UNIVERSIDADE FEDERAL DO CEARÁ
CENTRO DE TECNOLOGIA
DEPARTAMENTO DE ENGENHARIA HIDRÁULICA E AMBIENTAL PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA CIVIL

HELA GASMI

PARTICIPATORY CHARACTERIZATION OF WATER RESILIENCE IN RURAL COMMUNITIES IN BRAZIL'S NORDESTE AND CENTRAL TUNISIA

FORTALEZA
2023

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Thesis defended at the Water Resources and Environmental Sanitation Post-Graduate Program of the Technology Center at the Federal University of Ceará, as partial requirement to obtain the doctor degree in Civil Engineering. Concentration Area: Water Resources.

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2023

Dados Internacionais de Catalogação na Publicação
Universidade Federal do Ceará
Sistema de Bibliotecas
Gerada automaticamente pelo módulo Catalog, mediante os dados fornecidos pelo(a) autor(a)

G23p Gasmi, Hela.
Participatory characterization of water resilience in rural communities in Brazil's Nordeste and central Tunisia / Hela Gasmi. – 2023.
196 f. : il. color.

Tese (doutorado) – Universidade Federal do Ceará, Centro de Tecnologia, Programa de Pós-Graduação em Engenharia Civil: Recursos Hídricos, Fortaleza, 2023.
Orientação: Prof. Dr. Eduardo Sávio Passos Rodrigues Martins.
Coorientação: Prof. Dr. Marcel Kuper.

1. rural water supply system. 2. water resilience. 3. participatory approach. 4. Brazil. 5. Tunisia. I. Título.
CDD 627

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Approved on: 03/11/2023.

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ACKNOWLEDGMENTS

This dissertation would not exist without the help of many.

First and foremost, my deepest gratitude goes to my two thesis directors, Marcel Kuper and Eduardo Martins, as well as my supervisors, Julien Burte and Sylvie Morardet. I extend my heartfelt appreciation to each of you for allowing me to embark on this adventure. Your guidance in nurturing critical thinking, your generous allocation of time and attention, and your unwavering academic support, combined with your rich experience, have been instrumental in my journey. Your support during challenging moments and times of self-doubt has been pivotal in my success.

Marcel, your trust and support have allowed me to transition from an engineer's mindset to that of a researcher. Thank you for encouraging me during moments of doubt along this journey. Eduardo, your profound insights, both as a professional and a human being, encapsulated in your famous words, "Vai dar certo e se não deu certo é porque o final não chegou ainda," have been a constant source of motivation.

Julien, thank you for believing in me from the very beginning of this adventure, which started with my master's degree. Your infectious enthusiasm and brilliant ideas have made you an exemplary supervisor. Sylvie, your benevolence and dedication in sharing your time and attention are deeply appreciated.

I also want to express my gratitude to the members of the jury who agreed to participate as jury members and for their keen interest in this research work. Additionally, I would like to thank the Sertoes and Pacte project teams, as well as Funceme, CIRAD, G-EAU, AFD, and SIRMA for their generous financial support for this research. I am also grateful to the Universidade Federal do Ceara, Institut Agro Montpellier, and INAT for their contributions.

To my colleagues at Funceme and G-Eau, I am indebted for creating a congenial working environment and offering a helping hand when needed. I must also express my heartfelt thanks to my enduring fieldwork partners, Leticia and Soumaya, with whom I shared the joys and frustrations of the fieldwork.

This thesis took me to different parts of Brazil over the course of four years, providing me with the opportunity to meet many people. While the list would be too long, I would like to extend my thanks to all those who helped me discover the Sertão. Many thanks to the families in the communities who graciously opened their doors to me, especially Bida, Leorne, and their families.

My heartfelt gratitude also extends to my friends for their love, encouragement, and moral support.

To my family, your patience and love have been a great source of support.

RESUMO

Esta tese foi desenvolvida sob a supervisão conjunta da Universidade Federal do Ceará - UFC - (hospedada pela FUNCEME, Fundação Cearense de Meteorologia e Recursos Hídricos) e do INSTITUT AGRO MONTPELLIER - (hospedada pelo CIRAD na UMR G-Eau). A tese faz parte de dois projetos de parceria: Na Tunísia, este trabalho de tese foi associado ao projeto PACTE (2018-2023), "Programa de adaptação à mudança climática dos territórios vulneráveis da Tunísia - PACTE". Como parte da implementação do programa PACTE, foi realizado um diagnóstico territorial participativo e sistêmico das áreas de intervenção em consulta com os diversos parceiros e comunidades locais (Morardet *et al.*, 2020). O diagnóstico se concentrou na gestão territorial da água, que será levada em conta na tese. No Nordeste brasileiro, o projeto Sertões (2021-2023) tem como objetivo identificar trajetórias de desenvolvimento que tornarão as comunidades rurais resilientes às mudanças climáticas. Esta tese dá continuidade às atividades de pesquisa e desenvolvimento realizadas na região Nordeste do Brasil no período de 2019-2020, lideradas por Julien Burte (CIRAD) e Eduardo Martins (Burte *et al.*, 2020). Como parte dessa tese, participei da supervisão de uma dissertação sobre a dinâmica de uma comunidade percebida por meio de relações de ajuda mútua (Boillot, 2020), de um projeto de pesquisa Água-Sociedade-Gênero (Laudemira *et al.*, 2021) e do treinamento de um grupo de quatro jovens pesquisadores da Funceme em abordagens participativas aplicadas à minha pesquisa de tese na forma de entrevistas participativas e workshops com comunidades rurais, partes interessadas institucionais e organizações não governamentais. A tese alternou entre trabalho de campo e visitas metodológicas, analíticas e de redação durante o período de 2019 a 2023. O que tornou o trabalho de campo especial foi o fato de que, embora estivéssemos trabalhando em dois ambientes semiáridos, os contextos sociopolíticos eram muito diferentes. A ideia não era realizar uma análise comparativa, mas tornar a abordagem desenvolvida mais robusta testando-a nesses dois contextos. Além disso, fiz cursos na UFC e em Montpellier como parte dos requisitos acadêmicos da UFC (68 créditos, 1.088 horas de cursos). Finalmente, de 2020 a 2022, o trabalho de dissertação teve de enfrentar dificuldades de acesso ao campo e de mobilidade devido à crise de saúde ligada à COVID. Realizando vários movimentos na Tunísia, no Brasil e na França, consegui garantir que o trabalho do campo nunca parasse.

Palavras-chave: sistema de abastecimento de água rural; resiliência hídrica; abordagem participativa; Brasil; Tunísia.

ABSTRACT

This thesis was developed under the joint supervision of the Federal University of Ceará - UFC - (hosted by FUNCEME, the Ceará Foundation for Meteorology and Water Resources) and INSTITUT AGRO MONTPELLIER - (hosted by CIRAD at UMR G-Eau). The thesis is part of two partnership projects: In Tunisia, this thesis work was associated with the PACTE project (2018-2023), "Program for adaptation to climate change in vulnerable territories in Tunisia - PACTE". As part of the implementation of the PACTE program, a participatory and systemic territorial diagnosis of the intervention areas was carried out in consultation with the various partners and local communities (Morardet *et al.*, 2020). The diagnosis focused on territorial water management, which will be taken into account in the thesis. In the Brazilian Northeast, the Sertões project (2021-2023) aims to identify development paths that will make rural communities resilient to climate change. This thesis continues the research and development activities carried out in the Northeast region of Brazil in the period 2019-2020, led by Julien Burte (CIRAD) and Eduardo Martins (Burte *et al.*, 2020). As part of this thesis, I participated in the supervision of a dissertation on the dynamics of a community perceived through mutual aid relationships (Boillot, 2020), a Water-Society-Gender research project (Laudemira *et al.*, 2021) and the training of a group of four young Funceme researchers in participatory approaches applied to my thesis research in the form of participatory interviews and workshops with rural communities, institutional stakeholders and non-governmental organizations. The thesis alternated between fieldwork and methodological, analytical and writing visits during the period from 2019 to 2023. What made the fieldwork special was the fact that, although we were working in two semi-arid environments, the socio-political contexts were very different. The idea was not to carry out a comparative analysis, but to make the approach developed more robust by testing it in these two contexts. In addition, I took courses at the UFC and Montpellier as part of the UFC's academic requirements (68 credits, 1,088 course hours). Finally, from 2020 to 2022, the dissertation work had to face difficulties of access to the field and mobility due to the health crisis linked to COVID. By making several moves in Tunisia, Brazil and France, I was able to ensure that the work in the field never stopped.

Keywords: rural water supply system; water resilience; participatory approach; Brazil; Tunisia.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

AFD	French Development Agency
ASA	Brazilian Semiarid Articulation
CBM	Community-based Management
COGERH	Company for Water Resources Management of the State of Ceará
CRDA	Regional Agricultural Development Commissariat
CIRAD	French Agricultural Research and International Cooperation Organization
DFID	Department for International Development
FUNCEME	Ceará Foundation for Meteorology and Water Resources
GDA	Agricultural Development Group
GIS	Geographic Information Systems
HSTs	hydrosocial territories
IBGE	Brazilian Institute of Geography and Statistics
IDEA	Farm Sustainability Indicators
INAT	National Agronomy Institute of Tunisia
INS	National Institute of Statistics of Tunisia
MDGs	Millennium Development Goals
MUS	Multiple-Use Water Services
NS	Nucleated Settlement
ONG	Nongovernmental Organization
PACTE	Program for Climate Change Adaptation in Vulnerable Territories of Tunisia
PREMISSA	Project of Resilience and Sustainable Rural Development in Banabuiú
RWSN	Rural Water Supply Network
RWSS	Rural Water Supply Systems
SDA	Secretariat of Agricultural Development
SISAR	Integrated Rural Sanitation System
SRH	Department of Water Resources of Ceará
UFC	Federal University of Ceará
WHO	World Health Organization
WRAF	Water Resilience Assessment Framework

SUMMARY

1 GENERAL INTRODUCTION

1.1 Problem statement

1.1.1 A problematic water supply in rural areas

The Millennium Development Goals (MDGs), in 2000, set a target to reduce by half the proportion of people without access to safe drinking water and basic sanitation at the end of 2015. The challenge was huge and the water target was missed with a reported high rate of non-functionality of water systems in rural areas (WHO, 2015): "it is rural households who have largely been left behind" (Sutton; Butterworth, 2016:5). This is probably why, in 2019, a new agenda of Sustainable Development Goals was fixed committed to "leave no one behind" on the road towards sustainable development (WWDR 2019).

Yet in 2021, it was reported that over 2 billion people across the world are experiencing high water stress and millions of people lack access to basic[1] drinking water. Remarkably, 80% of these people live in rural areas (WHO; UNICEF, 2021). It can be argued that instead of setting the bar very high in international commitments and then continually adjusting them, it would be practical to identify the problems behind the non-functionality of the water supply systems already in place and to study ways of improving water access coverage in rural areas.

The literature debate on water supply systems shows a significant disparity in the coverage of piped water between rural and urban areas (WHO, 2017). The implementation of water infrastructures in rural areas is more complex than in urban areas for multiple reasons: low population density; high cost; long distances; low capacity for maintenance; and vulnerable infrastructures (Chouinard *et al.*, 2017). Climate change is another element that adds to worsen the situation of water supplies in rural areas.

Once rural water infrastructures are delivered the struggle turns to their sustained functionality (Briscoe; de Ferranti, 1988; Carter *et al.*, 1999; World Bank, 2009). Researchers have shown that there is a high breakdown rate of water supply options, poor operations and maintenance, and little-used water supply networks (Roark and al., 1993; Kleemeier, 2000; Montgomery *et al.*, 2009). As the age of infrastructure increases, the costs of operation and maintenance increase too and it will require high public financial support "which may reduce

[1] improved source, provided in less than 30 minutes for a round trip

funding available for new works" (Sutton; Butterworth, 2016:2). Hutton and Varughese (2016) claim that in 2029 the costs of maintenance will exceed projected capital requirements for basic supplies and that water users alone will not be able to handle it.

Another challenging point is the management model of water supply systems in rural areas which is highly dependent on the local context (population density, geographical location, organizational structure of communities, national policies, and the capacity of service authorities). There exist different models of management (self-management, community management, private and public management). Until 1980, most of the rural water supply was delivered and managed by Government institutions through a supply-driven approach (Harvey; Reed, 2007). High costs, insufficient supplies, and chronic deficits were the weak points of the purely public managed water supply (Lewis; Miller, 1987).

Since the 1980s, community-led approaches to management have been highly adopted in rural areas then replacing the government-led models (Schouten and Moriarity, 2004). This was accompanied by reflections on more 'resilient' water supply systems, by focusing on the hard and soft components of water infrastructure in a way that anticipates, prepares for, and adapts to climate change conditions (Bocchini *et al.*, 2014; Cervigni *et al.*, 2015; Giordano, 2012; Kennedy; Corfee-Morlot, 2013). Moreover, the resilient infrastructures follow the emerging global discourse on a new water storage paradigm to reinforce the resilience of water systems to climate change (Martins *et al.*, 2016; Pangestu, 2023).

However, this model represents several limits such as the struggle to manage services based on informality and voluntarism. An unsolicited responsibility for service provision has gradually moved from the national government to local people (Whaley; Cleaver, 2017), in line with recurring criticisms on the notion of resilience as a way to put the burden on the individual, while the State operates a retreat (see Krüger, 2019). The non-functionality of community management in many situations shows that rural water supplies cannot be assumed to be handled by communities alone, in line with the rising expectations of water users. Added to that, promoting a community management model without providing support to address its weaknesses is likely to fail while allowing authorities to avoid responsibility for ensuring universal services (Linkov *et al.*, 2019).

1.1.2 Specificities of rural water supplies: multiple uses, multiple sources

In rural areas, water supply schemes are generally planned to meet the drinking and domestic water supply needs of the population. However, rural populations also have productive water needs, including irrigation and watering animals (van Koppen *et al.*, 2006). It has been observed many times that water systems that were designed for a single use become after their construction de facto multiple-use schemes (Soussan *et al.*, 2004; Moriarty *et al.*, 2004). Also, in many cases the designed water supply systems are under-designed in terms of ensuring water quality for drinking water, which makes that community members source their drinking water elsewhere, when they have the choice.

These gaps were targeted by the Multiple-use water services (MUS) network which created a systematic approach where "Multiple-use water services meet people's domestic and productive needs while making the most efficient use of water resources—taking into account different water sources and their quality, quantity, reliability, and distance from point of use." (MUS Group, 2013:1). The MUS is a network of some 19 core organizations and over 600 individuals comprising various actors (researchers, practitioners, funders) who have developed a multidimensional understanding of multiple-use water services and the necessary steps to expand this approach (MUS, 2013)[2].

The MUS approach is defined as a participatory and integrated approach to implementing water services in poor rural and peri-urban areas. This approach takes people's multiple water needs (drinking water, domestic water, productive water) as a starting point for providing integrated services (Van Koppen *et al.*, 2009). The MUS approach has been implemented successfully in several countries in Asia, Africa (Maroc), and Latin America. However, this approach faced stiff challenges from service providers and sector agencies due to institutional barriers, including practical concerns, policy limitations, and lack of collaboration between the subsectors and the structuring of the water sector according to single end-uses (Smits *et al.*, 2010).

The multiple water uses systems are in a way a traditional strategy in water-scarce areas where communities manage water for multiple uses from multiple sources. The rural communities use multiple sources for drinking, cooking, washing, bathing, cleaning, sanitation, cropping, gardening, livestock, fisheries, tree-growing, brick-making, crafts, and small-scale enterprises. The water users select water sources depending on seasonal rainfall; water quality; water availability; and the distance between the home and the water source (Almedom *et al.*, 1994; Macdonald *et al.*, 2016). This strategy is still present in many rural communities where

[2] The MUS group "has been operating since 2003 as the platform for learning, synthesis, and joint advocacy around MUS. It brings together people from a wide range of disciplines and countries." The group "collects evidence, tools, and best practice from around the world", it organizes regular workshops and meetings to exchange experiences, and it publishes handbooks and manuals. https://www.musgroup.net/

the domestic water supply systems are used for small-scale productive activities such as backyard gardening and livestock (Pérez de Mendiguren Castresana, 2004; Gasmi *et al.*, 2022). Thus, in rural areas sites near homesteads are the preferred site for domestic and other water uses.

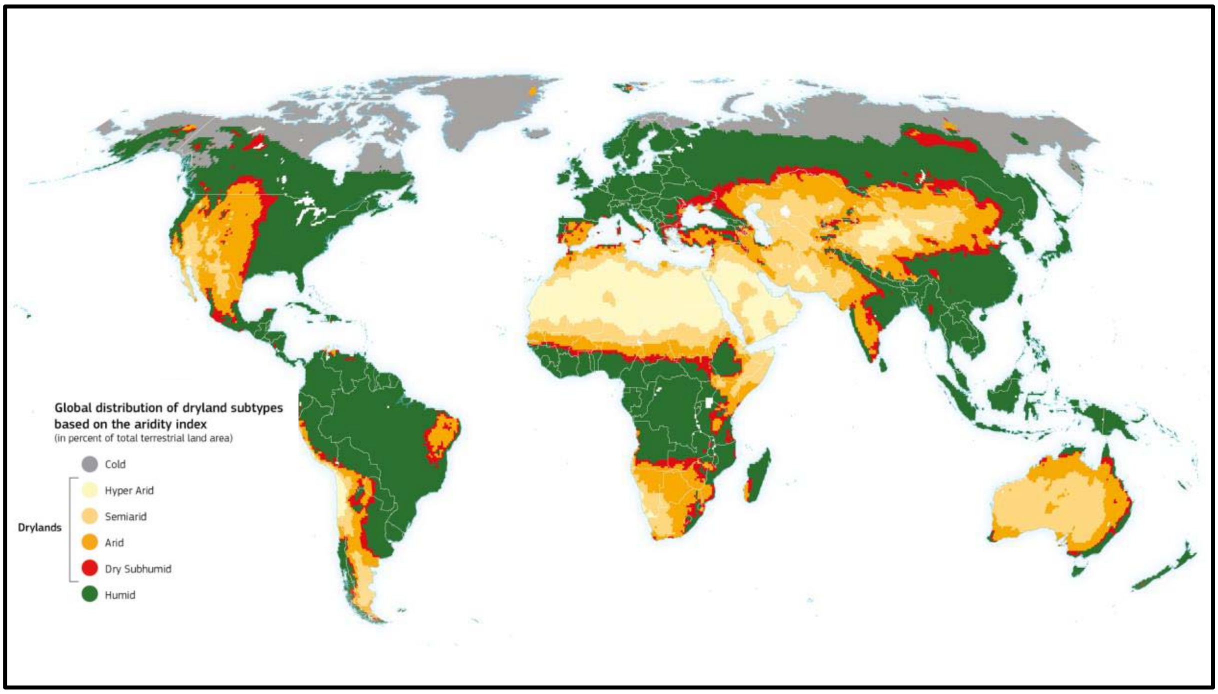
The homestead scale is an opportunity to increase the water resilience of households, an issue that is still poorly seized. Water sources near homesteads, including shallow dug wells, boreholes with pumps, ponds, and cisterns for harvesting roof water and runoff are most intensively used. For example, in India and Sri Lanka, cisterns are used for paddy cultivation, livestock, and domestic uses (Palanisami; Meinzen-Dick 2001; Somaratne *et al.* 2005), while in Tunisia and Brazil, the surface and underground rainwater-harvesting structures are used for cooking and drinking. Such infrastructures offer freedom from drudgery, guarantee quality water for drinking and cooking and give an additional benefit to livelihoods from the productive use of the homestead.

In other cases, irrigation systems are used for domestic purposes, such as drinking and washing (see Boelee *et al.*, 1999; Renwick, 2001). This may cause problems such as water resources pollution (cattle watering from irrigation or domestic canals and dams), irrigation system dysfunctions, and conflicts between the users (Moriarty *et al.* 2004). At the local scale, several arrangements are developed to use water from multiple sources for multiple purposes. These arrangements are dynamic and responsive to changes (Van Koppen *et al.*, 2007; Boudjellal *et al.*, 2011), which increase the resilience of local communities (Agarwal *et al.*, 2001; Van Koppen *et al.*, 2009).

In many cases, the arrangements around multiple uses touch the piped water network designed for human consumption in an unplanned way (Moriarty *et al.*, 2004; Van Koppen *et al.*, 2006). The unplanned uses can be absorbed by the system or can cause damage to water infrastructures (Gasmi *et al.*, 2022). Measures to prevent such water uses were taken by the states such as regulatory instruments (authorisations, restrictions on ‘‘illegal’’ connection to water networks), but they have been largely ineffective. To conclude, for rural communities in water-scarce areas, multiple uses from multiple sources are the main strategy of adaptation. However, the water sector continues structured according to single end-uses.

1.1.3 Brazil’s Nordest and Central Tunisia: a focus on infrastructure to deal with droughts and a call for community-management

Figure 1 – Global distribution of the climate classes over the periods from 1951-1980 and 1981-2010



Source: Global Precipitation Climatology Centre and potential evapotranspiration data from the Climate Research Unit of the University of East Anglia (CRUTSv3.20), WAD3-JRC, modified from Spinoni J. 2015. World Atlas of Desertification 2019.

Several researchers have studied water resource management in various semi-arid regions of the world, which constitute a difficult water context (Ragab; Prudhomme 2002; Branco *et al.* 2005; Hussain *et al.* 2019; figure 1). In Tunisia, for example, there is a long history of the water crisis and shortages, but most of the literature focused on infrastructural solutions (Feutras, 2021; see Rodina, 2019, for a larger argument on the 'hardware'). In a water scarcity context, several strategies were adopted to adapt to drought including water harvesting techniques (macro-collection and micro-collection methods).

The macro-collection method consists of floodwater harvesting and diversion methods. The runoff water is captured from hillsides or small arid watersheds (see Saidani, *et al.*, 2023). The micro-collection methods are implemented where the catchment area and the cropped area are distinct but adjacent to each other with a collection area of less than 100 m in length (Boers *et al.*, 1986). Rainwater can also be collected from rooftops in cisterns. Specifically designed dams (so-called "*açude*" in Brazil and "*as-sadd*" in Tunisia) can be used in certain locations to harvest rainwater depending upon geographic and topographical information are used for multiple uses (Molle, 1994).

For almost two centuries, the açude (see figure 2) has represented an original means of combating irregular runoff and mitigating the effects of drought. Because of their great multiplication, the açudes have become an integral part of the landscape of Nordeste Brazil, enabling the development of small-scale irrigated agriculture. Farmers are attached to their açudes. Significantly, in addition to increasing local production, dams and wells appeared as a source of prestige for some farmers an immaterial resource, and play a key role in structuring and maintaining local social groups (Riaux *et al.*, 2014). The operating limitations of these reservoirs lie mainly in the risk of drying up, especially during the dry season (8 months/year), due to the loss of a significant amount of water through evaporation and infiltration (Cadier, 1991). This led the State in Brazil's Nordeste to develop water reservoirs capable of withstanding several years of drought (Lepnm; Molieer, 1995).

Figure 2 – An açude used for domestic water and for watering livestock at the end of the dry season following a 6-year of drought in a rural community in Quixeramobim, Ceara, Nordeste Brazil

Source: Author, September 2019.

In Tunisia, the hill lake was introduced in the north of the country in humid and sub-humid climates as part of the national water and soil conservation strategy. Built entirely by local people, these water reservoirs were considered to be one of the most important factors in agricultural development in these regions. The main function of the hill lake was to mobilize runoff water. In the early 1990s, development projects changed significantly including the creation of 1,000 hill lakes, plus 4,000 structures for spreading runoff water. In 1994, these water storage infrastructures extended to several Sahel governorates and the governorate of Sidi Bouzid.

Then, the hill lake project covered the entire semi-arid zone, around half of the country's surface area (see figure 3) (Talieau *et al.*, 1994; Riaux *et al.*, 2014; Ogilvie *et al.*, 2019). Although natural potential varies greatly from region to region, all the areas where the hillside reservoirs are located have relatively similar development characteristics: poverty, remoteness, rugged topography, poor soil quality, and low and irregular rainfall (Albergel; Rejeb, 1997).

Figure 3 – An example of a communal hill lake in central Tunisia used for irrigation and domestic uses. This place has an important social value for rural women as it provides a meeting place to wash clothes and chat

Source: Author, April 2018.

To contribute to the development of rural areas and encourage administrative decentralization, the Tunisian government, which has been committed to a policy of structural adjustment since 1986, has tried to involve local authorities and organizations in the management of scarce natural resources. In this post-structural adjustment view, the role of the State is to mobilize water resources and initially provide a large part of the investment required to build water infrastructures. Meanwhile, water users must then take charge of the day-to-day management of the water networks. The water infrastructures available in recent decades have enabled Tunisia to store and transfer water. However, the drought from 2015 to 2023 in Tunisia has highly impacted the situation of water availability and the rural community resilience.

Tunisia has a longstanding experience with self-managed communal water systems going back several centuries, which were disturbed by a centralized public management system during the colonial and post-independence periods (Romagny; Riaux, 2007). In 1987, the management of all drinking water supply systems and borehole irrigation on public land was transferred to associations. This program was then extended to large-scale irrigation systems on public land. The purpose was to ensure that areas irrigated by boreholes and large dams were under the same management arrangements. However, extensive farming strongly affected by climatic hazards generates income that barely guarantees the financial surplus needed to cover the operation and maintenance costs of water networks, creating many difficulties for the communities supposed to manage them.

The semiarid areas of Nordeste Brazil represent one of the most densely populated regions of the country. Rainfall variability, land degradation, and poverty in rural areas make the Nordeste highly vulnerable to droughts. The principal approaches of adaptation to drought in the Nordeste of Brazil, are the implementation of drought infrastructure (associated with seasonal climate forecasts) and funds transfer and credits to affected farmers (Marengo *et al.*, 2022). For example, there were many public programs in the semi-arid area linked to the provision of cisterns to harvest rainwater (Figure 4). It is a strategy that targeted the increase of long-term water resilience in rural communities (Marengo *et al.*, 2021). This ambitious public policy of cisterns of developing “one million cisterns” was formulated in 2000 by the Brazilian Semiarid Articulation[3] (ASA) (Fonseca *et al.*, 2014).

The cisterns were implemented as a public policy and have been provided by nongovernmental organizations (NGOs) and the federal government, as an alternative for the population with difficulties in obtaining water for daily consumption. Before providing cisterns, women and children were forced to walk long distances to the nearest spring, fetching water in heavy containers (FOME ZERO, 2005). The collected water is often used for domestic and/or irrigation uses. In rural communities, harvested rainwater is the preferred water source because it is considered clean. Rainwater can also be harvested in the field by directing the surface runoff toward the agricultural fields. Another program of cisterns that was initiated in 2007 by ASA in the Brazilian semiarid region is the “One Land and Two Waters Program”. This

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[3] The ASA is a network that defends, promotes, and implements, including through public policies, the political project of living with semi-arid conditions, litt. coexistence with the semi-arid (Convivencia com semiarido). The network is made up of over three thousand civil society organizations of different kinds - rural unions, farmers' associations, cooperatives, NGOs, etc.

program aimed to construct rainwater harvesting technologies focusing on small agricultural productions (Alencar *et al.*, 2018; ASA, 2020).

Even with the low rainfall typical of semi-arid regions, the cisterns were shown as an efficient technology that is capable of meeting the water needs during the dry period (around 8 months) and have promoted “water independence” for families (Silva, 2006:1). However, the recent major drought from 2012 to 2022 has demonstrated that cisterns on their own were insufficient to withstand exceptional multiyear drought, leading the State to provide extra water through water tanker supplies. The insufficiency of stand-alone cisterns associated with drought is not limited only to the Brazilian semiarid, as other regions (Tunisia, Morocco) were also severely affected (Cunha *et al.*, 2019; Marengo *et al.*, 2021).

Figure 4 – Photo on the left presents an individual cistern for drinking and cooking during the dry season and for all uses during raining season in Brazil’s Nordeste. The cistern was delivered to the family through the project of “One Million Rural Cisterns - P1MC”, Forquilha. The photo on the right presents an individual cistern built by the family to stock rainwater in Rihana, central Tunisia

Source: Author, 2021.

Since the 1957 drought in Tunisia, the number of semi-buried cisterns has increased but it is still poorly supported by the State. The lack of a public policy encouraging the use of cisterns in Tunisia has not prevented communities from building several, in recognition of the adaptability of such a strategy to the semi-arid environment. In Tunisia, rural families often have two cisterns, one for storing rainwater (drinking and cooking) and the other for storing the water from the community network, which is cut off several times a day.

1.1.4 Self-supply, community management, and rural water supply

The community management model has been promoted from different perspectives: to reduce state involvement (Chowns, 2015; Schouten et al, 2003); related to water as a basic human right and a way to the empowerment of communities (Filmer-Wilson, 2005; RIGHTS, C., 2002); and to promote water as an economic good (Rogers *et al.*, 2002). From the perspective of reducing state involvement, community management can be seen as an approach that has been promoted because of the perceived failure of governments to provide services to large portions of their populations (Chowns, 2015; Schouten et al, 2003). Before the 1980s, most of the policies aiming to improve water access were based on a top-down approach without the direct involvement of rural communities and people.

From the empowerment perspective, national and local governments have to relate to population needs, in the way that external support agencies and non-governmental organizations brought a more adapted water supply project. Empowered communities may learn how to claim their human right to water access. From the perspective of water as an economic good, local communities are directly impacted by water pricing and play a crucial role in managing water resources sustainably, so their involvement is essential in determining fair and effective pricing structures; and, people first and empowerment approaches (WSSCC. 2000). Together, these perspectives contribute to better water governance and enhanced water resilience in various contexts.

In recent years, decentralized, community-driven approaches have been adopted in the design and implementation of development projects that often bring small water supply projects to rural communities. The water infrastructures decentralization started with community involvement in system construction and developed into community participation and community management. Water public policies in developing countries show a growing recognition of local users' role in rural water systems management. In this context, the participatory approach is seen as a means to transfer tasks, skills, and financial burdens to farmers.

Lockwood (2004) defines four key elements of community management: Participation; Control; Ownership and Cost sharing. However, these elements are revealed as myths (RWSN, 2010) and are based on the cultural idealization of rural communities (Harvey; Reed, 2007). Indeed, the first challenge does not concern only setting up water supply systems but also keeping them working over the long term (Schouten; Moriarty, 2003). Generally, the community management model begins to fall apart within 1 to 3 years after the implementation of the water supply system leading to the breakdown of the system (Harvey; Reed, 2007). External support is considered a key factor in the sustainability of water supply (Mazango; Munjeri, 2009).

1.1.5 Sustainability and Resilience of Rural Water Supply Systems (RWSS)

During my master's internship, I conducted an evaluation of the sustainability of small farms in central Tunisia using the IDEA method (Farm Sustainability Indicators). This method was initially developed for application in French farms and consisted of approximately 41 indicators covering the three dimensions of agroecological, socio-territorial, and economic sustainability (Vilain *et al.*, 2003). However, the method was not entirely suitable for the semi-arid and Tunisian context, and a set of new indicators were developed (Gasmi, 2019). Moreover, the concept of robustness was introduced to better qualify the trajectory of farms and the way farms resisted climate and socio-economic change. "Robustness… is a farm's ability to adapt to environmental, social, and economic fluctuations, and to deal with new conditions and/or disruption and external shocks. This property encompasses the concepts of resilience, adaptation, and flexibility" (Zahm *et al.*, 2018:6). This concept along with a set of revised indicators was introduced in a new version of the IDEA method.

This internship inspired me for two points in my Ph.D. thesis. The first point is that using a variety of European indicators to assess the sustainability of farms in a semi-arid context was not very adapted to the context and that the farmers tend appropriate more co-designed indicators to self-assess their farms. The second point is that the farmers who had been facing drought for years had a discourse strongly oriented towards resilience rather than sustainability. The reason for this is that the sustainability of farms is about thinking ahead, about future generations, whereas the current water situation is critical and requires emergency action.

As a result, I became convinced that a resilience lens, co-constructed with community members, would be pertinent to assess the sustainability of water supply systems at the scale of households and communities. Before starting my PhD, I started an internship at the Ceará Foundation for Meteorology and Water Resources (FUNCEME) where I worked on projects related to the resilience and the sustainability of (small) farmers in Brazil. It was an opportunity to conduct fieldwork and understand the way of life of rural communities in the Nordeste. The similarity of adaptation strategies of the rural community to drought in the Brazilian and Tunisian semi-arid contexts intrigued my scientific curiosity to engage in conducting fieldwork and interacting directly with community members in both countries during my thesis. A cross-view of two semi-arid contexts could only enrich the experience of the thesis and the reflection on water resilience. The sustainability or functionality of rural water supply is certainly a big challenge that needs to go further than the infrastructures and focus on providing a sustainable service.

Adopting a lens of resilience in this Ph.D. would prove to be quite challenging, because this term is at the same time the object of a rich body of literature with multiple debates (Folke, 2016), while the literature on 'water resilience' was only emerging (Rodina 2019; see 1.3 and chapter 2). Also, we found out quickly that while the term is loosely used in policy and project documents, generally without a clear definition, it is not at all familiar to the rural communities we encountered during the fieldwork of this Ph.D. This reinforced me in the idea to develop a participatory approach to co-define this term and co-develop indicators enabling to qualify this term.

1.2 Research objectives

Despite a growing interest in water resilience in rural areas, there is still significant scope for increasing its conceptual clarity and practical relevance in semi-arid contexts (Falkenmark *et al.*, 2019). Specifically, questions of what communities think of the delivered water systems and community water management model, and how these connect to water resilience remain unanswered (Rodina, 2019).

In this thesis research, we aim *to co-design, involving policymakers, water managers, NGOs, and communities, a conceptual and operational framework, developed around the notion of 'water resilience', that would enhance the understanding of how to design more sustainable rural water supply systems*. It seeks to stimulate reflection and contribute to the international debate on water resilience in semi-arid areas. Taking a systems perspective, we argue that 'water resilience' is a set of adaptative and dynamic properties of Rural Water Supply Systems situated within hydro-social territories (Hommes *et al.*, 2020). The specific objectives of this thesis are as follows:

1) Analyze and formalize the trajectory of community-based Rural Water Supply Systems;

The idea here is to identify and conceptualize the dynamic properties of community-based RWSS and the way these systems are adapted to maintain their functionality in the face of climatic or socio-economic change. The ambition was to enlarge the scope of the analysis by assuming that communities cannot be kept solely responsible for the functionality of RWSS (see Chapter 3).

2) Design a participatory approach to characterize the resilience of rural water supply systems;

To operationalize the conceptual framework (see specific objective 1), a participatory approach was designed and implemented to identify the key functions and features of water resilience (see chapter 4).

3) Analyze the effects of developing rural water infrastructure on water resilience at the level of nucleated settlements, communities and hydrosocial territories.

The notion of water resilience was investigated at different levels to account for water flows, which go beyond community borders, and for the multiple networks linking households, communities and hydrosocial territories (chapter 5).

The case studies chosen for investigation were the Nordeste region in Brazil (17 communities in the Quixeramobim municipality, Ceará State) and Central Tunisia (2 communities in Rihanna district, governarate of Sidi Bouzid), where the issues of water scarcity and resilience are particularly prominent. The idea was not to carry out a comparative analysis, but to select a diversity of case studies in order to develop a conceptual and an operational network that is robust and that 'works' for a range of situations in a semi-arid context (see chapter 3 and 4).

We propose a conceptual framework consisting of two parts (see for more details chapter 2). The first part aims to identify the rural water supply system's components and their trajectories. The second part answers questions such as "resilience of what in relation to what?". We focused on the water resilience of communities, linked to the trajectory of RWSS. We defined with different stakeholders in a participatory approach the notion of "water resilience" in rural areas and specifically in semi-arid areas. We operationalized the conceptual framework of RWSS by co-identifying three key functions of a resilient RWSS.

The operational framework gives practical content to the notion of rural water resilience by defining the features of water resilience for each function and by establishing the explanatory variables for these features at the intersection of scientific, practical, and local perspectives on rural water resilience. Our research provides an operational basis for building more resilient RWSSs. To address the perceived resilience of RWSS we identified and analysed the factors of water resilience at the scale of the nucleated settlements, community, and hydro-social territory.

To conclude, we developed a participatory approach to identify, analyse, and co-design water resilience at multiscale. Our work clarifies the ambiguity around water resilience in rural areas, and provides a viable basis for further theoretical and practical development.

1.3 Scientific debates that have inspired this thesis and key concepts

1.3.1 'Water Resilience' and 'Multiple Use of Water Services' (MUS)

Our work was first inspired by the rich resilience debates in the literature. Resilience is usually defined as the capacity of a system to absorb disturbance without significantly challenging its functions (Walker *et al.*, 2004). Resilience is driven by two factors, shocks and stresses, which are occasional, recurrent, and continuous perturbations such as drought, and flooding (Walker *et al.*, 2012; Folke, 2016).

Many researchers in the water and agriculture sector have tried to define resilience from different perspectives (see Table 1). However, the resilience linked to rural water supply has been less studied (see Falkenmark *et al.*, 2019), which intrigued our research to bring new reflections and contributions to this field. Resilience is now a very common word found in almost all project proposal documents as an objective of water supply infrastructures. This concept has become influential in development projects related to climate change adaptation, and disaster risk reduction. And the term resilience is increasingly used by international development agencies, donors and policymakers, non-governmental organizations and practitioners (Bené *et al.*, 2012, IRWG, 2012; TANGO, 2012; World Vision UK, 2013). The concept of water resilience has been also adopted in global policy discourses for water resilience governance (Brown *et al.*, 2009; Salinas Rodriguez *et al.*, 2014).

Lately, in 2021 (well after the start of our PhD), a general Water Resilience Assessment Framework (WRAF) has been developed, to support water resilience. It is based on three processes: visualize the current state of a water system, then define and measure the characteristics of resilience, and finally formulate the resilience strategies. This framework will be followed by guidelines that incorporate common practices and understandings, so that it can be applied by all stakeholders, in different contexts and at all scales of water systems (Chapagain *et al.*, 2021). The concept of water resilience is supposed to substitute conventional water planning (UN Water, 2012) and draw attention to nontechnical solutions (Rodina, 2019).

Resilience is commonly defined as the ability of a system or community to adapt or cope with shocks or stressors (climate change impacts, social crises, economic shocks, etc.) while continuing to maintain certain key functions or structures (Walker *et al.*, 2004). Despite all the progress, rural water resilience is still poorly understood when compared to "urban water resilience" (Heijman *et al.*, 2019; Kaaviya; Devadas, 2021; Makropoulos, 2019;). The complexity of conducting research on water resilience in rural areas is linked to the fact that water supply systems are used for unplanned multiple water uses.

Our understanding of this complexity was greatly enhanced by the literature on Multiple Use of Water Systems (MUS). Rural communities manage water for multiple uses (drinking, domestic, and agriculture uses) from multiple sources (Moriarty *et al.*, 2004). In many cases, the communities develop several capacities to adapt and to transform to face changes. These capacities are viewed as part of resilience strategies (Folke *et al.*, 2010; Walker *et al.* 2004; Brown; Kulig, 1996/97; Sonn; Fisher, 1998).

The local adaptation and transformation of water infrastructures are often traditional or informal, and in some cases, even illegal. Adopting the perspectives of the MUS group to prioritize the people's needs in the design of water supply systems in rural areas enables a more comprehensive understanding of their water resilience (MUS Group, 2013; Van Koppen *et al.*, 2009). However, in both literature and operational research, the reality of rural communities with multiple water supply systems has yet to be explored from a water resilience perspective.

Since *rural water resilience* is a relatively new term, efforts were made to find articles that might discuss the spirit of water resilience in rural communities even without using the exact term (see Table 1). Many theorists define the resilience of a 'system' but few define this entity and its boundaries. This is due to the multidisciplinary origins of resilience (Olsson *et al.*, 2015). The 'system' could be ecosystems, socio-ecological systems, a sum of resource systems, governance systems, and resource users.

In other cases, it can be applied in a community or city (Mayunga 2007; Holling 1973; Rodina 2019). Besides the nature of the system, we find a main division among the definitions based on the ability of the system to bounce back to normal, or the ability to adapt or transform to mitigate stressors and changes. Rodina (2019) has pointed out the need to "*understand the complex interactions between the technical, eco-logical, and societal dimensions of complex water systems and their governance implications.*"

Despite the many definitions, it appears that there is no consensus among researchers and practitioners on a common definition for the water resilience concept. Table 1 summarizes a few selected definitions of the resilience of the community, ecological and social-ecological systems, as well as water systems. As the list indicates, the definitions are diverse, reflecting the complex nature of the concept. The concept of resilience can be better understood in two ways.

Firstly, resilience is best perceived as an ability or process rather than merely an outcome, as suggested by Pfefferbaum *et al.* (2005) and Norris (2008). Secondly, it is more accurately characterized as adaptability rather than stability, as emphasized by Waller (2001) and Folke *et al.* (2010). Adaptability comes in various forms. On one hand, there is "engineering resilience," which involves a system remaining its function after experiencing a disturbance (Holling, 1973; Rodina, 2019). On the other hand, "Social-ecological Resilience" enables a system to have multiple desirable states that align with the surrounding environment (Gunderson, 2000).

Table 1 – Selected definitions of "Resilience"

Authors, year	Level of analysis	Definitions
Coles, 2004	Community	"Effective recovery can be achieved only where the affected community participates fully in the recovery process and where it has the capacity, skills and knowledge to make its participation meaningful"
Norris, 2008	Community	"A process linking a set of networked adaptive capacities to a positive trajectory of functioning and adaptation in constituent populations after a disturbance"
Walker *et al.*, 2010	Community	"The general capacity of a community to absorb change, seize opportunity to improve living standards and to transform livelihood systems while sustaining the natural resource base. It is determined by community capacity for collective action as well as its ability for problem-solving and consensus building to negotiate coordinated response."

