterns Programme (P1MC) across Brazil involved numerous non-governmental organisations and government offices. By 2009, the programme's significant contributions to achieving Sustainable Development Goals related to No Poverty, Quality Education, and Clean and Safe Water earned international recognition and several awards (RRH: Rural and Remote Health, 2018; Future Policy, 2022). However, a review two decades later revealed that the ambitious goals of the programme were not fully met; by 2020, only 628,355 families had benefited from the initiative (RRH: Rural and Remote Health, 2018; Future Policy, 2022). Notably, the programme data indicated that 70% of those registered were female, underscoring the initiative's reach and impact on women within these communities. This community-centred approach has facilitated significant advancements in food security and economic development, effectively fostering co-creation and capacity-building efforts, with a particular focus on empowering women (Jalil and Naves, n.d.).

In the North North-West states of the Amazon, the standard cistern design implemented under the P1MC was found to be unsuitable due to the unique bioclimatic challenges faced by riverside communities. Factors such as river tides, soil instability, and subsoil moisture significantly increased the risk of flooding, causing structural damage to the heavy concrete cisterns and leading to mould and algae growth within the porous materials used, ultimately contaminating the water (Veloso, 2019). Moreover, the design did not adequately address the high sediment levels in the collected water or the need for frequent maintenance to remove these deposits, which exacerbated the costs and material vulnerabilities in the high-humidity and fluvial transport conditions.

In response to these shortcomings, local communities initiated adaptations of the cistern technology to better suit their needs for clean water access within the framework of the P1MC (Veloso, 2012). To support these community-led innovations, the University of Para (UFPA) embarked on a research project aimed at identifying, testing, and implementing optimal rainwater harvesting technologies for potable water in riverside and rural Amazon communities. This research led to the adoption of Roof Top Rainwater Harvesting Systems (RTRWH), which utilise plastic tanks, elevated containers, and non-organic material rooftops, making them more suitable for the Amazon's bioclimatic conditions (Veloso et al., 2013).

The effectiveness of RTRWH systems was evaluated through comprehensive studies assessing their impact on the communities' access to quality water, health outcomes, and economic viability. These studies concluded that RTRWH systems significantly outperformed traditional cistern-based systems in all evaluated aspects, marking a substantial improvement in sustainable water resource management in the region (Veloso et al., 2013).

The implementation process of the Roof Top Rainwater Harvesting Systems (RTRWH) diverged significantly from that of the One Million Cisterns Programme (P1MC) in several key aspects. Unlike the P1MC, which combined efforts from various non-governmental and community-based organisations, the RTRWH was almost entirely government-funded and dependent. This initiative involved multiple federal and local agencies and NGOs with substantial regional influence, as well as community organisations.

However, within a few years, it became apparent that several RTRWH initiatives were failing. Cardoso et al. (2018) conducted

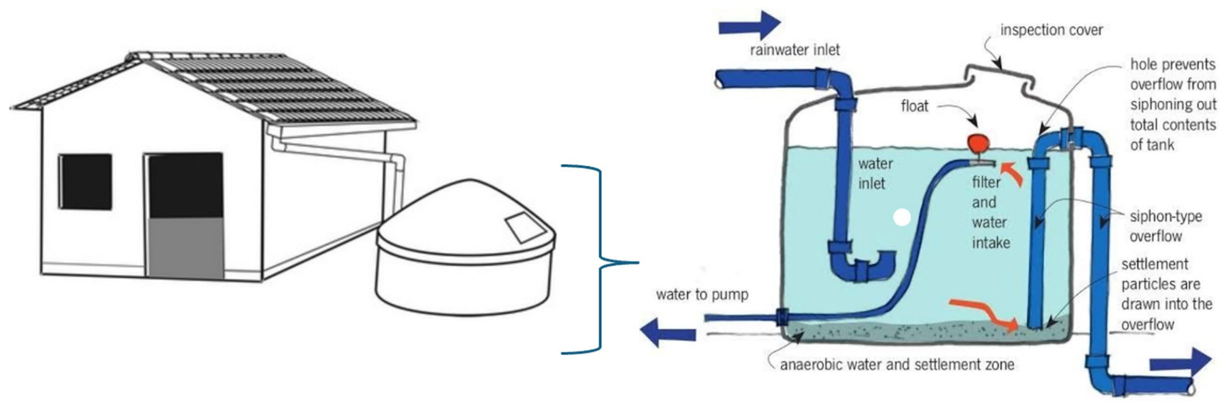

FIGURE 1
Rain water system—initial design of the P1MC. Modified from Drynet (2015) and the generic rainwater catchment systems by Paul Hemmerla.

a stakeholder analysis which revealed that crucial stakeholders had been overlooked in the implementation process. Additionally, they found that redundancies in the interventions by official agencies and NGOs adversely impacted the governance and viability of these regional initiatives. In a follow-up study, Cardoso et al. (2020) highlighted significant issues concerning the institutional governance of the RTRWH implementation, stressing the need for a more focused and systematic examination of the institutional arrangements and organisational structures that affect the adoption of these environmentally friendly water systems within communities. These findings underscore the importance of involving all relevant stakeholders and streamlining agency roles to enhance the effectiveness and sustainability of such initiatives.

