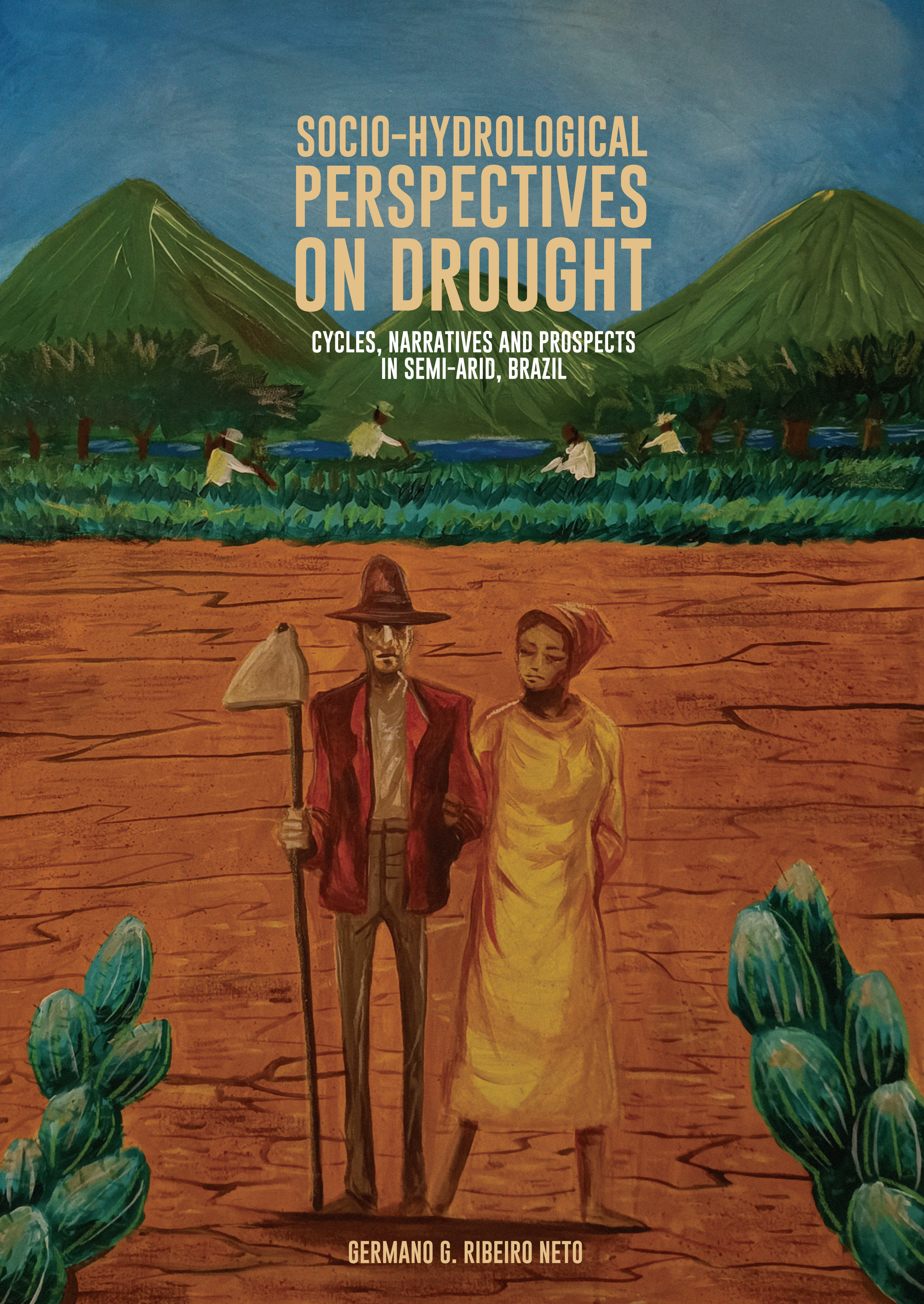

SOCIO-HYDROLOGICAL PERSPECTIVES ON DROUGHT

CYCLES, NARRATIVES AND PROSPECTS IN SEMI-ARID, BRAZIL

GERMANO G. RIBEIRO NETO

Propositions

1. Drought adaptation in semi-arid Brazil is a race against evaporation rather than water use .
(this thesis)
2. Drought assessment that does not consider socio-hydrological dynamics is not a drought assessment.
(this thesis)
3. High article publication charges are the biggest obstacle for global scientific inclusion.
4. Reviewing a scientific paper should be celebrated as much as publishing one.
5. The glaring wage gap between PhD candidates signals that colonizing processes persist.
6. Mandatory social activities are an ineffective strategy to improve the sociability of a group.
7. Mental health concerns are only respected after you've had a burnout.

Propositions belonging to the thesis, entitled

Socio-hydrological perspectives on drought: cycles, narratives and prospects in the semi-arid Brazil

Germano G. Ribeiro Neto

Wageningen, 24 April 2024

Socio-hydrological perspectives on drought: Cycles, narratives and prospects in semi-arid Brazil

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Socio-hydrological perspectives on drought: Cycles, narratives and prospects in semi-arid Brazil

Germano G. Ribeiro Neto

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Contents

Summary

Drought occurs in any climate and country, affects billions of people every year. Therefore, improving our understanding of drought is crucial for developing efficient mitigation practices and increasing drought preparedness. The realization that anthropogenic actions are causing profound changes in the Earth's systems has raised questions about how humans are contributing to the emergence and propagation of droughts. This thesis addresses these issues and presents research questions (Chapter 1) that, once addressed, contribute to improving the understanding water-human interaction in the context of droughts. These questions are addressed in Chapters 2 to 4, in which different methods are presented that analyse the socio-hydrological dynamics of the study area with the final aim to improve the understanding of how they influence the emergence and propagation of drought events.

This thesis focuses specifically on the semi-arid region of Brazil, focusing on analysing the socio-hydrological dynamics that influence the emergence and propagation of drought events in this region. The semi-arid region of Brazil, particularly the state of Ceará, serves as a suitable study area due to its diverse landscapes having both natural preserved and highly human modified areas, a long history of drought events, and extensive hydro-meteorological monitoring network. First, the influence of the interactions between small and large reservoirs on drought emergence was investigated. Next, a detailed analysis considers the uses of water and productive activities in the region, addressing how socio-hydrological dynamics impact the emergence and propagation of drought. Finally, a qualitative approach was used to explore individual perspectives on the impacts of drought, incorporating socio-hydrological principles and human behavioural theories.

Chapter 2, describes the influence of a Dense Network of unmonitored and informal small Reservoirs (DNR) on the onset of droughts in strategic reservoirs of the Riacho do Sangue watershed in the semi-arid region of Brazil. Results are based on an innovative method called “Drought Cycle Analysis” (DCA). DCA was used to analyze the concomitance of precipitation and water storage deficit and associates this with four hydro-meteorological stages in which a drought may evolve over time: Wet period, meteorological drought, hydro-meteorological drought, and hydrological drought. The volume stored in small reservoirs was estimated based on the combination of surface water extent (collected by satellite imagery) and an empirical equation. This methodological approach revealed that the unmonitored small reservoirs induced and modified drought events, extending the duration of

hydrological drought on average by 30%. This extended duration can even double for specific drought events. Drought Cycle Analysis has proved to be useful for drought monitoring and for comparing the evolution of various drought events. DCA is also potentially applicable to account for the effects the effects of drought in optimizing water resource management in large reservoirs. The results of this chapter highlight the importance of including small reservoirs in the development of water resource management strategies in regions susceptible to droughts.

In **Chapter 3**, the influence of a DNR on the emergence and intensification of drought impacts at the catchment scale was investigated, along with its local social benefits, using a medium-sized catchment in the semi-arid region of Brazil as a case study. To this end, the Socio-Hydrological-Agricultural-Reservoir (SHARE) model was developed. SHARE allows for simulating hydrological processes, agricultural yield and water use by rural households. The findings presented in this chapter revealed that the DNR prolongs the hydrological effects of drought in a large reservoir located at the outlet of the study catchment. Despite disrupting runoff connectivity, a DNR also plays a crucial role in local drought impacts mitigation. Small reservoirs can significantly increase local agricultural production, potentially up to five times compared to scenarios without them. The outputs of the SHARE model also indicate a considerable reduction in the need for emergency water supply by water trucks due to the presence of small reservoirs. These results highlight the importance of a balanced approach in implementing public policies on drought management, considering both the local benefits of small reservoirs and the possible downstream impacts.

Chapter 4 describes how individuals' perceptions of drought impacts emergence are intrinsically entangled in drought occurrence and evolution. This was inspired by interviews conducted during fieldwork in Brazil, during which we observed how the impacts of drought were felt by people who had been exposed to a multi-year drought and how their perceptions of these impacts changed over time. We found that Prospect theory, a behavioural economic theory that is generally applied to explain decision-making processes under uncertainty, has explanatory power in relation to what we observed in the field. An interdisciplinary approach was proposed to improve the understanding of drought impact emergence using Prospect theory. When employing Prospect theory in drought context, its impacts are considered failed welfare expectations (“prospects”) due to water shortage. This approach contributed to explain socio-hydrological phenomena, including reservoir effects, and helps bridge natural and social science perspectives, fostering integrated drought management with considering the local context.

This research has shown that droughts can be understood as socio-hydrological phenomena resulting from complex interactions between human actions and the environment. When analysed from an individual perspective, human actions play a crucial role in triggering drought events, being shaped by the choices made by individuals to achieve their desired levels of welfare. This influence, referred to as "local influence" in this study, can trigger unwanted consequences (reduced food and water security through environmental modifications), increasing the susceptibility of the individual themselves and others to experience droughts in the future. In addition, local influence on other individuals, usually located downstream, was categorized as "remote influence". This interconnection between individual actions and repercussions on a wider scale highlights the complexity of hydrological phenomena and underscores the importance of integrated approaches to dealing with drought-related issues. This perspective calls for a definition of drought that highlights the importance of the human component in its emergence and propagation. To this end, this thesis presents a definition that defines drought as an "*exceptional period of water shortage experienced or caused by humans*". The findings of this thesis are in line with other studies that reinforce the inadequacy of traditional drought assessment and monitoring methods in the face of complex contemporary demands on water resources. To ensure future water security, it is imperative to re-evaluate the conventional approach to framing droughts.

Summary (Portuguese)

Secas ocorrem em qualquer clima e país, afetando bilhões de pessoas a cada ano. Portanto, aprimorar nossa compreensão secas é crucial para desenvolver práticas eficientes de mitigação e preparação. A percepção de que ações antropogênicas estão causando mudanças profundas nos sistemas da Terra levantou questões sobre como os humanos estão contribuindo para o surgimento e propagação das secas. Esta tese aborda esses assuntos e apresenta perguntas de pesquisa (Capítulo 1) que, uma vez respondidas, contribuem para melhorar a compreensão da interação água-humanos no contexto das secas. Essas questões são abordadas nos Capítulos 2 a 4, nos quais diferentes métodos são apresentados para analisar as dinâmicas socio-hidrológicas da área de estudo, com o objetivo final de aprimorar a compreensão de como elas influenciam o surgimento e a propagação de eventos de seca.

Esta tese concentra-se especificamente na região semiárida do Brasil, analisando as dinâmicas socio-hidrológicas que influenciam o surgimento e a propagação de eventos de seca nessa região. A região semiárida do Brasil, em particular o estado do Ceará, serve como uma área de estudo adequada devido às suas paisagens diversas, que incluem áreas naturalmente preservadas e como também altamente modificadas pelo ser humano, uma longa história de eventos de seca e uma extensa rede de monitoramento hidrometeorológico.

Primeiramente, investigou-se a influência das interações entre pequenos e grandes reservatórios (popularmente conhecidos como "açudes"). Em seguida, uma análise detalhada considerou os usos da água e as atividades produtivas na região, abordando como as dinâmicas socio-hidrológicas impactam o surgimento e a propagação da seca. Por fim, uma abordagem qualitativa foi utilizada para explorar as perspectivas dos individuos sobre os impactos da seca, incorporando princípios socio-hidrológicos e teorias comportamentais humanas.

No **Capítulo 2**, descreve-se a influência de uma Densa Rede de (pequenos) Reservatorios (DRR) no surgimento de secas em reservatórios estratégicos na bacia do Riacho do Sangue na região semiárida do Brasil. Os resultados baseiam-se em um método inovador chamado "*Drought Cycle Analysis*"(Analise de Ciclo de Seca em português, ACS) introduzido neste capítulo. O ACS foi usado para analisar a concomitância de déficits de precipitação e de armazenamento de água, associando isso a quatro estágios hidrometeorológicos nos quais uma seca pode evoluir ao longo do tempo: período úmido, seca meteorológica, seca hidrometeorológica e seca

hidrológica. O volume armazenado em pequenos reservatórios foi estimado com base na combinação de informações sobre a extensão da água superficial (coletada por imagens de satélite) e uma equação empírica. Essa abordagem metodológica revelou que os pequenos reservatórios não monitorados induziram e modificaram eventos de seca, estendendo a duração de seca hidrológica em média em 30%. Essa duração estendida pode dobrar para eventos específicos de seca. A ACS mostrou-se útil para o monitoramento e para comparação da evolução de diferentes eventos secas. Além do mais, esse método também é potencialmente útil para considerar os efeitos da seca na otimização do gerenciamento de recursos hídricos em grandes reservatórios. Os resultados deste capítulo destacam a importância de incluir pequenos reservatórios no desenvolvimento de estratégias de gestão de recursos hídricos em regiões suscetíveis a secas.

No **Capítulo 3**, investigou-se a influência de uma DRR no surgimento e intensificação dos impactos da seca em escala de bacia hidrográfica, juntamente com seus benefícios sociais locais. Para isso, foi desenvolvido o modelo "*Socio-Hydrological-Agricultural-Reservoir*" (SHARE). O SHARE permite simular processos hidrológicos, produtividade agrícola e uso de água por famílias rurais. Os resultados apresentados neste capítulo revelaram que o DRR prolonga os efeitos hidrológicos da seca em um grande reservatório localizado exutório da bacia hidrográfica de estudo. Apesar de interromper a conectividade do escoamento superficial, a DRR também desempenha um papel crucial na mitigação dos impactos locais da seca. Pequenos reservatórios podem aumentar significativamente a produção agrícola local, potencialmente até cinco vezes em comparação com cenários sem eles. Os resultados do modelo SHARE também indicam uma redução considerável na necessidade de abastecimento de água de emergência por caminhões-pipa devido à presença de pequenos reservatórios. Esses resultados destacam a importância de uma abordagem equilibrada na implementação de políticas públicas de gestão de secas, considerando tanto os benefícios locais de pequenos reservatórios quanto os possíveis impactos a jusante.

O **Capítulo 4** descreve como as percepções dos indivíduos sobre o surgimento dos impactos da seca estão intrinsicamente entrelaçadas com a ocorrência e evolução da seca. Isso foi inspirado em entrevistas realizadas durante o trabalho de campo no semi-arido do Brasil. Nessas entrevistas foi observado como os impactos da seca foram sentidos por pessoas que foram expostas a esse desastre durante vários anos consecutivos e como suas percepções desses impactos mudaram ao longo do tempo. Descobrimos que a teoria dos prospectos, uma teoria econômica comportamental geralmente aplicada para explicar processos de tomada de decisão sob incerteza, tem poder explicativo em relação ao que foi observado em campo. Uma abordagem interdisciplinar foi proposta para aprimorar a compreensão do surgimento do impacto da seca usando essa teoria. Ao empregar a teoria dos prospectos no contexto da seca, seus impactos são considerados como expectativas de bem-estar frustradas ("prospectos") devido à escassez de água. Essa abordagem contribuiu para explicar fenômenos socio-hidrológicos, incluindo efeitos de reservatórios, e ajuda a unir perspectivas das ciências naturais e sociais, promovendo a gestão integrada de secas com consideração para o contexto local.

Esta tese demonstrou que as secas podem ser compreendidas como fenômenos socio-hidrológicos resultantes de interações complexas entre as ações humanas e o ambiente. Quando analisadas a partir de uma perspectiva individual, as ações humanas desempenham um papel crucial no surgimento de eventos de seca, sendo moldadas pelas escolhas feitas pelos indivíduos para atingir seus níveis desejados de bem-estar. Essa influência, denominada "influência local" neste tese, pode desencadear consequências indesejadas (como redução da segurança alimentar e hídrica por meio de modificações ambientais), aumentando a suscetibilidade do próprio indivíduo e de outros a vivenciar secas no futuro. Além disso, a influência local sobre outros indivíduos, geralmente localizados a jusante, foi categorizada como "influência remota". Essa interconexão entre ações individuais e repercussões em uma escala mais ampla destaca a complexidade dos fenômenos hidrológicos e evidencia a importância de abordagens integradas para lidar com questões relacionadas a secas. Essa perspectiva exige uma definição de seca que destaque a importância da componente humana em seu surgimento e propagação. Para tanto, esta tese apresenta uma definição que enquadra eventos de seca como um *"período excepcional de escassez de água experimentado ou causado por humanos".* As descobertas desta tese estão alinhadas com outros estudos que reforçam a inadequação dos métodos tradicionais de avaliação e monitoramento de secas diante das complexas demandas contemporâneas sobre os recursos hídricos. Para garantir a segurança hídrica no futuro, é imperativo reavaliar as abordagens convencionais aplicadas as secas.


01

Chapter 1

Introduction

"Agora é encararmos o destino
E salvarmos o que resta
É aprendermos com o Nordestino
Que pra seca se adestra"

Now we must confront our fate
To salvage what's left, it's getting late
Learn from Nordestinos, a crucial trait
In taming drought, we find our state.

(Lenine)

1.1 General Introduction

Turning on a tap and having clean, running water in the quantity and time required, an ordinary action for most readers of this thesis, as well as being a privilege, is a complex engineering achievement and a significant scientific advancement. Even so, at least two-thirds of the global population experience water insecurity at least one month of the year (Mekonnen and Hoekstra, 2016). To ensure reliable water availability, it is necessary to understand the processes of the hydrological cycle that determine the location, occurrence and maintenance of the water resources to be exploited to meet water demand. Natural spatial and temporal variability in hydrological processes often do not provide favorable conditions for the effective exploitation of water resources, therefore requiring the construction of infrastructure, such as reservoirs and deep wells.

The relationship between water availability and water demand defines the level of water security of a population. A period of exceptional lack of water compared to normal conditions defines the occurrence of a drought (Van Loon et al., 2016a). This drought definition was presented in the context of "Drought in the Anthropocene", which follows the idea that the world is now in the "Anthropocene": a new era that is characterized by the profound changes that anthropogenic actions have imposed on hydrological, atmospheric, ecological and geological systems (Benner et al., 2021). The "Drought in the Anthropocene" concept highlights the importance of human actions in the emergence and modification of drought events (Van Loon et al., 2016b), which contrasts with approaches that define droughts solely as a hydro-meteorological phenomenon or natural hazard different from anthropogenic water shortage (Hall et al., 2022; Van Loon et al., 2016a).

Drought in the Anthropocene fits the field of socio-hydrology. Socio-hydrology underlines the importance of the human component in the hydrological cycle, not only in drought assessment studies, but in all hydro-meteorological disasters (Sivapalan et al., 2011). In this thesis, the definitions of disaster and natural hazard follow those proposed by Monte et al., (2020). Natural hazard is a naturally occurring phenomenon that has the potential to harm the welfare of communities, populations or individuals and has a certain probability of occurring. A disaster is the result of interactions between hazards (natural or not) and individuals, communities or systems in a given area that causes disruption to social welfare and requires external assistance. This interdisciplinary field considers that people interact with the hydrological system in various ways (e.g. water consumption and landscape modification), which has the potential to alter hydrological processes which in turn can influence human actions. In other words, human actions are constantly co-evolving with the processes of the hydrological cycle (Di Baldassarre et al., 2018; Ross and Chang, 2020; Rusca and Di Baldassarre, 2019; Sivapalan et al., 2011).

In this thesis, drought is defined as a disaster resulting from an exceptional period of lack of water. This exceptional lack of water has both a physical and human component. The physical component is the natural hazard (e.g. meteorological variability) that has the potential to reduce the water availability of a region. An intuitive example of such a natural hazard is a long period of below-normal precipitation, which can lead to a reduction in water availability and can finally result in a lack-of-water situation: a drought. The human components are the social characteristics of the population that determines water use, and anthropogenic actions that have the potential to alter the inflow, outflow and storage of water. An example is the construction of reservoirs, that can positively influence water availability during below-normal precipitation. As such, drought can arise, further develop or be alleviated due to human influence (Van Loon et al., 2016b). In summary, the idea that drought is purely a hydro-meteorological disaster is misleading, when the human component can be more important than the physical one.

The societal impacts of drought events vary considerably around the world and over time. Drought causes severe economic damage because its impacts can affect production chains in locations outside of the geographical area where the drought is considered to be occurring (Huynh et al., 2020). Europe has been affected by around 45 major drought events in the 20th century, resulting in more than $27.8 billion in losses. To date, it is estimated that 17% of the European population is affected by droughts (European Environment Agency., 2017). In the same period on the African continent, more than 300 drought events were recorded (Wallemacq and Guha-Sapir, 2015) with economic losses estimated at 6.6 billion dollars (Ayugi et al., 2022). In the USA, agricultural losses due to 31 drought events that occurred between 1980 and 2023 caused an approximate loss of 344 billion dollars (NOAA-NCEI, 2023). In Brazil, between 2012 and 2016, an estimated 33.4 million people were affected by drought and the cumulative damage was estimated to be about 30 billion dollars (Marengo et al., 2017). It is estimated that, worldwide around 1.4 billion people were affected by drought events between 1995 and 2015 and 10 million died in the 20th century from hunger or diseases related to poor water quality due to droughts (Wallemacq and Guha-Sapir, 2015).

These cases demonstrate the importance of better understanding droughts in order to improve the ways in which they are managed with the aim to minimize their impact on society. Therefore, it is important to expand our understanding of the evolution of droughts and how they change in space and time. Socio-hydrology might help to explain, for example, why natural hazards do not affect a location in the same way at different times. Such an understanding can contribute to the assessment of the causes and consequences of a drought event and how they change over time. This is crucial to improve water resources management and to contribute to the development of measures to prevent and mitigate the impacts, guaranteeing human development and water security (Pande and Sivapalan, 2017). Yet, it remains underexplored how to use socio-hydrological concepts to improve drought assessment, taking human influence explicitly into consideration.

This thesis explores the potential of a socio-hydrological perspective for drought assessment in order to contribute to filling the knowledge gap mentioned above. To this end, the semi-arid region of Brazil was used as its study area, specifically the state of Ceará, which has a long history of intense drought events (Marengo et al., 2017). To explore this, Section 1.2 begins with a brief presentation of the study area, followed by an overview of drought management (Section 1.3) and assessment (Section 1.4). This converges towards the knowledge gap, main objective, research questions that are addressed in this thesis and research approach (Sections 1.5, 1.6, 1.7), followed by the thesis outline (Section 1.8). Figure 1.1 shows a flowchart connecting the topics covered in this chapter to the knowledge gap addressed in this thesis.

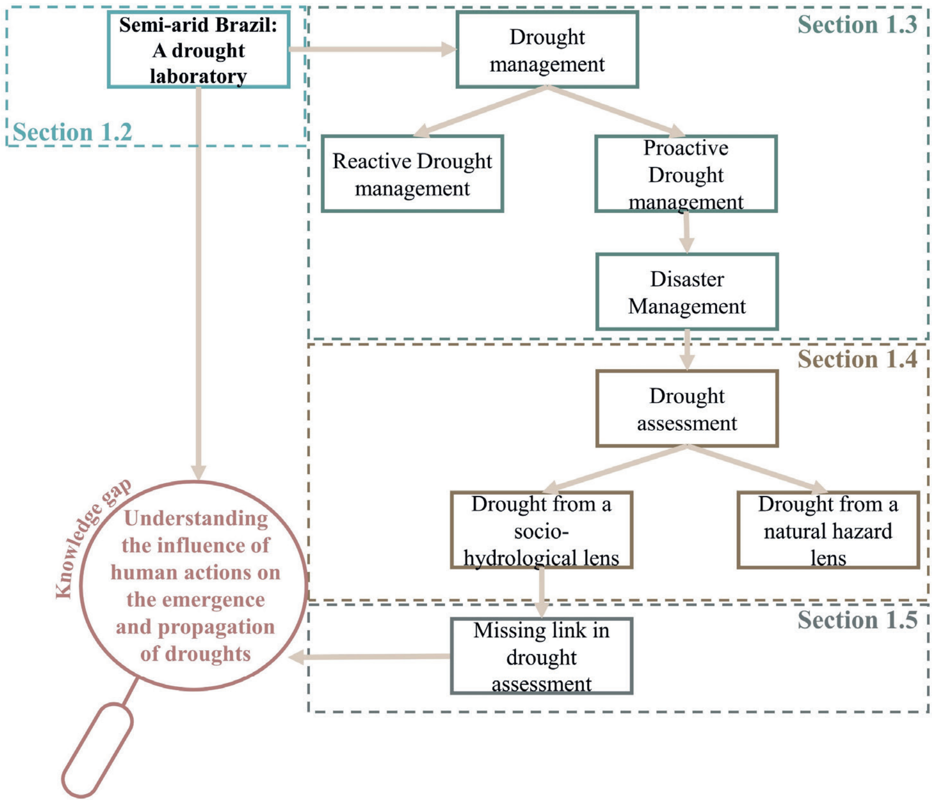

Figure 1.1 -Flowchart of the knowledge gap addressed in this thesis.

1.2 Semi-arid Brazil: A drought laboratory

Semi-arid Brazil covers around 13.2% (1128697 km²) of Brazil's territory and with a population of around 28 million inhabitants, it is one of the most densely populated dryland regions in the world (SUDENE, 2017). The rainfall regime occurs over 4 months of the year with high spatial and inter-annual variability, with an annual average of 750 mm (Martins & Reis Junior, 2021). The high temperatures and low humidity cause potential annual evapotranspiration of over 2000 mm, while the soils with low water storage capacity create a lack of large aquifers and only intermittent rivers (Magalhães, 2017).

The semi-arid region of Brazil is frequently affected by drought events, with the oldest record dating back to the 16th century (Marengo et al., 2017). The low availability of water in the region has resulted in a culture of reservoir construction, which for centuries has been the main strategy for adapting to the region's droughts (Campos, 2014). The "Cedro dam" built in Ceará state in 1884 can be seen as an inaugural milestone in this culture, as it is considered to be the first major modern hydraulic infrastructure in South America (IPHAN, 2023). Since then, the construction of reservoirs has become the predominant way of dealing with droughts. Many other public reservoirs have been built, as well as countless small private reservoirs. The latter generally have a surface water area of less than 5ha, are built informally and are not monitored, nor are any technical details known about them (Malveira et al., 2012a). Therefore, for many areas in the semi-arid region, the exact number of reservoirs is unknown. Ceará is one of the few states of Brazil that systematically identified the location of these small reservoirs (See Chapter 2). Figure 1.2 shows the location of the semi-arid region, Ceará state and also the density of small reservoirs in this state.

The small reservoirs are built to supply the local population and support the development of family farming activities, which account for 80% of agriculture of this region (Marengo et al., 2022). The region's production method is commonly associated with “slash and burn” practices, in which native vegetation is removed and then the land is "cleared" through controlled burns to make way for usually temporary crops (e.g. maize and beans), pastures and livestock (Vieira et al., 2018). These environmental modifications are one of the main causes of the desertification processes underway in the semi-arid region (Vieira et al., 2020). For example, the areas adjacent to these small reservoirs are used for planting temporary crops (e.g. maize, beans and rice), since the reservoirs increase the soil's humidity, supporting the development of agriculture. The use of irrigation systems is not common in the region.

The semi-arid region of Brazil, especially the state of Ceará, has a set of characteristics that make it a suitable drought laboratory to analyse the human influence on the emergence of drought. First, this is a region where you can still find vast landscapes that have undergone little anthropogenic modification as well as highly modified ones. Ceará state not only has a long history of drought events, but also, because of that, a vast hydro-meteorological monitoring network. Finally, the dense network of (small) reservoirs (DNR) in Ceará (Figure 1.2c) has been the subject of studies trying to understand the influence of these structures on the region's hydrological processes (Malveira et al., 2012a; Mamede et al., 2018, 2018). Yet, the influence of the interactions between the water use from these structures and their very presence on the emergence and propagation of drought events remains underexplored.

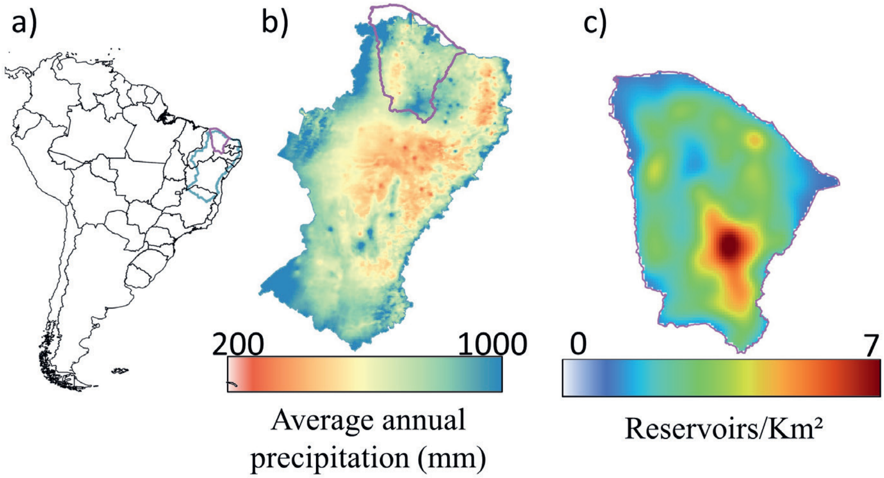

Figure 1.2 Study area. a) South American continent and the location of the study area indicated. The blue and purple polygons indicate the semi-arid region of Brazil and Ceará state respectively. b) Average annual precipitation (1981 to 2011) using the Climate Hazards Center InfraRed Precipitation with Stations (CHIRPS; Funk et al., 2015) dataset (available at https://www.chc.ucsb.edu/data, last access: 18 December 2023). c) Concentration of reservoirs in Ceará.

1.3 Drought management

Drought management refers to the planning, coordination and systematic implementation of measures to mitigate the impacts of drought and to prevent water shortage situations (Funk and Shukla, 2020). In general, managing drought can be divided into two types of approaches: reactive and proactive (Wilhite and Pulwarty, 2018). Actions related to drought management can also be seen from the perspective of crisis management and risk management. Although opposing in approach, they complement each other in the general panorama of disaster management proposed by the National Mitigation Centre at the University of Nebraska-Lincoln, which is called the disaster management cycle (Wilhite and Pulwarty, 2018) and is shown in Figure 1.3. This concept describes a continuous cycle of disaster management that encourages a shift from an exclusively crisis-oriented approach to a holistic risk-reduction strategy that prepares for and adapts to the evolving natural hazards related to disasters, ensuring a more effective and sustainable approach to their management (Wilhite, 2019).