Continuation

Table 1 – Selected definitions of "Resilience"

Authors, year	Level of analysis	Definitions
DFID, 2011	Community	"The ability of ...communities... to manage change, by maintaining or transforming the living standards in the face of shocks or stresses...without compromising their long-term prospects."
Frankenberger, 2013	Community	"A community is resilient when it can function and sustain critical systems under stress; adapt to changes in the physical, social, and economic environment; and be self-reliant if external resources are limited or cut off"
Pfefferbaum, 2005	Community	"Community resilience is grounded in the ability of community members to take meaningful, deliberate, collective action to remedy the effect of a problem, including the ability to interpret the environment, intervene, and move on"
Heijman *et al.*, 2019	Rural area	"Rural resilience may be defined as the capacity of a rural region to adapt to changing external circumstances in such a way that a satisfactory standard of living is maintained. This also includes the capacity to recover from management or government mistakes"
Folke *et al.*, 2010	Social-ecological system	"Is the capacity of a SES to continually change and adapt yet remain within critical thresholds. Three aspects are central: resilience, adaptability and transformability. These aspects interrelate across multiple scales"
Holling, 1973	Ecological system	"Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist"

Continuation

Table 1 – Selected definitions of “Resilience”

Authors, year	Level of analysis	Definitions
Waller, 2001	Ecological system	“Resilience, simply stated, is positive adaptation in response to adversity…Resilience is not the absence of vulnerability..Resilience is not static”
Gunderson, 2000	Ecological system	“The concept of ecological resilience presumes the existence of multiple stability domains and the tolerance of the system to perturbations that facilitate transitions among stable states”
Falkenmark, 2019	Earth system (water system)	“The role of water in safeguarding and sustaining a particular desired state of a social ecological system ranging from sustaining the state of ecosystems and biomes, and the ability of the hydrological cycle to maintain stable water supply for societies ..Water resilience is no longer just about water, they link to climate change, dietary choice, trade, consumption, and more”
Kaaviya and Devadas, 2021	Urban water system	“The system’s ability to retaliate and recover from various water-related disruptions”
Misund, 2019	Rural water supply systems	“Resilience is understood as the ability of a system to maintain performance and return to its former function after having endured stress or an unwanted incident. Resilience is in this seen to increase the overall sustainability of a system as it makes it more adaptive and robust. Infrastructure asset management has been applied as a framework to more directly address how to improve the resilience of rural water supply systems”

Continuation

Table 1 – Selected definitions of “Resilience”

Authors, year	Level of analysis	Definitions
Balaei *et al.*, 2019	Water supply system	“Water supply resilience in conjunction with community is defined as the physical status of water supply system and social, organizational, and economic capacity of the community to withstand the disaster and recover to a normal level of functionality in a timely manner. In studying resilience of water supply to disasters, the physical characteristics of the system is not the only dimension that can affect/be affected by the disaster. Economic state of the community, organizational well-being and preparedness, and social capacities of the community can affect water supply resilience significantly”
Rodina, 2019	Water systems	“Water resilience is commonly understood as the ability of water systems to withstand a variety of water-related shocks (floods, droughts, changes in water quality) without losing their ability to support key functions, as well as the ability of water systems to transform and adapt to new hydrologic regimes”
Béné *et al.*, 2014	Development context	“Building resilience would require interventions that strengthen the three components (absorptive, adaptive and transformative resilience) together, and at multiple levels (individual, households, communities, region, etc)”

Source: Author, 2023.

Conclusion

In this thesis, we chose the entry of resilience at the community level through the prism of systemic resilience strategies or capacities (absorption, adaptation, and transformation) (Folke *et al.*, 2010; Béné *et al.*, 2014). In a contextualized definition of water resilience, absorptive capacity is the capacity of a system (individuals, households, community) to cope with shocks and to meet their basic needs (Folke *et al.*, 2010). The ability to adapt and transform is therefore recognised to be at the core of resilience (Table 1). The adaptation represents the capacity to develop responses that touch on technical and organizational dimensions of water supply systems while allowing them to continue on the current trajectory. It can be done by diversifying livelihood strategies and engaging in new social networks (DFID, 2011).

Transformability is the capacity to develop a response by changing environmental or socioeconomic conditions and to shift into a new resilience trajectory. These three capacities could be used at the same time in a community to face one external shock. A simple example may illustrate this point: a multiannual drought in a semi-arid area in Tunisia may severely impact a community and drive it to be engaged in absorptive or adaptive resilience strategies. The community can create new wells while keeping the collective water network. whereas the same event may be absorbed differently by a household in the same community, which has an individual water network.

The concept of resilience has been heavily criticized because of its inability to appropriately capture and reflect social dynamics (Leach 2008; Hornborg 2009; Davidson 2010, Folke 2006). From this empirical starting point, we believe that communities adjust their expectations and aspirations when trying to cope with shocks (Teschl; Comim 2005). We can mention the following resilience strategies of rural communities: to accumulate water infrastructures (reservoirs, water networks, cisterns); to adapt and transform water systems to satisfy water needs; to be self-organized in ways to mitigate the stressors and adversities that may be attributed to natural, technological, or human causes; and to learn, plan for, and communicate about possible disruptions (see chapters 3 and 4; Coles, 2004).

1.3.2 Hydrosocial territories

At the first stage of our research, the investigation of water resilience was focused on the household and community levels, as they are considered the most targeted scales by public policies to reinforce the climate resilience of rural communities (Mattos *et al.*, 2022; Sabourin *et al.*, 2022). However, the close interaction with different stakeholders in Tunisia and Brazil and the community members allowed us to understand the importance to look also at higher levels of organisation, in particular the hydrosocial territories.

Such hydrosocial territories are defined as "socially, naturally and politically constituted spaces that are (re)created through the interactions amongst human practices, water flows, hydraulic technologies, biophysical elements, socio-economic structures and cultural-political institutions" (Boelens *et al.*, 2016). The historical approach of these authors prompted me to examine the history of water access in our study areas in Nordeste Brazil, and central Tunisia (chapter 3). Several development periods of hydrosocial territories in the study areas were identified: (i) extensive agriculture and associated infrastructures; the (ii) gradual appearance of irrigation and switching to a government interventionist strategy; and (iii) awareness of the impacts of over-implementation of water infrastructures on the resilience of rural communities.

Drawing on the broader literature of waterscapes, it is commonly defined as a biophysical space that should be included in water management (McLean 2012). This definition makes water issues appear as politically neutral that only depend on technical knowledge, and good governance to be solved. Contrasting with such a conception, we recognize the political and the social nature of waterscape or the so-called hydro-social territory-as the two concepts considered complementary (Flaminio *et al.*, 2022). The hydro-social concept can be applied to: water governance and politics of scale (Molle *et al.* 2009; Norman *et al.* 2012); territorialization processes (Boelens *et al.* 2016; Mustafa; Tillotson, 2019).

We adopted a hydro-social territory lens while investigating water resilience by considering the spatial dimensions of the coproduction of water and defining its boundaries, and actors with community members during participatory workshops. This lens enabled us to focus on the dynamic aspect of water resilience (temporal, spatial, and relational) by investigating dynamic relations between water users and stakeholders at different spatial scales (Adger *et al.*, 2005; Boelens *et al.*, 2016; Hoogendam, 2019). The resilience of rural communities (social resilience) to hydrological hazards requires significant inputs from social sciences. In our research, first, hydro-social narratives were used to capture the historical and geographical relations and processes of water territories in the basin (Bell, 2002).

In each hydro-social territory, the stories told by community members related to water infrastructure, the rules in use to provide sustainable access to water, and their relational networks with outside actors (Leong, 2021). Second. we chose hydro-social networks to highlight the social relations that connect stakeholders, infrastructures, and political, economic, and cultural scales. These scales are not fixed but are produced as defined by Boelens et al (2016:5): "that is, the geographically constituted 'levels' of social interactions and interconnectedness (e.g., household, community, watershed, region, nation, globe) – are produced, contested and reconfigured through myriad state, market, civil society and individual actions and everyday practices".

In addition, the hydro-social territory is a scale that provides some flexibility to deal with water problems on an appropriate scale and to offer institutional support (Garmestani; Benson, 2013). From the perspective of a resilient hydrosocial territory, this scale is not only needed for increasing water resilience but, potentially offers a feasible alternative for water governance.

We tend to focus on the political ecology aspect of hydro-social territory through the study of the evolution of these territories through the over-development of water infrastructures and their repercussions on existing water uses and users. Every year, national governments and international donor agencies invest in water infrastructure projects, and many still fail to maintain a sustainable water supply for rural communities.

For example, in the state of Ceará, there has been a massive investment by the state and by local actors in small-scale water infrastructure (cisterns, reservoirs, and boreholes)- 105,000 reservoirs and 36,947 boreholes were built in the last decade (Carrick-Hagenbarth, 2013; CPRM, 2023). In tandem with the increased use of water, these infrastructures have led to a spatial redistribution of water available from downstream reservoirs toward the upper basins (Campos *et al.*, 2000; Almeida 2016). We believe that learning from failures and barriers from case studies at multiple geographic scales in Ceará may contribute to the production of new knowledge for better water governance.

Figure 5 – The Ceará 's largest reservoir, Castanhão (6,7 billion m3), was at 5% of its capacity in 2019

Source: Author, November 2019.

The multiplication of reservoirs upstream, the overexploitation of large reservoirs downstream, and a drought of 10 years, have decreased the water resilience in the state of Ceará. In addition, at the end of the drought, the upstream reservoirs start to fill up first, which makes medium and small reservoirs an important water source for the state (Figure 5).

1.3.3 A participatory approach for the sake of research from a hydrosocial territory perspective

The limitations of state-led water management encourage the adoption of greater decentralization, where participation is identified as the main characteristic of the shift from governmental to non-governmental ownership and management of water resources and services (De Boer *et al.*, 2013). Participation is defined, following the World Bank (1996: xi), as « a process through which stakeholders influence and share control over development initiatives and the decisions and resources that affect them.

In this approach, stakeholders, including local communities, water users, government agencies, non-governmental organizations, and other relevant actors, are considered essential participants in decision-making processes related to water governance. Several principles for successful participation were identified by Luyet *et al.* (2012), including a fair, equal, and transparent process that promotes equity, learning, trust, and respect among different stakeholders; the integration of local and scientific knowledge; the establishment of rules in advance; early involvement of stakeholders; the integration of all stakeholders; the presence of experienced moderators; and adequate resources, including time.

Participatory approaches have become a major pillar in environmental resources management (Berkes; Folke, 2002). The participation of interested parties in development projects, irrigation systems, or drinking water systems can avoid (unexpected) resistance of actors while also providing access to different kinds of knowledge to solve management problems and find innovative solutions (Newig *et al.*, 2005). Thus, «public participation in water governance is typically motivated by normative concerns (people have a right to influence matters that affect them), substantive concerns (bringing diverse perspectives and knowledge together results in better policies), or instrumental concerns (the public accepts water policy because they were actively involved in shaping it) » (Ricart *et al.*, 2018:1).

A multifunctional water system irrigation is perceived as a hydrosocial territory as it is a spatially bound socio-material construct in which water is managed by interrelated physical elements, normative, organizational, and agro-productive elements (Seemann, 2016).

However, fragmented policy-making and implementation across the agricultural and water sectors are the main obstacles to governing multifunctional water systems irrigation (Akhmouch; Nunes, 2016). These obstacles may be tackled by mixing regulatory strategies and increasing stakeholder participation (Folke *et al.*, 2005).

Stakeholder engagement in multifunctional irrigation systems can contribute to shaping hydrosocial territories by reducing tension between stakeholders, redirecting regional planning and strategy, highlighting water crises, decentralizing water responsibilities, and integrating values and beliefs from different stakeholders (Ricart *et al.*, 2018). The engagement of stakeholders is a key ingredient for successful hydro-social territories management because it includes the inclusion of local knowledge, the integration of contrasting viewpoints, enhancing the quality of the project, and bringing of diverse forms of knowledge directly into the decision-making process (Graversgaard *et al.*, 2017).

However, in most public water infrastructure and multifunctional irrigation systems, stakeholders with competing perspectives are not asked to negotiate over policy (Susskind, 2013). In many cases, participatory approaches are implemented to validate choices that have already been made by technical services. There are critical variables that influence water governance, even with the implementation of successful participation, including the prior history of conflict, the incentives for stakeholders to participate, power and resource imbalances, and leadership (Ansell; Gash, 2008).

Scientific research can also be conducted through participatory approaches. The involvement of various stakeholders in scientific research provides opportunities for co-production and a shift in how science informs action pathways and decision-making (Lane *et al.*, 2011). This viewpoint is shared by Macaulay (2017), who regards participants as co-producers of knowledge by collaborating "with" individuals and communities rather than working "on" or "about" them. Regarding the tools used in a participatory approach, computer modeling and geographic information systems (GIS) provide a convenient means of integrating different types of collected data. However, these technologies can be complex for participants to access and share (Evers *et al.*, 2012).

To address this, participatory workshops with analog tools such as blackboards, paper, and participative maps, along with conceptual models may help to develop a shared vision throughout the research process (Roque *et al.*, 2022). For participatory modeling exists numerous methods with two well-known broader methodologies which are the Soft Systems Methodology (Checkland; Holwell, 1998), and the Companion Modeling (ComMod) approach

(Barreteau *et al.* 2003; Etienne 2014). In operational research, the mixing of methods has been viewed as a positive trend (Howick; Ackermann, 2011)

In this research, a variety of participatory tools are considered to investigate questions related to resilience and hydro-social territories.

2 METHODS

This section is structured into four parts. Initially, the research approach is presented, followed by a description of the tools used and the types of actors who were interviewed and engaged with us throughout the various phases of the thesis. The third part delves into the study areas in Nordeste Brazil and central Tunisia. Finally, we present the overall context in which this thesis was conducted.

2.1 Research approach

Our approach is based on involving stakeholders[4] throughout the water resilience assessment process to reinforce their role and their willingness to present their visions and participate in the decision-making process. However, the difficulties of implementing participatory actions are not specific to Brazil, as is the case in Morocco and Tunisia (Romagny; Riaux 2007). A decentralized approach influences the tool (indicators) appropriation by its future users. Moreover, simply copying the participatory process will not guarantee success in other case studies. Cultural, political, and historical contexts should also be taken into account in designing the methodology, which explains our interest in designing the methodology and validating it in another country with adaptation and by taking into account the heterogeneity of stakeholders (Irvin; Stansbury, 2004).

More operationally, we seek to answer the following questions: What methods should be applied to assess the trajectory of rural water supply systems and water resilience? At what scales should they be assessed?

This chapter introduces the study area and summarises the research method used. The methods are described in more detail in the respective chapters devoted to each stage (see Chapters 3, 4, and 5). The unit of analysis has not been the same for all research stages. For stage one (Chapters 3 and 4) four communities (2 in Tunisia and 2 in Brazil) and their households were studied. For stage 5 (Chapter 5) the Forquilha catchment as a whole (communities and nucleated settlements) was studied. The Forquilha catchment is regarded as significant by research institutes in Ceará due to the available data, making it a valuable scientific and experimental living lab. Thus, the involvement of the inhabitants in participatory

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[4] In this research, we consider the public as one specific stakeholder and therefore we use the term stakeholders for public, private and civil actors.

processes over the last 20 years. The focus in a catchment only in Brazil in the final stage is explained by fieldwork delayed due to the lockdown (COVID). However, this is planned for after the thesis.

The thesis research was built on an iterative process. The first stage was about to identify and to define the object of the thesis, *the Rural Water Supply System* through a territorial diagnosis. It was identified in the field, and it was around it that hypotheses and a research problem were progressively built. Our research is grounded in the theory approach (Multiple Uses Services approach and water resilience lens), which prioritizes the field as the basis for analysis, aiming to achieve a better alignment between theoretical formulations and empirical observations (Glaser; Strauss, 1967).

However, we approached the field with a critical lens, actively involving community members and stakeholders in the reflective phases. Furthermore, embracing multiple readings is essential to grasp the complexity of the observed phenomena in the field (Robbins, 2012), adding depth and richness to our understanding. During this research work, there were instances where observations in the field evoked previously read analyses. In other cases, dedicated reading periods aided in preparing for subsequent field phases. Noteworthy and unexpected findings from the field could thus be interpreted and enhanced through the literature.

To facilitate the process of distancing and ensure transparency regarding the deductive aspects of the approach, it was essential to document spontaneous thoughts or existing knowledge about the research subject prior to engaging in fieldwork. Maintaining regular field notebooks and reports also played a crucial role in this regard, allowing for a retrospective view of the evolving analyses constructed throughout the extensive duration of the research (Le Visage, 2020).

The research problematics evolved and refined as the study progressed in both countries, enabling us to question and formulate new hypotheses in a participatory approach involving community members and institutional actors. In the initial stage, we co-developed a conceptual framework for Rural Water Supply Systems (RWSS) that integrated the valuable experience of MUS practitioners in the water supply field, insights from our case studies, and relevant resilience literature. Subsequently, during the second stage, this framework was operationalized by involving various stakeholders to characterize the resilience of RWSS. Iteration involved revisiting analyses, adapting data collection, and validating or invalidating intuitions through constant interaction between theory and the field.

An example of the progressive reformulation of hypotheses and research problematics can be provided. In the first two years of the thesis, the plan was to focus on communities and co-designing resilient water supply systems as the final fieldwork phase. However, during interactions with various stakeholders on the field, the influence of administrative interventions at larger scales, such as the watershed, became apparent, leading to upstream-downstream conflicts. After further readings, it was decided to dedicate the third stage of the thesis to the spatial aspect of water resilience, examining them at two additional scales: a finer scale (nucleated settlements) and a broader scale (hydro-social territories) because we consider water resilience as a multi-scalar issue.

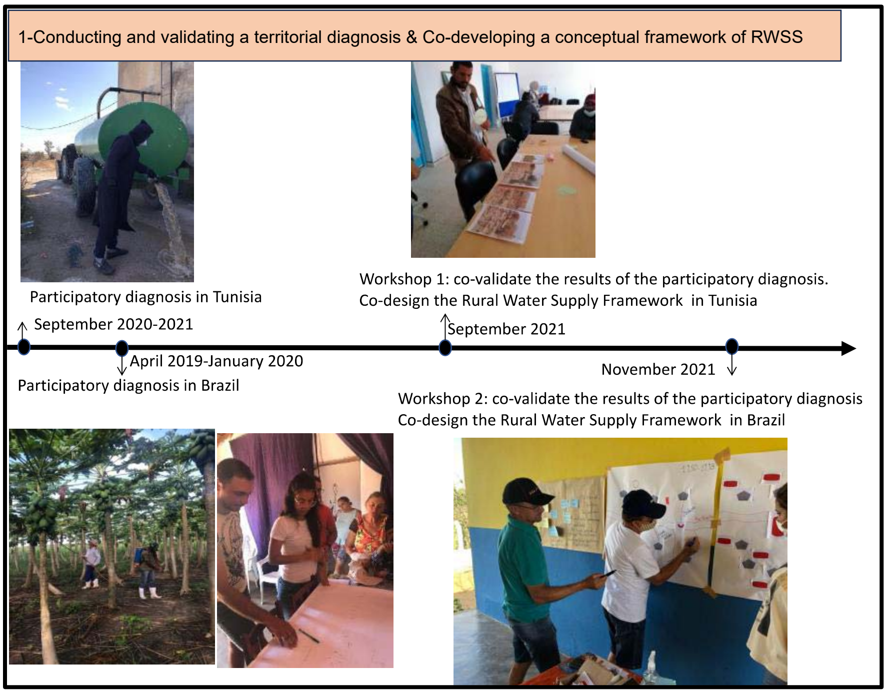
The first step was to prepare and validate the *territorial diagnosis*, using a participatory approach. The purpose of the diagnosis was to identify the Rural Water Supply System (RWSS) and to collect inventory data. This step was based on the farmers' understanding of their territory. During this step, we conducted exploratory surveys with local farmers in different communities to provide a preliminary diagnosis (Burte, 2015). The exploration of rural communities in Ceará had a profound influence on the development of the methodology of this thesis. Faced with the complexity of the access to water, which requires taking community members into account in the approach and in the construction of the object of these, extended stays with families were organized.

Then, we focused on four communities that had been subject to a recent multi-annual drought (2015 to 2023 in Tunisia and 2012 to 2018 in Brazil), while investment in infrastructure and institutional reforms have been intense (Campos; Studart, 2000; Johnsson; Kemper, 2005; Kemper *et al.*, 2007; Morardet *et al.*, 2020; Gasmi *et al.*, 2022; Dridi *et al.*, 2000). We identified different types of stakeholders including community members, and regional and national decision-makers. Our approach was progressive starting with open interviews and gradually moving towards semi-directive interviews that would help identify the local reality about water access. These interviews were combined with participatory observations which created a trustful climate with the community members needed for the reliability of data (O'Hara, 2009; Burte, 2016).

Then, we validated the diagnosis of the first phase with the communities and institutional actors. To accomplish this, we conducted a series of two workshops in Tunisia, combining the two communities, and two workshops in each of the two communities in Brazil (see figure 6). The two first workshops in each community aimed to validate the collected data through a triangulation process to feed the inventory phase. The workshops were also used to co-produce a typology of Rural Water Supply Systems and to identify adaptations of water infrastructure and rules made by community members to cope with drought. A conceptual model of the trajectory of RWSS territory was designed with community members to characterise the main components of the RWSS and their evolution in time, providing a simple representation of the adaptations and transformations made to maintain water access through time.

The information extracted through quantitative and qualitative semi-structured interviews was combined with participatory workshops to characterise the RWSS's typology. Based on the information gathered across the 4 communities, key water users and their statistical distribution were identified, leading to a typology by the community. The typology of RWSS helped to identify the links created among the different types depending on the period of the year (summer in Tunisia and dry season in Brazil). The typology (see Appendix 2) was used to choose the next workshop participants to ensure a representativity of each category.

Figure 6 – Different steps in the co-design of the conceptual framework of RWSS in Brazil and Tunisia

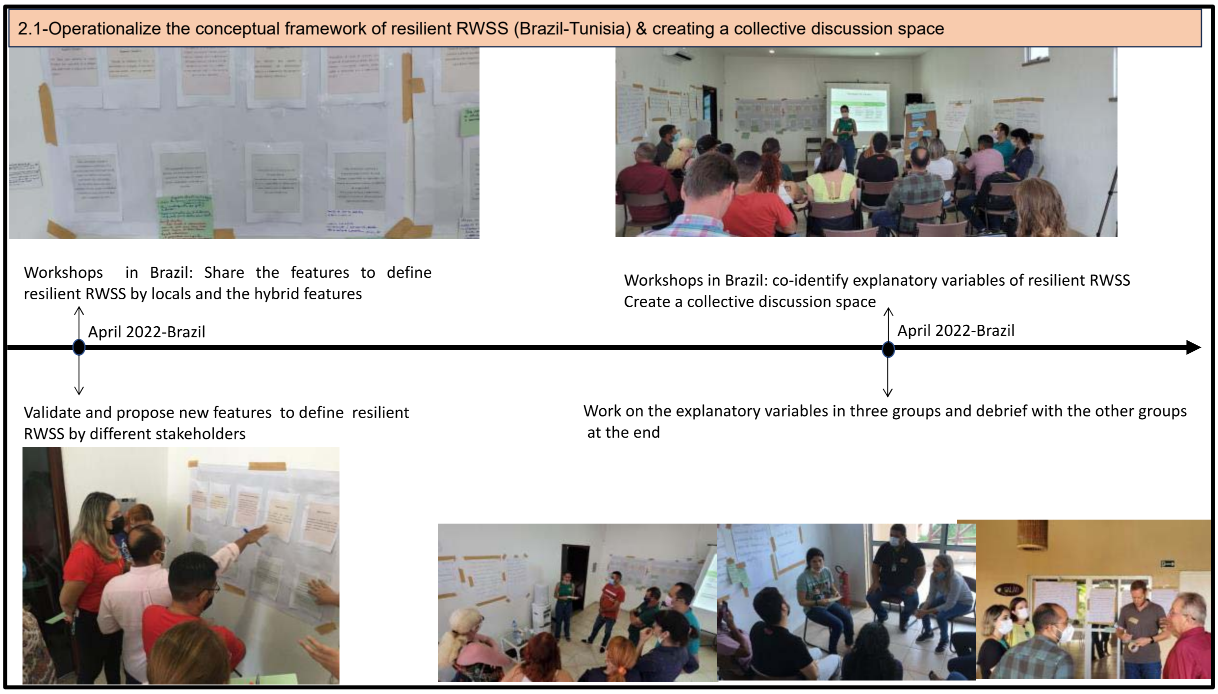


Source: Author, 2023.

The second phase had an objective to define water resilience and to define key functions to evaluate water resilience. Participatory workshops (6 workshops) were held in each community in Brazil and Tunisia to operationalize the conceptual framework of resilient rural water supply systems (see figure 7). Then a workshop was held with institutional stakeholders from national and regional water institutes, research institutes, and NGOs to align the visions about water resilience in rural areas.

This was followed by a mixed workshop with stakeholders from national and regional water institutes, research institutes, NGOs, and community members to validate the definition and key functions of water resilience. We brought in complementary elements from the resilience literature to open a discussion space. Then we validated the criteria of water resilience in a workshop with community members (step 2.2 in figure 8).

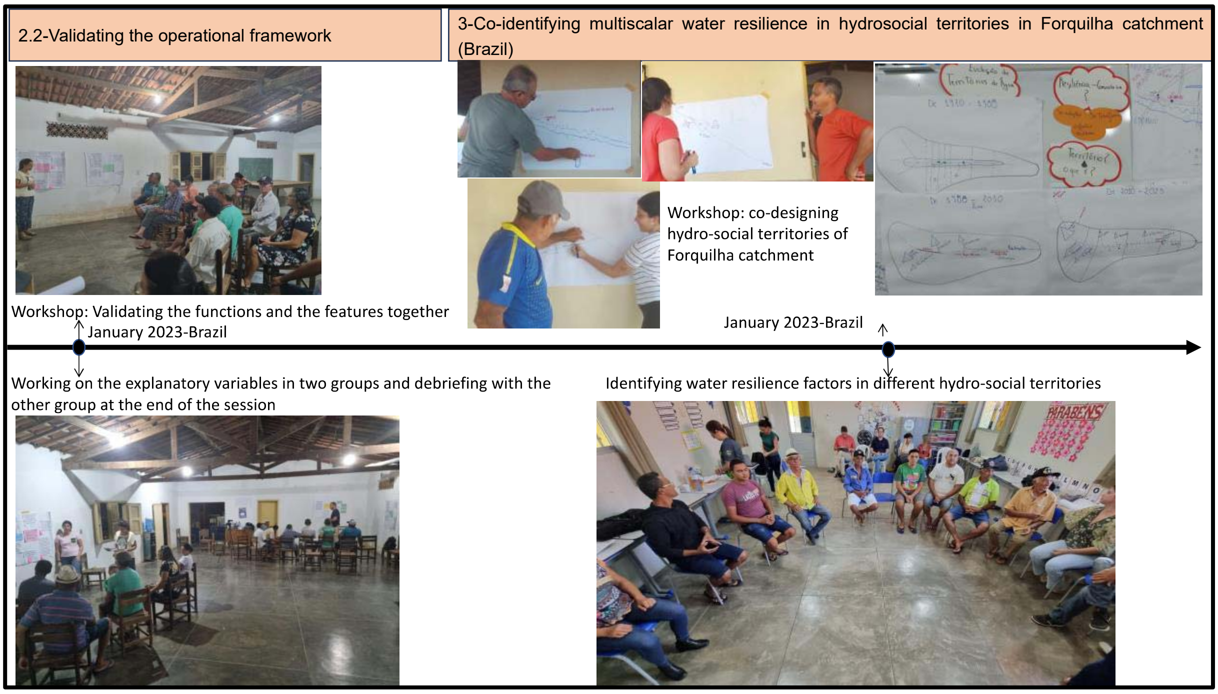
Figure 7 – The steps to operationalize the conceptual framework of RWSS framework and the co-identification of water resilience features and explanatory variables in Brazil and Tunisia



Source: Author, 2023.

And finally, the third phase consisted of combining water resilience literature with fieldwork which inspired us to investigate water resilience in multiscale (nucleated settlements and the catchment). Complementary fieldwork was held in a catchment in Ceará Brazil to identify nucleated settlements and the hydro-social territories. We also conducted interviews with women and seniors living in the selected rural communities. Seniors were interviewed for their historical knowledge in order to perform the diachronic analysis. Women are often responsible to fetch water when there is no piped water and for the maintenance of water cisterns for drinking and cooking. Men are responsible for providing water for agricultural use. To design the trajectories of hydro-social territory, participatory maps can be used to design external interventions and strategies for all types of human–water couplings on different scales from the community, river-basin to a global level. So finally, a territorial workshop was held with representatives of 9 communities of the Forquilha catchment to identify the factors of water resilience in different hydro-social territories in the catchment using a participatory map (see figure 8).

Figure 8 – Validating the operational framework of resilient RWSS & co-identifying the resilience factors of hydro-social territories in Brazil during focus groups and territorial workshop



Source: Author, 2023.

2.2 The tools used for collecting field data

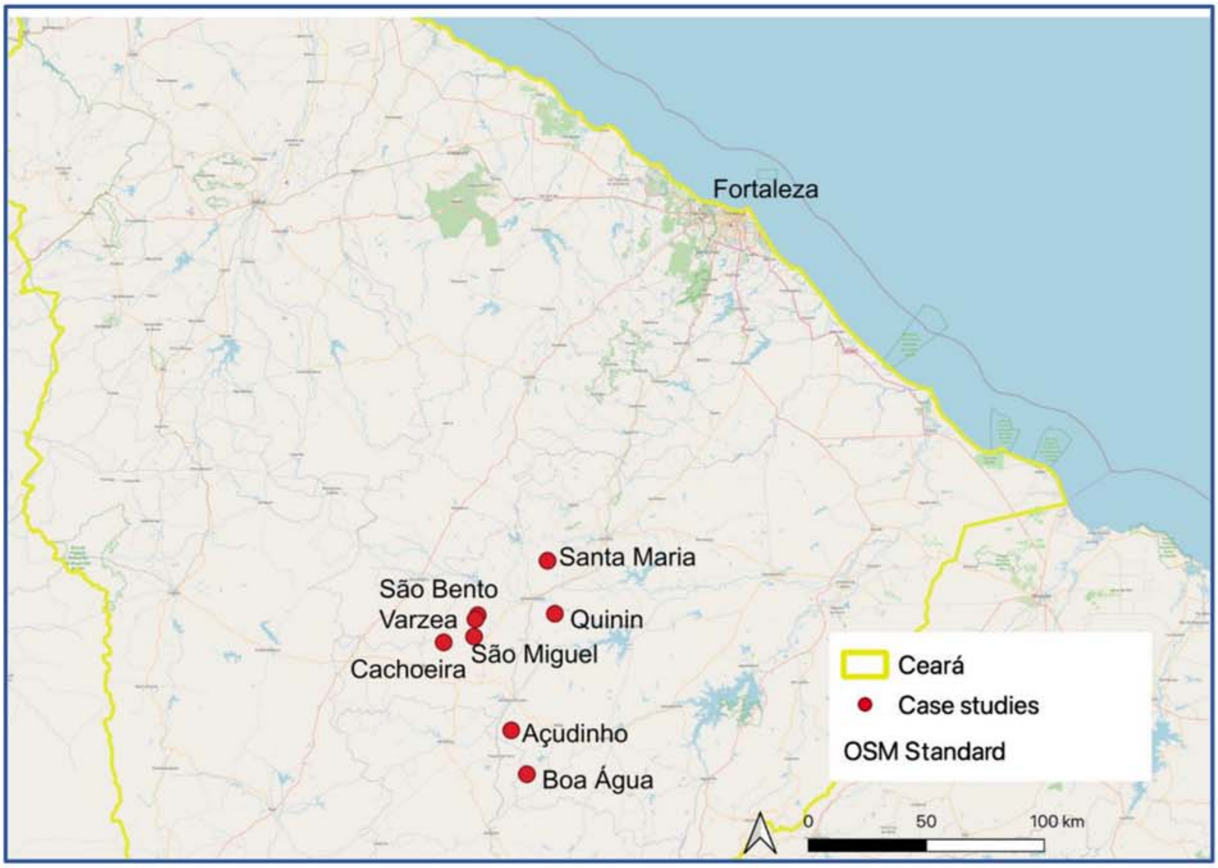
Different qualitative and quantitative research methods were used to gather empirical materials during the exploratory and in-depth investigation phases. Complementarily, four main methods were employed during the fieldwork: 1) participatory observation of agricultural landscapes, hydraulic infrastructure, irrigation practices, and interactions among specific actors; 2) open- interviews to reconstruct the trajectories of the individuals surveyed, as well as the trajectories of water supply systems and water policy; 3) semi-structured interviews to collect specific data; and 4) participatory workshops to validate the diagnosis and to co-design and co-define the water resilience.

2.2.1 Participatory and systematic diagnosis (Burte et al, 2020 in Brazil; Morardet et al, 2021 in Tunisia)

In our study, we explored eight rural communities (Figure 9), and then four were chosen for empirical evidence in two different contexts in central Tunisia and the Brazilian Nordeste.

These various case studies were selected in order to examine a variety of configurations based on different criteria: i) the presence of a community water network or not; ii) irrigation or rainfall-dependent; iii) the presence of a community association or not.

Figure 9 – Localisation of 8 cases study in Brazil



Source: Author, 2023.

The selection of these 8 cases study in Brazil has revealed a range of water supply management systems. We were also interested in observing water management as a dynamic process, as in several instances where communities that currently lack a community association for water management were previously organized as such, and vice versa. In Brazil, for instance, some communities were initially managed by a federation of association system but abandoned it due to the increased cost of water and, more importantly, because it restricted their autonomy. Conversely, in Tunisia, certain communities have expressed their interest in joining the national urban company.

Preliminary analyses considering the different dynamics, in terms of water resources, access, government support, presence of water use association, and agricultural practices in all 8 communities (in Brazil) distinguished 6 communities with a community association to manage the water network, 1 community with a federation of associations and 1 without. Further communities had unstable situations with a period with and another without association. A sample of 2 communities (Varzea do Meio and Santa Maria) was then chosen to conduct quantitative questionnaires about agricultural practices, water use, and management.

In Tunisia, I previously worked for my master's degree in communities in central Tunisia, specifically in the Kairouan governorate. As a part of the Program for Climate Change Adaptation in Vulnerable Territories of Tunisia (PACTE) which aims to enhance the governance of natural resources and strengthen climate change adaptation in rural territories, I had the opportunity to visit the five targeted governorates (Bizerte, Kairouan, Le Kef, Sidi Bouzid, and Siliana). However, for my PhD research, I chose the Sidi Bouzid governorate, particularly the city of Regueb. This city has a strong political engagement and has greatly influenced the revolution, which gives me personal motivation to work with the rural communities who see me as someone from within—a sense of belonging that I missed somewhat in Brazil. At the same time, this “facilitated” my access to institutional actors.

Unlike other governorates in Tunisia (such as Kairouan, Bizerte, etc.), the inhabitants of Rihana were not accustomed to communicating with students or researchers from the state. This only began with the PACTE project, and the residents were generally positive about these exchanges, which gave them hope that they were not forgotten by the government. Another aspect was the access to women, who are highly conservative in these areas but highly value the education of their sons. This motivated them to interact with me and to be engaged in a participatory approach with me as a doctoral student. However, permission from their husbands was generally required to participate in mixed workshops with men. However, I always introduced myself as a doctoral student to differentiate myself from researchers involved in development projects in both countries, as it could create false hopes for public actions.

2.2.2 Direct and participatory observations

Direct observation is an empirical research method that involves paying particular attention to situations, objects, and actors, and is thus essential for opening up and exploring the field: in this case, the trajectories of water supply systems, their construction, and their appropriation, which vary significantly from one resident to another or from one community to another. In addition, participatory observation was complementary, as the time spent with the communities allowed understanding of the population's daily life. This was an essential prerequisite for selecting the communities to study and delimiting the study areas (Arborio; Fournier, 2015). Once we selected the case studies, direct observation was also used during interviews. In fact, we often propose to accompany the community members being interviewed to their lands, which served as an entry point for the interviews. This approach allowed us to witness the practices they discussed, gain a better understanding of their narratives, and even locate the infrastructures they mentioned.

To understand the functioning of the first case study (Varzea do Meio), a family from the community hosted me for 15 days (Figure 10). During this first period, I accompanied the family head in the mornings on his irrigated plots (banana, papaya, beans, and corn), which helps me to become more familiar with Portuguese agricultural vocabulary. This contact with the family gave me access to their social circle of neighbours, cousins, relatives, and above all the network of women who are the main ones responsible for maintaining the water for drinking and cooking (cisterns, etc.).

Figure 10 – Participatory observations

Source: Author, 2023.

This period was important for my integration into the community, but also to maintain the bond of trust. Several other long visits were made during the 3 years in the same community and in the other community of Santa Maria.

2.2.3 Open interviews and Semi-structured, in-depth interviews in 4 communities

Conducting open interviews allows ample space for the individuals being interviewed to express themselves. Open interviews reveal issues that are identified as essential by the actors themselves (Becker, 2002; Blanchet; Gotman, 2007). The individuals met during the interviews may not necessarily be contacted in advance, which means the selection can be random (Becker, 2002) or sometimes suggested by other community members on the day of the interview. These open interviews explore various themes, such as the practices of the actors or significant dates and events in the community (e.g., the construction of reservoirs, roads, revolution, or several droughts). However, this does not prevent us from reintroducing pre-listed themes.

Semi-structured, in-depth interviews and surveys were undertaken (over 2019–2021) with community members on multiple water infrastructures, multiple uses, rules, and management issues identified through initial surveys. As a qualitative tool, semi-structured interviews were not meant to be extensively multiplied for the purpose of increasing representativeness. Instead, they aimed to provide illustrations and insights into specific complex issues that cannot be adequately addressed by other (faster) methods. (Longhurst, 2009). This tool, combined with participatory observations seek to build greater trust with the interviewee and allows to collection of multiple social (cultural, historical, political, institutional) and economic data which influence the practices around water.

Interviews trigger new questions and hypotheses which progressively reorient, refine, and nuance our evolving understanding of the rural water supply system in a water-scarce context.

The insights gained from exploratory interviews allowed us to design a RWSS questionnaire (see annex 2) to identify the spatial, statistical, and qualitative data around RWSS in some households and communities. The collected data in different communities were then triangulated, analyzed and compared (who shares the water resources, did the community have external support, what happened to the water user associations, and conflicts) until we discovered intermediary scales crucial for our analysis of water resilience such as nucleated settlements and hydro-social territory (De-Sardan, 2005).

Additional neighbour communities were visited to investigate the aid network between the communities. Almost all the households were interviewed on the following topics: livelihood strategies, agricultural practices across each plot (crop types, irrigation practices, livestock), water access and water multiple uses, water management, and future perspectives.

Additional questions on land rights and government assistance to draw out potential constraints influencing water use were also included especially in the community.

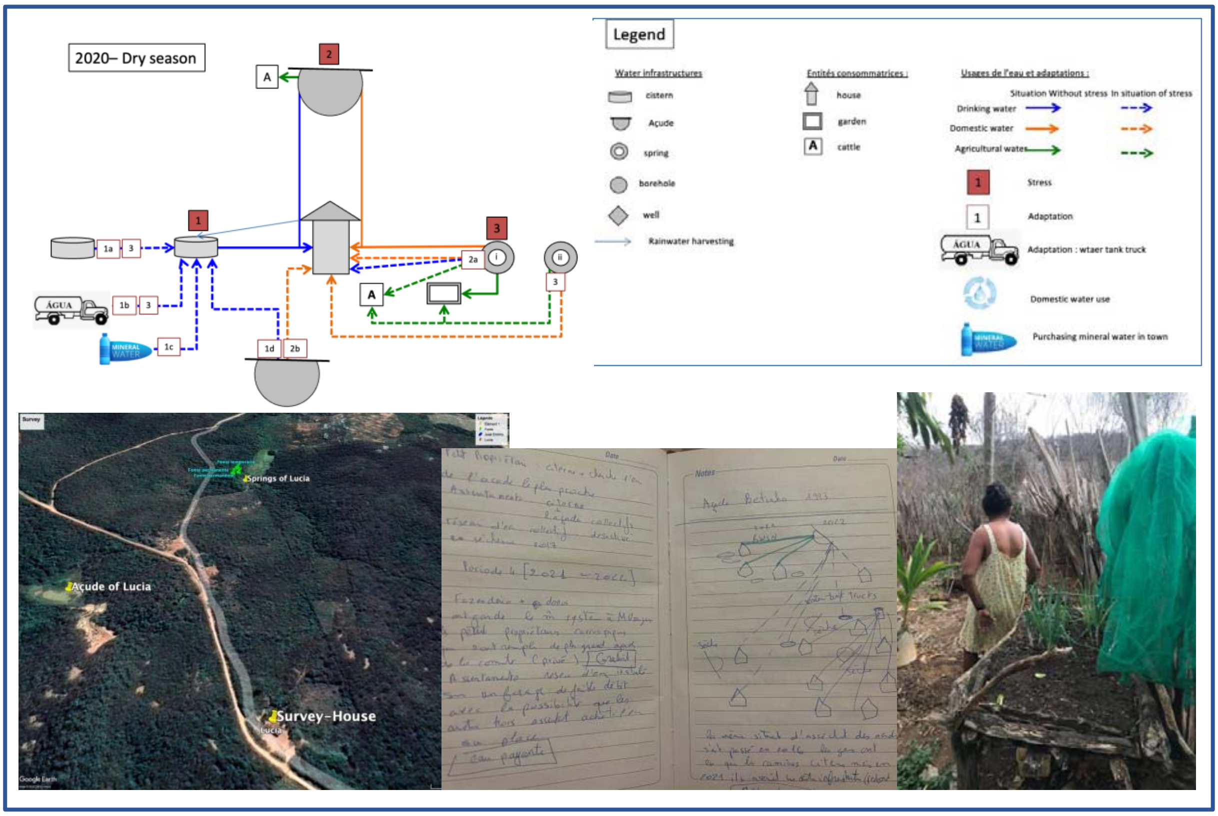
2.2.3.1 Life Story and historical analyses

The discussions were focused on the RWSS issues that were identified from the Multiple Uses Services (MUS) literatures and initial visits to the communities. Life Story sought to identify how practices and rules of water had evolved around the water infrastructures after their construction (Denzin et al, 2023). Focusing on the history of the RWSS, the origins of the water infrastructures (reservoir, well, spring, water supply network), their management, and water uses. The historical analyse sought to understand the influence of community associations, land ownership, and water rules, government vision.

