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Adaptation Measures for Increasing Water Security in Basins Under Change

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Adaptation measures for increasing water security in basins under change

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“Nothing in life is to be feared, it is only to be understood.
Now is the time to understand more, so that we may fear less”
Marie Curie

ABSTRACT

GESUALDO, G. C. **Adaptation measures for increasing water security in basins under change**. 2023. 111p. Tese (Doutorado) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2023.

Climate change and extreme events significantly impact water security in basins worldwide. The increasing frequency and intensity of extreme weather events such as floods and droughts threaten the sustainability of water resources, jeopardizing economic development and social welfare. Therefore, it underlines the importance of adaptation strategies to enhance water security and build resilience in the face of climate change. This thesis aims to put forward risk pooling and index-based insurance as viable adaptation measures to enhance water security and bolster the resilience of catchments experiencing environmental changes in Brazil. We begin with a review of water security in Brazil, analyzing the peculiarities of each geographic region and hydrographic area. This analysis highlights the following challenges and opportunities for water management in Brazil: (1) the need to consider climate change scenarios in current and future policies, (2) improve and invest in non-structural adaptation measures, (3) involve society in the development of these mitigation and adaptation measures, and (4) improve cooperation between researchers and decision-makers. Given these challenges, we proposed the first adaptation measure: risk pooling. In order to do so, we present a novel framework to identify the spatial connectivity of hydrological droughts and propose the risk-pooling regions based on catchment connectivity characteristics. We have identified five regions within the country exhibiting similar drought patterns. These regions serve as a basis for devising risk-pooling strategies. In such strategies, regions located outside the identified drought similarity regions can form risk pooling regions to mitigate the impact of widespread droughts. A case study was applied to propose the second adaptation measure, index-based insurance. The study simulates multi-year and multi-risk index-based insurance for a Water Supply System, considering the impacts of climate change on water availability and demand. Based on the findings of the study case, we can provide suggestions for a contract structure that may be valuable to Brazilian water supply companies. We could assume that water utilities and consumers can regulate and reduce the financial effect of drought and flood disasters by adopting index-based insurance. Overall, we can conclude that the implementation of risk pooling mechanisms and index-based insurance as adaptive strategies in Brazil's catchments would improve water security and resilience by reducing the impact of extreme events, managing water shortages, guiding adaptation plans, and mitigating economic losses. This thesis provides a valuable contribution to the understanding of water resource planning and management, providing insights for effective water governance, sustainable development, and improved water security in Brazil.

Keywords: Freshwater resources; water management; extreme events; hydrological drought; spatially compound events; risk pooling; index-based insurance.

RESUMO

GESUALDO, G. C. **Medidas de adaptação para aumentar a segurança hídrica em bacias sob mudança**. 2023. 111p. Tese (Doutorado) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2023.

As mudanças climáticas e os eventos extremos impactam significativamente a segurança hídrica em bacias hidrográficas em todo o mundo. A crescente frequência e intensidade de eventos climáticos extremos, como enchentes e secas, ameaçam a sustentabilidade dos recursos hídricos, comprometendo o desenvolvimento econômico e o bem-estar social. Portanto, enfatiza a necessidade de medidas de adaptação para segurança hídrica e construir resiliência diante das mudanças climáticas. Esta tese tem como objetivo apresentar o agrupamento ("pool") de riscos e o seguro baseado em índices como medidas de adaptação viáveis para aumentar a segurança hídrica e reforçar a resiliência de bacias que sofrem mudanças ambientais no Brasil. Iniciamos com uma revisão da segurança hídrica no Brasil, analisando as peculiaridades de cada região geográfica e área hidrográfica. Esta análise destaca os seguintes desafios e oportunidades para a gestão da água no Brasil: (1) a necessidade de considerar cenários de mudanças climáticas nas políticas atuais e futuras, (2) aprimorar e investir em medidas não estruturais de adaptação, (3) envolver a sociedade na desenvolvimento dessas medidas de mitigação e adaptação, e (4) melhorar a cooperação entre pesquisadores e tomadores de decisão. Diante desses desafios, propusemos a primeira medida de adaptação: o agrupamento de risco. Para isso, apresentamos uma nova estrutura metodológica para identificar a conectividade espacial das secas hidrológicas e propusemos regiões de agrupamento de riscos com base nas características de conectividade da bacia. Identificamos cinco regiões dentro do país que exibem padrões de seca semelhantes. Essas regiões servem como base para a criação de grupos de risco. Em tais grupos, regiões localizadas fora das regiões de similaridade de seca identificadas podem formar regiões de risco para mitigar o impacto de secas generalizadas. Um estudo de caso foi aplicado para propor a segunda medida de adaptação, seguro baseado em índice. O estudo simula um seguro baseado em índices plurianuais e multirriscos para um Sistema de Abastecimento de Água, considerando os impactos das mudanças climáticas na disponibilidade e demanda de água. Com base nos resultados do estudo de caso, podemos fornecer sugestões para uma estrutura de contrato que pode ser valiosa para as empresas brasileiras de abastecimento de água. Poderíamos presumir que as concessionárias de água e os consumidores podem regular e reduzir o efeito financeiro de desastres de seca e inundação adotando um seguro baseado em índices. No geral, podemos concluir que a implementação de mecanismos de agrupamento de riscos e seguro baseado em índices como estratégias adaptativas nas bacias hidrográficas do Brasil melhorariam a segurança hídrica e a resiliência, reduzindo o impacto de eventos extremos, gerenciando a escassez de água, orientando os planos de adaptação e mitigando as perdas econômicas. Esta tese fornece uma contribuição valiosa para a compreensão do planejamento e gestão dos recursos hídricos, fornecendo insights para uma governança eficaz da água, desenvolvimento sustentável e maior segurança hídrica no Brasil.

Palavras-chave: Recursos hídricos; Gerenciamento hídrico; Eventos extremos; Secas hidrológicas; Eventos compostos espacialmente; Agrupamento de risco; Seguro indexado.

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Chapter 1

GENERAL INTRODUCTION

Climate change and its associated extreme events, including floods and droughts, pose significant challenges to water security in basins worldwide. The frequency and intensity of these events have been increasing, endangering the sustainability of water resources (IPCC - Intergovernmental Panel on Climate Change, 2018). The increasing trends are observed globally, with reports of rising magnitudes and frequencies of extreme events in various regions such as the USA, Europe, and Australia (ALFIERI et al., 2015; WASKO et al., 2021; ZHOU; LENG; PENG, 2018). The consequences of these extreme events extend beyond environmental impacts as they also jeopardize economic development and undermine social welfare, highlighting the urgent need for adaptation measures to enhance water security and build resilience in the face of climate change (DOLAN et al., 2021; BERRANG-FORD; FORD; PATERSON, 2011). Despite being recognized for its abundant water resources, Brazil is confronted with water-related issues that threaten its water security and the resilience of its water systems. Notably, the country has experienced widespread and severe droughts between 2011 and 2017, including a water crisis in the metropolitan regions of São Paulo (MRSP) and Brasília (CUNHA et al., 2019; SOUZA et al., 2022; LIMA et al., 2018). The water scarcity situation in the MRSP nearly reached Day Zero, a critical point where dam levels were unable to meet the region's water demand, resulting in an estimated economic loss of 5 billion USD in 2014, ranking it as the fifth-largest worldwide in terms of overall losses due to drought that year (Munich Re, 2015). Additionally, the Pantanal biome region faced a significant drought in 2019, while the metropolitan region of Manaus encountered a historical flood in 2021 (MARENGO et al., 2021; ESPINOZA et al., 2022). Although investments in infrastructure have helped manage water scarcity to some extent, water security challenges persist, and the increasing frequency and intensity of extreme water-related events underscore the necessity of adaptation measures to mitigate their impacts (ANA - Agência Nacional de ÁguasA, 2019). In recognition of the importance of enhancing resilience, the Brazilian National Water Agency (ANA) based on the 2022 OECD report emphasizes the integration of resilience thinking into water infrastructure and investment planning. This approach aims to minimize the duration and magnitude of shocks and failures and assess the potential benefits of various techniques (OECD - Organization for Economic Cooperation and Development, 2022). However, there is still limited knowledge concerning the effectiveness, functioning, and limitations of adaptation measures that integrate resilience. Further research is needed to explore these aspects and advance the understanding of how these types of adaptation measures can effectively increase water security in Brazil.

Resilience plays a critical role in a climate-change world characterized by multiple spatial and temporal scales (SIMONOVIC; ARUNKUMAR, 2016). Its defined as the capacity of a system, community, and society to adapt while maintaining an appropriate level of functioning and structure in the presence of hazards (BRUNEAU et al., 2003). Resilience becomes particularly significant when considering the occurrence of spatially compounding events, which are extreme events that occur concurrently over many locations (ZSCHEISCHLER et al., 2020). These events have the potential to significantly amplify vulnerabilities and losses resulting in water and energy crises, simultaneous crop failures in diverse regions, and increased risks to local and global food security (ANDERSON et al., 2019; GAUPP et al., 2019; MEHRABI; RAMANKUTTY, 2019a). An example of the compounding challenges faced in Brazil occurred in July 2014. In the Southeast region, the Cantareira System encountered severe hydrological drought conditions while simultaneously, in the Northeast region, the states of Ceará and Paraíba also faced severe and long-term droughts (APAC -Agência Pernambucana de Águas e Clima, 2014; NOBRE et al., 2016). Furthermore, Tabari et al. (2021) projected a significant increase in the risk of droughts and floods in the South American continent. Given these circumstances, the importance of resilience becomes even more paramount, as it equips systems, communities, and societies with the ability to withstand and successfully adapt to these compounding challenges. However, there remains a knowledge gap regarding spatially compounding droughts, particularly in the Brazilian context, which necessitates further investigation. Moreover, due to Brazil's vast territorial area and regional heterogeneity, there is a need to develop precise methodologies for large-scale analysis of drought events (CUNHA et al., 2019).

A range of adaptation measures has been proposed in Brazil to enhance and maintain water security in the face of extreme events. The National Water Security Plan (PNSH) outlines a set of water infrastructure improvements including dams, water piping, and adduction systems to be implemented by 2035 (ANA - Agência Nacional de ÁguasA, 2019). While investing in infrastructure is necessary, non-structural adaptation measures have gained recognition for their role in enhancing water security and building resilience in the face of water-related challenges (POUSSIN et al., 2012; NAVARRO et al., 2021). The literature suggests several non-structural adaptation measures that are particularly relevant for Brazil such as nature-based solutions (NBS) (MACEDO; LAGO;

MENDIONDO, 2019), water reuse and recycling systems (LIMA et al., 2021), and the development of early warning systems (HORITA; ALBUQUERQUE; MARCHEZINI, 2018). Within the realm of non-structural measures, risk pooling, and index-based insurance have emerged as key strategies (GUZMáN; MOHOR; MENDIONDO, 2020; ABDI et al., 2022; BAUM; CHARACKLIS; SERRE, 2018; GAUPP et al., 2017). Risk pooling refers to an informal social insurance system that helps protect against unexpected losses (CRONK; AKTIPIS, 2021). It can involve the sharing of water resources among different regions or stakeholders to minimize the impact of water-related hazards (BAUM; CHARACKLIS; ASCE, 2020). For instance, Baum, Characklis and Serre (2018) described a risk pooling arrangement between water utilities where the redistribution of water supplies during periods of scarcity ensured availability for essential uses and mitigated the adverse effects of droughts or extreme events. This measure contributes to the resilience of water systems and reduces vulnerability in regions facing water stress. However, there is a lack of guidance on the establishment of risk pool regions, particularly in Brazil, a country of continental size and with distinct environmental and climatic characteristics. The identification and establishment of a network of risk pool regions require further guidance and research to ensure effective implementation and outcomes in the country.

The second non-structural adaptation measure is index-based insurance, also known as parametric insurance, which offers innovative financial protection against water-related risks, such as droughts or floods. It operates by providing preestablished compensations when a predetermined threshold is exceeded (BARNETT; MAHUL, 2007). The threshold is determined based on meteorological or hydrological variables that are correlated with hazard losses (CESARINI et al., 2021). Index-based insurance promotes sustainable water management and encourages proactive risk management strategies by mitigating the financial risks associated with water scarcity or excess (BENSO et al., 2023). While index-based insurance is implemented worldwide, its primary focus has been on the agricultural sector (AGUDO-DOMíNGUEZ et al., 2022; ABDI et al., 2022; EZE et al., 2020). An example of its application in Brazil is the cocoa insurance in Southern Bahia, which was the country's first index-based insurance designed to cover losses in cocoa production due to drought (WAACK et al., 2022). However, the development of parametric insurance specifically targeting the water supply sector is still in its early stages. An example, *"Flow"* is an indexed water-level insurance customized for companies with revenue and cost exposures to fluctuating river water levels in Europe (Swiss Re, 2022). Nevertheless, research on index-based insurance for water supply systems remains limited, indicating a lack of studies exploring its potential as an adaptation measure in this context. Additionally, integrating index insurance into water management strategies empowers communities to make informed decisions, invest in resilient infrastructure, enhance their adaptive capacities, therefore foster sustainable water practices increasing resilience to future water-related challenges.

This doctoral thesis aims to put forward risk pooling and index-based insurance as viable adaptation measures to enhance water security and bolster the resilience of catchments experiencing environmental changes in Brazil. By proposing the implementation of risk pooling mechanisms and index-based insurance, this research seeks to address the challenges posed by evolving hydrological conditions including the occurrence of spatially compound extreme events and shifts in water availability. The adoption of these adaptation strategies is anticipated to contribute to the overall improvement of water security and the capacity to withstand and recover from hydrological changes, ultimately fostering resilience in Brazilian catchments. Furthermore, this doctoral thesis aligns with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 6: Clean Water and Sanitation, which aims to ensure water and sanitation availability and sustainable management for all. It also contributes to addressing the 23 Unsolved Problems in Hydrology identified by the International Association of Hydrological Sciences (IAHS), especially for the variability of extremes and their interfaces with society, fostering advancements in the field of water resources research and management (BLöSCHL et al., 2019). Moreover, this research is conducted in collaboration with UNESCO's International Hydrological Programme (IHP), specifically within Phase 9, which focuses on advancing integrated water resources management and addressing water security challenges globally (UNESCO, 2022).

1.1 Research hypothesis

The implementation of risk pooling mechanisms and index-based insurance as adaptive strategies in Brazil's catchments provide significant improvements in water security and resilience by reducing the impact of extreme events, enhancing the ability to manage water shortages, guiding the development of effective adaptation plans, and mitigating long-term economic losses caused by extreme events.

1.2 Objectives

1.2.1 General objective

Propose risk pooling and index-based insurance as adaptation measures to improve water security and resilience in catchments under changes in Brazil.

1.2.2 Specific objectives

a) Review and analyze water security in Brazil, considering the impacts of extreme events, water shortages, and the progress of national water security policies.

b) Introduce a framework to identify the vulnerable regions in Brazil accounting for spatially compounding droughts.

c) Recommend a network of risk pool regions based on the identified vulnerable regions, aiming to enhance resilience and guide the implementation of future adaptation plans for hydrological extremes.

d) Propose index-based insurance as an adaptation measure aimed at mitigating and averting long-term financial losses in a water supply system in the face of extreme events.