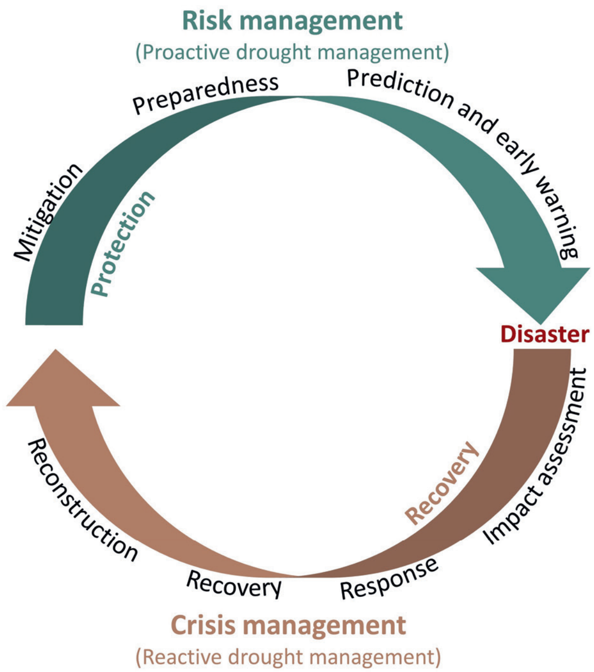

Figure 1.3 - The Cycle of Disaster Management (Wilhite and Pulwarty, 2018).

Reactive drought management implies dealing with drought based on temporary or short-term actions, triggered only when the drought is already consolidated. It can therefore also be considered as crisis management. Actions are usually a post-impact reaction and have been inopportune, less effective, poorly coordinated and disintegrated (Walker et al., 2022; Wilhite, 2019; Wilhite and Pulwarty, 2018). Reactive drought management does not necessarily aim at contributing to reducing the vulnerability or increasing the resilience of commonly affected populations, since response actions focus on mitigating impacts once they are already happening - rather than preventing them.

In Brazil, especially in the semi-arid region, reactive drought management is related to the prevalence of government strategies centered on welfare policies and hydraulic investments mainly related to the construction of reservoirs (Campos, 2014). These approaches mostly focus on increasing water supply as a response to the impacts of drought and are locally recognized as the "fighting against drought paradigm" (Cavalcante et al., 2022). The idea of solving water shortages by increasing water supply may seem reasonable, but this strategy largely neglects the human component of drought, for instance by not considering the growth in demand and the co-evolution between hydrological processes and society. Simply expanding water availability, without changing consumption patterns, promotes a continuous increase in demand that can eventually exceed the new supply, generating a vicious cycle between increasing supply and growing demand. This results in greater dependence on the new infrastructure and greater vulnerability to future drought events (Di Baldassare et al., 2018).

In response, proactive drought management has emerged, prioritizing preventive and preparedness measures over investments in infrastructure. The core idea of proactive drought management is to mitigate the impacts of drought before the situation intensifies or even occurs. Drought management based on the disaster management cycle can be summarized into four essential stages: Mitigation, preparedness, response and recovery (Gutiérrez et al., 2014). In the mitigation stage, the aim is to reduce vulnerability and strengthen the population's resilience. An example is the implementation of public water conservation policies or the adoption of crops that are more resistant to water stress (Marengo et al., 2022; Medeiros and Sivapalan, 2020b). The preparation stage is intrinsically linked to strategic planning carried out before the drought occurs, such as the development of contingency plans. The response focuses on immediate relief actions for affected populations as soon as drought strikes. This can be achieved, for example, through cash transfer programs or emergency water supplies (Campos, 2015; Marengo et al., 2022). The recovery phase covers measures applied after the drought has occurred, aimed at restoring all aspects of the impacts on the affected areas. An example of this are credit-line programs to facilitate the purchase of animals in cases of severe impacts on the agricultural sectors, contributing to the economic and societal recovery of the affected communities.

Although the disaster management cycle is a methodological framework aimed to minimize the impacts of drought, there is still a persistence on the part of governments around the world to deal with drought in a reactive rather than proactive manner (Wilhite, 2019). This is mainly due to a lack of information on the cost-benefit analysis of abandoning reactive practice in favor of a pro-active practice: there is a reluctance to make costly investments when there is uncertainty about the benefits of these investments (Ding et al., 2011). Therefore, it is crucial to conduct studies aimed to strengthen measures related to the key stages of proactive drought management. This will help underscore and improve the effectiveness of such approach.

Successful drought management from a proactive perspective depends on efficient drought monitoring and early warning systems (Nhamo et al., 2019) since it transversely reaches the mitigation, preparedness and response stages. Drought monitoring in turn depends on in-depth knowledge of the causes, consequences, thresholds and characteristics related to drought events in a given region, which is intrinsically related to drought-assessment methodologies. The development and application of comprehensive and holistic drought assessment methodologies are therefore crucial to effectively support (proactive) drought management strategies.

1.4 Drought assessment

Drought assessment aims to explore the causes, consequences and characteristics of drought. This process is essential for effective management of water resources, agricultural planning and the development of mitigation strategies (Paredes-Trejo et al., 2017). Drought assessment is part of the methodological framework related to drought-risk reduction and is directly part of the monitoring and prediction, impact assessment and other stages of the cycle of disaster management presented in Figure 1.3.

1.4.1 Drought through a natural hazard lens

Drought has typically been analyzed as the propagation of a precipitation deficit throughout the hydrological cycle (Lloyd-Hughes, 2014). Associated with this, typologies of drought have emerged based on the main impacts that the precipitation deficit causes at different stages of the hydrological cycle (Ding et al., 2021; Feldpausch et al., 2016; Sheffield and Wood, 2011; Wilhite and Glantz, 1985). An anomalous reduction in precipitation is referred to as a meteorological drought (McKee et al., 1993). When this reduces soil moisture and affects vegetation, especially crops, it is called agricultural or soil moisture drought (Liu et al., 2016). When the reduction in soil moisture affects the recharge of water bodies, it is termed a hydrological drought (Van Loon, 2015). This classification of drought makes it logical to develop methodologies to assess each drought type separately.

These drought types have commonly been assessed by monitoring standardized indices. These indices indicate in a standardized way and for different time scales how far a given (usually hydro-meteorological) variable is from the climatological average (Laimighofer and Laaha, 2022; McKee et al., 1993). These indices are associated with thresholds that are used to indicate the duration of drought events as well as their intensity and magnitude (Brito et al., 2018; Dracup et al., 1980). The ease and practicality of this approach has made it a reference in the study of drought assessment (World Meteorological Organization, 2012). The popularization of standardized drought indices was also reinforced by the significant advances in remote sensing technologies observed at the end of the 20th century (West et al., 2019). Several space missions launched in recent decades have enabled the systematic collection of meteorological, hydrological, and surface condition data directly providing insights on the onset, development, and propagation of drought events (AghaKouchak et al., 2015). Remote sensing represented a breakthrough for the field of drought assessment since it opened up the possibility of studying isolated and data-poor regions.

Remote-sensing products combined with drought-assessment methodologies based on standardized indices have enabled the creation of large-scale Drought Monitoring and Early Warning Systems (DEWS) (e.g. US National Drought Mitigation Center, Princeton Flood and Drought Monitors, Brazilian Drought Monitors, European Drought Monitor). This marked a major advance for proactive drought management based on risk reduction policies (see section 1.2). DEWS can provide strategic information for decision-makers and help develop more effective mitigation measures (Cunha et al., 2019). However, the innovation and success of systematic drought monitoring promoted by the DEWS, based on monitoring hydro-meteorological variables through standardized indices, may also have contributed to overlooking the human component in the emergence and propagation of drought events. This is evidenced by the mismatches often observed between the identification of drought events based on hydrometeorological indicators and their actual impacts (Kchouk et al., 2023). Many of the DEWS do not monitor drought impacts, but instead associate the probability of experiencing drought impacts linearly with the size of the hydrometeorological anomaly (Kchouk et al., 2022).

Drought assessment methodologies based on standardized indices have served their purpose in a context of a less interdisciplinary environment with a lack of information, in which scientists and practitioners often only had access to hydro-meteorological information. However, the methodological limitations of standardized indices are already evident in their very designation. To standardize a hydro-meteorological variable is to remove its interpretation from the local context. For example, the same (standardized) precipitation deficit will not necessarily result in impacts of the same magnitude when comparing different regions or the same region over different periods. The focus on the physical component of drought events leads to drought being interpreted as a natural phenomenon or a natural hazard inherent to any climatic region. This way of thinking may make sense when seeking to understand the physical principles related to the emergence and propagation of natural hazards related to drought events, but it is insufficient to answer relevant questions related to common and growing problems in today's society concerning water security issues.

1.4.2 Drought through a socio-hydrological lens

The socio-hydrology timeline can be considered to have begun in the mid-1970s when Ehrlich et al. (1971) published one of the first studies that considered the human impact on water availability. In that same decade, Falkenmark (1977) proposed the concept of "hydro-sociology." This field differs from socio-hydrology as it focuses on the analysis of social aspects of water resources management, concentrating on the social dimension of water use (Xia et al., 2022). Based on these ideas, Integrated Water Resources Management emerged in the 1990s with the aim of developing comprehensive, holistic, sustainable, and equitable water resources management (Savenije and Van Der Zaag, 2008). IWRM represented a major advance in water resources management as it began to consider the potential impact of anthropogenic actions on hydrological processes, but it did so in a static way through scenarios.

In 2011, Sivapalan et al., (2011) presented the concept of socio-hydrology that advances in relation to the IWRM concepts by considering that anthropogenic dynamics co-evolve with the processes of the hydrological cycle, and that this is crucial to understanding the complex relationships between water and society. This discipline is also influenced by more recent interdisciplinary frameworks such as socio-ecological systems and complex systems science (Adger, 2006; Cosens et al., 2018; Folke, 2010, 2006).

When a socio-hydrological lens is applied to drought events, which was done in this thesis as clarified in Section 1.1, the impacts generated by drought are the result of both hydroclimatic and anthropogenic factors (e.g. human decisions, water management policies and socio-economic dynamics). It is therefore necessary to include aspects beyond physical characteristics in the drought assessment, such as the perceptions of the affected communities, water use practices, and mitigation policies and strategies (Xia et al., 2022). This cannot be achieved through traditional methodologies based purely on standardized indices (Section 1.4.1).

Socio-hydrology also tries to identify so-called socio-hydrological phenomena, which are unintended patterns that arise from human-water systems feedbacks (Sivapalan and Blöschl, 2015). Such phenomena have been studied through the system archetype concepts, stemming from systems thinking. Systems thinking presents archetypes that summarize common behaviors observed in systems from different areas. This discipline applies a holistic approach to analyzing complex systems. The cause and effect relationships and feedback between the components of the system as a whole, are taken into account, instead of analyzing each component in isolation (Zare et al., 2019).

Among the various system archetypes applied in socio-hydrology, "Fixes that backfire" stands out for explaining socio-hydrological phenomenona directly related to the occurrence of droughts (Di Baldassare et al., 2018). This archetype describes situations in which immediate solutions, which alleviate the symptoms of a problem without addressing the root causes, create a cycle of poor balance that will lead to unintended consequences (Gohari et al., 2013). The quick fix triggers a stronger reinforcing cycle, causing the problem to reappear in the future in an aggravated form, often with challenging and unintended consequences (Bahaddin et al., 2018).

When "Fixes that backfire" are applied to situations in which water shortages are solved only by expanding infrastructure (a short-term solution) in the absence of demand control, water use tends to increase (positive reinforcement). In the long term the water demands can eventually outweighing the original benefits of expanding water availability. The consequence of this is that, in the long term, there may be greater vulnerability to droughts, since a situation of water scarcity would have more significant impacts due to increased dependence on infrastructure (the “Reservoir Effect”, Di Baldassare et al., 2018).

The application of systems thinking to drought assessment contributes to a better identification and representation of the socio-hydrological dynamics acting on the hydrological system. This facilitates both the explanation and identification of socio-hydrological phenomena related to droughts. Furthermore, it contributes to the main processes to be considered in methodological frameworks based on socio-hydrological simulation.

Recent work has advanced approaches to incorporate human influence into drought risk assessment studies from a socio-hydrological simulation perspective (Streefkerk et al., 2023; Van Oel et al., 2018; Wens et al., 2019, 2021). However, these initiatives still face limitations, especially with regard to data availability, computational cost of socio-hydrological models, more detailed representation of socio-hydrological dynamics, and incorporation of local context. System thinking could contribute to each of these. As such, incorporating socio-hydrology into drought assessment through the inclusion of the intricate relationship between human actions and society in catchment context (socio-hydrological dynamics) is a remaining challenge.

1.5 Knowledge gap in drought assessment

Drought, a disaster of billions, whether in the number of people affected or annual economic losses, shows that it is not always easy to deflect or prepare for something that emerges slowly (Section 1.1). Because it occurs in all climates and in virtually all countries, its billion-dollar losses are a global wake-up call, reminding us of our inability to properly respond to and prepare for drought. The *status quo* in drought management has long been based on looking at drought from a crisis-management perspective. The responses came only to mitigate the impacts observed when the drought event was already consolidated (Section 1.3).

Time has shown something counter-intuitive about drought management: simply increasing the water supply in response to shortages is not enough (Section 1.3). The way forward is to reduce drought risks. This requires to think about drought management in a broad and systematic way, indeed applying crisis management measures once the drought is consolidated but putting greater effort and focus on preparedness and mitigation possibly even preventing it to happen (Section 1.3).

Preparing for a drought involves increasing a population's resilience and understanding vulnerabilities in order to reduce it (Section 1.3). Being properly prepared for something to happen is also about understanding when it can or will happen. In the context of droughts, this means implementing monitoring and early warning systems (DEWS) that should be able to provide decision-makers with strategic information regarding the onset, propagation, intensity and area of a drought event (Sections 1.3 and 1.4.1).

In general, DEWS are powered by drought assessment methodologies based on the use of standardized indices of hydro-meteorological variables (Section 1.4.1). In theory, the standardization of such variables makes it possible to compare drought characteristics in different regions or at different times. In practice, standardization leads to a loss of the characteristics and local context related to drought emergence (Section 1.4.1). The mismatch between drought indices and their impacts is mainly because these indices are generally based only on physical variables, disregarding the human component (Sections 1.4.1 and 1.4.2).

In short, we have moved from a purely reactive approach that saw droughts as an engineering problem to be solved mainly by expanding water infrastructure, to an approach that tries to reduce the risks of drought by strengthening mitigation and preparedness measures (Section 1.3). This shift has led to a more systematic and planned way of managing drought, which required, for example, the implementation of DEWS. Furthermore, currently society has at its disposal accurate meteorological and climatological models, simulated and calibrated in research centers using what seems to be the cutting-edge methodologies and computing power. Yet, drought impacts continue to occur every year around the world not differentiating countries according to their economic development level (Section 1.1).

The inefficiency of DEWS and forecasting methods is associated with the way drought has been defined. It is logical to think that if the definition being used does not actually apply to what is being monitored or predicted, it is to be expected that this monitoring or prediction will commonly fail. Renowned institutions and exponents of drought monitoring, such as the World Meteorological Organization and the European Drought Observatory, continue to see drought as a purely hydro-meteorological phenomenon as is stated on their website (WMO, 2023; EDO, 2023). These institutions define drought in detail, highlighting its emergence as solely the result of natural hazards without mentioning the human component. This shows that drought management has evolved in recent decades, but not the way that drought itself is viewed. Today's challenges put greater pressure on water resources. If we don't change our view of drought in the near future, this pressure could be even greater, fueled by population growth, climate change, and other developments.

Socio-hydrology has placed human actions in a prominent position in the study of hydro-meteorological disasters (Section 1.4.1), however this understanding is relatively new and many questions and knowledge gaps remain open. Today we understand that human actions are profoundly influencing various components of the Earth systems, resulting in climate change. This in turn can increase the frequency and intensity of natural threats related to the onset of drought (Marengo et al., 2020). However, this does not tell the whole story. Section 1.6 discusses how the knowledge gap presented in this section was used to define the main objective and research questions of this thesis.

1.6 Positioning of this thesis and research questions

Summarizing the previous section, it is clear that in an era governed by increasing human interference in natural processes, there is a need to place the human component at the center of drought assessment studies. This is crucial to improve the understanding about droughts and also to support the development of strategies that will alleviate the pressure on water resources to meet human demand. Hence, the main objective of this thesis is *to increase understanding of the human influence on the emergence and propagation of drought events*.

In this thesis I explore the human influence on drought with the semi-arid region of Brazil as study area, specifically the state of Ceará (See Section 1.2). To achieve the main objective, the thesis focuses on socio-hydrological concepts (See Section 1.4.2) in drought assessment, and tries to find answers to the following research questions.

1. *What is the influence of a dense network of informal reservoirs on the evolution of hydrological drought events?*
2. *What is the effect of local socio-hydrological dynamics on the emergence of drought impacts?*
3. *What are the local impacts of a dense network of reservoirs during a drought event?*
4. *How could including perspectives of individual water users in a drought prone region support drought impact assessment?*

Each chapter in this thesis addresses at least one of these questions. The outline of the thesis is presented in the next section. The connection between the chapters is illustrated within the research framework in Figure 1.4.

1.7 – Research approach

The research method adopted in this thesis was designed to be applied in the semi-arid region of Brazil, since this is suitable case for analysing the influence of socio-hydrological dynamics on the emergence and propagation of drought events (Section 1.2). The first step was to identify if some of the main socio-hydrological dynamics play a role in the emergence and propagation of drought events. This initially addressed by exploring the interactions between small and large reservoirs in the processes of drought evolution, providing answers to the first research question (bottom level of Figure 1.4). The next stage of the research method sought to assess how socio-hydrological dynamics influence the emergence and propagation of drought events through a more detailed analysis in which the region's water uses and productive activities were considered. It was also analysed how these interactions act locally to mitigate or intensify the impacts of drought (intermediate level of Figure 1.4), thus addressing the second and third research questions. The last part of the research approach was dedicated to analyse why the perspective of individuals in relation to the emergence of drought impacts influences the occurrence of these events. At this stage, a qualitative approach was applied that combines principles of socio-hydrology and concepts from human behavioural theories (top level of Figure 1.4), which answered the last research question.

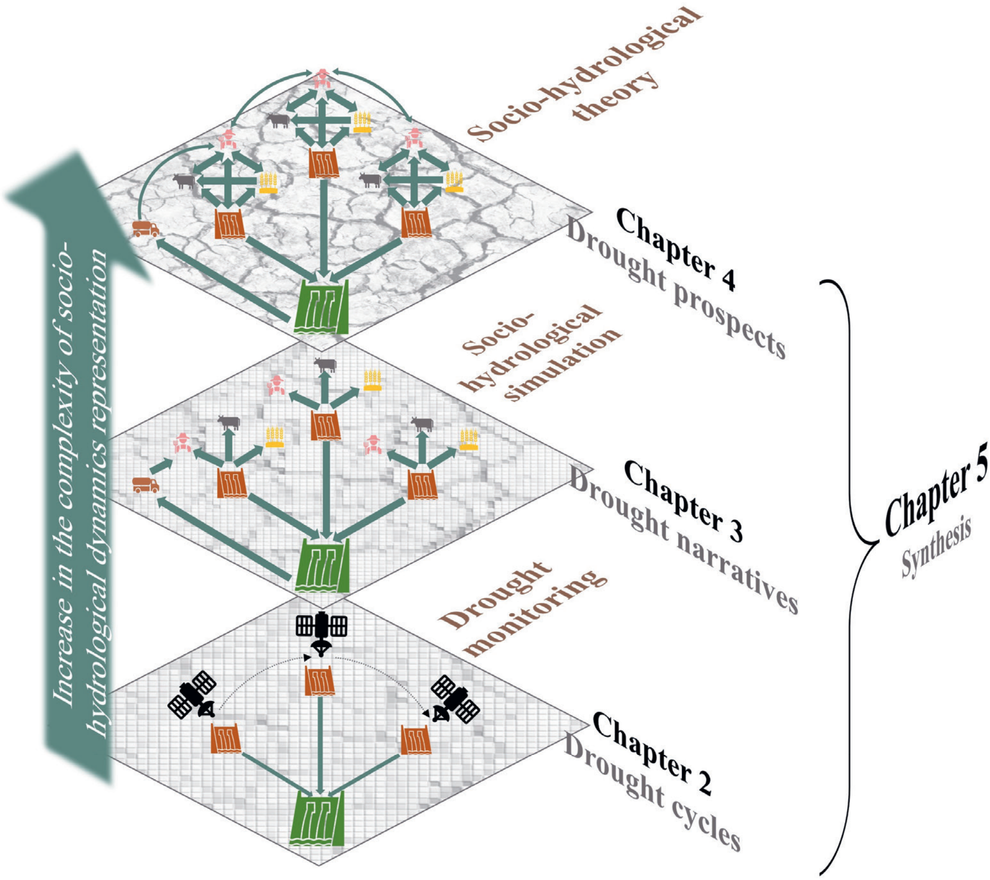

Figure 1.4 -Thesis outline conceptualization presenting the title and the theme of each chapter, as well as a graphic representation of the complexity of the socio-hydrological dynamics considered.

1.8 Thesis outline

Drought monitoring traditionally considers only physical variables, without taking into account the local context. Chapter 2 presents a new method for **drought monitoring** called Drought Cycle Analysis (DCA) which simultaneously tracks a hydro-meteorological and a socio-hydrological variable. This method includes the human influence in drought monitoring and assessment through the representation of the socio-hydrological dynamics existing between large and small reservoirs. The volume stored in small reservoirs were estimated using remote sensing imagery (bottom layer of Figure 1.4). DCA was applied to analyze the effect of a dense network of small reservoirs on the emergence of hydrological droughts in large reservoirs and thus address the first scientific question.

These small reservoirs are popular structures in semi-arid regions and are one of the main drought coping strategies in the study area (see sections 1.2 and 1.3). They are generally built informally and without centralized planning that takes into account the overall aspect of the watershed. Although small reservoirs generally have a low storage capacity, certain hydrological impacts such as reduction of the hydrological connectivity of the watershed during and after multi-year drought events are attributed to the combined effect of these structures. In order to assess these effects, a more detailed representation of the socio-hydrological dynamics than those considered in Chapter 2 is required. Furthermore, to assess the local benefits that small reservoirs can provide during drought events, a methodological framework for **socio-hydrological simulation** is required (middle layer of Figure 1.4). These issues are addressed in Chapter 3, thereby addressing the second and third research questions.

Chapter 4 delves even deeper into the socio-hydrological dynamics of the study area by exploring the intricate relationships between human action, hydrological processes and individual perceptions of drought impacts (top layer of Figure 1.4). To this end, an interdisciplinary approach was applied, combining concepts from drought assessment with prospect theory to enhance **socio-hydrological theory**. This chapter addresses the last research question of this thesis.

Starting with a practical drought monitoring method presented in Chapter 2 (bottom layer of Figure 1.4) and arriving at a broader theoretical methodological framework with greater detail on socio-hydrological dynamics in Chapter 4 (top layer of Figure 1.4), the conclusions, synthesis, recommendations and future research opportunities related to this thesis are presented in Chapter 5.


02

Chapter 2

Drought **cycles**

The contents of this chapter is based:

Ribeiro Neto, G. G., Melsen, L. A., Martins, E. S., Walker, D. W., & Van Oel, P. R. (2022). Drought cycle analysis to evaluate the influence of a dense network of small reservoirs on drought evolution. *Water Resources Research*, 58(1), e2021WR030799.

Abstract

Drought-affected regions often contain high densities of small reservoirs, usually informally built, as drought-coping mechanism. These structures influence socio-hydrological dynamics and have the potential to alter hydrological processes relevant to drought emergence and development. This study aimed to analyze the influence of a high concentration of small reservoirs on the intensification and evolution of drought events. We present an innovative method, which we call “Drought Cycle Analysis”, that tracks the concomitance of precipitation and water storage deficit and associates this with four drought stages: Wet Period, Meteorological drought, Hydro-meteorological drought and Hydrological drought period. The methodology was tested for the Riacho do Sangue River watershed located in the semi-arid region of northeast Brazil. We used a combination of satellite imagery (Landsat 5, 7 and 8) and an empirical equation to estimate the volume stored in the dense network of small reservoirs. Using the Drought Cycle Analysis, we show that the unmonitored small reservoirs induced and modified drought events, extending the duration of hydrological drought on average by 30%. Furthermore, this extension can double for specific drought events. The Drought Cycle Analysis method proved useful for monitoring and comparing the evolution of different drought events, in addition to being applicable as an auxiliary tool in the improvement of water resources management of large reservoirs. This study demonstrates the importance of considering small reservoirs in water resource management strategy development for drought-prone regions.

"O sabiá no sertão
Quando canta me comove
Passa três meses cantando
E sem cantar passa nove
Porque tem a obrigação
De só cantar quando chove. "

The thrush in the drylands
When it sings makes me cry.
Spends three months singing
And in silence it stays nine
Because it holds the duty
*To only sing when the rains arrive***.**

(Cordel do Fogo Encantado)

2.1 Introduction

The construction of reservoirs without a systematic and holistic analysis of the watershed can lead to a concentration of water in certain parts of the basin, and scarcity elsewhere (Di Baldassarre et al., 2018). In this way, reservoirs can intensify or induce drought events, defined as periods of exceptional lack of water that negatively impact human activities or environmental demands (Van Loon et al., 2016b, 2016a). This, in turn, can result in water availability inequality and thus societal pressure to build more reservoirs, which may further aggravate the problem. Both large publicly managed reservoirs and smaller privately owned reservoirs can play a role in this process. Especially because the latter are usually unmonitored, their influence on water distribution during drought events is unclear (Habets et al., 2018). Understanding the hydrological impact of a Dense Network of (small) Reservoirs (DNR) is highly relevant, both from a societal as well as from a water management perspective.

Dense networks of small reservoirs occur in many places around the world: Australia (Fowler et al., 2015), Northeast Brazil (Mamede et al., 2012a), Ethiopia (Lasage et al., 2015), France (Habets et al., 2014), Ghana (Annor et al., 2009), India (Mialhe et al., 2008), South Africa (Hughes and Mantel, 2010), South Brazil (Collischonn et al., 2011), Southern Brazilian Amazon (Arvor et al., 2018), Southern Syria (Avisse et al., 2017), West Africa (Liebe et al., 2005), and Zimbabwe (Sawunyama et al., 2006). It is expected that small reservoirs, when analysed individually, would not cause major impacts to a hydrological system, since their maximum storage capacity is negligible. However, the accumulated effect of a DNR may be greater than the impact of a single large reservoir. Evaluating a DNR is, however, not a trivial task. These DNRs often occur in regions where there is a general lack of observational data, and furthermore, such analysis requires incorporating many informal, small and private reservoirs that are unmonitored and rampantly constructed.

The semi-arid region of Brazil occupies about 11% of the Brazilian territory (1,542,000 km^2, Chapter 1, Figure 1.2) and contains 30% of its population (Marengo, 2020a). It is an example of a region with a high concentration of reservoirs with great variation in size and storage capacity. The region has a highly irregular spatio-temporal precipitation regime and a predominance of soils and geology with low water storage capacity, which creates a dependency on the superficial storage of water, and means the region is frequently affected by intense drought events (Marengo et al., 2017a; Marengo et al., 2017b). A recent drought event lasted almost seven years (2012–2018) with accumulated losses up to 2016 of over US $30 billion events (Marengo et al., 2017a; Marengo et al., 2017b). These conditions stimulated the construction of both small (capacity less than 0.2 hm^3) and large/middle-sized reservoirs, and for centuries this has been the main coping strategy for drought in this region (Rebouças, 1997). Most of the small reservoirs aim to meet the demands of subsistence farmers (who mostly depend on this water source for their livelihood) only in the short term. These structures therefore play a relevant societal role on a local scale. However, it remains unclear how the DNR, in a region such as the semi-arid region of Brazil, influences the emergence, intensification and propagation of drought events at watershed level. A more detailed picture of this situation can be exemplified within Ceará (a state in semi-arid Brazil) where it is estimated that there are close to 100,000 reservoirs (FUNCEME, 2021); for some regions of this state the reservoir concentration is higher than 7 reservoirs per km^2. The regulatory agencies operating in Ceará systematically monitor the volume of 155 large/middle-sized reservoirs, for the remaining more than 99,000 reservoirs, information and characterization remain unknown.

Mapping reservoir locations and estimating storage capacities of numerous small reservoirs using remote sensing products may be a suitable approach to capture the hydrological impacts of a DNR on drought events. Full calculation of storage capacities requires topographic or bathymetric surveys which can be very time consuming and require substantial specialized efforts. Several studies employed remote sensing to estimate storage capacity of reservoirs, based on a combination of optical satellite imagery and digital elevation models or topography/bathymetric surveys (Avisse et al., 2017; Getirana, 2016; Peng et al., 2006; Pereira et al., 2019; Rodrigues et al., 2012; Sawunyama et al., 2006; Van Den Hoek et al., 2019; Vanthof and Kelly, 2019; Zhang et al., 2016). Most studies also relied to some extent on in situ surveys, or presented methods that were suitable only for large reservoirs, which limits their application to a region with a large number of small reservoirs. Furthermore, these studies did not analyse the impact that these small reservoirs have on the studied hydrological system, particularly during drought events.

There are studies that evaluated the impact of reservoirs on drought development. However, most of these studies focused on large reservoirs (Biemans et al., 2011; Di Baldassarre et al., 2018; van Langen et al., 2021a; van Oel et al., 2011; Pieter R. Van Oel et al., 2018; Wu et al., 2017). Although some studies have analysed the effect of small reservoirs on sediment/water dynamics (Berg et al., 2016; Bronstert et al., 2014; Mamede et al., 2018; Medeiros et al., 2014, 2010), water availability (Malveira et al., 2012b), evaporation losses (Craig, 2008; Gallego-Elvira et al., 2010; Tanny et al., 2008), and streamflow impact (Habets et al., 2014; Lasage et al., 2015; Lowe et al., 2005), there is a scientific gap related to the cumulative effect of a DNR on drought in a hydrological system.

In this study we analysed the effect of a DNR on the evolution and intensification of drought events. For this, we present the "Drought Cycle Analysis" which is a new method for drought evaluation, based on the combination of a precipitation index and information directly related to impacts generated by drought events. We employed remote sensing to estimate the volume stored in the DNR, and use the Drought Cycle Analysis to estimate the effect of this storage on drought impact. The method was tested for the Riacho do Sangue watershed in Ceará state in Brazil. Unveiling the role of small, unmonitored reservoirs on drought development is relevant information for water managers, which tend to focus mainly on monitored reservoirs, thereby ignoring the role that the DNR might have on drought onset and duration.

2.2 Materials and Methods

The goal of this study is to understand how small reservoirs can influence the intensification and evolution of drought events. The graphical summary of the methodology is presented in Figure 2.1.