3 RTRWH key programmatic aspects

In 2014, the Sanear Amazonia project was established as the overarching framework for the implementation of the One Million Cisterns Programme (P1MC) in the Amazon region. This initiative involved significant customization and adaptation to local bioclimatic conditions, innovations initially spearheaded by the residents who were early adopters of the cistern technology within this project. As a direct result of these initial efforts, a programme supported by the European Union was launched to develop an engineer-assisted design for the current Roof Top Rainwater Harvesting Systems (RTRWH). This design focused on enhancing cost-effectiveness and simplifying maintenance.

Through this enhanced initiative, 1,100 families across four Protected Extractivist Reserve Areas (RESEX) in the state of Pará (Figure 2, left) were equipped with the new RTRWH systems. This implementation highlights the importance of local adaptation in technology deployment, ensuring that solutions are tailored to meet specific environmental and community needs effectively.

The implementation considered the following methodological premises:

- Knowledge generation to develop autonomy: via facilitating collective processes, aiming to identify problems, solutions and priorities compatible with the needs and resources of the families.
- Learning by doing through the use of pedagogic practises focused on involving the families in the appropriation of knowledge via the practical use of concepts, practises and procedures related to the building and use of the RTRTWH.
- Connecting partnerships: networking events were planned to shift the mindset and behaviours of the families around the management of water resources, to build mutual support mechanisms between families, communities, and relevant institutions.
- The objective was to improve the self-esteem of individuals and communities, empower them to use and maintain the RTRWH independently, and involve families actively in all stages of the implementation process (planning, execution, monitoring, and evaluation).
- Promoting community interaction: conducting workshops to promote the exchange of experiences, fostering the creation of community-based initiatives aimed at enhancing the utilisation of the RTRWH.
- Enhancing extractivism through the acknowledgement of extractivists' knowledge and experience, aiming to promote responsible utilisation and conservation of natural resources, and incorporating RTRWH for improved quality of life.

The project targeted families with an income of up to half a minimum wage per capita, living in the rural area of the municipality

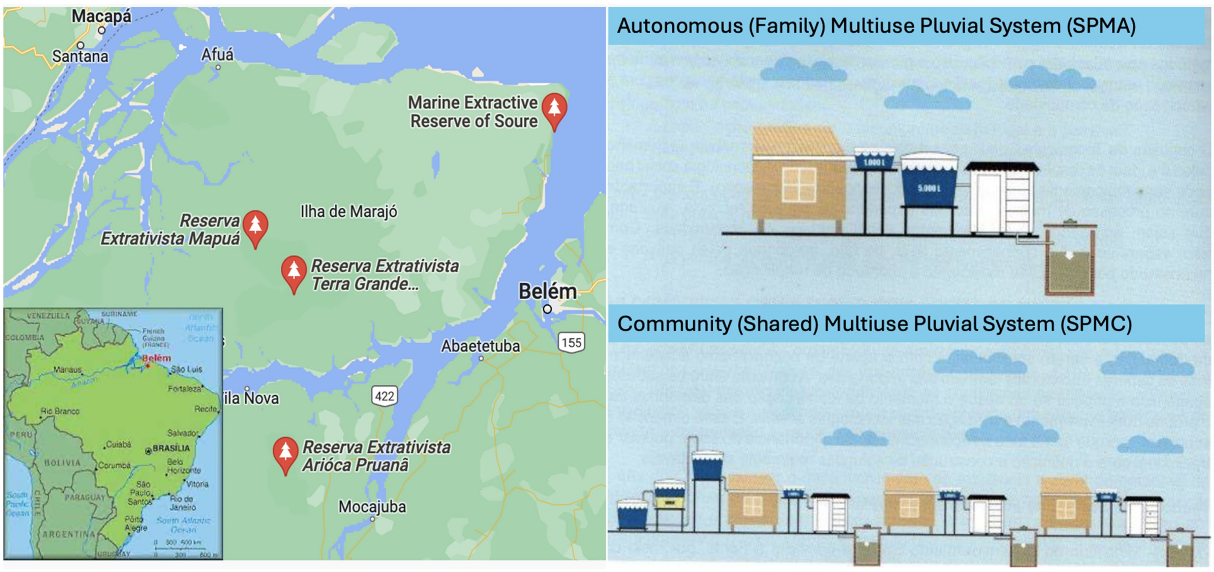

FIGURE 2
Left: Location of the RESEX in PARA & diagram of the two RTRWH: Right top: Single family user (SPMA); and right bottom: multiple user/community system (SPMC). Modified from Veloso (2012).

and without access to potable water, where the prioritisation criteria for family care followed at least the characteristics and order below (MCM, 2018):

- in a situation of extreme poverty;
- headed by women;
- with (a greater number of) children from 0 to 6 years old;
- with a greater number of children of school age;
- with people with special needs;
- directed by elderly individuals (whose family income is three times the minimum wage).