1.3 Thesis structure

This doctoral thesis aims to propose risk pooling and index-based insurance as viable adaptation measures to enhance water security and bolster the resilience of catchments experiencing changes in Brazil. The **first chapter** serves as a general introduction, providing an overview of the research hypothesis and objectives, as well as, the importance of addressing water security concerns in the context of climate change and extreme events. The **second chapter** of this thesis presents a detailed review of water security in Brazil, assessing the specific characteristics and challenges faced by different geographic regions and hydrographic areas. The **third chapter** focuses on presenting a novel framework to identify the spatial connectivity of hydrological droughts within catchments. Based on the spatially compounding droughts and their characteristics, the study proposes the first adaptation measure: a network of risk pool regions. In the **fourth chapter**, a case study is conducted to propose the second adaptation measure: index-based insurance. By simulating multi-year and multi-risk index-based insurance for a Water Supply System, the study presents the measure to mitigate financial risks associated with water shortages caused by climate change impacts. In the **fifth and final chapter,** the thesis concludes by providing a summary of the key findings, drawing overarching conclusions, and presenting recommendations. The study emphasizes that the implementation of risk pooling and index insurance as adaptation measures contributes to the overall improvement of water security and the capacity to withstand and recover from hydrological changes, ultimately fostering resilience in Brazilian catchments.

1.4 Code and data availability

The codes and data related to **Chapter 3**, which includes the hydrological drought extraction and drought connectedness analysis, can be found in the GitHub repository:**<https://github.com/gabichiquito/Hydrological-drought-connectedness>**. Similarly, the codes and data related to **Chapter 4**, which focuses on the multi-risk index-based insurance for a Water Supply System, are available in the GitHub repository: **<https://github.com/gabichiquito/Index-based-insurance-WSS>**.

Additionally, we would like to mention that although not directly related to the thesis, the drought extrication analyses in Chapter 3 were also conducted for floods, as we recognize the importance of this analysis. The flood extraction codes can be accessed at: **<https://github.com/gabichiquito/hydrological-flood-extraction.git>**. These repositories contain the necessary codes and data to reproduce and further investigate the findings presented in the respective chapters of the thesis.

Chapter 2

WATER SECURITY IN BRAZIL - CURRENT CHALLENGES AND FUTURE PERSPECTIVES [1]

Abstract

Water crises have risen over the past decade. In the Brazilian context, extreme events have been intensified over the country undermining water systems in regions that already face water shortages. Although existing studies focused on individual regions of Brazil, an overview of the entire country will contribute to developing a national action plan for mitigating water inequalities. Therefore, we reviewed and analyzed water security in Brazil, presenting a diagnosis focused on the peculiarities of each geographic region and hydrographic area. One of the biggest threats is the slow-paced steps toward a robust policy for strengthening national water security. As shown here, water security depends on several variables such as availability, quality, and external factors such as climate forcing and anthropogenic pressure. Therefore, water governance needs to integrate human needs with the ecosystem functioning considering climate uncertainties to move towards better water resources planning.

Keywords: Freshwater resources; Extreme events; Consumptive water use; Water management.

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2.1 Introducion

Water is an essential resource for all ecological and socioeconomic activities. Although freshwater is enough to meet the world demand, spatiotemporal variations in its availability are wide leading to water scarcity in many parts of the world. Moreover, approximately 80% of the world's population live in areas subjected to water scarcity (VöRöSMARTY et al., 2010), and two-thirds of them suffer from water shortage for at least one month of the year (MEKONNEN; HOEKSTRA, 2016).

The water resources are constantly under pressure as demand for water, energy, and food is increasing due to global population growth and enrichment of nations (WADA et al., 2016). Furthermore, water availability is affected by climate change, and water-related extreme events — intensification of droughts and floods, changes in seasonal precipitation and evaporation — threaten the sustainable development of societies and maintenance of ecosystems (KONAPALA et al., 2020; PADRóN et al., 2020; TABARI, 2020). Likewise, climate projections indicate a reduction in renewable surface and groundwater resources, intensifying competition among the multiple uses of water and multiple economic sectors (IPCC - Intergovernmental Panel on Climate Change, 2013).

Global water crises — from droughts in the world's most productive farmlands to the hundreds of millions of people without access to safe drinking water — are among the most significant threats the planet has faced (WEF - World Economic Forum, 2015). Other global risks are inextricably tied to water management and access, extreme weather events, failure of national governance, state collapse or crisis, rapid and massive epidemics, and failure to adapt to climate change. Particularly in Brazil, a country with a continental dimension, water-related problems stem from contrasting vulnerabilities (DEBORTOLI; CAMARINHA; RODRIGUES, 2016), which undermine local water security. While the Northeast region faces prolonged drought spells, floods are recurrent in some parts of the Southeast and South.

According to Marengo (2007) and Cunha et al. (2018), in the last century, every Brazilian region faced extreme events, which will become more frequent in the future due to climate change. There are several studies that show these trends for specific regions of the country: Amazon region (BARICHIVICH et al., 2018; CORREA et al., 2017; GLOOR et al., 2013), Northeast region (CUNHA et al., 2018; MARENGO; TORRES; ALVES, 2017; OLIVEIRA; SILVA; LIMA, 2014), Southeast (ÁVILA et al., 2016; LYRA et al., 2018; ZILLI et al., 2017), and South (MURARA et al., 2019). Although existing studies focused on individual regions of the country, an overview of the main vulnerabilities resulting in water insecurity in the entire country will contribute to developing a national action plan for mitigating water inequalities exacerbated by climate extremes.

To incorporate all water-related challenges, the water security concept characterizes interactions between water conditions, ecosystem functioning, and societal needs (SCOTT et al., 2013). Thus, water security consists of having access to water in acceptable quantity and quality (OECD - Organization for Economic Co-operation and Development, 2016) for health, livelihoods, ecosystems, and production, coupled with an acceptable level of water-related risks to people, environments, and economies (GREY; SADOFF, 2007). Similarly, it is intrinsically associated with the society's ability to adapt to extreme events and especially to better predict periods of scarcity (TAFFARELLO et al., 2016). Therefore, we reviewed and analyzed water security in Brazil based on the database of the National Water Resources Information System (from Portuguese Sistema Nacional de Informações sobre Recursos Hídricos – SNIRH – available in <http://www.snirh.gov.br/portal/snirh/snirh-1/acesso-tematico/usos-da-agua#wrapper>) implemented by the National Water and Sanitation Agency (from Portuguese Agência Nacional de Águas e Saneamento Básico - ANA). It is the first attempt to characterize and examine the current and future water security situation on a national scale. We are motivated by important discussions that have not been addressed in the literature:

1. How is the current situation of water security in the country in terms of water availability and demand?
2. What are the emerging challenges in water security following a development path?
3. What are the prospects of water security in Brazil?

Firstly, we provide a detailed overview of water availability and demand of the main consumptive uses affecting water security in Brazil. The diagnosis was focused on the peculiarities of each geographic region and hydrographic area. Moreover, based on the coauthors' expertise, we discussed the current and future challenges concerning regional and national water security, mainly those related to negative impacts caused by climate change. At the end, perspectives are provided to guide the next steps towards overcoming water insecurity in Brazil.

The current discussion aims to contribute to the Panta Rhei global initiative by enhancing the knowledge of changes in hydrology and related societal systems (MONTANARI et al., 2013). Moreover, our discussions collaborate on achieving the Sustainable Development Goals (SDGs), particularly the SDG-6 (Clean water and sanitation) aiming at ensuring the availability and sustainable management of water and sanitation for all, which in turn will support many other goals (UN - United Nations Department of Economic and Social Affairs, 2019).

2.2 An overview of water security in Brazil

2.2.1 Water availability

Brazil has a privileged position in the world regarding water resource availability, accounting for about 12% of the world's freshwater (SHIKLOMANOV et al., 2000). Notwithstanding, this resource varies enormously throughout the country both spatially and temporally. Brazilian water resources can be geographically divided into 12 hydrographic regions spread across the geopolitical divisions and six different biomes, which are large scale ecosystems that share similar vegetation, soil, climate, and wildlife characteristics: Amazon, Cerrado, Atlantic Forest, Caatinga, Pampas, and Pantanal (fig.1). There is high variability in climate characteristics due to the country's continental proportion. Therefore, water resources are unevenly distributed leading to local socioeconomic crisis due to water scarcity. The water supply system frequently deals with quality and quantity problems, mainly in the metropolitan regions of the country such as the cities of São Paulo, Rio de Janeiro, Porto Alegre, Curitiba, Belo Horizonte, Brasília, Manaus, and São Luis (fig. 1b).

The Amazon (AMZ) and Parana (PRN) regions represent distinct portraits of water-related problems caused by the heterogeneous distribution of water resources. The AMZ accounts for 4.5% of the country's population and provides about 80% of the total surface water availability in Brazil. Conversely, the PRN is the most economically developed region in the country notwithstanding that it represents 5% of the total surface water availability and is home to 32% of the Brazilian population (the most populous hydrographic regions). To overcome mainly the lack of water supply, several cities in Brazil rely on groundwater as only or complementary source of freshwater. For instance, about 17% of Brazilians rely exclusively on groundwater, in turn, also contributing to surface water endurance during drought spells (HIRATA et al., 2019). The last water resources report issued by the ANA (estimates 2.4 million wells in the country (ANA - Agência Nacional de Águas, 2019a). Groundwater availability in the Brazilian territory is equivalent to around 18% of the total surface water even though it is also unevenly distributed due to different hydrogeological characteristics and aquifer yield. Specifically, in the semiarid Northeast of Brazil, the combination of soil salinity and low drainage capacity of the crystalline formation that dominates the area severely limits available groundwater resources.

Although water quality and quantity are often treated separately, we need to provide humans and the environment with both clean (quality) and sufficient (quantity) water supply, as in many water security definitions (OECD - Organization for Economic Co-operation and Development, 2016; STRICKERT et al., 2016; UNESCO, 2013; WITTER; WHITEFORD, 1999). Thus, the integrated water balance — quality and quantity — is fundamental for assisting effective management actions and policies for ensuring water security at a national level. From an integrated quali-quantitative analysis depicted in

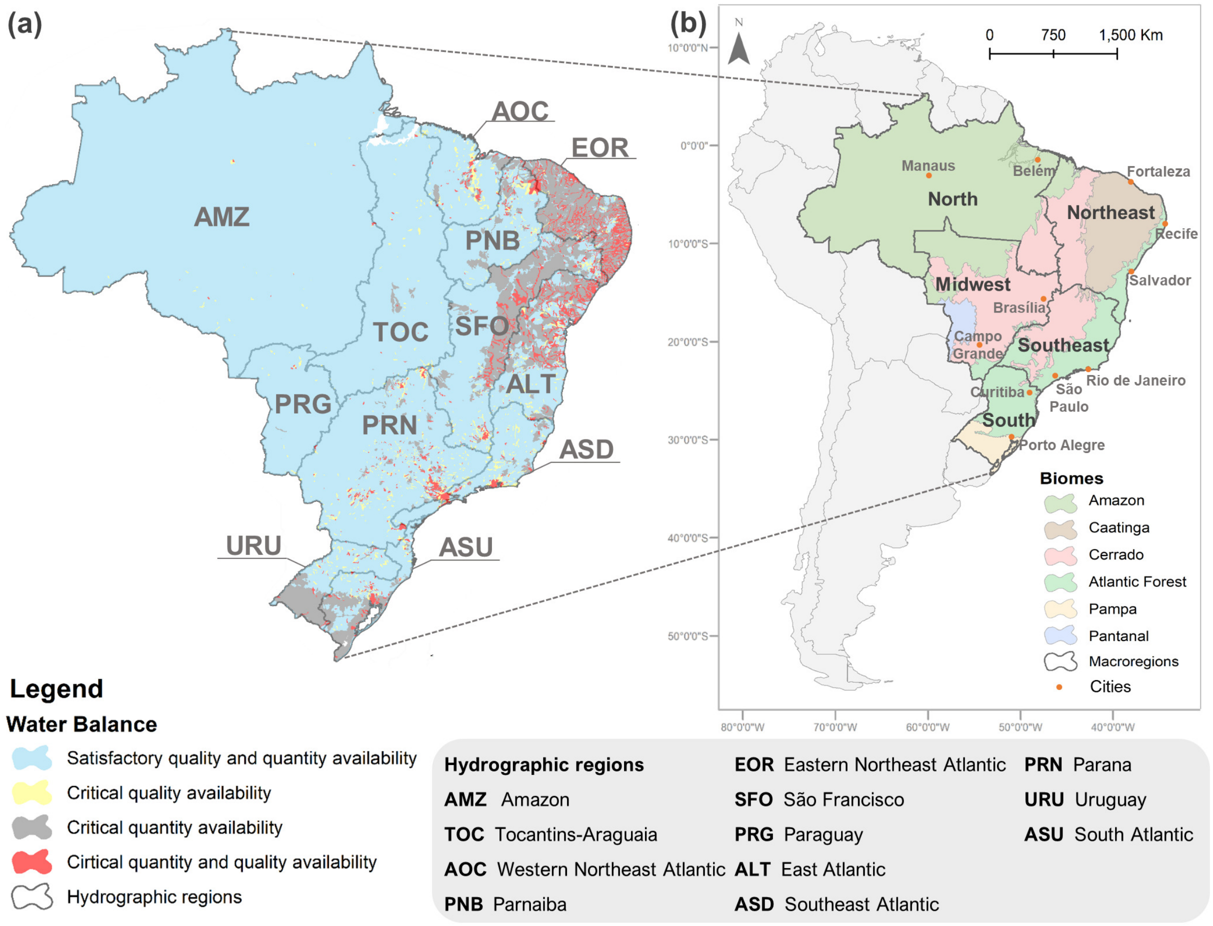

Figure 1 – Brazil's location in South America, where figure (a) shows the water balance status over the Brazilian hydrographic regions and (b) provides additional information on the biomes and the main Brazilian cities in the geopolitical divisions of microregions

Fig.1a, the Eastern Northeast Atlantic (EOR), São Francisco (SFO), and East Atlantic (ALT) regions stand out for presenting a high level of water insecurity (critical quality and quantity availability). These hydrographic regions along with the Parnaiba region (PBN) are located in the Brazilian semiarid region, one of the world's most densely populated dryland regions (MARENGO, 2008). Despite its natural hydroclimatic characteristic, climate change projections indicate an intensification of droughts in the Brazilian semiarid region (MARENGO; TORRES; ALVES, 2017). Therefore, to manage water resources, considering climate change uncertainties is of paramount importance for overcoming the current and future water vulnerabilities.

The hydrographic regions of Uruguay (URU) and South Atlantic (ASU), located in the Brazilian south region, face recurrent challenges on water availability in adequate quantities for meeting public demand (see Fig. 1a). In this case, water quantity is a major component undermining water security, therefore, strengthening conflicts over the multiple uses of water. For instance, balancing water demand and availability in this region is key due to large rice fields that are cultivated under flooded conditions. Meantime, climate change projections show an increase in precipitation pattern and in water availability in the region (ALMAGRO et al., 2017; AVILA-DIAZ et al., 2020; CHOU et al., 2014; NETO et al., 2016). Yet, this increase will affect agricultural production, since the increase in precipitation has the potential to increase soil erosion rates (ALMAGRO et al., 2017). Hence, it is essential to incorporate these projections in water resources management.

2.2.2 Imbalance between supply and demand of the consumptive water uses

Here we use two important concepts of the consumptive uses of water: Water withdrawal and water consumption. We defined water withdrawal (or water abstraction) as the total amount of freshwater withdrawn from a surface water or groundwater source that could return or not to the water source. On the other hand, water consumption is defined as the portion of water withdrawal that was consumed and does not return to the original water source. Understanding these concepts is crucial to evaluate water stress as water withdrawal could indicate the competition level and dependence on water resources. Additionally, water consumption is essential to evaluate water shortage and scarcity (GLEESON, 2017).