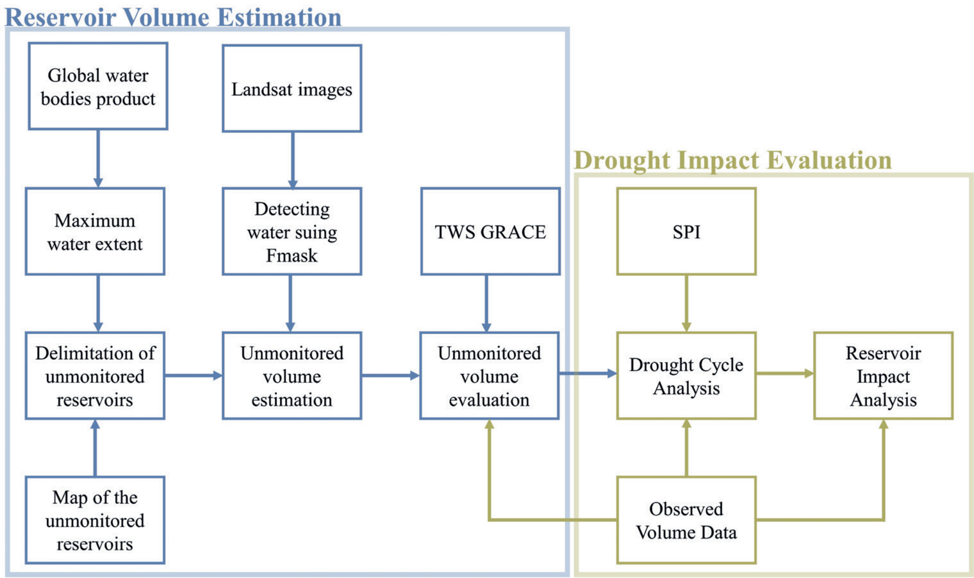

Figure 2.1 - Flowchart of the methodology. The blue and yellow colors indicate the processes related to Reservoir volume estimation (step 1) and Drought impact evaluation (step 2), respectively. The numbers refer to the sections of this manuscript.

The methodology consists of two main steps:

1. **Reservoir Volume Estimation:** Estimating the volume stored in the DNR based on remote sensing products and an empirical equation. We used the Surface Water Extension (SWE) time series of each reservoir as an input to the Molle equation (Molle, 1994, 1989) which relates this information to the volume stored in these structures. The location of each reservoir was obtained using the map of unmonitored reservoirs (FUNCEME, 2021) created by Research Institute of Meteorology and Water Resources of Ceará (FUNCEME). The SWE time series were extracted from 331 images (from 1986 to 2020) of Landsat (5, 7 and 8) scene 217/064 reclassified with the Fmask algorithm (Zhu et al., 2015; Zhu and Woodcock, 2012). We selected Landsat images that had less than 40% of cloud. The volume estimation procedure is described in Section 2.2.2.2.
2. **Drought Impact Evaluation:** Evaluating the role of a DNR in the evolution of a drought event. We developed a new methodology, which we call "Drought Cycle Analysis", based on a combination of the Standardized Precipitation Index (SPI) and the hydrological Volume Deviation (VD), which is described in Section 2.2.2.3.

2.2.1 Study Area

We applied our analysis to the Riacho do Sangue watershed (1368 km2) which is part of the Jaguaribe river basin (75,000 km2) and is located in Ceará State in Brazil (Figure 2.2).

The Riacho do Sangue watershed was selected because of its high density of reservoirs and due to the frequent experience of drought impacts. The average annual precipitation and potential evapotranspiration in the Riacho do Sangue watershed is respectively 740 mm and 2300 mm (1981–2019). A crystalline complex associated with shallows soils limits the occurrence of aquifers in this regions. Consequently, in combination with the meteorological characteristics, all rivers in the region are intermittent (de Araújo & Bronstert, 2016; Fontenele et al., 2014). The study area has three reservoirs that are managed and operated by governmental agencies: Riacho do Sangue Dam (RSD), Tigre Dam (TGD) and Jenipapeiro Dam (JPD; Figure 2.2). Their maximum storage capacities are respectively 58.43 hm^3, 3.51 hm^3 and 14.59 hm^3.

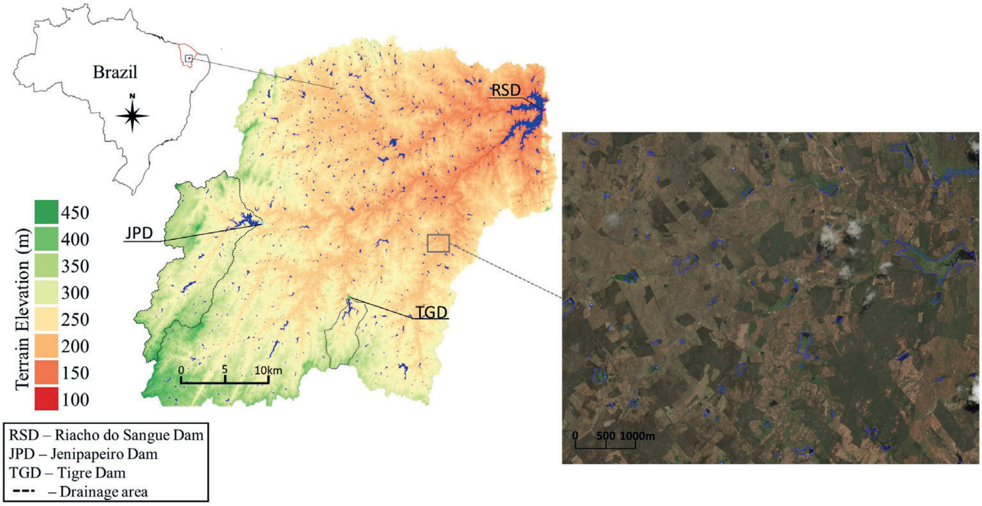

Figure 2.2 - Location and topography of the Riacho do Sangue watershed with the three large monitored reservoirs indicated. The small and unmonitored reservoirs are indicated by the dark blue color (1138 reservoirs). The grey rectangle is a detailed example of the high concentration of small reservoirs in the Riacho do Sangue watershed.

Precipitation Regime Characterization

To characterize the precipitation regime of the study region, we evaluated three variables: climatology (Figure 2.3a), interannual variability (Figure 2.3b) and the time series of the Standardized Precipitation Index application (SPI, McKee et al., 1993) at the 12-month time scale (Figure 2.3c). The SPI is calculated through two steps. First, the accumulated precipitation data (e.g., a moving window of 12 months) was fitted to a gamma distribution and then transformed into a normal distribution, in line with the guidelines of the World Meteorological Organization (World Meteorological Organization, 2012). The values of this index can be interpreted as the number of standard deviations by which the precipitation deviates from the long-term mean. This information is relevant for understanding the emergence and propagation of drought events in the study area.

As can be seen in Figure 2.3a, the precipitation in the study area has an intense seasonality, the first 5 months of the year usually receive close to 85% of the annual precipitation. We chose to use the 12-month time scale (SPI12) because in this way, each SPI time step considers the entire rain season, which is most relevant to the study area. A shorter time scale (e.g., 3 or 6 months) could capture a reduction in precipitation during the dry season, and indicate a meteorological drought related to this situation. However, reductions in rainfall during the dry season are less relevant for the study area as it hardly rains during this period and the vast majority of socio-economic activities in this region depend directly on precipitation from the rainy season. Due to the characteristics of the precipitation regime in the study area, the use of SPI with a time scale below 12 months can lead to the identification of drought events not directly linked to the dynamics that we seek to explore in this study. Details on the SPI calculation methodology can be found in Guttman, (1999) and McKee et al. (1993). We used the average precipitation over the study area to calculate the SPI, since this variable does not show strong spatial variability over the study region.

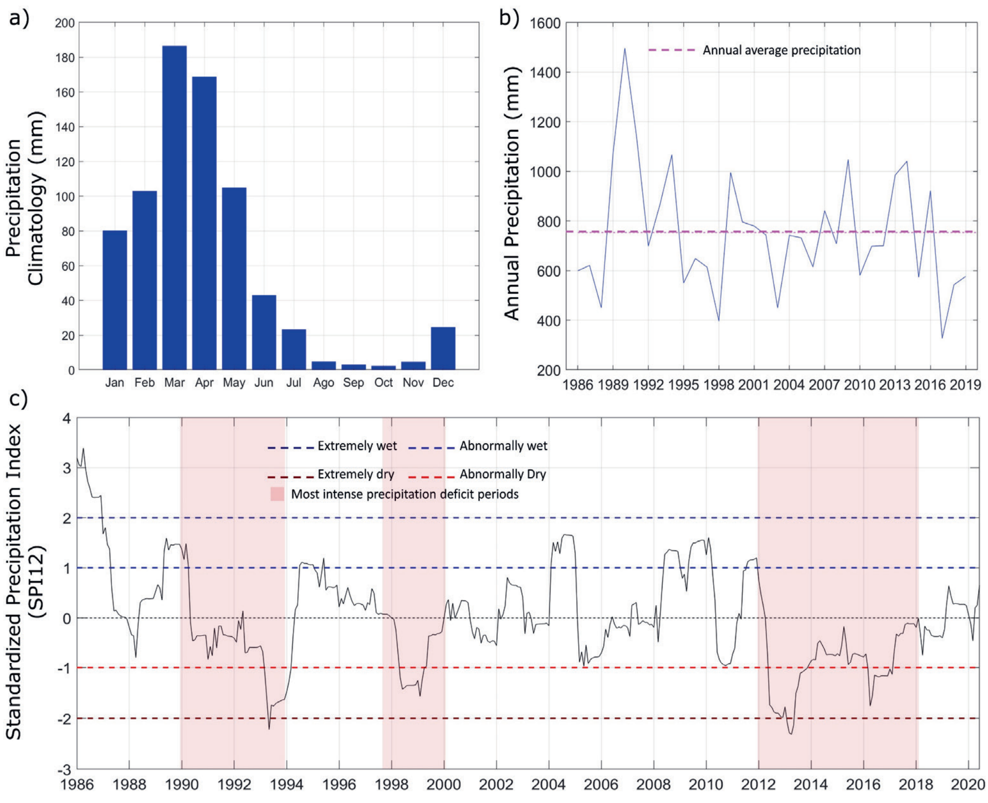

Figure 2.3 - Discretization of the temporal variation of precipitation in the study area. (a) Climatology of precipitation over the study period, (b) Time series of annual precipitation, (c) SPI12 time series.

The second version of the Climate Hazards Group InfraRed Precipitation with Stations product (CHIRPS, Funk et al., 2015) was utilized to represent the precipitation of the study area. This product runs from 1981 to near-present and integrates satellite imagery with rain gauge data to create gridded precipitation time series with quasi-global coverage (50°S−50°N, 180°E−180°W) at 0.05° resolution. This product was selected due to its high accuracy for the semi-arid region of Brazil (Paredes-Trejo et al., 2017) and its high spatio-temporal resolution.

2.2.2 Reservoir Volume Estimation

Delimitation of Unmonitored Reservoirs

The estimation of the water volume stored in a Dense Network of (small) Reservoirs (DRN) starts with defining the Maximum Surface Water Extent (MSWE). This information is used to delimitate the area to estimate the temporal variation of the surface water extent, which is the input for the estimation of the volume stored in each reservoir of the DRN. We used the Maximum water extension product that was developed by Pekel et al., (2016) which is available in the Global Surface Water Explorer platform (https://global-surface-water.appspot.com/). This product has global coverage, a 30m spatial resolution, and was developed based on 37 years of satellite imagery data from the Landsat missions (5, 7, and 8). This product considers all water bodies; there was no differentiation between those that have natural or anthropogenic origin. Therefore, we used the recently released map of unmonitored reservoirs, established by FUNCEME (FUNCEME, 2021), which is currently the most accurate product regarding the location of these structures in the study area. The FUNCEME map was developed based on high-resolution satellite imagery from the CBERS 4A satellite (spatial resolution ranging from 2 to 8 m) and only reservoirs with a dam structure of at least 20 m long were counted (FUNCEME, 2021). According to this product, the study area features a DNR with 3,432 reservoirs, of which 1138 have also been identified in the Maximum water extension product developed by Pekel et al. (2016). This means that 2294 reservoirs possibly present a MSWE smaller than the pixel area of Landsat derived products (900 m2). Since it was not possible to extract the Surface Water Extension (SWE) time series of these structures, these reservoirs were not included in the estimated volume stored in the DNR. We note that the median size of the 1138 identified reservoirs is 3,600 m^2.

Detecting Water in Landsat Using Fmask

After the delimitation of the Maximum Surface Water Extent (MSWE) of each reservoir, the temporal variation of the Surface Water Extension (SWE) needed to be estimated. This is the main input to estimate the volume of water stored in the

DNR. The SWE time series were extracted from 331 images (from 1986 to 2020) of Landsat (5, 7 and 8). We applied the Fmask algorithm (Zhu et al., 2015; Zhu & Woodcock, 2012) to systematically discriminate cloud and shadow coverage from water bodies and therefore the SWE. This algorithm allows automatic processing and analysis of Level 1 Landsat images with a cloud detection accuracy close to 96% (Zhu & Woodcock, 2012). Fmask is integrated in the Landsat Level 2 development (Frantz et al., 2018) and was well used in other studies (Abileah et al., 2011; Avisse et al., 2017; Frantz et al., 2018; Qiu et al., 2019; Schwatke et al., 2019). The input data of the Fmask are digital number values of Landsat L1T band 1,2,3,4,5,7 and band 6 Brightness Temperature (BT). The digital number values are converted to Top of Atmospheric reflectance (TOA) and brightness temperature (Celsius degree) with the LEDAPS atmospheric correction tool (Masek et al., 2006). Then routines are applied to extract potential cloud and cloud shadow layers which results in the generation of the final cloud and cloud shadowed mask (Zhu & Woodcock, 2012). The detailed methodology of this algorithm can be accessed at Zhu et al. (2015) and Zhu and Woodcock (2012).

We observed that several reservoirs present on the FUNCEME map which were also present in the MSWE product developed by Pekel et al. (2016) did not appear in the water maps generated by the original version of Fmask. Thus, we tested a modification of this algorithm to improve the water pixel identification. In the original algorithm this step is based on a logical test that uses the Normalized Difference Vegetation Index (NDVI) and Near Infrared band (NIR; Equation 2.1).

$$\text{Water} = (\text{NDVI} < 0.01 \ \& \ \text{NIR} < 0.11) \text{ or } (\text{NDVI} < 0.1 \ \& \ \text{NIR} < 0.05) \quad (2.1)$$

Although the NDVI is a simple method for water identification, there are other indices that can be used for this purpose with a higher accuracy. The Normalized Difference Water Index (NDWI, McFeeters, (1996)), and its modified version (MNDWI, Xu, 2006) were developed specifically for water identification with the same concept and simplicity as the NDVI. These two indices use the green band, which is more sensitive to water features compared to the red band used in the NDVI. The difference between NDWI and MNDWI is that the modified version uses the Short Wave Infrared band (SWIR) instead of NIR, since it has better cloud penetration and water has lower reflectance in this band (Xu, 2006). Consequently, MNDWI is more accurate than the original version and has been used in several studies related to water identification through remote sensing (Deng et al., 2020; Du et al., 2016; Ji et al., 2009; Wang et al., 2011; Zhang and Chen, 2017). Therefore, we proposed the following modification for the Fmask water logical test:

Water=(MNDWI>0 & SWIR<0.07) or (MNDWI>-0.25 & SWIR<0.05) (2.2)

Positive values for the MNDWI usually indicate water. However, the combined effect of a thin cloud layer, presence of sediment, and chlorophyl-a in water can result in negative values of MNDWI, which demands the water threshold to be manually adjusted to the situation of the study area (Ji et al., 2009; Zhang et al., 2014). Most of the water pixels are identified by an MNDWI higher than 0 and SWIR lower than 0.07. Some of the water pixels may have relatively large SWIR reflectance because of influence of thin clouds or high sediment concentration which is common in small reservoirs of the study area, and they will be captured by using MNDWI higher than −0.25 and SWIR less than 0.05.

It is expected that these modifications in Fmask will increase the sensitivity of the water pixel identification, and consequently, the estimation of the spatio-temporal variation of SWE of the unmonitored reservoirs should be more accurate. To evaluate this, we calculated the MSWE through the original version of the Fmask, and by applying the proposed changes (Equation 2.2) using as input Landsat images from 2009 to 2011. We chose these years as they represent a recent period in which there was above average annual accumulated precipitation (see Figure 2.3). We created for both Fmask versions a data set of water mask maps considering each Landsat image from the 2009–2010 period. The MSWE was then defined as being the overlay of all maps of each data set. Finally, we checked for each of the two MSWE maps how many reservoirs identified by the FUNCEME map (FUNCEME, 2021) that were also present in the MSWE Global Water Bodies product (Pekel et al., 2016) could also be identified in these maps. The proposed algorithm modification substantially improved the detection of water pixels: 40% more unmonitored reservoirs were detected using Equation 2.2, compared to the original version of this algorithm based on Equation 1. Therefore, we continued the analysis with the modified Fmask version.

Estimation of the Volume of Unmonitored Reservoirs

The estimation of the volume stored in the DNR was conducted using the Molle equation(Molle, 1989, 1994) that relates the SWE with the volume stored in the reservoirs (Vr). This equation was developed using empirical data from 416 reservoirs located in the semi-arid region of Brazil (Mamede et al., 2018; Molle, 1989, 1994). The Molle equation has been validated in several studies related to the analysis of small reservoirs in this region and is also used in the deterministic, process-based, semi-distributed hydrological model WASA-SED, that was developed specifically for the hydrological simulation of semi-arid watersheds (Bronstert et al., 2014; Guntner, 2002; Krol and Bronstert, 2007; Lima Neto et al., 2011; Malveira et al., 2012b; Mamede et al., 2012b; Medeiros et al., 2010, 2014; Pilz et al., 2019) The Molle equation looks as follows:

$$Vr = d \times \left(\sqrt[\frac{c-1}{c}]{\frac{SWE}{c \times d}} \right) \quad (2.3)$$

where “Vr” and “SWE” are the volume stored (m^3) and the surface water extent (m^2) of the reservoir, respectively. “c” and “d” are empirical parameters, that were obtained through the analysis of 416 reservoirs conducted by Molle (1989), with values of 2.7 and 1500 respectively. We derived the SWE from Landsat (5, 7, and 8) images that were reclassified using the Fmask algorithm. There were some temporal gaps in the time series of the volume stored in the unmonitored reservoirs, related to the absence of useful Landsat Images. In order to conduct scenario analysis (see Section 2.2.3.2) these gaps were filled with a linear regression for up to four consecutive months of lack of data, since over this timescale drastic changes in the variation trend of the storage do not occur.

Evaluation of the Volume of Unmonitored Reservoirs

As previously explained, there are no observational data regarding the water volume stored in the Dense Network of (small) Reservoirs (DNR) of the study region. It is therefore not possible to quantitatively validate the estimation of the stored water volume in these structures, but we can assess the plausibility. The Riacho do Sangue watershed presents characteristics that can be used to assess the plausibility of the estimated storage in the unmonitored reservoirs. Firstly, a relatively strong correlation between the small unmonitored reservoirs and the large monitored reservoirs is expected, because there is a strong cause-and-effect relationship: a full DNR leads to an increase in the recharge of the large reservoirs. Another relevant aspect related to the physical characteristics of the study area is that the temporal variation of the Terrestrial Water Storage (TWS) is strongly influenced by the Surface Water Storage (SWS) which in the Riacho do Sangue watershed corresponds mainly to the volume of water stored in all the reservoirs. Therefore, it is expected that a coherent estimate of the volume stored in the unmonitored reservoirs displays a high correlation with the total volume stored in the monitored reservoirs and that the combination of these variables (SWS) presents an even higher correlation with the TWS.

We assessed the plausibility of the DNR volume storage estimates for the study area through two different statistical analyses. In the first analysis, we calculated the correlation between the estimated volume stored in the DNR with the volume stored in the monitored reservoirs during three periods (see Figure 2.3): Wet years (1986–1989, 1995–1997, 2001–2011 and 2019–2020); Dry years (1990–1994, 1998–2000, and 2012–2018) and the whole study period (1986–2020). This division was made because the correlation between these variables is expected to change due to the occurrence of drought events. In the second analysis, we evaluated three different correlations: TWS × Monitored volume (the three large reservoirs); TWS × DNR volume (only the unmonitored and small reservoirs) and TWS × SWS (large reservoirs and DNR combined). It is expected that this last set will provide the highest correlation, since the sum is conceptually closer to the TWS.

We used the Jet Propulsion Laboratory (JPL) Mascon solution to represent the TWS derived from the spatial missions Gravity Recovery and Climate Experiment (GRACE) and Follow On (GRACE-FO). This solution has a higher spatial resolution (0.5°) and accuracy than the regular GRACE TWS products (Watkins et al., 2015). The TWS data from the GRACE and GRACE-FO missions are widely used in the scientific literature (e.g. Getirana, 2016; Li et al., 2019; Melati et al., 2019) For this analysis, we consider the period 2002–2020 which corresponds to the complete time series of this GRACE/GRACE-FO mascon product.

2.2.3 Drought Impact Evaluation

Drought Cycle Analysis

Once the water storage of reservoirs in the Dense Network of (small) Reservoirs (DNR) was estimated, their role in drought intensification and evolution was evaluated. We present a novel method called “Drought Cycle Analysis” which is based on a combination of precipitation and hydrological indices. It classifies drought events into four possible stages regarding the simultaneous occurrence of precipitation deficit and water storage deficit. Each pair of observations is positioned on a coordinate axis divided into four quadrants, in which each is associated to a stage related to the evolution of a drought event (Figure 2.4). We use a hue and tone variation scheme to represent the intensity of the drought event as well as its classification. The set of these four quadrants, as well the hue and tone variation, shown in Figure 2.4 will be referred to as the “Drought Wheel” to simplify the presentation and discussions of the results.

The first quadrant is the "Wet quadrant", the non-occurrence of drought. This stage is defined by positive values of the Precipitation Index (PI, vertical axis) and the Water Storage Index (WSI, horizontal axis). The next quadrant indicates the occurrence of meteorological drought, when there is a precipitation deficit (PI < 0) but it has not yet affected water storage (WSI > 0). The third quadrant is related to the occurrence of hydrological-meteorological drought, when the persistence and/or intensification of the precipitation deficit starts to affect water storage. This is indicated when both indices show negative values. The fourth and final quadrant is related to what we call the "Hydrological drought quadrant" and is characterized by the absence of a precipitation deficit (PI > 0) and the persistence of hydrological impacts (WSI < 0).

We used standardized indices since this allows a better division of the four quadrants proposed. We used the SPI12 from CHIRPS data as input to represent the precipitation index (vertical axes). The variation of the Riacho do Sangue Dam volume was used as a proxy to analyse the water storage of the study area, since this reservoir is the largest and most important in the study area besides being located at the Riacho do Sangue watershed outlet. The volume stored in the Riacho do Sangue reservoir depends not only on climatic conditions but also on the water released by the monitored reservoirs and the overflow from small reservoirs upstream. Furthermore, as it is located in the most downstream part of the study area, the accumulated effect of the presence of small reservoirs will be most evident. As a result, this is a key variable to understand the role of the small and unmonitored reservoirs in the intensification and evolution of drought events. To use the variation of Riacho do Sangue Dam volume as a Water Storage Index (horizontal axis in the drought wheel), we standardized this variable considering a deviation from half of the maximum capacity of this reservoir and we called this Volume Deviation (VD). Thus, the VD varies from −1 to 1, where a positive value indicates that the reservoir is more than half full while negative values indicate the opposite. Half full is a relevant threshold to capture the emergence and propagation of hydrological drought events in the study region, because water availability is considered critical when the reservoirs has a level less than half of the maximum capacity.

The Drought Cycle Analysis was used to identify the drought events that occurred in the study area over the past 34 years. We consider that a drought event is a disaster related to the exceptional lack of water that is prejudicial for human activities or environmental demands. This method considers not only a meteorological index for monitoring droughts (the vertical axis of the drought wheel), but also information directly related to the impact that this can cause (the horizontal axis of the drought wheel), as such allowing to identify drought events. We consider that a drought event starts when the pair of observations (SPI and VD) leaves the wet quadrant and remains at least 3 months in the hydro-meteorological or hydrological drought quadrant while the cessation of a drought event occurs when these indices return to the wet quadrant.

Reservoir Impact Analysis

The analysis of the effect of a DNR on the intensification and evolution of drought events was based on the combination of the Drought Cycle Analysis method with an event attribution analysis. For this, we compared the occurrence of drought events in two scenarios: the All Reservoirs Scenario (ARS) and the Large Reservoirs Scenario (LRS). In both scenarios, we consider the volume deviation (VD) of the Riacho do Sangue reservoir in the Drought Cycle Analysis as a proxy for the hydrological impacts due to the occurrence of drought. In the ARS, all reservoirs are considered, thereby representing the actual situation. The application of the Drought Cycle Analysis for this scenario only considers as input the information related to precipitation (SPI) and the volume deviation is calculated using the observed volume of the Riacho do Sangue reservoir.

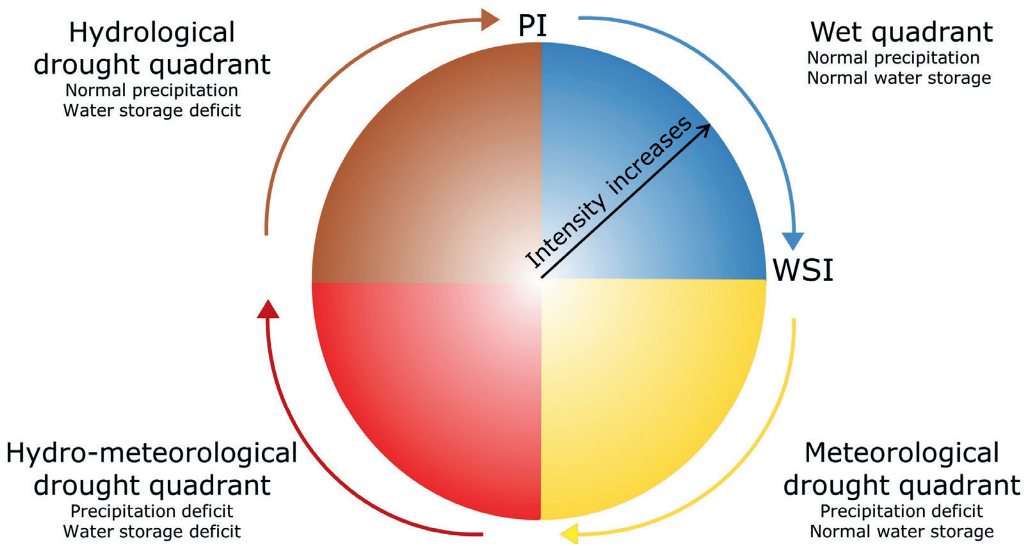

Figure 2.4 - Graphical representation of the Drought Cycle Analysis. The y-axis related to a precipitation-based index, and the x-axis to a water storage index. A series of events during the evolution of a drought, or simply “drought cycle”, can be projected on the four quadrants of the “Drought Wheel”.

In the LR Scenario, we assume that the small unmonitored reservoirs do not exist, and all water that would be stored in these reservoirs directly flows into the large, monitored reservoirs downstream. For this scenario, we use the estimated volume stored in the DNR, and the volume stored in the other two large monitored reservoirs (Tigre and Jenipapeiro) in the study area (see Figure 2.2). The assumed absence of the DNR in the drainage basin of the large monitored reservoirs could lead to an maximum capacity overflow and this extra volume would flow and reach the Riacho do Sangue reservoir. The principles considered for simulating the LR Scenario are summarized in Equations 2.4-2.7.

$$\begin{cases} \mathrm{VLRS}_{(t,r)} = \mathrm{VLRS}_{(t-1,r)} + \Delta\mathrm{VARS}_{(t,r)} + \Delta\mathrm{VDNR}_{(t,r)} + \mathrm{ov}_{(t,r)}, & \Delta\mathrm{VARS}_{(t,r)} \geq 0 \\ \mathrm{VLRS}_{(t,r)} = \mathrm{VLRS}_{(t-1,r)} \times \delta\mathrm{VARS}_{(t,r)} + \Delta\mathrm{VDNR}_{(t,r)} + \mathrm{ov}_{(t,r)}, & \Delta\mathrm{VARS}_{(t,r)} < 0 \end{cases} \quad (2.4)$$

$$\Delta\mathrm{VARS}_{(t,r)} = \mathrm{VARS}_{(t,r)} - \mathrm{VARS}_{(t-1,r)} \quad (2.5)$$

$$\Delta\mathrm{VDNR}_{(t,r)} = \begin{cases} \mathrm{VDNR}_{(t,r)} - \mathrm{VDNR}_{(t-1,r)}, & \mathrm{VDNR}_{(t,r)} > \mathrm{VDNR}_{(t-1,r)} \\ 0, & \mathrm{VDNR}_{(t,r)} \leq \mathrm{VDNR}_{(t-1,r)} \end{cases} \quad (2.6)$$

$$\delta\mathrm{VARS}_{(t,r)} = \frac{\mathrm{VARS}_{(t,r)}}{\mathrm{VARS}_{(t-1,r)}} \quad (2.7)$$

where VLRS(t,r) and VARS(t,r) are the stored volume in the large monitored reservoir "r" for the Large Reservoir Scenario and All Reservoir Scenario, respectively, at time "t" which is the timestep in months. VDNR(t,r) is the volume stored in the DNR located in the watershed of the analysed large monitored reservoir "r". ov(t,r) is the maximum capacity overflow volume of the upstream large monitored reservoirs that the reservoir "r" may receive.

The volume stored in large monitored reservoirs is a socio-hydrological variable, that is, its variation depends both on human actions (e.g., reservoir operation rules, water withdrawals) and natural conditions (e.g., recharge due to surface runoff and evaporation). We made some simplifying assumptions regarding the recharge and emptying patterns of large monitored reservoirs in the LRS. First, we consider that the possible volume increase in the large monitored reservoirs due to the absence of the DNR would not be enough to change the local meteorological conditions. Therefore, we consider that these conditions are the same in both scenarios. The consequence is that when there is an increase in the volume stored in the ARS, this will also occur in the LRS (Equation 2.4 upper part). Furthermore, we assumed no change in behaviour in the LRS compared to the ARS, which could occur in response to changed storage. In periods of greater water availability it is common to have more authorization for water withdrawals and greater water release to downstream, while the opposite occurs in periods of drought. Accurately simulating this dynamic would involve a specific model based on local information. Since this is beyond the scope of this work, we decided to apply a simplified approach to capture these process. We assumed that the reduction in the volume stored in the LRS scenario would follow the same reduction rate presented in the ARS for the same month "t" (Equations 2.4-2.7). For example, if in the ARS there is a 5% reduction in volume storage compared to the previous month, the same relative reduction is applied to the LRS scenario. Subject to the assumptions, the LRS captures the storage dynamics in the large monitored reservoir, given that no water is stored in upstream small reservoirs.