The selection process involved social organisations representatives (RESEX community representatives, cooperatives, unions of workers, and others), which assessed the level of involvement and participation in community actions of the potentially benefited family. The social mobilisation of the project was configured from two moments: the assemblies and meetings/visiting the beneficiary families, where the local/regional assembly provided information and encouraged dialogue about the project with the different actors. The meeting concluded with the disclosure of the list of potential family units who would benefit, followed by an invitation to the beneficiaries for upcoming social mobilisation activities (MDS, 2016). The next phase covered the training of beneficiaries and labour teams through workshops on two different subjects: water management, and environmental and technical health issues for the construction and maintenance of the physical components of the technology. The final step was the construction of the systems, conditioned to the participation of the family representative to the workshops before mentioned. Two types of RTRWH were introduced—(a) the autonomous/single user SPMA and the community user SPMC, where the difference is the number of houses served by a single roof top rainwater collector (Figure 2, right).

4 The community case study (IADF + VSM)

In 2016, reports of the abandonment and misuse of Roof Top Rainwater Harvesting Systems (RTRWH) prompted a detailed investigation between 2016 and 2018, with additional follow-ups in 2022, particularly focusing on the state of Pará. This study involved a diverse sample of 109 actors, including both users of the systems and stakeholders, across four Protected Extractivist Reserve Areas (RESEX), aiming to uncover organisational and institutional factors that influenced the adoption and sustainability of RTRWH (Veloso, 2019).

The research methodology employed open interviews with 76 system users and 33 stakeholders to gather in-depth insights. The data from these interviews were analysed using two complementary frameworks: the Institutional Analysis and Development Framework (IADF) and the Viable System Model (VSM). These frameworks were chosen for their shared principles of autonomy, emphasising self-organisation and self-regulation, as well as their ability to address different structural levels of action and manage complexity effectively.

This integrated approach was aimed at preparing for a future round of implementation by understanding and addressing the underlying issues that led to the suboptimal performance of the RTRWH initiatives. The insights gained were expected to inform better-designed systems and implementation strategies that could enhance the sustainability and effectiveness of rainwater harvesting efforts in similar contexts.

The Institutional Analysis and Development Framework (IADF), as articulated by Ostrom (2005), serves as a comprehensive, multi-tier conceptual map. Its fundamental schematic identifies the action arena as a core unit of analysis, which is instrumental in analysing, predicting, and explaining behaviour within institutional arrangements. Action arenas consist of an action situation and the actors involved. The action situation is characterised by seven clusters of variables: (1) participants, (2) positions, (3) outcomes, (4) action-outcome linkages, (5) the control that participants exercise, (6) information, and (7) the costs and benefits assigned to outcomes.

Within this model, an actor—whether an individual or a collective entity—operates based on assumptions concerning four additional clusters of variables: (1) the resources an actor brings to a situation, (2) the valuation actors assign to states of the world and actions, (3) the methods actors use to acquire, process, retain, and utilise knowledge, contingencies, and information, and (4) the processes actors employ to select specific courses of action. These interconnected variables can be analysed at various organisational levels, examining the interactions among resource systems, resource units and services, governance systems, and actors. The focal action situation, where these interactions and outcomes become evident, serves as a proxy for these analyses (Figure 3, left).

The Viable System Model (VSM), developed by Beer (1972, 1979, 1985), is a methodology for analysing complex social systems through the principles of cybernetics and the concepts of viability, recursion, and requisite variety. This model emphasises the importance of understanding the underlying structure and dynamics of a social system to identify inefficiencies, vulnerabilities, and opportunities for improvement. It involves a thorough examination of the interactions, feedback loops, and information flows that define the interaction among the three main components of any social system: the environment, the operation, and the management (Figure 3, right).

The VSM outlines the architecture (components and connections) necessary for the viability of any social system to assimilate the complexity of the environment in which it operates. The components of the VSM are as follows:

- **System 1 (S1):** This includes operations and units that interact directly with the environment. Operations perform activities essential for viability and constitute the organisation's purpose.
- **System 2 (S2):** This role/function is responsible for coordinating and regulating operations, developing mechanisms to prevent conflicts among them.
- **System 3 (S3):** This role/function oversees the organisation's current operations, ensuring they have the necessary resources, processing accountability of operational units, and enforcing policies, identity, and ethos. A subsystem (S3*) at this level monitors S1.
- **System 4 (S4):** This role/function handles strategic planning and the organisation's future, scanning the wider environment and anticipating changes that could affect the organisation. In close relation with S3, both decide on actions to prepare the organisation for upcoming environmental changes.