Participatory Maps [5]were used as a visual aid to represent the location of plots and water infrastructures, and stimulate discussions (Collard; Burte, 2014). Some of the interviews were recorded (after asking permission), and then transcribed and typed up to clarify some ambiguities. Given the complexity of a trajectory of a water supply system with multiple resources, multiple uses, and multiple users, the very first household surveyed took a long time to complete. In one particular instance, in one of the case studies where the community went under agrarian reform, to ensure the accuracy of the information gathered (Figure 11), I visited a specific woman "Lucia" for three consecutive days. Each day, after transcribing the survey, new intricate questions emerged, particularly about spatial and temporal analysis. This included considerations of the past and present, as well as distinctions between the rainy and dry seasons.

[5] It is a form of participatory cartography created by farmers collectively. The produced maps in Varzea do Meio community was highly appreciated by the workshop participants who asked us to let it in their association's local space to be seen by the rest of the community during mensal meetings.

Figure 11 – An example of how I would process information during the fieldwork phase in order to define the research object of my thesis (using maps, conceptual model, interviews and taking notes)



Source: Author, 2023.

2.2.4 Other tools focused on the spatial and temporal dimensions of water resilience

This field approach was complemented by data collection from literature, press sources, social networks, and other documents provided by the encountered administration employees. Various tools were also employed to facilitate field exploration as well as to enrich and strengthen the collected empirical materials: landscape readings, Satellite maps, drone photos, participatory mapping, and life stories.

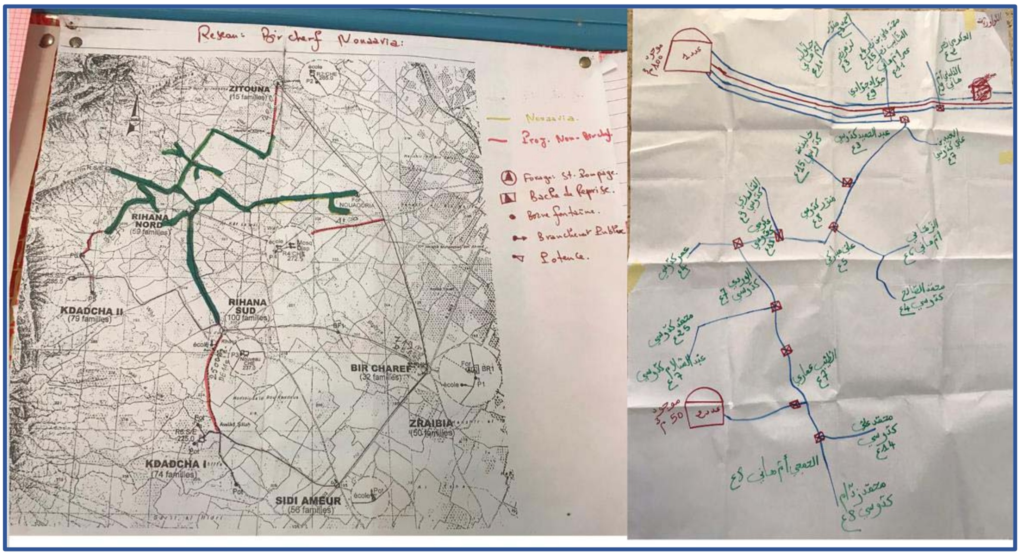
Firstly, landscape readings conducted during the initial months of fieldwork provided an overview of the organization of the studied territory. Observations were documented through written notes, photographs from cameras, and drone photos (Figure 12). At a more local scale, simple designs were also used to identify water infrastructures and networks. In Tunisia, in addition to these individual observations, field visits were also conducted with an employee from the CRDA of Sidi Bouzid, two presidents of GDA, a representative from the territorial committee in Rihana, as well as other researchers from INAT and my thesis supervisors and directors.

Several participatory maps were designed, where individuals were given a blank template to represent their community, farm, or plot. These maps deepened the information gathered on the participants' perception of their territory, including its strengths, constraints, water access, and agricultural water management. The maps served as a basis for discussion during the interviews as well as a support for the following workshops. By combining community input with drone imagery, the resulting maps became a collaborative representation of the communities' territories, incorporating both their lived experiences and the objective data captured by the drones which was a collaborative work with another geographic researcher from Funceme.

Figure 12 – Co-production of maps with various communities, with several of them, were then validated using drone photos.

Source: Author, 2023.

Figure 13 – The maps of the domestic water networks in North Rihana: on the left, one was created by the consulting firm, and on the right, by the Tunisian administration. Both maps are kept at the local community association's office, but they are not updated



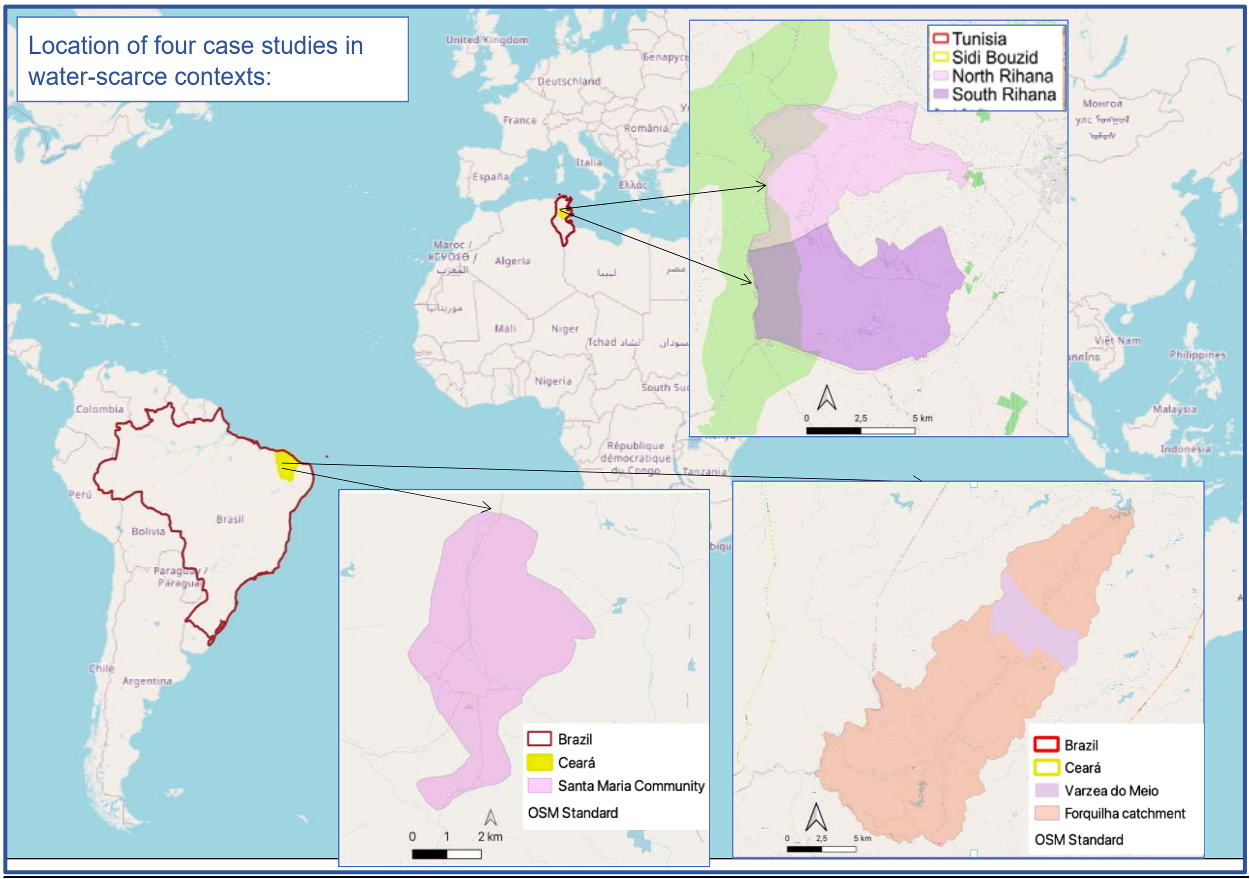
Source: Author, 2023.

2.3 Description of the Study areas

The advantage of working in two semi-arid contexts is to guarantee diversified case studies and thus a more general problematization of the subject of this thesis (not limited to a case study). This enabled us to examine better the socio-political differences and the similarity in the rural water supply systems. A very important point is that is not a comparative approach, but rather a methodological designing and validation process that takes place in the 2 contexts (Figure 14).

The Tunisian and Brazilian contexts are relevant in this research because 1) they are representative of regions where it is difficult to apply classical methods of resilience assessment, particularly due to the lack of reliable data and the limits of territorial systems that are difficult to define, which raises the question of the choice of the assessment scale 2) if territorial and development actors are not involved in the construction of the assessment method, it will be little or not used or will not be appropriate to meet the needs of decision support in terms of natural resource management, investment in water services and policy to support family farming. It is therefore proposed to implement a participatory approach to define indicators of water resilience, involving stakeholders at different scales (rural households, water service managers, and water resource managers).

Figure 14 – Two water-scarce areas (semi-arid), are Nordeste Brazil, and Central Tunisia. Location of four case studies: Varzea do Meio in Forquilha catchmentand Santa Maria community, Quixeramobim, Ceará, Brazil; Rihana north and Rihana south, Sidi Bouzid, Tunisia.)



Source: Funceme, Agricultural Map of Sidi Bouzid, author.

Table 2 – The administrative scales in Brazil and Tunisia

Tunisia	Brazil
Central Tunisia	Ceará-Nordeste
Government (Sidi Bouzid)	Municipality (Quixeramobim)
Village (Regueb)	District (Manituba and São Miguel)
Community “Douar-Ouled”	Community “comunidade”

Source: Author, 2023.

2.3.1 The Nordeste of Brazil

The Nordeste in Brazil has a history of recurrent water stress (Gaiser *et al.*, 2003; Guerra; Guerra, 1980; Villa, 2000), which is related to both rainfall variability and human intervention. This approach became known as the *'solução hidráulica'* (hydraulic solution) (Guerra and Guerra, 1980). The Brazilian semi-arid region has developed special public policies linked to drought (Neves, 2003). Before the 1990's, these policies focused on the '*lutar contra a seca*'(fight against drought), linked to the fear of massive migration to the cities. This policy provided for the construction of big dams for water storage and the creation of institutions to manage local water resources.

However, many state initiatives were directed to the benefit of a minority, such as digging wells and building small dams on the private land of big landowners. Water shortages and poverty in periods of droughts (1979-1983, 1987, 1990-1993, 1997-1998) accelerated the migration to coastal urban centers. In this context, "concentration camps" were constructed in the state of Ceará taking in compulsorily the refugees to move them away from the urban center (Neves, 1995). However, the policy of dam construction associated with emergency actions was inadequate to face droughts. After 1990, drought policies were therefore focused on "living with drought", putting the fight against poverty center stage.

The policies for the modernization of the economic base in the countryside and the alternative practices of coexistence with drought have, therefore, been implemented simultaneously with an income distribution policy. Social programs like the rural retirement fund and the family allowance (*Bolsa Família*) contributed to the fight against poverty and inequality in Brazil. In the state of Ceará a public policy for rural infrastructure, focused on 'coexisting with the drought', was implemented in 2000.

The late paradigm was followed by a new State Water Resources Law (Port; Kelman., 2000). It was principally about incorporating technical and participatory organisms. This resulted in the emergence of the Users Commissions and the River Basin Committees to enable the debate and the allocation of water (Lemos; de Oliveira, 2014; Mesquita, 2018).

However, the Users Commission was poorly formalised and faced various problems as such as competitiveness between multiple users; and conflicts between users from upstream and downstream of the basin. The River Basin Committee was formalised, but its role has been challenged by government sectors. The State administrators and technocrats were threatened to lose control over natural resources management (Lemos; de Oliveira, 2004).

Then, the Water Law defined the river basin as a planning unit, where stakeholder participation is limited to the negotiated allocation of water and to conflict resolution. This makes local stakeholders powerless in decision-making that affects them directly, such as the inter-basin transfers. According to Formiga Johnsson and Kemper (2007) the basin scale as the lowest appropriate level for decentralization, is not relevant and the state needs a smaller territorial level. In 2007, the Management Commissions of Dams was created, which is composed of users, civil society representatives, and government representatives (Secretariat of Water Resources, 2007). Currently, this structure functions as a local management body and is linked to the basin committees to conduct negotiated water allocation, environmental education, and conflict mediation (Frota *et al.*, 2013).

At the rural community scale, we can visualize institutional collaborative synergies, as in the case of the Secretariat of agricultural development (SDA) with the federation of associations called 'Integrated Rural Sanitation System SISAR'. In this partnership, after SDA finalizes the infrastructure – the rural water supply system - it seeks SISAR's support to carry out the management of its water system with the community (Meleg, 2012).

This collaboration requires the presence of a community association as a partner in water supply management. However, the SISAR does not provide services for less than 50 families and has to be well organized and have good physical infrastructures and easy access to the communities (Alves; De Araújo, 2016). As a consequence, the isolated communities without difficult access are not covered by water utilities like Sisar.

As a solution, modern water supply networks managed by community associations have been set up in rural communities by external investments. However, most associations have a low capacity for self-organization and cannot deal with external hazards due to a lack of financial sustainability. This explains the persistence of emergency assistance, such as tank trucks, during times of water crisis. So far, little institutional support has been given to water management in rural areas with isolated and sparsely populated communities.

Two communities Santa Maria and Varzea do Meio were selected in the municipality of Quixeramobim. Quixeramobim is located in the Banabuiú basin in the state of Ceará. The most rain falls in the period January-June. Temporal rainfall variability is highly significant on a range of levels: decadal variability (Souza Filho; Porto, 2003), inter-annual variability, and seasonal variability.

Two kinds of competition for water seem to occur. First, there is competition between upstream and downstream users. User communities that are located directly upstream of reservoirs tend to disagree with downstream user communities over water releases. Upstream users generally oppose water releases, while downstream users favor them (Broad *et al.*, 2007; Taddei, 2005). Secondly, water users within a local user community compete, generally more or less equally, for water from the same local water resource such as a reservoir or aquifer.

2.3.2 Central Tunisia

Before going into the review of the application of rural development policies at the territorial level of the study areas, we will present briefly their evolution at the national level. After independence in 1956, the water strategy in Tunisia was focused on maximum resource mobilization and the construction of large dams. Since 1960, water policies underwent major reforms, which aimed at better control of water demand and better planning of its use. Tariff instruments and promotion of water-saving techniques were promoted.

Since the mid-1980s, there has been an evolution of public policies in Tunisia corresponding to rural development based on a territorial approach, multi-sectorial, and management by the local public, private or associative actors (Campaign, 2004). Expectations were created for job opportunities, improved standard of living, increased agricultural income, access to social services, and the creation of infrastructure (drinking water, electricity, communications, businesses) (Lazarev; Arab, 2002).

After the implementation of a strategy focused on maximum resource mobilization and the construction of large dams (95% of resources are already mobilized), water policies underwent major reforms in the early 1990s. These aimed at better control of water demand and better planning of its use, through the implementation of tariff instruments and the promotion of water-saving techniques. They were also accompanied by legal and institutional reforms that allowed the transfer of management to water users' associations, more commonly known as agricultural development groups (GDAs). However, the State's disengagement from the water sector has not led to a rationalization of its management and real empowerment of the GDAs.

The GDAs lacked the necessary expertise and there were organizational problems preventing them to provide sustainable water services. The increasing demand for water (drinking water and irrigation) is now leading to various conflicts, especially since the Tunisian revolution of January 14, 2011. In this thesis, we selected two communities in Rihana: The Ouled Salah community (Rihana south) and the Ouled Om Hani community (North Rihana). The Rihana district (90 km2) in Central Tunisia (governorate of Sidi Bouzid) is among the most environmentally and socio-economically vulnerable areas of the country. In Rihana, there are two logics of water conservation strategies: In upstream, preserving local natural resources to maintain productive potential (Figure 15).

This aims to fix the soil and limit runoff in order to preserve arable land and guarantee soil fertility (Figure 16). This has led to policies encouraging the adaptation of production systems through traditional water management strategies. Downstream, the main strategy is to preserve downstream hydraulic infrastructures and settlements, where major economic stakes and more intensive activities are at stake. In vulnerable rural areas, hydraulic equipment such as dams and embankments must be installed to protect water quality and public equipment (roads and houses) (Roose *et al.,* 1993). Livestock is a major traditional activity maintained by surface water in Brazil and around groundwater in Tunisia. However, due to multi-annual droughts, farmers declared progressively abandoning this activity. Rihana is considered to be a marginal area with a pastoral vocation, characterized by massive emigration and a strong rural exodus, particularly in mountain areas.

Figure 15 – Public water erosion protection measure upstream in Rihana catchment

Source: Author, 2023.

Figure 16 – Individual water erosion measure (Tabia) protection upstream in Rihana catchment in a private land

Source: Author, 2023.

Water management in both contexts has several features in common. Natural and climatic constraints mean that access to water is highly variable. Mobility, flexibility in land and resource use, and diversification of agricultural production have been the most adaptive communities faced with different types of hazards (Figure 17). Moreover, both areas have experienced relative isolation from centralized areas deprived of economic resources to develop infrastructure and improve living conditions. The public intervention has significantly contributed to the profound changes in these rural areas. On the other hand, their collective, technical, and social organization skills also represent different cultural and historical heritages (colonization, slavery, religion).

Table 3 – Comparing the contexts of Tunisia and Brazil

Differences	- Management systems - Institutional and social frameworks: For drinking water people prefer rainwater but the construction of cisterns is a public policy more encouraged in Brazil than in Tunisia. -Public policies: water resource management at basin level by basin agencies in Brazil and a centralised management system in Tunisia based on government regulation. - Know-how and practices. -the type of resources used (surface water in Brazil, groundwater in central Tunisia);
Common points	- Natural and climatic limitations result in variability in the conditions of water access. - These regions have experienced relative isolation from the central government, which provides economic resources for the development of infrastructure and the improvement of the population's living conditions. - Mobility, flexibility in the use of territories and resources, diversification of production are the main adaptation strategies of the communities. - The dissatisfaction with water services creates problems of collective management and leads to individual adaptations. - The social capital is well developed and mobilized by people

Source: Author, 2023.

Figure 17 – Photo on the left. a community member with a means of transport buys a 1000-liter water tank himself (this quantity of water is considered small and is often offered free of charge). Photo on the right the water truck operator buys water from a private well

Source: Author, 2023.

2.4 The general context in which this thesis was carried out

The investigations carried out for the analysis of water supply system trajectories were spread over time, with successive field visits. First, I participated in a participatory diagnosis and exploratory fieldwork on water resilience as part of the development project (PREMISSA project, see Burte et al, 2020) conducted by Cirad and Funceme. This led to the award of a doctoral scholarship, which subsequently facilitated further field visits during the thesis. These field visits helped refine the research focus and confirm the relevance of the selected communities for the study, after identifying the use of multiple water sources (surface water and groundwater) for multiple purposes and through multiple water infrastructures.

These fieldwork phases were also punctuated by meetings with stakeholders located outside the studied communities, such as regional and municipal employees and officials at the national level in Tunis and Fortaleza, employees from the Ministry of Agriculture, as well as representatives and employees of active associations and NGOs. Meetings with hydraulic administration engineers in Quixeramobim were frequent, with multiple visits during each stay.

In addition to these fieldwork phases, the research work was also completed through analysis, reading, and writing periods. Several trips were made to Montpellier as part of the cotutelle. Stays were organized in Montpellier and elsewhere to exchange with researchers working on water. Other experts on Tunisia were met at the National Agronomy Institute (INAT) in Tunis during my stay in Tunisia (table 4). Participation in seminars and conferences was challenging during the COVID period, but I managed to participate in a few since the writing of the thesis papers was stimulating in light of the encounters made on such occasions.

Table 4 – Research organization

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
2019*	Literature review Fieldwork in Brazil					Fieldwork in Tunisia		Identify and analyse the research object			Writing paper 1 in Montpellier	
2020*	Attending courses online (see figure bellow)				Inscription at Institut Agro Montpellier	Literature review		Inscription at UFC	Fieldwork in Tunisia		Writing paper 1 in Montpellier	
2021*	Literature review Fieldwork in Tunisia: Designing a participatory methodology										Writing paper 2	

Continue

Table 4 – Research organization

Month / Year	1	2	3	4	5	6
2022*	Fieldwork in Brazil: Validating the methodology & codesign water resilience criteria	Writing paper 2	Paper 1 published Writing paper 2	Fieldwork in Tunisia	Fieldwork in Brazil	
2023	Writing paper 3 in Montpellier	Thesis writing				

Source: Author, 2023.

Conclusion

*The classes required at UFC-Brazil were attended over 4 years instead of one complete year which gave me time to conduct research work.

Figure 18 – Hight requirements for classes at the Federal University of Ceara

High requirements for classes at UFC-Brazil (1088 hours)

Program Information

Department: **Graduate Program in Civil Engineering**

Program: **Doctoral Program in Civil Engineering (Water Resources)** Curriculum: **2016RH**

Field of Research:

Advisor: **258.425.873-00 - EDUARDO SAVIO PASSOS RODRIGUES MARTINS**

Admission Procedure: **INTERNATIONAL JOINT SUPERVISION OF** Initial Month/Year: **August/2020**

Status: **Active** Final Average Grade: **8.99**

Deadline for Program Completion: **February/2026** Current Month: **33rd**

Reason for Exit: ---

Ongoing Courses/Activities and Earned Credits

Start Date	End Date		Course Description	Credits	Attendance %	Grade	Status
9/2020	3/2021	TDP7877	WATER RESOUCE CONSERVATION	3	87.50	8.5	Pass
9/2020	3/2021	TDP8011	WATER RESOURCE MANAGEMENT: INSTITUTIONAL AND LEGAL ASPECTS	3	100.00	10.0	Pass
9/2020	1/2021	TDP8417	ADVANCED HYDROLOGY	4	100.00	8.5	Pass
4/2021	10/2021	ABP8615	DEVELOPMENT OF SEMI-ARID REGIONS	4	100.00	8.5	Pass
4/2021	9/2021	CJP7233	SPACE, TERRITORY, LANDSCAPE, REGION	6	100.00	9.0	Pass
4/2021	9/2021	TDP0184	TEACHING INTERNSHIP II	4	100.00	10.0	Pass
4/2021	9/2021	TDP8418	RIVER AND OPEN-CHANNEL HYDRAULICS	4	100.00	7.0	Pass
9/2021	2/2022	CJP7155	ANALYSIS OF DEGRADATION/DESERTIFICATION PROCESSES	6	100.00	10.0	Pass
9/2021	2/2022	CJP8000	URBAN CLIMATE	6	100.00	10.0	Pass
9/2021	2/2022	TDP0201	TEACHING INTERNSHIP III	4	93.75	9.0	Pass
9/2021	10/2022	TDP5555	FOREIGN LANGUAGE PROFICIENCY	1	100.00	---	Pass
--	--	CGP8155	STRATIGRAPHY	4	85.93	7.5	Credit transfer
3/2022	7/2022	TDP7133	SPECIAL TOPICS IN WATER RESOURCES III	3	100.00	9.0	Pass
8/2022	12/2022	CJP8166	HYDROGEOGRAPHY AND WATER MANAGEMENT	6	100.00	9.0	Pass
2/2023	--	TDP6666	QUALIFYING EXAMINATION	1	100.00	--	Enrolled

Compulsory Credits:	68	Earned Credits:	58	Pending Credits:	10
Compulsory Contact Hours:	1088	Earned Contact Hours:	928	Pending Contact Hours:	160

Institutional Enrollments (affiliation without course enrollments), Student Mobility, and Leaves of Absence

Full Program Withdrawals: **N/A.**

Student Mobility: **N/A.**

Deadline Extensions: **7 months**

Pending Compulsory Courses/Activities: 2

Code	Course Description	Credits
TDP6666	QUALIFYING EXAMINATION	1
TDP8999	DOCTORAL THESIS	12

Source: Author, 2023.

In Brazil, my articulation with the Meteorology and Water Resources Foundation (Funceme), facilitated my access to institutional interviews. The rural community members were accustomed to field visits by students from the Federal University of Ceará, creating a positive atmosphere for conducting fieldwork. However, strong restrictions were imposed in Ceará during the COVID period, completely blocking fieldwork in 2020. Nevertheless, I continued to engage with community members through social media platforms. This situation compelled me to return to Tunisia, where I undertook an unexpectedly intense fieldwork that was not initially planned (Figure 19).

Figure 19 – A participatory approach is resilient to shock and stress?

Source: Author, 2023.

In general, in Tunisia, a tense atmosphere was felt during the investigations with various institutional actors and community members. Interlocutors were often wary, and it was sometimes difficult to secure appointments for interviews necessary to obtain certain information. This can be attributed to an unstable socio-political environment since the 2011 revolution, further exacerbated by the COVID period. Fortunately, the fieldwork was not completely blocked, as contacts with several actors had already been well established during previous stays. Similarly, field phases were completed remotely during lockdowns through phone calls and video conferencing during the COVID period.

These unique contexts significantly slowed down certain field phases but also led to the emergence of new institutional and political information. In both countries, members of communities, as well as institutional actors, were curious during workshop sessions or interviews to ask questions about the other country (e.g., how do they build their tanks? What types of crops do they have? How do they adapt to drought? What types of water resources do they have?). It was a moment of exchange in both directions.

2.5 Conclusion

This chapter has presented how a participatory research approach was co-designed and validated in two countries, focusing on water resilience. It involved continuous back-and-forth between theoretical readings and fieldwork. The aim was to justify the choice of the research object: rural water supply systems. Successive stays in the field allowed an exploratory phase before more in-depth study periods.

The selected communities were chosen to capture different configurations of water infrastructure projects in two water-scarce contexts. In Brazil, where communities rely mainly on surface water but also groundwater, and in Tunisia, where communities focus on groundwater, there is a specific emphasis on collective management of these water resources through community associations or, in other cases, individual approaches. In the next chapter, the focus will shift to the sustainability of the community management model and the trajectories of water supply systems.

The research was carried out in three stages, in analogy with the three research questions formulated in Section 1.3:

Stage 1. Co-define the Rural Water Supply System and analyse its trajectory (Chapter 3).

Stage 2. Co-define and analyse the water resilience of communities, linked to the trajectory of RWSS (Chapter 4).

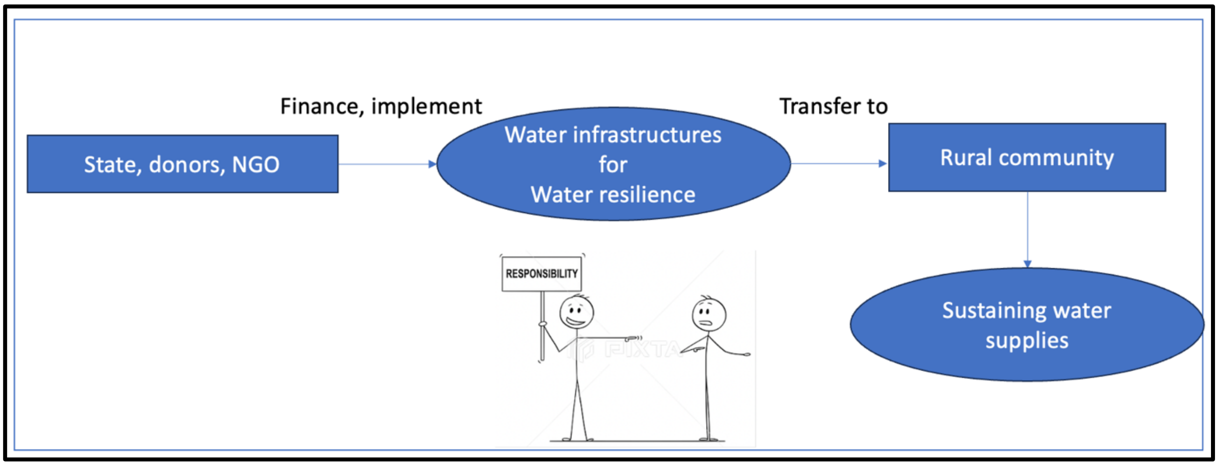
Stage 3. Co-identify the hydro-social territories and analyse the relation between them and water resilience at a multi-scale (Chapter 5).

3 SUSTAINING COMMUNITY - MANAGED RURAL WATER SUPPLY SYSTEMS IN SEVERE WATER-SCARCE AREAS IN BRAZIL AND TUNISIA[6]

In many countries, the challenge of sustaining rural water supplies is entrusted to the community organizations, which have difficulties in performing durably the operation, maintenance, and cost recovery of rural water supply systems. This paper analyzes how rural communities struggle to ensure sustainable access to water, once the infrastructure has been implemented by outside actors, in particular the State and NGOs. The analysis is based on field observations, interviews, and participatory workshops in four community-managed water supply systems in Brazil's Nordeste (Ceará state) and central Tunisia (Sidi Bouzid governorate).

This chapter highlights the particularity of rural water supplies, where communities often rely on multiple water resources and have multiple water uses, including drinking, domestic and agricultural uses. It looks at four communities located in central Tunisia and Nordeste Brazil. By analyzing the trajectories of rural water supply systems, we demonstrate how rural communities struggle with the responsibility of maintaining sustainable access to water (Figure 20).

Figure 20 – Whose responsibility is it to sustain rural water supply anyway?



Source: Author, 2023.

[6] This paper was published in Cahiers Agricultures Journal in 2022: Hela Gasmi*, Marcel Kuper, Eduardo Sávio Passos Rodrigues Martins, Sylvie Morardet and Julien Burte. doi.org/10.1051/cagri/2022019

3.1 Introduction

The sustainable access to water for rural communities has been a persistent problem in many countries. From 1990 to 2015, rural coverage of piped water has increased from 62% to 84%. However, a significant disparity exists between rural and urban areas. According to the World Health Organization (2017), "Two out of five people in rural areas and four out of five people in urban areas now use piped supplies". This is also the case in Brazil and Tunisia, where our study takes place. In Brazil, 93.9% of urban households are connected to reliable water services versus only 34.5% in rural areas (IBGE, 2014). In Tunisia, in urban areas, 99.8% of the population receive piped water compared to 65% in rural areas (INS, 2018). Nevertheless, beyond coverage, the challenge is to keep rural water supply systems (RWSS) working (Schouten; Moriarty, 2003). This explains the lively debate on the functionality of RWSS, in terms of both infrastructure and organization required to manage it (Whaley; Cleaver, 2017).

Since the International Drinking Water Supply and Sanitation Decade in the 1980s, community management has been promoted to facilitate lasting access to water, as previous top-down approaches that did not involve communities largely failed (Schouten; Moriarty, 2004). However, there is a growing feeling that too much has actually been asked from communities: "Part of the implicit appeal of the community-based management (CBM) concept for key development players (international donors, development organizations, and governments) is that it allows them to highlight a concern for sustainability whilst at the same time distancing themselves from much of the responsibility for delivering it" (Whaley; Cleaver, 2017).

In some cases, there was even an explicit objective of rendering communities autonomous and bypassing rural elites and politicians (Machado *et al.*, 2019). Yet, communities have consistently continued to mobilize external actors (the State, NGOs) when in difficulty, including through clientelist relations (Collard *et al.*, 2013). The debate has, therefore, increasingly focused on the coproduction of rural water supply, defined as "an arrangement between State (or other supporting agency) and citizens for delivering (public) services" (Hutchings, 2018).

While many authors agree that community engagement with RWSS has played an important role in improving the coverage of water supply in rural areas, there is a more critical debate on how communities fared in actually sustaining water supplies (Hutchings *et al.*, 2015). Critical problems for communities related to financing and cost recovery (Whittington *et al.*, 2009), the difficulty of designing "resilient, affordable and reliable" technology (González

Rivas *et al.*, 2014; 573), the continued use of alternative water sources (Aleixo *et al.*, 2019), the lack of sustained external financial and technical support (Smits *et al.*, 2013), and organizational issues in the community (Hutchings *et al.*, 2015).

RWSS are often planned for domestic uses only, but communities also use water supplies for a wide range of productive uses around homesteads, including irrigation and livestock breeding (Renwick *et al.*, 2007; Smits *et al.*, 2010). Moreover, implementing agencies propose RWSS with the belief that the piped network will exclude all other water sources. Yet, local users maintain multiple sources, depending on: the seasonal water availability (Macdonald *et al.*, 2016); the water quality related to specific water uses; and the distance from the household and convenience of fetching water (Almedom; Odhiambo, 1994).

When piped networks designed for human consumption do not match local expectations, they are converted to non-consumptive purposes in an unplanned way (Moriarty *et al.*, 2004). Unplanned uses can create a higher demand than the network can manage, may complicate the management and cause damage to infrastructure. Conversely, people with unreliable RWSS look for alternative water sources or make adaptations to infrastructure and organization (Elliott *et al.*, 2019). We argue that observing such adaptations, often made in close interaction with external actors, is an opportunity to understand how individual households and the community sustain access to water (Sweya *et al.*, 2021).

This paper analyzes how rural communities, in interaction with outside actors (the State, NGOs, and politicians) struggle to ensure sustainable access to water. In this paper, RWSS are analyzed as systems: catering to multiple water uses; that depend on one or more water resources; that include water infrastructures and the organization managing them; that are embedded in social relationships, within the community and with external actors, that have contributed to its establishment and development. This article is not about "saving" the community-managed model (Whaley; Cleaver, 2017), but about the fact that engaging in a meaningful practice-based dialogue with rural communities about water supply provides valuable lessons for implementing RWSS.

3.2 Study areas and methodology

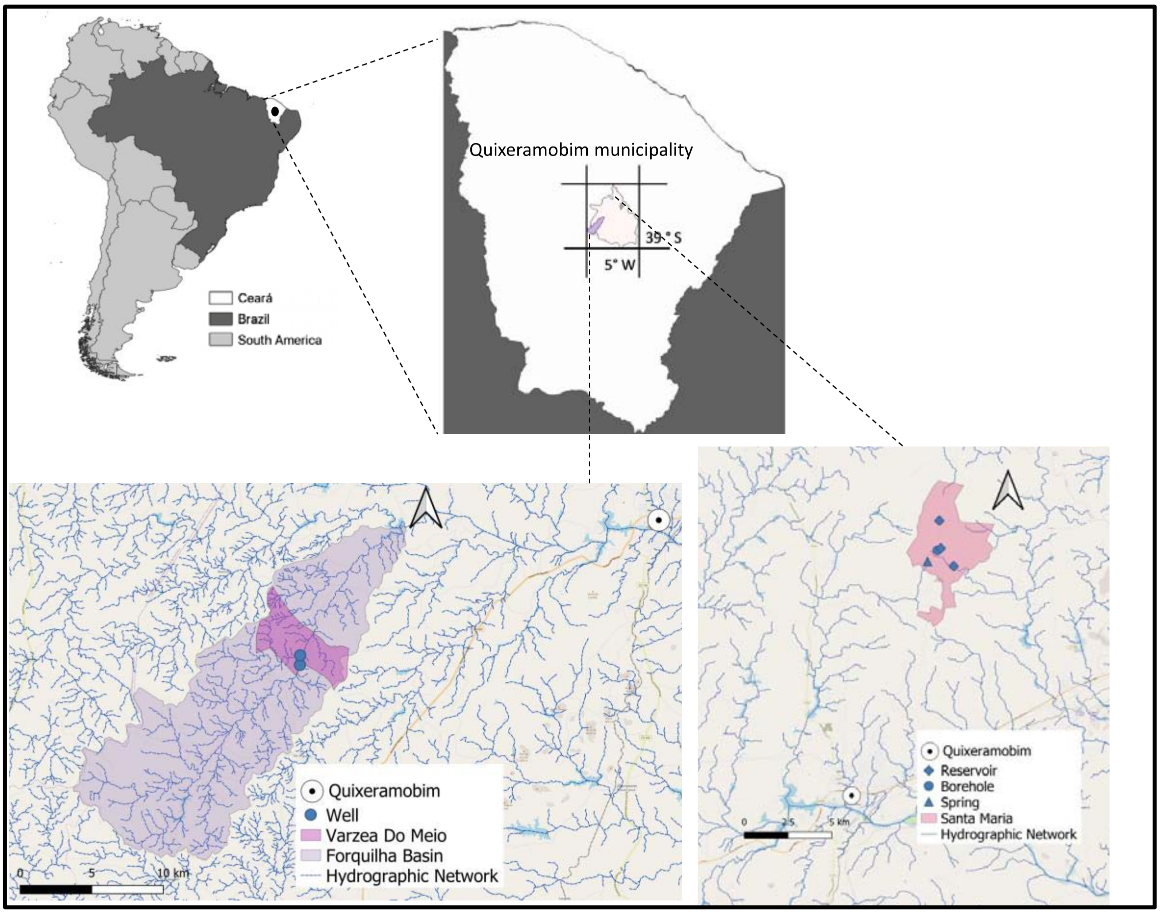
3.2.1 Four case studies in water-scarce contexts

Our analysis is based on four rural communities in the Northeast of Brazil and in Central Tunisia. These communities all have problematic access to water, but the socio-political context, affecting the way rural water supply is arranged, is very different. While in Ceará (Brazil) there has been a diversity of public and private actors involved in rural water supply (State agencies, NGOs, large-scale breeders–fazendeiros) in a context of clientelism and land inequality (Collard *et al.*, 2013), in Sidi Bouzid (Tunisia) there is basically a relation between the community and the State, which provides the financial and technical support to RWSS, mediated by local elite; nevertheless, the 2011 Arab Spring has changed the power relations among the three parties.

3.2.1.1 Varzea do Meio and Serra Santa Maria Communities (Ceará, Brazil)

Varzea do Meio and Serra Santa Maria are two communities in Quixeramobim municipality (Ceará), located in the region most affected by droughts (Figure 21). Agriculture in Quixeramobim is characterized by the coexistence of large cattle ranches (fazendeiros) and subsis- tence farming (e.g., corn and beans) with small-scale animal husbandry (e.g., poultry, cow, goat, pig). Farmlands are often fragmented and located around the river with limited irrigation. The climate is characterized by two seasons: the rainy season.

Figure 21 – Location of the Serra Santa Maria and Varzea Do Meio communities, Ceará, Brazil, south America



Source: Funceme, 2023.

From February to April and the dry season from May to January. Quixeramobim is located on a massive crystalline basement, meaning that groundwater exploitation requires expensive drilling and yields saline water (Burte *et al.*, 2009). The Varzea do Meio community (19km2) is composed of 90 families. It is located in the Forquilha valley (mid hill area) with an average rainfall of 750 mm/year. Rainfall is extremely irregular in terms of frequency and intensity.

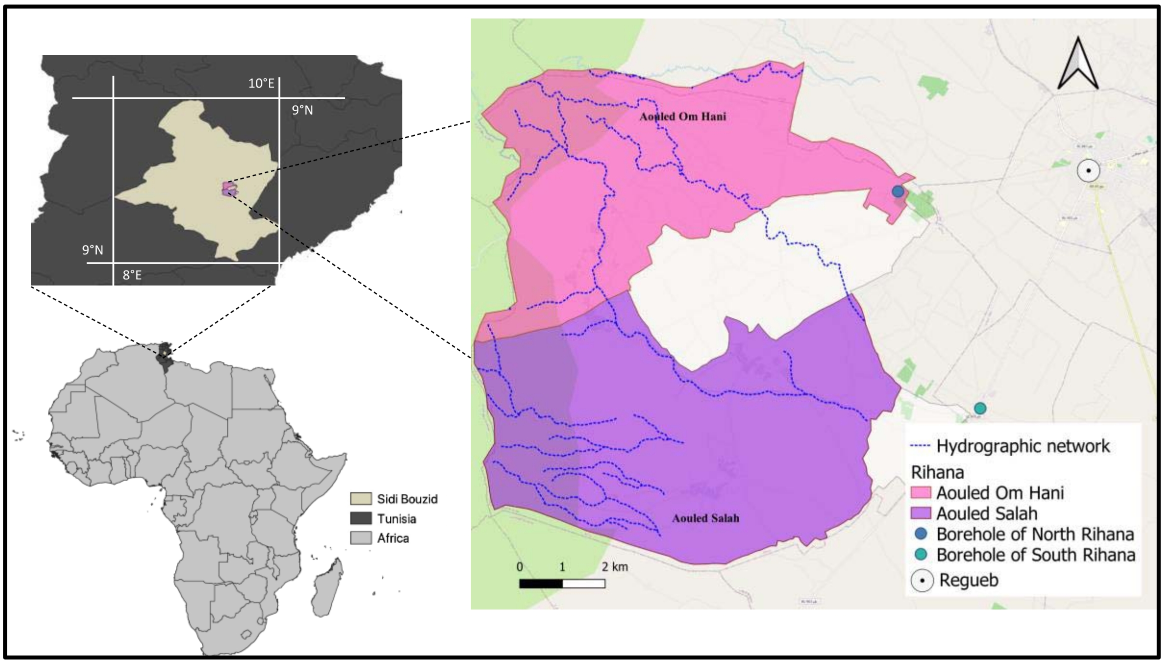
Three water resources are used for domestic and agricultural use: surface water reservoirs, alluvial aquifers and cisterns, a centerpiece of a rainwater harvesting system from the roof of houses. Reservoirs are located in the upper catchment, while groundwater is essentially used in the lower catchment for irrigation, cattle watering and domestic uses (Burte *et al.*, 2009). The Serra Santa Maria community (22km2) is composed of 31 families. Located in a hilly area, it presents a diversity of land ownership status, shaping water resources and uses. The agrarian reform association possesses two small collective reservoirs for all uses, individual cisterns for drinking and cooking, and shallow dug wells for domestic uses. Fazendeiros use their own reservoirs, springs or wells, which are shared with their workers, who own neither the land nor the homestead. Some small landowners have individual water infrastructures. Water from cisterns or wells is shared with family members and neighbors, especially for drinking and cooking.