Total water consumption has steadily increased in Brazil, comprising the main consumptive uses as irrigation, human and animal consumption, industrial purposes, power generation, and mining. At the national level, annual water consumption increased by 17 billion m3 from 1950 to 2000, an average annual growth of 8.7%. Nevertheless, the average annual growth in the subsequent years, from 2000 to 2017, declined from 8.7% to 3.9%. According to ANA's projections, the water consumption average annual growth may continue to decrease reaching 1.1% per year for the period from 2017 to 2030 (Fig 2). Despite the decrease in relative annual growth rate in recent years, water consumption reached 36.5 billion m3 in 2017. Irrigation accounting for 52 - 68.4% of total water withdrawal and consumption respectively, urban and rural supply for 25.5 - 11%, industry for 9.1 - 8.8%, livestock for 8 - 10.8%, thermopower for 3.8- 0.2 %, and Mining for 1.6 – 0.8% (Fig. 2). The Northeast and Southeast regions respectively accounted for 23% and 34% of the total national water withdrawal and consumption. Conversely, both regions have presented historical cases of drought spells and water shortages such as the most severe drought recorded in the Northeast from 2010 to 2018 (ORSINI et al., 2018; FILHO et al., 2020) and the unprecedented drought mainly faced by the São Paulo e Rio de Janeiro States in 2014 and 2016 (NOBRE et al., 2016) (two of the most important states in Southeast). In this context, supply-demand water resources imbalance reveals the high water supply vulnerability affecting the socioeconomic sectors in these regions, which have endured an increase in frequency and magnitude of extreme events according to Marengo (2014).

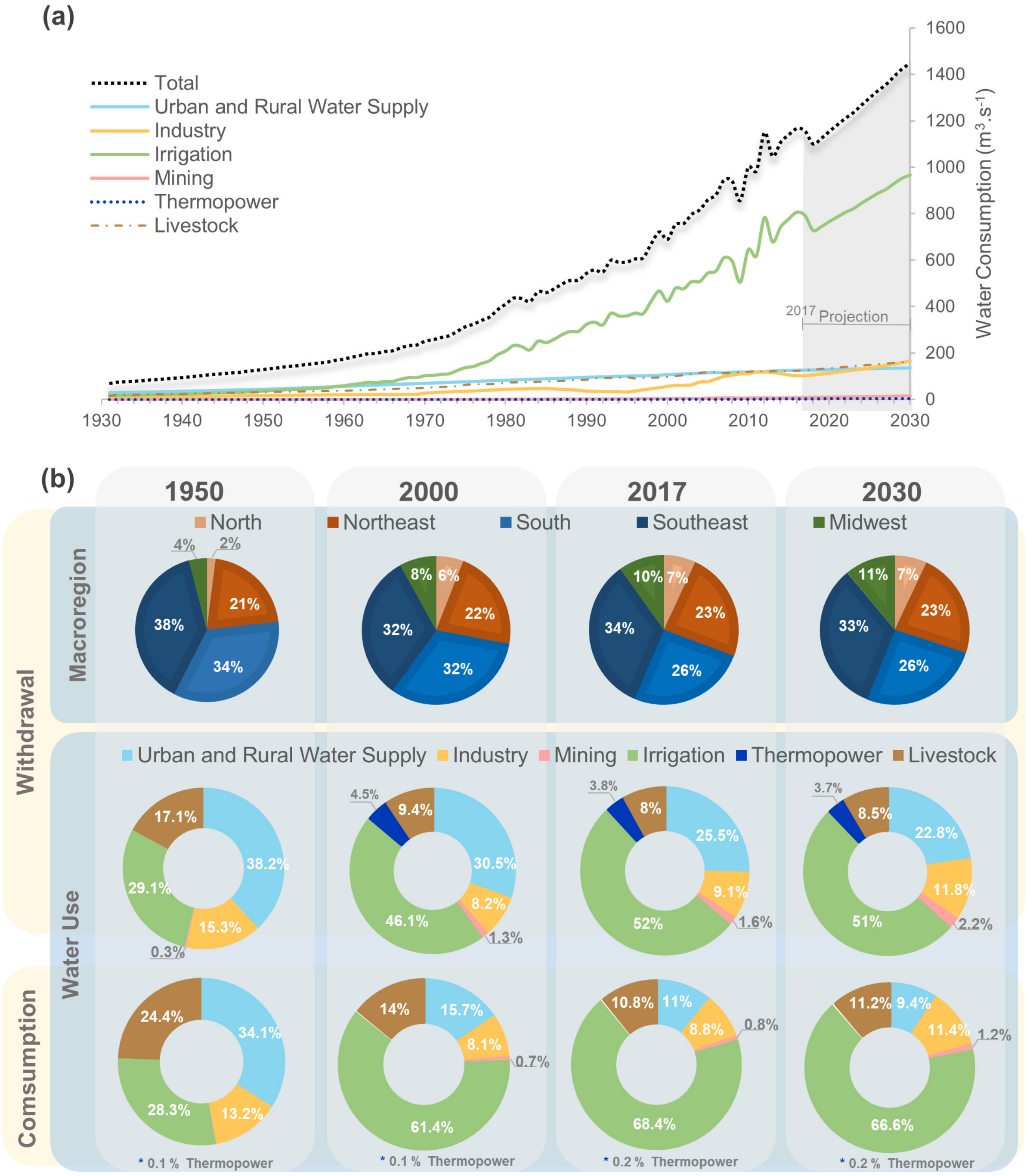

Figure 2 – Total water consumption and withdrawal, where (a) shows the water consumption per uses from 1930 to 2030, and (b) provides additional information about water withdrawal per region and water consumption per water use in 1950, 2000, 2017 and projected for 2030

The water consumption for the agricultural sector is highly representative, mainly irrigation and livestock production representing 80% of the total water consumed by the consumptive uses (Fig.2). Brazil is currently the world's largest exporter and second-largest beef producer; also, livestock production is a booming sector and already accounts for 6% of Gross Domestic Product (GDP), an increase by 45% over the last five years (GOMES; FEIJó; CHIARI, 2017; O'DONOGHUE; HANSEN; STALLINGS, 2019). Although this number is substantial, only one-eighth of the total water used by agricultural activities is attributed to livestock. Since 1960, irrigation has been the main responsible for water withdrawal in the country, corresponding to 52% of total withdrawal in 2017. For instance, water withdrawal for irrigating rice crops increased from 1 to 12 billion m3 in the URU and ASU hydrographic regions even though its national contribution on total water withdrawal decreased from 76% to 36% during a period from 1950 and 2017. The continuous growth of the consumptive water uses along with the low water availability in the EOR, SFO, ALT, URU, and ASU hydrographic regions suggest a high pressure on the Brazilian water supply system, therefore, leading to water insecurities. Water withdrawal for irrigation increased by 32 billion m3 from 1950 to 2017 due to agricultural expansion. Zalles et al. (2019) reported that the cropland extent more than doubled in the Cerrado biome from 2000 to 2014, mainly in the states of Maranhão, Tocantins, Piauí, Bahia (agricultural frontier known as MATOPIBA), Mato Grosso, Mato Grosso do Sul, and Pará. Furthermore, grain cultivation increased by 80% in these areas between 1996 and 2006 (MERTEN; MINELLA, 2013). Irrigation is of paramount importance for allowing crop cultivation in the Semiarid region or regions with prominent drought spells as the Midwest of Brazil (ANA - Agência Nacional de Águas, 2018). Since 1950, water withdrawal for irrigation increased by 36% in the Midwest (mostly covered by Cerrado biome) and the Northeast (Caatinga and Cerrado biomes). It is important to highlight the semiarid region (Northeast Brazil) dependency on irrigation for agricultural production, alone it is responsible for 27% of all irrigation withdrawals in the country. An increasing trend is expected considering adverse climate change scenarios (MARTINS; TOMASELLA; DIAS, 2019) for sustaining productivity in those regions.

The urban and rural water supply services are the second-largest water use in the country. Despite the large withdrawal value (25.5% of total) (Fig. 2b), approximately 80% returns to water bodies as sewage, of which only 46.3% is treated although about 75% is collected (Brasil - Ministério do Desenvolvimento Regional, 2019). Compared with the other regions, the Midwest and Southeast present the highest treatment rates of 54 and 50%, respectively. On the other hand, sewage treatment corresponds to 22 and 36% in the North and Northeast regions, respectively. These lower sewage treatment rates not only degrade water quality negatively impacting the population's health but also intensify disputes among the multiple water uses downstream the effluent discharge in regions already highly vulnerable to water scarcity. It also reflects the quali-quantitative aspect of water insecurity faced by most of the country's metropolitan regions (see fig. 1a).

The industry is another sector with significant water consumption, which has increased by 310% from 1950 to 2017. It accounts for 9% of the total water withdrawal, approximately 6 billion m3 per year; nevertheless, the actual consumption is approximately 55% of the water withdrawn. Specifically, the food industry is responsible for about 56% of the total water consumed by the sector, highlighting the Southeast region for 47% of the total industry consumption in Brazil (ANA - Agência Nacional de Águas, 2019a; ANA - Agência Nacional de Águas, 2019b) (ANA - Agência Nacional de Águas, 2019a; ANA - Agência Nacional de Águas, 2019b). Besides, the mining industry also corresponds to a large water consumption mainly in the Southeast and North regions. Together, they are responsible for 80% of the total water used for mining. The water demand for mining activities is equivalent to supplying the entire Brazilian rural population (ANA - Agência Nacional de Águas, 2019b). Although Brazil is one of the largest producers of iron ore, bauxite and aluminium oxide, niobium, and phosphate, mining activities do not off-set negative social and environmental impacts on health, welfare, deforestation, and water pollution (MILANEZ; OLIVEIRA, 2013). A potential alternative for overcoming the high rates of withdrawal and consumption by industry is water reuse. Even though the Brazilian Sanitation Act 9,9984 and the National Basic Sanitation Plan (PLANSAB) (Brasil - Ministério das Cidades, 2014) establish the promotion of water reuse, it is still a limited practice in Brazil (Brasil - Ministério das Cidades; IICA - Instituto interamericano de Cooperação para a Agricultura, 2016). In addition to reducing costs of water supply and treatment, reusing water in the industry may reduce pressure on water resources (FREEDMAN et al., 2016) contributing to water security in Brazil.

The last representative water use is for power generation, mainly the thermopower source. This electricity source represents 3.8% of total withdrawal in the country, but it only consumes 0.2% of what is withdrawn. Nonetheless, this percentage is important because more than 70% of the Brazilian energy is supplied by hydropower plants. Thermopower plants play a key role in supporting the energy supply as a flexible and safe alternative to hydropower generation during water shortages. For instance, about 27% of the energy supply relied mainly on thermoelectric plants during the 2014-2016 water crisis in the Southeast. Nonetheless, the water use by thermopower is expendable, since this energy source can be replaced by renewable energies that do not need water, such as solar and wind sources.

2.3 Main challenges in the Brazilian context

In the previous sections, we discussed the uneven distribution and heterogeneous needs of water resources over the Brazilian macroregions. Over the last two decades, water withdrawal increased by 80%, and projections show a further increase of 30% by 2030 to meet the population growth and, consequently, future demand for water, food, and energy. The water demand growth indicated by projections and historical data is intrinsically linked to the pattern of increase in the CO2 emissions in the country (Fig. 3), mainly due to the population growth and economic development. Figure 3 does not depict a scenario of proportional economic and emissions growth. Whereas emissions increased by 80% from 1990 to 2014 (from 600 to 1080 Mt CO2), the Gross Domestic Product (GDP) only increased 50% in the same period (from US$ 8,000 to US$12,000 per capita). Furthermore, there is still a positive trend in CO2 emissions indicating that Brazil will possibly fail to comply with the 2025/2030 Nationally Determined Contributions (NDCs) under the Paris Agreement goals. When also considering a post-COVID-19 impact scenario, the agricultural sector is expected to increase despite the fall in emissions from the industry and energy sectors due to potential economic recession (CAT - Climate Action Tracker, 2020). It indicates the paramount importance of legal apparatus implementation to meet the Brazilian NDCs targets, specially, in face of the unprecedented fires in the Pantanal and the Amazon biomes. Deforestation in the Amazon also registered the highest rate since 2008 and a steep rise since 2017 (INPE - Instituto Nacional de Pesquisas Espaciais, 2020a; INPE - Instituto Nacional de Pesquisas Espaciais, 2020b).

The dismantling of the Brazilian environmental policy not only affects the world's climate but also threatens water security by contributing to increasing the frequency and magnitude of droughts and floods. Marengo, Torres and Alves (2017) also showed a tendency for longer periods with consecutive dry days, more frequent and intense dry spells, and droughts in the Northeast region, corroborating to Marengo et al. (2009) and Jenkins and Warren (2015). In the southeastern region, there may also be an increase in the average temperature and a decrease in total precipitation while cloudburst and short events may become more frequent exacerbating interannual rainfall variability (CHOU et al., 2014; VIOLA et al., 2015). The frequency of rainy days and extreme daily precipitation events have increased in São Paulo state. Similarly, precipitation has been more concentrated and sporadic in Rio de Janeiro and Espírito Santo states where observed data indicate positive trends in the intensity of extreme daily rainfall (ZILLI et al., 2017). All those climate change scenarios in the Brazilian regions will trigger conflicts for water allocation and will negatively affect communities that are already vulnerable to extreme events (JONG et al., 2018; MARENGO; TORRES; ALVES, 2017). Furthermore, those changes in the rainfall regime may cause a shift in the crop production cycle and may worsen existing situations of agricultural drought. For instance, the current expansion of Eucalyptus plantations located in the South and Southeast (e.g. Carriello et al. (2016)) might further aggravate water security in a region which has experienced recent scarcity. There are also studies indicating increases in productivity under climate projections as a positive impact of climate change (ELLI; SENTELHAS; BENDER, 2020).

Climate change is one of the main challenges regarding water security worldwide.