2.3 Results

2.3.1 Volume Estimation Comparison

The first result of this study is an evaluation of the estimated volume stored in the DNR. This was done based on the correlation between this variable and the volume stored in the monitored reservoirs, the correlation between estimated storage in the DNR and terrestrial water storage (TWS), and the combination of storage in monitored and unmonitored reservoirs compared to TWS (Figure 2.5). The first row of this figure shows the correlation analysis between the volume stored in the DNR (horizontal axes) and the monitored reservoirs (vertical axes) considering the dry years identified in Figure 2.3c (1990–1990–1994, 1998–2000, and 2012–2018), wet years (years excluding dry years) and the entire study period (1986–2020). There is clearly a high correlation between both variables, especially in the driest years, when there are more periods in which the monitored volume is closer to the total volume stored in the DNR. The second row of Figure 2.5 shows the results related to the TWS GRACE. The unmonitored volume estimation had the lowest correlation with the TWS GRACE, however, when this was combined with the monitored volume, the correlation increases compared to when the unmonitored volume estimation was not considered in the correlation. Even though this is an indirect assessment, the results agree with the expected pattern previously discussed. This indicates that we obtained plausible values of the volume stored in the DNR, which allows us to proceed with the subsequent analyses.

2.3.2 Drought Impact Evaluation

To get a first idea of the role of small reservoirs in the evolution of drought, we compare the SPI value of each observation (represented through the color variation in Figure 2.6) with the volume deviation (VD) in both the All Reservoirs Scenario

(ARS, representing the actual situation) and the Large Reservoirs Scenario (LRS, assuming that the small reservoirs do not exist and all water flows directly toward the large reservoirs).

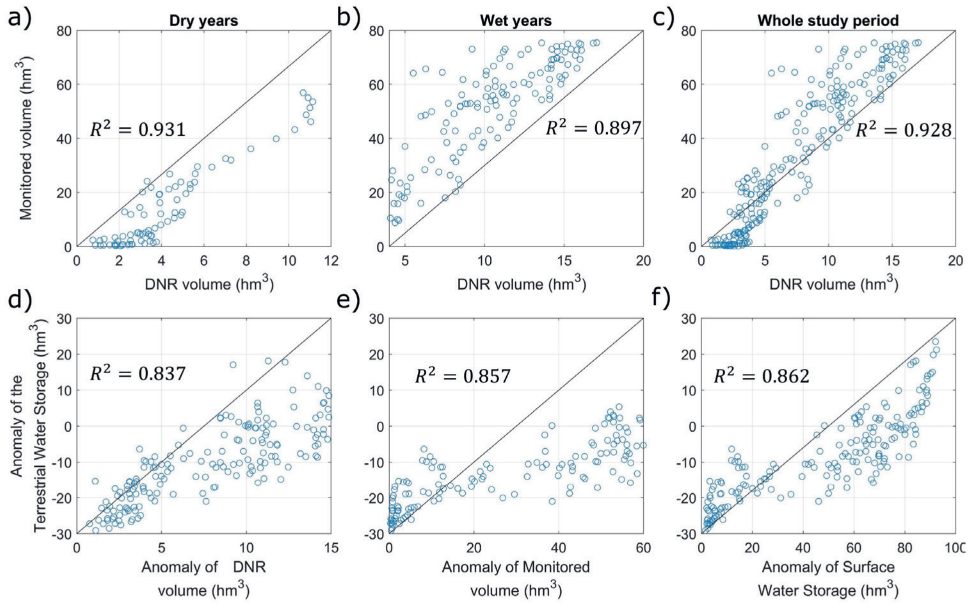

Figure 2.5 - Correlation between the estimated volume stored in the DNR with the volume stored in the monitored reservoirs, and Terrestrial Water Storage obtained from GRACE/GRACE-FO mascon product. Panels(a–c) compare the estimated volume in the unmonitored reservoirs with the volume stored in the monitored reservoirs for the dry years (1990–1994, 1998–2000, and 2012–2018), wet years (1986–1989, 1995–1997, 2001–2011, and 2019–2020) and complete study period, respectively. The Anomaly of the Terrestrial Water Storage from GRACE/GRACE-FO mascon product is correlated with estimated volume in unmonitored reservoirs (d), with the volume stored in the three monitored reservoirs (e), and with the unmonitored and monitored reservoirs volume combined (Surface Water Storage, f).

In Figure 2.6, three distinct patterns of VD can be observed when both scenarios are compared. First, in the upper right part of the graph, a high proximity between the scenarios is observed (green rectangle), meaning that the small reservoirs have limited impact on the volume stored in the main reservoir. This is because the storage in the area was close to the maximum capacity in the All Reservoirs Scenario (see also the high SPI values). Consequently, even if the small reservoirs did not exist, an overflow would occur to the downstream part of the Riacho do Sangue watershed. In the central part of Figure 2.6, there is a zone in which the greatest divergence occurs between the two scenarios (blue rectangle). Negative VD in the ARS are associated with positive values in the LRS: there is a clear impact of the small reservoirs on the volume stored in the main reservoir. During these periods, the volume stored in the DNR would have been enough to mitigate the hydrological impacts of these drought events in the monitored reservoirs. In the bottom left part of this figure there is again a proximity pattern between the two scenarios (red rectangle), indicating limited impact of the small reservoirs. However, this time associated with an intense water stress situation (extreme negative VD for both scenarios). Storage was so low that the little water stored in unmonitored reservoirs during this period would not have been sufficient to directly mitigate the hydrological impacts.

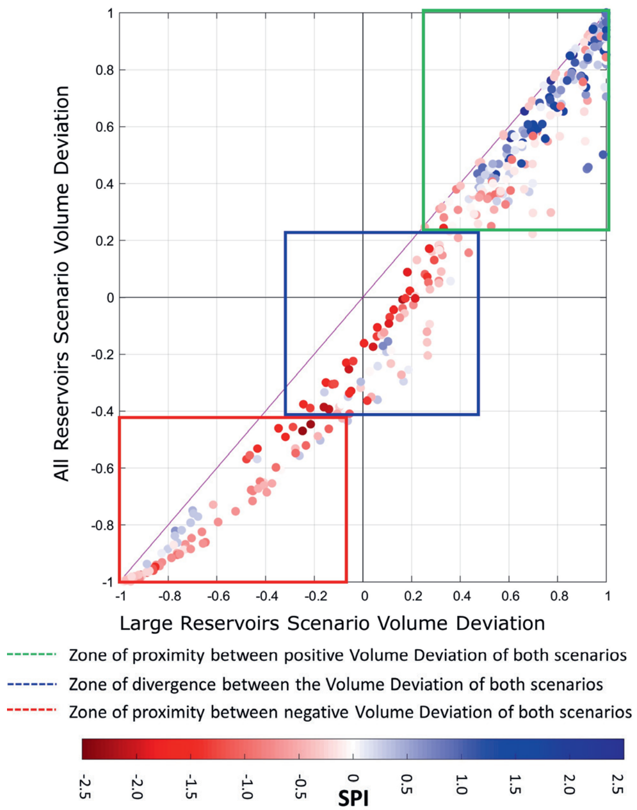

Figure 2.6 - Scatterplot between the Volume Deviation of the two scenarios associated to the SPI. The coloured rectangles (red, blue, and green, discussed in the main text) indicate zones of influence of the small reservoirs in the DNR on the intensification and evolution of drought events.

The most important result that can be extracted from this figure is that there is a threshold at which a reservoir will enter a phase most likely to be affected by small upstream reservoirs during the occurrence or continuity of drought events. This threshold is the lower limit of the region in Figure 2.6 where the VD values of the All Reservoirs Scenario are negative while those of the Large Reservoirs Scenario are positive. This means that the unmonitored reservoirs are not yet in a critical storage situation. For the Riacho do Sangue Dam this threshold is −0.2 in the All Reservoirs Scenario which can be seen to be associated with positive VD values in the Large Reservoirs Scenario.

We conducted and evaluated a Drought Cycle Analysis for the three most intense recent drought events, identified using this method, 1992–1994, 1997–2002 and 2012–2020 (Figure 2.7). The horizontal bars of this figure represent the time series on the monthly scale of the results related to Drought Cycle Analysis for both scenarios of each of the three drought events. The colours printed in each rectangle of the horizontal bars align with the colours in the Drought Wheel (Figure 2.4) and indicate in which drought stage the scenario is for a particular month. Through these results it is possible to observe the influence of reservoirs on the intensification and evolution of drought events.

The Drought Cycle Analysis method allows to identify the interval between the onset of a precipitation deficit and the occurrence of hydrological drought (impacts). This can be done by counting the number of continuous months (rectangles of the horizontal bars in Figure 2.7) of the meteorological drought stage (yellow colours) prior to the emergence of the drought-hydrometeorological stage (red colours), indicated by the black arrows in Figure 2.7. For example, in the ARS scenario for the 1992–1994 drought event, the lag between the onset of the precipitation deficit and the occurrence of hydrological impacts is 11 months, while for the 2012–2020 event this lag was only 4 months. The difference in lags between the analysed scenarios indicates the effect that a DNR can cause. Prolongation of drought impacts due to the DNR is identified when the drought stage of the LRS is less intense than in the ARS for the same month. It can be seen that, in general, the presence of the DNR caused an earlier onset of hydrological impacts (red and brown colours) of 3–4 months indicated by the green rectangles, and an extension of these impacts by at least 2 months in the 2012–2020 event indicated by the purple rectangle. When, for a particular month, it is observed that the same colour was registered in both scenarios, though with different shades, this indicates that the DNR influence the intensity of the drought stage (black rectangles in upper and lower drought events).

As described in Drought Cycle Analysis section, drought events can evolve to cover all quadrants of the Drought Wheel. To facilitate the observation of this effect, as well as to present another way to visualize the influence of the DNR, we selected periods of each event and showed them directly in the Drought Wheel. The Drought Cycle Analysis is based on the combination of a precipitation index (SPI) which does not vary between the scenarios and a water storage index (VD) which does vary between both scenarios. The vertical axis of the Drought Wheel is related to the SPI and as both scenarios have the same value for this index, each pair of observations will always be horizontally aligned. A greater horizontal distance between the markers indicates a greater influence of the DNR on drought evolution.

We also evaluated the fraction of time that the system is in a particular drought stage, for the different drought events as well as for the whole study period (Figure 2.8). The difference between both scenarios demonstrate the impact of the DNS. It is shown that the small reservoirs can prolongate and advance drought, because the small reservoirs alter the temporal proportion of each drought stage.

For example, for the 1997–2002 event in the All Reservoirs Scenario (ARS, representing the actual situation), approximately 60% of the time the system was in a hydro-meteorological drought, and 26% of the time in a hydrological drought when small reservoirs are present. This means that the hydrological impacts lasted for 86% of the time. Comparing this with the scenario without the DNR (the Large Reservoir Scenario, LRS), only about 25% of the period was in hydro-meteorological drought and 13% was in hydrological drought, that is, the hydrological impacts lasted only 38% of the time. In this case, the DNR almost doubled the duration of hydrological impacts. In general, the hydrological impacts in the ARS scenario lasted about 36% over the whole studied period, while in the LRS scenario this was only 28%. Thus, the presence of the DNR can lead to a 30% increase in duration of the hydrological impacts.

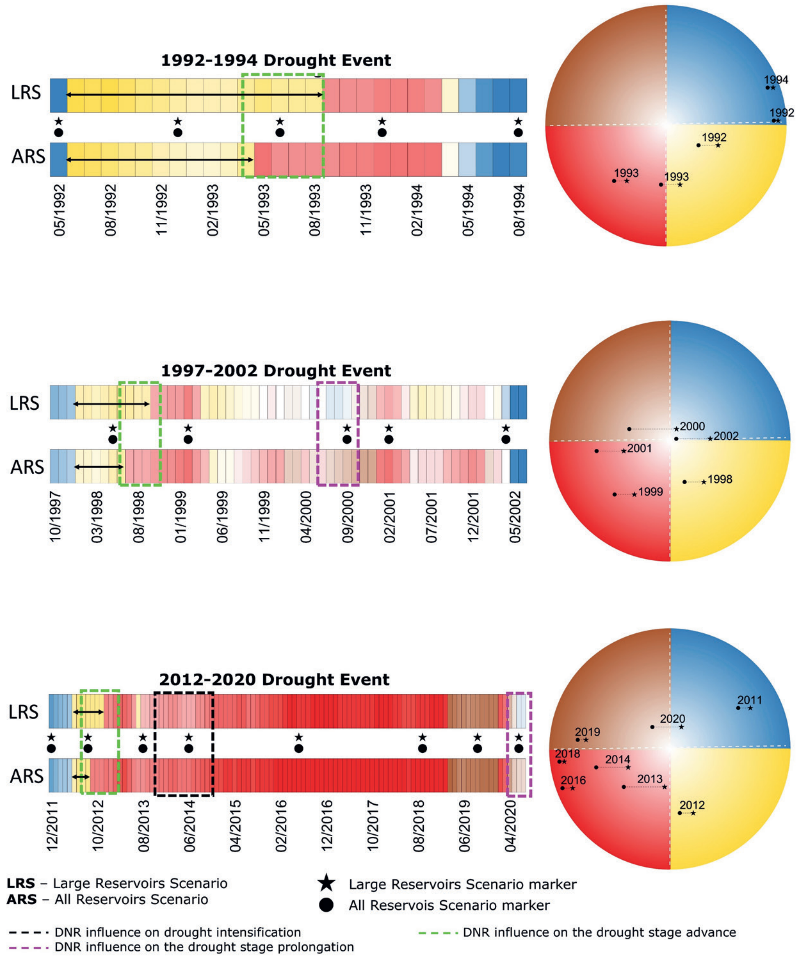

Figure 2.7 - Results of the Drought Cycle Analysis for three distinct drought events. The colours of the horizontal bars align with the colours in the Drought Wheel, indicating the drought stage for a particular month. The black circle and star in between the horizontal bars indicate time periods that are indicated inside the Drought wheel itself. For instance in the top figure, the circle and star for 05/1992 corresponds to 1992 indicated inside the wheel. The distance between the circle and the star is the difference between both scenarios, thereby demonstrating the impact of the small reservoirs in the DNR on volume deviation.

To capture some of the uncertainty associated with our volume estimation of the small reservoirs, we have analysed the sensitivity of our results in Figure 2.8 to a 20% variation in the estimated volume stored in the DNR (minus 10%, plus 10%). The outcomes show that hydrological-drought duration would still increase relative to scenario where no DNR is assumed, by 12% and 45% for the cases of minus 10% and plus 10%, respectively.

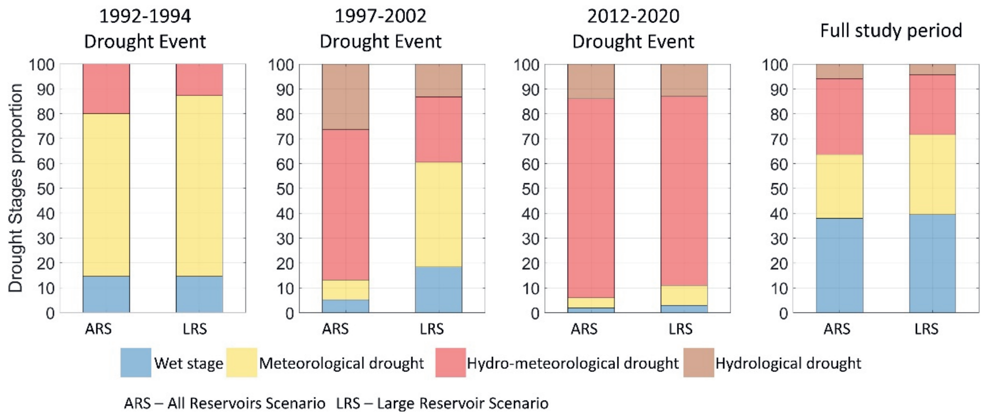

Figure 2.8 - Proportion of time that the system is in each drought stage over the three main drought events (1992–1994, 1997–2002, 2012–2020) and the complete study period for the two scenarios.

2.4 Discussion

2.4.1 Volume Estimation of Unmonitored Reservoirs

The first results obtained in this study were related to the estimation of the volume stored in the Dense Network of (small) Reservoirs (DNR). The validation of these results is challenging as there are no observational data for the overwhelming majority of (small) reservoirs in the study area. However, evaluation is necessary because these results are crucial for the subsequent analyses and conclusions regarding the potential impact of these structures on the evolution and intensification of drought events. The lack of observational data lead to the selection of two indirect evaluation methods:

1) We correlated the total volume stored in the DNR with the total volume stored in the monitored reservoirs. It was expected that these variables would show a high correlation since the hydro-meteorological processes responsible for the recharge of these structures are the same. The rivers in the study area are intermittent, that is, stream drainage flow ceases during the dry season which increases the potential for water loss through infiltration and evaporation. The consequence is that there is an interruption in surface runoff connectivity. This hydrological process is crucial to understand the potential hydrological impacts that small reservoirs can have, since the return of the watershed surface runoff connectivity increases the recharge of large reservoirs and is achieved only when these small reservoirs are full. Hence, there is a strong cause-and-effect relationship between the small reservoirs being full and an increase in the recharge of the large reservoirs. Therefore, a high correlation between these two variables is an indication that the dynamics of estimated storage in the DNR was plausible. During the wet season, the monitored show well-defined interannual seasonality of the stored volume, that is, in general they present similar and homogeneous patterns of recharge and emptying throughout this period. In the drier years, a more persistent and prominent pattern of depletion is observed, associated with lower volumes that can still be retained by unmonitored reservoirs. Thus, the low volumes stored in monitored reservoirs during the driest years would be closer to the stored volume in unmonitored reservoirs and should therefore lead to a higher correlation compared to wet years. Although in general high correlations were found between the estimated volume storage in the monitored reservoirs and the DNR ($R^2 > 0.89$), the highest value was indeed found for the driest years, which confirms our assumption and endorses that the dynamics of the estimated storage in the unmonitored reservoirs was plausible

2) We attempted to show that the estimation of the total volume stored in the DNR was consistent with remotely sensed water storage. We conducted a series of correlation analyses between total storage in the DNR added to the storage in the monitored reservoirs and the Terrestrial Water Storage (TWS) defined from the GRACE and GRACE-FO missions. The volume stored in the monitored reservoirs had a higher correlation (R^2 close to 0.85) with these remote sensing products than the unmonitored reservoirs, however, the highest value was obtained when the monitored and unmonitored (small) volumes were combined

In addition to the limitations of the DNR volume estimation method and precision of the TWS products, the fact that the Riacho do Sangue watershed (1368 km^2) is almost half the size of the GRACE/GRACE-FO pixel (2500 km^2) may explain why not a perfect correlation ($R^2 = 1$) was found. There are possibly thousands of reservoirs that are not part of the study area, but are part of the GRACE/GRACE-FO pixel and therefore should be accounted for in the SWS calculation. If these reservoirs had been considered in the indirect validation using the TWS products, we would possibly have found a more significant increase in the correlation between SWS and TWS.

Furthermore, we assume that the 2294 unmonitored reservoirs that are part of the study area and were not accounted for because their maximum surface water extent is less than the Landsat pixel area do not contribute significantly to the increase in the uncertainties of our results. The maximum volume stored in these reservoirs (considering the Molle equation) would be less than 1.5% of the total storage capacity of the 1138 unmonitored reservoirs that were considered in this study, even if the surface water extent of these small uncounted reservoirs were equal to a Landsat pixel (900 m²).

Another source of uncertainty that could have contributed to the low increase in the correlation between TWS and SWS is the accuracy of the method for identifying water pixels (see Section 2.2.2.2). We used fixed thresholds for water identification with the Modified Normalized Difference Water Index (MNDWI) and Short Wave Infrared band (SWIR). A detailed analysis of the water detection sensitivity of this index through dynamic threshold definition methods (e.g., Du et al., 2014; Ji et al., 2009; Otsu, 1979; Pan et al., 2020) could improve the results presented in this study. Nevertheless, we consider that these results, in addition to the indications that our estimation of the volume stored in DNR is satisfactorily plausible, raise more questions beyond the scope of this study which can be addressed in future research. Possible future directions are: Is it possible to use surface water storage information to downscale GRACE/GRACE-FO products? Is it possible to use GRACE/GRACE-FO products directly or indirectly (e.g., combined with socio-hydrological models) to estimate the volume stored in reservoirs in drought-prone regions with similar physical characteristics to those of the Riacho do Sangue watershed? Answering these scientific questions could improve the understanding of the socio-hydrological dynamics of semi-arid environments, which would be useful to improve water resource management in such regions.

2.4.2 Drought Event Attribution

The Drought Cycle Analysis method has the advantage of considering not only a meteorological index for drought monitoring, but also information directly related to the impact that drought can cause, within this study addressing hydrological impacts. This method can easily be adapted for the study of vegetation droughts (which are not the subject of this study) by choosing a more suitable precipitation-based index time scale for this kind of drought, and by using an index related to vegetation conditions for the horizontal axis.

The index on the horizontal axes should always be tailored to the specific application. Some of the large reservoirs in Ceará and the semi-arid region of Brazil are oversized, that is, their maximum storage capacity is greater than what would be expected based on the hydro-meteorological conditions of the region. Thus, they are rarely completely full and because of this, the volume deviation as defined here based on half of the storage capacity, should not be applied in these situations. We recommend using another hydrological index or to find a value that better represents the median volume of these reservoirs, and to calculate the deviation in volume deviation based on this value. We used the Volume Deviation (VD) from half of the total capacity of the Riacho do Sangue reservoir as a proxy for the storage situation of the study area, since this is the largest and most important reservoir of this region. Furthermore, this information is a socio-hydrological variable, as its variation relies on human demand and the presence of upstream small reservoirs, in addition to the climatic conditions. Therefore, when we consider a socio-hydrological variable that captures the impact that a drought event can cause, what we can actually achieve is an analysis of drought as a hybrid disaster, that is, those that have natural and anthropogenic components (Monte et al., 2020). This differs from many studies that only use meteorological drought indices (e.g., SPI, percent of normal precipitation, K Index) to analyze drought events (Kchouk et al., 2021). These indices characterize the occurrence of precipitation deficit, but without actually associating it to human activities or environmental demands.

Furthermore, the Drought Cycle Analysis method divides a drought event into four possible stages, which allows for detailed analysis of the progression and intensification of this disaster over time. Through this method it is possible to identify in a more precise way when a precipitation deficit starts to cause impacts. This information can be used by decision makers to determine triggers for short-term preparedness and mitigating measures. Figure 2.6 confirms that this delay is significant since it can be seen that the most negative values of SPI did not occur concomitantly with the most negative values of the VD. Analysing the drought events in Figure 2.8, it can be seen that this lag ranged between 3 and 6 months for the Riacho do Sangue watershed.

The comparison of scenarios related to the existence (ARS) or not (LRS) of a DNR can be used to attribute the causes of the drought events. Our results indicate that the high concentration of small reservoirs structures can induce and modify drought events. This is useful to determine whether decision makers should focus on strategies to adapt to natural conditions or mitigate the human actions that are inducing the occurrence of droughts (Van Loon et al., 2016a, 2016b). It is important to note that even during extreme and long-lasting drought events (e.g., 2012–2020) there is not a complete absence of precipitation but an anomalous decrease in precipitation levels (Figure 2.2.3b).

The spatio-temporal distribution of rain can also influence drought conditions; precipitation can occurs over a short time period and only in a small area. This demonstrates the high relevance of understanding the socio-hydrological dynamics of the study area. Human-induced drought events due to the presence of a high concentration of small reservoirs can occur during a meteorological drought, when there is still enough precipitation to recharge these structures but not the main water reservoir of the study area. We attributed that as the cause of the 1997–2002 event, since in the All Reservoirs Scenario (ARS) of this event we observed the development of the four drought stages, while in the LRS (assuming an absence of the small reservoirs) there was mainly an smooth oscillation between meteorological drought and short periods of hydrological drought.

In the study area, the vast majority of reservoirs in the DNR are small, informal and unmonitored. It is known that these structures aim to meet the demands of the respective users only in the short term. Therefore, these reservoirs need to recharge more water during the rainy season than the human and evaporative demands of the dry season, in order to maintain water security. The effect of prolonged droughts results in changes in the water balance of the small reservoirs, to a situation where they are always empty (or partially empty) during the recharge period. In addition, these structures only release water downstream when they are completely full and overflow; coming from an empty situation, it therefore requires longer or more intense periods of precipitation to reach this point. This process, events associated with a high concentration of small reservoirs, can cause human-modified drought, in which the partial or complete emptying of these structures for long periods delays the recharge of the main storage of the study area. The consequence is an increase in the hysteresis of the hydrological system (decrease in resilience) and intensification of drought events, since the little water retained in these structures could otherwise lessen the hydrological impacts. We attributed that the periods 1992–1994 and 2012–2020 were predominantly human-modified drought events, since a high similarity was observed between the ARS and LRS mainly for hydro-meteorological and hydrological drought stages of these events (e.g., black rectangles Figure 2.8).

Conceptually, it is possible that a single event can be attributed both as human-modified and human-induced drought, as was the case for the 2012–2020 event. At the beginning of this period the DNR induced the occurrence of the hydro-meteorological drought over at least 3 months. The human-modification can be noticed at the end of this event in which, due to the intensification of the precipitation deficit, there was a significant reduction in the volume stored in the small reservoirs. This resulted in the persistence of the hydrological impacts. At the end of the Large Reservoirs Scenario of this event, the wet period began at least 2 months earlier than in the ARS. Overall, the hydrological impacts (hydrological drought plus hydro-meteorological drought periods) lasted about 30% longer due to the presence of the high concentration of small reservoirs, and this duration could almost double for specific drought events, such as the 1997–2002 drought event.

The prolongation of hydrological impacts directly affects water availability, aggravating drought impacts. On the short term, impacts are mitigated through emergency policies. For the Riacho do Sangue basin, these measures are related to water supply programs by water trucks (Chapter 3, Figure 3.1f), construction of cisterns(Chapter 3, Figure 3.1c) and income transfer programs, which in general present high financial costs for society (Marengo et al., 2017; Marengo et al., 2017). In the mid to long term, societal pressure may arise to increase storage capacity in order to sustain water security during future drought events. Meeting this demand can be achieved through governmental efforts to build large public reservoirs. However, it is more common that the expansion of storage capacity is conducted by individual initiatives, related to building new small reservoirs. The methods presented in this study can be used as complementary tool to minimize the vicious cycle of the effect of small reservoirs. Estimating the amount of water stored in these structures using remote sensing products provides practical and low cost information relevant to more efficient water resource management, since it reveals the real situation of the analysed hydrological system. In addition, the comparison of the two scenarios (Figure 2.6) can be used for reservoir management. It can be applied for determination of operating rules to prevent the reservoir from entering a stage where its filling would take longer due to the empty condition of the small reservoirs upstream. This information is particularly useful because it helps in the development of contingency plans for the management of large reservoirs during drought events.

This study does not aim to bring discussions about the societal benefits or negatives of the presence of small unmonitored reservoirs in a region. Further detail on the hydrological impacts of small reservoirs as well as the possible benefits of alleviating local impacts of drought events are explored in the next chapter. In the context of the Riacho do Sangue watershed, and in the Brazilian semi-arid region in general, these structures are strongly linked to the history, culture, and productive practices of tens of thousands of subsistence farmers who mostly depend on this water source to survive. Therefore, it is important to emphasize that the idea behind the Large Reservoirs Scenario is purely hypothetical and we do not make any recommendation of policies aimed at removing or limiting the use of these kind of reservoirs.

2.5 Conclusions

This study analysed the role of a Dense Network of (small) Reservoirs (DNR) in the evolution of drought events. The case study was the Riacho do Sangue watershed, located in the semi-arid region of Brazil. The volume stored in these structures was estimated using remote sensing products combined with an empirically based equation. The analysis of the DNR effect was conducted through a new and innovative Drought Cycle Analysis method, which tracks the simultaneous (non)occurrence of precipitation and hydrological deficits and associates this with four drought stages. This method is a useful and simple approach for a better understanding of drought evolution and therefore provides relevant information to improve drought and water management at the watershed level. The influence of small informal reservoirs on these processes was evaluated by comparing a scenario that represents the current situation in the study area and one in which it is considered that the dense network of small reservoirs never existed. The results showed that the small reservoirs can not only intensify the hydrological impacts, but also lead to an earlier drought onset of 3–4 months, and a delay in the recovery of the drought event with at least 2 months.

In response to the frequent occurrence of meteorological drought, the local population has constructed small reservoirs as a coping mechanism. Our results indicate that a high concentration of such structures can induce and modify drought events, mainly with regard to extending hydro-meteorological and hydrological droughts. On the other hand, we also showed that these structures increase the amount of water retained in the study area (although not optimized and managed) and their absence would impose an overall decrease in the cumulative storage in the hydrological system due to the release of water downstream. We showed that a large number of small reservoirs acutely influences water storage of a hydrological system and this should be taken into account in water resources management. The lack of information regarding small unmonitored reservoirs need not hinder their consideration in water resources management, since we showed that it is possible to estimate the volume stored in the DNR using mainly remote sensing products. We also show that the methods presented in this study can be used for the management of large reservoirs considering the storage situation of small unmonitored reservoirs, which can reduce the vulnerability of a region to the occurrence of hydro-meteorological and hydrological droughts.

Overall, this research provides an approach that is helpful for water managers in drought-prone regions with a dense network of small unmonitored and unmanaged reservoirs. While these small reservoirs are invaluable for the livelihoods of smallholder farmers, this study shows that they do adversely impact water storage in large reservoirs and consequently prolong hydrological droughts at the basin scale.

03

Chapter 3

Drought **narratives**

This chapter is under review for Earth's Future from the American Geophysical Union as:

Ribeiro Neto, G. G., Melsen, L. A., Costa, A. C., Walker, D. W., Cavalcante, L., Kchouk, S., Brêda, J. P., Martins, E. S. P. R., and van Oel, P. R. (2023). Clash of drought narratives: A study on the role of small reservoirs in the emergence of drought impacts, *under review, Earth's Future.*

Abstract

In regions characterized by a high concentration of small reservoirs, there is often public debate about the effectiveness of these structures in locally adapting to and mitigating drought impacts, bearing in mind their potential to modify or induce drought events in downstream areas. In this study, we investigated the influence of a Dense Network of Small Reservoirs (DNR) on the emergence and intensification of drought impacts at catchment scale, as well as their local social benefits. This analysis was based on the Socio-Hydrological-Agricultural-Reservoir (SHARE) model, specially developed for this purpose, with a medium-sized catchment in the semi-arid region of Brazil as a case study. We identified that, while a DNR can prolong the effects of a hydrological drought on storage in a large strategic reservoir at the catchment outlet by obstructing surface-runoff connectivity, it plays a crucial role in mitigating drought impacts on a local level. Specifically, the presence of small reservoirs has the potential to boost local agricultural production by up to 5 times compared to scenarios without these structures. In addition, our simulation results suggest there is a notable reduction in the need for emergency water distributions by water trucks in the presence of a DNR. This study highlights the need for a balanced approach to implementing public policies, weighing the local benefits of small reservoirs against the possible downstream impacts on large reservoirs.