3.2.1.2 Ouled Salah and Ouled Om Hani communities in Sidi Bouzid, Tunisia

Rihana district (90 km2) in Central Tunisia (governorate of Sidi Bouzid) (Figure 22) is among the most environmentally and socio-economically vulnerable areas of the country. Average rainfall amounts to 200 mm/year. Rainfed olive and almond trees dominate the landscape; irrigation is limited to rich inhabitants with private boreholes. The RWSS in the Ouled Salah community (120 families) in South Rihana and in the Ouled Om Hani community (200 families) in North Rihana only cater to part of the households due to dispersed habitat.

In these communities, there is considerable heterogeneity of households in water access and water uses (Morardet *et al.*, 2020). Some households are connected to the RWSS and store water in cisterns for domestic use, for vegetable gardens irrigation and for livestock watering.

Figure 22 – Location of the Ouled Om Hani and Ouled Salah communities in Rihana, Sidi Bouzid, Tunisia, Africa



Source: Agricultural map of Sidi Bouzid, 2024.

Most households have rainwater collection tanks for drinking and cooking. Others, not connected to the RWSS, have built two cisterns, one for rainwater harvesting (for drinking and cooking) and the other for storing water from tanker trucks purchased from private wells (for other uses). Wealthy households also have private boreholes for irrigation, which can be used for domestic purposes if necessary. Local leaders are key actors to mediate relations with the State on the investment, cost recovery, operation, and maintenance of the RWSS.

3.2.2 Data collection and analysis

Table 5 – Overview of different methodological steps and tools used for data collection and analysis

	Steps	Methods
1	Literature review	Review of relevant academic articles, reports and associated documents. Use of existing data from maps, reports and similar sources
2	Selection of case studies	Participatory diagnosis Participatory mapping
3	Historical analysis of RWSS trajectory in selected case studies	Participant observation Life narratives Semi-structured interviews (15 in Tunisia and 20 in Brazil; individual and group interviews; virtual and in-person meetings) with key stakeholders: community health agent, water users association members, district engineers, and local water technicians.
4	Analysis of the functioning of the RWSS	Surveys (30 in Tunisia and 40 in Brazil) to collect information at the household and community levels on: - Water users - Water uses (drinking, domestic, agricultural) - Infrastructures (lay-out, quality, location) - Resources (quantity, quality, location) - Rules of use (formal and informal) - Evolutions and adaptations in infrastructure and rules

Continue

Table 5 – Overview of different methodological steps and tools used for data collection and analysis

	Steps	Methods	
5	Co-design of RWSS trajectories  	Participatory modeling: using a conceptual model as a discussion support	Workshops in Tunisia and Brazil Tunisia: -10 interviews to prepare the workshop -1 workshop mixing both communities (Ouled Salah and Ouled Om Hani) -12 participants: 4 women and 8 men (6 from Ouled Salah and 6 from Ouled Om Hani communities) Brazil: -12 interviews to prepare the workshops -1 workshop in Santa Maria community 8 participants (4 women and 4 men) -1 workshop in in Varzea Do Meio community 8 participants (4 women and 4 men)

Source: Author, 2023.

Conclusion

First, we reviewed existing literature, including unpublished documents, maps, and reports. Second, we conducted a participative diagnosis on people's living conditions and water issues and selected the communities for our case studies (Table 5); four communities were chosen, reflecting a diversity of situations: water services (individual, collective), commu- nity organization (with an active association, without association), and type of water resources (surface and groundwater) and infrastructures (collective and individual networks, wells, storage dams and cisterns).

Third, we undertook a historical analysis of the trajectory of the RWSS in the different cases through participant observation, developing live narratives and semi-structured interviews with key stakeholders (Table 5). Fourth, we undertook surveys to analyze the functioning of the RWSS over a period of three years (2019–2021) on the following themes: the water actors, the different uses, the infrastructures and resources, the rules of use, and the technical and organizational adaptations made.

Fifth, once a relationship of trust was established with local actors, we organized workshops in each study area to co-design conceptual models, representing the trajectory of RWSS, involving community members with a diversity of gender, age and water supply systems (Table 5. The conceptual model was inspired by the local development paths approach of Sabourin *et al.* (2004), which is useful to represent social and technical trans- formations of rural societies allowing a more generic character to the results obtained in each case study. We applied this approach to RWSS, in particular to the transformations in the infrastructures, the rules-in-use, the type of water resources used, and the water users and their uses. We used simple symbols for these different items to co-design the trajectory of RWSS with community members.

3.3 Results

3.3.1 Trajectories of RWSS in two communities in Ceará, Brazil

3.3.1.1 Santa Maria: a community RWSS born again?

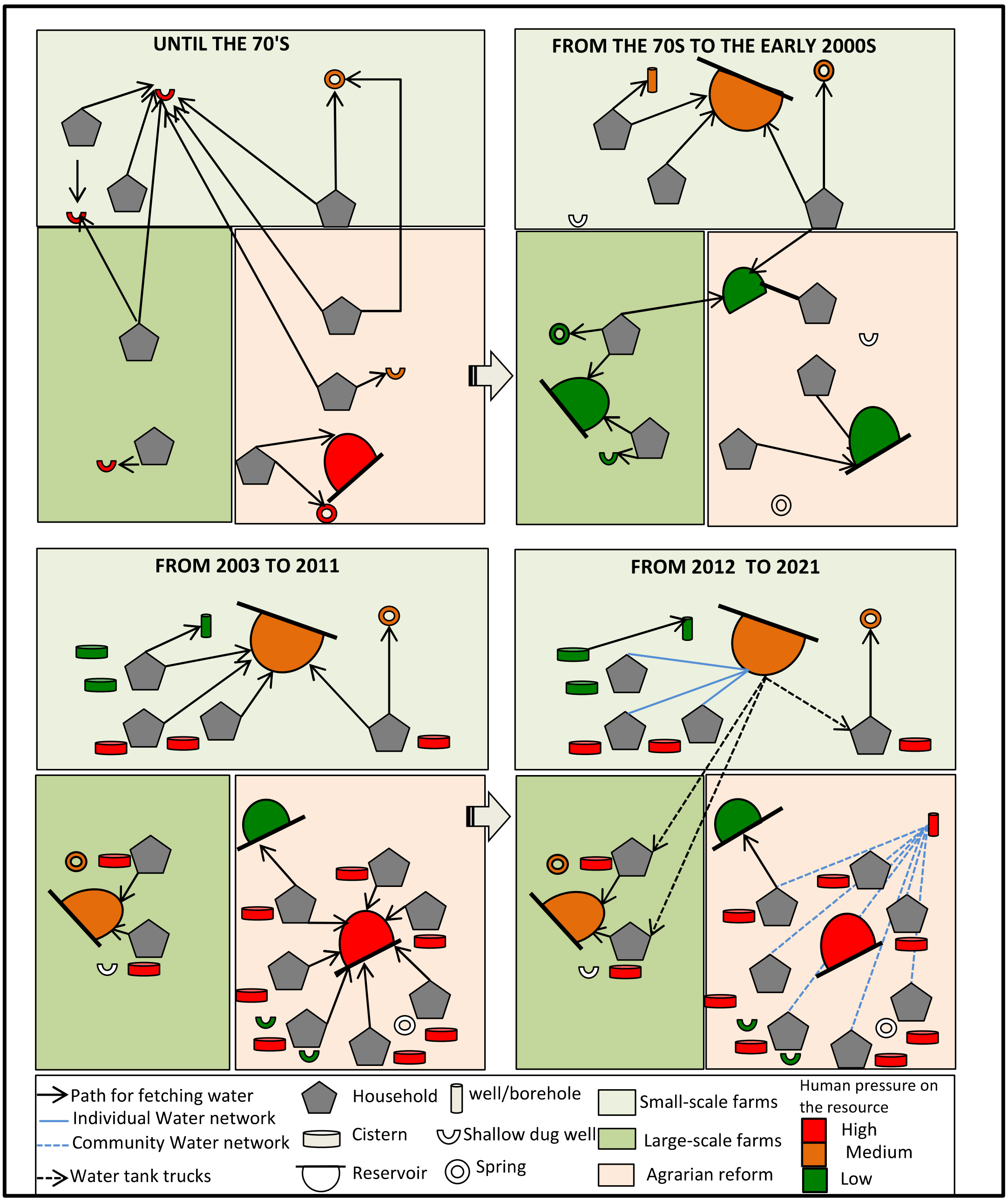
The case of Santa Maria shows the many problems faced during implementation of a community-based RWSS with an extremely heterogeneous community. Despite several break- downs and even a collapse, the community remains interested in the community RWSS, looking for collective solutions with outside support.

We went back to more than 50 years ago. Before the 1970s, there was a plurality of water sources in this mountainous area, including springs and shallow dug wells along water courses (see Fig. 23). Some were intended for specific uses, while most shallow dug wells were used for multiple purposes. The flows of the sources depended on the season (wet or dry) and on the year. The cost of maintaining the sources was low, and there was a lot of solidarity among local inhabitants to provide water access when sources dried up.

State intervention to deal with water scarcity from the 1970s to the 1990s, linked to the fear of massive rural migration to cities, focused on technical fixes. Shallow dug wells were converted to wells and two small surface water reservoirs were built. These reservoirs were meant to serve all inhabitants, but in practice they were privatized by large landowners, as they had been constructed on their land. The focus of public policies from 2000 onwards was on poverty alleviation, and in Santa Maria a large farm was expropriated for the benefit of landless residents through agrarian reform. This implied they had to carry out farming operations through imposed collective action. The State provided them with training and material to construct cisterns, along with a water harvesting system from house roofs (Fig. 4). The cisterns were located next to the houses and reduced the drudgery of water fetching. However, this did not solve the problem of water scarcity and, especially during the dry season, water was still provided from outside by trucks.

In 2008, the State and NGOs constructed a community RWSS, including a pump, a water tower and taps. The RWSS was connected to the existing reservoir, situated on the expropriated large farm, and was to be managed by the agrarian reform association. The initial beneficiary group also included 10 additional households. However, the association decided to restrict the RWSS to its members' households, because the reservoir could not meet the demand of a network designed for domestic purposes and also be used for watering gardens and animals during the dry season.

Figure 23 – RWSS trajectory in Serra Santa Maria community



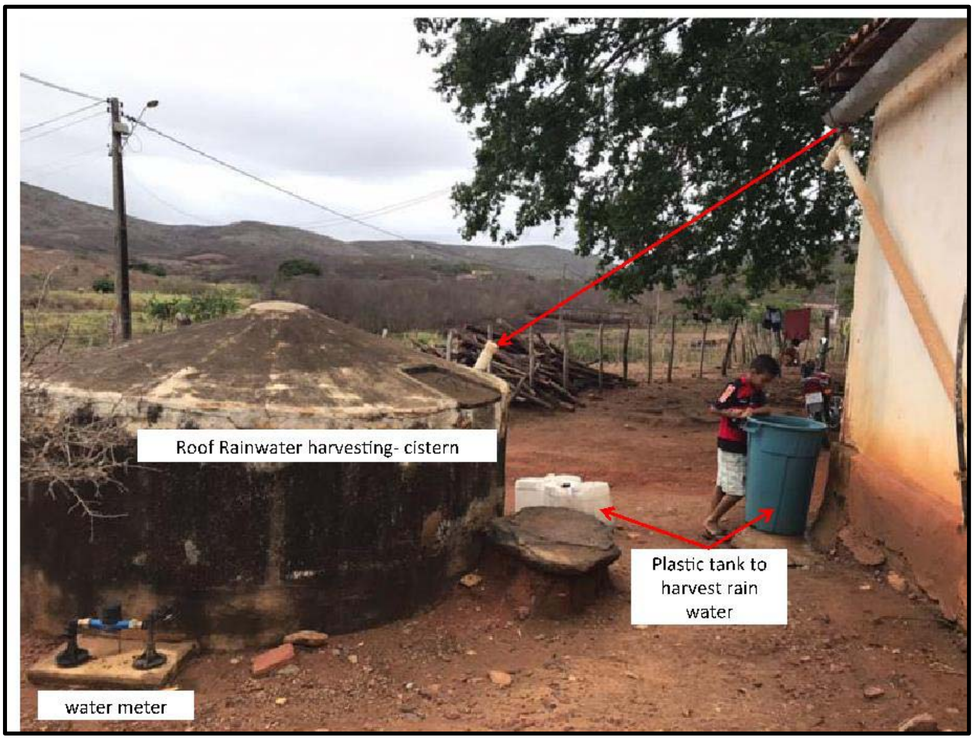
Source: Author, 2023.

The operation of the RWSS began in 2012 but stopped in 2016. Many factors were responsible for its collapse. First, the network was developed while the residents split up the collective farm, turning away from what they felt as imposed collectivism. The president of the association looked for work outside during the drought (2012–2017) and, when he quit his position in 2016, no one took over the responsibility. Then, in an uncontrolled slash-burn of his land, a farmer burned the electrical wires powering the floating pump, and the association did not have the financial means to replace it.

Second, the inhabitants lost interest in the provided services. They had expected a big change in their lives with the provision of tap water but were disappointed by the high price for untreated water, available free of charge elsewhere. Also, the reservoir dried up three years after installing the network, reinforcing the perception that it was not a sustainable response to droughts. The exclusion of small farmers not being members of the agrarian reform association caused a division in the community and weakened the ability to cope with droughts. There was another plan to restart the community RWSS in 2018 with the installation of a borehole on the land of the president of the association. However, the energy costs for operating the borehole were too high and only the president's household used it.

From 2016 to 2020, the community members used a diversity of water supply systems. Large landowners with financial means built their own infrastructure (reservoir, motor pump, storage tank, and taps) along with rainwater cisterns. Small landowners used rainwater cisterns, which were filled for free by tanker trucks from the large landowners' reservoirs. The trucks were contracted by the Federal Government, while the landowner aimed to maintain good and multiple (family, business, and labor) relations with community members.

Figure 24 – Photo 1. A typical backyard in the Serra Santa Maria community with a cistern and plastic tanks



Source: Author, 2020.

Members of the association used rainwater cisterns, collected water from two collective reservoirs in the rainy season, and received tanker trucks in the dry season. Yet, they kept the water meters of the RWSS intact in the hope that maybe one day they could use them again (Figure 24). In 2021, the reservoirs of the agrarian reform association dried up, forcing the inhabitants to think of a collective solution. They received water from tanker trucks every month to fill their cisterns from the large landowner's reservoir.

For domestic water, they contacted the community advisor to reactivate the RWSS based on the existing borehole. In April 2021, the community received a storage tank with taps, where residents who are not connected to piped water could buy water in a bucket. A meeting with the inhabitants to identify the beneficiaries and the purpose of this new infrastructure, financed by the municipal authority, was planned but never happened. The storage tank is currently used by all members of the association, who shared the costs for the renovation of the water pipes and a new water pump. Faced with the poor quality (salinity) and high energy costs of this new RWSS, the beneficiaries hope to obtain solar energy and a desalinator to improve their situation.

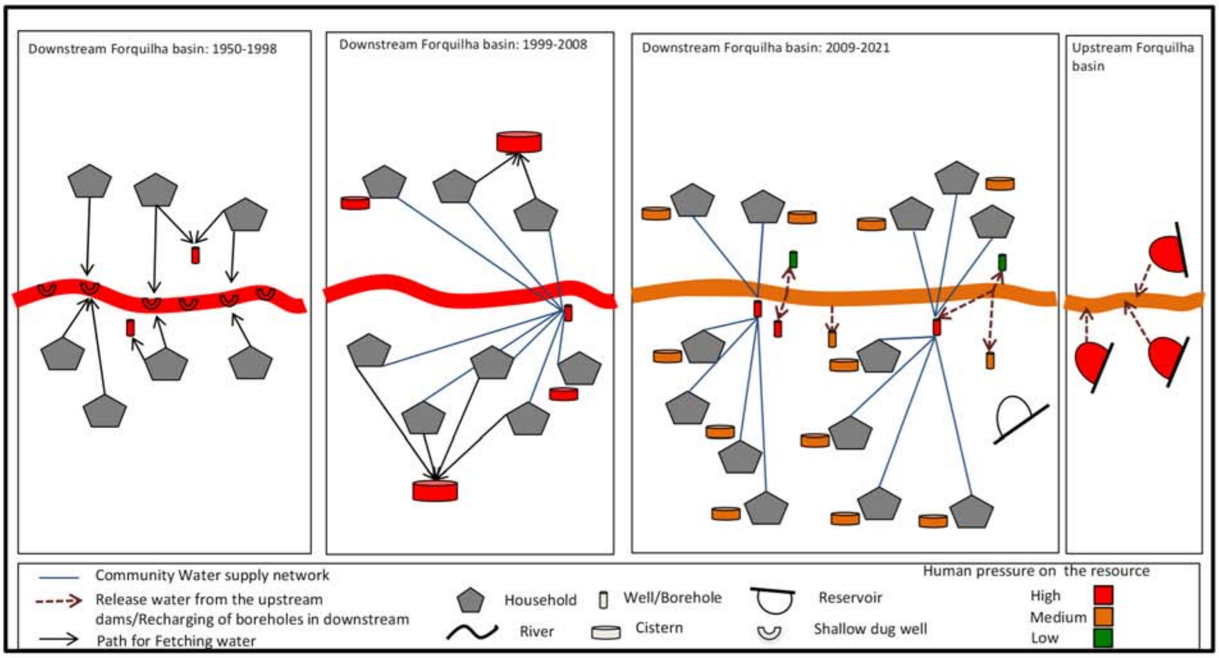
3.3.1.2 Várzea do Meio: a failed design but appropriation through collective adaptation

To this day, the main factors that have kept the community-based RWSSs functional, despite the limited number of water sources in Varzea do Meio, are the good political connections of the community and the active community water association.

During the first period (1950–1998), the water was mainly supplied from the river (Figure 25). Originally the community was based on three families and a few scattered houses, and the water supply was organized through three shared shallow dug wells for human consumption and three additional small shallow dug wells for watering cattle. There were a few private wells for domestic use.

External interventions (Federal Government, Ceará State, NGOs, and International Donors) on the water supply system started in the 1990s. The community received five collective water cisterns, each supplying ten families. During the dry season, they were filled by tanker trucks and reserved for drinking water. The river water was used for all other purposes. Then the community received electricity and the municipal authority implemented a pilot project to install boreholes in the region. The municipality financed the drilling equipment and the community provided labor force. The water availability and a sense of abundance prompted inhabitants to practice intensive irrigated agriculture. As a result, shallow dug wells were abandoned as the population considered that the surface water was polluted by chemicals (fertilizers and pesticides). In 2008, all boreholes dried up and the communities turned to use wells located in the riverbed (Figure 25). These wells were deepened during the multi-year drought (2012–2017). How- ever, access to groundwater depends on its recharge from surface water releases from small reservoirs located upstream in the watershed. The community has thus become dependent on upstream communities to release, or not, water. In 2017, almost all households had individual cisterns for drinking, abandoning the collective cisterns.

Figure 25 – RWSS trajectory in Varzea do Meio community



Source: Author, 2020.

From 2017 onwards, the community was supplied by two RWSS and individual cisterns. The first RWSS supplies thirty houses through the private well of a community resident, for which the residents pay only for electricity. The second RWSS supplies sixty houses from a well belonging to a large landowner who lives in town. The beneficiaries pay a fixed fee for the rent of the well and electricity fees. In the meantime, a few households created their own access to water, but the majority of the community looked collectively for a cheaper solution. In 2018, the community benefited from the construction of a State-funded reservoir. The reservoir will replace the private well, even though it is not yet supplying the collective water network due to the multi-year drought in the area.

3.3.2 Trajectories of RWSS in two communities in Rihana (Tunisia)

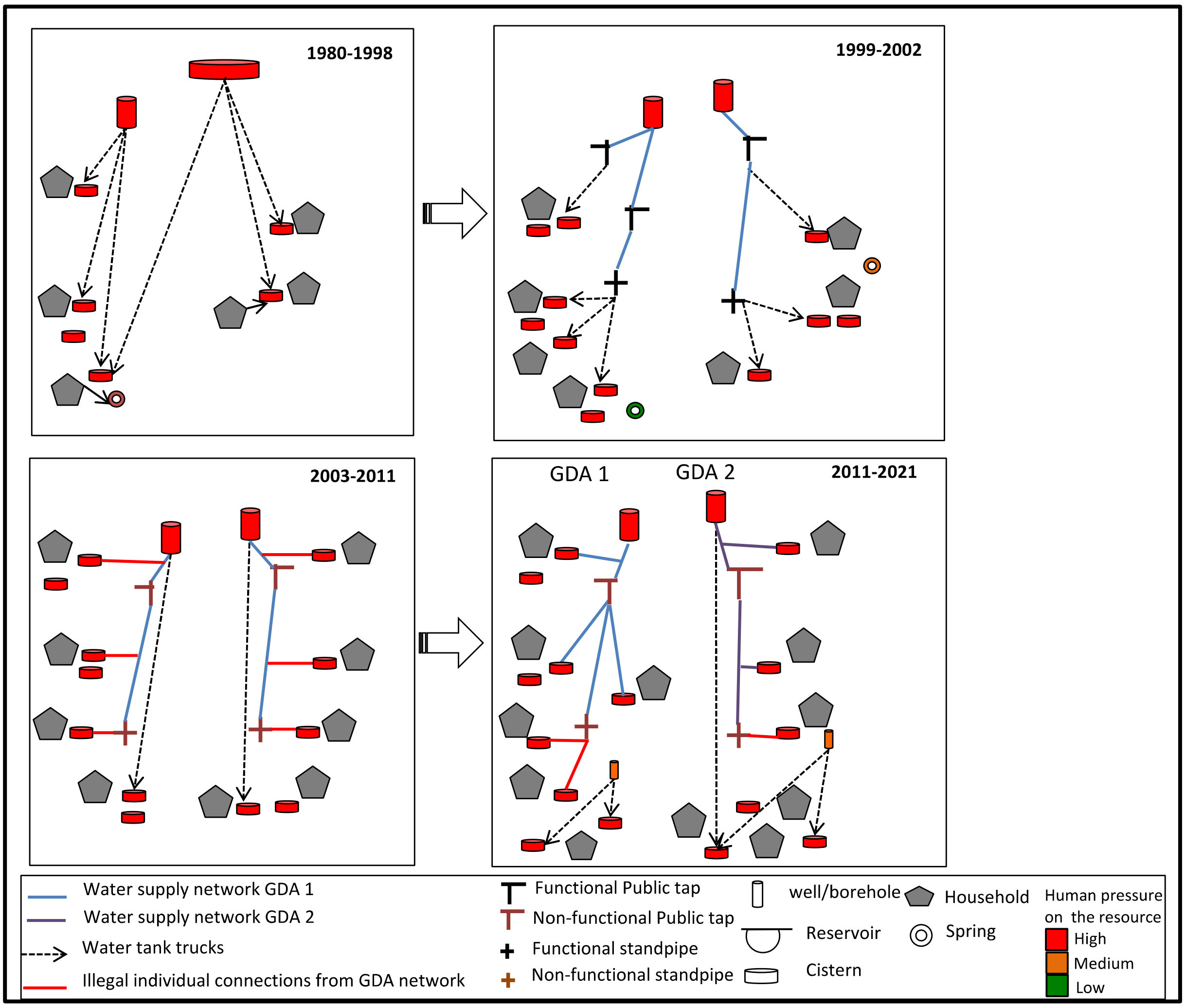
There has been a long litany of State interventions, often financed by international donors, in the community managed RWSS in Rihana. As it was designed for only part of the households, those excluded regularly attempted to join. This resulted in several illegal connections, which were then regularized and integrated in the RWSS, leading to the physical breakdown of the system and prompting, in turn, State interventions to upgrade the infrastructure. Yet, the RWSS has never been able to provide access to all community members. Currently, another international donor-financed project is underway in the study area, offering the opportunity to finance the rehabilitation of both North and South Rihana RWSSs. Drinking water cisterns are also built in North and South

Rihana for the most disadvantaged households. The population is asking for wells for supplementary irrigation, but this is unlikely to be accepted in a context of groundwater overexploitation. Community members are still in a strategy of expansion of water use in a severely constrained environment. Tensions are likely to continue and pressure on the community system will even increase, preparing for further breakdowns to come.

The trajectory of the RWSSs in Rihana is problematic. Before 1980, the community collected rainwater in a collective basin and diverted flash floods to irrigate agricultural lands. The community fetched water from the collective basin by private tractors or through 500-liter tanks fixed on donkey carts. Water access was reinforced by a well in South Rihana in 1980 from which people fetched water on foot, with animals, or by hiring a private transporter (Figure 26).

Since the 1970s, the seasonal migration of men to the coast and to Libya has led to a change in living standards and in expectations towards water services and water quality. In 1999, rural development programs were implemented to provide electrification, and the well got replaced by a borehole, standpipes, and public taps. The infrastructure was then entrusted to a community association and no longer managed directly by the State. However, the association lacked human, financial, and technical resources and the State continued to interfere in the borehole management, often at the request of the dissatisfied inhabitants. The borehole was insufficient to supply the whole of Rihana and in 1999 the State decided to build an additional borehole to supply North Rihana, while using the existing borehole only for South Rihana. The new borehole was initially planned to be located next to the existing one, but inhabitants of North Rihana asked that it be installed near their houses, in a place where water is less salty.

Figure 26 – RWSS trajectory in Rihana (GDA 1 in South Rihana; GDA 2 in North Rihana)



Source: Author, 2020.

From 2003 to 2011, the inhabitants, who had standpipes near their houses, transformed them into private taps. The other inhabitants, thus excluded from the RWSS, made illicit connections on the pipes (Figure 26). To control illicit connections, user contracts have been established and the majority of people were thus able to join the agricultural development group (GDA), manager of the RWSS (2007–2011). The rest of the community had to buy water from the GDA borehole, transported by towed tanks.

In the aftermath of the Tunisian revolution in 2011, the number of illegal connections of non-members of the GDA increased. This caused numerous dysfunctions, frequent interruptions in water distribution, and conflicts. The non-payment of water bills caused the indebtedness of the GDA. The GDA had thus grown progressively into an unmanageable entity. In 2011, the GDA was split in two, a second GDA being created in North Rihana. This RWSS was initially composed of 25 public taps and five standpipes. However, residents wanted individual access to water and established illegal individual connections. In South Rihana, 180 families are connected to the RWSS, while there are still 30 families not connected. In North Rihana, 300 families are connected to the RWSS, while 300 more families are still waiting to join.

The individual connections resulted in reduced water flow and pumping failures. The GDA president explains “Due to illicit connections, the water supply network is out of control... Theoretically, the water volume pumped from the well is sufficient to supply the entire region of South Rihana, but these illegal connections do not allow this [...]” (interview conducted in January 2021). Between 2009 and 2020, the borehole of South Rihana was replaced three times for technical reasons by the State, although this was theoretically the responsibility of the GDA.

Today the population of South Rihana uses water from the network for domestic use, livestock watering, and irrigation: “No one drinks GDA water. This water is only used for domestic purposes or to irrigate some olive trees in the backyard of the house. The standard of living in the area has evolved and the inhabitants want to drink very good quality water, mineral water or rainwater [...]” (Interview with the GDA president conducted in January 2021). Due to the high frequency of outages, the population with access to this RWSS stores water in semi-buried cisterns when water is available. People also harvest rainwater, stored in semi-buried cisterns (different from those used for GDA water), for drinking and cooking.

In North Rihana, the GDA water is used for all purposes including drinking and cooking. However, the GDA distribution network cannot satisfy all demands, and inhabitants buy water from private boreholes or from the GDA borehole through tanker trucks.

3.4 Discussion and conclusion

Our analysis of water supply systems in four very difficult contexts showed how rural communities ensured sustainable access to water for multiple uses, including drinking water, domestic water, irrigation, and livestock. In keeping with the idea that communities cannot be solely responsible for doing so (Hutchings, 2018), we analyzed community actions in their interactions with external actors, including politicians, NGOs, and the State. Our results qualify, first, the importance of a collective rural water supply system for the community. Drinking water is, in all case studies, provided for outside of the RWSS, through individual water harvesting on house roofs or through deliveries by public or private tanker trucks, and stored in cisterns. Indeed, the water quality delivered through the RWSS generally does not fit for drinking, which would require substantial investments (Collard *et al.*, 2013).

Also, community members do not want to be totally dependent on RWSS and keep other water sources active. This shows, second, the ambivalent relation that communities have with community-managed RWSS. The collective system was abandoned (in Santa Maria, Brazil); considerably modified by the community because it did not respond to their needs (in Varzea do Meio, Brazil); or even partially destroyed by the population not satisfied with the service provided (in Rihana, Tunisia). Yet, in all cases, the communities made considerable effort to keep the RWSS functional and never gave up on it. For example, in Santa Maria, inhabitants kept the water meters of the collective system, even when the system had stopped to function; five years later, the RWSS was gradually pieced together again.

Third, in all case studies, communities entertained close relations with external actors to ensure access to water. These interactions concerned emergency services like the tanker trucks (in all case studies) and the RWSS itself. In Varzea do Meio, political networks were mobilized to install a dam to change the main water source from groundwater to surface water, while in Rihana the community would contact the State, through influential members of their community, to step in and handle, for example, the arrears of members in the electricity bill or to rehabilitate the RWSS when the infrastructure became too degraded. This raises questions about the strategy of the State and the funding agencies, aiming to eliminate intermediaries and political figures from local development projects (Collard *et al.*, 2013). More generally, the question then is: when the academic community, practitioners and community members all understand the limits of community- managed RWSS, why do we still engage in developing such projects without an explicit coproduction lens (Hutchings, 2018)?

The fourth issue is how to define a community of water users. In Santa Maria, members of the agrarian reform association excluded other small farmers when the RWSS was not sufficient to meet all water demands. In Rihana, membership was determined at the project stage in an opaque interaction between the State, the funding agency and the community. Whenever the RWSS was upgraded, new house- holds would be included, particularly those that had already created an illicit connection on their own. The crux of the matter is that these projects have always been poorly designed, excluding a large number of households, which would then become part of the network, which was not designed to handle this influx. This is symptomatic of water projects that remained focused on infrastructure design and implementation with little attention to existing water uses, community dynamics, and how the network would be managed (Smits *et al.*, 2013).

Fifth, even though we advocate decentralizing the focus on hardware, the design of adequate technology remains an important issue. This relates in the first place to the agreement with the community on the standards of water services (water quality, cost) to expect. Such design choices were rarely discussed collectively. In all case studies, the RWSS was designed for drinking water but without ensuring the corresponding water quality. The network was, therefore, exploited for multiple uses (basic domestic uses; irrigating the vegetable gardens; watering livestock), leading to a higher demand for water and pressure on the collective system, resulting in disruption of services, conflicts, and in some cases voluntary degradation of the network. Also, water providers failed to build on local knowledge about the inter- and intra-annual variability of water resources leading to disruptions in the RWSS.

Sixth, communities kept their RWSS functional by engaging in institutional and technical bricolage (Whaley; Cleaver, 2017). Institutional bricolage related, for instance, to the inclusion of new members of the community, out of solidarity or simply to avoid degradation of the network by excluded users (Rihana), or conversely, the exclusion of certain users (Santa Maria); this, then, necessitated to adapt the rules-in-use for water distribution, payment and maintenance and, as explained by Cleaver (2017; 34) to legitimize these rules and imbue them with authority. Technical bricolage was about changing the main water resource (Varzea do Meio) or adding semi-underground cisterns to deal with frequent outages of the RWSS (Rihana).

Through technical bricolage, the communities challenged the initial design (and the underlying assumptions) of the RWSS for which they were often not consulted, including their needs in terms of water quality, quantity and delivery. Indeed, for technology to function, it is important that users can challenge and adapt it (Akrich *et al.*, 2002). However, not all bricolage is aimed at sustaining the RWSS, as shown by: 1) the privatization of public taps in Rihana by individual households not satisfied with the standards of the collective system, or 2) the community members investing in alternative water infrastructure so as not to rely solely on the collective network. Keeping the RWSS at the center of the community's interests is hard work and will ultimately determine whether it remains functional.

In the international literature there is a strong focus on expanding the scope of managing rural water supply (post-construction) beyond, but not without, the community (Whaley and Cleaver, 2017). However, in the cases we studied this policy change has not yet been operationalized. In several municipalities in the State of Ceará (Brazil), an NGO, supported by the State-owned Water and Sewage Company, is now entrusted with the management of such RWSSs, while coordinating with the presidents of water users' associations. Yet, there are many difficulties in making this work in isolated or sparsely populated areas. In Tunisia, a new water law has been under discussion to entrust municipalities with the responsibility to manage RWSS. The parliamentary debate has discontinued for the time being and there are no details available on the technical, organizational and financial consequences of such a transfer. In the midst of profound organizational changes (to come), we argue that the notion of coproduction whereby the community and external actors come together for the design, the construction and the management of the RWSS will remain important.

3.4.1 Acknowledgements

This work was carried out as part of a joint PhD program at UFC (Federal University of Ceará) and Institut Agro, Montpellier. The research was supported by Funceme (Ceará Foundation for Meteorology & Water Resources) and CIRAD (Montpellier) through the Pacte and Sertões projects, funded by the French Development Agency (AFD) and FUNCEME. Part of the field work and analyses in Brazil were carried out jointly with Elie Boillot.

3.4.2 Implications of the paper

The four case studies presented in these two countries clearly demonstrate the difficulties faced by decentralized water management models. To sustain the access to water, communities limit their dependance on community-managed water supply systems and diversify water sources for different uses; they adapt the technical and organizational dimensions of water supply systems through bricolage; and use political leverage to obtain financial and technical support. Consequently, managing multiple water sources for various purposes through multi-purpose infrastructure is the norm in these communities, with single-purpose systems being the exception.

Including rural communities in the design phase of rural water supply systems is crucial for their sustainability. By involving the local population in the decision-making process, their needs and challenges can be better understood and addressed. In the next chapter, we will place these insights at the core of our approach by engaging in a participatory process with community members, water association users, and institutional stakeholders to co-design an operational framework. This framework aims to characterize the resilience of rural water supply systems. It can guide decision-making and interventions to enhance the resilience and sustainability of rural water supply systems.

4 A PARTICIPATORY APPROACH FOR CHARACTERIZING THE RESILIENCE OF RURAL WATER SUPPLY SYSTEMS IN SEMI-ARID AREAS (PAPER UNDER REVIEW ON REGIONAL ENVIRONMENTAL CHANGE)[7]

Rural communities in water-scarce contexts are often facing problems in securing a sustainable supply of water (chapter 3). Rural water supply systems are complex and open systems, which involve multiple water sources and infrastructures for multiple uses. However, the existing literature on water resilience often tends to focus on individual aspects such as technical, institutional, or social aspects of water resilience, neglecting the holistic perspective.

In this chapter, we will introduce a framework for analyzing water resilience in rural areas that was co-designed with four communities in central Tunisia and Nordeste Brazil, NGOs, and institutional stakeholders (Figure 27). This framework takes into account the specific challenges and needs of rural communities, considering the interconnectedness of technical, institutional, and social factors in achieving water resilience.

The framework was operationalized to give practical content to the notion of water resilience. First, it (referring to the framework) incorporates the three key functions of a resilient Rural Water Supply System, including 1) the productive function: to provide water at all times, even in the case of shocks and stresses; 2) the internal regulation function: the community institutions enabling to organize water supply; and 3) the territorial integration function: the ways in which a community is integrated territorially. Second, features of water resilience were co-defined for each function, and finally, explanatory variables were established for these features at the intersection of scientific, practical, and local perspectives on rural water resilience.

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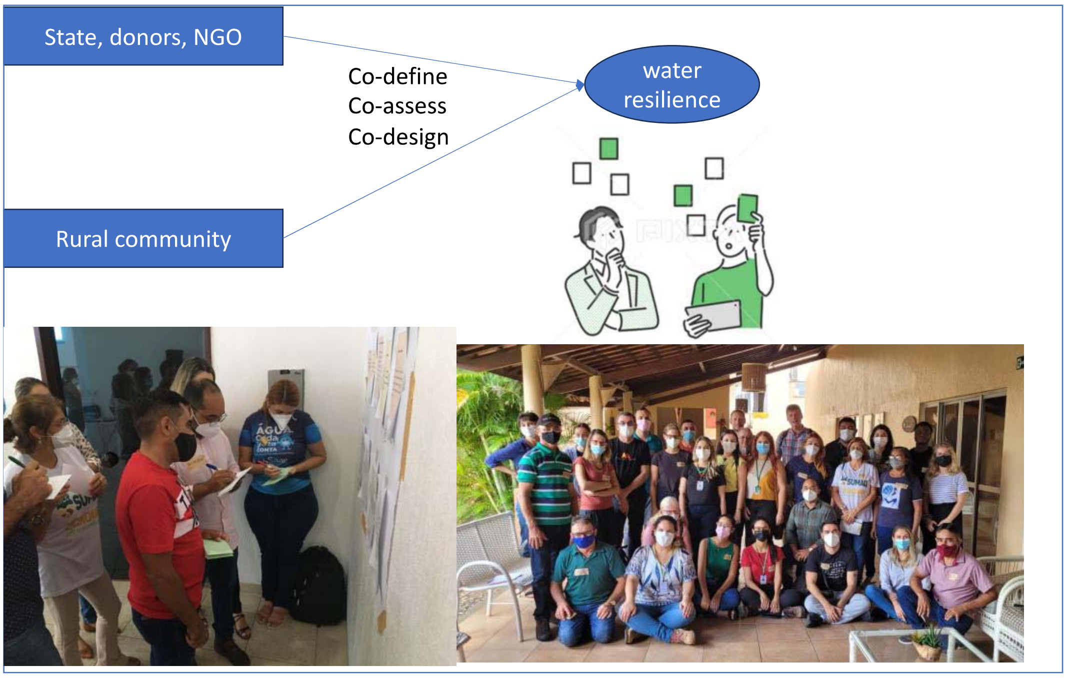
[7] This paper was published in Regional Environmental Change Journal in 2024: Hela Gasmi*, Julien Burte, Eduardo Sávio Passos Rodrigues Martins, Soumaya Younsi, Sylvie Morardet and Marcel Kuper. Regional Environmental Change (2024) 24 :12 https://doi.org/10.1007/s10113-023-02161-9

Figure 27 – A participatory approach to co-design and characterize water resilience in rural communities. Photos from a mixed workshop with national and regional institutes, research institutes, NGOs, 6 representatives of rural communities to define and characterize water resilience



Source: Author, 2022.

4.1 Introduction

In water scarce regions, rural communities are facing mounting difficulties maintaining sustainable access to water (Whaley; Cleaver 2017), particularly in the face of disasters and climate change (Manyena *et al.* 2008). Climate change entailing high variability in water availability, in tandem with organizational problems in supplying water to scattered dwellings for multiple uses, and dependance on external interventions to implement infrastructure projects, often jeopardize the resilience of rural water supply systems (RWSS) (Munasinghe 2019). Resilience is commonly defined as the ability of a system or community to adapt to or cope with shocks and stressors (climate variability and change, social crises, economic shocks, etc.) while maintaining key functions (Rana 2020).

The concept of resilience is increasingly applied to urban water systems and climate change in high-income countries, mainly focused on "engineering resilience in water supply infrastructure" (Rodina 2019:1). However, little attention has been paid to the resilience of rural water supply systems, despite the multiple shocks and stresses they encounter (Heijman *et al.*

2019). Rural water systems are very different from urban water systems due to lower population densities, scattered dwellings and multiple uses of water, including for agricultural purposes and watering livestock. As a result, the management of rural water supply systems by water utilities is both very expensive and complicated. Consequently, RWSS are often entrusted to community-based organizations that struggle to secure sustainable access to water (Whaley; Cleaver 2017; Gasmi *et al.* 2022).

The concept of resilience makes it possible to analyze how (water) systems "resist shocks in a … responsive fashion" while acknowledging that the systems themselves are on trajectories of change (Leach *et al.* 2010, p. 373). Resilience explicitly recognizes the complexity of (evolving) socio-technical systems and their environment, while also drawing attention to their non-technical dimensions (Rodina 2019). Moreover, resilience underlines the importance of community participation in policy processes and decentralized institutions, although the concept is often used at other levels (e.g. Schilling *et al.* 2020).

On the other hand, the concept of resilience has often been criticized when it is used to justify or accompany interventions that provide diminishing resources to support communities, which are then blamed for their lack of resilience (Robinson; Carson 2016). Resilience thinking often considers external shocks as "natural or inevitable" rather than as consequences of political choices and socio-economic dynamics (Platts-Fowler and Robinson 2016, p. 5). Moreover, household and community resilience is typically difficult to measure and little is known about the factors underlying community resilience (ibid).