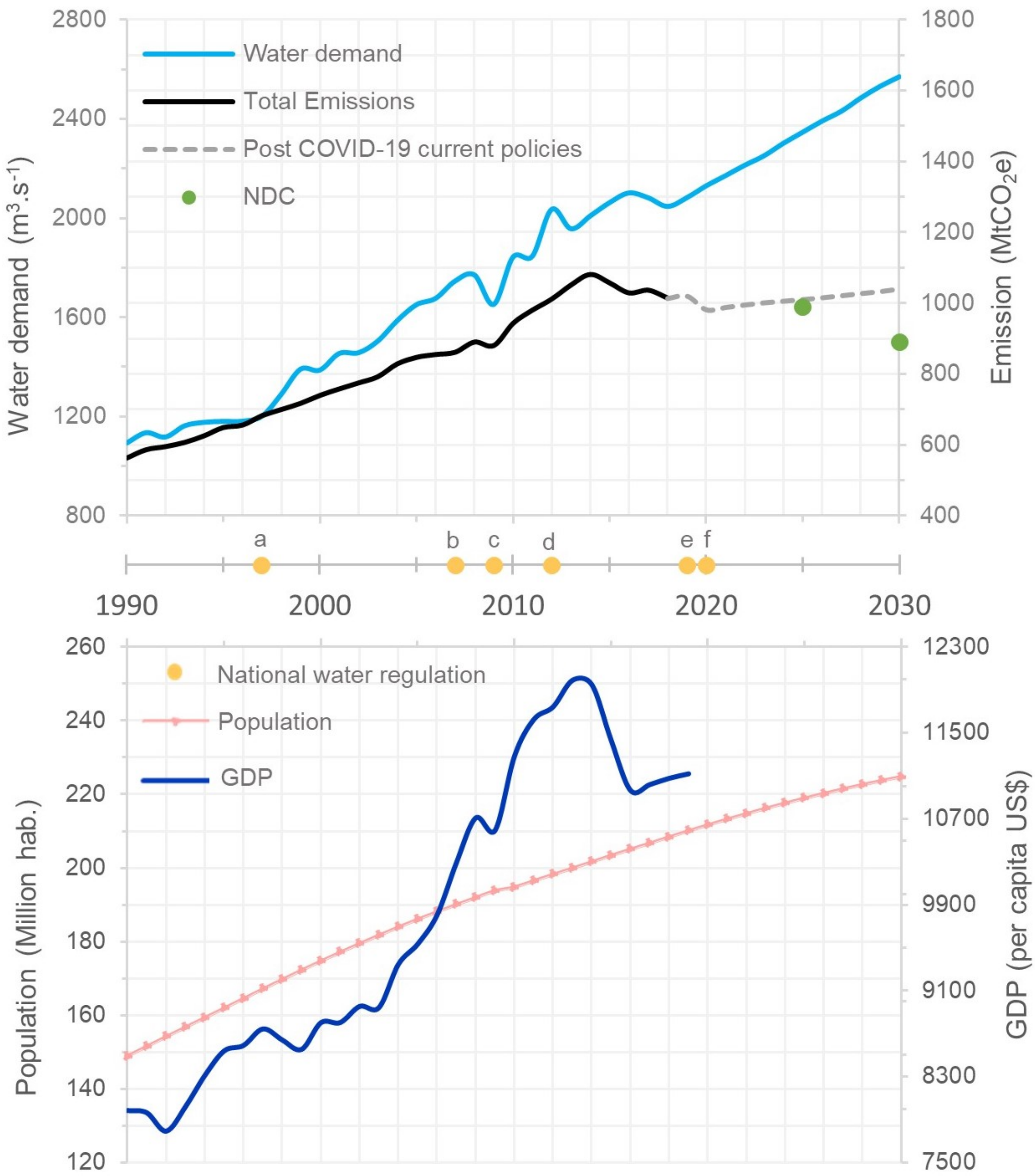

Figure 3 – Correlation of data on water demand, CO2 emissions, population growth, Gross Domestic Product (GDP), Nationally Determined Contributions (NDC), and national water regulations from 1990 to 2030. For the national water regulations: (a) Act. 9,433/1997: National Water Resources Policy; (b) Act. 11,445/2007: National guidelines for basic sanitation; (c) Act. 12,187/2009: National Policy on Climate Change; (d) Act. 12,608/2012: National policy for civil protection and defense; (e) Water Security National Plan; (f) Act 14,026/2020: Update of the basic sanitation Act. * Data are in constant 2010 U.S. dollars. Sources: CAT - Climate Action Tracker (2020), World Bank (2020), IBGE - Instituto Brasileiro de Geografia e Estatística (2020)

Nonetheless, the National Water Security Plan (PNSH) (ANA - Agência Nacional de ÁguasA, 2019) does not consider climate change scenarios and models for defining its objectives and developing its strategies. This represents a major limitation in the conceptualization of the plan, jeopardizing the national water security. Despite the uncertainties related to the future climate, several countries already struggle to overcome the negative impacts of climate change on the environment, society, and economy. Thus, water policies and action plans have to account for possible climate scenarios to address the current and future challenges (AYENSU, 1999).

The PNSH aims at reducing the negative impacts of droughts and floods on water resources by using a set of infrastructure improvements by 2035. Although investing in infrastructure is necessary, the adoption of non-structural measures is vital to minimize environmental and socioeconomic losses (HORN; ELAGIB, 2018; KUNDZEWICZ et al., 2002; SIMONOVIC, 2002; WATANABE et al., 2018). Since water governance needs to integrate human needs with ecosystem functioning (TUNDISI; TUNDISI, 2016), involving society in the development of feasible mitigation and adaptation measures are fundamental to deal with future climate uncertainties. Furthermore, investing in more precise and accurate prediction of extreme events will help society make better decisions, consequently reducing vulnerabilities to impacts of climate change. Thus, a cooperation between researchers and decision-makers is crucial and has the potential to deliver robust solutions for the current and future needs (MASON; CALOW, 2012).

Evidence shows that higher community involvement in governance contributes to increasing the sustainability of water resources (TSUYUGUCHI et al., 2020). In Brazil, a more democratic and participatory management of water resources was legalized and incentivized with the establishment of the National System of Water Resources Management (from Portuguese Sistema Nacional de Gestão dos Recursos Hídricos - SINGREH) by the Water Act 9,433/1997. Notwithstanding, there are still some management failures (NETO et al., 2018; VEIGA; MAGRINI, 2013) such as the unequal distribution of river basin committees over the hydrographic regions. These committees are deliberative and collegial organizations for river basin management in Brazil, lying at the heart of the participatory management at local and regional scale. The main challenges converge to the lack of governance at the local scale where, for example, small dikes and drilling wells are implemented without any governance due to management focused on macro-systems. Thus, it is necessary to strengthen the local management system through more independent and active basin committees, dialoguing with macro-governance.

Brazil has made little effort to align the apparatus of the government with national and international climate-change policies. In addition, there is a general lack of investment in building resilience, and there is no municipal policy for preparation, education and mitigation of medium- and long-term impacts of water-related climate extremes. The complexities involved require political will to support development and execution of policies aimed at better understanding, mitigating, and adapting to current and future challenges in water resources. It is worth emphasizing the importance of integrated management encompassing all Brazilian regions and their particularities. Still, the integration of legal frameworks for water resources (Act 9,433/1997), basic sanitation (Act 11,445/2007 and Act 14,026/2020), climate change (Act 12,187/2009), and civil defense (Act 12,608/2012) are missing. Further, we need to implement active regulatory mechanisms (top-down) and community action with citizen science (bottom-up) to manage the sector's water demand.

2.4 Concluding remarks and future perspectives

Ensuring sufficient and clean water for human consumption and economic activities as well as reducing the risks associated with critical events — droughts and floods — are at the heart of water security. The recent water crisis in water supply, such as those faced by the metropolitan regions of São Paulo and Rio de Janeiro, has broadened the discussion on water security in large population centers supplied by complex systems (GESUALDO et al., 2019; KELMAN, 2015; MOHOR; MENDIONDO, 2017; TAFFARELLO et al., 2016; ZHANG et al., 2018). Despite the advances, there is still an urgent need for water security in other regions besides the large urban centers such as the north and northeast regions, where most of the population is subject to vast water inequality. The project to integrate the São Francisco River basin with the others in the Northeast region (PISF) is a potential opportunity for alleviating water inequalities to communities in the Brazilian semiarid region, consequently, ensuring water security. The PISF is a water infrastructure project of water abstraction from the São Francisco River to distribute it to the states of the semiarid region. Although the objective is to guarantee water security in the region, it has been a great challenge to integrate all local needs and conflicts due to multiple uses.

If the environmental policies follow the track of the last years, we expect a water stress aggravation and a water conflict rise in regard to the projected increase in frequency of extreme events all over Brazil. In the agricultural sector, more water conflicts may emerge in the future mainly when contrasting the possible decrease in annual rainfall with the irrigated area expansion of 45.6 Mha estimated by the National irrigation Policy (Act 12,787). Multsch et al. (2020) already suggest that an expansion of irrigated areas without considering climate change would strongly impact surface water resources resulting in 26.0 Mha under critical and very critical water scarcity in all the regions of Brazil, except Amazonia. Besides the negative impacts on agriculture, water supply, and industry, climate change risks hydropower generation, the main energy source in Brazil. Ensuring water security depends on a participative management, flexibility to adapt to the current and future climate change, and mainly political will. Climate variability and anthropogenic pressures have made the Brazilian biomes more vulnerable, risking ecosystem functioning and water availability. There has recently been a breakthrough in the Brazilian environmental policy with the approval of the National Policy for Payment for Environmental Services (PES). The PES is an instrument that can be used to encourage adaptation to climate change.

Future investments in drinking water supply and sewage are respectively estimated at US$24,074 and US$35,849, according to the National Plan for Basic Sanitation (Brasil - Ministério das Cidades, 2014). Urban areas will require approximately 95% of the amount. These investments are required to meet the goals of basic sanitation universalization in Brazil by 2033 and its related SDGs. Besides water supply and sanitation, a legal policy for water reuse needs to be developed. Notwithstanding that the new legal framework for basic sanitation (Act 14,026/2020) invokes the potential water reuse from wastewater and rainfall, there is still no regulatory instruments defining, for example, thresholds for water quality parameters at the national scale. Therefore, the Brazilian government urgently needs to move towards integrated risk management focusing on optimizing water use and storage (ANA - Agência Nacional de Águas, 2018) whether on a macro scale or on a local scale. It requires planning and implementation of adequate water infrastructure and non-structural measures for water resources management.

Chapter 3

SPATIALLY COMPOUNDING EVENTS TO MULTI-HAZARD RISK ADAPTATION IN BRAZIL [1]

Abstract

Spatially compounding drought events affect multiple locations at once and can have severe impacts on the food, water, energy, human health and infrastructure sectors. Despite the cascading impacts and challenges compound droughts impose on society, we still lack an in-depth understanding of spatially connected drought occurrences. Droughts are also complex and costly in Brazil, so identifying regions likely to co-experience droughts is critical for developing adaptation and mitigation measures. Here, we developed a novel framework to assess the spatial co-occurrence of hydrological drought events to investigate their spatial connectedness in 511 Brazilian catchments over 39 years. We examine how hydrological droughts are spatially connected across Brazil, and we classify catchments based on drought characteristics such as duration, intensity, deficit, and number of events, as well as connectedness to identify regions with similar drought behavior. Our findings demonstrate that drought characteristics and connectedness differ greatly across the country. The country's Central-Northeast and Amazon's Northwest are most affected by multiple and widespread droughts. We divided the country into five regions with distinct drought behavior and catchment attributes such as the aridity index, catchment area, and seasonality of precipitation. Our results highlight the importance of taking into account the interactions of spatially compounding hydrological droughts in hazard assessment. The spatial drought co-occurrence methodology developed here can be transferred to other regions to assess the spatial connectedness of droughts beyond Brazil. Furthermore,

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[1] A modified version of this chapter has been submitted as: Gabriela Chiquito Gesualdo, Marcos Roberto Benso, Manuela Irene Brunner and Eduardo Mario Mendiondo (2023) Spatially Compounding Drought Events in Brazil, Water Resources Research.

the identified drought regions can be used to guide the implementation of adaptation measures and as a reference for developing a network of risk pool regions. Our assessment contributes to the creation of future adaptation plans for hydrological compound extremes at the catchment and regional scales, including risk-transfer mechanisms.

Keywords: Hydrological drought; compound events; Water management.

3.1 Introduction

Hydrological droughts are characterized by periods of water scarcity or reduced water availability within the hydrological system (LOON, 2015). As part of the broader drought phenomenon, hydrological droughts can encompass large areas and persist for months to years, posing risks to individuals, economies, natural resources, and ecosystems (BAKKE; IONITA; TALLAKSEN, 2020; MISHRA; SINGH, 2011; WAN et al., 2017). Additionally, the intensification of the hydrological cycle due to climate change is projected to exacerbate future drought conditions in various regions worldwide, i.e. Southwestern South America, Mediterranean Europe, and Northern Africa (SATOH et al., 2022). These impacts have far-reaching consequences, including implications for global food production (VOGEL et al., 2019; TIGCHELAAR et al., 2018) and the (re)insurance industry (THISTLETHWAITE; WOOD, 2018). Consequently, it is imperative to implement effective climate change governance and adopt disaster risk reduction (DRR) strategies, as emphasized by the Sustainable Development Goals (SDGs), the Sendai Framework (2015-2030), and Climate COP21 (PEDUZZI, 2019).

Within the Sendai Framework, it is crucial to promote and strengthen risk transfer, risk sharing, and insurance at the national level, with support from the international community and other stakeholders (UN - United Nations, 2015). One effective approach is through risk pooling, which forms the basis of insurance. By pooling risks, the benefits of risk diversification can be achieved, resulting in aggregate costs of coverage being lower than the sum of individual costs (BROBERG; HOVANI, 2019). A notable example is the African Risk Capacity (ARC), which addresses the risk of droughts across its 33 member countries (MARTINEZ-DIAZ; SIDNER; MCCLAMROCK, 2019). Through risk pooling, the ARC's exposure to co-variant drought risk is significantly reduced compared to the exposure a member country would face when shouldering the risk alone. This enables the ARC to manage drought risks more efficiently with fewer funds, highlighting the value of risk pooling schemes in providing first-response relief promptly. While these schemes may not cover all losses resulting from extreme weather events, their primary aim is to swiftly provide initial relief (BROBERG; HOVANI, 2019). Thus, it is essential to consider the significance of these risk pooling schemes in the broader context of disaster risk reduction (DRR).

Many previous studies on DRR have primarily focused on individual hazards, neglecting the complex nature of climate extremes, which arise from a combination of spatially and temporally dependent processes (WARD et al., 2022; ZSCHEISCHLER et al., 2018). To better understand the risks associated with extreme events, it is crucial to consider compound events, particularly at regional and global scales (ZSCHEISCHLER et al., 2020). Compound events involve multiple drivers and/or hazards that contribute to societal and environmental risks. One specific type of compound event is spatially compounding events, which occur when multiple locations are affected by the same hazard within a specific timeframe (ZSCHEISCHLER et al., 2018). These events can have cascading effects on food, energy, and economic systems at both regional and global levels, making them an important area of study (ZSCHEISCHLER et al., 2020).

In recent years, there has been significant progress in understanding spatially compounding drought events on a global scale. Singh et al. (2021) have investigated the synchronized occurrence of droughts resulting from large-scale climate variability. Their findings reveal that the probability of experiencing widespread and severe compound droughts is heightened during these occurrences of large-scale climate variabilities. Additionally, Mondal et al. (2023) have identified the potential for simultaneous large-scale droughts across regions known as drought hotspots, including Southern Europe, Northeast Brazil, Australia, and Northwest United States of America (USA). Furthermore, (BRUNNER et al., 2021b) have observed an increase in the spatial extent of droughts, and they suggest that ongoing global warming may further expand drought coverage in the USA. Despite these global research efforts, limited attention has been given to South America (SA), specifically Brazil, which encompasses approximately 50% of the continent. Previous studies in Brazil have primarily focused on specific areas and other types of compound events, such as the combination of droughts and heatwaves (LIBONATI et al., 2022; GEIRINHAS et al., 2021).

Brazil, renowned as one of the world's main breadbaskets, plays a critical role in global food production (ZEIGLER; NAKATA, 2014). Large-scale and spatially connected droughts in Brazil can result in synchronized crop yield failures, impacting not only the agricultural sector but also other sectors heavily reliant on water resources (MEHRABI; RAMANKUTTY, 2019b; GAUPP et al., 2019). Recent findings indicate increased climatic pressure in the MATOPIBA region of Brazil (the most productive region of the country, encompasses the states of Mato Grosso, Tocantins, Piauí, and Bahia), necessitating further evaluation of the impacts of drought connectedness on food production in these regions (MARENGO et al., 2022). Moreover, the cascading effects of extreme events like widespread droughts can negatively affect financial markets and insurance industry operations (MILLS, 2005). However, climate change adaptation and DRR efforts, including financial services and risk pooling, can play a vital role in addressing and mitigating these risks (SHUKLA et al., 2019)

For the design of effective disaster-response plans and adaptation measures to future extreme weather events, it is crucial to account for the temporal and spatial aspects of extremes and the implications of their co-occurrence (RAYMOND et al., 2022). Hence, the regional nature of hydrologic extremes is an important challenge to be addressed by considering spatial correlations when modeling extremes and their extent and regional occurrence probabilities when predicting extremes (BRUNNER et al., 2021a). Despite their importance, spatially compounding hydrological drought events have not yet been throughout the Brazilian territory. Therefore, this study aims to analyze how hydrological droughts are spatially connected across the country and to group catchments according to their drought co-occurrence risk in order to propose risk pooling regions.