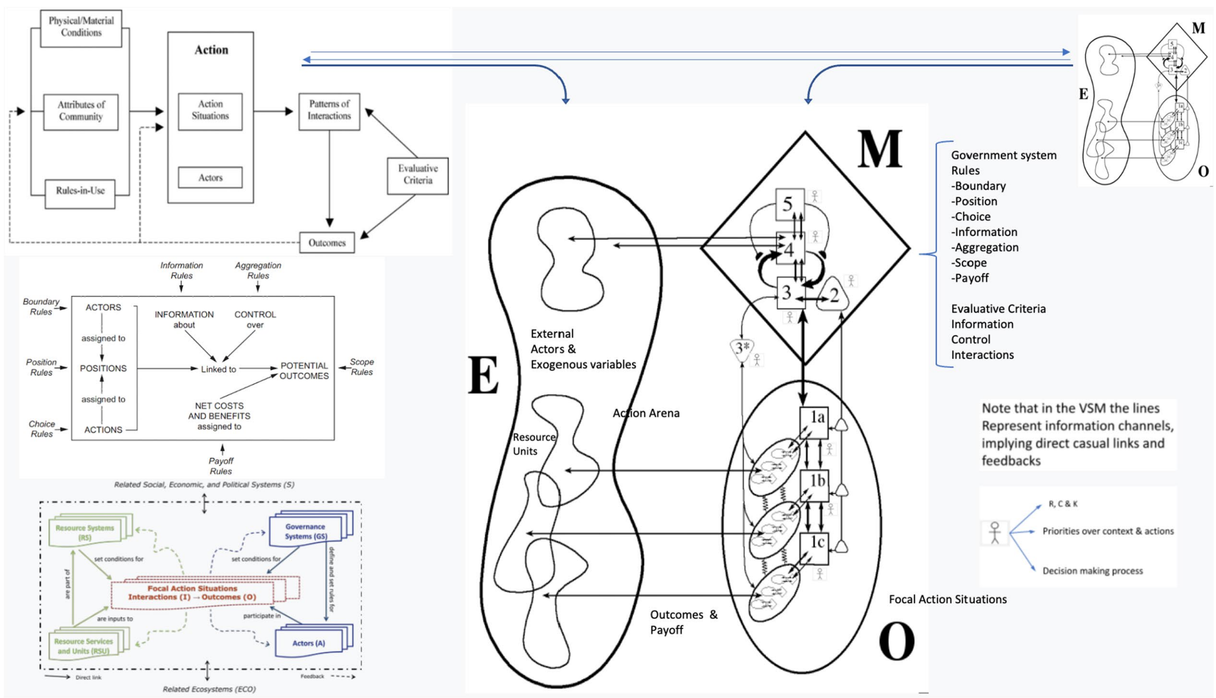

FIGURE 3
Illustration of the synergies in the combined use of IADF & VSM. Modified from Ostrom (2005, p. 829), McGinnis and Ostrom (2014) and Walker (n.d.).

- **System 5 (S5):** This role/function oversees the actions of S4 and S3, defining the organisation's overall identity, policy, values, purpose, and ethos.

This framework provides a comprehensive approach to understanding and improving the viability and adaptability of social systems.

Within this context, the principle of recursion is expressed in the understanding that each System 1 (S1) is, by definition, a complete viable system with all the necessary systems, connections, and conditions for viability. This means that a viable system both contains and is contained by another viable system. This embeddedness functions as a mechanism to assimilate the complexity of the environment at various levels of scale.

The similarities between Ostrom's theories and models and the Viable System Model (VSM) were explored by Espinosa and Walker (2017). Espinosa and Walker examined the relationship between actions related to the management of common-pool resources (CPR) and the principles of self-governed organisations, as outlined by Ostrom, within the context of sustainability and viability at the town or village level. They also explored how these principles align with the principles of the VSM.

Their study describes clear similarities between the two theories, which can be summarised as follows:

- Boundaries of the system must be clarified to determine who is part of the system, who has agency, and who has access to the system.
- The concept of recursive or nested systems.
- Organisational structures (and rules) must be created around the work to be done and its related context.
- Operative units must have autonomy, being capable of organising themselves to respond to their needs and stimuli from their environment.

Overall, Espinosa and Walker (2017) affirm that, in VSM terms, Ostrom's CPR clearly defines the roles/functions of S1 and S2. While S3 and S4 are not explicitly defined in Ostrom's eight principles, some mechanisms of these roles/functions are described as emergent in some of the case studies documenting Ostrom's model. Finally, in relation to S5, within the eight principles, the definition of rules could cover some of the higher-order functions associated with defining the policy, identity, ethos, and purpose of the system.

Our observation complements the theorising of Espinosa and Walker (2017) based on Ostrom's CPR by exploring the similarities and complementarities between Ostrom's Institutional Analysis and Development Framework (IADF) and the Viable System Model (VSM). In alignment with Espinosa & Walker's initial comparison of models, the IADF and the VSM concur on the definition and need for analysis of different levels of organisation (recursion). Both models emphasise the interactions between the environment and a purposeful action/operation conducted by organised operative units (actors, System 1). Additionally, these actions are defined as being controlled and regulated by managerial roles/functions (S2–S5) through a clear taxonomy of rules, roles, and positions of actors. Furthermore, both models stress the importance of observing interactions in the form of control mechanisms and information flows, considering the deployment of agents to perform specific roles/functions based on their knowledge, capability, and access to resources.