The nature of conceptual frameworks that can be used to characterize water resilience is subject to debate, raising questions about the political nature of how the concept is defined, by/for whom and for what and why (Dewulf *et al.* 2019). While much work has been done on supposedly 'objective' frameworks, increasing attention is now being paid to measuring the 'subjective' resilience of households and communities (Jones 2019). Based on the premise that stakeholders have a profound understanding of their environment, the RWSS and the shocks and stresses they face (Nguyen; James 2013), "perceived resilience is therefore about (measuring) how people rate their own resilience, and the resilience of the wider community of which they form part" (Jones; Tanner 2017:230).

Perception-based subjective indicators and observable variables such as access to assets and livelihood capital may then inform the resilience within a community in a holistic manner (Jones; Tanner 2017). Similarly, Helfgott (2018, p. 855) has underlined the importance of using "participatory methods for understanding, modelling or managing resilience" to include the perspectives of the various stakeholders involved. Indeed, the idea of this paper was not to provide an expert view of the resilience of an RWSS. We intended rather to explore with the communities, which had been entrusted with the daily management and operation of these RWSSs and the external actors (state services, NGOs, politicians) involved in their development, their assessment of the resilience of an RWSS.

Pursuing this line of thought, we designed a participatory approach to develop an operational framework to characterize the resilience of rural water supply systems at the community level, combining subjective and objective approaches for resilience measurement. This approach was inspired by the conceptual framework of Smits *et al.* (2010, p. 102), which specifically targets rural water supplies through a multiple-use water services, taking into account that "people use water for multiple purposes". The approach was also informed by the many existing resilience frameworks in different domains, generally not (exclusively) related to water (e.g. Tariq *et al.* 2021). Building on this, we developed our own operational framework, targeting specifically the particular conditions of rural water supplies in semi-arid regions.

This article provides insights into the key functions of a RWSS, along with the features of water resilience for each function and the explanatory variables established for these features at the intersection of scientific, practical and local perspectives on rural water resilience. The results are presented in the form of a framework that describes the functions, features (the distinctive attributes of each function that allow the RWSS to fulfil the function when dealing with shocks and stresses), and the explanatory variables of water resilience that allow these functions to be maintained.

4.2 Methodology

4.2.1 Using a water resilience lens in a participatory process with rural communities

The development of an operational framework to characterize the resilience of RWSSs, using a participatory approach, was inspired by the rich resilience debates in the literature (Tariq *et al.* 2021). We consistently related these debates to the current understanding of rural water supplies as multiple-use water services (Smits *et al.* 2010) to verify their pertinence for our study. First, the resilience literature urged us to focus on the dynamics and trajectories of the system under consideration (Gondard *et al.* 2021). In the case of rural water supplies, this makes particular sense because of the considerable intra- and interannual variability of available water resources, the changes in water demand (quantity, quality), the modifications in infrastructure (investment, maintenance, bricolage, decay etc.) and rules of use

(Gasmi *et al.*, 2022; see also Pagano *et al.* 2017; Simonovic, 2009 on the dynamic behaviour of water supply systems).

Second, it encouraged us to adopt a systematic approach to RWSS in which resilience is seen “as a sequence of systemic interdependent interactions through which actors secure the resources required for sustainability in stressed environments” (Ungar 2018:1; see also Liu *et al.* 2017). Third, it showed the need to account for different shocks and stresses, including climate-related shocks, socio-political or economic crises, all of which are of course particularly relevant for rural water supplies (Moriarty *et al.* 2013). Fourth, it recognized the multi- or cross-scale and feedback dynamics (Adger *et al.* 2005) and the fact that any given system is “*open, dynamic and complex*” (Ungar 2018:1).

And fifth, we explored existing operational frameworks on resilience (in particular, Lallau; Archambaud 2018; Gondard *et al.* 2021; Tariq *et al.* 2021). Although these frameworks were not focused on (rural) water supplies, they inspirated us in identifying the key functions and features of a resilient RWSS. More generally, Helfgott (2018, p 854) nicely resumes the guidance provided by existing operational approaches to resilience:

> Any method used to characterize resilience relies on a clear specification of the boundaries of the system under consideration, of the notion of improvement within those boundaries, and for whom, the type and magnitudes of disturbance to be considered and the timescale to be considered (see also Grafton *et al.* 2019).

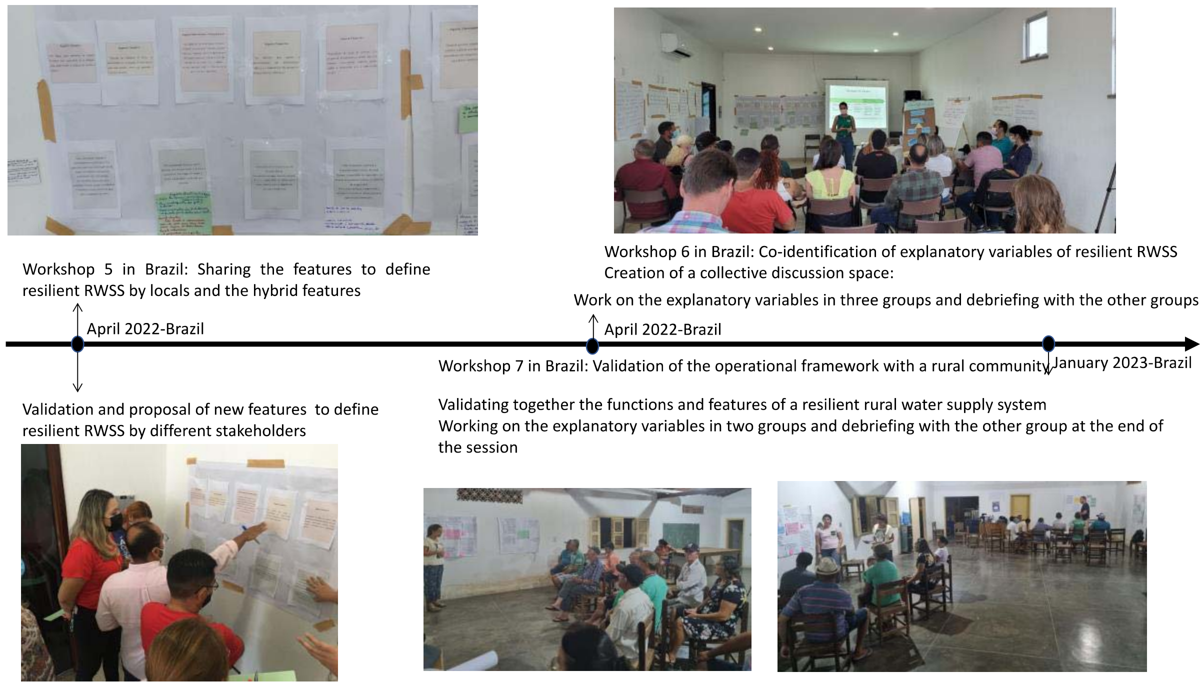
Before engaging on the participatory research process of designing an operational framework to analyze the resilience of RWSSs, we first had to gauge the interest of the communities for such an engagement through a preliminary participatory diagnosis (figure 28; see Faysse *et al.* 2014 on local participatory research processes related to adaptation to climate change and on the ethical and methodological safeguards in participatory approaches; see also Hassenforder *et al.* 2015). Our approach was also informed by some of the visual tools proposed by Voinov *et al.* (2016) and by the Cooplage approach[8] (Ferrand *et al.* 2021). During the diagnosis, we agreed with community members about the objective of the approach. Through a series of workshops, we then confirmed with community members the pertinence of using a lens of water resilience to qualify the trajectory of a RWSS. We co-constructed a social representation of the trajectory of a RWSS faced with past and actual different shocks and stresses (Figure 28, see Gasmi *et al.* 2022 on the trajectories of RWSS in four communities in

[8] Supplementary methodological material on the Cooplage approach can be found here: http://www.g-eau.fr/index.php/fr/productions/methodes-et-outils/item/888-l-approche-cooplage

Tunisia and Brazil), thus progressively making visible the notion of water resilience with the community (Jones and Tanner 2017). Then, in the following workshops, we co-constructed and operationalized a water resilience framework by defining the key functions and features of a resilient RWSS.

The key functions were inspired by the literature and encompassed the productive function (typically to provide water in times of shocks and stress), the internal regulation function (the institutions governing the RWSS and social cohesion), and the territorial integration function (the ways in which a community is integrated in the external world) (Gondard *et al.* 2021). With community members, we distinguished between the features, i.e., the distinctive attributes or state variables of each function that allow the RWSS to fulfil the function when dealing with shocks and stresses, and the explanatory variables that allow these functions to be maintained (Lallau; Archambaud 2018).

Figure 28 – Different steps in the co-design of the RWSS framework and the co-identification of water resilience features and explanatory variables in Brazil and Tunisia



Source: Author, 2022.

4.2.2 The four case studies

Our analysis is based on the RWSS of four rural communities in semi-arid regions of Northeast Brazil and Central Tunisia (Table 6). The study was conducted between January 2019 and April 2022. The case studies are situated in different socio-political contexts but have in common the issue of water scarcity and complicated access to water by the communities. All four case studies are situated in a societal environment poorly endowed with organized responses to stressors and hazards. However, communities affected by such events often show considerable ingenuity in dealing with hazards and stressors.

The main author of the study interacted closely with two action research projects: the Program for Climate Change Adaptation in Vulnerable Territories of Tunisia (PACTE) which aims to enhance the governance of natural resources and strengthen climate change adaptation in rural territories and the project so called Sustainability and resilience of water supplies and land in Nordeste (Sertões) which intends to support decision making and public agricultural and water policymaking, taking account of energy and environmental issues, both projects are funded by the French Development Agency (AFD). Both projects facilitated access to the field while guaranteeing a lively debate on the issue of rural water supplies.

Table 6 – Characteristics of the communities in the four study areas

BRAZIL		TUNISIA	
Community 1	Community 2	Community 3	Community 4
Varzea Do Meio	Santa Maria	Rihana south (Ouled Salah)	Rihana north (Ouled Om Hani)
- 90 families	- 31 families	- 120 families	- 200 families
-Irrigation of vegetables, fruit trees -Subsistence farming -Small-scale animal husbandry -Rainfed corn and beans		-Livestock farming -Subsistence farming -Rainfed olive and almond trees -Irrigation limited to inhabitants endowed with private boreholes	

Source: Author, 2022.

4.2.3 Research approach

The different methodological steps are listed in table 7. Our approach consisted of a series of workshops to co-design an operational water resilience framework, preceded by a participatory diagnosis (step 1). We undertook a historical analysis to understand the adaptations made by communities to secure water supply. Then, we analysed the functioning of the RWSS (step 2). At the end of this stage, a workshop was organized in each study area (step 3) to 1) characterize the trajectory of each RWSS using conceptual models covering different periods of time (Gasmi *et al.* 2022); and 2) design a conceptual framework of a resilient RWSS.

By identifying the past and actual shocks and stresses as well as the adaptations made, we introduced the concept of water resilience in a series of six workshops (step 4). In the first workshop (step 4.1), we identified the variables that allow the resilient RWSS to fulfil its functions. Next we organized a workshop with stakeholders (step 4.2) to validate and propose new features to define water resilience. This workshop was only organized in Brazil, as project activities in Tunisia were suspended at that time. However, we (partially) compensated this difficulty by mobilizing the results of earlier surveys in the study area in Tunisia. These results have enhanced our reflection in Brazil, especially when we reorganized and complemented the features. The advantage of working in two semi-arid contexts in the earlier part of this research is to guarantee diversified case studies and thus a more general problematization of water resilience in rural areas. The workshop participants in Brazil validated the functions and the features and proposed three additional features. A mixed workshop (step 4.3) was then organized in which participants reviewed the definition of water resilience and the features.

The participants identified 30 explanatory variables for the features to characterize water resilience. The authors subsequently added 5 explanatory variables from the literature, which echoed their field observations, to cover all dimensions of water resilience. For example, we had observed in all communities a competence to carry out repairs through bricolage, sustaining the functioning of their RWSS. Finally, the framework was validated in one rural community in Brazil (step 4.4). One of the limits of this study was that we have not codefined indicators for explanatory variables of a resilient RWSS. This is a logical next step in future research, but not included in this study. However, towards the end of the paper we have provided some ideas on possible indicators, based on the last workshops in Brazil.

Table 7 – Overview of different methodological steps and tools used in the data collection and the workshops held in Brazil and Tunisia to co-define and characterize water resilience

#	Steps	Methods	
		The steps carried out in Brazil and Tunisia:	
1	Undertaking a historical analysis of trajectories of the RWSS in the four selected case studies	-Participatory observations (Arborio and Fournier, 2021) -Participatory mapping (Cochrane and Corbett, 2018)	Semi-structured interviews (15 in Tunisia and 20 in Brazil) with key stakeholders: community health agent, water users association members, district engineers, and local water technicians.

Continuation

Table 7 – Overview of different methodological steps and tools used in the data collection and the workshops held in Brazil and Tunisia to co-define and characterize water resilience

#	Steps	Methods	
2	Analysing the functioning of the RWSS	Field surveys (Hammes *et al.* 2016)	Surveys (30 in Tunisia and 40 in Brazil) to collect information at the household and community levels on: - Water users - Water uses (drinking, domestic, agricultural) - Infrastructures (lay-out, quality, location) - Resources (quantity, quality, location) - Rules of use (formal and informal) - Evolutions and adaptations in infrastructure and rules
3	Co-designing the RWSS Framework & Co-designing the RWSS trajectories	-Participatory modeling: using a conceptual model as support for discussion (Gasmi *et al.* 2022; Sabourin *et al.* 2004)	Workshops in Tunisia and Brazil 1 workshop in Tunisia: -10 interviews to prepare the workshop -1 workshop with participants from the two communities -12 participants: 4 women and 8 men (6 from Ouled Salah, 6 from Ouled Om Hani) 2 workshops in Brazil: -12 interviews to prepare the workshops -1 workshop in Santa Maria community 8 participants (4 women and 4 men) -1 workshop in in Varzea Do Meio community 8 participants (4 women and 4 men)
4 Co-defining and characterizing the resilience of RWSS (Brazil-Tunisia) & creating a collective discussion space			

Continuation

Table 7 – Overview of different methodological steps and tools used in the data collection and the workshops held in Brazil and Tunisia to co-define and characterize water resilience

	#	Steps	Methods
4.1	Identifying features to define water resilience with community members	Workshop with community members: -identifying shocks, stresses and adaptations (McPeak *et al.* 2017) -using familiar words to describe features of resilience in the native language (Arabic in Tunisia and Portuguese in Brazil)	Workshops in Tunisia and Brazil 1 workshop in Tunisia: -12 participants from the two communities : 4 women and 8 men 2 workshops in Brazil: -1 workshop in Santa Maria community; 8 participants (4 women and 4 men) -1 workshop in Varzea Do Meio community; 8 participants (4 women and 4 men)
		The steps carried out in Brazil:	
4.2	Validating and proposing new features to define water resilience	-Using the results of previous workshops to validate the RWSS conceptual framework (NGOs, state services) -Reorganization of features linked to the 3 functions of the resilience of RWSS by the authors -Video presentation and group discussion	-1 workshop in Brazil with mixed stakeholders 20 participants from national and regional water institutes, research institutes, NGOs.

Continuation

Table 7 – Overview of different methodological steps and tools used in the data collection and the workshops held in Brazil and Tunisia to co-define and characterize water resilience

#	Steps	Methods	
4.3	Co-identifying explanatory variables of water resilience	-Listing and debating explanatory variables by participants in three groups based on the three functions of water resilience and debriefing with the other groups at the end of the session (Gondard *et al.* 2021)	-1 workshop in Brazil with mixed stakeholders 29 participants (national and regional institutes, research institutes, NGOs, 6 representatives of both communities)
4.4	Validating the operational framework	-Validating the functions and the features together -Working on the explanatory variables in two groups and debriefing with the other group at the end of the session	-1 Workshop in Brazil with 15 members of rural community (2 women and 13 men)

Source: Author, 2022.

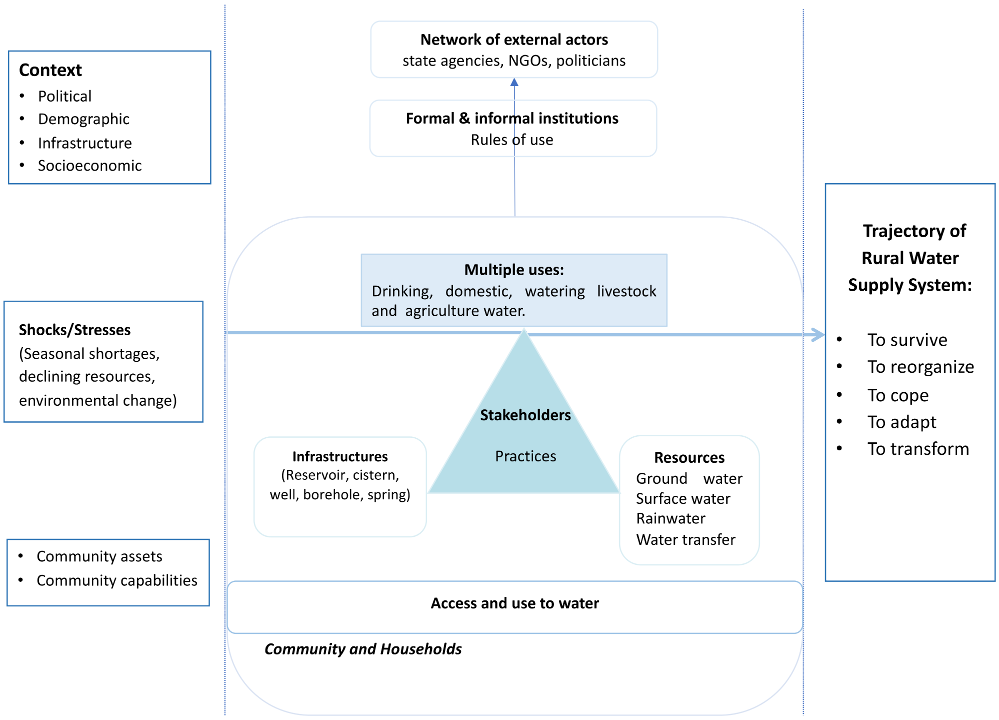
Conclusion

4.3 Results and discussion

4.3.1 Co-defining a conceptual framework of the trajectory of Rural Water Supply Systems

We co-designed a conceptual framework to represent the trajectory of a RWSS in the face of adversity. As indicated above, we did not use term resilience at this stage during the workshops. However, the term adversity, associated with shocks and stresses experienced by stakeholders and the subsequent changes (to survive, reorganize, etc.), in relation to their RWSS, was clearly inspired by our conceptual lens of resilience. For operational purposes (Lallau; Archambaud 2018), the framework of figure 29 focuses on only two scales: the household and community scales, but incorporates interactions with external actors. This framework can be used by development actors, water managers, non-governmental-organizations, and community stakeholders to represent the dynamics of RWSSs.

Figure 29 –The co-designed conceptual framework of the resilience of the trajectory of a Rural Water Supply System in the face of shocks and stresses



Source: Authors with active contributions of stakeholders. 2022.

The workshop participants chose to define the RWSS as a system (Figure 29), and in both countries deliberately went beyond the sole physical infrastructure when representing a RWSS (Manyena *et al.* 2008). A RWSS thus includes the different water resources (surface water, groundwater, rainwater, transferred water), different types of infrastructure (wells, dams, cisterns, water networks), the community stakeholders and their connections with outside actors, the rules governing the design, implementation, maintenance and use of the RWSS (formal and customary institutions) practices used for access to and the multiple uses of water (drinking water, domestic water, agricultural production). A RWSS was therefore considered to be shaped by the social relationships that contributed to its establishment and development.

The left section of the middle column in the Figure 29 lists the vulnerabilities caused by political interventions, demography (migration, in particular), infrastructure (roads, health, schooling), and socio-economic change, along with water-related shocks and stresses in rural areas. In each country, the specific examples related to such vulnerabilities were different, so we regrouped them in four categories (Figure 29). Contrary to several international frameworks, which define resilience with a specific focus on climate shocks and stresses, the communities indicated they were facing different kinds of shocks and stresses that were hard to differentiate (McPeak *et al.* 2017).

The shocks and stresses mentioned by the participants included drought, floods, groundwater overexploitation, and water pollution due to excessive use of fertilizer and pesticides. The rural community also disposes of financial, physical, human, social, and natural assets and capabilities to make use of its assets, and these are the factors that make it possible, or not, to maintain the key functions of a RWSS (Lallau; Archambaud 2018). They comprise resilience factors that influence the trajectory of the RWSS. Together, we defined this trajectory (right section of the middle column in the Figure 29) as temporal and spatial changes to be made to the rural water supply systems by a group of stakeholders, in a defined territory, in order to develop a set of strategies for adaptation and transformation to meet their multiple needs.

The choice was made to first work with the stakeholders on how to represent the trajectory of the RWSS rather than to first discuss the meaning of 'resilience'. The term resilience exists in Portuguese (Resiliência), although it is not used in the villages we worked in, and in Arabic, the word 'resilience' does not exist. We consequently introduced and discussed the word through the prism of resilience strategies, using words like persistence, adaptation and transformation to reach a shared understanding of how the four rural communities address shocks and stresses related to water.

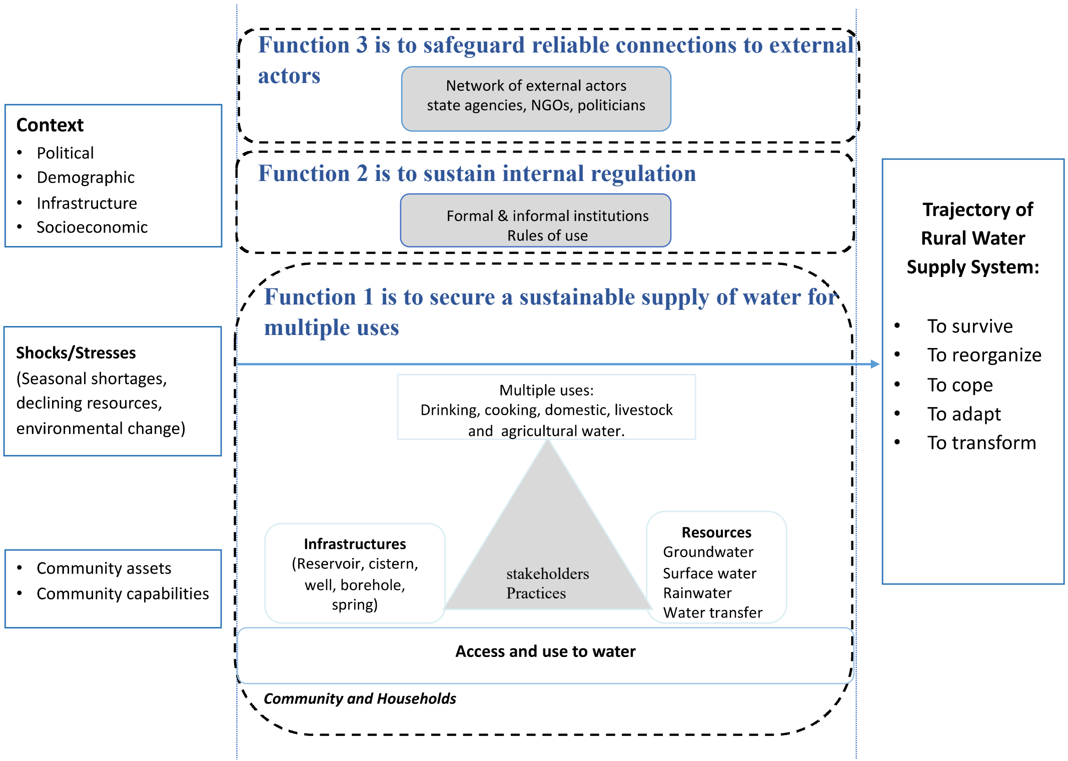
We translated all the terms from English to Portuguese and Arabic and vice versa (*convivência com o semiárido, adaptação e transformação*: coexistence in (a) semi-arid (context), adaptation and transformation; *منظومة مائية قوية وصامدة ضد التغيرات والصدمات* : a robust and resilient water system against changes and shocks). On the basis of these discussions, the following definition of the resilience of a RWSS was proposed, validated, and adopted by workshop participants: "*In the face of water-related shocks and stresses, the capacity of a RWSS is to maintain or restore its essential functions. A RWSS might have to deal with shocks, adapting to changing conditions and transformations in situations of crisis while maintaining internal regulation and external connections. There may be adaptation of hydraulic infrastructures, a reorganization of rules and social institutions, a transformation of agricultural activities, public policies etc.*". Based on this definition, we then operationalized the conceptual framework by defining the main functions and features of a resilient RWSS (see following section).

4.3.2 Characterizing the resilience of RWSS: functions, features and explanatory variables

Building on the representation of a resilient RWSS (figure 29), the three key functions of such a resilient system were specified jointly with the participants during the workshops (Figure 30): 1. the productive function is to secure the sustainability of the multiple uses of water; 2. the internal regulation function is to maintain a functional RWSS; and 3. the territorial integration function is to safeguard reliable connections with external actors, who are key to dealing with both occasional and recurrent problems of the RWSS, such as mechanical breakdowns or periods of drought. The different features of resilience linked to these key functions were co-defined in the four selected communities in Central Tunisia and in Northeast Brazil. Indeed, despite the differences in the two contexts, people share a similar vision of resilience of RWSS at the community level.

The resilience framework was further operationalized by designing 35 explanatory variables for the 12 features (Tables 8,9,10). This was done in a workshop with all stakeholders in Brazil. Interestingly, the explanatory variables identified combine subjective variables and more objective variables, i.e., that can be observed or measured. This outcome was not planned by the research team, but connects well with the work of Maxwell et al (2015), who underlined the importance of combining subjective and objective approaches for resilience measurement (see also Clare *et al.* 2017; Jones and Tanner 2017 for subjective approaches to resilience).

Figure 30 – Interpreting how the three key functions of a resilient RWSS relate to the three components of the system (Function 1: infrastructure, multiple uses, multiple resources; Function 2: institutions; Function 3: network of external actors)



Source: Author, 2022.

4.3.2.1 The first function is to secure a sustainable supply of water for multiple uses

Workshop participants first worked out the definition of the first function (Table 8). In rural areas, the communities do not rely on a single water resource, as this would render the water supply vulnerable (Elliott *et al.* 2019). The communities thus opted for a combination of strategies (Rey *et al.* 2017) to make best use of available water sources while accounting for infrastructure constraints.

They generally aim to exploit multiple resources and different types of infrastructure to secure a supply of water for their everyday uses, including in times of crisis. A RWSS also needs to secure a sufficient quantity and quality of water for different uses: drinking and domestic use, watering livestock, and irrigation (Smits *et al.* 2010).

Two features and eight explanatory variables were attributed to this productive function (Table 8). The results in Brazil and Tunisia converged for this function, although communities in Tunisia were more skeptical about their ability to adapt to changes and shocks. This did not alter the definition of the two features (and explanatory variables).

The first feature is that a community manages its water resources sustainably to be sure to access the quantity and quality of water it needs. This can be characterized by documenting the perception of the community of the four explanatory variables listed in Table 8 (changes in water resources, changes in the satisfaction of basic needs and for socio-economic uses, and access to public emergency supplies such as water trucking). Interestingly, the basic needs defined by the members of all the communities include not only drinking and domestic water, but also watering of livestock and a minimum level of irrigation in critical situations.

They are aware of their RWSS' trajectory and compare their current situation with public norms as well as with their situation in the past. Socio-economic uses are linked to irrigation, milk cooperatives, and small industries. These uses are governed by social norms concerning the rational use of water. Balancing supply and demand is important, because failure to do so may encourage water users to access the resource in ways that threaten the sustainability of RWSS and may cause mechanical breakdowns (Schouten; Moriarty 2003).

The second feature is that a resilient community owns the physical resources (water infrastructure, roads, energy) and has the ability to use these resources in order to adapt to shocks and changes. To characterize this feature, we propose four explanatory variables listed in Table 8 (access to multiple water resources, dependance on energy to operate the water infrastructure, the state, nature and security of hydraulic infrastructures, and the existence of sanitary control of water quality).

Sustainable access to multiple water uses could be achieved by combining different technologies and types of infrastructure (Smits *et al.* 2010). When designing water infrastructure, it is crucial to consider the use of energy. The need to lift or pressurize water through pumps increases costs and makes the RWSS dependent on the energy supply.

Table 8 – The features (2) and explanatory variables (8) of function 1

Function 1 is to secure a sustainable supply of water for multiple uses. Function 1 is linked to the capacity to exploit multiple water resources. The community needs to use its assets to adapt supply to changes and emergencies.	
Features	Explanatory variables
1. A community with a resilient RWSS manages multiple water resources sustainably. The RWSS needs to maintain access to the quantity and quality of water required. The community members should practice rational use of water.	1. Changes in the quantity, quality, regularity and diversity of water resources 2. Changes in the satisfaction of basic needs 3. Changes in the satisfaction of socio-economic water requirements 4. Public emergency supply from external water resources
2. A community with a resilient RWSS has access to physical resources (water infrastructure, roads, energy). It has the capacity to use all these resources to adapt to shocks and changes.	5. Access to multiple water resources 6. Dependance on energy infrastructure for access to water 7. Functionality, nature (collective/individual) and security of hydraulic infrastructures that supply water 8. Sanitary control of drinking water, domestic water and of water for other uses.

Source: Author, 2022.

4.3.2.2 The second function is to sustain internal regulation

Maintaining the internal organization of the RWSS in the face of adversity depends on social regulation and organization. This function is defined by six features and 17 explanatory variables (Table 9). This is the function for which the results obtained in Brazil and Tunisia diverged the most. Whereas in Brazil, the communities projected to play an active role in dealing with problems, Tunisian communities systematically referred to the role of the State in dealing with trends and shocks and proposed that responsibility should be shared between the State and the community.

This may be explained by the fact that past policies and programs in Tunisia are largely state-driven. From the viewpoint of the stakeholders, we interacted with, existing associations in Tunisia do not have sufficient resources to sustain the functioning of the RWSS.

In Brazil, communities can rely on a wider range of external actors (NGOs, associations, and State services). Collective action consequently tends to be more formal in Brazil, whereas in Tunisia it is mostly informal.

At the same time, social solidarity in both countries is strong, especially in case of problems concerning drinking and domestic water. As the features and explanatory variables were only validated in Brazil, it would be interesting to carry out the same exercise in Tunisia. While based on our earlier workshops, we would expect these features and explanatory variables to be validated in Tunisia too, it cannot be excluded that some will be modified or that a few other variables will be added.

The first feature is that a community is organized, informed and disposes of a platform for internal communication, allowing people to meet, identify problems and suggest possible solutions.

The second feature is the collective (community) and individual (households) capacity to analyze, anticipate and take preventive action. This can be characterized through knowledge of the different uses and associated consumption of the water resource, and the level of commitment of community members to collective action. Collective preventive actions such as water saving measures require coordination, information sharing and trust between inhabitants (Fan *et al.* 2013). Of course, preventive actions do not only depend on community actions, but can also be established by external stakeholders preparing contingency and emergency planning (function 3).

The third feature is that a community is collectively and individually able to tinker with and transform water systems when faced with adversity. The fourth feature is that a resilient RWSS has the ability to self-regulate water use. Water users have the knowledge and are able to understand natural limits and to adapt their practices to avoid degrading the environment, i.e. to "coexist with limitations" as stated by a Brazilian community member (see Norris *et al.* 2008).

The fifth feature is that a community with a resilient RWSS has the necessary solidarity and social cohesion to maintain its functions under stress and shocks (Arbon 2014). The importance of collective action in maintaining and building the physical infrastructure was emphasized by the communities (*mutirão* or community work in Brazil; Sattler *et al.* 2015).

The final feature is that a community with a resilient RWSS is economically viable. It has the ability to mobilize internal and external resources (including government financial support) to sustain and adapt the RWSS to sudden changes and long-term trends. This relates first to the cash flow generated by the RWSS that enables the community to pay for the variable costs (energy, workforce) of their own water network, the purchase of water from private boreholes or water trucks, the maintenance and repair of the RWSS, and the capacity to invest in new infrastructure. Often, the maintenance and repair of existing systems and investment in new infrastructure is particularly reliant on external financial support due to low tariffs and the low density of inhabitants (Whittington *et al.* 2009; Tong *et al.* 2022). However, the workshop participants highlighted the importance for the users' association to have its own financial resources, as dependance on external actors can weaken the resilience of the RWSS.

Here, our results are in line with those obtained by Béné (2013), who measured the resilience at household/community level in terms of the costs of facing a particular shock. These costs were categorized as anticipation costs; the costs of destruction; the costs of recovery including replacement costs; and the various costs after a shock associated with change, adaptation, or transformation. Adaptation strategy at community scale was identified as a crucial strategy to cope with climate change (Metcalfe *et al.* 2020).

Interestingly, a number of the explanatory variables listed in the workshop corresponded to the "constraints" to the adaptation strategies identified by Beauchamp *et al.* (2019) who worked on the perceptions of climate resilience by local communities in Mali and Senegal, in particular "the lack of financial resources to invest in assets and new livelihoods"; "lack of capacity of technical services to maintain natural resource governance institutions; and the presence of conflicts in local natural resource management" (Beauchamp *et al.* 2019: S304; see also table 9: variables 2, 15-17, and table 10: variable 10).

Table 9 – The features (6) and explanatory variables (17) of function 2

Function 2 is to sustain internal regulation. It is based on social regulation and organization.	
Features	Explanatory variables
1. A community with a resilient RWSS is organized, informed and has a platform for internal communication. The organization allows people to meet, identify problems and suggest possible solutions.	1. Collective organization (formal or informal), exists and is recognized within the community 2. Conflict management 3. Social cohesion and inclusion of community members

Continuation

Table 9 – The features (6) and explanatory variables (17) of function 2

Function 2 is to sustain internal regulation. It is based on social regulation and organization.	
2. A community with a resilient RWSS has the capacity to analyze and anticipate (planning, collective preventive actions). It is aware of possible future problems. Water users are also able to anticipate and take preventive action, adapting their activities to their knowledge of the different uses and associated consumption.	4. Level of knowledge of the different water uses and associated consumption 5. Capacity of anticipation (existence of a plan) (inspired by Gunderson, 2010) 6. Level of commitment to collective preventive actions
3. A community with a resilient RWSS is collectively and individually able to tinker with and transform water systems when confronted with adversity.	7. Internal ability to use bricolage to repair, maintain, and renew water supply systems (inspired by Norris *et al.* 2008)
4. A resilient RWSS has the capacity for self-regulation of water use. Water users have the knowledge and are capable of understanding the natural limits and of adapting their practices to avoid degrading the environment, i.e. to “coexist with limitations”.	8. Monitoring of water resources and water uses (inspired by Olsson *et al.* 2004) 9. Sharing of knowledge and information among farmers 10. The limits of exploitation of water resources are known 11. Preventive and contingency measures to reduce water consumption 12. Actions for the preservation of soils, forests, riverbanks, streams and permanent collective conservation zones

Continuation

Table 9 – The features (6) and explanatory variables (17) of function 2

Function 2 is to sustain internal regulation. It is based on social regulation and organization.	
5. In a community with a resilient RWSS, there is solidarity and social cohesion.	13. Level of solidarity and social cohesion 14. Existence of collective actions around water that involve the whole community
6. A resilient RWSS is economically viable and the community has the ability to mobilize internal and external resources to adapt to sudden changes and long-term trends. It is able to maintain, substitute and invest in small-scale water infrastructure when needed.	15. The income from the water tariff is sufficient to maintain a cash flow for the water association 16. Transparent management of the water users association's money 17. The community has the money or can obtain it to maintain, replace and invest in water infrastructure

Source: Author, 2022.

Conclusion

4.3.2.3 The third function is to safeguard reliable connections to external actors

Having access to strong network of external actors is crucial when a community is faced with an emergency, for example, repair a breakdown, replace infrastructure or request a water truck. These networks can be activated to solve local health, political or security problems or to obtain funding for community water projects. However, many community members in our workshops emphasized that local autonomy must be respected in a way that community resilience does not depend entirely on external aid.

The first feature is that a community with a resilient RWSS has strong connections with State services, politicians, NGOs, and with other communities. Maintaining these connections in the long run is hard work for the community (Collard *et al.* 2013). In the current political context in Tunisia, frequent changes in the representation of the communities we studied have destabilized the way these politicians can be mobilized for water-related problems.

The second feature is that a community with a resilient RWSS is recognized as an actor in the territory, this is usually only partially the case. Where a collective network does exist, there is a formalized entity (association) that is recognized by external actors and can play the role of intermediary.

The third feature is the incorporation of the water supply in that of the larger territory. It can be characterized through the level of physical and hydrological isolation of the community from infrastructure and State services. On the other hand, certain communities have guaranteed access to water resources, for example from a neighbouring community in the case of a crisis, which increases the resilience of their RWSS.

The fourth feature is access to information, advice, and training. A community with a resilient RWSS has permanent access to the information it needs, benefits from continuous training that empowers it, and receives regular technical assistance adapted to its needs.

In the workshops, community members called for better access to, for example, hydrological data (groundwater levels, surface flows) available in government institutions. They expressed a need for specific knowledge on zero-pesticide agricultural practices or drinking water treatment. Sharing information, advice and knowledge is an important dimension of getting the communities more involved in the design, running and maintenance of RWSS (Tong *et al.* 2022). Communication between the community and external actors can create a collective space to identify opportunities and to articulate needs and opinions (Norris 2008). A number of quantitative explanatory variables are included in objective frameworks, such as the distance to the water network and to roads, proximity to towns, and the presence of dependable communication networks (Beauchamp *et al.* 2019).

Table 10 – The features (4) and explanatory variables (10) of function 3

Function 3 is to safeguard reliable connections to external actors, which makes it possible to assess the mode of integration of the RWSS in the rest of the territory and favors its existence. Function 3 includes the integration of the RWSS in the economy, society and territory.	
Features	Explanatory variables
1. A community with a resilient RWSS is connected to the outside world. It has a strong network of external actors it can call on in an emergency to replace infrastructure or to request a water truck. These networks can be activated to solve local health, political or security problems or to obtain funding for community water projects.	1. Links between the community and public, private or community actors (number and diversity) 2. Changes in these links 3. Frequency of contact with these actors
2. A community with a resilient RWSS is recognized as an actor in the territory. It is institutionally represented. Its economic, social and environmental role is recognized.	4. Representation of the community (institutional, economic, environmental and social) (inspired by Saikia *et al.* 2022)
3. Integration of the water supply in the larger territory.	5. The level of physical isolation of the community from infrastructure and State services 6. Hydrological isolation (distance from the main water supply network) 7. Existence of guaranteed external water supply

Continue

Table 10 – The features (4) and explanatory variables (10) of function 3

Function 3 is to safeguard reliable connections to external actors, which makes it possible to assess the mode of integration of the RWSS in the rest of the territory and favors its existence. Function 3 includes the integration of the RWSS in the economy, society and territory.	
4. A community with a resilient RWSS has permanent access to the information it needs, benefits from continuous training that empowers it, and receives regular technical assistance adapted to its needs.	8. Access to information (on climate, hydrology, agriculture) (inspired by Saikia *et al.* 2022 and Norris *et al.* 2008) 9. Access to training 10. Access to technical support

Source: Author, 2022.

Conclusion

Indicators can then be defined with different stakeholders for the explanatory variables of the three functions, which was not done in the present study. However, we propose three potential indicators for the Brazil case (table 11). These indicators have not been defined with stakeholders and are only provided to illustrate possible pathways for future research.

Table 11 – Three possible indicators for explanatory variables of the key functions and features

Features	Indicator	Questions	Measurement	Unit of measurement
Function 2, feature 1	Collective organization	In your community are there organizations, associations or groups in which issues related to water are discussed?	List of different collective organizations (formal and informal)	Number of (in)formal groups active Scale: the higher the score the more resilient is the community

Continue

Table 11 – Three possible indicators for explanatory variables of the key functions and features

Features	Indicator	Questions	Measurement	Unit of measurement
Function 2, feature 1	Inclusion of community members	Can all households of the community join the collective organization?	Number of families that participate in meetings	Percentage of the families that participate in the collective organizations Scale: the higher the score the more resilient is the community
Function 3, feature 4	Access to information	How often did you have access to information (on climate, hydrology, agriculture) over the last year?	Frequency in access to different types of information (weather forecast services, irrigation/livestock, development projects etc.)	Often, sometimes, very rarely/never

Source: Author, 2022.

Conclusion

4.4 Conclusions

The operational framework for resilient Rural Water Supply Systems (RWSS) developed in this study seeks to give practical content to the notion of rural water resilience (Heijman *et al.* 2019). Rather than taking an existing operational framework and adapting it to rural water supplies, we made the choice to codesign an operational framework with communities and other stakeholders. This choice is of course debatable, but in a context where the concept of resilience was not employed by most actors, we found it easier to start with the concrete issue of the RWSS itself - its infrastructures, rules-in-use, water resources and of course multiple uses – and its dynamics, before moving on to the issue of resilience. This turned out to be a rather fluid transition and the next step to codesigning an operational resilience framework was equally well understood, as workshop participants knew their physical and socio-political context very well. However, as indicated in the methodology, the existing operational resilience frameworks provided valuable lessons in identifying the key functions, features and explanatory variables of a resilient RWSS.

The three key functions of a resilient RWSS that need to be sustained in the face of changes and shocks are 1) securing the sustainably of multiple water uses; 2) maintaining functioning internal regulation; and 3) safeguarding reliable connections to external actors.