"Everything should be made as simple as possible, but not simpler."
(Albert Einstein)

3.1 Introduction

There is broad consensus that hydro-climatic disasters should not be analyzed solely from a natural sciences perspective, since the human component plays a relevant role in this context (AghaKouchak et al., 2021; Chapter 2; Sivapalan et al., 2011; Walker et al., 2022). This idea contests any narrative that places a hydrometeorological catastrophe as purely a "natural disaster", since anthropogenic actions are now seen as an endogenous component of the hydrological cycle (Di Baldassarre et al., 2019a). In the context of recognizing the importance of the human component in the study of disasters, the field of socio-hydrology emerged, dedicated to evaluating the interactions and relationships between social and hydrological systems, considering how human activities impact water resources and vice versa (Pande and Sivapalan, 2017). Specifically in the context of drought, socio-hydrology sheds light on debates related to the effectiveness of mitigation measures, considering that such actions can induce and/or modify drought events (Van Loon et al., 2022, 2016b).

In regions with low water availability, the construction of small reservoirs is a common strategy for adapting to droughts (Cavalcante et al., 2022; Medeiros and Sivapalan, 2020a; Walker et al., 2022). However, if executed without adequate planning, it can alleviate impacts in one part of the catchment and intensify them in other parts (Wanders and Wada, 2015), which can generate internal social tensions (Studart et al., 2021) and discussion related to the effectiveness of these structures (Donchyts et al., 2022). This tension was clearly observed by the authors during fieldwork in the semi-arid region of Brazil. It was evident that there were conflicting narratives about the role of small reservoirs versus large reservoirs. Some actors, mostly linked to the government water sector, described small reservoirs as detrimental to the recharge of large (so-called "strategic") reservoirs. On the other side, farmers and some governmental stakeholders mostly from the agriculture sector considered the same small reservoirs as crucial to their water security, asserting that they do not impact hydrological processes of the catchment. One of their arguments was that water in the large reservoirs would evaporate if not utilized, making it more advantageous to use it in the small reservoirs.

Studies show that the collective effect of small reservoirs can reduce the streamflow into the “strategic” reservoirs (Krol et al., 2011; Udinart Prata Rabelo et al., 2022; Chapter 2), however the overall impact and local benefits remain unclear. The role of a Dense Network of Small Reservoirs (DNR) on drought emergence is still not well understood. In this study, we focus on the clash of these two contrasting narratives, exploring the role of small reservoirs and farmers' water use in the emergence and intensification of drought impacts. We based our study on simulations using a novel socio-hydrological modelling framework capable of simulating hydrological processes, agricultural production, and water resource management at catchment and farm scales, with a medium-sized catchment in the semi-arid region of Brazil as a case study.

3.2 Methods

We aimed to understand the role of a DNR on the emergence of drought impacts. To this end, we evaluated drought narratives commonly related to reservoir structures, which can be summarized as an evaluation of two conflicting hypotheses:

Downstream impacts hypothesis - The DNR has the potential to induce, aggravate or extend hydrological drought events especially in the downstream reservoirs of the catchment.

Local benefits hypothesis - The DNR does not cause (serious) negative hydrological impacts in the downstream region of the catchment and is significantly beneficial to local farmers.

To evaluate the foundation of these two hypotheses, we divided the analysis into three stages: 1) Analysis of the spatio-temporal distribution of water storage; 2) Analysis of evaporative losses and DNR storage efficiency; 3) Analysis of the local benefits of a DNR. We evaluated both hypotheses using the Piquet Carneiro catchment as case study, which is a socio-environmentally representative area for semi-arid Brazil. Through data analysis and interviews in the field, we identified the main local socio-hydrological dynamics. Based on these dynamics and hydro-meteorological data, we developed a spatially explicit socio-hydrological model and simulated several scenarios to investigate the two hypotheses.

3.2.1 Case study

Figure 3.1 presents the location and some features of the study area. The Piquet Carneiro catchment (170km^2, Figure 3.1a) is part of the Brazilian state of Ceará, which is within the semi-arid region of Brazil. The study area presents an irregular annual distribution of precipitation (670mm/year on average, Figure 3.1b), but with well-defined wet (4 months) and dry (8 months) seasons. Potential evapotranspiration is high, around 2000 mm/year. Its shallow soils and crystalline bedrock limit the existence of regional aquifers and perennial rivers, making artificial reservoirs damming intermittent rivers the main source of water during dry periods.

There is a large public reservoir (13.6 Mm^3), centrally managed and therefore called "strategic". From a water management standpoint, its strategic function consists in serving as primary sources for urban water supply and for water trucks when necessary. This reservoirs was built with public funding. It is monitored by the Company of Water Management of the State (COGERH) and Ceará Research Institute of Meteorology and Water Resources (FUNCEME).

The Dense Network of Small Reservoirs (DNR) of the study area consists of 364 small reservoirs. They are privately owned, built by individuals or communities (sometimes with credit lines provided by governmental programs) to fulfill their own needs. These mainly meet the needs of dairy herds, the main local economic activity, and domestic use. Besides, the vicinity of the reservoirs facilitates agriculture due to higher soil moisture levels (Figure 3.1h). For all small reservoirs there is only information available on their location and maximum surface area, which was made available by the Ceará Research Institute of Meteorology and Water Resources (FUNCEME), but their storage is not monitored.

The previous drought event that occurred in the study area was, according to various studies, one of the most intense in the area's recent history. Although the exact duration is not easy to determine, there is common understanding in literature that it persisted for at least six years, from 2012 to 2018 (Costa et al., 2021; Cunha et al., 2018; Cunha et al., 2019; Dos Santos et al., 2019). It is estimated that by 2016 the economic losses associated with this drought event were in the order of 30 billion dollars for the entire semi-arid region of Brazil (Marengo et al., 2017). In this same year, 39 out of the 153 strategic reservoirs of Ceará state were completely empty, while another 42 reached levels below the active volume, requiring specific pumping systems to access the remaining water. As a result, 52% of the municipalities, including Piquet Carneiro, faced water-supply interruptions during this drought (Martins et al., 2018). This event will be referred to in this study as the 2012-2018 drought.

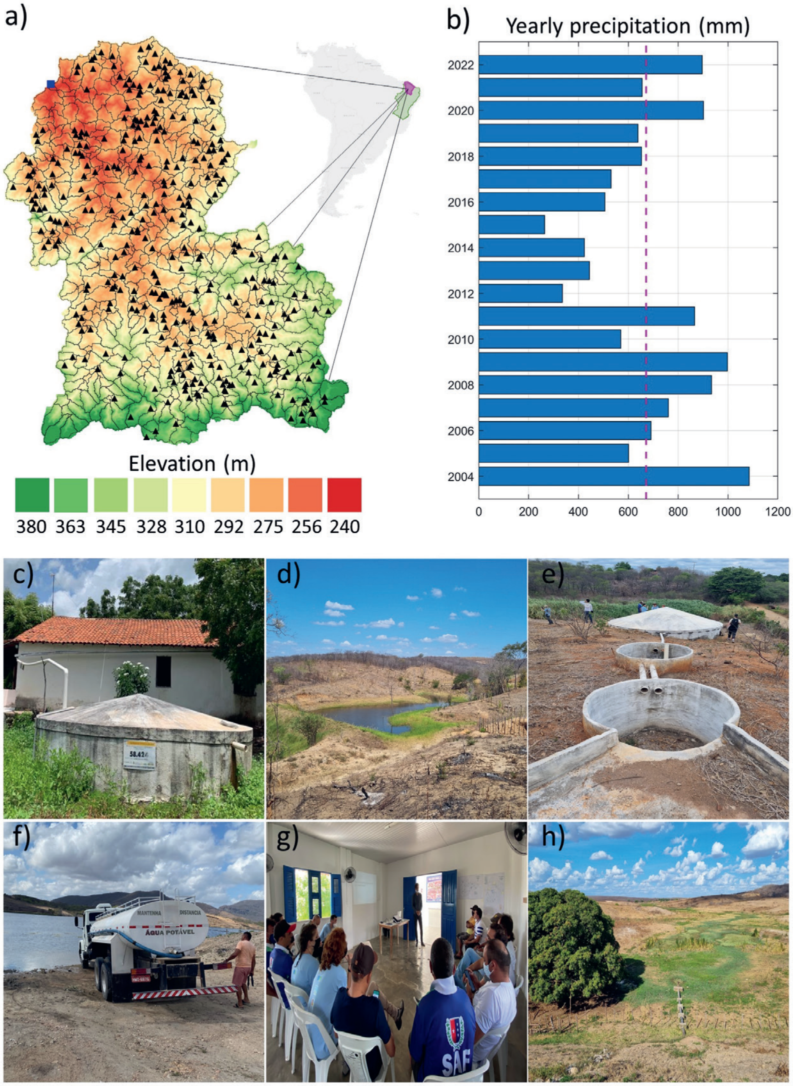

Figure 3.2 - Location and features of the study area. a) Location and elevation of the study catchment and sub-catchments (see section 3.2.2). The blue square and black triangle represent the strategic reservoir São José II and small reservoirs from the DNR, respectively; b) Yearly precipitation time series. The dashed purple line represents the average precipitation through the study period (2004 to 2022); c) Common rooftop rainwater cistern for domestic uses used by farmers in the study area; d) Example of a small reservoir; e) Cistern for production purposes that collects water from surface runoff (ground cistern); f) Water truck being refilled at the only strategic reservoir in the study area; g) Workshop conducted by the authors of this study with farmers and water practitioners in the study area in November 2021; h) Crop being sustained by high soil-moisture content due to the presence of a small reservoir.

The majority of the rural population has no access to piped water, therefore the main water source for basic household needs (drinking, cooking and basic personal hygiene) is the rooftop rainwater cistern, which collects water through the house's rooftop (16 m^3, Figure 3.1c). The second type of cistern is for production purposes, which collects water through surface runoff (52m^3, Figure. 3.1e). However, this type of cistern is more expensive for the population and therefore not as common in the study area as the rooftop rainwater cistern. In this study, our focus was on cisterns used for domestic purposes, hereafter referred to as "cistern". In times of shortage, such as during a drought, water trucks run by the municipality and the army provide emergency water supply to the rooftop rainwater cistern (Figure 3.1f).

3.2.2 Socio-hydrological modelling framework

We developed the Socio-Hydrological-Agricultural-Reservoir (SHARE) model, first presented in this study, to investigate the influence of socio-hydrological dynamics on drought impacts at multiple scales. The SHARE model is capable of spatially-explicit simulation of the main hydrological processes, water use, and agricultural production, using a daily time step. This model innovatively combines the water-balance approach following the MGB model (Collischonn et al., 2007), the crop-water productivity of the AquaCrop model (Raes et al., 2009), and a water use model based on information obtained by field observations and interviews. In the SHARE model we also considered the observed drought mitigation measures at different scales, such as cisterns, water trucks and small reservoirs. SHARE's water use model is able to simulate water use from individual households as well as water availability from the strategic reservoir. A summary of the structure of this model is shown in Figure 3.2. The precipitation and temperature data used in all stages of SHARE come respectively from the rain gauges of Brazil's National Water Agency (ANA) and the meteorological stations of Brazil's National Meteorological Institute (INMET).

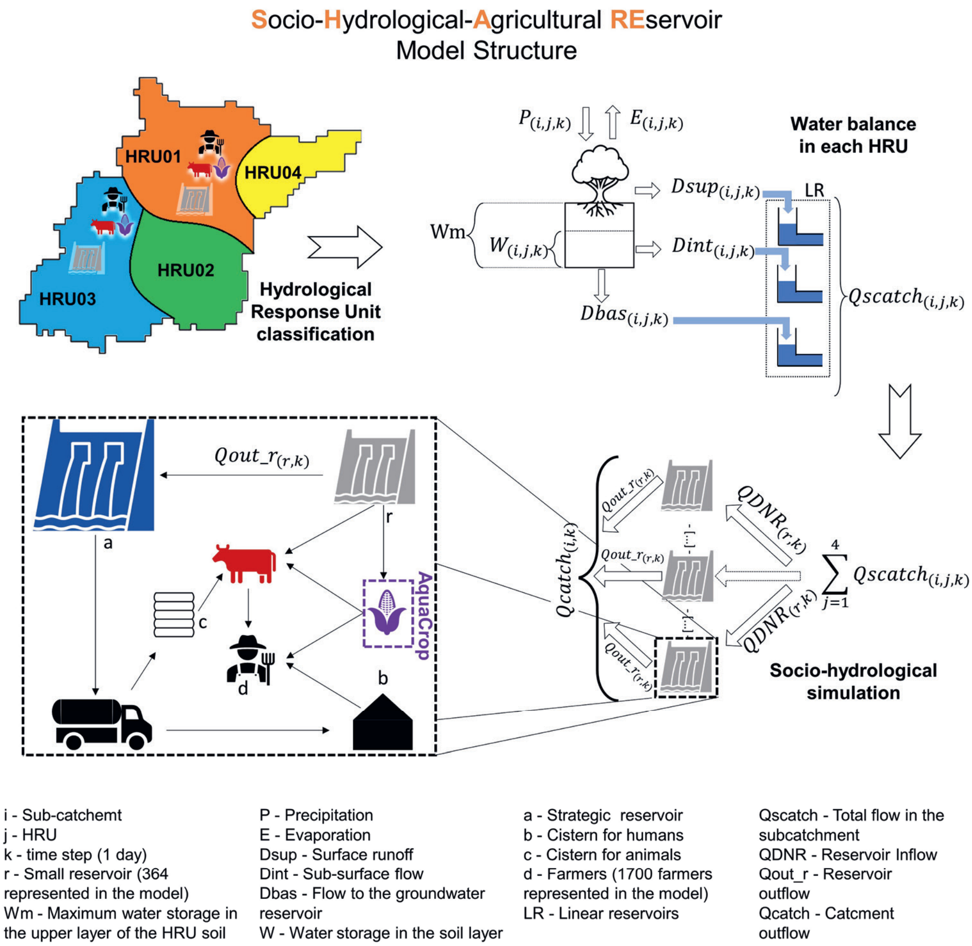

Figure 3.3- SHARE model structure

The study area was segmented into 512 sub-catchments of 0.33 km^2 on average, connected through drainage channels that were defined using the digital elevation model of the NASADEM product with a horizontal resolution of 30 m (Crippen et al., 2016). Each sub-catchment is classified into Hydrological Response Units (HRU), which represent common vertical hydrological processes zones (natural vegetation, agriculture, pasture and non-vegetated areas) and for which the water balance is calculated. We consider there are three possible types of runoff acting in the sub-basins, which are surface (Dsup), sub-surface (Dint) and underground (Dbas) flow, as shown in the Water-balance section of Figure 3.2. The types of runoff vary according to the speed at which they appear and propagate. Surface runoff" reaches the drainage network quickly, while "sub-surface runoff" has an intermediate speed, and underground runoff is the slowest. Each type of runoff is collected by a different ("hypothetical") simple linear reservoir ("LR" Figure 3.2). The combined volume released by these reservoirs corresponds to the flow in the sub-basin (Qscatch). These hydrological processes are calculated according to the following equations based on Collischonn et al, (2007):

$$W_{(i,j,k)} = W_{(i,j,k-1)} + \left(P_{(i)} - ET_{(i,j)} - Dsup_{(i,j)} - Dint_{(i,j)} - Dbas_{(i,j)}\right) \times \Delta t \quad (3.1)$$

Where Δt is the time step (one day); $W_{(i,j,k)}$ is water storage in the soil layer, at the end of the time step (k), of the HRU (j) of catchment (i); P_i is the precipitation that reaches the soil; $ET_{i,j}$ is the potential evaporation calculated by McGuinness-Bordne equation (McGuinness & Bordne, 1972); The runoff pathways were calculated based on soil water storage at the start of the time step and on model parameters. Collischonn et al. (2007) estimates of Dsup are taken from the ARNO model (Todini, 1996).

$$Dsup_{(i,j)} = \Delta t \times P_{(i)} - (Wm_{(j)} - W_{(i,j,k)}) \text{ for } y \leq 0 \quad (3.2)$$

$$Dsup_{(i,j)} = \Delta t \times P_{(i)} - \left(Wm_{(j)} - W_{(i,j,k-1)}\right) + Wm_{(j)} \times \left[\left(\left(1 - \frac{W_{(i,j,k-1)}}{Wm_{(j)}}\right)^{\frac{1}{b_{(j)}+1}} - \left(\frac{\Delta t \times P_i}{Wm_j \times (b_{(j)}+1)}\right)\right)\right]^{b_{(j)}+1} \text{ for } y > 0 \quad (3.3)$$

$$\text{Where } y = \left[\left(1 - \frac{W_{(i,j,k-1)}}{Wm_{(j)}}\right)^{\frac{1}{b_{(j)}+1}} - \left(\frac{\Delta t \times P_{(i)}}{(b_{(j)}+1) \times Wm_{(j)}}\right)\right] \quad (3.4)$$

Where $Wm_{(j)}$is maximum water storage in the $HRU_{(i,j)}$ upper soil layer ; $b_{(j)}$ is the HRU related parameter.

$$Dint_{(i,j)} = Kint_{(j)} \left(\frac{W_{(i,j,k-1)} - Wz_{(j)}}{Wm_{(j)} - Wz_{(j)}}\right)^{\left(3 + \frac{2}{\gamma_{(j)}}\right)} \quad (3.5)$$

$$Dbas_{(i,j)} = Kbas_{(j)} \times \frac{(W_{(i,j,k-1)} - Wc_{(j)})}{(Wm_{(j)} - Wc_{(j)})} \quad (3.6)$$

Where $Wz_{(j)}$ and $Wc_{(j)}$ are respectively the lower limit below which there is no subsurface and ground flow; $Kint_{(j)}$ and $Kbas_{(j)}$ are related to the subsurface drainage and percolation rate to groundwater in case of saturated soil; and $\gamma_{(j)}$ is the soil porosity index.

$$Qscatch_{(i,k)} = \frac{1}{TKS_{(i)}} \times Vsup_{(i,k)} + \frac{1}{TKI_{(i)}} \times Vint_{(i,k)} + \frac{1}{TKB_{(i)}} \times Vbas_{(i,k)} \quad (3.7)$$

Where TKS, TKI, and TKB are time response parameters. Vsup, Vint, and Vbas are respectively the water volumes in the surface, sub-surface and groundwater reservoirs of the sub-basin “i”, at time step “k”. $Qscatch_{(i,k)}$is the total flow of the sub-catchment.

The sub-catchment runoff (Qscatch) is distributed proportionally to the capacity of the small reservoirs located in the sub-catchment (similar to Güntner et al., 2004). For example, a reservoir responsible for 20% of the sub-catchment’s total storage capacity will receive 20% of Qscatch. The relationship between the water surface and the volume stored in the DNR reservoirs is represented by the equation developed by Molle, (1994):

$$SWE_{(r,k)} = c.d\left(\frac{Vr_{(r,k)}}{d}\right)^{\frac{(c-1)}{c}} \quad (3.8)$$

Where SWE and Vr are respectively the surface water extent and stored volume of the reservoir “r” on the time step “k”. c and d are empirical parameters related to the geometry of the small reservoirs, with average values of 2.7 and 1500 calculated by Molle, (1994). The runoff leaving each sub-catchment is the sum of the volume exceeding the maximum storage capacity of the DNR reservoirs, which is propagated directly to the sub-catchment immediately downstream.

3.2.3 AquaCrop

The AquaCrop model (Raes et al., 2009) was developed by the Food and Agriculture Organization of the United Nations (FAO) to simulate the growing process and yield of crops under water stress. It can simulate how water excess or deficit affect crop development. This model can also be used to indicate the optimal water need for irrigation. In this study, AquaCrop was used to simulate the crop yield in all scenarios considered (see section 2.5). For those scenarios that include irrigation, we consider that the farmers would irrigate following the indication simulated by the AquaCrop. This model demands specific parameters related to crop and soil characteristics (e.g. duration of flowering, maximum temperature in which the pollination happens, number of plants per hectare, soil texture) which were derived from Martins et al., (2018) and Martins et al., (2019).

3.2.4 Socio-hydrological modeling decisions

After completing the routines for generating and propagating surface runoff, SHARE simulates water use and agricultural production at a daily time step. A rural house location product developed by the FUNCEME was used to include farmers in a spatially-explicit way. The following modelling decisions applied to the SHARE model were based on workshops (Figure 3.1g) and interviews with farmers and water practitioners in the study area. This revealed contextualized details, which led us to simplify the representation of some socio-hydrological dynamics in the model.

Each house represents a family of five, with a daily water consumption (cis_dm) of 14 liters per person, supplied primarily by cisterns, which is aligned with the technical recommendation for designing such structures (Silva et al., 1984). The volume stored in each cistern was updated each time step, considering the consumption and the recharge due to rainfall on the sub-catchment to which the house belongs. An interception area of 100 m^2 per home was assumed (roof_area), given the similarity of houses in the region. If a cistern drops to 2% of its capacity (cis_tr), it is supplied with 8 m^3 of water from a water truck, which comes from the strategic reservoir in the region (Figure 3.1f represents exactly this moment).

According to interviews, we consider that the most relevant agricultural production to be simulated is maize, which is mainly destined for family consumption and to produce silage for the dairy herd. The annual agricultural production of maize in the study area was obtained from the Brazilian Institute of Geography and Statistics (IBGE). The number of animals was fixed through the simulation period and defined by the ratio between the expected agricultural production (assumed 8ton/ha/year, exp_yield) and an average consumption of silage per cow of 30 kg/day (sil_dm). Secondary water use corresponds to 80 liters/day per person for domestic activities (dnr_dm) and 100 liters/day per animal (animal_dm). The farmers use the small reservoirs to meet these demands. If the reservoirs dry up, they request water trucks, also from the strategic reservoir in the region. Table 3.1 presents a summary of all parameters of the SHARE model also showing the source.

Although water use can vary in response to water availability, as in the case of adopting different agricultural strategies, this possibility was not considered in our simulation. We could not infer this information from the collected data, and there is a lack of validation data (such as storage in small reservoirs) to justify a further increase in model complexity.

Parameters such as daily water demand from cisterns (cis_dm), daily human water demand from the DNR (dnr_dm) and daily animal water demand (herd_dm) have a direct impact on the volume of water stored and the potential need for water trucks. The daily animal silage demand (sil_dm) and expected agricultural production (exp_yield) define the number of animals per farmer, affecting animal water demand. The maximum daily irrigation (max_irr) influences agricultural production and is related to the Aquacrop model in scenarios that include irrigation (see section 3.2.5). All the parameters linked to human and animal demands have the potential to affect agricultural production, since these demands compete with irrigation demands.

Table 3.1 –SHARE parameter list

Parameter number	Parameter name	Definition	Source
Hydrological component			
1	Wm	Maximum water storage in HRU upper soil layer	Calibration
2	Wz	Lower limit below there is no subsurface flow	Calibration
3	Wc	Lower limit below there is no ground flow	Calibration
4	Kint	Subsurface drainage parameter	Calibration
5	Kbas	Percolation rate to groundwater parameter	Calibration
6	b	HRU related parameter	Calibration
7	y	Soil porosity index	Calibration
8	TKS	Surface reservoir time response	Calibration
9	TKI	Sub-surface reservoir time response	Calibration
10	TKB	Ground reservoir time response	Calibration
Water use component			
11	cis_dm	Daily water demand from cistern	Fieldwork
12	dnr_dm	Daily human water demand from DNR	Fieldwork
13	animal_dm	Daily animal water demand from DNR	Fieldwork
14	roof_area	Interception area of each house	Data analysis
15	cis_tr	Minimum volume that the cistern can reach before an emergency supply by water truck is necessary	Fieldwork
Agricultural component			
16	sil_dm	Daily animal silage demand	Fieldwork
17	exp_yield	Expected crop yield used to define the fix number of animals	Fieldwork
	-	AquaCrop parameters for maize crop (Table A1 in the Appendix A)	Martins et al., (2018)

We tested the influence of the fieldwork-derived parameters on the evaluated output metrics (total water storage, agricultural production and number of water trucks) varying the parameters one-at-a-time, considering a scenario that includes irrigation (SC2, see section 3.2.5). The results are depicted in Figure A1 in the Appendix A. As expected, total water storage and the number of water trucks respond linearly to daily water demand. All the parameters linked to human and animal demands also affected agricultural production, since these demands compete with irrigation demands. The fieldwork-derived parameters could be tailored to other regions with comparable water systems. In our analysis, the parameters are kept constant among the different scenarios (Section 3.2.5), which allows for consistent mutual comparison.

3.2.5 Scenarios analysis

To evaluate the two diverging hypotheses on the role of the DNR in drought impact emergence, we explored and compared four different scenarios. The first scenario (SC1) represents the current situation in the study area, where small reservoirs are used to meet the water demand of households, livestock and as a way of increasing soil moisture to increase agricultural productivity. The second scenario (SC2) follows SC1 but assumes that all farmers are also able to use the water stored in the DNR for irrigation. The SC2 aims to assess the local benefits and hydrological impacts of intensive use of the water stored in the DNR in the catchment. The third scenario (SC3) follows the same pattern as the SC2 but assumes that the reservoirs of the DNR have 30% increase in storage capacity. This scenario was developed to encompass the narrative that an increase in reservoirs would be beneficial for the local population, which was reported during some field interviews. In the last scenario (SC4) we evaluated the effect of the total absence of the DNR in the study area. The SHARE model was validated using the results obtained in SC1 for the volume stored in the strategic reservoir and for simulated total agricultural production. The calibration period was from 2002 to 2010 and the validation period from 2011 to 2022.

3.2.6 Evaluation of the spatio-temporal variation of the water storage

One way of assessing the downstream impacts of the DNR is by analyzing the spatio-temporal variation in water storage. We propose an innovative approach for this assessment: the Center of Water Storage (CWS), as shown in the following equation.

CWS refers to a (hypothetical) location where all the surface water in a catchment could be concentrated, considering the volumes of all the surface storage sources (reservoirs) within the analyzed catchment and their distance to the outlet.

$$CWS = \frac{\sum_{r=1}^{n}(Vr_{(r,k)} \times d_{(r)})}{\sum_{r=1}^{n} Vr_{(r,k)}} \quad (3.9)$$

Where Vr is the volume stored in the reservoir (r) at time step (k) and d is the distance from the considered reservoir to the outlet. This approach is analogous to the physical concept of center of mass and similar to the concept of Downstreamness presented by Van Oel et al., (2018), which considers the drainage area of each reservoir instead of the distance to the outlet. Both CWS and Downstreamness assess the temporal variation of water storage throughout a catchment, and can indicate whether there is a greater concentration of water downstream or upstream. The CWS has the advantage of being easier to determine considering a DNR, since the small size of these structures can make it difficult to determine their exact drainage area.

3.3 Results

3.3.1 Model evaluation

Before evaluating the scenarios, the model results for the current scenario (SC1) were compared to available observations. Figure 3.3 shows the validation stage of the SHARE model based on the SC1 outputs. The data available for validation were the time series of the monthly volume stored in the strategic reservoir and the region's annual agricultural production (maize). It can be seen that the model was able to accurately simulate the volume of the strategic reservoir, with a Nash-Sutcliffe index of 0.89. The model tends to overestimate the observed values, especially in drier periods. This may be due to possible changes in the operating rules, as we did not have access to details of these dynamics; we assumed that the reservoir was operated according to a simple rule of releasing a constant flow corresponding to the 95% quantile of the inflow during the rainy season only. The agricultural production simulated by the SHARE model showed a good similarity to the observed series, with a correlation of 0.68, indicating that the model was able to capture the general trend in the temporal variation of this variable. The results were expressed as an anomaly due to the uncertainties related to the annual planted area, since farmers do not always use all the area available for planting. Although a thorough evaluation of the model is impossible due to a lack of relevant observations, for instance of water storage in the small reservoirs, these results provide confidence that the model is able to capture the main dynamics relatively well.

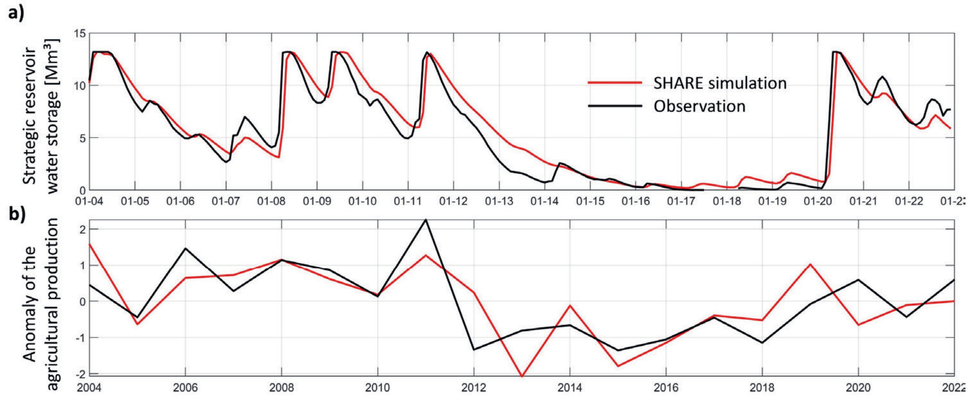

Figure 3.3 - SHARE model validation. a) Strategic reservoir water storage; b) Anomaly of agricultural production.

3.3.2 The spatio-temporal distribution of stored water

Figure 3.4 shows the spatio-temporal distribution of surface water storage in the study area, simulated using the SHARE model. The absence of the DNR would significantly increase the volume stored in the strategic reservoir, by up to 11 times during the 2012-2018 drought, compared to a situation where these structures are present. Hence, even though the total storage capacity of the study area is lower without DNR, the total surface water storage (strategic reservoir plus DNR) in the drier periods is higher (e.g. 2012-2018 drought Fig.3.4c), by up to 5 times. This can be attributed to an increase in the system's storage efficiency, by concentrating all the surface water in a single, larger reservoir instead of distributing part of the system's water in smaller structures that promote proportionally greater evaporative losses. The evaporative losses and storage efficiency aspects of the DNR are also part of the narrative related to the "*Downstream impacts hypothesis*" and will be discussed in more detail in section 3.3. 3.

During the 2012-2018 drought in SC4 (the scenario without DNR) the strategic reservoir would have reached alarming levels (<50%) 2 months later than actually recorded. Considering critical level (<25%) this difference would have been 15 months. The length of periods in these ranges varied considerably between SC4 and the other scenarios. Without the small reservoirs, the strategic reservoir would have remained below 50% of total storage capacity for 82 months (36% of the period studied) and below 25% for 30 months (13% of the period studied). For the other scenarios, it would have been approximately 132 months (58% of the period studied) below 50% and 80 months (35% of the period studied) below 25% of total storage capacity.