The most notable differences between the models include:

1 The IADF focuses on economic evaluative criteria (payoff) to assess the interactions of agents towards achieving a purposeful action and its respective set of outputs.
2 The IADF presents a taxonomy of rules and norms embedded in four levels:

o Operational: day-to-day operation
o Collective-choice: regulating and changing operative rules
o Constitutional-choice: regulating and defining collective rules
o Meta-constitutional: overseeing, regulating, and defining the norms to change constitutional rules. These levels order the relationships of the agents.

3 The IADF defines prescribed variables to assess the environment (resource systems, resource services), interactions, outcomes, governance systems, and actors.

Alternatively, the VSM provides a more detailed understanding of the distribution and interactions of agents and their actions, as well as a clear description of managerial roles needed to assess coherence, viability, and adaptation to change (via the distinction of Systems S2–S5). The VSM also offers a more comprehensible representation of recursion and facilitates the early identification of well-documented organisational pathologies.

The integrated framework (illustrated in Figure 3, centre) provides a comprehensive overview of the fundamental components of both the VSM and IADF frameworks. This combined framework encompasses the observatory of distributed decision-making centres, which consist of actors defined by their roles, functions, positions, and their capabilities, knowledge, and access to resources. Additionally, it includes essential connections such as information, communication, and control flows.

In more detail, the IADF offers guidance on observing and measuring the environmental system and its services that impact the functioning of the operation (S1). Additionally, the taxonomy of rules can enhance the VSM's observation of actor distribution by considering factors such as membership, rights, agency, and location within the system. In this respect, the rules apply and/or are enforced by different metasystemic functions (S2–S5), and these can be mapped against actors who personify agency. Furthermore, the role/function of the actors can be assessed regarding their knowledge, capability, and access to resources relevant to their function and position in the system.

In this context, whereas the VSM indicates the minimum but sufficient interactions, roles, and functions to provide viability, the IADF suggests the variables to be considered to assess such interactions, the agents involved, and the governance structure.

The observation and modelling exercise conducted through interviews and fieldwork with this combined method revealed that 48% of the RTRWH systems included in the sample were modified, which negatively affected their capacity to provide clean water as intended. Detailed observations identified the following causes for the misuse/disuse of the RTRWH systems:

General Issues (affecting most of the systems in misuse or disuse):

1 *Criteria for the selection process (rules of membership, scope, and boundaries) were not applied rigorously*.
2 *Key stakeholders were not included in the assemblies* (e.g., water intermediaries—rules of membership, scope, and aggregation).
3 *Technical conditions for implementation were not addressed rigorously* (e.g., roof materials, location of the reservoirs, and quality of structural materials—rule of boundary).
4 *Lack of clarity on the technical implications of operation and maintenance* of the communal RTRWH systems (e.g., maintenance materials & maintenance budget—rules of position, choice, and aggregation).
5 *Mismatch between the capacity of the RTRWH and the size of some beneficiary communities* (rule of scope).
6 *Modifications of the RTRWH designs that negatively affect the functioning of the system* (e.g., height of the reservoir vs. height of the distribution pipelines and points of use, changes in the filters, elimination of key sanitation components).
7 *Lack of systematic monitoring and follow-up activities* during the implementation and operation stages of the RTRWH by the agencies and founders of the P1MC (lack of interactions, control mechanisms, definition of information needs, and avoidance of established evaluative criteria; all expressed in the systems in focus and various recursive levels).
8 *Changes in the occurrence and length of the rainy season affecting the practical use of the RTRWH* (climate change—lack of monitoring of exogenous variables or dismissing reports related to these variables, evident in middle and high levels of recursion).
9 *Unclear definition of rules of use (self-organisation)*, particularly in the distributed roles and functions of maintenance of the system, resulting in a lack of maintenance.
10 *Inadequate recognition of the potential to enhance the value of extractive activities* through the acquisition of a dependable and sustainable clean water source (Rules of Payoff).

Similarly, the remaining 52% of systems analysed were in good condition and provided insights into the attributes of successful systems:

General Characteristics (common to most of the systems operating as expected):

1 *Integration of rules of use within the framework of existing community/family rules and operative protocols*.
2 *Clear definition of rules of membership, boundary, choice, and payoff*.
3 *Good articulation of access to clean water with the enhancement of value to existing extractive activities*.
4 *Adequate technical conditions for the installation and operation of the system* (e.g., quality of roof material, correct construction specifications, and good maintenance practises).
5 *Selection process included complete participation of beneficiaries in training workshops for the construction and maintenance of the system*.
6 *Awareness of the potential to add/create value to extractive activities through improved access to clean water*.
7 *Fairly good articulation with higher levels of recursion*.

From an institutional perspective, observing actors through the theoretical lens of the VSM enhanced understanding of the sources of some of these conditions for success/failure in the implementation and use of the RTRWH systems.

Key observations:

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1 *Extensive bureaucracy associated with the provision of public resources* distributed across six hierarchical/recursive levels (RL), as illustrated in Figure 4. In this structure, the last level responsible for implementation (recursive level 5 in Figure 4) is an external contractor with neither agency nor capacity for effective systematic monitoring (accountability). This issue is prevalent in recipient communities post-construction (delivery) of the systems.