The framework was co-developed and tested in rural communities in Northeast Brazil and Central Tunisia. A RWSS is a complex and open system connected to multiple water resources through different types of infrastructure, governed by common rules and characterized by practices regarding access to water and its multiple uses (Gasmi *et al.* 2022). The particularity of rural RWSSs catering to multiple water uses (drinking, domestic and agricultural water) is often ignored (e.g. Smits *et al.* 2010) and it is particularly challenging to assess them from a resilience perspective.

The participatory design of this operational framework enabled a comprehensive understanding of how communities and external actors (NGOs, State services at different levels) perceive the resilience of a RWSS. This was done by defining 12 essential features that characterize a resilient RWSS, explained by 35 explanatory variables. This exercise connected stakeholders at different scales (households, communities, NGOs, state agencies) to share knowledge and to identify the different social, ecological and hydrologic vulnerabilities of a given RWSS. This research provides an operational basis for building more resilient rural water supply systems and increases the efficacy of development interventions to build long lasting responses to shocks and stresses (Lallau; Archambaud 2018).

The approach was conceived and applied in two quite different socio-political contexts, in two different communities and natural settings in each context. Although all the cases are characterized by a semi-arid climate, the existence of family agriculture, and highly vulnerable water resources that make it difficult to secure the multiple uses of water, developing and testing the approach in two different albeit comparable contexts was, intentionally, a way to verify the process and make the operational resilience framework more robust. Interestingly, in both countries, the definition of water resilience, codefined with communities, was similar. This may be due to the fact that the key functions (and to a lesser extent the features) of resilience that were discussed during the workshops, and on which our definition of resilience is based, have been inspired by a host of existing studies in multiple cases around the world (Lallau; Archambaud 2018; Helfgott 2018; Gondard *et al.* 2021; Tariq *et al.* 2021). Although we developed a new operational framework, we thus took advantage of the solid experience available in the literature on operationalizing resilience frameworks.

Considerable differences around the priorities in identifying water resilience features were revealed during this study. In Central Tunisia, the technical and financial aspects of water supply systems appeared to be the most urgent, given that the water network is outdated and that the state has few resources to invest. In Brazil's Nordeste, on the other hand, the governance aspect and representation in legal institutions were prioritized by communities, which express a sense of isolation and seek better articulations with the state. The key functions of a resilient RWSS are, therefore, likely to converge in most cases (although this should not be the starting point of a given approach), but the features and explanatory variables will certainly need to be adjusted. In terms of research perspectives, the explanatory variables identified in this study need to be complemented by resilience indicators. We suggested some examples of such indicators on the basis of our research in section 3.

Working across these cases allowed us to reach a common understanding of the concept of the resilience of RWSSs. However, we do not claim our framework is a universal model of RWSS resilience; its extension to other rural semi-arid areas will only be possible by contextualizing it with the communities and stakeholders concerned (Beauchamp *et al.* 2019). To achieve this, the methodolocical steps of Table 7 may be of help to those designing or implementing operational resilience frameworks. In doing so, it is important to keep in mind that "operationalising resilience, even for descriptive purposes, becomes a value-laden intervention" (Helfgott 2018, p. 863).

Recognizing this is a first step to safeguarding the research or intervention process, but like for operational resilience frameworks there is a wealth of literature addressing different safeguards in participatory processes (see Hassenforder *et al.* 2015, in the field of environmental research). Whether or not the actual resilience of RWSSs in the study area was affected by our study remains open. Although our approach was foremost metholological, the interest expressed by communities and other stakeholders shows that this issue, made visible in the workshops, is of importance to them. However, we did not evaluate or measure this.

The co-produced operational framework and its constituent parts (functions, features and explanatory variables) contribute to what is called territorial intelligence, that is "a practice devoted to obtaining, analyzing and valuing information and knowledge about a territory and its environment to design and implement territorial plans on strategic matters"

(García-Madurga *et al.* 2020, p.1), in our case, rural water supply. The participatory process can be used to bring stakeholders together to discuss water resilience in a context of climate change, to jointly produce understandable information, and to reach an understanding of the weaknesses and strengths of a RWSS. However, the supply of water is a major political issue in rural areas and many existing problems related to existing social hierarchies and power relations, need to be investigated at other levels (Collard *et al.* 2013).

In this study, we explored the resilience of RWSS at the household and community levels, and we emphasize the importance of conducting the analysis at the scale of hydrosocial territories (see Ferdous *et al.* 2018), understood as a scale at the intersection of social organizations and waterscapes.

4.4.1 Acknowledgements

This study was conducted as part of a joint PhD program at UFC (Federal University of Ceará) and Institut Agro, University of Montpellier. The research was funded by FUNCEME (Ceará Foundation for Meteorology & Water Resources) and CIRAD (Montpellier) through the Pacte and Sertões projects, funded by the French Development Agency (AFD), FUNCEME, CIRAD and FUNCAP (Ceará State Science Foundation/Technological Innovation Fund). Part of the fieldwork in Brazil was carried out jointly with Leticia Vieira.

4.4.2 Implications of the paper

The trajectories of rural water supply systems (RWSS) developed in Chapter 3, along with the three key functions of a resilient RWSS, confirm our hypothesis of considering water resilience as a dynamic concept. Function 2, which focuses on internal regulation, has intrigued us to explore water resilience at a local level, extending beyond the community level. Similarly, Function 3, which highlights connections to external actors, has prompted inquiries regarding territorial water resilience.

The next chapter will provide us with further insights into the multiscalar nature of water resilience in semi-arid areas, illuminating how resilience operates across different scales.

5 THE ROLE OF SMALL-SCALE HYDRAULIC INFRASTRUCTURE IN TRANSFORMING HYDROSOCIAL TERRITORIES IN A CATCHMENT IN CEARÁ, BRAZIL[9]

In the context of climate change, there has been an excessive development of water storage infrastructure in the name of water resilience. For example, in Ceará, water infrastructures (cisterns, water supply networks, dams, and reservoirs) were often implemented by the state, NGO, and donors as well as by local communities as emergency measures to adapt to the semi-arid areas to resist the multi-annual drought. However, the rules governing their use and responsibility have been inadequately explained, leading to conflicts among water users and fragmentation within the basin. The over-development of water storage infrastructures in the Forquilha catchment in Ceará led to its progressive fragmentation into several hydro-social territories which has jeopardized the water resilience of the communities concerned, as the state proceeded to store water in medium reservoirs in the upper catchments to ensure urban and rural water supplies.

This chapter examines the overlapping evolution of these hydro-social territories in the Forquilha catchment in Ceará over time. To investigate the internal and external factors affecting water resilience (Figure 31), we have adopted a multi-scalar analysis process based on hydro-social territory literature while maintaining a close connection to the field.

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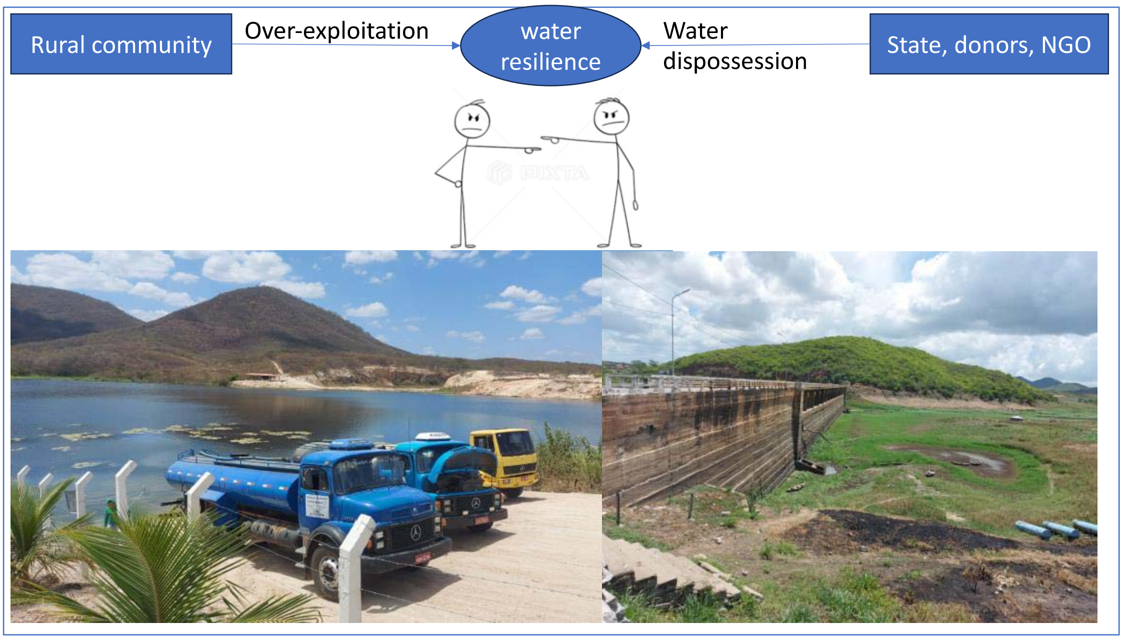
[9] The role of small-scale hydraulic infrastructure in transforming hydrosocial territories in a catchment in Ceará, Brazil This paper was published in Water Alternatives Journal 17(1): 46-72 in 2024: Hela Gasmi, Letícia de Freitas Vieira, Marcel Kuper, Eduardo Sávio Passos Rodrigues Martins, Julien Burte.

Figure 31 – Photo on the right of the reservoir of Quixeramobim of 7,8 hm3 in a critical situation. Photo on the left of Cachoeira Do Germano reservoir of 4 hm3 which is used to supply water to six municipalities by water tankers; to supply two community water networks, and to provide water to a nearby city through a pipeline; and for leisure activities)



Souce: Author, January 2023.

5.1 Introduction

Water storage has been an important feature in Brazil's policies to deal with drought in the semi-arid *Nordeste*. For almost a century, beginning in 1885, the main focus was on creating large-scale "strategic" reservoirs (the 'hydraulic solution'), in parallel with the development of irrigation schemes (Campos, 2015). After a "reflexive phase" in the 1980s (ibid.: 1058), a decentralised water policy was implemented from the early 1990s with small-scale water infrastructure (reservoirs, cisterns) created at the community and household scale to promote the paradigm of 'Living with drought' (*Convivência com a seca*; Lima *et al.*, 2011). The main idea was to better involve rural populations in the development of this infrastructure, to which they would contribute actively, and to reinforce the resilience of rural communities (Mattos *et al.*, 2022). As a result, several government infrastructure projects have been implemented to improve adaptation to drought and to build the long-term resilience of communities (Martins *et al.*, 2016).

When we started this study in the Forquilha catchment (Ceará state) in 2019, we observed a marked contrast between the perception of the state services dealing with a critical shortage of water and that of peasant families we met in the catchment, who expressed their satisfaction with the more humid year after the prolonged drought of 2012-2018. The major "strategic" reservoirs were, however, only filled to 4% of their capacity, thus threatening the supply of water to cities and to rural communities who had no access to water (Burte *et al.*, 2020). At the same time, there were now about 300 small reservoirs (*pequenos açudes*) in the catchment- more than 1 reservoir per km^2 – (FUNCEME, 2021) that had started to fill up and peasant families were thus quite satisfied with water supplies. A *pequeno açude* is a small hillside reservoir created by constructing a simple embankment barring a watercourse.

More generally, in the state of Ceará, there has been a massive investment by the state and by local actors in small-scale water infrastructure (cisterns, reservoirs and boreholes), in particular through the well-documented São José projects advocating the *Convivência* paradigm (Carrick-Hagenbarth, 2018). There are now more than 105,000 *açudes*, among which only 166 are monitored by the state (Funceme, 2021), while there were also 36,947 boreholes in 2023 (CPRM, 2023). In tandem with increased water use, this infrastructure has interrupted water flows, and more largely, led to the spatial redistribution of water available from downstream reservoirs towards the upper basins (De Araújo; Medeiros, 2013). While in the literature, the discussion on the fragmentation of river systems mainly focuses on the adverse ecological impacts of the construction of large reservoirs (e.g. Grill *et al.*, 2014), in Ceará, empty large-scale reservoirs may be at the origin of river fragmentation in the downstream stretches of large rivers, but are also at the receiving end due to the development of small-scale water infrastructure upstream (*ibid.*).

Faced with empty strategic reservoirs during periods of drought, the government of Ceará state decided to construct large-scale water infrastructure to transfer water from river basins to cities. Meanwhile, smaller cities in the interior also faced increasing problems with water supply. For example, the city of Quixeramobim, the municipality to which Forquilha catchment belongs, faced 11 successive months of water service failures during the recent drought (Barbosa, 2018). This explains the increasing focus of municipalities on gaining access to upstream reservoirs in small catchments to capture water for cities and rural communities facing water shortage. This policy has created conflicts with water users located in the catchments on water sharing (Formiga Johnson; Kemper, 2007).

The proliferation of water storage facilities, along with the fragmentation of river systems and the spatial redistribution of water, challenge the conclusions drawn in the emerging global discourse on "a new water storage paradigm" for "more resilient water services" in the face of climate hazards (Burke *et al.*, 2023: ix, x). These conclusions assume that constructing more water storage facilities, and reducing the "storage gap" of freshwater in the world will lead to higher levels of climate resilience (*ibid.*: ix; Pangestu, 2023). However, there is increasing evidence of "over-development" of water infrastructure (Hennig; Harlan, 2018), including water storage facilities, often leading to the reallocation of water in many basins around the world in which all water resources are already allocated and used (Molle *et al.*, 2010).

There has been much attention to "the ways in which infrastructures simultaneously shape and are shaped by social and political forces" (Obertreis *et al.*, 2016). This "relational understanding of infrastructure" (ibid.) calls attention not only to how politics are "embedded in and enacted through infrastructure", but also points to "the various ways in which territorial relations are reconfigured through infrastructure" (Hommes *et al.*, 2022). In hydrosocial territories, infrastructures and territorial relations are constantly (co)evolving through messy and contested processes (Obertreis *et al.*, 2016). Longtime seen as stable and durable (Obertreis *et al.*, 2016), there is a rich literature pointing to the multiple ways "infrastructures are interpreted, understood, adapted, and integrated by its users in very diverse ways that often do not correspond with the original ideas of those that implement them" (Mirhanoğlu *et al.*, 2023; see also van der Kooij *et al.*, 2015).

In this study, we investigate the central role of water infrastructure in transforming hydrosocial territories through a case study of the Forquilha catchment, where a variety of water storage infrastructure has been implemented by the state, NGOs, local communities and households, often in the name of water resilience. Using the lens of hydrosocial territories, we will first analyse how state- and NGO-led programmes of small-scale water supply infrastructure, in tandem with private individual and collective initiatives, led to more sustained access to water by rural communities. We will then analyse how the (over)development and use of small-scale infrastructure disrupted water flows (and indeed the hydraulic connectivity at different scales) and weakened social linkages around water, thereby fragmenting the hydrosocial territories as well as creating water shortages downstream. Finally, we examine how the state regained access to catchment water by targeting upstream reservoirs to channel water outside the catchment area.

5.2 Analytical lens and Methods

5.2.1 Analytical lens: investigating the central role of water infrastructure in transforming hydrosocial territories

In this study, we adopted a relational understanding of infrastructure, building on the recent literature on hydrosocial territories (Obertreis *et al.*, 2016). Hydrosocial territories are defined as 'socially, naturally and politically constituted spaces that are (re)created through the interactions amongst human practices, water flows, hydraulic technologies, biophysical elements, socio-economic structures and cultural-political institutions' (Boelens *et al.*, 2016:1). We concentrated on the relational networks around infrastructure within the hydrosocial territories and with outside actors (Neumann, 2009).

Following Hommes *et al.* (2022), we identified how the water infrastructure in the Forquilha catchment came into being, the normative contents embedded in this infrastructure (in our case typically the community focus of the infrastructure), and the becoming of the infrastructure once it has been implemented. In our case study, we focused on the temporal and spatial dynamics of the hydrosocial system under consideration in order to visualise how the construction and adaptations of infrastructure shape and transforms territorial relations (Hoogendam, 2019).

In the literature related to the 'living with drought' paradigm in the Nordeste, the main analytical focus is on communities and households as these are the scales that are targeted by water infrastructure investments to mitigate drought (Carrick-Hagenbarth, 2018). Mapping and analysing the networks around infrastructure and paying attention to how hydrosocial territories are shaped by this infrastructure expands this focus in multiple ways (Hommes *et al.*, 2022).

First, Whaley and Cleaver (2017), in their analysis of water point functionality, saw the organisation of rural water supplies as "unnecessarily circumscribed" to (formal) community organisations, and thus encouraged to scrutinise the wider systems of governance. The community-driven development approach of rural water supplies indeed places the responsibility for sustaining these supplies on the community and away from the state. But, as Collard (2013) has shown, despite this community focus, communities and individuals in the Nordeste maintain strong links with state representatives, politicians and NGOs when dealing with problems in water infrastructure.

Second, Whaley and Cleaver (2017) observed that the focus of infrastructure programmes on "regularised and formalised" organisations and activities conceals the more informal arrangements around water. Community-level infrastructure projects in Brazil's

Nordeste, for example, are typically conducted with community associations that are legally recognised organisations that have a bank account and are mandated to engage in small-scale development projects. Indeed, community associations, "were often formed around a particular need rather than a geographic focus" (Carrick- Hagenbarth, 2016: 14); however, "the family, the hamlet (*sítio*), the community (*comunidade*), the networks of proximity" continue to play an important role in the rural areas (Caron; Sabourin, 2001).

These informal forms of organisation are based on kinship, proximity, or shared experience. They are often governed by peasant reciprocity relationships that enable access to collective resources including water, land, and farm equipment (Sabourin, 2007). In the Nordeste, a typical rural community has from 30 to over 250 households which are often dispersed in several "nucleated settlements" (Ferreira *et al.*, 2006). We define a nucleated settlement (NS) here as a group of households composed of neighbours and extended family who share water for drinking or other purposes on a daily basis and/or in times of stress.

Our relational take on infrastructure encouraged us to identify and analyse the "unique system of dynamic interactions and dependencies" within the Forquilha catchment. Our study considered both formal and informal organisations and networks and the multiple actors in the outside world (Rivière-Honegger ; Ghiotti, 2022). This involved recognising the multiplicity and imbrication of scales, actors and infrastructure (Hoogesteger *et al.*, 2016).

We show the complexity of defining territories in space because a hydrosocial territory can correspond to, or limit, a watershed or can extend beyond it. In our case, the hydrosocial territory was not closed; on the contrary, it was in direct communication with outside actors, such as the neighbouring cities (through water tankers and pipelines), representatives from local or state administrations, politicians and NGOs. Moreover, we extended the analysis beyond the habitual formal community association and households by showing the important role of more informal arrangements, particularly at the level of nucleated settlements.

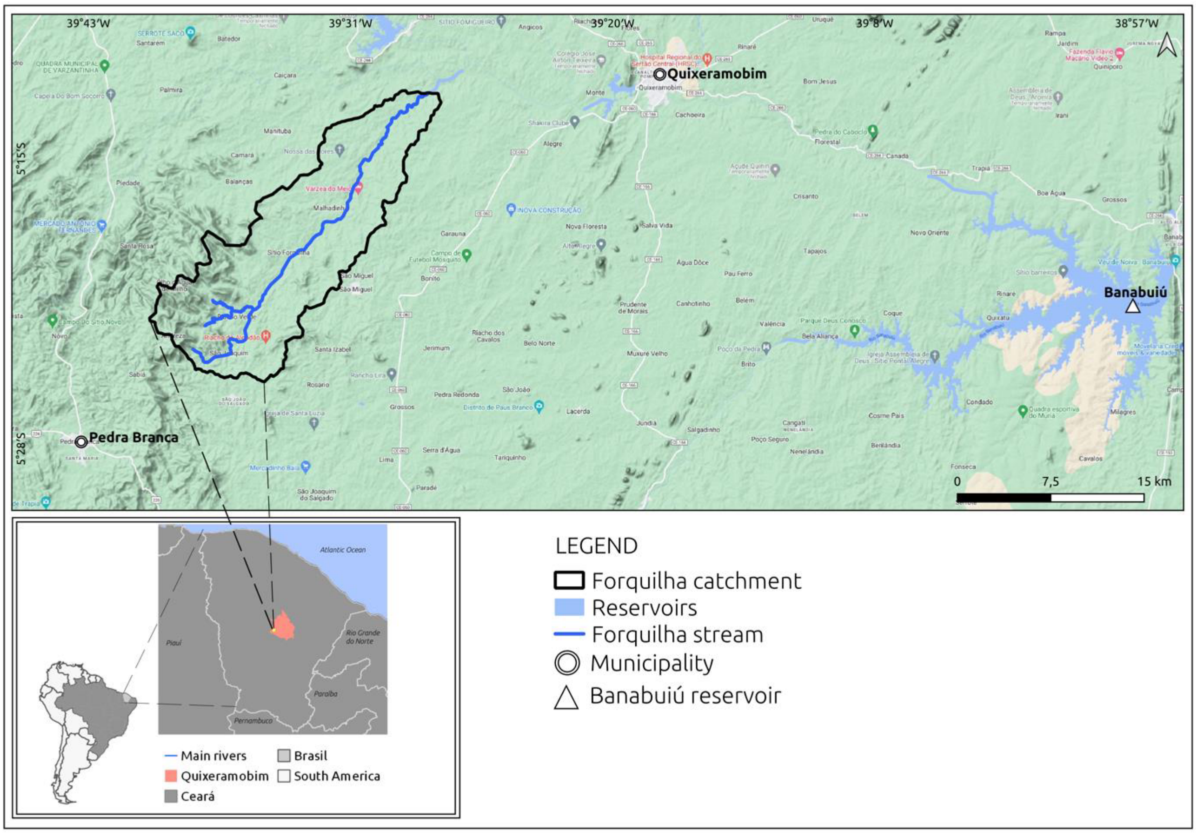
5.2.2 Study area and data collection

5.2.2.1 Study area

The 221 km^2 Forquilha catchment in the Quixeramobim municipality (Ceará state, Northeast Brazil; Figure 32) is part of the Banabuiú basin. This basin includes the strategic reservoir Banabuiú (1.6 Bm^3 capacity), one of the three biggest strategic reservoirs in Ceará.

The population of Quixeramobim municipality is distributed between a diffuse habitat and an urban core. In 2022, the population was 78,500 inhabitants, 39% of whom lived in rural areas (IBGE, 2010; IBGE, 2022). The population of the Forquilha catchment is divided into 17 communities, each with its own community association.

Figure 32 – Location of the Forquilha catchment connected to Rio Quixeramobim, which feeds the large-scale Banabuiu reservoir, Ceará, Brazil



Souce: Author, 2023.

Agriculture in the Forquilha catchment consists of cattle ranches and subsistence family farming with maize and beans and small-scale animal husbandry. Irrigated horticulture and fruit farming are practised downstream in the catchment. The climate is semi-arid and rainfall is extremely irregular in terms of frequency and intensity. The average annual rainfall in the period from 1988 to 2022 was 657 mm (Funceme, 2022). The climate is characterised by two seasons: a rainy season from February to April and a dry season from May to January.

There are three sources of water for domestic and agricultural use: surface water reservoirs, alluvial aquifers and cisterns. Indeed, the main strategy of rural communities and the development actors has been and still is the creation of different types of water infrastructure with diverse water sources (Gasmi *et al.*, 2022). This includes individual and collective cisterns with a volume of 16 m^3 for drinking and/or domestic uses; community water supply systems that take water from the alluvial aquifer or small or medium-size reservoirs; and the drilling of boreholes (60 m deep) in crystalline areas, or wells (2-15 m deep) in alluvial areas (Pinheiro; Fabre, 2004). The alluvial aquifer extends over 6.0 km^2 (23 km long and 250 m in width) with an average sediment depth of 6.8 m with a piezometric level of 2.8 m below ground level at the end of the rainy season (Burte *et al.*, 2005). Reservoirs are located in the upper catchment, while the groundwater in the lower catchment is mainly used for irrigation, watering cattle and domestic purposes (Burte *et al.*, 2009).

Each community water supply system is composed of a collective network with an electric pumping system taking water from a community reservoir, well or borehole; a water tower and a piped network that supplies the households. The management of the water source (reservoir, well, borehole) is often the responsibility of the community association.

5.2.2.2 Data collection

Data collection for this study involved a mixed methods approach at several scales. Qualitative and quantitative data on rural water supplies in the Forquilha catchment were collected between 2019 and 2023. We first collected data about the policies and projects that had been implemented to enhance rural water supplies in Ceará; this data collection was based on a review of working papers, organisational websites and official documents.

Second, the research for this paper was facilitated by a recent inventory of the rural water supply infrastructure in the Forquilha catchment (FUNCEME, 2021). We analysed the functioning of this infrastrastructure through field surveys and interviews at the household and community levels in one of the communities (Varzeo Do Meio) (see Gasmi *et al.*, forthcoming, on more details on the methodology). There are different types of infrastructure (wells, tube-wells, reservoirs, cisterns, community water supply networks), depending on different water sources (surface water, groundwater, rainwater, water tanker) and managed by various actors (mainly communities or individual or multiple households in a nucleated settlement). We mapped the connections of community members and outside actors with specific infrastructure, to identify the rules governing the use of the infrastructure, and to retrace the historical evolution of this infrastructure (design, implementation, maintenance and use).

We conducted 30 surveys and 24 interviews with community members and leaders as well as with leaders of community associations. We analysed stakeholder discourse through investigations, participatory mapping (Figure 33), and life stories. To do so, we used hydrosocial narratives (Bell, 2002 ; Leong, 2021) to capture the complexity of past changes in hydrosocial territories in the Forquilha catchment. The actors we met had long-standing experience in dealing with the consequences of drought; they had a dynamic view of infrastructure and of the rules governing water supply systems, and understood that they needed to be continuously adapted by mobilising relational networks (Jones ; Tanner, 2017).

Figure 33 – Participatory mapping of hydro-social territories in Forquilha catchment with community members (photo on the left). Identifying the nucleated settlements of Varzeio do Meio community (photo on the right)

Source: Photo on the left Kuper, 2023; Photo on the right Vieira, 2023.

Third, 20 semi-structured interviews were conducted with state and regional stakeholders (state officials, policy makers and NGOs staff) to understand how water infrastructure projects were implemented. This was completed through observations and interviews with members of communities, truck drivers, construction workers and staff of the state water company.

Fourth, we conducted a detailed investigation of the Varzea do Meio community, one of the 17 communities in the catchment. This community (19 km2) is composed of 90 families and has always been involved in collective action on water issues at the community and catchment levels. Thanks to an active community association, the community has good connections with external actors (Gasmi *et al.*, 2022). We identified the different nucleated settlements and their inhabitants using participatory mapping and interviews, finally using drone footage to confirm their geographical limits.

Fifth, we held a series of six participatory workshops. Three workshops with community members (8 participants in each of the first 2 workshops and 15 participants in the third) were aimed at identifying adaptations made to water infrastructure and rules made by the community to cope with drought. A workshop was subsequently held with 20 stakeholders from national and regional water institutes, research institutes and NGOs to identify different visions of rural water supplies. This was followed by a mixed workshop with 29 stakeholders from national and regional water institutes, research institutes, NGOs and community members to validate the definition of rural water supply systems and to analyse their trajectory. Finally, a territorial workshop was held with representatives of nine communities in the Forquilha catchment to identify the catchment's trajectory and its different hydrosocial territories.

5.3 Results and discussion

5.3.1 Weaving water and the social: The example of Varzea do Meio community

Varzea do Meio, one of the catchment's 17 communities, provides a good illustration of how water infrastructures and social structures are intermingled through a multitude of projects, investments and initiatives.

A wide range of water projects to build resilience

In the context of consecutive droughts, Ceará state has been promoting a 'living with drought' public policy to enhance the resilience of rural communities[10] (Milhorance *et al.*, 2022). The community scale was identified as an appropriate level for state intervention (Collard, 2013). The World Bank, as part of its wider international discourse on community-driven management, supported the development of rural water supply projects at this scale (Coirolo *et al.*, 2001). It was felt that community-scale infrastructure would help avoid misappropriation of money and would ensure more local participation in public actions (Masud *et al.*, 2019). To benefit from state- or NGO-driven rural water supply projects (and more generally from development projects), rural communities needed to be organised into community associations.

The focus on rural water supply projects for rural communities led to a drive to ensure sustained water supplies through a single 'replicable', albeit 'locally tailored', rural water

[10] A rural community is considered resilient by Frankenberger et al. (2013: 1) when, "it can function and sustain critical systems under stress; adapt to changes in the physical, social, and economic environment; and be self-reliant if external resources are limited or cut off".

supply system. This should include, "small wells, rainwater collection, surface water collection by individual households (for example, carrying water in barrels from nearby ponds or small reservoirs or relying on water collected by tankers from distant reservoirs), and small reservoirs" (Enéas da Silva *et al.*, 2013). Several studies have shown that rural communities in Brazil and elsewhere diversify water sources and multiply infrastructures in order to ensure sustained water supplies (Smits *et al.*, 2010). In Ceará, the state and NGOs have long supplied a wide diversity of water infrastructures at the household level (individual cisterns) and at the community level (collective cisterns, community rural water supply systems); however, the resilience of rural communities to drought has also been enhanced by progressive public social policies (rural retirement pensions, family allocations) (Sabourin *et al.*, 2022; Mattos *et al.*, 2022).

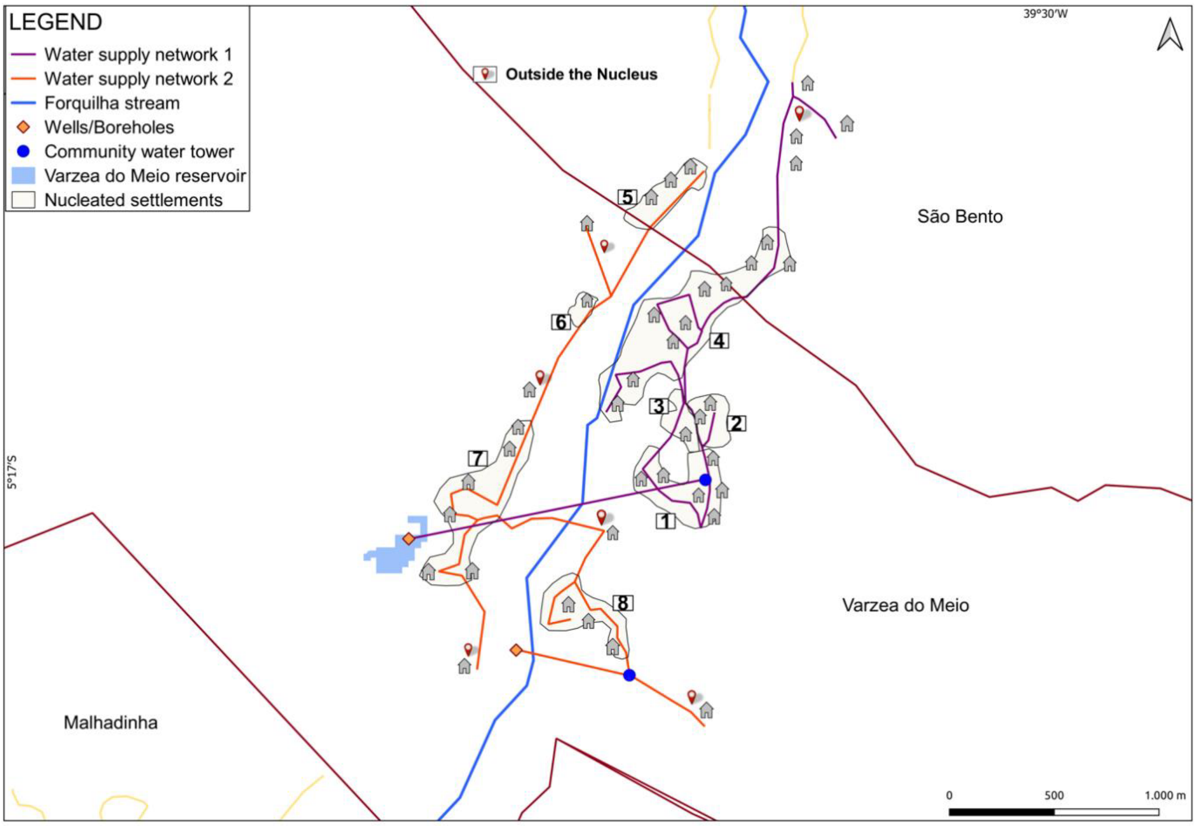
The Forquilha catchment has benefited from multiple interventions by the state and NGOs, and individuals and collectives have been actively developing infrastructures. This was one of the factors that explained why our interviewees considered that the impacts of the 2012-2018 drought were less drastic than those of previous droughts. As one member of the Lagoa Cercada community told us in an interview, "I am afraid of one day returning to my father's time. My father used to drink a glass of water mixed with mud. There was no water in the 1980s. Today, there is water here, even if it is salty, there is water".

A 'nucleated settlement' is the basic unit of water solidarity

Our fieldwork and workshops with members of the Varzea do Meio community showed that the basic unit of water solidarity is the nucleated settlement (NS) as we have defined it above. Inhabitants of Varzea do Meio identified eight such settlements (numbered 1 to 8 in Figure 34), some of which straddled two communities. According to our interviewees, to belong to an NS one has to have a shared history of drought and to have collectively struggled to obtain water and productive infrastructure. Within these NSs, the informal arrangements to facilitate access to water are generally based on geographical proximity and personal affinity (kinship, neighbours) and on the principle of reciprocity. The arrangements for (shared) access to water are thus imbricated in, "multiple (family, business and labour) relations" (Gasmi *et al.*, 2022). The support networks inside the nucleated settlements are not formally linked to the community association, although in practice there are many interactions. These networks also do not necessarily follow the limits of the community association. The five red dots in Figure 34 represent families who come from outside the catchment and do not belong to any NS.

We started our analysis with the two community water supply networks that have existed since 2017. The networks were planned for the delivery of drinking water, but the communities instead use the untreated water for a wide range of other uses around homesteads, including irrigation and watering livestock (Gasmi *et al.*, 2022). The first water supply network supplies 60 houses that belong to NSs 1 to 4; it draws from a well belonging to a large landowner who lives in town and, from 2023 onwards, it has drawn water from a community reservoir. The second network supplies 30 houses belonging to NSs 5 to 8 from a private well belonging to a community resident, for which residents only pay the electricity cost.

Figure 34 – Domestic water supply to dispersed nucleated settlements (numbered 1 to 8) via community water networks



Souce: Author, 2023.

The social organisation of the Varzea do Meio community association is hierarchical, with NS1 at its centre; all other groups are both spatially and socially peripheral to it. NS1 participates actively in collective actions for the benefit of the community. It is composed of households belonging to two large families who are all cousins. Two brothers and a sister have been swapping the functions of president and treasurer of the community association among themselves and their influence has played a role in obtaining access to water sources (wells and a community reservoir) and agricultural aid from the state.

The social cohesion among the members of the family group is strong. They share private cisterns in times of need and they do so on a continuous basis with families who have no cistern: "My well never dried up, I use it for irrigation. I let people get water there for free, people can go there, I don’t even charge for electricity. I leave it open so they can get in to get the water and that’s it" (Interview with a member of NS1 in Varzea do Meio).

Members of NS1 lobbied for, and were then actively involved in organising, a community water supply system, a primary school, a community centre and a milk collection facility. Despite the strong social role of this group, they all agreed on the importance of interacting with other NSs to ensure a sustainable water supply. Members of this NS have developed a strong external network that includes the municipality, the mayor, and agricultural services. They stay informed about all calls for projects published by the state and by NGOs to solve individual or collective water problems.

Although NS2 and NS3 are geographically linked to NS1 (Figure 35), they only play a passive role in the community water association. Families receive domestic water from the community network but at the same time they share a small reservoir for agricultural use. They also have an alternative water network based on a private well to which several houses are connected. In case of water shortage, the members of these settlements help one another or look for outside help from a neighbouring settlement, the community association, or external actors. NS4 is made up of an extended family that is not integrated into the community. They are not satisfied with the operation of the community association, especially as the management is still in the hands of a single family. As a consequence, they receive no support or subsidies from the state through the association, which has created a feeling of exclusion for them. An agent of the extension services of Quixeramobim city lives in this settlement, however, which has facilitated their connection to external regional actors.

Figure 35 – Photo showing nucleated settlements 1, 2 and 3

Source: Drone photo by Vieira, 2022.

NSs 5 to 8 receive water from the second community water supply network. Each settlement shares their drinking water cisterns with houses that do not have one. In NSs 5 to 7, thanks to their proximity to the river, some inhabitants have wells that provide water for their livestock or for irrigation. These three settlements were able to ensure their water supply even during the multi-year drought, however the water was only shared in critical periods. NS8 receives water from the same network. This settlement is located in the highest area of the community and is considered clandestine while its inhabitants are considered to be marginalised outsiders. Descended from slaves, the original members of NS8 found refuge in this small area of fertile land, which has since become highly fragmented due to inheritance. They help each other with water from their drinking water cistern but they are less connected to the other NSs and to external actors.

The analysis at the NS level revealed the wide range of water sources that operate at that level (collective and individual drinking water cisterns; collective and individual wells, boreholes and individual or small reservoirs for agricultural purposes and watering livestock). These settlements, however, are part of a community whose association played an important role in obtaining and operating the community rural water supply systems. Families' water access in times of drought is therefore linked to both the NS and to the community to which they belong.

<u>The important role of community associations</u>

While some families may have individual political contacts, obtaining and then managing community- based water development projects requires an active community association. As illustrated in the preceding section, the community association of Varzea do Meio obtained access to multiple sources of water through collective action and through their connections with the local elite, politicians and the state (Gasmi *et al.*, 2022). Despite several droughts, the Varzea do Meio community has thus managed to maintain sustainable access to water.

In 2018, it negotiated with the Company for Water Resources Management of the State of Ceará (COGERH) for the construction of a community reservoir to recharge the alluvial aquifer, as the previous water source (a private well belonging to a large landowner) was considered too expensive (Figure 34). The negotiation with the state was at first informal via their political network, but it was subsequently formalised through the active community association. At the same time, the leading families (in NS1) negotiated with the inhabitants of NS7, which donated part of their land to build the community reservoir of Varzea do Meio. This alliance enabled the leading families to obtain an alternative and less expensive water source for the first network (NSs 1 to 4), while it gave the inhabitants of NS7 the advantage of using the reservoir directly to grow fodder crops in its vicinity.

After the community reservoir was completed, it took almost four years – till December 2022 – for it to be filled. In the meantime, the association had to continue renting the well from the large landowner. The water association ensured that users contributed to renting the well and paying for the electricity used to pump water for cattle and to irrigate fodder crops. But in 2022 the price of electricity increased significantly, coinciding with the accumulation of water in the community reservoir. The community contacted the Quixeramobim municipality and asked for help to connect the community water network to the small reservoir to increase their autonomy. This is a good example of how the community succeeded in activating connections with external actors.

Water supply is regulated by rules of use, which are defined locally. These rules and the price of water vary from one community to another and are defined collectively in association meetings. In these community networks, a sense of belonging was developed around the collective use of water infrastructures, uses, rules and organisational arrangements, but the different nucleated settlements also arranged for alternative water supplies thus avoiding complete dependence on the community association. Importantly, the community association also catered to water demand beyond the limit of the community, in this case from some households in the nearby community of São Bento.

5.3.2 The gradual fragmentation of the Forquilha catchment

The example of Varzea do Meio illustrates the active role of informal networks and community associations in ensuring durable access to water supplies, however communities also depend on water flows and sociopolitical dynamics at the catchment scale. Conversely, community-based water development projects influence water flows and sociopolitical dynamics at the catchment scale. Moreover, interventions from outside actors not only concern community-based projects, but also target catchment-level projects and households.

To identify the water-related dynamic interactions between the communities of the Forquilha catchment and between communities and outside actors, we explored the historical, cultural and political settings of the catchment by co-identifying the current six hydrosocial territories (Figure 38). The criteria for this patterning were shared water resources, similar water practices, geographical proximity, past conflicts and a shared history of drought mitigation. The criteria were identified during our investigation in the Forquilha catchment (from surveys, interviews, life stories and participatory maps) and were then validated at a territorial workshop with representatives of communities.

A closer look at these territories reveals an impressive number and diversity of water infrastructures that have been developed through various initiatives (see Appendix 1). In addition to the collective water infrastructure implemented by outside actors at the catchment or community level, families have built 279 small reservoirs and have dug 108 individual wells and boreholes (Appendix 1). This explains the improved and robust water access perceived by the communities. As one community member described in an interview:

The drought of the 1980s was cruel, we had to transport water by donkey. We went wherever there was water to drink, to cook or we dug a shallow well in the stream to get water. But in the last drought when it dried up here in 2015 the municipality helped us, water tankers came to fill our cisterns, they also installed a water tower for the community.

At the same time, the multiplication of water infrastructures explains the increased use of water for domestic purposes and (especially) agriculture, which disrupted the flow of water between the territories and fuelled a feeling of competition for water. As a member of Varzea do Meio community commented in an interview, "There are three big reservoirs upstream of Forquilha (town). The communities with water plant nothing there but do not release water to those who irrigate downstream of Forquilha town". Importantly, our interviews showed that communities feel much less connected to the upstream or downstream territories than they did in the 2000s as they now rely on water infrastructure at the level of communities and NSs. The massive introduction of water infrastructure in Forquilha catchment thus led to its fragmentation, resulting in the formation of smaller-scale hydrosocial territories. In other words, "These overlapping hydro-political projects tend to generate 'territorial pluralism' and make diverse 'territories-in-territory' – that is, overlapping, often contested, and interacting hydro-territorial configurations in one and the same space" (Boelens *et al.*, 2016: 8).