Specifically, our analysis addresses the following questions: (1) "How susceptible is Brazil to droughts on a local scale?", (2) "Which climatic factor and physiographic attributes influence this local drought susceptibility?", (3) "What do spatial drought dependencies look like?", and (4) "Which catchments are similar in terms of their local and regional drought hazard ?". In order to answer these questions, we propose a novel framework to assess the spatial co-occurrence of hydrological drought events in 511 Brazilian catchments over 39 years. This novel framework can in future studies also be used to describe spatially compounding drought occurrences in other regions of the world. We defined five regions with similar drought characteristics and connectedness. The regions can be used as a reference for creating a network of risk pool regions and disaster risk management strategies.

3.2 Material and Methods

3.2.1 Study delineation and data set

The spatially compounding hydrological drought event assessment consists of three main steps (Figure 4) described in the following subsections: (a) extracting drought events in individual catchments; (b) determining drought co-occurrence across all catchments; and (c) grouping catchments according to their drought co-occurrence risk.

The hydrological drought co-occurrence was investigated in 511 catchments in Brazil using a large-sample data set of Catchment Attributes for Brazil (CABra) (ALMAGRO et al., 2021a). The CABra dataset provides daily climate and streamflow variables for a 30-year period (1980 to 2010), with up to 10 % of missing data. Moreover, it provides catchment attributes related to topography, climate, streamflow, groundwater, soil, geology, land use and land cover, and hydrologic disturbance classes. In this study, we update the daily streamflow time series of the CABra data set for a 39-year period (1980 to 2019). The catchments' distribution within the country, across biomes, and the 12 Brazilian hydrographic regions are visualized in Appendix A - Figure 14.

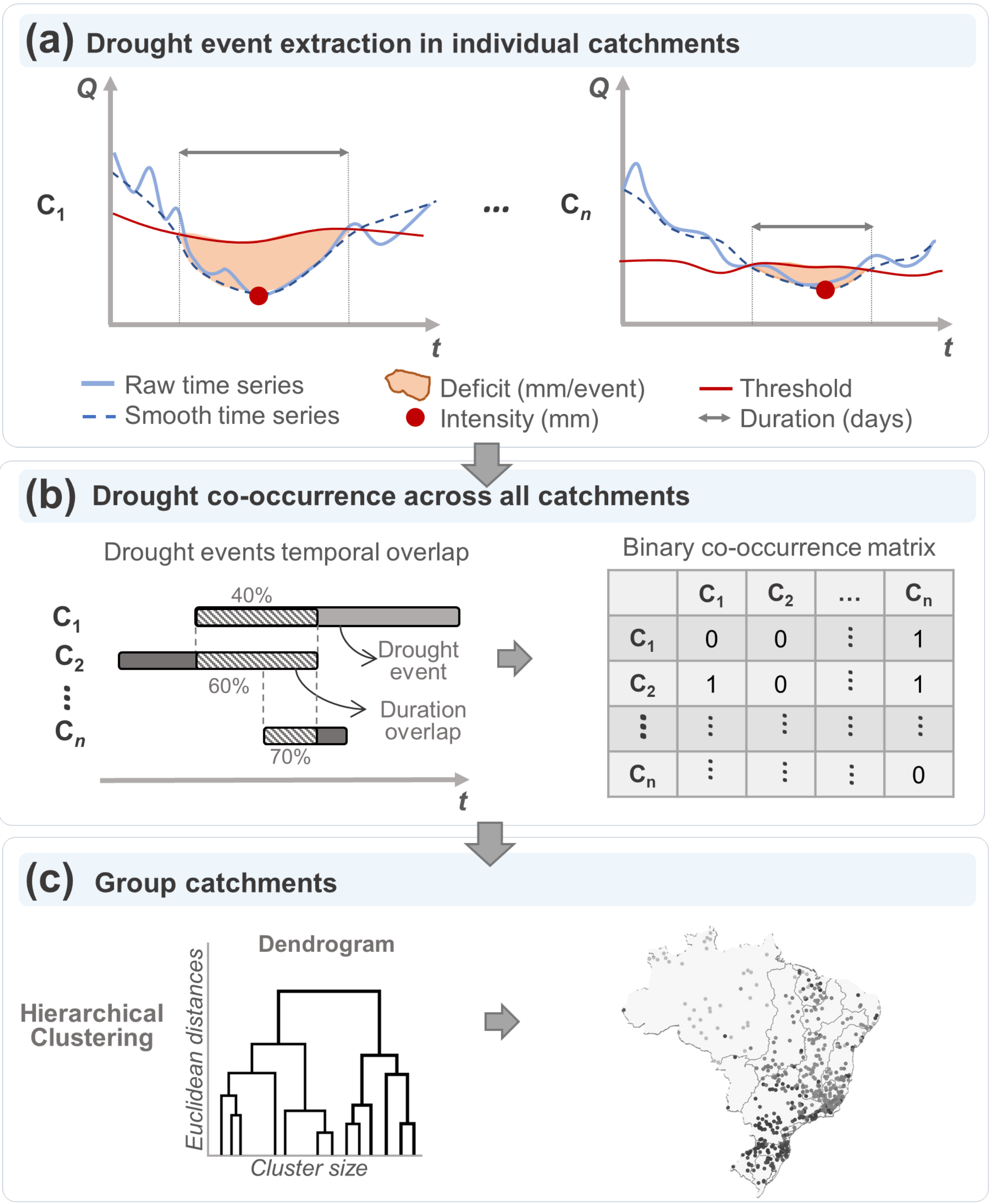


Figure 4 – Workflow illustration of the spatially compounding hydrological drought event assessment: (a) Drought event extraction in individual catchments $(C_1, \ldots, C_n)$ using a variable threshold level method (VTLM); (b) determine drought co-occurrence across all catchments $(C_1, C_2, \ldots, C_n)$; and (c) group catchments according to their drought co-occurrence risk applying agglomerative hierarchical clustering computed on different drought characteristics.

3.2.2 Drought event identification

The drought events were extracted in individual catchments using a variable threshold level method (VTLM) and the 15th flow percentile with a 30-day moving window (Figure 4-a). The VTLM identifies streamflow anomalies instead of low flows and is suitable for regions with seasonal streamflow regimes (BRUNNER et al., 2021b; LOON, 2015). The daily streamflow time series were smoothed over a 30-day moving window prior to event identification to avoid the identification of dependent events (BRUNNER et al., 2021b) and the drought threshold was set at the 15th flow percentile. In this way, each day of the year has a unique threshold level based on the 15th percentile determined 15 days after, 15 days before, and on the day of interest. For each event identified, we computed the drought characteristics such as duration (days), deficit (mm.event^{-1}), and intensity (mm). In addition, we determined the number of drought events for each catchment. The duration was determined as the number of consecutive days during which the smoothed streamflow time series was below the threshold. To limit the selection to significant events, we only considered events with a minimum duration of 30 days. The drought deficit, drought volume, is the area between the drought threshold and the smoothed time series, calculated by the sum of deviations from the threshold times the number of days during the entire drought event. The intensity is the absolute value of minimum streamflow during the drought event.

To investigate the relationship between catchment attributes and drought characteristics, we computed the Spearman's correlation. The selected attributes cover topographic, climatic, hydrological, groundwater, and hydrological disturbance attributes (Table 1), available in CABra dataset (ALMAGRO et al., 2021b).

We performed a sensitivity analysis to investigate changes in drought characteristics by varying the drought threshold and moving window at individual sites. We varied the drought threshold between the 10th, 15th, and 20th percentile and the moving window between 10, 20, and 30 days. The sensitivity was investigated concerning threshold and moving window effects and assessed the impacts of these variations on the number of events, drought intensity, deficit, and duration (Appendix A - Figure 15). A more restrictive threshold resulted in fewer events with lower duration, deficit, and intensity values. Similarly, shorter moving windows were associated with a lower number of drought events, duration, deficit and intensity. While the number of events and event duration were to some degree sensitive to threshold choice, event deficit and intensity did not vary substantially with the threshold and moving window variation. A drought threshold at the 15th flow percentile and 30-day smoothing window was chosen for the subsequent analysis resulting in an average of 20 drought events per catchment over the 39-year period, with a median duration of 66 days.

Table 1 – Catchment attributes

Type	**Attribute**	**Description**	**Unit**
Topographic	Area of a catchment	-	Km^2
	Mean slope	-	%
	Mean elevation	-	m
Climatic	Precipitation seasonality	The timing of the precipitation and temperature seasonal cycles, with positive values indicating summer precipitation, and negative ones referring to winter precipitation.	-
	Aridity index	The ratio between mean-annual potential evapotranspiration and precipitation, that is, the higher the index value, the greater the aridity (NETO et al., 2020).	-
Hydrological	Streamflow elasticity	Indicates the impact of precipitation on streamflow as a sign of perennial condition.	-
Groundwater	Height above the nearest drainage (HAND)	Normalized drainage version of a digital elevation model, which indirectly indicates the water table depth, for the groundwater attribute.	m
Hydrological Disturbance	Distance to coast	Distance between the gauge (outlet) and the nearest coast.	km
	Distance to urban centers	Distance between the gauge and the nearest urban center.	km
	Hydrological disturbance index	Estimates the degree of human interactions on water fluxes by taking land use and land cover into account.	-

3.2.3 Quantification of drought event co-occurrence

The spatially compounding drought events were identified based on the connectedness measure introduced by Brunner et al. (2020), which relies on complex network analysis to assess the spatial connectedness of floods in the United States. Here, we adapted the method of analyzing the co-occurrence of droughts, which requires major modifications to the metric, because droughts have a much longer duration than floods. When a catchment co-experiences at least eight drought events with another catchment in a temporal overlap of 50%, these catchments are considered connected. The procedure is illustrated in figure 4-b using an example of three catchments. The drought event in C_2 has a temporal duration overlap of 60% with C_1, so C_2 is considered to co-experience drought with C_1. However, the opposite is not true, as the drought event in C_1 has only 40% of temporal duration overlap with the drought event in C_2, which does not satisfy the connectedness condition. The same behavior happens with C_n, which is considered co-experience drought with both C_1 and C_2, with a temporal overlap of 70%, although the drought in C_1 and C_2 is unconnected with C_n, since their temporal overlap is much smaller than the threshold of 50%. By introducing this overlap measure, we prevent catchments with short or very long drought events from having excessive or poor co-occurrences. Similar to this, catchments with sporadic connections were left out by defining the connectivity criteria of at least eight co-experience drought events. The threshold of eight events was defined considering that catchments co-experience at least one drought event every 5 years. The co-occurrence results are then summarized in a binary matrix, where 1s indicate event co-occurrence and 0s indicate no event co-occurrence between each pair of catchments. This matrix allows us to identify the connectedness of individual catchments, which is the number of times a catchment co-experiences a drought event with others.

3.2.4 Grouping regions

In order to identify groups that are similar in terms of drought occurrence and are likely to co-experience drought, we applied an agglomerative hierarchical clustering algorithm (Figure 4-c). The similarity matrix used for hierarchical clustering was computed considering different drought characteristics, i.e., deficit, intensity, duration, number of events, and spatial connectedness. Using the algorithm, every catchment is assigned to its own cluster, and at each iteration, the two most similar clusters are joined, until there is a single cluster. The similarities between clusters are measured at each iteration using Ward's criterion (RAO; SRINIVAS, 2006). Ward's algorithms (WARD, 1963) of agglomerative hierarchical clustering used here are available at Scikit-learn package from Pedregosa et al. (2011). The appropriate number of clusters was determined by combining clustering trees at different levels, the dendrogram, and their average silhouette width. To study the similarities in catchments belonging to a certain drought cluster, we studied the catchment characteristics of catchment clusters including streamflow elasticity, aridity index, mean elevation, mean slope, distance from coast, hydrological disturbance index, catchment area, and precipitation seasonality.

3.3 Results

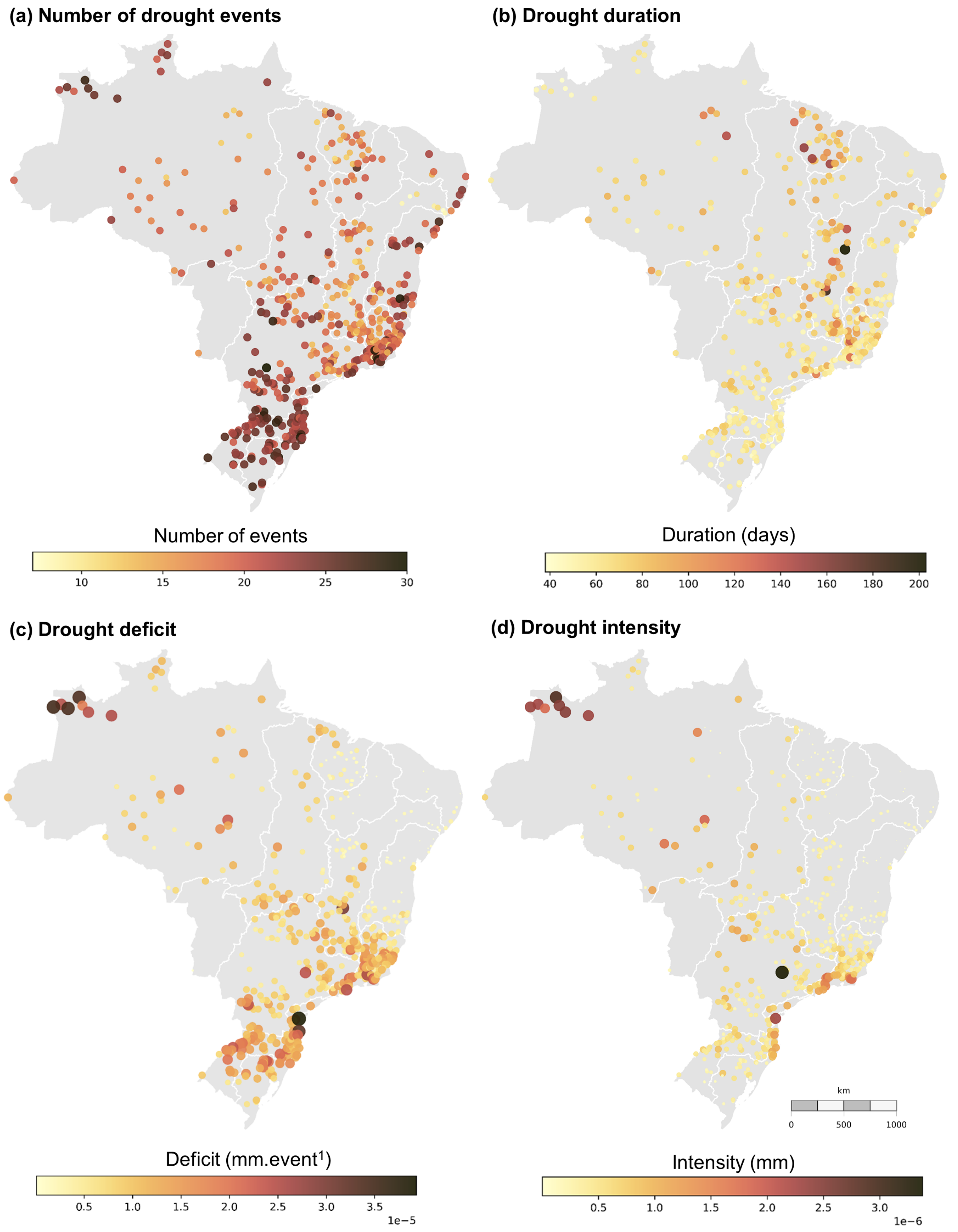
3.3.1 Spatial and temporal patterns of droughts

Our findings show that drought characteristics vary significantly across the country (Figure 5). The number of drought events is substantially higher in the Amazon's Northwest, the country's South and Southeast, and coastal areas than in the country's North-Central region (Figure 5a). At the same time, the regions with a higher number of events experience shorter droughts in terms of duration (Figure 5b). The long-lasting droughts are found in the country's semi-arid region, which is a drought-prone area. Despite a high number of short-term events in the Northwest Amazon region, deficit and intensity are the highest reported in the country, a region characterized by short and intense droughts (Figure 5c, d). The country's Southeast is another region that is characterized by intensity and deficit. We highlight the high drought intensity found in the catchment near the Metropolitan Region of São Paulo, a highly vulnerable and populous region.