Figure 3.4d presents the spatio-temporal distribution of water as a function of distance from the catchment outlet and considering the stored volume in relation to the storage capacity for SC1, which represents the current situation. For example, the reservoirs that are around 12 kilometers from the outlet had a storage volume close to 70% of their storage capacity during the rainy season of 2021, while those around 6 kilometers away were at about 18% of their capacity at this time. During the analyzed period, there were two drought episodes in the study area: a weak/milder one from 2006 to 2008 and the last, more severe one from 2012 to 2018, as mentioned above. During these droughts, the reservoirs emptied evenly regardless of their position in the catchment but the recovery of stored water occurred from upstream to downstream.

From 2004 to 2012, the Center of Water Storage (CWS) did not show major seasonal variations throughout the year. With the onset of the drought in 2012, the CWS remained close to the strategic reservoir due to a uniform reduction in the volume stored in the river basin. However, from 2014 onwards, the CWS moved upstream, indicating that even when the strategic reservoir was on the verge of depletion, there was still water stored more upstream in the study area, in the DNR.

Between 2016 and 2020, the small reservoirs delayed the recovery of storage in the strategic reservoir, evidenced by the gradual recovery of the volume stored in the area, which occurred from upstream to downstream. The existence of the DNR influences the recharge of the strategic reservoir, delaying its recovery and prolonging the impacts of drought events as measured by the level of the strategic reservoir. On the other hand, the lack of major difference between the storage in the DNR and in the strategic reservoir, when comparing the scenarios with and without irrigation (Figure 3.4a and Figure 3.4b) indicate that the way farmers use water from small reservoirs do not influence dominant hydrological processes related to the recharging of these structures. This also indicates that the emptying of small reservoirs is dominated more by evaporation losses than by local anthropogenic demands.

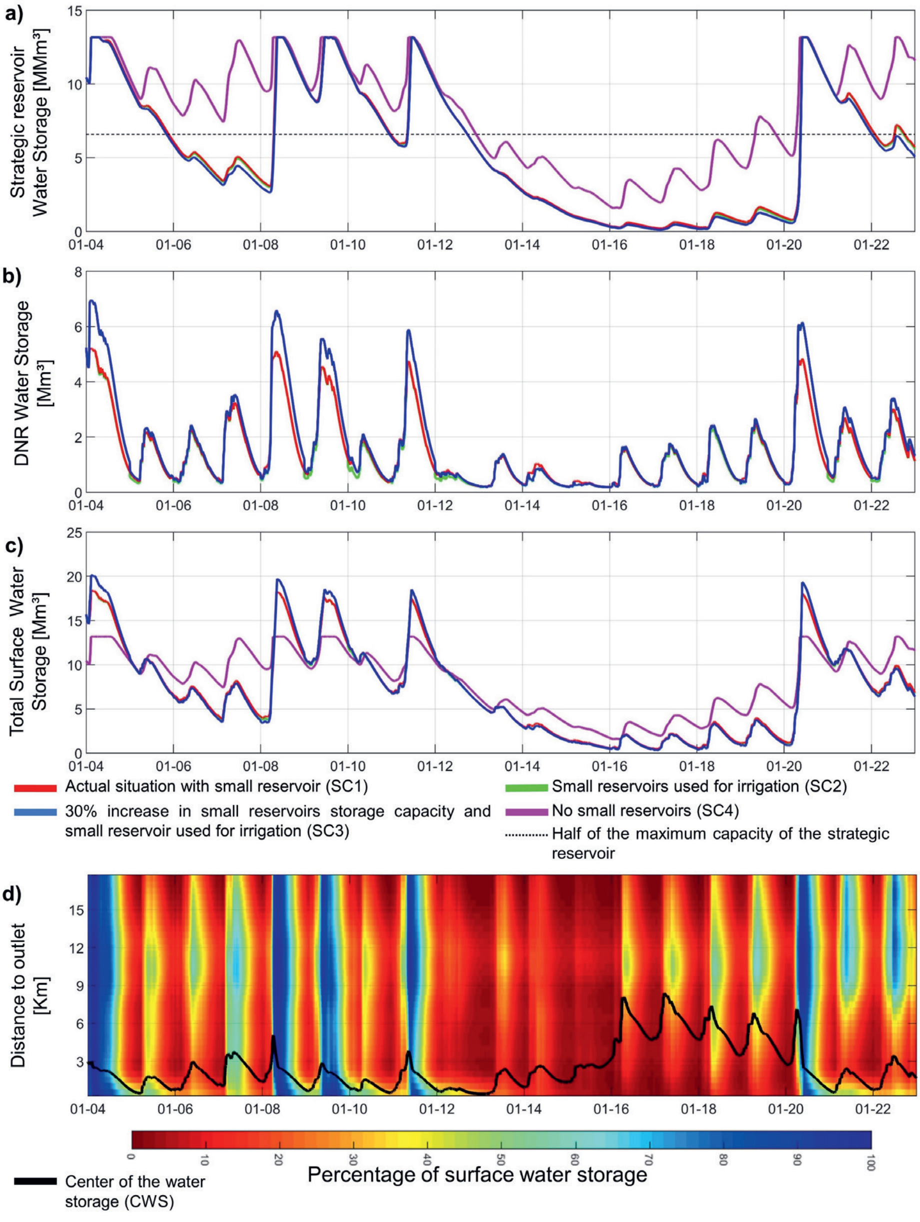

Figure 3.4 - Spatio-temporal water storage distribution. Panels "a", "b", and "c" present the volume variations in the strategic reservoir, Dense Network of (small) Reservoirs (DNR), and total surface water storage (TSWS), respectively. Panel "d" illustrates storage distribution based on distance from the catchment outlet, related only to the current scenario (SC01). The black line in this figure indicates the distance of the Center of Water Storage (CWS) to the outlet.

3.3.3 Water storage efficiency

An argument often used against small reservoirs is that these structures are inefficient from a storage point of view due to relatively high evaporation losses. Evaporation from reservoirs is evaluated in Figure 3.5a, which shows the annual evaporation for both small and strategic reservoirs. Only between 2014 and 2016 was there similarity between the evaporative losses of all the scenarios and this coincides with the most intense period of the 2012-2018 drought. In the other periods, the small reservoirs caused, on average, 60% more evaporation, while increasing surface water storage capacity by only 17% in comparison to the scenario without the DNR (SC4).

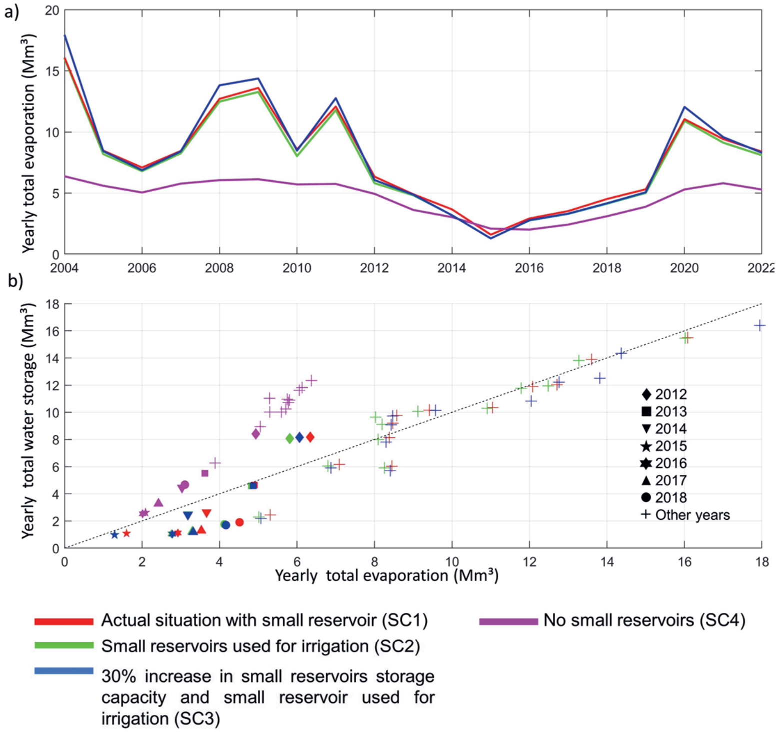

Figure 3.5 - Water storage efficiency. a) Yearly total evaporation; b) Ratio between total water storage and total evaporation in the catchment.

On average, evaporation accounts for 35% of the total storage capacity in the scenario without the small reservoirs (SC4) and 42% in the scenario with the small reservoirs (SC1). The storage efficiency of each scenario was also analyzed using the ratio between annual stored volume and evaporation, shown in Figure 3.5b. In this scatter plot, the pair of values below the 1:1 line indicate that the total water storage at the end of the year is lower than the total evaporated over the same period.

We consider this situation to be an inefficient water storage system and the optimal alternative would be indicated by a pair of values as high as possible above the 1:1 line. On average, 1.37 Mm^3 evaporated for every 1 Mm^3 stored. The lowest performance in this ratio was 2.7 Mm^3 evaporated for every 1 Mm^3 stored. Thus, in addition to delaying the recovery of the strategic reservoir, the DNR also considerably reduces the system's water storage efficiency, especially during drought events.

3.3.4 Analyzing the benefits of a DNR

Despite delaying the recovery of the strategic reservoir, and higher evaporation rates, small reservoirs are still defended as coping strategies by farmers (*Local benefits hypothesis*). Therefore, we also explored the benefits that small reservoirs can bring. Figure 3.6 shows annual agricultural production (maize) and the use of water trucks for all four scenarios considered. Interestingly, small reservoirs boost agricultural production, which is on average 5 times higher in the scenario without irrigation (current situation, SC1) and approximately 8.7 times higher in the scenarios with irrigation (SC2) when compared to the scenario that does not consider the existence of the reservoirs (SC4). Furthermore, without the small reservoirs there would be greater dependence on water trucks for livestock farming, up to 15 times higher, as we assumed that farmers would not abandon this activity due to local water shortage. Thus, the small reservoirs substantially increase agricultural production and decrease dependency on water trucks.

Further increasing the storage in small reservoirs, as foregrounded by some farmers in the field, does not equivalently increase production. SC3, which assumes that the small reservoirs are 30% larger, shows an average agricultural production 1% higher than SC2, suggesting that the amount of water stored in the reservoirs already meets most of the demand for irrigation. Irrigation can increase production by 66% on average and 130% during droughts. However, this extra demand for water would accelerate the depletion of the reservoirs, increasing the need for water trucks during times of water shortage. In short, the use of water from small reservoirs has a greater influence locally, by alleviating drought impacts through boosting agriculture and reducing the need for water trucks, than on downstream water availability, when considering the water storage in the strategic reservoir.

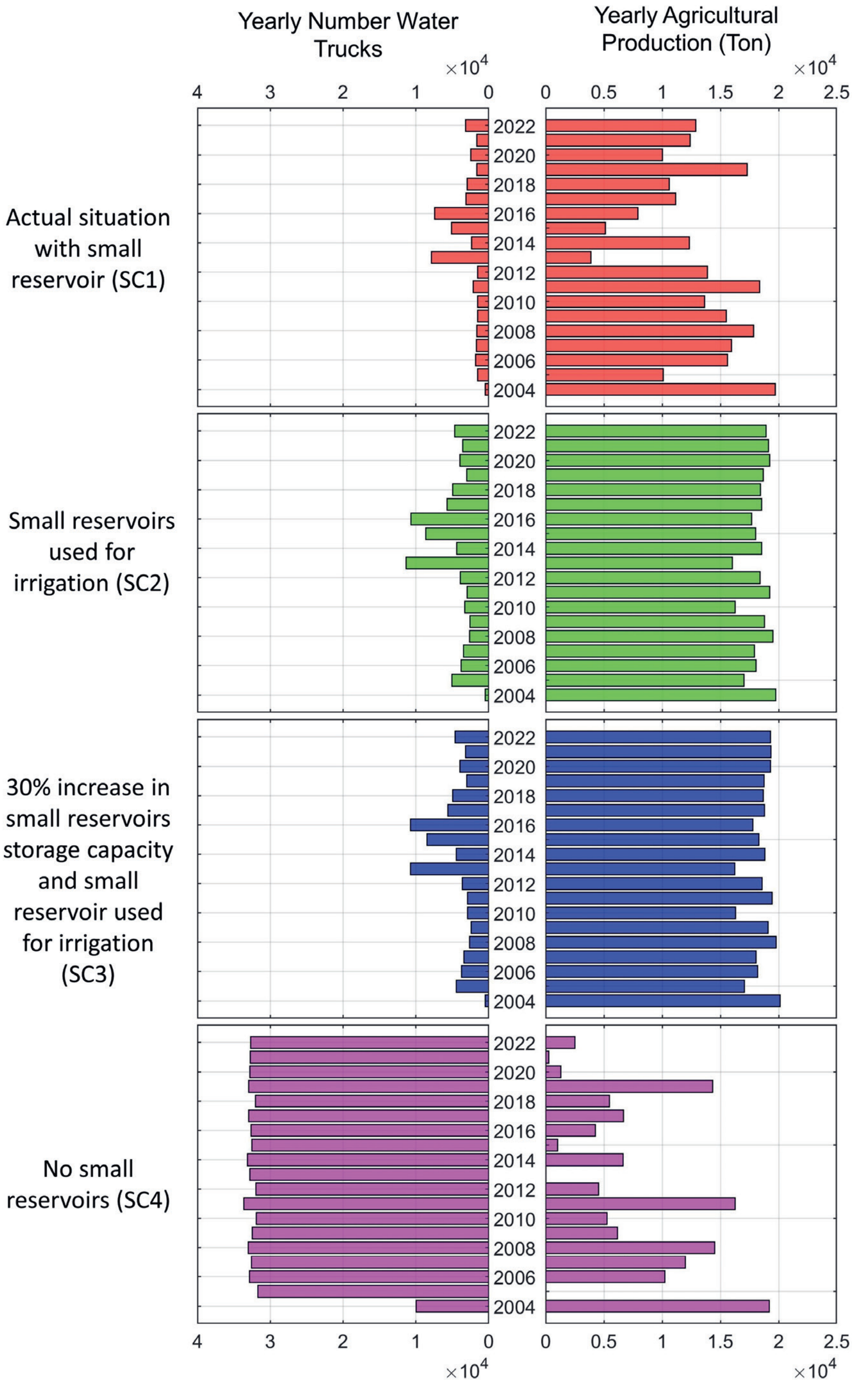

Figure 3.6 - Assessment of the benefits of a Dense Network of (small) Reservoirs (DNR).

3.4 Discussion

The Downstream impacts hypothesis considers that a Dense Network of (small) Reservoirs (DNR) can induce or modify hydrological droughts, especially in the downstream part of the catchment. During normal and above-average rainy seasons, most of the reservoirs are recharged, maintaining the storage balance, with small reservoirs not obstructing runoff connectivity or water availability in downstream areas. In other words, in years of normal precipitation, the DNR does not have significant hydrological impact on downstream areas – in line with the *local benefits hypothesis*. However, an intense precipitation deficit results in an imbalance in the recharging-emptying dynamic, leading to a storage deficit that spreads spatially and temporally throughout the catchment. The inefficiency of reservoir storage in small reservoirs, reflected in the relationship between evaporated and stored volumes (Figure 3.5), is central to understanding the narrative that relates the presence of a DNR to the occurrence of hydrological droughts (water shortages in downstream areas). The lower the relative water volume stored in the DNR, the higher the relative evaporative loss. This implies that the same volume of recharge will have different effects on total water availability depending on how full the small reservoirs are. This pattern is directly related to maintaining the storage deficit in the downstream reservoir since small reservoirs need to be completely full to maintain surface-runoff connectivity, which is crucial for overall recharge of water storage in the area.

The influence of the DNR on the spatial-temporal recharge of the catchment storage could easily be observed through the Center of Water Storage (CWS), a novel method presented in this study. This indicator is a weighted average of the volumes stored in relation to the distance from the outlet (strategic reservoir in this case), indicating where proportionally more water is stored. Analyzing CWS allows us to observe that during an intense drought there can be a gradual shift in the CWS, moving from downstream to upstream (Figure 3.4d). An increase in precipitation (indicating the ending of the meteorological drought) intensifies this shift, showing a higher concentration of water upstream while areas closer to the outflow maintain low storage volumes. This means that the water-storage recovery after intense meteorological droughts is delayed due to the presence of a DNR and that recovery only occurs slowly in an upstream-downstream direction. Similar patterns have been observed in an adjacent catchment, although these studies only considered a cascade of large reservoirs, not taking into account the effect of small reservoirs (Van Langen et al., 2021; Van Oel et al., 2018).

The effect of the DNR on the water storage recovery associated with simulations of the volume stored in the strategic reservoir confirms the hypothesis that the DNR has the potential to induce and modify hydrological droughts (*Downstream impacts hypothesis*). The triggering of drought events was evident by observing that the volume in the strategic reservoir would only have reached more alarming storage levels (<25%) approximately 15 months later than recorded (Figure 3.4a). The main modification of drought events due to the existence of the DNR is related to the delay in the recovery of volumes in large reservoirs located downstream, such as the strategic reservoir in our study area. Consequently prolonging the impacts of hydrological drought for populations that depend on these water resources. Other studies that have analyzed the effect of DNR on hydrological droughts agree with the findings in this study, including Chapter 2 based on the Drought Cycle Analysis and hydrological-modelling studies by Krol et al., (2011), Malveira et al., (2012), Mamede et al.,(2012), Rabelo et al., (2021), and Rabelo et al., (2022).

The confirmation of the *Downstream impacts hypothesis* does not necessarily invalidate the *Local benefits hypothesis* of the DNR. Although the presence of small reservoirs can influence the hydrology of the catchment, the way in which farmers use the water storage from small reservoirs does not seem to have a major impact on downstream water availability. This was also observed by Lima et al., (2023) who analyzed the impact of intensive water use from small reservoirs on strategic reservoirs. Even with intense water use for irrigation from small reservoirs, the water storage in strategic reservoirs would remain almost unchanged. Without the existence of the DNR, the demand for water supplied by water trucks would increase greatly (15 times higher on average, assuming no adaptation in water-use activities) and local upstream agricultural production could be reduced by up to 5 times.

The *Local benefits hypothesis*, even though it may disregard the hydrological impact of DNR at the catchment scale, suggests clear benefits for local upstream farmers using water from small reservoirs, which we confirmed. However, an increase in the storage capacity of the DNR, advocated for by some farmers, would not substantially influence these benefits. The absence of a DNR would lead to an increased dependence on water trucks and reduced agricultural production, and subsequent socioeconomic impacts to the population. The water supply by water trucks is not only expensive but also inefficient. The decrease in agricultural production would lead to a greater demand for imported forage to meet local livestock demand, which would increase virtual-water transfers into the area. Furthermore, lower agricultural production in this region would result in higher public spending on social programs to transfer income to the affected populations (Cavalcante et al., 2022).

In the absence of an accessible rural water supply system for farmers, or other ways of storing water more efficiently, small reservoirs fulfill their role in reducing local drought impacts, even if they prolong/induce/modify drought impacts downstream. Nonetheless, DNR is far from being the best solution for water storage in a semi-arid region, mainly due to the high evaporation losses inherent to such structures. Furthermore, an increase in the evaporation and reduction in precipitation in the semi-arid region of Brazil is projected due to climate change (Cook et al., 2020; Marengo, 2020b; Marengo et al., 2019; Papalexiou et al., 2021). The modification in the climate regime of this region can potentially reduce the window of opportunity for the use of water stored in the DNR and intensify the local drought impacts. Future research should evaluate the effects of climate change in semi-arid regions, based on a socio-hydrological framework such as the SHARE model, also considering water storage and supply alternatives that are less susceptible to high evaporation rates, such as ground cisterns (Figure 3.1e) and rural water-supply systems.

Socio-hydrological modelling, an interdisciplinary approach that integrates hydro-meteorological and social aspects to analyze human-water systems faces a number of methodological challenges (Pande and Sivapalan, 2017). The main one is the representation of anthropogenic dynamics, both due to the lack of observational data and the high complexity of these dynamics. The lack of socio observational data, for instance, made it unfeasible to include a representation of farmers' behavioral variations in water management and agriculture in the SHARE model. The high complexity of the dynamics related to the availability of water trucks meant that we had to impose certain simplifications in our analysis. Although we considered universal access to this resource in the simulation without any adapting behavior during low water availability, in reality, remote regions and political aspects influence this availability. Including these “nuances” would require new parameters and/or structures in the model, which would not necessarily result in more accurate simulations, since the absence of data related to the total yearly number of water trucks makes it impossible to calibrate or validate this kind of information. As such, the number of water trucks simulated with SHARE is indicative of the amount of water required to sustain the system as is.

The clash of drought narratives, translated in this study into the analysis of two hypotheses regarding the potential of DNR to influence hydrological droughts, hides the pitfall of analyzing complex problems without a proper holistic view. Using a "conventional" hydrological model would probably enable reaching a similar conclusion as we did about the hydrological impacts that DNR causes downstream, which confirm the *Downstream impacts hypothesis*. However, such an approach would not easily allow evaluation of the local benefits that these structures bring and that partially confirm the *Local benefits hypothesis*.

Although the SHARE model presents certain limitations, it accurately simulated the volume in the strategic reservoir and the temporal trends in local agricultural production. It also adequately reproduced the recharge of water storage after prolonged drought events in an upstream and downstream direction, in line with previous studies (Van Langen et al., 2021; Van Oel et al., 2018) Moreover, SHARE can be used to address drought impact forecasting methods, which can contribute to better preparedness and response to drought (AghaKouchak et al., 2023). To improve the representation of the anthropogenic dynamics, more interaction with local communities would be needed, creating opportunities for activities based on citizen science and scientific communication. Incorporating information from such interactions could increase interdisciplinarity in drought assessment studies, since hydrology and meteorology alone do not provide the means towards comprehensively understanding the relevant human dynamics related to drought (Chapter 4).

3.5 Conclusion

We analyzed the effect of a Dense Network of (small) Reservoirs (DNR) on the emergence of drought impacts at the catchment scale and contrast this with the local benefits of these structures. This analysis was motivated by the ongoing clash of drought narratives often observed in semi-arid regions, related to the ideas of supporting or opposing the presence of these structures. The clash of drought narratives was summarized in this study into the evaluation of two hypotheses: *Downstream impacts hypothesis* which considers that DNR has the potential to induce, aggravate or extend hydrological droughts and the *Local benefits hypothesis* which considers that DNR only promotes local benefits for farmers. We developed the Socio-Hydrological-Agricultural-Reservoir (SHARE) model to explore these conflicting hypotheses and applied it to the situation in drought-prone Piquet Carneiro catchment (170km^2) in the semi-arid region of Brazil that contains 364 small reservoirs located upstream of one large strategic reservoir. The DNR can directly influence the recharge of downstream reservoirs, including the strategic one, by obstructing the surface-runoff connectivity, which prolongs the impacts of a hydrological drought. Furthermore, DNRs contribute to higher evaporation rates. These arguments favor the narrative that describes small reservoirs as an inappropriate drought adaptation strategy. In this study, we have shown that this narrative does not tell the whole story. We showed that the water demand that puts the highest pressure on the water availability in the study area is evaporation and, in this sense, rapid use of the water stored in the small reservoirs generates the greatest benefits. In the absence of better alternatives that promote equality in terms of water security, small reservoirs may particularly reduce the impacts of droughts locally. This is mainly due to the increase in agricultural production by up to 5 times compared to the scenario without small reservoirs, as well as a drastic reduction in emergency supply situations relying on water trucks. These contrasting narratives indicate the challenges in understanding human-water dynamics, yet this should not be discouraged for further investigation. With this study, we have taken a step further in reconciling socio-dynamics into models.

The SHARE model proved to be a useful tool for better understanding the complex socio-hydrological processes of a semi-arid region. Limitations of the approach relate to simplified representation of the spatio-temporal variation in agricultural management by farmers. Overcoming these limitations, would require a comprehensive interdisciplinary approach which would allow this model to support local operational management of water resources. Given the growing pressure on water resources, even more so in the face of uncertain climate change scenarios, it is imperative to further develop tools like the SHARE model to support sustainable and equitable water resource management strategies. Doing so may help to avoid drought-management decisions that are only informed by one perspective in a clash of drought narratives.


04

Chapter 4

Drought **prospects**

This chapter is based on:

G. Ribeiro Neto, G., Kchouk, S., Melsen, L. A., Cavalcante, L., Walker, D. W., Dewulf, A., Costa, A. C., Martins, E. S. P. R., and van Oel, P. R.: HESS Opinions: Drought impacts as failed prospects, *Hydrol. Earth Syst*. Sci., 27, 4217–4225, https://doi.org/10.5194/hess-27-4217-2023, 2023.

Abstract

Human actions induce and modify droughts. However, scientific gaps remain with respect to how hydrological processes, anthropogenic dynamics, and individuals' perceptions of impacts are intrinsically entangled in drought occurrence and evolution. This adds complexity to drought assessment studies that cannot be addressed by the natural and environmental sciences alone. Furthermore, it poses a challenge with respect to developing ways to evaluate human behaviour and its pattern of co-evolution with the hydrological cycle – mainly related to water use and landscape modifications. During fieldwork in Brazil, we observed how drought impacts were experienced by people who were exposed to a multi-year drought. Evaluating our data, it appeared that prospect theory, a behavioural economic theory that is usually applied to explain decision-making processes under uncertainty, has explanatory power regarding what we observed in the field. Therefore, we propose an interdisciplinary approach to improve the understanding of drought impact emergence using this theory. When employing prospect theory in this context, drought impacts are considered failed welfare expectations ("prospects") due to water shortage. A shifting baseline after prolonged exposure to drought can therefore mitigate experienced drought impacts. We demonstrate that this theory can also contribute to explaining socio-hydrological phenomena, such as reservoir effects. This new approach can help bridge natural science and social science perspectives, resulting in integrated drought management that considers the local context.

"Inverno é curto intervalo entre duas secas."

'Winter is the short period between two droughts."

(Roosevelt Garcia)

4.1 Introduction

During fieldwork conducted by the authors of the paper on which this chapter is based, in the semi-arid region of Brazil (SAB), a farmer was asked how the 2012–2018 multi-year drought event (Cunha et al., 2019a; Cunha et al., 2018; Cunha et al., 2019b; Marengo, 2020b) had affected his livelihood and welfare. The farmer responded by asking “Drought? What drought?”. We wondered how a drought event that lasted for almost 7 years and was characterized by an average 60 % reduction in annual precipitation had gone unnoticed by someone who had been in the middle of it. A spatial contextualization helped us answer this question. The farmer's property was located at the edge of an upstream reservoir with low water abstraction that retained water throughout this drought event. Therefore, he never experienced water insecurity during this period.

The farmer's response implicitly reveals the relationships between human actions that modify hydrological processes (in this case, the construction of a reservoir) which alter exposure to a drought hazard (in this case, no exposure because of a filled reservoir) as well as individuals' perceptions of disaster occurrence (“Drought? What drought?”). This is in line with the concept of “Drought in the Anthropocene” (Van Loon et al., 2016a), which underlines the need to consider the human component as an inseparable part of the complex and interrelated processes of a drought. It calls for more balance between the analysis of the physical and human component of drought events, where we define drought as an exceptional period of lack of water compared with normal conditions. This is not restricted to a physical cause (e.g. a negative rainfall anomaly) but can also be caused, or mitigated, by human actions. These ideas are developed in the context of socio-hydrology. In summary, this discipline considers that people interact with the hydrological system in various ways (e.g. water consumption and landscape modification), and this has the potential to alter hydrological processes, which in turn influence and impact human actions, creating a co-evolution (Chapter 1, sections 1.1 and 1.4.2).

Perceiving the human component as an inseparable part of the hydrological cycle creates new research avenues – for instance, the study of drought events and other disasters at scales that are commonly disregarded, such as starting from the individuals in the hydrological system that experience impacts and evaluating the decisions that they make to avoid these impacts. This may reveal the emergence of patterns and phenomena unobserved at other spatio-temporal scales or when focusing on other hydrological variables (Van Oel et al., 2012; Walker et al., 2022b; Wens et al., 2019, 2021). Although the patterns of co-evolution between the human component and the hydrological cycle have been widely debated in the scientific literature (Di Baldassarre et al., 2019b, 2015; Sivapalan et al., 2012; Tian et al., 2019; Van Loon et al., 2016a), gaps remain regarding the relationship between hydrological hazards (e.g. drought), the perception of the impact of this hazard, and the occurrence of the hazard itself. With the ideas presented in this paper, we aim to contribute to this discussion, focusing on drought hazards.

We argue that the collectivity of individuals' perception of the impacts that they experience, which is related to both environmental and socio-economic factors, determines the magnitude and the very occurrence of a drought event. Using prospect theory (Kahneman and Tversky, 1979), which stems from the field of behavioural economics, we can explain the emergence of drought impacts, considering impacts as failures in expected welfare due to water shortages. We build our case by first presenting the concept of drought impacts as failed prospects and then outlining the relationship between socio-hydrology and prospect theory to finally present how this can be applied to real-world cases of drought events.

4.2 Impacts as failed prospects

Satisfying our needs for welfare, and not just survival, is one of the characteristics that define us as humans. An improved understanding of how this influences decision-making related to water use and landscape modification can lead to a better drought assessment. Human beings, as individuals, anticipate a desirable level of welfare and then choose among the possible prospects that they believe have the highest chance of achieving this goal (Kahneman and Tversky, 1979). These prospects are the decision options that are associated with an expected outcome within a scenario of uncertainties.

The chosen prospect defines how well an individual is adapted to their environmental conditions; therefore, it is directly related to their vulnerability and resilience. We propose that, when an individual has a failed prospect because of a lack of water, influenced by a hydroclimatic anomaly and/or human actions, this negatively affects the individuals' level of welfare, which they will feel as an impact; consequently, the situation will be perceived as a drought by this individual. For example, a prospect can be a farmer's choice to grow a certain crop (rather than another) in order to achieve greater gains or fewer losses depending on the context. This choice is made with the expectation that this crop will contribute to the achievement of the desired welfare level.

If, for instance, the prospect is to grow a water-consuming crop in a region characterized by low water availability, it can be an indication of the maladaptation and vulnerability of the individual. In this example, if a precipitation deficit occurs (hazard) and this negatively affects the chosen crops, resulting in unsatisfactory production (failed prospect), the individual will feel the impact and consider this event to be a drought. If, at some point, a critical mass (of people) experiences impacts, this might lead to the (official) declaration of a drought. This is the result of a complex interaction that includes many factors, such as those experiencing impact, their societal position, media exposure, power relations, and the political consequences of formally declaring a drought.

With respect to the real-world example of the farmer mentioned above, there were no failed prospects during the multi-year drought event, mainly because the farmer had a secure water source throughout this period; consequently, his desired level of welfare was never affected. Considering this, the simple answer that he gave us is coherent and logical: he did not experience impacts related to the negative hydroclimatic anomaly (meteorological drought) that occurred in that region and, therefore, for him, a drought event never happened.