2 The detailed observation of the unfolding complexity revealed the *lack of connectivity between several intervening agents (organisations) at different organisational/recursive levels*. The absence of cohesion among higher levels of the institutional arrangement resulted in the entire responsibility of implementing the RTRWH being shifted to a smaller number of disconnected government actors at middle recursive levels (RL 2 & 3). This placed the burden of implementation on unmonitored external agents (NGOs) at a lower recursive level (RL4). It was evident that at this level, there were only a few official agencies in the institutional system tasked with providing accountability. However, they had no connections to other agents in the system.

3 Regarding specific features of the unfolding complexity, it became evident that *higher flows of information in the institutional arrangement of the RTRWH were generated and contained in recursive levels 3, 4, and 5*. This was aggravated by limited flows and channels connecting with the higher levels of recursion, with *negative implications for the informed definition of institutional policy, identity, purpose, strategy,* and effective allocation of resources from the higher-level functions of recursive levels 0, 1, and 2.

4 The effects of these deficiencies were evidenced in the *poor definition of the levels of work, purpose, and capability—especially sensitive in the middle and lower levels of recursion—where the high-order functions (e.g., definition of strategy, purpose, identity, policies, and allocation of resources) collapsed upon agents at lower levels* of recursion (RL 3 and 4). In numerous cases, these agents lacked the capability, knowledge, and human power, which altered the definition of their existing operative mandates, boundaries, and agency.

A clear example of the consequences of the poorly defined identity and purpose of the RTRWH at RL 0 and the consequent transduction to the subsequent levels of recursion, as well as the lack of feedback from these lower levels of recursion was the imposition of a "solution that fits all" for the cisterns design, ignoring the local characteristics and demands of the different bioregions. This dysfunction resulted in (almost anarchic) local adaptations made by the recipient communities and organisations at RL 4 and 5. Ultimately making the lower levels of recursion responsible for most of the high order roles and functions (planning, strategy, design, funding, monitoring), adding to their existent roles/function of implementation and functioning of the

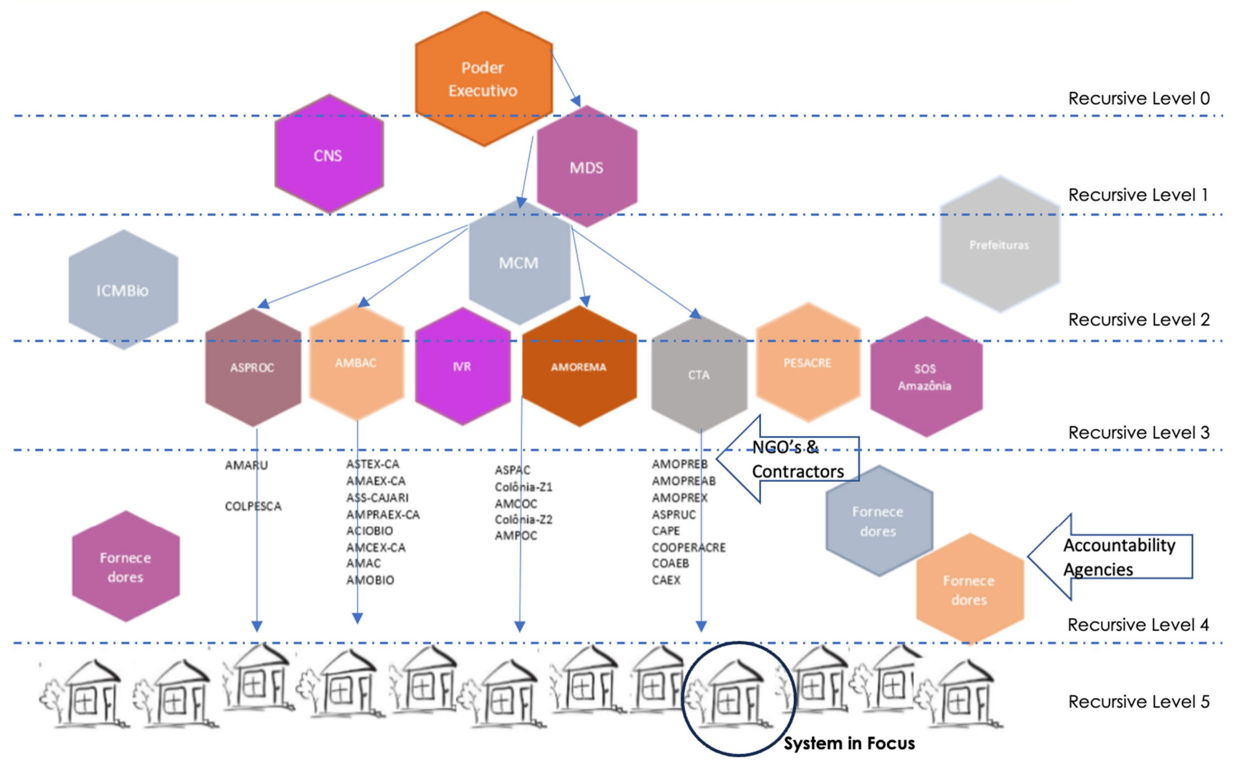

FIGURE 4
Unfolding complexity—institutional structure. The acronyms inside geometric figures represent official agencies. Acronyms outside geometric figures represent independent suppliers/contractors. Note the critical path for the implementation of RTRWH and the lack of connection with accountability agencies. Modified from Veloso (2012).