The Spearman's correlation between the drought characteristic and the 11 selected catchment attributes (Table 1) is summarized in Figure 6. We find significant correlations between catchment aridity and all drought characteristics. The aridity index correlates positively with drought duration (p=0.31) and negatively with deficit *(p=-0.70)*, intensity *(p=-0.57)*, and the number of events *(p=-041)*, implying that more arid regions have longer-lasting events with lower deficit and intensity. These arid catchments are located along Northeastern Brazil and are known for frequent droughts (BRITO et al., 2018). We also observed a significant positive correlation between catchment area and drought duration *(p=0.30)* and a negative correlation between catchment area and drought deficit *(p=-0.37)*, implying that larger basins have longer-lasting droughts with lower deficits. In terms of drought intensity, the second most correlated attribute with this characteristic is streamflow elasticity *(p=-0.37)*, which has a negative correlation, indicating that catchments with a higher sensitivity of streamflow to precipitation have less intense droughts. These catchments can be found in Brazil's Northeastern region. We also find a negative correlation between precipitation seasonality and the number of drought events (*(p=-0.35)*, indicating that places, where the precipitation cycle occurs in summer (precipitation seasonality values close to +1), have fewer drought events.

3.3.2 Drought connectedness

The drought connectedness represents the number of synchronized drought events between catchments, as indicated by the grey lines in Figure 7. Furthermore, the color of the nodes indicates the mean number of connected events per year; with darker colors indicating more connections. The number of connected events per year was calculated by considering an average of the number of times a catchment co-experiences a drought event with other catchments over a 39-year period. We find that drought connectedness varies substantially across the country. It is high (connectedness ≤ 18) along the Central-Northeast and Amazon's Northwest. In addition, the Central-Northeast region, which includes the large basins of the São Francisco and South Atlantic, as well as the Parnaiba and Tocantins-Araguaia rivers, has the highest number of connected events per year. This makes the region the most vulnerable to the occurrence of multiple and widespread droughts. Despite the fact that the Amazon's Northwest has a high level of drought connectedness, the mean number of connected occurrences per year is low (≥ 30). This could be because the catchments in the region are connected to one another, but the probability of co-occurrence with drought events in other regions of the country is low. As a result of this disconnection, the number of connected events per year decreases. A



(a) Number of drought events

(b) Drought duration

(c) Drought deficit

(d) Drought intensity

Figure 5 – Spatial distribution of drought characteristics: (a) number of drought events, (b) drought duration in days, (c) drought deficit in mm.event^{-1}, (d) drought intensity in mm.

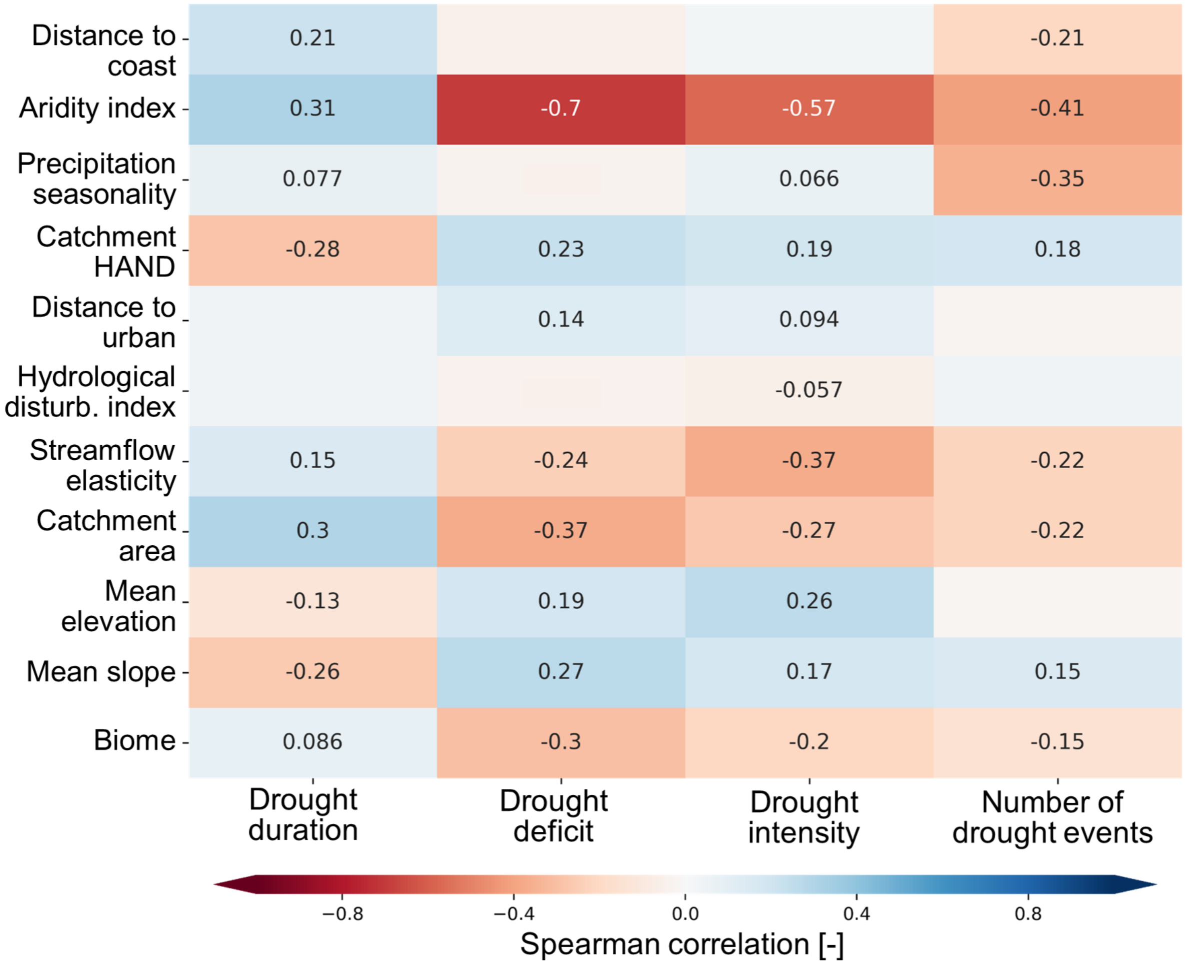


Figure 6 – Spearman's correlation heatmap between drought characteristics and catchment attributes. Reported values exhibited a significant correlation ($p - value \leq 0.05$). Positive and negative correlations are indicated by red and blue colors, respectively.

similar connection pattern is observed in the country's Southern catchments. They are mostly linked to one another but appear to be independent of drought events in other parts of the country.

3.3.3 Drought similarity regions

The country was divided into five regions (clusters) based on similar drought characteristics and catchment spatial connectivity (figure 8). The first cluster (C1) consists of catchments in Central Brazil with high connectedness, low deficit and intensity, and great variability in terms of the number of events and duration. This cluster includes catchments in the great basins North of Paraná, South of Tocantins-Araguaia and São Francisco, as well as the majority of the catchments in Southeast Atlantic. The seasonality and timing of precipitation is especially noticeable in this cluster (Figure 9-h). The second

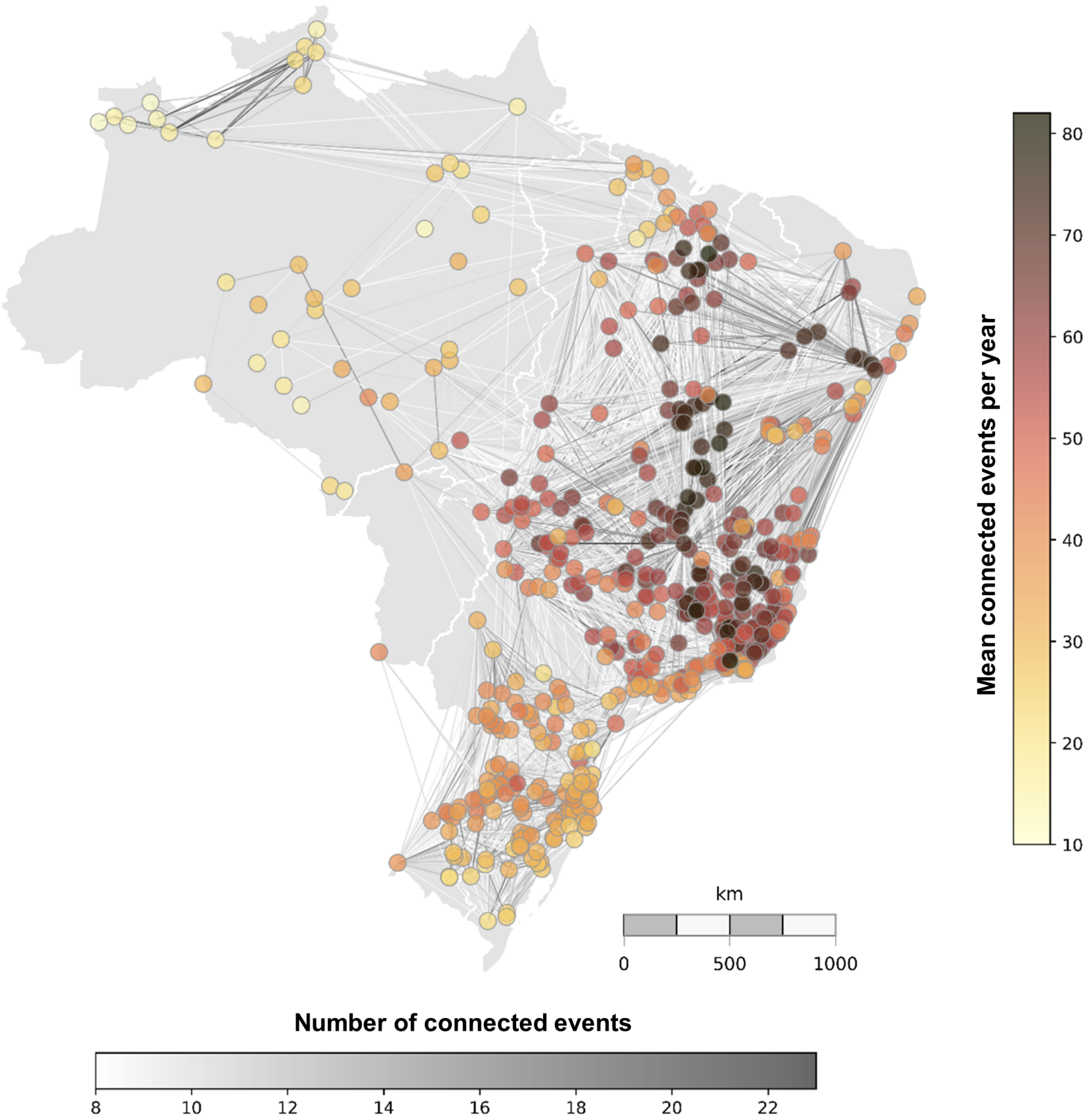


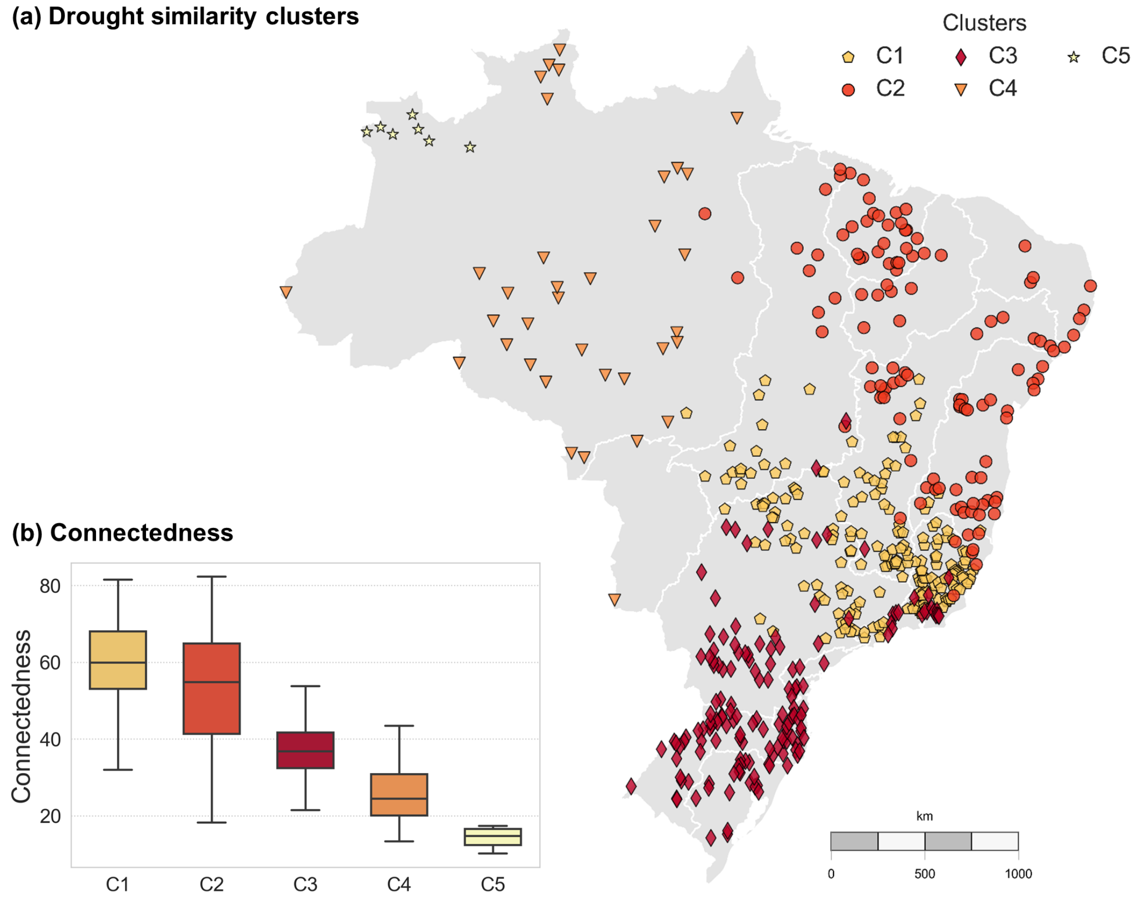
Figure 7 – Brazil's drought co-occurrence network. The lines represent drought connectedness between catchments, which have at least eight events in common. The catchment nodes are colored according to the mean number of connected events per year, calculated by considering an average of the number of times a catchment co-experiences a drought event with other catchments over a 39-year period. The darker the color, the greater the number of connections.