Considering drought as the collective impacts that emerge as failed prospects due to a lack of water makes it necessary to predict how individuals choose which prospects are more attractive. Prospect theory (PT) explains how individuals choose alternatives when the outcome is uncertain (Kahneman and Tversky, 1979; Tversky and Kahneman, 1986). This theory has been widely debated, especially in the socio-economic sciences. In the environmental sciences it has been applied in different contexts, such as reservoir operation (Bahrami et al., 2022), asymmetries in drought response (Tian et al., 2019), disaster management (Osberghaus, 2017), and irrigation water resources management (Wang et al., 2022).

One of the novel concepts that PT presented is that individuals in the real world do not maximize total wealth but instead react to possible or perceived gains or losses, which are emotional and short term. In other words, human beings do not necessarily seek to maximize their net benefit (or utilities) by always choosing the prospects that produce the highest level of benefit (Jones, 1999). To clarify this concept, we invite the reader to participate in a simple experiment (Kahneman and Tversky, 1979) consisting of choosing one of the options in the following two problems: (1) 80 % chance of winning USD 4000 or 100 % chance of winning USD 3000; (2) 80 % chance of losing USD 4000 or 100 % chance of losing USD 3000.

If you chose the second and first options in problems 1 and 2, respectively, you behaved like most people who participated in such an experiment (Kahneman and Tversky, 1979). This means that you presented risk-averse behaviour when the prospects were related to certain gains (problem 1) and risk-seeking behaviour when the prospects were related to certain losses (problem 2). The combination of these two patterns illustrates the idea presented by PT that the human tendency is to overvalue a certain (or highly likely) outcome, relative to outcomes that are probable (Edwards, 1996; Kahneman and Tversky, 1979; Levy, 1992). The problem indirectly illustrates another concept presented by PT, which is the “loss aversion” effect. This highlights the asymmetry in an individuals' perception of gains and losses; losses feel more “painful” than gains of equal magnitude feel “pleasurable”. The consequences can be a preference for the *status quo* and the acceptance of riskier prospects to avoid certain losses (risk-seeking behaviour).

To define whether the outcome of a prospect is seen as a gain or as a loss, the prospect is compared with a reference point. The reference point can be influenced by what is experienced as the *status quo* or the “normal” situation but also by the way the decision problem is perceived (Kahneman and Tversky, 1984). This latter is called the “framing effect”, whereby, depending on how individuals perceive and make sense of decision prospects in terms of gains or losses, they will show a tendency towards risk-averse or risk-seeking behaviour, respectively.

4.3 Socio-hydrology and prospect theory

We argue that the onset and propagation of human drought impacts (which we consider to be those that negatively affect an individual's welfare) and socio-hydrological phenomena (e.g. the reservoir effect and supply–demand cycle) can be explained through the lens of prospect theory. Figure 4.1 presents an overview of how prospect theory is related to socio-hydrology phenomena and drought emergence. The first concept to consider from PT is the reference point, which is the general term for the starting point from which to make different kinds of decisions. For drought assessment, we consider the reference point to be the minimum welfare level that individuals tolerate to feel satisfied and secure with the results of chosen prospects; deviations from this point are defined as a gain or loss. The environment guides the individuals' expectations regarding their level of welfare (reference point) and, in turn, the prospects chosen to achieve this desired level. For instance, the reference point can be influenced by environmental conditions such as water availability, which is related to aspects of food and water security, previous experiences (e.g. past drought events), community interactions (e.g. peer comparison), and socio-economic trends (e.g. production costs, goods prices, and local culture and governance). Importantly, the reference point will vary over space and time. For instance, a higher yield loss might be incorporated as acceptable in the reference point after years of drought or in a region with a consequent insecure water supply. The higher the reference point, the greater the potential for human drought impacts.

Once the individual has defined their reference point and delineated the desired level of welfare, they evaluate the decision prospects for achieving it. When faced with a situation of high water availability, individuals have more freedom to choose prospects that offer certain gains (risk-averse behaviour; blue cycle in Figure. 4.1), even if this promotes a reckless water use pattern and/or the development of activities that are not necessarily the most adapted to the environmental conditions of the region in which they are inserted. Successive gains associated with this behaviour will, in the short term, reinforce the selected prospect (short-term response; dashed arrow in Figure 4.1) and, in the long term, raise the reference point. Levels of welfare below the reference point will be perceived as losses and will be avoided, even though the individual may have already experienced such levels as a gain in a previous situation (framing effect).

A series of successful prospects maintain the upward trend in the reference point, and this persists as long as the water resources to which the individual has access can sustain their water demand. This continues even if there is an impending drought situation, as a reduction in water consumption while the reference point is associated with satisfactory water availability can be framed by individuals as a direct decrease in welfare. When water is lacking and it is no longer possible to maintain the water consumption standards that the individual requires, this results in failed prospects and, consequently, drought impacts arise.

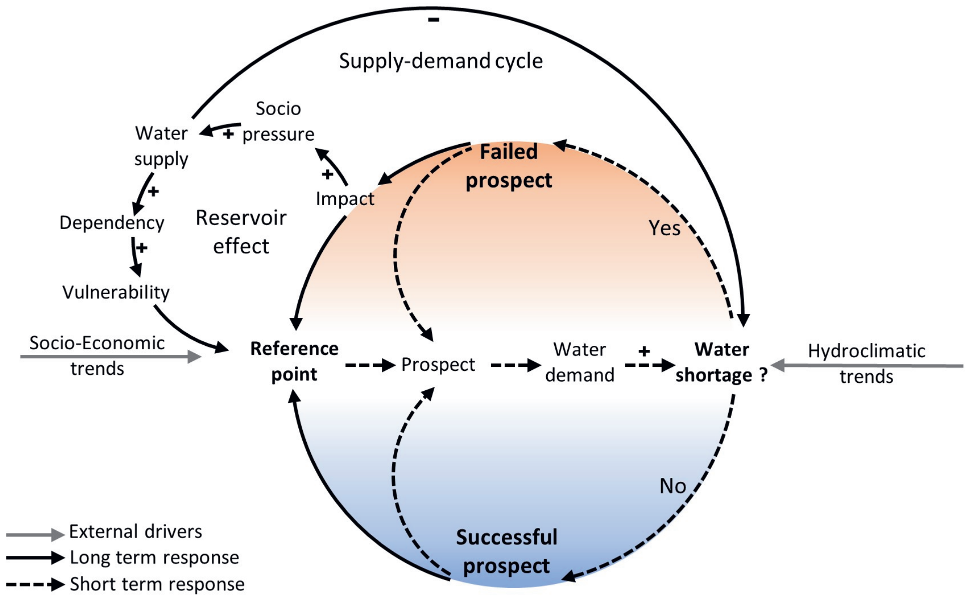

Figure 4.1 - The cycle of human drought impacts. Our hypothesis emphasizes the centrality of the human component (starting from the reference point) in the emergence of drought impacts, with the individual as the primary scale. Moreover, the combination of how they are linked to the hydroclimatic trends and socio-economic trends results in the emergence of long-term socio-hydrological dynamics (reservoir effects and supply–demand cycle) that can be explained by concepts related to prospect theory, such as the reference point, the framing effect, and risk-averse (blue cycle) and risk-seeking (orange cycle) behaviour.

Initially, the drought situation is typically perceived as a loss, as we consider that it starts after a failed prospect. In the short term, individuals tend to focus on prospects that can at least prevent further losses, even if they were previously seen as risky (risk-seeking behaviour; orange cycle in Figure 4.1). However, in the long term, if low water availability persists, it can cause individuals to adjust their expectations by lowering the reference point. In other words, individuals can be less impacted by water shortages simply because they accept suboptimal outcomes (e.g. lower agricultural production). Once this shift in the reference point occurs, individuals may no longer view the situation as a drought but rather as the "new normal".

As water availability gradually increases, either due to natural causes (hydroclimatic trends) or due to the expansion of water infrastructure, individuals are likely to shift away from their lower reference point and search for prospects that offer more certainty, thereby restarting the cycle anew (blue cycle in Figure 4.1). We hypothesize that the demand to expand the water infrastructure can be related to situations in which individuals attribute the occurrence of drought impacts to low water availability without considering the suitability of their own chosen prospects under local environmental conditions. This behaviour can then, in the long term, result in social pressure to increase the water supply (e.g. reservoir construction and water transfer); when this demand is met, individuals can re-enter the cycle of increasing water consumption (blue cycle in Figure 4.1). As the demand continues to rise, it can eventually offset the new maximum supply capacity. This can lead to more social pressure to increase the water availability, thereby creating a vicious cycle (supply–demand cycle in Figure 4.1), greater dependency on water infrastructure, and greater vulnerability to drought events (reservoir effect in Figure 4.1; Di Baldassarre et al., 2018).

3.4 Prospect theory and drought – insights from the Brazilian semi-arid region

The 2012–2018 meteorological drought in the semi-arid region of Brazil (SAB) is used as a practical example to highlight how prospect theory fits into the narrative of drought impacts as failed prospects. We focus on Ceará state, which is one of the sub-regions most impacted by this event. Figure 4.2 presents the percentage anomaly of annual precipitation relative to the long-term climatological average (1981–2011) for the SAB and Ceará state during the 2012–2018 drought event. The years prior to this drought were characterized by precipitation levels above the climatological average, which meant that most reservoirs in Ceará had stored volumes close to their maximum capacity.

This region has a historical susceptibility to drought events, and there has been observable change in the preparation and management of such disasters in recent times. This change is related to a shift from a "fighting against drought" perspective, which relied on hard solutions (such as significant investments in water infrastructure), to a "cope with drought" perspective, which relies on soft solutions (such as renewed focus on public policy towards adaptive measures and integrated water resources management) (Cavalcante De Souza Cabral et al., 2023; Medeiros and Sivapalan, 2020). Nevertheless, the high water availability experienced during the years prior to the 2012–2018 drought contributed to the support of high water demand production activities, such as rice paddies and irrigated fruit crops.

Before the occurrence of this drought, Ceará had been experiencing a gradual growth in dairy cattle farming, but this growth was intensified during the drought event. Farmers increasingly started to see this activity as a prospect more adapted, from a local perspective, to droughts because it guaranteed a source of perennial income and served as a capital reserve (part of the herd could be sold at any time). Furthermore, it is considered that cattle farming is less dependent on locally produced inputs and on the spatio-temporal heterogeneity of the precipitation regime when compared with rainfed crops.

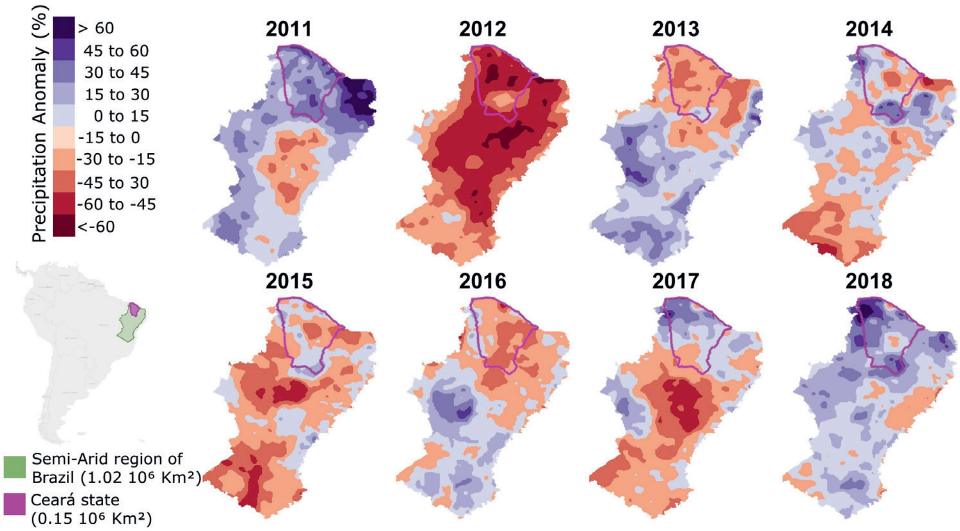

Figure 4.2 - Precipitation variability in the semi-arid region of Brazil during the 2012–2018 drought. The percentage anomaly of annual precipitation relative to the long-term average (1981 to 2011) using the Climate Hazards Centre InfraRed Precipitation with Stations (CHIRPS; Funk et al., 2015) dataset (available at https://www.chc.ucsb.edu/data, last access: 20 May 2023) is shown.

Figure 4.3 presents an overview of prospect theory applied to the Ceará study case. We hypothesized, based on field interviews, that periods of high water availability provided a certain stability to farmers who depended on rainfed crops (short-term positive response; first dashed blue arrow in Figure 4.3). However, the following and more frequent occurrence of intense meteorological drought events caused them to experience consecutive production losses (failed prospects) which led the individuals to view the exclusive production of rainfed crops as a riskier prospect (short-term negative response; dashed red arrow in Figure 4.3) and dairy production as a prospect that would avoid further losses (long-term negative response; red arrow in Figure 4.3). One of the barriers that made individuals view this activity as unattractive or risky was the low and volatile price of a litre of milk in the local market. This changed when associations of small dairy producers were created, and they started to have more bargaining power within the dairy industry. Due to this new socio-economic trend, individuals began to see cattle farming as a prospect more adapted to drought and that promoted more certain gains (short-term positive response; second dashed blue arrow in Figure 4.3). This is further evidenced by farmers who had already adopted this activity due to previous drought events and who continued to favour this kind of prospect in later periods of greater water availability (long-term positive response; second blue arrow in Figure 4.3).

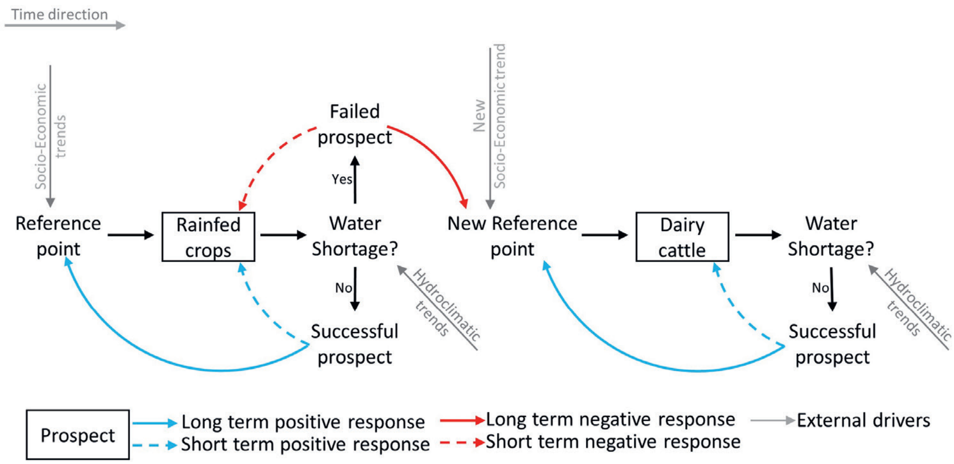

Figure 4.3 - Prospect theory in socio-hydrology applied to the Ceará study case.

The expansion of dairy production in Ceará has resulted in an increase in small (informal) reservoirs to support forage production and to provide water for livestock consumption. In some regions, the high concentration of small reservoirs has decreased the surface runoff connectivity of the watershed, impacting the recharge of large reservoirs downstream that serve multiple purposes (Chapter 2). As a result, the persistence of this hydrological impact affects the region's water availability, as the large reservoirs remain at reduced water storage levels for longer periods, which in turn can influence individuals' perception of water security (component of welfare) and, consequently, their definition of the reference point.

Interviews with farmers and agricultural extension officers regarding desirable reservoir volumes illustrated the concept of the reference point and how it can vary according to previous experiences. Interviews revealed that volumes were consistently around 5 % during the 2012–2018 drought; the lower water availability had become the *status quo* (or the reference point). Therefore, increased volumes up to 20 % of capacity were celebrated, as they were considered gains, even though such a level would have been considered a loss prior to the multi-year drought.

Based on the case study presented here, we identified situations that can be analysed using the loss aversion effect. Loss aversion is related to the attempts of individuals to adapt to drought, aiming, in general, to avoid greater losses through measures that reduce water demand. We observed that one of these adaptations was the search for hybrid bovine breeds, resulting from the crossing of local breeds that are resistant to drought with European breeds that have a higher milk production. These hybrid breeds were already known by the local farmers, but they were long seen as not worth the investment, due to the high cost of acquisition. However, during the 2012–2018 drought, an acceleration in herd replacement with these hybrid breeds was observed. Many farmers decided to sell part of their herd to raise capital to invest in these hybrid breeds. They realized that it would be safer, in a scenario of low water availability, to maintain a smaller but more productive herd.

The increase in the number of wells in Ceará between 2012 and 2018 is another practical example that illustrates the loss aversion effect. For Ceará, this alternative water supply can be considered a risky prospect, as it presents high implementation costs and is associated with uncertainties regarding whether a viable water resource will be found for exploitation, either due to the water quality (brackish groundwater is common) or because crystalline geology often provides low yield. Therefore, it was perceived that individuals in this region who chose to install wells were willing to take more risks to avoid greater losses.

4.5 Simulating prospect theory effects – applications, challenges, and opportunities

The lack of studies considering patterns of co-evolution between hydrological processes and human dynamics within a hydrological system has mainly been because human dynamics have been considered insignificant and due to the low spatio-temporal resolution at which hydrological models originally operated. Implicitly, the idea existed that it would be impossible or unfeasible to implement anthropogenic actions as an intrinsic component of the hydrological cycle has been successively refuted by various studies related to drought assessment (Bakarji et al., 2017; Streefkerk et al., 2023; Van Oel et al., 2012; Pieter R. Van Oel et al., 2018;

Wens et al., 2019, 2020, 2021). The presented concept of (human) drought impacts as failed prospects provides a different perspective to incorporate the socio-hydrological characteristics of a region into drought analysis. Drought impacts as failed prospects can especially contribute to the improvement and development of drought monitoring and early-warning systems, socio-hydrological characterization, drought risk analysis, forecast/reanalysis of drought events, and the development of public policies for the mitigation and prevention of drought impacts. On the other hand, prospect theory has limitations – mainly related to the lack of explanatory power regarding how decisions are made, especially with respect to the definition of an individual's reference point and how this is influenced by the environment and the full range of affective and emotional states.

We consider that, when applied to drought assessment, the reference point is related to the minimum level (with respect to well-being) required for an individual to feel satisfied with the outcome of the chosen prospects. To represent this concept, it is necessary to study the evolution of human dynamics, mainly related to how water and land have been used over time by individuals in the hydrological system. Agent-based models (ABMs) are a promising framework for these kind of studies, as they allow explicit probabilistic simulation of human decision-making with the ability to respond, learn, and adapt to variations in environmental states and other agents (Schrieks et al., 2021). Moreover, ABMs have been successfully applied in socio-hydrological studies, combined with hydrological and/or agricultural models (Wens et al., 2021, 2019; Streefkerk et al., 2023). These types of analyses often require expertise and methods usually associated with the social sciences, such as interviews, workshops, companion modelling, and serious games (Acosta-Michlik and Espaldon, 2008; Massuel et al., 2018; Pouladi et al., 2019; van Duinen et al., 2016). This further underlines that drought assessment studies are conceptually interdisciplinary and, therefore, require solutions beyond those associated only with the natural sciences.

The possibility of explaining the occurrence of a drought event through the use of prospect theory endorses the importance of the human component in drought assessment, in addition to fostering new discussions on this topic. The core concept presented here advocates for a greater focus on the human component within drought assessment studies and places the emergence of human impacts as a precursor to the disaster. This viewpoint contrasts with the methodological approach of numerous studies in which drought events are analysed only considering the spatio-temporal variability in hydrometeorological variables, disassociated from the human component (Kchouk et al., 2022). Furthermore, the reference point concept provides a theoretical basis for considering drought impacts dynamically, in contrast to the static vision on drought impacts that is now often encountered (e.g. in drought assessment studies). Prolonged drought impacts lead to a change in the individuals' perception of drought occurrence: the impacts become the new normal situation and are, therefore, no longer experienced as impacts. Moreover, we argue that the concept of drought impacts as failed prospects reinforces the perspective that drought is first and foremost a socio-hydrological phenomenon that materializes in the form of a disaster.

4.6 Conclusions

We demonstrated the application of the concept of drought impact as a failed prospect. We argue that the collective perception of individuals regarding the emergence of drought impacts plays a crucial role in both the magnitude and the occurrence of this kind of disaster. We argue that prospect theory, which originates from behavioural economics, can provide a new angle to analyse the human dimensions of drought by including the individual's perception at the centre of the analysis. We presented the idea that drought impacts arise when individuals perceive that they have not achieved their desired welfare level due to water shortage. This observation emerged from the multi-year drought event that occurred in the semi-arid region of Brazil from 2012 to 2018, which was used as a case study. Applying prospect theory and its concepts, such as the reference point, helped us understand that individuals' perceptions of drought impact emergence vary over time. In simpler terms, prolonged water shortage periods can be seen as a new normal situation. Consequently, individuals may no longer experience impacts, as their welfare expectations align with the new water availability condition. Other concepts, such as the loss aversion effect and framing effect helped us understand the tendency of individuals to change their water consumption pattern only when this resource is lacking as well as their tendency to adapt to drought events.

This understanding offers the opportunity to bridge the knowledge gaps related to the human influences on drought events by acknowledging the individual human dimensions. We showed the potential of prospect theory with respect to addressing interdisciplinary methodological and conceptual gaps between natural and social sciences. The hypothesis presented here can contribute to the identification of new socio-hydrological phenomena and improve the understanding of phenomena already described in the literature. Furthermore, our insights contribute to the demand for a change in perspective regarding how studies related to disasters involving hydrometeorological extremes, especially drought events, should be conducted, providing new ideas about the importance of representing the human component. We also support the idea of introducing more balance between the "socio" and "hydro" components in studies related to drought assessment, in which more interdisciplinarity should be sought, as hydrology and meteorology alone simply do not provide the means to understand human dynamics within the (socio-) hydrological cycle.


05

Chapter 5

Synthesis

"A ciência é uma irmã caçula (talvez bastarda) da arte."
Science is a younger sister (perhaps illegitimate) of art.
(César Lattes)

5.1 Main findings

The increase in frequency and severity of drought impacts associated with the perspective of increased human pressure on water resources calls for the development of new methodologies that can contribute to better management of this disaster. There is now an increasingly accepted understanding that effective drought management should be informed by assessment of both social and hydro-meteorological processes. In a world highly modified by anthropogenic actions, it is illogical not to consider the central role of people in the study of droughts. This is why the main objective of this thesis is to increase understanding of the human influence on the emergence and propagation of drought events. In previous chapters, new socio-hydrological drought assessment methods and concepts have been presented, with the drought-prone region of semi-arid Brazil as the study area. Here, I summarize the main scientific findings of this thesis, and present the novel insights, outlooks and conclusions on the themes addressed in this thesis.

5.1.1 Drought monitoring

In semi-arid or drought-prone regions characterized by low groundwater storage capacity, surface reservoirs are commonly used to ensure local water supply. A dense network of (small) reservoirs (DNR) can lead to a concentration of water in certain parts of the catchment and a shortage in others, which becomes more evident during drought periods.

After prolonged periods of precipitation deficit, it can be seen that water storage in large reservoirs, also known as strategic reservoirs which, in general, are public, monitored, and serve multiple sectors of society, takes a relatively longer time to recover. It is common to see the emergence of hypotheses associating this delayed recovery with the presence of the dense network of small reservoirs. Chapter 1 of this thesis therefore introduced the following research question: "*What is the influence of a dense network of reservoirs on the evolution of hydrological drought events?*". The Drought Cycle Analysis (DCA) methodology presented in Chapter 2 was then applied to answer this question. The DCA is helpful of identifying four possible stages: Wet Period, Meteorological Drought, Hydro-meteorological Drought and Hydrological Drought.

The effect of small reservoirs on the onset of droughts was analysed by isolating their effect by comparing a scenario that represents the current situation of the studied catchment with a scenario in which these structures do not exist. DCA was then applied to these two scenarios to compare the characteristics of key drought events and thus identify the influence of the DNR on the evolution of drought. The results presented in Chapter 2 reveal that a high concentration of small reservoirs can induce and modify drought events in large (strategic) reservoirs. This is especially true with regard to the extension of hydrometeorological and hydrological droughts by an average of 30%, which can reach 200% for specific events.

DCA has proved to be a valuable method for monitoring and comparing the evolution of different drought events and can serve as an auxiliary tool for improving water resource management of large reservoirs. This also represents a step forward for drought monitoring and assessment by combining a meteorological variable (precipitation deficit) with a socio-hydrological variable directly related to the onset of a drought impact (in Chapter 2: lack of water in the strategic reservoir). Furthermore, the success of the method applied in Chapter 2 also shows that the lack of data related to small reservoirs can partly be overcome by applying satellite imagery (e.g. Landsat mission) together with empirical equations that relate the surface area of water to the volume stored in these structures.

Finally, the findings of Chapter 2 also revealed that the DNR increases the amount of water stored in the study area (although not optimized and managed) and their absence would impose an overall reduction in cumulative storage in the hydrological system due to the release of water downstream by the strategic reservoir. These findings further highlight the need to include small reservoirs in water resources management and to improve understanding of their local influence on the emergence and/or alleviation of drought impacts. The findings of Chapter 2 have shown that the socio-hydrological dynamics of the study area can influence the onset and propagation of drought events. However, it remains to be seen how this occurs and whether there is also any alleviating effect of drought impacts due to these socio-hydrological dynamics. In Section 5.1.2, I address these issues.

5.1.2 Socio-hydrological simulation

The methods applied in Chapter 2, while useful for drought monitoring, do not reveal whether the way water is used and managed locally by DNR users has any effect on the drought impacts in other parts of the catchment, nor does it reveal the local benefits that such structures might provide to alleviate drought impacts. Based on this, the following research questions were presented in Chapter 1: "*What is the effect of local socio-hydrological dynamics on the emergence of drought impacts?*" and "*What are the local impacts of a dense network of reservoirs during a drought event?*". These questions were addressed in Chapter 3 through a methodological framework based on the development and application of a new socio-hydrological model called the Socio-Hydrological-Agricultural-Reservoir model (SHARE). This model is capable of simulating not only hydrological processes but also water use and agricultural productivity.

Simulations of the SHARE model demonstrated the same dynamics as described in Chapter 2, showing the hydrological impacts that a DNR can cause on large downstream reservoirs in more detail. Through a new index called the Center of Water Storage, it could be observed that a network of small reservoirs directly interferes with the hydrological connectivity of the catchment by concentrating water in the upstream areas after during long periods of precipitation deficit, which reduces the recharge of strategic reservoirs downstream and delays their recovery. Even more, if the small reservoirs did not exist, the volume stored in the strategic reservoirs would be greater (also shown in the Chapter 2) and, consequently, it would take longer for the individuals who depend on these water resource to experience a drought event.

With the SHARE model it was also possible to explore why these small reservoirs cause such hydrological effects. Generally shallow, they have a substantially higher ratio of surface area to stored volume than large reservoirs. The consequence is that small reservoirs dry up easily because of the high evaporation demand. This occurs regardless of whether they are used to meet human water demands, even if human demand would be higher to support intensive irrigation use. This finding reveals that the socio-hydrological dynamics related to small reservoirs are first and foremost related to the construction and subsequent existence of these small reservoirs, and not to the way they are used, since the greatest acting water demand is evaporation.

One of the great advantages of using a socio-hydrological approach is that it makes it possible to explore aspects beyond hydrological processes. "Conventional" hydrological models would probably help to assess the impacts that small reservoirs can have on the spatiotemporal distribution of surface water storage in the catchment and lead to the same conclusions. However, they would hardly allow to simulate the local benefits of small reservoirs, which can be done through socio-hydrological frameworks.

The socio-hydrological modelling conducted with the SHARE model revealed that in the absence of more efficient alternatives that promote equality in terms of access to water, small reservoirs can substantially reduce the impacts of drought locally. This is made explicit through an increase in agricultural production of up to 5 times compared to scenarios without such structures, as well as a drastic reduction of up to 15 times in the number of water trucks needed to serve the population as emergency water supply alternative (assuming no adaptive behaviour in the face of water shortage). In other words, although the DNR could prolong hydrological drought events in strategic reservoirs, its absence would result in a significant intensification of drought impacts in other parts of the catchment.

The findings of Chapter 3 show that it is possible to improve drought assessment through socio-hydrological models, as well as showing that models such as SHARE can be used to improve the water resources management and the implementation of public policies that can weigh the local benefits of small reservoirs against the possible impacts on strategic reservoirs downstream. It therefore provides balance to the findings of Chapter 2, which show mainly the negative aspects that a DNR can bring.

5.1.3 Socio-hydrological theory

Chapter 3 also revealed that socio-hydrological models such as SHARE are a useful tool for improving understanding of socio-hydrological dynamics in the context of assessing drought events in a region. However, the SHARE model as presented in Chapter 3 has methodological limitations when it comes to a more detailed representation of these dynamics. Based on this, the following research question was posed in Chapter 1: "*How could including perspectives of individual water users in a drought prone region support drought impact assessment?*". This question is answered in Chapter 4 by presenting the innovative concept of drought impacts as failed prospects.

Including the perception of individuals in drought assessment creates the possibility of taking as a starting point for this type of analysis the individuals' own perception of the environment, how they experience and try to avoid drought impacts. This can contribute to the identification of socio-hydrological phenomena and improve the understanding of those already described in the literature, since this analysis is carried out on a scale that is commonly disregarded by traditional methods.

In Chapter 4 it is proposed that drought impacts arise when individuals perceive that they have not achieved the desired level of welfare due to a lack of water. The collective perception of individuals regarding the emergence of drought impacts plays a crucial role in both the magnitude and the actual occurrence of drought. This innovative concept uses prospect theory, from the field of behavioural economics, to explain the dynamics of the human component in the perception of impacts.

The concept of the reference point from prospect theory has made it possible to explain that individuals' perception of drought impacts emergence varies over time. In short, this reveals that prolonged periods of water scarcity can come to be seen as a "new normal" situation. Consequently, individuals may no longer experience impacts, as expectations of welfare have been aligned with the new condition of water availability. This finding explains why, within the drought assessment, there are situations in which hydro-meteorological indices indicate the occurrence of a drought, but which are not associated with a report of the occurrence of impacts.

Chapter 4 also revealed that other concepts from prospect theory, such as the loss aversion effect and the framing effect, help explain the tendency of individuals to change their water consumption pattern only when this resource is in short supply, as well as their tendency to adapt to drought events. This contributes to improving drought assessment, since it allows us to explore in more detail the vulnerability and resilience of individuals, which is directly related to the onset and intensity of drought impacts. As such, prospect theory has the potential to improve simulation frameworks like the SHARE model by enhancing the representation of socio-hydrological dynamics.