RTRWH systems. This overload of high order functions invited the emergence of inefficiencies at all levels of operation, expressed as organisational pathologies in the System in Focus at RL 5 (Figure 5). However, this same pathology allowed the emergence of unexpected initiatives to provide further viability to the RTRWH and elements of community resilience through interaction of agents at RL 4 and 5. For instance, influential stakeholders—identified in Cardoso et al. (2018)—such as Caritas and the University of Pará, played a mediating role in optimising Rooftop Rainwater Harvesting Technology (RTRWH). This optimization involved incorporating community local resources and technologies to improve water purification. The project aimed to achieve technological autonomy and independence by enabling communities to develop and maintain their water filters using byproducts from local farming activities, specifically açaí crops (Farrell et al., 2021).

The summary of the organisational pathologies expressed in the SIF relates to an informal (local) definition of the identity of the system, defining it as a mean to satisfy the need of clean water, operated by the users; being evident the lack of connections with higher levels of recursion (as perceived by the communities), configuring an independent/disjoint level of recursion. The S4 is not well-developed in both cases, being more frequent the occurrence of this pathology in the case of single users. Making the running of the RTRWH systems reactive, lacking the capacity to anticipate problems or adapt to changes in the local conditions of use.

The S3 in both cases is underdeveloped or almost non-existent. This is related to lack of capability, human power, and knowledge, generating deficiencies in the definition of rules of use, choice, and the overwhelming collapse of higher order functions from higher LR, related to the access to resources (above local capacities), definition and enforcement of policies and rules, and elements of accountability and monitoring of operative functions. These issues were more critical in the single-user systems because of the limited human resources.

Regarding the operative roles/functions, the only evident limitation was related to human power in the single-user systems—inviting a discussion about the correct size of a group of beneficiaries to receive the RTRWH, and in a wider context, of an institutional arrangement to be viable. Issues of coordination of actions/operations were also insinuated in this analysis.

In both cases (community and single user) information about the exogenous variables (environmental system and services) was not available, and even being available the operators at this level would not have the knowledge and capability to use the information effectively.

Similarly, in both cases the observable variables of governance, agents, interactions, and outcomes were related to family (implicit) protocols that in turn defined the rules of membership, scope, choice, boundary, position, aggregation, information, and payoff. This same family-based structure and dynamics provided the foundations for the mechanisms of control, information, and