The current pattern of hydrosocial territories in our case study is the result of a dynamic reconfiguration of available water resources, water infrastructure and water use arrangements in recent decades (Boelens *et al.*, 2016). Workshop participants commented that the catchment had evolved from a single hydrosocial territory in 1970 to six hydrosocial territories in 2023. To explain this gradual fragmentation, we periodised changes in hydrosocial territories as follows: 1) a period of shallow dug wells (1970-1988); 2) a period of community water infrastructure development (1988-2010); and 3) a period of fragmentation of hydrosocial territories.

Table 11 – Water infrastructure and uses in six hydrosocial territories of Forquilha catchment in 2022

Hydrosocial territories	Communities	Water infrastructure	Uses
1	-Cachoeira do Germano -Riacho Verde 1 -Riacho Verde 2	- Two medium collective reservoirs in Cachoeira and Riacho Verde 1 - Individual reservoirs (47) - Collective well in Riacho Verde 2 (1) - Individual wells, boreholes (9) - Individual cisterns*	- Domestic use and irrigation of fodder crops around reservoirs - Cachoeira reservoir supplies other households in the catchment, but also households outside of the catchment (by water tanker) -No irrigation due to scarcity of land

Continuation

Table 11 – Water infrastructure and uses in six hydrosocial territories of Forquilha catchment in 2022

Hydrosocial territories	Communities	Water infrastructure	Uses
2	-Riacho do Algodão -Quandu	- Small collective reservoir (Riacho do Algodão) - Individual reservoirs (42) - Collective wells (1) -Individual wells (3) for cattle and to irrigate fodder crops - Individual cisterns	-Both communities are supplied by the same community water supply network connected to the reservoir -Individual wells for cattle and to irrigate fodder crops
3	-Jardim -Varzea Formosa -Lagoa Cercada -Trapiazeiro	-Two small collective reservoirs (Jardim and Lagoa Cercada) - Individual reservoirs (44) - Individual wells (18) and boreholes (21) - Collective wells (4) - Individual cisterns	-Jardim and Lagoa Cercada communities have access to groundwater and surface water for domestic and agricultural use -Varzea Formosa and Trapiazeiro only have access to groundwater for domestic and agricultural use -Individual wells and boreholes for cattle and to irrigate fodder crops

Continuation

Table 11 – Water infrastructure and uses in six hydrosocial territories of Forquilha catchment

Hydrosocial territories	Communities	Water infrastructure	Uses
4	-Forquilha -Malhadinha -Varzea Do Meio -São Bento 2	- Small collective reservoir (Varzea do Meio) - Individual reservoirs (72) - Collective wells (3) - Individual wells, boreholes (41) - Individual cisterns	-Biggest consumers of water in the catchment to irrigate fruit trees, beans and maize -Many cattle breeders (intense production of silage and fodder)
5	-São Bento 1 -Veneza	- Ford crossing in Veneza - Individual reservoirs (37) - Collective wells (2) - Individual wells, boreholes (10) - Individual cisterns	-Watering livestock and irrigation -São Bento relies on wells and benefits from a ford river crossing, facilitating the aquifer recharge
6	-Boa Vista -Agreste -Campinas	- One collective reservoir in Campinas - Individual reservoirs (37) - Collective well (2) - Individual wells, boreholes (6) - Individual cisterns	- Watering livestock

Souce: Author, 2023.

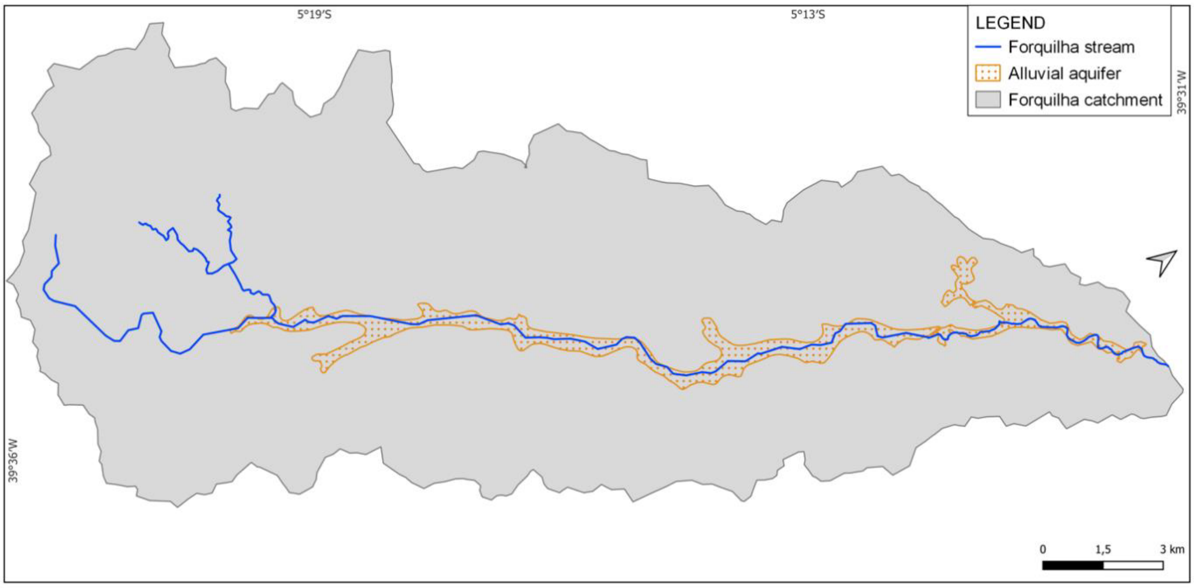
*Almost every household has a cistern

Conclusion

1970-1988: The period of cacimbas (shallow dug wells)

In the 1970s, there were no reservoirs in the catchment. According to the workshop participants, the catchment formed a single water territory with the Forquilha river forming its structural axis

Figure 36 – Hydrosocial territories in the Forquilha river catchment from 1970 to 1988.



Source : Burte, 2008.

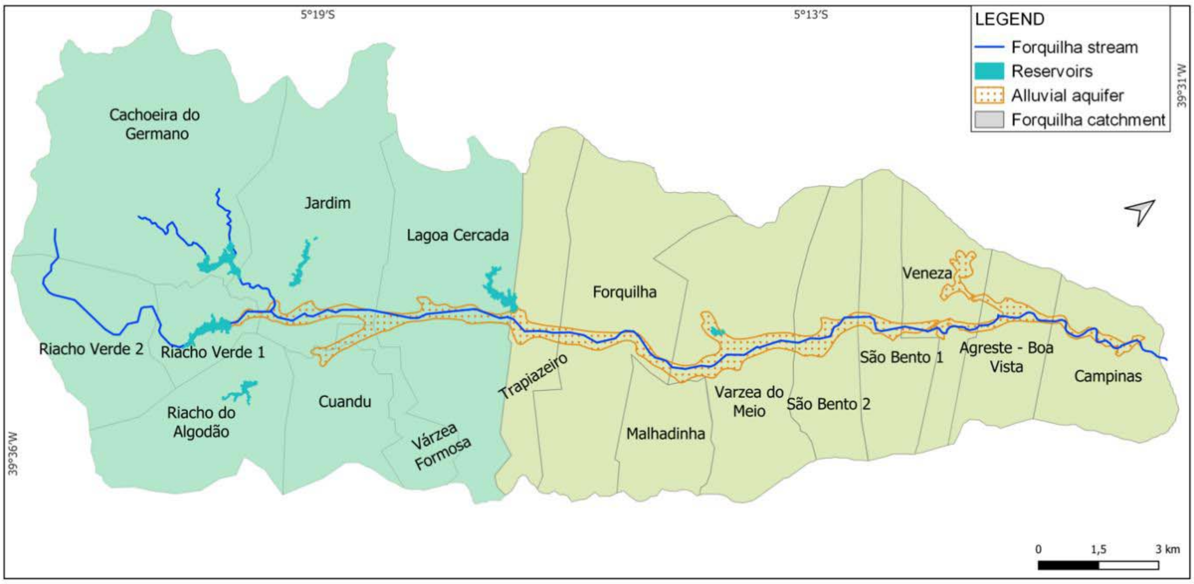
At the time, there were similar practices for obtaining access to what were considered shared water resources. In the rainy season, the communities only used surface water. In the dry season, the main water resource for domestic water was the alluvial aquifer, which was tapped through shallow dug wells or holes (*cacimbas*) and replenished during the rainy season. The dug wells were used during the dry season to water livestock and for domestic purposes. Due to the dispersed habitat, however, some households that were located six or more kilometres away from the river had problems accessing water, thus challenging the vision of a single homogeneous water territory. As an ex-president of a community association told us in a January 2023 interview, "We had a guaranteed water supply through these *cacimbas* but it was really difficult to fetch water and to regularly maintain them".

1988-2010: State-led water infrastructure development in the catchment – convenience or dependency?

The construction of water infrastructure (reservoirs, wells) modified the hydrosocial territory - especially the construction of four reservoirs in the upper part of the catchment - dividing it into two territories: an upstream territory containing reservoirs, and a downstream territory that remained organised around the river (Figure 37; Burte, 2008).

Following droughts in the early 1980s, in 1988 the first collective public reservoir, with a capacity of 7 million m3 (Mm3), was built in Riacho Verde as part of public policies focused on coping with drought. The reservoir provided water to the Riacho Verde community for all uses. It progressively gained importance for fodder production and livestock rearing, thereby increasing water consumption (Table 11). In 2002, the state constructed three other reservoirs upstream, thus creating a territory of four reservoirs.

Figure 37 – Two hydrosocial territories in Forquilha catchment from 1988 to 2010.



Source : Burte, 2008.

In 1998, along with the introduction of wells, rural electrification became a key factor of change. As part of a water infrastructure project, a well was drilled almost every 100 m along the river, especially in the downstream sections (Burte, 2008). Wells were used to supply water for domestic, drinking and agricultural purposes. Water availability and a sense of abundance prompted inhabitants to practice intensive irrigated agriculture, especially horticulture and fruit farming. Increased water use through irrigation in turn lowered the water table, thereby jeopardising irrigated agriculture. During the drought year of 1998, the Quixeramobim municipality requested that water be released from Riacho Verde reservoir to sustain the Forquilha stream. Water was released without consulting the Riacho Verde community and the reservoir was emptied in a few weeks. This was the first instance of water 'dispossession' experienced by upstream communities. Angrily, members of the Riacho Verde community shut off the water supply and informed the municipality and other communities that they would never release water again.

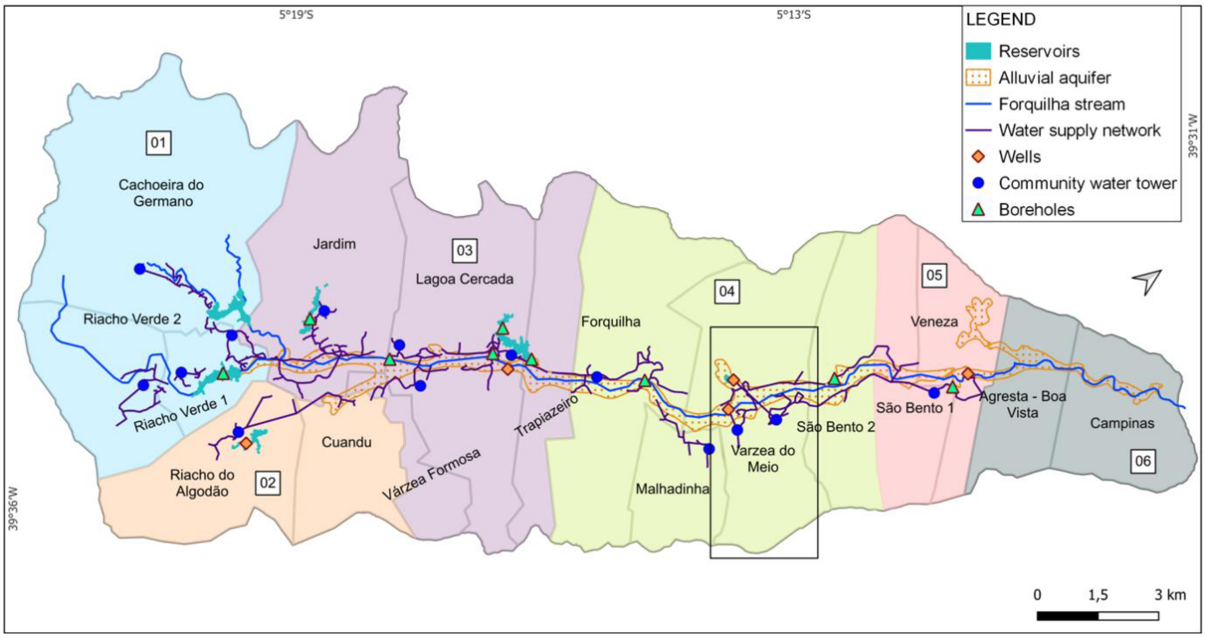
Meanwhile, downstream communities continued to push for the release of water from the Riacho Verde reservoir for aquifer recharge. In 2003, meetings were held between local communities and institutional actors and an agreement was reached to release water, but in an organised manner. In 2004, the reservoir of Riacho Verde was refilled with rainwater making water release possible. By contributing collective labour (*mutirão*; Sattler *et al.*, 2015), communities cleaned the river and dug ditches. Water was then released in a controlled way, with some water remaining in the açude for the local community. The water released, however, only reached halfway down the catchment. Moreover, many arguments arose during releases due to the conflicting interests of communities and the laboriousness of the riverbed cleaning. The drought of 2012 put an end to water releases from the upstream reservoir.

External actors such as the state and NGOs provided downstream communities with collective water cisterns, each cistern supplying 10 families. In the dry season, the cisterns were filled by water tankers and the water was reserved for drinking. Since 2000, government projects have supported the development of community water infrastructure including small reservoirs, collective distribution networks and drilled wells. These rural water supply systems gave a degree of autonomy to communities in accessing domestic water, thereby improving quality of life and reducing social tensions in the catchment. Providing water infrastructures without a sustainable local management model, however, made communities highly dependent on the local economic agents and politicians who were able to guarantee that drinking water would be supplied by water tankers during droughts.

2010-2023: The gradual formation of six hydrosocial territories

In the past, interactions between families were shaped around the river and its individual and collective use (Neumann, 2009). Without interdependence around water, however, the Forquilha network has literally become 'dry', thus explaining its fragmentation into six hydrosocial territories (Figure 38). During the workshops in 2022/2023, several participants expressed their desire to reunite the communities and the catchment. As one workshop participant commented, "Bringing the catchment together to create projects would be great". This was mostly expressed by representatives of downstream communities, however, as upstream participants were cautious about restoring a collective dynamic in the catchment, presumably to avoid claims from downstream participants on upstream reservoirs. This points to the paradox that successful collective action at the level of nucleated settlements and communities – which in turn materialised in the six hydrosocial territories – could in the end lead to internal division at the scale of the Forquilha catchment.

Figure 38 – The co-identified hydrosocial territories in Forquilha catchment in 2023. The figure combines individual participatory maps that were co-produced and then validated during a territorial workshop in Forquilha.



Source : Burte, 2008.

Note: The figure combines individual participatory maps that were validated during a workshop in Forquilha.

In 2010, all 17 communities of the Forquilha catchment submitted a joint application to the municipality for the construction of a reservoir in the upstream community of Cachoeira do Germano. This initiative demonstrated the collective force and the robust social network of the communities. Problems soon arose with the Cachoeira community, however, when they were confronted with the loss of arable land and the displacement of households. To facilitate social acceptance of the construction of the 4 Mm3 reservoir, the state agents promised that all the communities would be able to use the water in the reservoir. The reservoir would thus enable the development of productive activities in the downstream part of the catchment while guaranteeing access to water for upstream communities. It would allow aquifer recharge for downstream communities and would ensure the supply of drinking water for the entire catchment through a piped network. These promises were never fulfilled, however, and only

Cachoeira and (some) Riacho Verde communities currently have direct access to the reservoir, while the state uses it to fill its water tankers, supplying water to households outside of the catchment.

The upstream catchment now includes four main reservoirs with multi-year storage capacity. Upstream communities in three separate hydrosocial territories have organised water uses around these reservoirs. In addition, many households have constructed small individual reservoirs (133 in the 3 territories), in particular for irrigated fodder production. The communities downstream have been deprived of water due to enhanced upstream storage capacity and reduced recharge of the water table. This spurred the fragmentation of the downstream catchment into three hydrosocial territories, where each community or group of neighbouring communities organised itself separately to respond to the new situation and enhance their own water security.

A number of consequences followed from the fragmentation of hydrosocial territories. First, the population had difficulty undertaking collective action to solve issues that reached beyond the community, as illustrated by the events around the Cachoeira reservoir. This applied not only in terms of negotiating solutions with the state (such as limiting water diversions), but also in terms of social mobilisation and contestation. State representatives and politicians have become privileged interlocutors of rural communities, who consequently spend less and less time discussing issues among themselves (Collard, 2013). Yet, collectives willing to shape their hydrosocial territory also need to solve water conflicts within their collectives and to defend their rights against the threats posed by powerful outsiders including state agencies (Hoogesteger *et al.*, 2016). To this end, they need to cooperate and to mobilise their members to protect and control a common water resource (Hoogesteger and Verzijl, 2015).

Politicians project themselves as being an integral part of the history of the communities and as being committed to improving the situation in the catchment. Proximity to politicians thus ensures a certain level of security (for example, in the financing of community water infrastructure) and a feeling of being represented. At the same time, the emphasis in politicians' narratives on infrastructure projects as vectors of beneficial change and modernity makes it difficult for communities to develop alternative discourses (Figure 39).

Figure 39 – Political event held in the catchment of Forquilha to announce a road construction project and a political commitment to construct a pipeline to supply all communities of Forquilha using Cachoeira reservoir

Source : Burte, 2023.

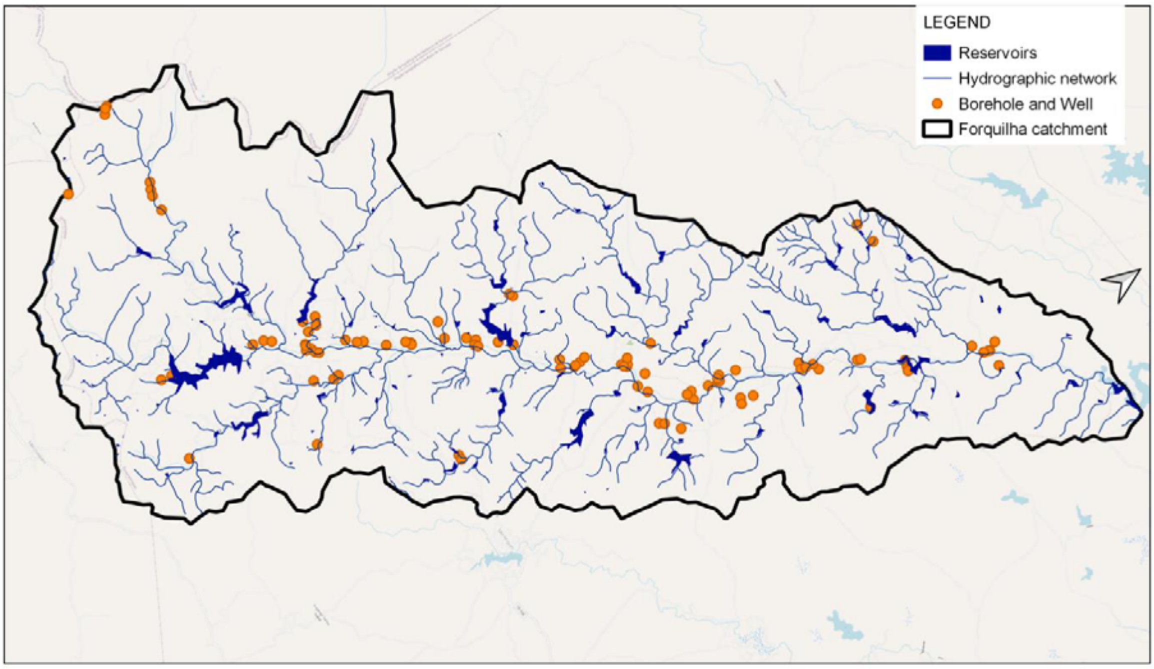
Second, communities have consistently sought to diversify their sources of water for multiple uses and, at the same time, to maintain relations with different strategic outside actors (Gasmi *et al.*, 2022). Some households and communities, however, have become increasingly dependent on a single source and a single actor – often a state service or politician – which increases their vulnerability. Akallah and Hård (2020), in two settlements in Kenya, similarly showed that communities that rely only on piped water were more vulnerable to water shortages than inhabitants who have several water sources. Increased convenience, therefore, does not automatically mean increased water resilience.

Third, not all communities have been able to successfully negotiate their dependence on the state, as we observed during our territorial workshop. As asked by the president of the Riacho Verde community association to the ex-president of the Varzea do Meio association during the January 2023 workshop, "How did you succeed in getting these water infrastructures? When we asked to rehabilitate our under- dimensioned network, the answer we got from the state was no, because there are situations worse than ours". In fact, some communities with a strong territorial integration have obtained support to cope with adverse conditions, while other communities have faced increased water stress.

5.3.3 Water transfer out of the Forquilha catchment: Reshaping hydrosocial territories

In 2017, the Banabuiú Basin, of which the Forquilha catchment is part, was in a critical situation due to the severe 2012-2018 drought, with nine strategic reservoirs dry and seven with water only in dead storage (Rabelo and Lima Neto, 2018). In 2019, when the rains returned, reservoir levels were barely restored, and in 2020 reservoir levels remained at 9.5% despite 912 mm of rain that year. This failure of reservoirs to refill can be explained by the massive amount of individual and collective water infrastructure in the different catchments, along with the increased use of water for agriculture and livestock; for example, almost 279 reservoirs and 108 boreholes and wells are currently in use in the Forquilha catchment (Figure 40). This has caused the spatial redistribution of water in the state of Ceará from large-scale downstream strategic reservoirs to small reservoirs upstream (de Araújo and Medeiros, 2013; Frischkorn *et al.*, 2003; Malveira *et al.*, 2007).

Figure 40 –Map of the Forquilha catchment with 279 reservoirs and 108 boreholes and wells in 2021



Source: FUNCEME,2021.

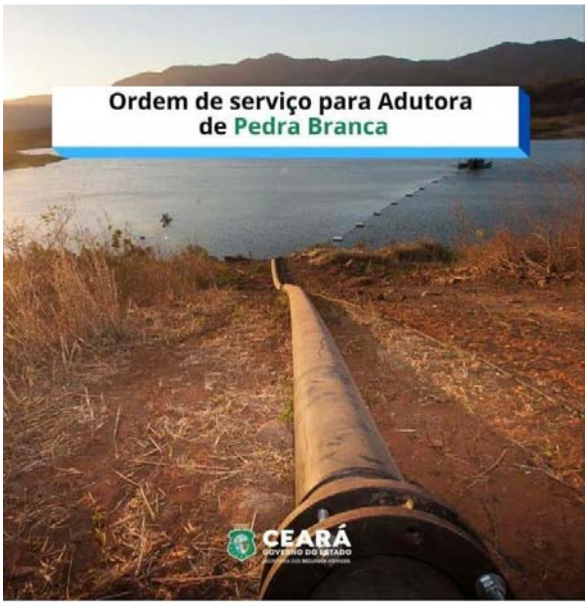
Note: Only five reservoirs are medium-sized public reservoirs, the rest are small private reservoirs.

Viewpoint of the communities: Rediscovery of watershed interdependence

The large reservoirs situated close to the study area (Pedra Branca, Fogareiro and Quixeramobim) have failed to supply sufficient drinking water to cities. This has motivated the state to consider transferring water from upper catchments to the city, which is considered to be a 'priority' user under National Water Law No. 9433 (Brazil, Ministry of Environment, Water Resources Secretariat, 1997). This led to the decision, after the drinking water crisis in 2022, to transfer water from the Cachoeira reservoir in Forquilha catchment to the nearby city of Pedra Branca. The reservoir at this point was already a strategic supply point for water tankers delivering water to rural communities outside of the Forquilha catchment.

COGERH, the state water resource company, failed to inform the communities of Forquilha about the decision to transfer water, even though the same water law specifies that, "Water resources management should be decentralized and rely on the participation of the government, users, and communities" (ibid). The decision was announced on the Instagram account of the Secretary of Water Resources of Ceará (Figure 41). Soon after that, work began on the construction of the pipeline connecting the reservoir to the nearby city. This event confirms some of the challenges of the inclusion of communities in decisions around water allocation and in the design and implementation of water infrastructure (see García and Bodin, 2019, for some of the barriers to inclusion in Brazil).

Figure 41 – Announcement of the water transfer project from Cachoeira reservoir to Pedra Branca



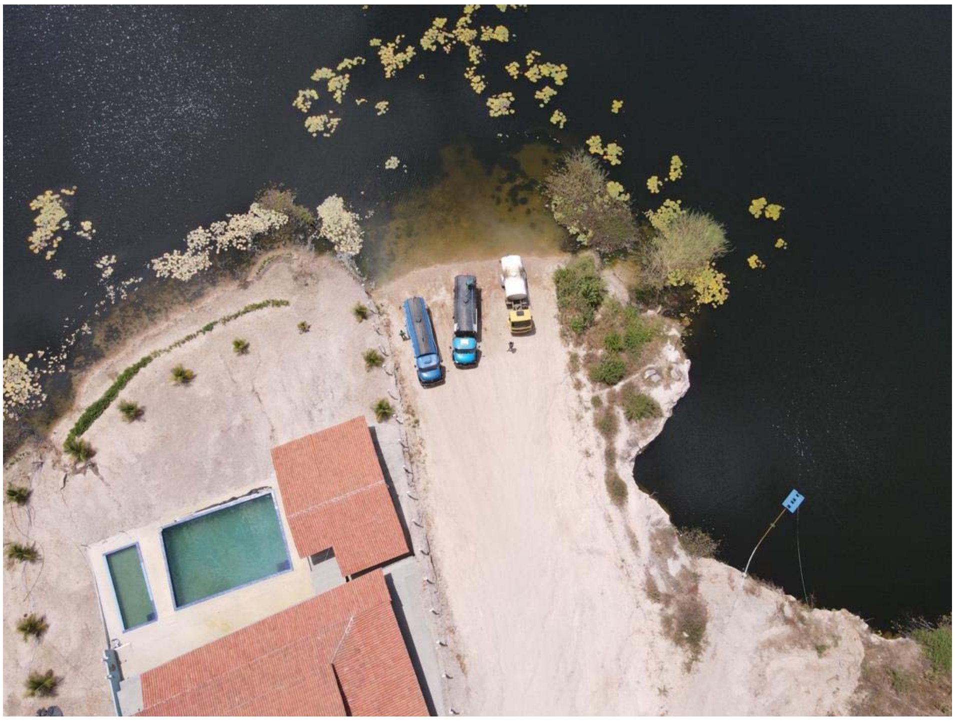
Source: Instagram account of the Secretary of Water Resources of Ceará, 2022.

Cachoeira reservoir now provides water to Pedra Branca city through a pipeline and to rural communities in 6 municipalities via approximately 80 water tankers per day (Figure

42). Communities in Forquilha have mixed feelings about these transfers. They are proud to provide water to those in real need via water tankers but argue that water should only be distributed for domestic use and that the volumes concerned must not risk drying out the reservoir. The new pipeline to Pedra Branca is more controversial.

A feeling of identity ('our water') emerged in discussions and interviews in September and October, 2022, and participants in a January 2023 workshop expressed feelings of inequity and dispossession. Are rural communities in Forquilha catchment being left without water? What local effects do water transfers to the city have? As members of the Cachoeira community commented in interviews, "We have no authority over this reservoir. It’s not our water (...) it’s the state that decides (...) the inhabitants of Pedra Branca really need it, as we saw on TV and they also talked about it on the radio (...)". The reaction of the communities was thus clearly expressed in the question asked by Lemos (2009): "Whose water is it anyway?"

Figure 42 –The Cachoeira Do Germano reservoir reservoir and its different uses



Source: Drone photo by Vieira, 2023.

Note: The reservoir supplies water to: 1) six municipalities by water tankers (from Monday to Saturday); 2) two community networks (the small blue pump to the right of the picture); 3) a nearby city through a pipeline; and 4) leisure activities (swimming pools, fishing, recreation).

According to local inhabitants, the pipeline construction has been supported by stories and discourses on local radio channels, TV news, and social media about the neighbouring city's severe water crisis. These stories implied that communities had a moral duty to collaborate in solving that crisis, for example by not contesting the transfer pipe to the city. This points to a strategy of establishing social and ethical norms to accompany the infrastructure project; in this case the media helped justify the rural – urban water transfer (Hommes *et al.*, 2020). The construction of pipes and the use of a powerful pump leaves the population worried that the reservoir will dry up and feeling that they have lost all control over the water. At the same time, because of promises made during a recent political meeting (Figure 8), the inhabitants of the Forquilha catchment are hopeful that a new pipeline will be installed which uses the new pumps to supply the entire Forquilha catchment with domestic water from the Cachoeira do Germano reservoir. It remains to be seen whether that promise will be fulfilled.

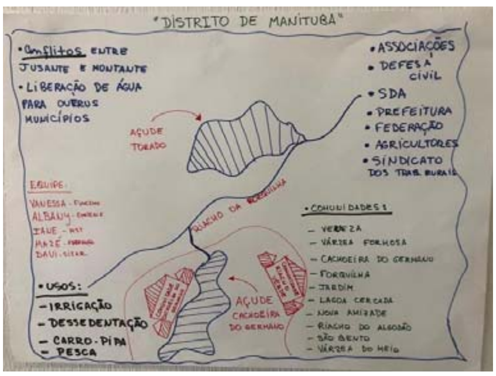
What we can observe from this story of the water transfer is that it has led to a rediscovery of catchment interdependence among the various communities that had been focusing so much attention on formal and informal water access at the level of households, nucleated settlements and communities. Workshop participants expressed a loss of control over water sources, which may affect water security in various ways for different communities. The question is then whether this renewed sense of interdependence may give rise to new forms of water ownership, collective action and, as a consequence, new hydrosocial territories. *The viewpoint of the institutions: Hydrosocial territories organised around reservoirs in the upper catchments*

Rural communities' internal arrangements to maintain functional water supplies are invisible to larger institutions. The role of the state is to provide water infrastructure and it is then the responsibility of the community to manage the water systems. In a context of pressing water shortages in cities, water resources in the upper catchments have become more visible to institutional actors. This was noted in a 2022 workshop with institutional stakeholders, during which three separate working groups were asked to define and limit, according to their opinion, what constitutes hydrosocial territories (HSTs) in the Forquilha catchment.

The three working groups thus identified three rather similar HSTs organised around medium-sized public water reservoirs in the upper catchment of Forquilha (see Table 12). These reservoirs were considered crucial for local uses (irrigation, drinking water and domestic use); however, they are also increasingly being seen as strategic resources for the transfer of water to cities. The territories were very different from those identified by the communities themselves, as the working groups (made up of representatives of institutions) focused on the water resources that could be obtained for transfer from the Forquilha catchment. All three working groups, however, paid particular attention to conflicts inside the territories. In fact, state water institutions have the legitimacy and the power to interfere as mediators in the solving of water-related conflicts; they thus have the authority and regulatory power to extract water and shape water territories by controlling water infrastructure (Hoogesteger *et al.*, 2016).

They also, however, have to deal with intricate social relations particularly in cases of water transfer, and experience has taught them to be very attentive to these relations. In our case, the fact that the three upstream reservoirs had been constructed by the state and that they were being partly used to fill water tankers legitimised further intervention in the form of the construction of a pipeline to feed a neighbouring city. State services have their own vision of how water and water users should be territorialised, with a clear priority on the provision of drinking water to cities. As we showed previously, however, the fact that six hydrosocial territories had progressively come into being in the Forquilha catchment also made the communities less united in their stance towards the state-led abstraction of water, to the benefit of the city of Pedra Branca.

Table 12 – Hydrosocial water territories identified by institutional actors in three working groups

<table>
<tr><th>The hydrosocial territory identified</th><th>Explanation given by the three working groups</th></tr>
<tr><td>Figure. The hydrosocial territory was delimited around the area of the Cachoeira do Germano reservoir

</td>
<td>This is a medium-sized reservoir that supplies communities in the vicinity and immediately downstream of the reservoir. The reservoir is monitored by the state and currently a pipeline connects it to a nearby city.
The reservoir has several uses: irrigation, supplying drinking water, supplying water trucks and enabling fish farming.
There are potential conflicts between upstream and downstream communities in the catchment. Tensions emerged in the catchment because of water transfer to the city.</td></tr>
</table>

Continue

Table 12 – Hydrosocial water territories identified by institutional actors in three working groups

<table>
<tr><th>The hydrosocial territory identified</th><th>Explanation given by the three working groups</th></tr>
<tr><td>Figure. The hydrosocial territory is linked to two strategic reservoirs in the catchment (Riacho Verde; Cachoeira dos Germanos).

</td><td>The demarcation of a water territory (Territorio da agua), limited to three upstream communities (Cachoeira, Riacho Verde 1 and 2) and partially extending to Jardim and Riacho do Algodão communities, was justified by its water potential. Participants declared that management of a larger area is not feasible, as the region is densely populated. Water uses include drinking, extensive irrigation, watering livestock, fish farming and filling water tank trucks. Problems and conflicts are related to indiscriminate recreational use, use of agrochemicals, deforestation of the strip bordering the reservoir.</td></tr>
</table>

Source: Author, 2023.

Conclusion

5.4 Conclusion

5.4.1 The formation of hydrosocial territories for sustainable water access in rural communities

The paradigm shift from the hydraulic era to 'living with drought' in Brazil's Nordeste has led to the massive expansion of decentralised water infrastructure at the community and household levels (Formiga Johnsson and Kemper, 2007). The idea is to build on "the innovative capacity of peasant families", thus "creating a socio-ecological system with great resilience" (Mattos *et al.*, 2022: 33). This paradigm shift has been manifested in the development of community water supply networks for drinking water, cisterns for drinking water and small-scale productive activities (fish farming, gardening), and boreholes and small reservoirs for irrigation and watering livestock (Gutiérrez *et al.*, 2014; Mattos *et al.*, 2022). The decentralisation of water infrastructures, however, resulted not only from state or NGO programmes.

We showed that an impressive number and diversity of small-scale water infrastructures have been implemented by households, nucleated settlements and communities in the Forquilha catchment, as elsewhere in Ceará. This plurality of small-scale infrastructure for multiple purposes (see Smits *et al.*, 2010), reduces their dependence on a single source that may dry up at some point, or on a single actor or organisation. For instance, families avoided relying exclusively on community associations, some of which have experienced serious organisational problems, or on the state and its water tankers; instead they built individual reservoirs, dug wells, and/or drilled boreholes.

State- and NGO-led programmes of small-scale water supply infrastructure alongside private individual and collective initiatives have woven a dense web of water reservoirs, wells and boreholes, pipes and taps; these are shaped by, and also reshape, social structures and networks. We have shown how these diverse initiatives have influenced the formation of a multitude of hydrosocial territories in Forquilha catchment; we have revealed the multiple and dynamic set of interactions between infrastructures, water flows and social networks (Boelens *et al.*, 2016). Within these territories, there has been improvement in sustained access to water for (most) rural households and therefore enhancement of the resilience aimed for by state- and NGO-led programmes. Not all community associations were equally active, which may account for variations in the functionality of community networks. No families in Forquilha catchment communities, however, relied exclusively on these community water supply networks; instead, they favoured multiple water sources and infrastructures that were linked to multiple actors through formal and informal arrangements. Sustained water access is thus a social construct that results from a plurality of strategies and dialogues among stakeholders in a rapidly changing (water) environment; it challenges the "intended hydrosocial fix" whereby water infrastructure is implemented through formal arrangements (Hommes *et al.*, 2022).

Our analysis of the relational networks around the implementation and use of small-scale water infrastructure also showed that households and communities invested in institutions and arrangements, enabling the operational functioning of community domestic water supply networks while guaranteeing a certain solidarity among households, especially for drinking water but also water for agricultural uses at the NS level. We also observed the strong relations that communities maintain with outside actors around decentralised infrastructure (including state representatives, politicians and NGOs) despite the explicit community focus of rural water supply programmes (Enéas da Silva *et al.*, 2013). Despite state efforts to eliminate clientelism, for instance (Collard, 2013), politicians were often mobilised to contribute to finding solutions when water supplies failed, as demonstrated by the Varzeo do Meio community. Such arrangements are part of the messy and contested processes through which infrastructure and territorial relations co-evolve (Obertreis *et al.*, 2016), even if clientelism is often challenged by scholars and activists (Nelson and Finan, 2009). Yet without such relations, it is very difficult to maintain access to water. At the same time, the interactions among community representatives during the workshops showed that not all communities are successful in mobilising outside actors. Indeed, some communities and households still have weak access to water, in particular households that have only recently settled in the catchment.

5.4.2 Fragmenting basins, fragile communities?

We have shown in this paper the dynamic nature and flexible geographical boundaries of hydrosocial territories, which are subject to change and transformation (Hommes *et al.*, 2022). While it can be argued that the formation of small community-based hydrosocial territories has improved the sustainability of water access for families in the Forquilha catchment, it is important to also consider how infrastructural interventions have changed water flows and social relations at other scales (Hoogendam, 2019). In the case of Forquilha, this has led to the loss of hydraulic connectivity and the fragmentation of the catchment area through the formation of smaller hydrosocial territories. It has weakened social linkages around water while contributing to water shortages in downstream strategic reservoirs.

The community focus on water infrastructure development by the state led indirectly to three different but interrelated phenomena that show the central role of water infrastructure in shaping hydrosocial territories. First, there was a fragmentation of the Forquilha catchment into multiple small hydrosocial territories, and water infrastructure is now considered to be linked to single communities. Community reservoirs have become part of the identity of rural communities and indeed are often named after them. According to Freire and Calijuri (2011: 681), they are sometimes referred to as "waterworks of coexistence with (...) drought". Even medium-sized reservoirs in the upstream part of the catchment have been appropriated by nearby communities and 'our water' is the discourse generally used by upstream communities members for such reservoirs. Despite several attempts, the more distant downstream communities have not succeeded in obtaining access to these reservoirs and water flows in the Forquilha River have been disrupted, resulting in a loss of hydraulic connectivity. This has prompted downstream communities to lay claim to a reservoir as 'theirs' in order to guarantee future water availability; in one case they were able to construct a new reservoir for use by their community (see Mosse, 1997).

Second, decentralised water infrastructure has become a massive phenomenon in the Nordeste with the construction of thousands of boreholes and reservoirs, most of which are below the radar of the state (de Araújo and Medeiros, 2013). This decentralised water infrastructure has vastly expanded stable water access, thus encouraging farmers to increase the amount of water they use for livestock and/or to adopt more intensive forms of irrigation. This, combined with climate change, has reduced inflows into the large so-called strategic reservoirs (ibid), which has, in turn, challenged the urban drinking water supply.

Third, and perhaps paradoxically, the over-development of small-scale water infrastructure in upstream catchments such as Forquilha has combined with the community focus of the infrastructural programmes to create the conditions for the state to become more closely involved in catchment affairs. The state gained a strong motivation to act (severe water shortage in urban areas), while the social cohesion between Forquilha communities was weakened through the creation of autonomous small hydrosocial territories. The state renewed its interest in some of the medium-sized reservoirs in upper catchments. The analytical lens of hydrosocial territories is particularly enlightening with regard to the dynamic and multi-scalar nature of hydrosocial territory and its contested nature linked to the diverging perspectives of the different stakeholders (Obertreis *et al.*, 2016). The main stakeholders – the state and the upstream and downstream communities – had a radically different perspective on the hydrosocial territory and on the productive function of the reservoirs in the upper catchments. The Forquilha case clearly shows how hydraulic infrastructures have shaped power and moral relations, which has led to the transfer of water to urban areas. A similar case was reported by Hommes *et al.* (2020: 417) in Mexico, where "[w]ater technology is moralized, to the benefit of the city and affluent social actors (while, simultaneously, rendering these unequal social relations invisible)". As we have shown, in a context of fragmented water flows and hydrosocial territories, communities were quite powerless in their negotiations with the state (Hommes and Boelens, 2017). In the absence of such negotiations and without regulatory arrangements that give voice to rural communities, state projects that connect water flows at different levels may lead to processes of dispossession of water, and livelihoods, of vulnerable groups.

Given their dynamic character, the present hydrosocial territories are likely to be reshuffled, in particular by state transfers of water to neighbouring catchments. In a semi-arid region struck with repetitive droughts, the state's covetous approach is well-represented by an institutional view that sees a catchment as being organised around its upstream reservoirs. We have also shown, however, that transformations of hydrosocial territories will not be homogeneous across the catchment because of the diverse sociopolitical and water realities (see Hoogendam, 2019). Moreover, a renewed appreciation by communities of the interdependence within the catchment is certainly going to play a role in these transformations.

5.4.3 Acknowledgements

This study was conducted as part of a joint PhD programme at UFC (Federal University of Ceará), Brazil and Institut Agro, University of Montpellier France. The research was funded by FUNCEME (Ceará Foundation for Meteorology & Water Resources) and CIRAD (Montpellier) through the Pacte and Sertões projects funded by the French Development Agency (AFD), FUNCEME, CIRAD and FUNCAP (Ceará State Science Foundation/Technological Innovation Fund).

6 CONCLUSIONS

This thesis aimed to characterize the water resilience of communities in rural areas, specifically in the context of semi-arid regions in central Tunisia and Nordeste Brazil. This research faced three main challenges. Firstly, resilience is a well-debated notion in the literature, necessitating a thorough exploration of the existing knowledge in order to develop a coherent and focused approach. Secondly, and perhaps paradoxically, the notion of resilience was often mentioned in relation to water, but the literature on water resilience was not very comprehensive, which needed to be addressed in this thesis. Lastly, although resilience was mentioned in some policy and project documents, it was not commonly used by the actors in the field.