5.2 Synthesis on drought assessment based on socio-hydrology

5.2.1 Drought as a socio-hydrological phenomenon

The findings of this thesis support the idea that since we are living in an era ruled by human modifications (the Anthropocene), drought has to be seen from this perspective and not just as a hydro-meteorological phenomenon (Chapter 1, Section 1.4.1). I propose that drought can be framed as a socio-hydrological phenomenon (Chapter 1, Section 1.4.2) as follow: Drought is an unintended consequence (since practically no one wants it), of the way water is managed (exceptional water shortages are influenced by socio-hydrological dynamics, Chapter 2 and 3), in order to achieve a desired societal objective (failed prospects due to water shortages are perceived as drought event by the individuals, Chapter 4). However, it is still necessary to understand how specific human actions, translated in socio-hydrological dynamics, influence the occurrence of droughts. Chapters 2, 3, and 4 demonstrate in different ways how human actions influence the emergence and propagation of drought, and by combining their findings a more detailed picture can be obtained. As will be shown below, the "Fixes that backfire" archetype (Chapter 1, section 1.4.2) can be used to explore drought as a socio-hydrological phenomenon.

Immediate solutions to mitigate susceptibility to drought, without addressing its fundamental causes, such as the adoption of prospects and solutions that are not adapted to the environment, trigger a more intense cycle of reinforcement, driven by the short-term success of environmental modifications. This generates positive reinforcement for the prospects that are not adapted to the environment, maintaining or even increasing the individual's vulnerability to the effects of the hydroclimatic trends. The consequence is that the individual may experience drought situations again in the future, in a more aggravated form, often with unforeseen challenges and consequences, such as reduced water availability for other individuals (Chapter 2 and 3) and environmental degradation. Some examples will be provide bellow.

The individual decisions that contribute to their own susceptibility to experience a drought event can be referred as "*local human influence*". The impact that the *local human influence* has on third parties can be defined as "*remote human influence*" on the emergence of a drought event, because the actions of an individual "A" unintentionally impact an individual "B" in another location, usually downstream. Keeping with the terminology concept of "backfire", the remote human influence on drought emergence could be called "friendly fire" since it describes a situation when unintentional "damage" is caused to someone who is not an opponent. Therefore, drought can be seen as a socio-hydrological phenomenon characterized by the fixes that backfire and friendly fire. This can be further evaluated by considering the lessons from the semi-arid region of Brazil presented through this thesis. Both this case study as well as a causal loop diagram explaining the effect of Fixes that backfire (and friendly fire) are presented in Figure 5.1.

In the semi-arid region of Brazil, exposed soil (Figure 5.1f), the result of crop failure due to the natural variability of hydroclimatic trends or the end of a production cycle since the crops are temporal (e.g. maize and beans), accelerates surface runoff once the rainy season begins (Figure 5.1d). This reduces infiltration and intensifies erosion processes (Figure 5.1j), resulting in shallower soils (Anache et al., 2017).

Compaction caused by livestock (Figure 5.1m) amplifies the reduction in infiltration, also contributing to an increase in the speed of surface runoff and the associated consequences (Marques et al., 2022). Less infiltration and shallower soils result in less water being stored in the soil, reducing the underground recharge of reservoirs (Figure 5.1h). Greater erosion implies greater sediment transport in the runoff, leading to the silting up of reservoirs (Figure 5.1k), reducing their storage capacity (Lima et al., 2023; Medeiros et al., 2014). In addition, fast surface runoff flows increase the risk of these structures rupturing, which is quite common in the region during the rainy season (Oliveira and Lima Neto, 2022). The exposed soil around the reservoirs reduce the albedo, raising the temperature and increasing evaporation (Figure 5.1g), making the reservoirs even less efficient, meaning they start to dry out even faster (Rodrigues et al., 2021). At a local level, all the mentioned processes contribute to a reduction in water availability both locally and downstream (Figure 5.1n) due to reduction of runoff connectivity.

The "slash and burn" method (Figure 5.1b) used to prepare the land for farming damages the biota that are essential for maintaining nutrients in the soil. This biota is further harmed by the high temperatures that the soil reaches as it is directly exposed (Nunes et al., 2012). The reduction in the infiltration also contributes to increase soil salinity (Lins et al., 2023). These processes, combined with the removal of nutrients from the surface layers due to the accelerated runoff mentioned above, gradually cause the soil to lose its fertility (Araújo et al., 2024). This hinders agricultural development and makes individuals more susceptible to crop losses associated with the natural variability of hydroclimatic trends. This leads individuals to seek out new areas of native vegetation to be cleared, restarting the cycle of environmental degradation. Furthermore, these processes can be irreversible, resulting in sterile soil even for native vegetation (desertification, Vieira et al., 2021).

The example of Brazil's semi-arid region shows that the main impacts of drought associated with agricultural losses, animal deaths and situations of lack of water for human supply are the direct result of human interaction with the environment and water resources under the natural variability of the region's hydroclimatic trends. In short, the persistent attempt to maintain practices that are not adapted to the environment, combined with short-term solutions that in fact do not address the real causes of the water shortages, generates unexpected and unintended consequences (e.g. environmental degradation), increasing susceptibility to drought situations and aggravating the impacts associated with these conditions locally and for other regions of the basin.

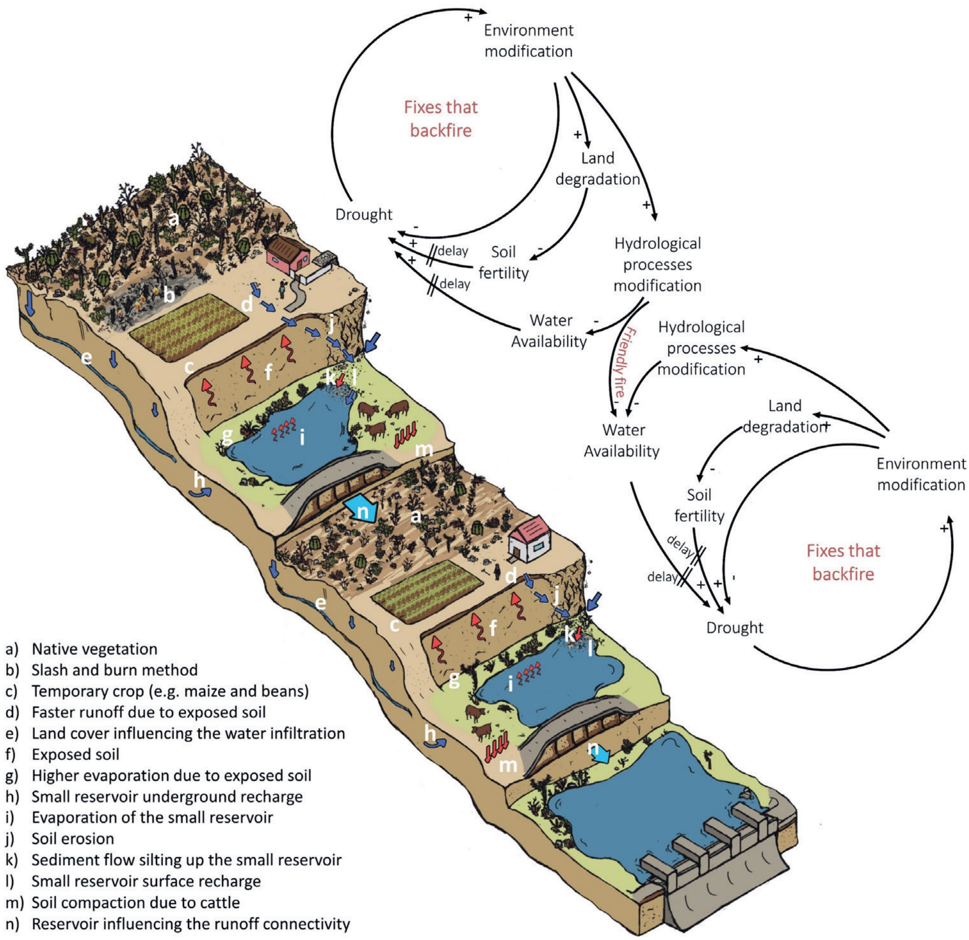

Figure 5.1 – Representation of drought as a socio-hydrological phenomenon based on a case study in semi-arid Brazil. ‘

5.2.2 Drought in the Anthropocene

The findings of Chapter 4 highlight the importance of individual perception in the emergence of drought impacts and how collective perception determines the magnitude and occurrence of drought. This contrasts more traditional approaches where the magnitude of drought impacts is often assumed to scale linearly with the anomaly of a hydro-meteorological variable (Section 1.3). The findings of Chapters 2 and 3 demonstrate the potential of human actions to cause, intensify and alleviate drought events. From these findings, drought can be framed as a socio-hydrological phenomenon characterized by "fixes that backfire and friendly fire" effects, as worked out in the previous section. Although this description reveals details of how droughts emerge and propagate from a socio-hydrological perspective, it is not self-explanatory. Therefore, I advocate that the centrality of the human component in the drought emergency process should be made clear in its definition, since the semantics and perceptions of drought used in the disaster management field can significantly affect the development and application of relevant policies and actions related to that (Smakhtin and Schipper, 2008).

Here, I propose that drought should be seen as "**an exceptional period of water shortage experienced or caused by humans**". Note that the term "exceptional" already connotes something that deviates from what is considered "normal", so there is no need to include this in the definition. Indirectly, this definition highlights the importance of impacts as a decisive factor in the beginning and end of drought events. In the practice of monitoring, it becomes essential to develop systems capable of tracking both impacts and drivers, such as natural hazards, in real time. This approach holds significant potential to provide benefits for water and food security in drought-prone regions. By providing decision-makers and governments with advanced information on the possible occurrence of impacts, it would contribute to a more effective response to these events (AghaKouchak et al., 2023; Funk et al., 2019, p. 2; Merz et al., 2020; Sutanto et al., 2019).

The definition presented here directly encompasses the concepts of "Anthropogenic Drought" (AghaKouchak et al., 2021), "Human-induced drought" and "human-modified drought" (Van Loon et al., 2016b) and places them within the same definition. Furthermore, the definition proposed here does not refute or discard the others commonly found in the literature, such as agricultural drought and hydrological drought. These could be seen as classifications that denote the type of anthropogenic impact associated with the "exceptional period of water shortage" (drought) in question. In other words, agricultural drought under this new definition would be an exceptional period of water shortage that negatively affects agricultural production and hydrological drought an exceptional period of water shortage that negatively affects the water resources on which human activities are dependent.

The definition proposed here excludes the classification "meteorological drought" since this defines a long period of lower than expected precipitation (Wilhite et al., 2000) and does not directly associate this with the occurrence of any impact. Meteorological drought could be renamed "prolonged dry spell" or "precipitation deficit period" since it is only related to the emergence of one of the natural hazards related to droughts. It is interesting to note that in Chapter 2 "Meteorological Drought" was used as one of the stages of the DCA. This consideration does not invalidate or reduce the conclusions of that chapter. However, the understanding of droughts built up by combining the findings of this thesis shows that this nomenclature should be changed for future work.

At first glance, one might conclude that the drought as an exceptional period of water shortage experienced or caused by humans disregards droughts that occur in natural ecosystems. This is not the case. Crausbay et al., (2017) proposed the terminology of ecological drought "*as an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems*." These authors argue that anthropogenic processes are a fundamental part of ecosystems vulnerability and also of the driving processes that trigger drought events (e.g. higher temperatures and precipitation reduction due to climate change). Based on this, "ecological droughts" are directly or indirectly caused by anthropogenic actions and therefore fit the drought definition proposed here.

Crausbay et al. (2017) argue that there is already too much focus on human impacts and that this takes attention away from drought impacts on ecosystems. I, on the other hand, argue the opposite. I believe that once it is accepted that impressive scenes of environmental devastation during droughts are the result of human interactions with the environment, it becomes easier to mobilize efforts and social support to promote the development of mitigation and protection measures associated with these issues.

Accepting a definition of drought such as the one proposed in this thesis implies in practical terms that there can be no monitoring or evaluation of drought without taking into account the human component of this disaster. Drought assessment studies can be carried out using as a starting point an assessment of drought impacts, accessing its causes, consequences and range, as has been proposed by Walker et al., (2022). From there, it will eventually be necessary to assess the climatological characteristics of the natural hazards related to the drought events studied. Standardized indices of hydro-meteorological variables would then be useful for this stage (Chapter 1, Section 1.4.1).

This does not mean that the many "drought" monitoring systems that are generally based on a combination of standardized indices are useless or counter-productive. On the contrary, these systems are able to accurately capture the emergence of natural hazards that have the potential to reduce the water availability and therefore contribute to drought event emergence (Kchouk et al., 2022). The proposed definition highlights what these systems are actually indicating. Hence, it reveals more precisely what their capabilities, applications and limitations are which is crucial for actually monitoring drought events. Section 5.4.1 presents proposals for improving these systems based on the conclusions of this thesis.

5.3 Opportunities and outlook

5.3.1 Drought indexes contextualization: The future of drought monitoring

One of the pillars for reducing the risk of drought is the development and implementation of monitoring and early warning systems (Chapter 1, Section 1.2), but these systems are still the least developed compared to those in place for other disasters (Hao et al., 2014). In an extensive bibliometric review of more than 5000 papers related to so-called "drought indices", Kchouk et al. (2022) revealed that traditional drought monitoring systems, as well as drought assessment studies, tend to disregard the human influence on drought. This has been discussed at length in this thesis, but one of the interesting take home messages from the study of Kchouk et al. (2022) is that the improvement of drought monitoring systems requires the development of contextualize drought indices. The authors suggest, for example, that such indexes should take into account local aspects related to human well-being (e.g. water and food security). The findings of this thesis can inform future research focused on the development of such indices.

The Drought Cycle Analysis (DCA) method presented in Chapter 2 can be the backbone of a methodological framework for this, since it is directly related to drought monitoring. The theoretical concepts presented in Chapter 4 can be combined with the principles of socio-ecological systems applied to drought, such as those presented by Kchouk et al., (2023) and contribute to a better representation of the human-water dynamics to be considered in socio-hydrological modeling. The SHARE model presented in Chapter 3 can be the methodological framework that will simulate these dynamics, generating contextualized outputs regarding water and food security. These results can be combined with conventional standardized indices and integrated into the monitoring framework presented by the DCA. Besides, a more contextualized and representative drought classifications can be sought, since those used in Chapter 2 are related to socio-hydrological dynamics between small and large reservoirs.

The development of a drought monitoring methodology that integrates contextualized information such as that proposed here would represent a significant advance in (proactive) drought management, especially in relation to the mitigation and preparation stages, as well as being an important step towards developing the capacity to predict drought and drought impacts. Through this methodological framework, it would also be possible to take drought monitoring to another level. On the long term, the aim should be to not only observe the standardized distance that given hydro-meteorological variable is from the long-term average, but rather the distance that local populations are from achieving certain desired welfare level.

5.3.2 Socio-hydrological modelling: A pathway for improving public policies

Although the most recent studies related to droughts have increasingly highlighted the importance of taking the human component into account in the development of both assessment and monitoring studies to create solid foundations for the development of more efficient public policies, in practice it can be observed that old-fashioned and obsolete strategies for addressing drought persist in many parts of the world. Ding et al, (2011) points out that one of the main reasons for this is that for many regions the return-on-investments for such approaches is not clear, i.e. the cost-benefit of proactive management is still uncertain.

Changing paradigms when the benefits are not clear represents a risk for the decision-maker, who might therefore prefer to stick with the *status quo*. This behaviour is similar to the cognitive investment related to drought adaptation presented in Chapter 4. Socio-hydrological modelling can be an important step in simulating new public policies and drought mitigation and preparedness strategies. The primary characteristics and possible changes in socio-hydrological dynamics can be included in socio-hydrological models such as SHARE presented in Chapter 3 and from there simulate key characteristics to evaluate the effectiveness of the policy or strategy in question in achieving the proposed objective.

Dependent on the level of complexity added to the model to simulate the public policy or mitigation/preparedness strategy, it may be necessary to use Agent-Based Models. Especially if it is necessary to simulate patterns that emerge due to interactions between individuals in the hydrological system. Works such as Wens et al., (2022), Streefferk et al., (2023), Van Oel et al., (2019) present methodologies that can serve as a basis for integrating more complex behavioural dynamics into drought-related studies.

A hypothetical example to draw how socio-hydrological models could be used to simulate drought policy can be created from the case study in Chapter 3. Since small reservoirs cause negative and positive impacts during and after drought events, one could consider replacing such structures with more efficient ones. For instance, the SHARE model could be used to evaluate the impacts of replacing a network of small reservoirs with a network of floor cisterns (structures that capture surface runoff but do not have significant evaporation losses, see Figure 3.1e).

Another kind of policy that causes major local changes and for which a socio-hydrological model could be used to simulate its effectiveness , are those related to nature-based solutions. Environmental valuation methods could be associated with the SHARE model to analyse the cost benefits of such measures. Similar work has already been carried out in this direction, but only using qualitative and indirect methods to assess the effectiveness of nature-based solutions for reducing the risk of drought (Kalantari et al., 2018; Sintayehu et al., 2023). These examples demonstrate the relevance of applying methods based on socio-hydrology to drought management, which in addition to supporting the improvement of drought policies allows for an increase in interdisciplinary studies related to this disaster.

It is important to note that models such as SHARE do not represent all the socio-hydrological dynamics of a region and that this must be taken into account when interpreting and applying the results, especially when it involves the development of public policy. Over- or under-representation of a given process can create a conceptual bias and misinform those using the model's outputs, once these methodological limitations are not clarified. In other words, a socio-hydrological model cannot be treated as a black box; the information produced by such tools needs to be understood, as well as the methods used to produce such outputs.

5.4 Socio-hydrology limitations and new directions

The "socio" component of the socio-hydrology applied in this thesis was mostly "static" in the sense that temporal variations in the socio-hydrological dynamics were not considered, although its details evolved over the course of the chapters. This does not imply that the methods applied in this thesis are wrong or should not be replicated in future work. On the other hand, the difficulty in representing and validating socio-hydrological processes, which are directly influenced by variations in human actions, is not unique to this thesis (Wens et al., 2020; Wens et al., 2019; Streefkerk et al., 2023; Van Oel 2018; Schrieks et al., 2021; Shanono & Ndiritu, 2023). It is reasonable for a relatively new discipline such as socio-hydrology that such limitations still exist. Highlighting these limitations indicates to future scientists which knowledge gaps remain open.

Future work will have to look for ways to acquire more observational data related to socio-hydrological dynamics, especially regarding human behaviour, agricultural practices and water use decisions. This is related to one of the 23 unsolved problems in hydrology listed by the International Association of Hydrology (IAHS): *"How can we extract information from available data on human and water systems to inform the process of building socio-hydrological models and conceptualizations?"* (Blöschl et al., 2019).

The authors of this study raised this scientific question to point out that there are data sets from socio-hydrological studies in all the literature and these need to be compiled and meta-analysed in order to support the development and simulation of socio-hydrological models. This is indeed relevant, but I would emphasize that it is even more important to build and maintain new databases related directly to the human component, dedicating the same effort that has gone into building time series of hydro-meteorological data over the centuries. Socio-hydrology will not advance if research is carried out entirely in offices. I emphasize the importance of this even more by bringing up the development of my thesis as an example. I would not have been able to present the findings in Chapter 4 or represent socio-hydrological dynamics (even though still represented in a limited way) in Chapter 2 and 3 if I had not done fieldwork and talked directly to people in the respective study areas. The interactions based on interviews and workshops were crucial to reveal details about the study area that I wouldn't have had access to if I hadn't gone there in person.

This also shows that future work should be interdisciplinary, since hydrology does not have all the means to systematically collect this kind of socio data in a more comprehensive way. Burrhus Frederic Skinner, considered the father of human behaviour analysis, said: "*Men and women act upon the world, and change it, and are changed in turn by the consequences of their action*." (Overskeid, 2018). This was said 55 years before the creation of socio-hydrology (taking the article by Sivapalan et al., 2012, as the starting point for this discipline), showing that one of the core concepts of socio-hydrology is already consolidated in other areas, such as behavioural psychology. This does not imply that a (socio)-hydrologist needs to be a specialist in psychology, but it does indicate that interdisciplinarity can be a way of solving problems that we cannot find a solution to by interacting only with our peers in the same scientific field.

5.5 Concluding remark

If human actions modify the Earth's systems, it is crucial that we ask ourselves how these actions may contribute to the emergence and propagation of disasters directly related to the scarcity of the most precious resource for human welfare. This thesis investigated this issue, demonstrating that incorporating concepts from socio-hydrology enables a deeper understanding of the human influence on the emergence and propagation of drought events. The lifestyle adopted by individuals to achieve a certain level of well-being determines their own susceptibility to drought events. Changes in the environment resulting from their lifestyles can lead to unwanted consequences, contributing to water and food insecurity for both themselves and others. This is also directly related to their susceptibility to facing drought situations in the future.

Throughout the chapters of this thesis, it has become clear that there is a need to go beyond methods that approach drought solely as a hydro-meteorological phenomenon or a natural hazard. Instead, attention should be directed to the pivotal role that human actions play in the emergence of drought. Socio-hydrology provides the means for such considerations, revealing that drought is a socio-hydrological phenomenon resulting from the way humans interact with the environment. If there are still doubts about whether we are in the Anthropocene era geologically, in (socio)-hydrology, there is no doubt that we have been in this era for a long time. Therefore, the definition of drought should reflect this reality. Here, I advocate that drought should carry this anthropogenic load in its definition and should be defined as an exceptional period of water shortage experienced or caused by humans.

Socio-hydrology is a relatively new discipline that is proving its worth and gaining ground within the environmental sciences. In this thesis I have demonstrated that this discipline is valuable in accessing the processes and dynamics that result in the emergence of drought events. I finish this thesis proudly considering myself a socio-hydrologist. Even so, I long for the day when this definition is no longer used. Once there is a unanimous understanding that human actions are an endogenous component of the hydrological cycle, the name of this discipline will become a pleonasm so that adding "socio" in front of "hydrology" will no longer be necessary.

Appendices
Bibliography
Authorship contribution
List of publication

Appendix A

Additional results of Chapter 3

Figure A1 shows the results of the test of the influence of the parameters derived from the field work on the output indicators of the SHARE model (total water storage, agricultural production and number of water trucks). Parameters 11-15 and 15-17 in Table 3.1 were varied one by one, considering the SC2 scenario, which includes irrigation.

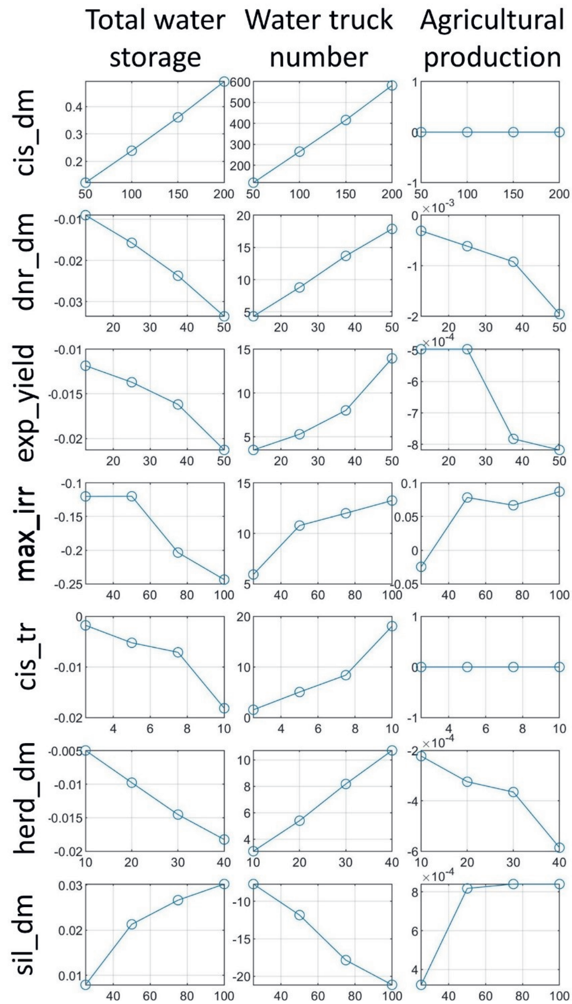

Figure A1. Analysis of the influence of the parameters inferred based on fieldwork on the evaluated output metrics.

The parameters related specific to the AquaCrop for maize production simulation were based on the information presented by Martins et al., (2018) and are presented in the Table A1.

Table A1. AquaCrop specific parameters.

Base temperature (°C)	10
Upper temperature (°C)	30
Time from sowing to emergence (day)	6
Time from sowing to maximum rooting depth (day)	99
Tim from sowing to start senescence (day)	99
Time from sowing to maturity (day)	120
Time from sowing to flowering (day)	56
Length of the flowering stage	56
Minimum effective rooting depth (m)	0.3
Maximum effective rooting depth (m)	0.6
Shape factor describing root zone expansion (dimensionless)	13
Water productivity normalized for ETo and CO2 (g m-2)	34
Canopy growth coefficient (CGC) (fraction per day)	0.10089
Maximum canopy cover Fraction (CCx) in fraction soil cover	0.85
Canopy decline coefficient (CDC) fraction per day	0.08
Number of plants per hectare (plants ha-1) 62500 Number of plants per hectare (plants ha-1)	62500

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List of publications

Peer-reviewed journal papers - **In this Thesis**

<u>Ribeiro Neto, G. G.</u>, Melsen, L. A., Martins, E. S., Walker, D. W., & Van Oel, P. R. (2022). Drought cycle analysis to evaluate the influence of a dense network of small reservoirs on drought evolution. *Water Resources Research*, *58*(1), e2021WR030799.

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Peer-reviewed journal papers - **Other**

Van Langen, S. C., Costa, A. C., **<u>Ribeiro Neto, G. G.</u>**, & Van Oel, P. R. (2021). Effect of a reservoir network on drought propagation in a semi-arid catchment in Brazil. *Hydrological Sciences Journal*, *66*(10), 1567-1583.

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Publication in Portuguese – **Book chapter**

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"The only fight that is lost is the one that is abandoned."
(Carlos Marighella)

The journey of completing a doctoral thesis was one of the greatest challenges I faced until this moment, and it is very rewarding to finally reach this moment of gratitude. Besides all the knowledge I acquired to achieve the results, the discussions and conclusions presented in this book, I believe I managed to crystallize my identity as a scientist and have in mind the paths I wish to pursue in my professional life. I never imagined how difficult this journey would be, especially in the last year. Nor did I imagine all the changes and new experiences that the pursuit of a doctoral degree would bring to my life. Many times, walking this path was a solitary process in which giving up always seemed like an easier and more seductive alternative to follow. However, the direct and indirect support of various people over these nearly 5 years kept me focused and moving forward. To these people, I dedicate this thesis and express my deepest gratitude.

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"A única luta que se perde é aquela que se abandona."
(Carlos Marighella)

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About the Author

Germano Gondim Ribeiro Neto was born in João Pessoa, Brazil, on May 5th, 1992. Since childhood, he had harboured the dream of becoming a scientist, and this desire persisted throughout his adolescence. As a result, in 2010, he began his degree in Civil Engineering at the Federal University of Paraíba, where he developed an interest in hydrology. In 2015, he was accepted into the Water Resources and Environmental Sanitation master's programme at the Hydraulic Research Institute of the Federal University of Rio Grande do Sul.

From the first orientation meeting, he decided to focus his studies on droughts, a subject that has always fascinated him due to the great influence of this disaster on the culture and traditions of his native region. After completing his master's degree in 2017, he joined the drought research group at the National Centre for Monitoring and Warning of Natural Disasters (Cemaden) as a fellow researcher. His time at Cemaden consolidated his desire to pursue an academic career, leading him to seek a PhD.

In 2019, due to the political context in Brazil, which at the time was adverse to science and education, he decided to look for opportunities abroad. He was accepted to join the research project "3DDD: Diagnosing Droughts to Better Understand Droughts" at Wageningen University. Germano specialized in socio-hydrology, seeking to better understand the human influence on the emergence and propagation of drought events.

He currently works as a research associate in the hydroclimatic extremes research group at the School of Geographical Sciences at the University of Bristol (UK). Germano's plans are to continue in academia, further exploring the socio-hydrological aspects of drought events, also considering the context of climate change.

Statement of authorship contribution

The general research idea was proposed by my co-supervisor as part of the research project called "Diagnosing drought for dealing with drought in 3D: Toolbox for increasing drought preparedness of actors in water and climate governance, starting from north-eastern Brazil", however I formulated the research plan and specific research questions. I wrote all text in Chapter 1 and 5, with minor comments from my promotor and co-promotors. Chapter 2 to 4 result from a collaboration with the authors listed here. Their contributions are presented per chapter below.

GR: Germano Gondim Ribeiro Neto (WUR)

AC: Alexandre Costa (Unilab)
AD: Art Dewulf (WUR)
DW: David Walker (WUR)
EM: Eduardo Martins (FUNCEME/UFC)

JB: João Paulo Breda (WUR)
LC: Louise Cavalcante (WUR)
LM: Lieke Melsen (WUR)
PO: Pieter van Oel (WUR)
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Chapter 2
Conceptualization: GR
Modelling, data analysis and interpretation: GR in consultation with LM, DW, PO
Drafting of manuscript: GR
Revision of the article and approval for publishing: LM, DW, PO

Chapter 3
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Modelling, data analysis and interpretation: GR in consultation with LM, AC, DW, PO
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Conceptualization: GR
Modelling, data analysis and interpretation: GR in consultation with LM, AC, DW, AD, PO
Drafting of manuscript: GR
Revision of the article and approval for publishing: LM, AC, SR, LC, EM, DW, PO

Graduate school certificate

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(SENSE) declares that

Germano Gondim Ribeiro Neto

born on the 5th of May 1992 in João Pessoa, Brazil

has successfully fulfilled all requirements of the
educational PhD programme of SENSE.

Wageningen, the 24th of April 2024

SENSE coordinator PhD education

Dr Ir Peter Vermeulen

The SENSE Director

Dr Jampel Dell'Angelo

The SENSE Research School declares that **Germano Gondim Ribeiro Neto** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 37.2 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2019)
- Research in context activity: Workshop with water practitioners and rural populations of Northeast Brazil (2023)

Other PhD and Advanced MSc Courses

- Companion Modelling course, Wageningen University (2020)
- Introduction to the Google Earth Engine, Federal University of Paraiba, Brazil (2021)
- Introduction to python programming language , Federal University of Paraiba, Brazil (2021)
- CNDS Summer School on Exploring Frontiers in Natural Hazards: Drivers, Impacts, and Responses, Uppsala University, Sweden (2022)
- Process-Based Hydrological Modelling, University of Saskatchewan, Canada (2020)
-

Management and Didactic Skills Training

- Supervising 3 MSc students with thesis (2019, 2020, 2021)
- Participation in the PhD council (2019)
- Supervision of a fellow researcher at Research Institute of Meteorology and Water Resources (FUNCEME) (2020)

Oral Presentations

- *From meteorological to reservoir drought: The influence of a dense network of unmonitored small reservoirs on drought evolution in a semiarid region.* AGU, 14-17 2020, Online
- *Socio-hydrological simulation as a tool for analyzing drought impacts due to human actions.* Water Solutions 4-5 December 2021, Fortaleza, Brazil
- *The influence of a dense network of small reservoirs on drought evolution in a semiarid region.* XIth Scientific Assembly of the International Association of Hydrological Sciences 29 May- 3 June 2022, Montpellier France
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