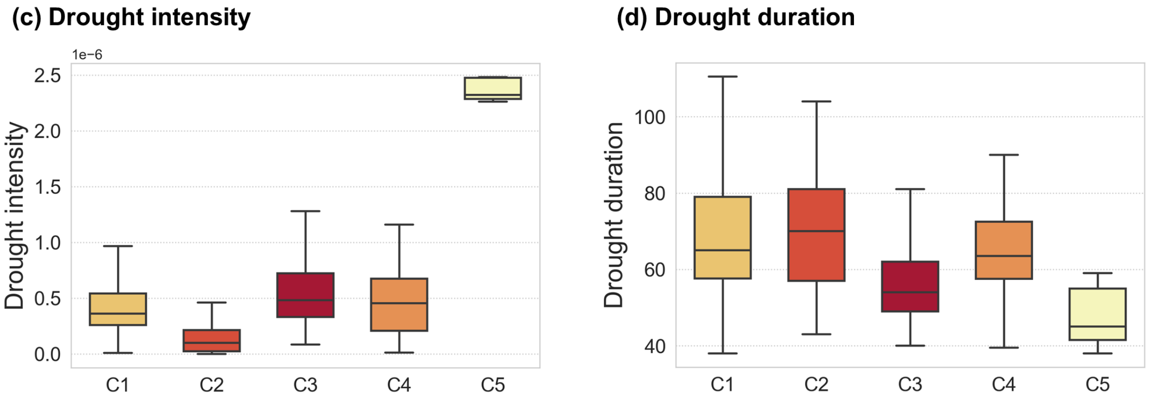
cluster (C2), on the other hand, comprises the majority of catchments in Northeastern Brazil, which stands out due to the region's significant aridity (Figure 9-b). This cluster is characterized by a large variety in terms of duration, number of drought events, and connectedness. However, in comparison to the rest of the country, the intensity and deficit are small. The catchments in the country's Southeast and South build the third cluster (C3). It has medium connectedness and deficit, as well as moderate duration and intensity, but a high number of events. These catchments are characterized by their high hydrological disturbance values and, therefore for having the strongest anthropogenic influence (Figure 9-f). The fourth cluster (C4) includes the majority of the Amazon and Pantanal catchments. These catchments share traits such as weak connectedness and intensity, and large variability in drought duration. The fifth cluster (C5) is comprised of seven catchments in the Northwest Amazon. This cluster includes catchments ranging in size from small to the largest in the country (Figure 9-g). Its catchments are characterized by low drought connection and duration, as well as high intensity, deficiency, and number of events.

We further explore the catchments' physiographic and hydro-climatic attributes across the drought clusters (figure 9). Catchments located in the C1 and C3 regions have a low aridity index, with substantial variability in slope and elevation, characterized by small catchment areas and high precipitation seasonality. These regions are distinguished by the hydrological disturbance characteristic, with C1 having a medium disturbance and C3 having a wide variation, with catchments without any disturbance and also having the highest value of hydrological disturbance among all catchments. Catchments in C2 are located mostly in the semi-arid region of the country, with a high streamflow elasticity and seasonality of precipitation. We highlighted that C4 and C5 are both characterized by low elevations and weak hydrological disturbances but differ in terms of precipitation seasonality, with seasonality being very low in C5.

3.4 Discussion

We here combined a local hydrological drought characteristic assessment with an assessment of the spatially compounding nature of hydrological drought. This assessment includes computing drought duration, deficit, intensity, and frequency, as well as examining the co-occurrence of droughts across all catchments. Additionally, we classified the catchments based on their connectedness and drought characteristics. Our regional hazard assessment reveals that the Amazon Northwest experiences intense droughts characterized by relatively short event duration. These findings align with previous studies reported in the literature. For instance, Chaudhari et al. (2019) observed severe meteorological droughts across most of the Amazon River basin in 1995; nevertheless, the severity of the hydrological drought was relatively minor due to its strong sub-surface storage regulation.





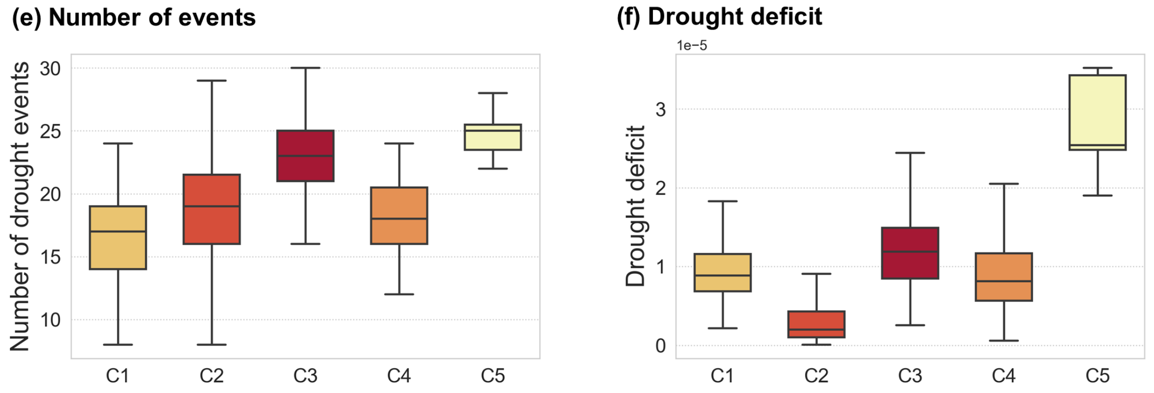
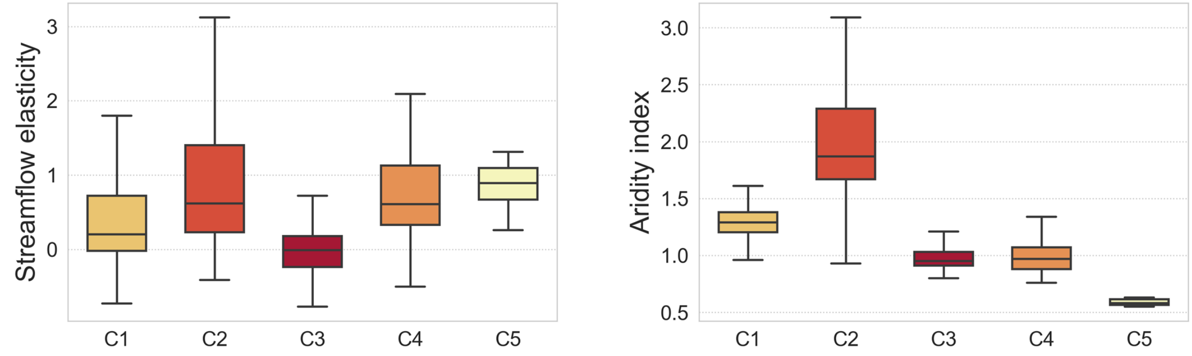
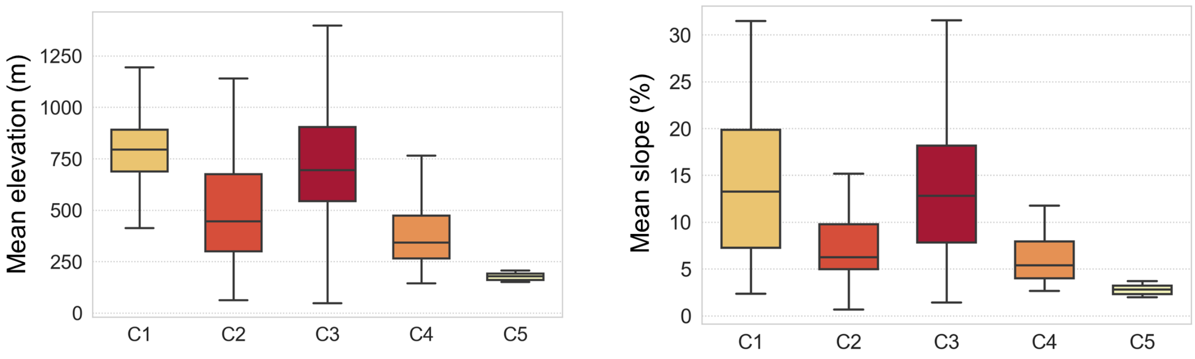


Figure 8 – Drought similarity clusters and their characteristics. (a) drought similarity clusters, (b) connectedness, (c) drought intensity (mm), (d) drought duration (days), (e) number of events, and (f) drought deficit (mm.event^{-1}). The drought characteristics (b-f) were used to compute the similarity matrix with hierarchical clustering.

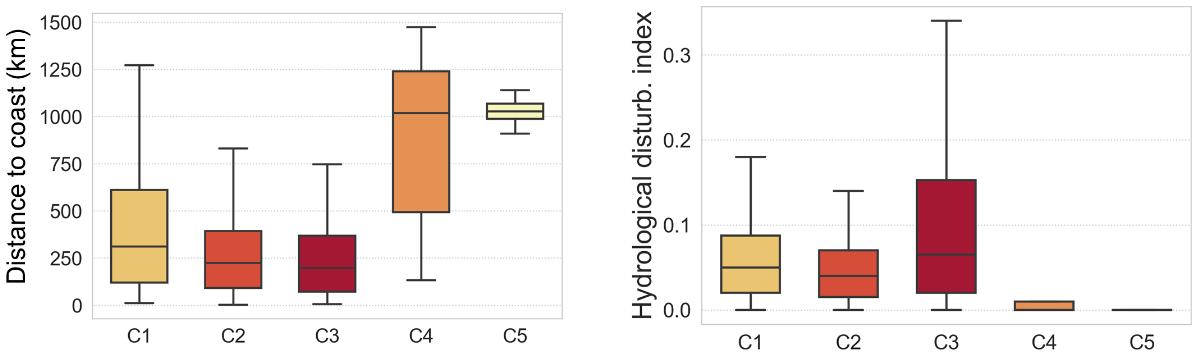
(a) Elasticity of daily streamflow **(b) Aridity Index**



(c) Mean elevation of the catchment **(d) Mean slope of the catchment**



(e) Distance from gauge to the nearest coast **(f) Hydrological disturbance index**



(g) Catchment area **(h) Precipitation seasonality**

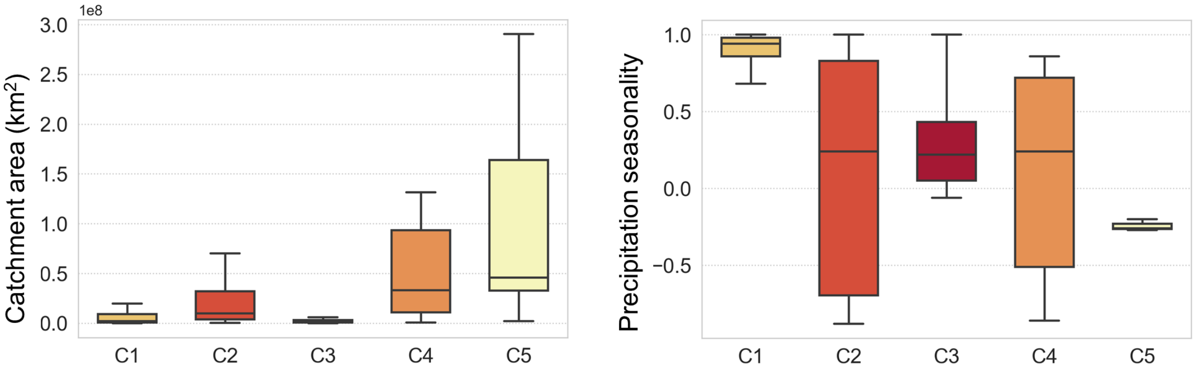


Figure 9 – Catchment attribute variability across drought similarity clusters. (a) streamflow elasticity, (b) aridity index, (c) mean elevation of the catchment (m), (d) mean slope of the catchment (%), (e) distance from gauge to the nearest coast (km), (f) hydrological disturbance index, and (g) catchment area (km^2), (h) precipitation seasonality. These characteristics were not used in cluster formation.

This highlights the significant role of groundwater-surface water exchange in mitigating dry conditions and contributing to comparably short drought duration, despite indications of an extended dry season and increased frequency of dry events in the region(ESPINOZA et al., 2016; MARENGO; ESPINOZA, 2016). In contrast, the Central North region of the Amazon experiences a smaller number of drought events, characterized by lower deficit and intensity but longer duration compared to the Northwest region. This spatial difference can be attributed to the correlation between the catchment area and drought duration (positive correlation) as well as with drought deficit (negative correlation). The larger catchments are predominantly situated in the Central North region of the Amazon, which contributes to longer-lasting drought events in terms of duration. The number of drought events is notably higher in the Northwest region of the Amazon, as well as in the South, Southeast, and coastal areas of Brazil, compared to the North-Central region. These findings align with the systematic investigation of hydrological drought in Brazil conducted by Tang et al. (2023).

In terms of the drought duration, the semi-arid region of the country experiences the most severe droughts. This region is characterized by a complex network of over 17 thousand reservoirs (NASCIMENTO; NETO, 2017), which not only alter local flow regimes but also impact hydrological extremes. Previous studies have demonstrated that reservoir regulation has a local-scale influence on drought hazards, reducing their severity in terms of magnitude and volume but increasing their duration (BRUNNER, 2021). This may help explain the negative correlation observed between the aridity index and drought intensity and deficit. Although most parts of the semi-arid region exhibit low drought deficit and intensity, studies have reported a drying trend over recent decades (CHAGAS; CHAFFE; BLöSCHL, 2022; MARENGO; TORRES; ALVES, 2017; TOMASELLA et al., 2022; CUNHA et al., 2018). Furthermore, Chagas, Chaffe and Blöschl (2022), attribute this drying trend to decreased rainfall and increased water use in agricultural areas in Central and Northeastern Brazil. Our findings in the headwaters of the São Francisco River basin, an intensively irrigated region with long-term drought duration and significant deficit, support this observation. Furthermore, the analysis by Scanlon et al. (2023) pointed out a strong negative trend in water storage in the San Francisco basin, emphasizing the direct impact of irrigation on water resources and, consequently, on drought conditions. The Southeast and South regions of the country, which are heavily irrigated and account for approximately 65% of all irrigated areas in Brazil (ANA - Brazilian National Water Agency, 2021), also experience substantial drought deficits. In fact, irrigation currently represents 52% of the total water withdrawals in the country (GESUALDO et al., 2019). This significant water abstraction for irrigation purposes likely contributes to the pronounced drought deficit observed in these regions.

The catchments located in densely populated areas, particularly in the South and Southeast regions of Brazil within the metropolitan areas such as São Paulo, Rio de Janeiro, and Curitiba, exhibit notable characteristics in terms of drought deficit and intensity. These findings are consistent with the research conducted by Bevacqua et al. (2021a), which identified the most severe and prolonged hydrological droughts in areas of Brazil most impacted by human activities. It is understandable that the severity of hydrological drought is significantly influenced not only by terrestrial hydrological processes but also by anthropogenic activities (LOON, 2015). Additionally, temperatures and extreme dry and hot conditions have been on the rise in the South and Southeast regions over the past decade (GEIRINHAS et al., 2021), which may help explain the occurrence of intense droughts with significant deficits in these areas.