To overcome these challenges, this thesis aimed to co-design a conceptual and operational framework that would enhance the understanding of rural water supply systems, involving policy makers, water managers, NGOs, and communities. It sought to stimulate reflection and contribute to the international debate on water resilience in semi-arid areas. The case studies chosen for investigation were the Nordeste region in Brazil and Central Tunisia, where the issues of water scarcity and resilience are particularly prominent. Through in-depth analysis and empirical research, the thesis aimed to shed light on the dynamics of water resilience in these contexts and provide valuable insights for future policies and practices.

6.1 Main research results of the thesis and reflection on the research approach

6.1.1 A fresh perspective on rural water supply systems

The Multiple-Use Water Services (MUS) literature was a logical starting point for this thesis on the water resilience of rural communities (Renwick, 2001; Renwick *et al.*, 2007; van Koppen *et al.*, 2009; Smits *et al.*, 2010; Srinivasan *et al.*, 2012; Winrock International, 2012). The MUS approach inspired this thesis in identifying and then characterizing and analyzing, the main research object: Rural Water Supply Systems. The three main points that were of particular interest in this perspective are: 1) Multiple water sources for multiples uses are the norm in rural areas, something that is often forgotten in rural water supply projects; 2) The MUS approach strives to go beyond the sole implementation of water infrastructure, as it focuses on providing sustainable water supply services and promotes the resilience of communities to climate resilience (GC, 2016; Matoso *et al.*, 2017; Stedman *et al.*, 2018); it can thus be qualified as a people-centred approach; and 3) The MUS approach emphasizes the importance of involving rural communities in the design and implementation of rural water supply services; this draws attention to the fact that the sustainability of rural water supply projects is enhanced by designing a participatory approach that involves planning, finance, and management of integrated water services.

The research results of this thesis show that the MUS approach yields very valuable lessons. First, it helped me to consider all water uses of rural communities in an integrated manner, beyond the sectoral views separating, for example, drinking water from agricultural water. It thus influenced directly the analytical framework, but also the main results of the Ph.D. For example, it helped to better evaluate the use and functioning of the community-based water supply networks, as they catered to a much wider variety of uses than planned.

Second, the MUS approach recognizes the often-informal ways in which communities have been developing and managing their water resources. Following North (1990), this thesis adopted “a broad definition of institutions that includes both formal and informal arrangements (Kuper *et al.*, 2017). As in many other places and situations, in the context of semi-arid areas rural communities have always used both formal and informal arrangements to organize their access to multiple water sources for multiple uses (Gasmi *et al.*, 2022). This explains, for example, that in summer or in times of crisis, people irrigate their gardens and livestock with tap water, using the state-financed drinking and domestic water supply network. This is linked to their value system, as they consider saving their crops to be a priority use even more than their domestic uses. Considering both the formal and informal institutions was also instrumental in analyzing the multiplicity of networks and initiatives of rural communities to maintain satisfactory access to water.

Third, the MUS approach influenced my analytical framework in adopting a multi-scalar approach, focusing both on the household and community levels. However, the recent literature on the pitfalls of community-driven approaches to rural water supply (see Whaley and Cleaver, 2017; Hutchings, 2018), debated in chapter 3, inspired this thesis in explicitly incorporating in the analytical framework all of the actors in the broader institutional landscape (the different state services, politicians, NGOs). Following Collard (2013), this thesis showed, for example, the continued important role of politicians in catering to rural water supplies.

As explained in chapters 4 and 5, I incorporated the notion of resilience in the analytical framework of this thesis. The initial reason for this (see Chapter 5) was that this notion figures prominently in scientific, policy, and project documents of rural water supply systems and that it was often used by institutional actors. At the same time, I was increasingly inspired by this very rich literature, promising that this concept would make it possible to analyze how (water) systems "resist shocks in a … responsive fashion" while acknowledging that the systems themselves are on trajectories of change (Leach *et al.* 2010, p. 373). However, while the notion of (water) resilience is often employed in the literature on rural water supply systems, it is rarely defined. For instance, in a seminal and recent paper on household water provisioning and consumption in *Nature*, showcasing 'water resilience' in the title, the authors made a conclusive plea on why it was important to account for multiple water sources for multiple water uses of households (Elliot *et al.*, 2019).

However, the paper was not very precise on what was meant by water resilience (referring to it, interchangeably as water and climate resilience) and to whom the term was applied (both households and communities are mentioned in the paper). Recent literature has highlighted the urge to consider water resilience as a new approach to water resource management, as well as a new way of managing water resources.

In the 2021 book by Baird and Plummer, the authors emphasized the importance of adopting a multidisciplinary approach to combine theoretical and practical progress on water resilience: "A new water paradigm – water resilience – has emerged that acknowledges and considers the complex, dynamic, and uncertain nature of social-ecological systems. It emphasizes the need for systems to both persist and provide a set of functions and to adapt to changing conditions" (Plummer and Baird, 2021:6). However, water resilience literature presents some limitations in rural areas because attention has been focused on studies of water resilience mostly in urban areas (Head, 2014; Jian *et al.*, 2017), and mainly focused on "engineering resilience in water supply infrastructure" (Rodina 2019:1).

The definitions of water resilience, in general, are rare and fuzzy and often do not capture the complexity and multidimensional aspect of the water systems. The little attention paid to the resilience of rural water supply systems has intrigued me to explicitly incorporate the 'water resilience' lens in the research approach of this thesis, thus providing the first result of this thesis which is a fresh perspective on water supply systems in rural communities. We defined the Rural Water Supply Systems (RWSS) as complex systems catering to multiple water uses; that depend on one or more water sources; that include water infrastructures and the organization managing them; that are embedded in social relationships within the community and that are firmly connected to external actors, that have contributed to its establishment and development.

The results of the thesis (see Chapter 3) confirmed our hypothesis that communities often limit their dependence on community-managed water supply systems and diversify water sources for different uses. The community members invest in alternative water infrastructure so as not to rely solely on the collective network. Keeping the RWSS at the center of the community's interests is hard work and will ultimately determine whether it remains functional. Moreover, faced with water-related shocks and stressors (drought, floods, seasonality, groundwater overexploitation, water pollution, and management issues), communities did not give up; instead, they demonstrated several adaptations to maintain access to water, which I associated with water resilience.

The originality of combining the lens of water resilience and the MUS approach in this thesis (chapter 4) is that enabled me to define a resilient RWSS as a system that might have to deal with shocks, adapting to changing conditions and transformations in situations of crisis while maintaining internal regulation and external connections. There may be an adaptation of hydraulic infrastructures, a reorganization of rules and social institutions, a transformation of agricultural activities, and the implementation of new public policies. The very early investigation phase of the thesis in both countries has shown that communities were only approached by the state and NGOs during the implementation phase of water projects or when assuming responsibility for managing water networks.

In this thesis, we challenged this approach and engaged community members during all the phases of this research on water supply systems. Proceeding through a participatory approach with different stakeholders (communities, researchers, state agents, and NGOs) in co-developing a framework of a resilient rural water supply system was important to, first, conceptualize the framework and validate the initial intuition that water resilience could explain past and ongoing experiences related to rural water supply systems in the eyes of those having implemented and managed such systems. Second, it was crucial not to neglect important (and dynamic) features of rural water supply systems. The combined experience of a diversity of stakeholders was indeed impressive and their inputs turned out to be very valuable in describing and analyzing these systems.

The two added values of adopting a resilience lens that has been presented in this thesis are: 1) the resilience of water supply systems in rural communities is better seen as a trajectory than as an outcome (Sabourin *et al.* 2004); we operationalized this by identifying and analysing the trajectories of RWSSs; and 2) the resilience of the rural community is revealed through the prism of systemic resilience strategies (or capacities): absorption, adaptation, and transformation (Ungar, 2018).

6.1.2 Operationalizing the notion of water resilience

The transition from a conceptual to an operational framework was challenging because translating theoretical concepts of resilience into practice is a complex task. The study by Matoso *et al.* (2017) highlights the challenge of using terminology associated with resilience, such as absorb, anticipate, and adapt, which may not be easily understood by field officers and communities. The authors propose deconstructing and simplifying these concepts to align with the terms already familiar to project, technical, and field officers, as well as to communities.

Similar to the results of this study, we observed that official documents in Tunisia and Brazil of water projects promote resilience and adaptation to climate change (Mattos *et al.*, 2022; AFD, 2023), but community members and technical officers do not commonly use these terms. From a research perspective, it was helpful to adopt a participatory approach that involves the community members and institutional actors in a reflection on water resilience. In this thesis, we made a choice to introduce and discuss the word resilience through the prism of resilience strategies, because we noticed that this was the way how community members appropriate the resilience concept. We used words like persistence, adaptation, and transformation to reach a shared understanding of how the four rural communities address shocks and stresses related to water with examples from the field. This allowed an active engagement and input, ensuring that the concepts and terminology used resonated with their existing knowledge and language. Together we identified and analyzed the trajectories of RWSS in the four selected rural communities. In this thesis, the trajectories of RWSS are defined as temporal and spatial changes made to the rural water supply systems by a group of stakeholders, in a defined territory, in order to develop a set of strategies for adaptation and transformation to meet their multiple needs.

The debates on the resilience of RWSS with different stakeholders immediately raised the question of what key functions a resilient RWSS must maintain to deal with shocks and stress. In this stage of the thesis, we operationalized the concept of water resilience for rural water supply systems by identifying three key functions inspired by the socio-ecological system's resilience by Gondard *et al.* (2021). The first function is the productive function: to provide water at all times, even in the case of shocks and stresses. Function 1 is to secure a sustainable supply of water for multiple uses. The community needs to use its assets to adapt the water supply to changes and emergencies. Interestingly this function obtained through the water resilience lens is at the heart of the MUS concept (Smits *et al.*, 2010). Such results confirm our hypothesis in Chapter 1 on the complementarity between the two lenses.

The second function is the internal regulation: the community institutions enabling to organize water supply. The third function is the capacity to safeguard reliable connections to external actors, which makes it possible to assess the mode of integration of the RWSS in the rest of the territory and favors its existence. Function 3 includes the integration of the RWSS in the economy, society, and territory. Subsequently, we co-defined and explained 12 essential features (the distinctive attributes of each function that allow the RWSS to fulfill the function when dealing with shocks and stresses), and 35 explanatory variables of water resilience that allow these functions to be maintained (see chapter 4). The co-identified explanatory variables were then confronted with the literature on water resilience and have shown some similarity with other studies as the specified and general resilience attributes of aquatic system governance by Plummer *et al.* (2014) and the characteristics of resilient water systems from the Rodina's (2019) systematic mapping review.

Interestingly, the identified explanatory variables combined subjective variables and objective variables. The resilience assessment literature has shown increasing attention paid to measuring the subjective resilience of households and communities: "placing considerable value in people's knowledge of their own resilience and the factors that contribute to it" (Jones, 2019:2). Béné (2013) also recommended taking into account both objective and subjective measurements for a new resilience framework to be generic enough to be used in different contexts.

6.1.3 A participatory approach for crossed points of view from Brazil & Tunisia:

Working across four cases study in two water-scarce contexts allowed us to reach a common understanding of the concept of water resilience and hence the possibility of replicating the methodology in other contexts. Characterizing water resilience in rural communities, as explained in this thesis, is an approach elaborated in two geo-political contexts rather than a simple tool. This gives robustness to the approach and to the framework we propose. However, we do not claim our framework of resilient RWSS is a universal model of water resilience. Its extension to other semi-arid areas will only be possible by contextualizing it with the communities and stakeholders concerned (Beauchamp *et al.*, 2019). As Rodina (2019:6) has mentioned "stakeholder engagement and participation tend to be seen as processes that help get buy-in or social acceptance of resilience building actions that remain predominantly decided on by governments and water managers. This implies that participation tends to be seen as important only in later stages of resilience-building, not necessarily in the planning and strategic decision-making ones”. The key functions of a resilient RWSS are likely to converge in most cases, but the features and explanatory variables will certainly need to be adjusted.

In the resilience literature, there is no consensus on metrics and methods that translate the theoretical multidimensionality of resilience into practical assessments (Levine, 2014; Sharifi, 2016). In terms of research perspectives, the explanatory variables identified in this study need to be complemented by resilience indicators. Researchers should adopt an open posture to adapt and incorporate information proposed by the community members and stakeholders involved in their future research on water resilience. This collaborative approach will enrich the debate among researchers and enable the sharing of knowledge with community members and different stakeholders.

Adopting a participatory approach with different stakeholders was a long and complex process. However, we have demonstrated the advantages of this process, such as fostering shared trust among stakeholders, collecting reliable data, actively engaging community members, and ultimately generating a shared understanding of how communities and external actors (such as NGOs and state services at various levels) perceive the resilience of water supply systems.

6.1.4 At the heart of this thesis: communities and nucleated settlements

In a systematic mapping review on water resilience Rodina (2019), has observed that water distribution systems were the primary scale where resilience was commonly explored. However, the review also highlighted the absence of scale specificity, the multiplicity of applicable scales, and the insufficient consideration of interactions in the overall understanding of water resilience. We noticed that the literature on water resilience does not take into account the flexibility of the boundaries between different scales (households, communities, and basins). This limitation was addressed, in this thesis, as I illustrate some of the points of cross-fertilization among resilience and water scholars on water supply and waterscapes lenses. I challenged the standard approaches to rural water supply (Prokopy, 2005) by adopting an intermediate level between household and community levels, which was identified in the field and mixed with the hydro-social territory lens to forge this research. The uniqueness of this perspective lies in its emphasis on the spatial dimension of water resilience, while also uncovering the social, institutional, and political interactions involved.

In this thesis, we linked nucleated settlement to water resilience and defined it as a group of households in which, in times of stress, or even routinely, drinking water, and sometimes water used for other domestic purposes, is shared among the extended family, neighbours, and friends (see Figure 43). The community members rely on this network to adapt and resist to water related-shocks. Building on Ungar (2018:1) - where any given system is described as "open, dynamic, and complex" - we incorporated communities and nucleated settlements into a broader vision of hydro-social territories to understand the dynamic relations between water uses and stakeholders at different spatial scales (Boelens *et al.*, 2016).

Figure 43 –This photo shows an example of a nucleated settlement that was identified in a case study (Varzea Do Meio community). These households are connected by kinship and have a small collective reservoir used for watering livestock. Almost all families have a borehole of 5 to 8 meters used for agricultural production, the same for drinking water from cisterns. Interestingly, when a family faces a problem, they can temporarily or permanently share the borehole with their neighbors' houses. This aid network is based more on the nucleated settlement than on community bonding

Source: Drone photo by Vieira, 2023.

Through the combination of the water resilience and hydro-social territory lens, a key finding emerged: Focusing solely on enhancing water resilience at the community level may inadvertently create vulnerabilities at the broader hydro-social territory level. The concept of resilience has faced criticism when it is used to justify interventions that allocate limited resources to support communities, ultimately placing blame on these communities for their perceived lack of resilience (Robinson and Carson, 2016).

This thesis showed that accessing multiple water sources and multiple infrastructures through external interventions has contributed to the enhanced adaptive capacity of rural communities, enabling them to cope with climate change and improve water access in rural areas. However, an unexpected discovery has arisen from this multiscale analysis: excessive development of water infrastructures within a catchment area led to its fragmentation into smaller and multiple hydro-social territories. This fragmentation resulted in the displacement and disempowerment of rural communities during water negotiations. In fact, resilience thinking often treats external shocks as "natural or inevitable," failing to consider the role of political choices and socio-economic dynamics (Platts-Fowler and Robinson, 2016, p. 5). However, this oversight can limit a comprehensive understanding of the complexities surrounding water resilience and its governance.

Studies on water resources management at the basin level often lack cooperation with downstream areas, even when the basin is managed by local authorities or users (Van Oel, 2009). In various cases, downstream water availability relies on the actions of individual upstream water users, leading to issues such as reduced inflow, severe water shortages, and spatial redistribution of water during drought (Venot *et al.*, 2007). Similar to the findings of this study, Venot *et al.* (2007) demonstrate the increasing interdependence between basins, water users, and regions. The results of this thesis, viewed through a hydro-social lens at the catchment level, confirm this interdependence. From a social standpoint, there is no one-size-fits-all scale or level for water management (Van der Zaag and Gupta, 2008). The appropriateness and acceptance of water management at a specific level are influenced by the chosen perspective and the political culture within a particular country or region (Molle, 2006).

In Chapter 5, we showed that water resilience extends beyond the borders of local communities, largely influenced by linkages within territories, including hydrogeographic dynamics (upstream-downstream in the basin) and socio-political dynamics. The findings of this thesis align with Burte's (2009) perspective in Nordeste Brazil, suggesting that integrated management can enhance the comprehension of water use and water users within hydro-social territories. Consequently, there is a need to invest in monitoring these hydro-social systems to facilitate participatory, decentralized management, while also ensuring integration into the national water resources management system.

6.2 Implications for interventions in rural water supply

6.2.1 Implications worldwide

The water resilience approach has been gaining momentum in scholarly discussions and is receiving increasing attention in practical applications and public policy worldwide. The international community's efforts to aid climate adaptation, exemplified by the Green Climate Fund (GCF, 2018), have made the establishment of resilience goals and measures a pressing priority. Recently, the GCF Board adopted the Fund's 2024-2027 Strategic Plan, approving USD 755.8 million in finance for new climate resilience projects in developing countries. The GCF co-chair Nauman Bashir Bhatti stated that these projects have a strong focus on increasing direct access and building resilience in vulnerable countries facing the impacts of climate change.

The future projects emphasize crucial resilience-related terms such as 'Resilient Homestead and Livelihood,' 'Resilience to climate change,' 'Enhanced climate resilience,' and 'Enhancing the climate change adaptive capacity of smallholder farmer communities.' Furthermore, water resilience aligns with the emerging global discourse on a new water storage paradigm, aiming to reinforce the resilience of water systems to climate change (Martins *et al.*, 2016; Pangestu, 2023).

The growing international interest in implementing resilience projects is evident in Tunisia and Brazil as well. For instance, the Community and Ecosystem Resilience Program in Tunisia aims to develop an integrated, territorial approach to address environmental changes, working closely with civil society and local communities (AFD, 2023). Given the focus on building community resilience, exploring how local interpretations of resilience align with existing resilience frameworks used by international donor communities (Clare *et al.*, 2017) is essential.

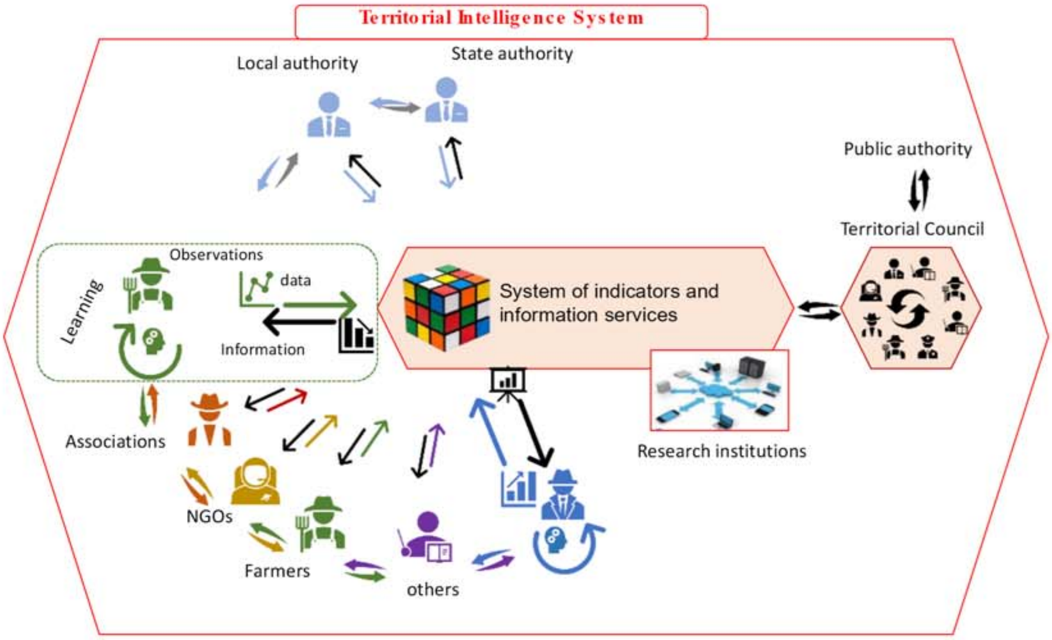
The definition and the conceptual frameworks of resilience which were used in past projects significantly influence the interventions design. Béné (2013) stresses the importance of feedback from previous interventions to gain insights and guide future initiatives for donors, agencies, and stakeholders. In a study conducted by Beauchamp *et al.* (2019) in a project aiming to enhance the resilience of local communities to climate change by providing them with access to adaptation funds under their control, it was revealed that using resilience indicators in isolation does not sufficiently capture the complexity required to reflect adaptation processes and resilience outcomes. For local purposes, a concise set of indicators, including self-assessed perceptions, may meet the necessary standards of evidence while being feasible within local monitoring and evaluation contexts. Thus, the importance of resilience tools that employ participatory and community-based approaches to uncover specific local attributes crucial for enhancing resilience (Bene *et al.*, 2011; Choptiany *et al.*, 2017).

6.2.2 Implications in Tunisia & Brasil: A research project design to inspire development projects:

In my thesis, I have interacted closely with two action research projects on rural water supplies in Brazil (the Sertoes project) and Tunisia (the Pacte project), which facilitated access to the field while guaranteeing a lively debate on the issue of rural water supplies. The methodology of participatory workshop design and the holistic view of water supply systems has been adopted in part in these projects (conception in Tunisia and validation with some adaptation in Brazil). In addition, there is the possibility of producing water resilience indicators based on the 35 variables (chapter 4), which will be included in a territorial intelligence system (García-Madurga *et al.* 2020) to be applied in the intervention areas of the two projects (Figure 44). Béné et al (2014:612) argued that one of the characteristics of a resilient system is decentralized governance: "Effective governance and institutions, which may enhance community cohesion. These should be decentralised, flexible, and in touch with local realities; should facilitate system-wide learning; and perform other specialised functions such as translating scientific data on climate change into actionable guidance for policymakers". Participants in the validation workshop found the essential features that define a resilient RWSS and the explanatory variables to be clearly explained through language and easily comprehensible explanations. This is because it has been designed in a way that unpacks the complexity of water hazard adaptation and uses language commonly used by community members and institutions.

At present, I am involved in supervising a student on a final year project who is developing resilience indicators in Morocco based on the results of the thesis. An application of these indicators in Morocco as a third semi-arid context will make it possible to test and validate the robustness of the results of this research, given at the same time robustness to the approach and the framework of water resilience proposed in this thesis.

Figure 44 – Territorial intelligence system



Source: Burte, 2023.

Moreover, we assume that scale and participation matter, and that the way in which the two were combined in this thesis is important to understand actors' perceptions, interests, and problem-solving (Schmitter, 2002; Hein *et al.*, 2006; Hunsberger and Kenyon, 2008). This thesis touched on the territorial scale in a case study of the Forquilha catchment (Chapter 5). The conceptual considerations and the empirical findings have stimulated more questions about the links between water resilience and hydro-social territories. A researcher who has been involved in the thesis fieldwork in Brazil shows an interest to address this question in an upcoming Ph.D. on hydro-social territories at a regional scale.

Although the focus of this thesis research was not on the implementation of the results in water governance, some conclusions can be useful for water managers. In general, it was found that it is important to implement development projects that take into account the interrelation between scales with a territorial approach because otherwise, rural water supply systems will not be sustainable. Water managers (involved in this research or external ones) can be inspired by the participatory methodology used in this research of water resilience (developed in Chapters 2 and 4) to be implemented in future participatory development projects. So, there is a necessity to move towards a higher spatial level to enhance water resilience. A few possible directions to enhance water resilience are explored, adopting a territorial approach;

engaging the local actors in the process; and creating an articulation between the local territorial committee and the municipal institutions.

This thesis acknowledges the complexity of water supply systems in diverse geopolitical contexts, particularly in water-scarce areas that share common characteristics such as family agriculture and highly vulnerable water resources. One limitation of this research is the inability to extrapolate findings from one context to another. However, by working across these detailed small-scale cases, we have achieved a shared understanding of the water resilience approach and developed a methodology that could be replicated in other contexts. The primary objective of this research was to facilitate stakeholder collaboration and encourage discussions on water resilience in the context of climate change, ultimately co-generating accessible and comprehensible information regarding resilient RWSS.

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APPENDIX A – TABLE

Table – Overview of different methodological steps and tools used in the data collection and the workshops held in Brazil and Tunisia to co-define and characterize water resilience.

#	Steps	Methods	
1	Undertaking a historical analysis of trajectories of the RWSS in the four selected case studies	-Participatory observations -Participatory mapping	Semi-structured interviews (15 in Tunisia and 20 in Brazil) with key stakeholders: community health agent, water users association members, district engineers, and local water technicians.
2	Analysing the functioning of the RWSS	Field surveys	Surveys (30 in Tunisia and 40 in Brazil) to collect information at the household and community levels on: -Water users -Water uses (drinking, domestic, agricultural) -Infrastructures (lay-out, quality, location) -Resources (quantity, quality, location) -Rules of use (formal and informal) -Evolutions and adaptations in infrastructure and rules
3	Co-designing the RWSS Framework & Co-designing the RWSS trajectories	- Typology of RWSS -Participatory modeling: using a conceptual model as support for discussion	Workshops in Tunisia and Brazil Tunisia: -10 interviews to prepare the workshop -1 workshop with participants from the two communities -12 participants: 4 women and 8 men (6 from Ouled Salah, 6 from Ouled Om Hani)

			Brazil: -12 interviews to prepare the workshops -1 workshop in Santa Maria community 8 participants (4 women and 4 men) -1 workshop in in Varzea Do Meio community 8 participants (4 women and 4 men)
4 Co-defining and characterizeing the resilience of RWSS (Brazil-Tunisia) & creating a collective discussion space			
4.1	Identifying features to define water resilience with community members	Workshop with community members: -Identifying shocks, stresses and adaptations -using familiar words to describe features of resilience in the native language (Arabic in Tunisia and Portuguese in Brazil)	Workshops in Tunisia and Brazil Tunisia: -1 workshop with participants from the two communities -12 participants: 4 women and 8 men Brazil: -1 workshop in Santa Maria community; 8 participants (4 women and 4 men) -1 workshop in Varzea Do Meio community; 8 participants (4 women and 4 men)
4.2	Validating and proposing new features to define water resilience	-Using the results of previous workshops to validate the RWSS conceptual framework (NGOs, state services) -Reorganization of features linked to the 3 functions of the resilience of RWSS by the authors -Video presentation and group discussion	-1 workshop in Brazil with mixed stakeholders 20 participants from national and regional water institutes, research institutes, NGOs.

4.3	Co-identifying explanatory variables of water resilience	-Listing and debating explanatory variables by participants in three groups based on the three functions of water resilience and debriefing with the other groups at the end of the session	-1 workshop in Brazil with mixed stakeholders 29 participants (national and regional institutes, research institutes, NGOs, 6 representatives of both communities)
4.4	Validating the operational framework	-Validating the functions and the features together -Working on the explanatory variables in two groups and debriefing with the other group at the end of the session	-1 Workshop in Brazil with 15 members of rural community (2 women and 13 men)
5 Co-identifying multiscalar water resilience in hydrosocial territories in Forquilha catchment (Brazil)			
5.1	-Identifying nucleated settlements -Identify the hydrosocial territories	-Participatory observations -Participatory mapping -Field surveys	-Interviews -Confirming geographic limits using a drone -Hydrosocial narratives of male and female inhabitants in Forquilha -Participatory mapping of hydro-social territories with community members (presidents of the water association and farmers
5.2	to identify the factors of water resilience in different hydro-social territories	-Validate the trajectory of hydrosocial territories -Identify water resilience factors linked to the trajectory of hydrosocial territory	-Territorial workshop 12 participants (representatives of 9 communities of Forquilha catchment): 2 women and10 men Using the results of the fieldwork (maps and narratives) to identify the trajectory

			of hydrosocial territories in Forquilha catchment

APPENDIX B – THE CO-DESIGNED TYPOLOGY OF RWSS

Photo from a participatory workshop in Tunisia, Rihana to co-design the typology of water users

1) The Varzea do Meio (VDM) community:

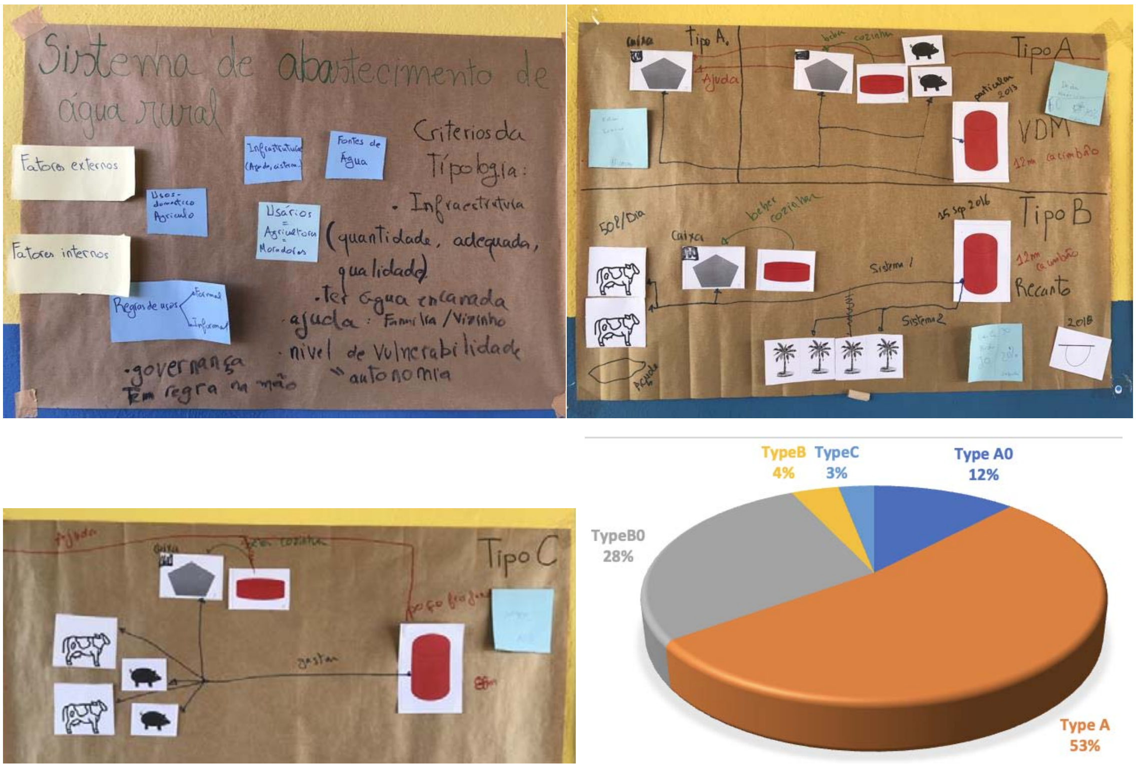


Figure. panels of Type A0, A, B and C of rural water users in the community VDM, with the estimated proportion of water users in the community.

The typology criteria:

-Having or not a piped water supply

-Infrastructure (quality, quantity, and adequacy)

-level of vulnerability

-help=solidarity

-governance

-autonomy

Type A: (47 households)

- They have piped water from the community network for general consumption and the pigs, and chickens (a small water tank on top of the house with a tap)
- They have a cistern for drinking and cooking & helps families of type A0

Type B0: (26 households)

- They have piped water from the community network for general consumption and cattle watering.

- They have a small water tank on top of the house with a tap
- They have a cistern for drinking and cooking

Type B: (4 households)

- They have piped water from the community network for general consumption and cattle watering.
- They have a small water tank on top of the house with a tap
- they have a private piped network for irrigation
- They have a cistern for drinking and cooking with small reservoirs for the cattle in the winter

Type C: (3 households)

- They have private water network for general consumption (a private well, a small water tank on top of the house with a tap)
- The have the same individual water network to water cattle, pigs, and other animals
- Help the neighbours who come to fetch water from the well with a bucket
- They have a cistern for drinking and cooking

2) The Santa Maria community

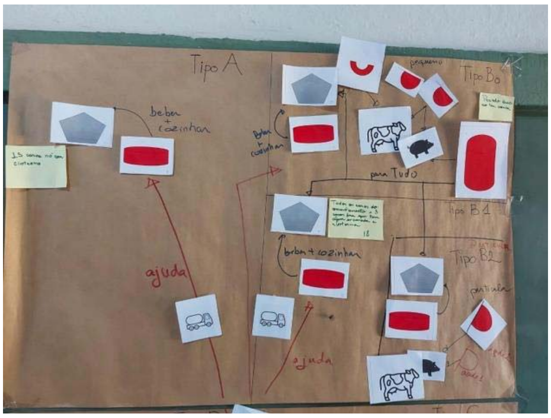
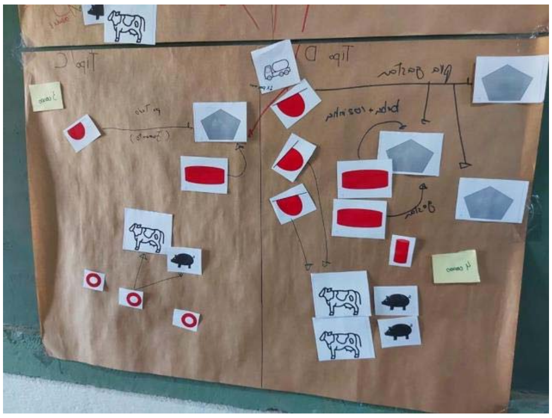
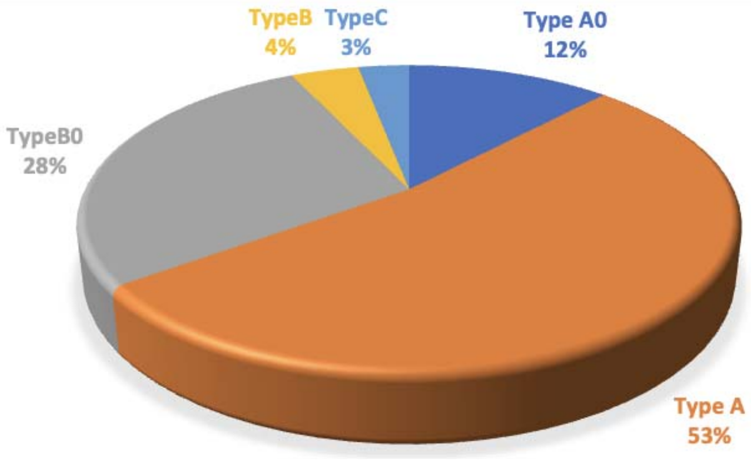



Figure. The panels of Type A, B0, B1, and B2 of rural water users in the SSM community, with the estimated proportion of water users in the community.



The typology criteria

Diversity of water infrastructures
Water Resources
Financial resources
Autonomy
Landownership
Aid network

Type A : (3 households)

- They have piped water
- They have a cistern and needs help from neighbors for domestic water

Type B0: (2 households)

- They have piped water from the community network for general consumption and the pigs, and chickens (a small water tank on top of the house with a tap)
- They have a cistern for drinking and cooking
- They have two communal dams for domestic water and livestock (collective use)

The household has another temporary water source for use during the winter (a shallow dug well)

Type B1: (11 households)

- They have piped water from the communal network (borehole) for general consumption and watering livestock. They have a small water tank with a tap
- They have a cistern for drinking and cooking
- They have two communal dams for domestic water and livestock (collective use)

Type B 2: (1 household)

- They have piped water from the communal network (borehole) for general consumption and watering livestock
- They have a small water tank with a tap
- They have a cistern for drinking and cooking
- They have two communal dams for domestic water and livestock (collective use)
- They have another permanent water source (2 small private dams for the cattle)

Type C: (3 households)

- does not have piped water
- has a cistern for drinking and cooking
- has permanent springs (2 private water sources for livestock and domestic use, private dams for domestic water and livestock)

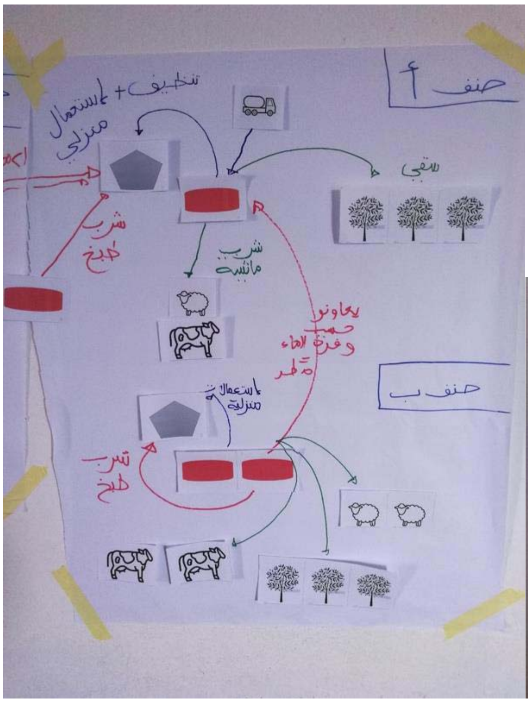
Type D: (4 households)

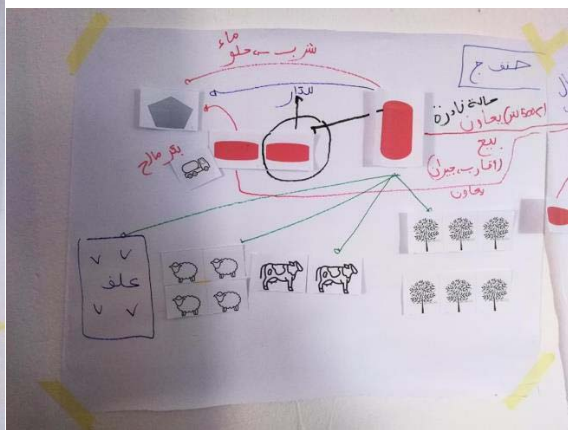
- They have piped water from a private network (big dam) for general consumption and livestock watering. They have a small water tank with a tap
- They have a cistern for drinking and cooking
- They have a cistern for domestic uses
- They have other permanent water sources (2 small dams and a private well for domestic water and livestock)
- helps types A, B0, B1, B2, and C with water from the big dam during the summer through the water tanker

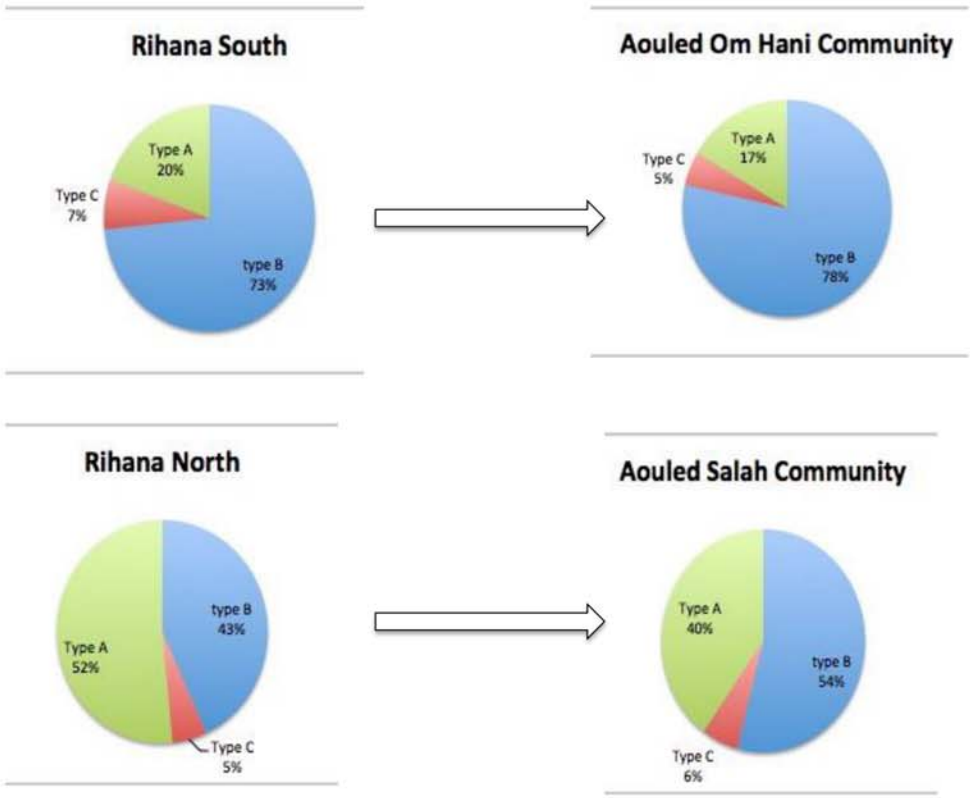
3) The Rihana northa and south communities

Criteria of the typology:

- Having or not a GDA water network
- Availability of water
- Solidarity
- Degree of vulnerability
- Diversity of water infrastructures







Type A :

- They are linked to the Groupe Development Agricole (GDA) network but do not receive water or are not even linked to the GDA network.
- They have a "Fesguia" cistern to store water purchased from private boreholes.

Type B:

- They are linked to the GDA network with continuous access
- They are linked to the GDA network with discontinuous access
- They have a "Fesguia" cistern, to store purchased water when there's a water supply failure
- They have a second rainwater harvesting cistern, and share water with some type A neighbors/extended family

Type c:

- They have a well for multiple uses
- They can be linked or not to the GDA network with continuous/discontinuous access
- They have a "Fesguia" cistern, to store purchased water when there is a water cut
- They have a second rainwater harvesting cistern, share water with some type A neighbors/extended family