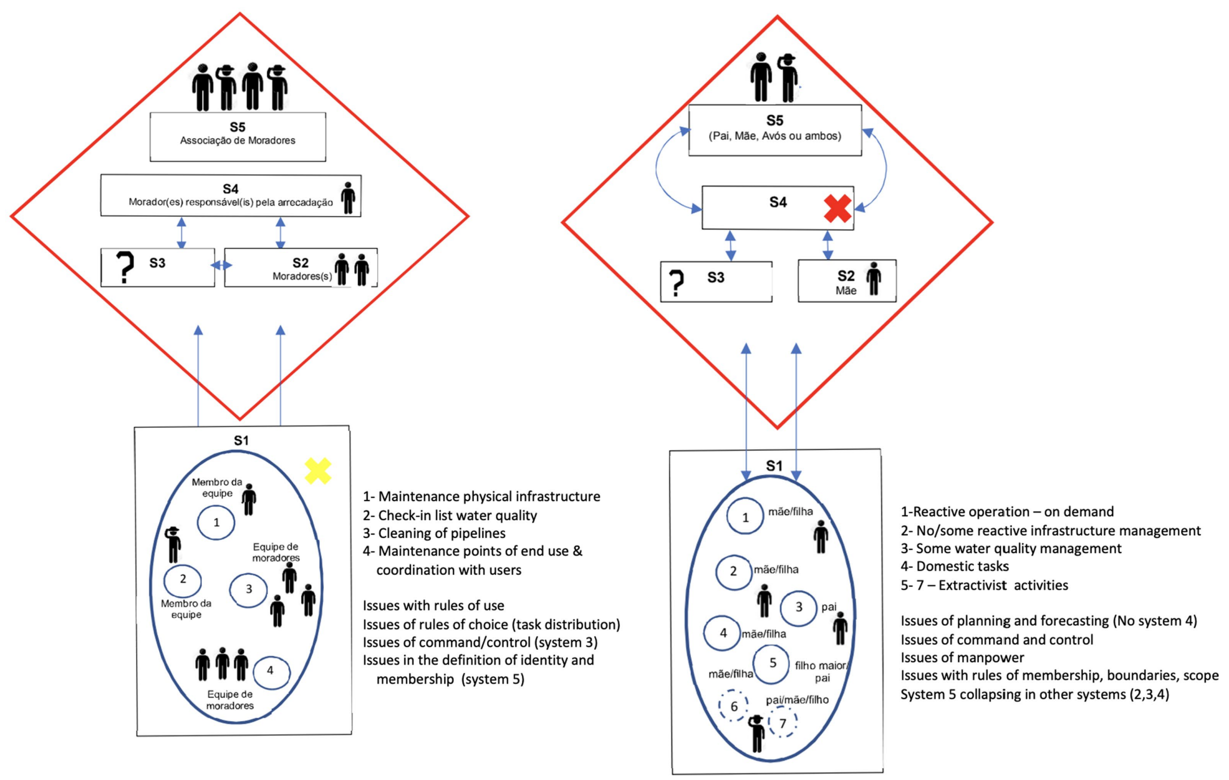

FIGURE 5
VSM diagnostic for the System in Focus (SIF) with two different arrangements: the community—SPMC (left) and single user—SPMA (right) RTRWH. Modified form Veloso (2012).

interaction. These were characterised by a mostly patriarchal culture, with an active political influence of women informally concentrating power and influence in flows of information, conflict resolution, the architecture of interactions, and the measure of success (evaluative criteria).

5 Practical implications, lessons learned for future applications

The IADF/VSM diagnostic revealed key institutional and organisational issues that must be addressed for the successful implementation of RTRWH systems. Institutionally, there is a need for enhanced monitoring and accountability of contractors and users. This should be accompanied by a rigorous application of selection criteria and technical conditions for implementation, ensuring active participation of beneficiaries in all training workshop cycles. Equally important is the inclusion of relevant stakeholders in assemblies, particularly those affected by RTRWH implementation, to provide financial support, further training, and ongoing oversight (e.g., water traders, Caritas, University of Pará).

Organizationally, accurately assessing the number of users is crucial for two reasons: (1) For SPMC, the number of beneficiaries should align with the system's capacity; (2) For SPMA, better selection criteria are needed, as families with five or fewer members (adults) may struggle to meet the operational demands of RTRWH.

Addressing these challenges requires a thorough examination of the complex political and power dynamics surrounding RTRWH governance, particularly regarding women's roles in programme governance and potential power imbalances. Understanding these dynamics is essential, given the intentional targeting of women-led recipients. This focus on female leadership aligns with documented realities of fishing communities, where women play a critical role in community water management and crisis response through their networking abilities, stakeholder engagement, and leadership capacities (Freeman and Svels, 2022; Campos, 2022; Silva et al., 2022).

During implementation, it is vital to explicitly identify the rules and their operativity within all VSM systems in each community. This includes defining membership, task allocation, resource deployment, responsibilities, and usage rights. This procedure will enhance managerial functions, mitigating frictions and inefficiencies in S3. Additionally, incorporating information about the well-documented benefits of RTRWH, such as superior water quality and health impacts compared to other methods (e.g., Farrell et al., 2021), is essential. This contrasts with earlier reports of metal and organic pollution in regional water sources (Fenzl and Mathis, 2004; Gregorio and Mendes, 2009).

The observation of exogenous environmental variables is increasingly relevant. For instance, changing rain/dry seasons, with dry periods becoming more extended, render RTRWH non-viable during dry seasons, particularly for SPMC users. This poses a significant threat to the future implementation of RTRWH systems, as studies indicate the savannization of the Amazon and longer dry seasons (Bottino et al., 2024). Forecasting capabilities for these observations exceed RL5's capacity, necessitating decisions at higher RLs, possibly RL3 or RL4, where organisations like universities and official agencies with weather forecasting capabilities are located. Consequently, improved feedback and connections between key actors with complimentary S4 capabilities at different RLs are also required.

Methodologically, a more detailed study is needed to clarify the distribution of different rule categories in the VSM and develop better connections between IADF metrics and VSM concerning exogenous factors and operational efficiencies.

Following the case study analysis, recommendations were delivered to key stakeholders at RL4 and RL5, including the University of Pará, local authorities, community associations, and NGOs like Caritas. These recommendations emphasised the success factors identified in the case study, the need for further research on governance, particularly regarding women's roles, and addressing differences between the two user profiles. A positive outcome was the continuation of research and development with local communities, as evidenced by Farrell et al. (2021).

However, the programme's future is uncertain due to shifting governmental priorities under the Bolsonaro administration, which redirected focus and funding towards underground water sources for agro-industry expansion, despite evidence of their unsuitability for human consumption in the region under study. With unclear signals for change under the new Lula administration, future governmental investment in RTRWH remains uncertain. Additionally, research focus on RTRWH appears to be shifting towards urban contexts, as indicated by recent studies (Almeida et al., 2023; Castier and de Barros, 2023). The University of Pará seems to be aligning with this trend, to the detriment of advances made with riverside communities over the past decade. Consequently, external variables such as climate change and new political and research trends pose uncontrollable challenges that surpass local communities' capacity to govern and decide on RTRWH development.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Center for Amazon Studies (NAEA), University of Para, Belem, Brazil. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

PC: Conceptualization, Formal Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization. MV: Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. NR: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation. NV: Conceptualization, Data curation, Funding acquisition, Investigation, Resources, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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