Conversely, the country's Northeast region experiences less intense droughts. Streamflow elasticity, which represents the sensitivity of streamflow to precipitation, is the second most correlated attribute with drought intensity *(p=-0.37)*, exhibiting a negative correlation. This indicates that catchments with higher streamflow sensitivity to precipitation tend to have less intense droughts. The Northeast region has particular characteristics that influence the surface and subsurface hydrological processes (MONTENEGRO; RAGAB, 2010), contributing to the observed negative correlation between drought intensity and streamflow elasticity. This negative correlation could be attributed to the water loss condition of catchments in the region, where effective precipitation exceeds surface runoff and contributes to subsurface flow. This signifies that these catchments have a minimal baseflow contribution from deeper groundwater to surface flow (SCHWAMBACK et al., 2022). Catchments with summer-dominant rainfall patterns, such as those in the Midwest and Southeastern Brazil, exhibit fewer drought events. Despite Brazil's precipitation regime being highly seasonal in many areas, there is a negative correlation between precipitation seasonality and the frequency of drought occurrences. In Brazilian catchments, high precipitation seasonality (values close to one) appears to favor baseflow and discourage quickflow (BALLARIN et al., 2022). This may explain why catchments in Southern Brazil and the upstream basin of the Amazon, which experience uniform precipitation throughout the year (precipitation seasonality close to zero), have a higher frequency of drought occurrences.

Drought connectedness variations in Brazil might be influenced by a range of meteorological factors. The South Atlantic convergence zone (SACZ) emerges as the most probable driver of significant spatial interdependence in the Central-West and Southeast regions of Brazil, as the failure of SACZ can contribute to a deficient rainy season in these areas (PEZZI et al., 2023; ZHANG; TANG; CHEN, 2017). The SACZ plays a critical role in transporting moisture from the southern Amazon region to the Southeast, traversing the Central-West and Southeast regions of Brazil. The absence of SACZ development during the Austral summer has the potential to trigger widespread droughts. A notable example of the consequences of SACZ suppression, coupled with the resultant decrease in rainfall, was evident in Brazil during the 2013/14 period, which led to water shortages across the country (RODRIGUES et al., 2019). A similar pattern of connectedness is observed in the

North and Northeast regions of Brazil, where the Inter Tropical Convergence Zone (ITCZ) influences the rainfall patterns (CUNHA et al., 2018). The effects of the ITCZ have been linked to the occurrence of droughts in the Central-eastern Amazon and Northeast Brazil (LIU et al., 2022). Furthermore, the connectedness in the Amazon and Northeast regions may also have effect of the El Niño-Southern Oscillation (ENSO) teleconnections, as El Niño aided can shift the ITCZ northward, causing anomalous warming in those areas (LIU et al., 2022).

The notable spatial dependence observed in the Central-Northeast region of Brazil - the Great Basin of São Francisco, Southeast, and East Atlantic - underscores the region's vulnerability to spatially compounding droughts. These regions are characterized by the presence of water-intensive crops and significant hydropower production, and the increasing frequency of drought events coincides with declining trends in both streamflow and baseflow (JONG et al., 2018; LUCAS et al., 2020). The reduction in baseflow is primarily attributed to groundwater and surface water withdrawals (LUCAS et al., 2020). The East Atlantic and São Francisco regions stand out as the driest areas in the country, exhibiting a prolonged propagation period from meteorological to hydrological drought (BEVACQUA et al., 2021a). Moreover, the recovery time from drought in these regions can be over four times longer compared to other parts of Brazil, such as the South and Northeast Amazon (BEVACQUA et al., 2021a). When considering catchment attributes and land use patterns in conjunction with these characteristics, the high level of drought connectedness observed in these regions can be better understood.

The consideration of geographical proximity among catchments is commonly associated with a higher likelihood of co-experience drought events, making regions defined based on weather and hydrologic patterns valuable for drought management purposes. The recognition of spatial connections is crucial for comprehending the extent of widespread drought risk. To capture the heterogeneity in drought characteristics and connectedness, the country was divided into five distinct groups sharing similar drought attributes and spatial dependencies. These regions also exhibit common sets of physiographic and hydroclimatic attributes. The propagation of hydrological droughts is driven by catchment attributes and strongly influenced by terrestrial processes and human activities (BEVACQUA et al., 2021b; LOON, 2015). Interestingly, our analysis revealed an antagonistic relationship between connectedness and the number of drought events within the clusters. Clusters with relatively low connectedness (c4 and c5) tend to experience a higher average number of drought events compared to clusters with higher connectedness (C1 and C2). Additionally, there is a spatial consistency in the patterns of connectedness and drought duration. Clusters characterized by catchments with longer-lasting droughts (C1 and C2) exhibit higher levels of connectedness, whereas clusters with more frequent droughts (C3, C4, and C5) demonstrate relatively lower connectedness.

3.4.1 Implications of the understanding of drought connectedness for potential advances in disaster risk reduction

The variability of drought connectedness in Brazil exhibits significant differences, emphasizing the need to consider spatial and temporal variations when designing risk management strategies. In this study, five regions were identified based on similar drought characteristics, providing a framework for establishing a network of risk pool regions. Risk pooling, which involves sharing unexpected loss risks among multiple entities, can be effectively implemented within a large and diverse network to mitigate the impact of widespread shocks (CRONK; AKTIPIS, 2021). Consequently, we propose that catchments outside the same cluster form risk pooling regions as they are less likely to simultaneously experience drought events. Widespread droughts pose substantial threats to various sectors, including food production, energy generation, and water supply. Risk managers commonly seek to assess the probability of drought events affecting multiple businesses simultaneously (BAUM; CHARACKLIS; ASCE, 2020).

Local governments are increasingly utilizing novel risk transfer instruments, including reinsurance and catastrophe bonds, to finance resilience projects and support disaster recovery efforts (COLLIER; COX, 2021). An exemplary illustration is the Caribbean Catastrophe Risk Insurance Facility (CCRIF), which represents the world's first multi-country risk pool comprising 17 Caribbean nations(HARAGUCHI; LALL, 2019). Through diversification of risks beyond national boundaries, these countries assist each other in addressing short-term cash constraints following natural disasters. Another multi-country risk pool is the Southeast Asia Disaster Risk Insurance Facility, enabling vulnerable countries like Cambodia, Indonesia, Japan, Myanmar, and Singapore to mitigate climatic shocks (HARAGUCHI; LALL, 2019). The African Risk Capacity (ARC) provides a compelling example of pooling drought risk, showcasing significant benefits in its application. However, the authors emphasize the importance of thorough investigation into membership allocation and examination of extreme weather dependencies across various risk pool combinations(AWONDO, 2019). In addition to exploring these combinations, we propose that future studies should assess the impact of different sectors within the five defined groups to evaluate the effectiveness of risk pooling. Regions exhibiting high connectedness are more susceptible to widespread drought events, offering valuable information for risk managers seeking portfolio diversification strategies. For instance, when aiming to mitigate financial risk in multiple water utilities situated in regions C3 and C1, the risk manager should consider that region C1 demonstrates higher connectedness with fewer drought events, whereas region C3 displays lower connectedness but a higher frequency of drought events.

The established drought similarity regions derived from this study hold potential for enhancing drought forecasting models and warning systems by incorporating spatial dependencies between regions into model calibration. Typically, risk assessments neglect spatial dependencies by assuming complete dependence between sites. However, as highlighted by Mondal et al. (2023), incorporating drought regions with similar characteristics and climate models can provide objective metrics for process structure models. Neglecting the spatiotemporal aspects of drought in spatial drought event modeling within drought hazard and risk assessment may result in under- or overestimation of risk, as demonstrated by Brunner et al. (2020) in the context of flood risk. Considering climate change and its impacts on land-surface processes, there is a projected increase in spatial dependence and, consequently, a heightened likelihood of widespread drought events. Further research is warranted to investigate the behavior of drought connectedness under climate change scenarios. This research will aid in identifying the associated risks of such events and in developing strategies to mitigate "shocks" arising from compounded extremes.

3.5 Conclusions

Here, we developed a novel approach to study the spatial connectedness of hydrological droughts, combining a local assessment of drought characteristics with an examination of the co-occurrence of droughts across catchments. The applicability of this approach extends beyond our study area, as it can be extrapolated to investigate spatial drought connectedness in different regions worldwide. The insights gained from such investigations have the potential to enhance drought management and facilitate the development of strategies aimed at reducing associated risks. This approach can be generalized and applied in other regions of the world to study spatial drought connectedness, providing valuable insights for drought management and risk reduction strategies. Employing our distinctive methodology, we have identified five regions within the country exhibiting similar drought patterns. Each region possesses distinct drought characteristics and demonstrates specific spatial dependencies.

Our findings revealed that the Amazon Northwest experiences intense droughts with a relatively short event duration, while the Central North region exhibits fewer drought events but with longer duration. The semi-arid region of the country experiences the most severe droughts, influenced by a complex network of reservoirs and increased irrigation. Densely populated areas in the South and Southeast regions, as well as the Northeast region, are also prone to severe droughts, influenced by anthropogenic activities and changing climatic conditions.

The implications of these findings for society are significant. The comprehension of spatial connectedness among drought events serves as a basis for devising risk pooling strategies. In such strategies, regions located outside the identified drought similarity regions can form risk pooling regions to mitigate the impact of widespread droughts. This approach holds particular value for sectors vulnerable to drought hazards, including food production, energy generation, and water supply.

Future work should focus on assessing the impact of different sectors within the defined drought similarity regions to evaluate the effectiveness of risk pooling strategies. Furthermore, investigating the behavior of drought connectedness under climate change scenarios is crucial to identify associated risks and developing mitigation strategies. By considering the spatial and temporal aspects of drought and incorporating climate change projections, we can better understand the potential for widespread drought events and develop more effective strategies for disaster risk reduction.

In summary, our study contributes to the understanding of drought connectedness in Brazil and provides valuable insights for drought management, risk pooling, and future research directions. By recognizing the spatial dependencies and characteristics of droughts, we can improve our ability to mitigate the impact of droughts on society and develop more resilient strategies for managing drought risks.

Chapter 4

INDEX-BASED INSURANCE TO MITIGATE CURRENT AND FUTURE EXTREME EVENTS FINANCIAL LOSSES FOR WATER UTILITIES [1]

Abstract

Mitigation and management strategies for extreme weather events become increasingly important for the development and maintenance of society as these events become more frequent and intense. Drought and flood management strategies have focused on structural measures; however, they are not sufficient to prevent water supply disruptions and economic losses. In this concept, adaptation plays the role of anticipating the adverse financial impacts of extreme weather events and taking appropriate measures to minimize them. Thus, insurance is a valuable adaptation tool to offset unexpected losses and prevent financial damage from turning into long-term economic damage. We simulated multi-year and multi-risk index-based insurance for a Water Supply System, responsible for providing water to 7.2 million people. Our methodology comprises (1) characterizing the indexed variable, (2) calculating economic losses by Loss Distribution Approach (LDA) for current and future periods, and (3) estimating risk premiums based on expected losses of the low, medium, and high coverage levels. Our findings indicate a linear relationship between premium and coverage level, i.e, the higher the premium, the higher the insurance coverage level. We suggested a premium fee for each scenario evaluated which would be introduced

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[1] A modified version of this chapter has been submitted as: Gabriela Chiquito Gesualdo, Marcos Roberto Benso and Eduardo Mario Mendiondo (2022) Index-based insurance to mitigate current and future extreme events financial losses for water utilities, International Journal of Disaster Risk Reduction.

in the water bill as a novel way to pool risk among customers and protect them from surcharge fluctuations.

Keywords:Adaptation Measures; Water Management; Extreme Events.

4.1 Introduction

Water is an essential resource for all ecological and socio-economic activities. The water demand is increasing as the world's population grows and nations become wealthier(WADA et al., 2016). Water scarcity is evidently becoming a threat to society's sustainable development as a result of the rising demand. Furthermore, climate change tends to increase existing and future risks associated with managing water resources systems and natural disasters (MANDAL; SIMONOVIC, 2017). While Brazil has a privileged position in the world in terms of water resource availability, accounting for around 12% of the world's freshwater (SHIKLOMANOV et al., 2000), its water resources are not evenly distributed throughout the nation. The rising complexity of climate risks reflects in the greater susceptibility of emerging countries, owing to their greater economic reliance on climate-sensitive primary activities, as well as infrastructure, finance, and other variables that hinder successful adaptation (KUNREUTHER; MICHEL-KERJAN, 2014).

In economic terms, between 1995 and 2014, direct losses related to drought and flood events in Brazil are estimated at BRL 9 billion per year (ANA - Agência Nacional de Águas (Brasil), 2017). These economic losses can be minimized and compensated through adaptive tools, such as insurance against extreme weather events, as cited by (NAVARRO et al., 2021). In this context, insurance prevents financial losses from turning into long-term economic losses (SEIFERT-DäHNN, 2018). The traditional approach to designing an insurance scheme involves calculating the insurance premium based on the expected disaster risk (KUNREUTHER; MICHEL-KERJAN, 2014). Likewise, in index insurance (index-based), the indemnity is triggered by the magnitude of the index variable, such as precipitation, streamflow, or reservoir level (MOHOR; MENDIONDO, 2017).

Despite several successful examples around the world (GUILLIER, 2017; HANGER et al., 2018; RUIZ-RIVERA; LUCATELLO, 2017) and large organizations support this important adaptation measure, index insurance is not widely adopted, and little attention has been given to energy and water supply sector (BENSO et al., 2023). Therefore, this study attempt to contribute to index-based insurance scheme design planning to assess the current and future impacts of climate change on a regional scale. We present the development of multi-year and multi-risk index-based insurance for water utilities, aiming at identifying highly correlated indices linking hydrological conditions to financial losses, describing the impact of disruption on the water supply, and estimating the size of payouts in case of extreme hydrological conditions of flood and drought. Our focus is to provide technical-scientific information about a financial tool to mitigate losses as an additional solution for water resources management.

4.2 Material and Methods

Claims in an index-based insurance scheme are associated with a pre-agreed index value that is highly correlated with the losses (CESARINI et al., 2021; BARNETT; MAHUL, 2007). Thus, the index acts instead of the damage assessment to trigger insurance payments and determine their magnitude (DENARO et al., 2020). The logic behind index-based insurance is that hazards can be monitored using known meteorological or hydrological variables i.e. precipitation, temperature and streamflow, and these variables are tailored to a specific sector (BENSO et al., 2023; BAUM; CHARACKLIS; SERRE, 2018). When the monitored index variable reaches or exceeds the maximum limit (in the case of floods) or minimum limit (n the case of droughts), the insured entity will be reimbursed regardless of the actual physical damage. The advantages rely on the fast indemnification after the occurrence of disasters the reduction of operational expenses and the minimization of asymmetric information due to not being required in loco damage assessment aiding an effective and predictable post-disaster recovery (FIGUEIREDO et al., 2018; HILL et al., 2019). The fast payout in the index-based insurance structure is critical in developing countries, particularly as they tend to be more exposed to long-term liquidity gaps that overwhelm their ability to deal with major disasters (CESARINI et al., 2021). In addition, the index-based insurance model benefits from the transparent way it is presented by stakeholders, whether the insurer or the insured. In high-uncertainty future scenarios, the index-based insurance scheme can be set up by participatory platforms to seek the best profile for users in terms of risk, impact (damage), coverage format, willingness to pay (WTP), and the level of risk aversion.

The index-based contract is settled financially by using the index as an input to a payout function. In practice, any function could be used as a payout, but simple structures with straightforward economic purposes are the most common ones (JEWSON; BRIX; ZIEHMANN, 2005). We have considered the derivative pay-offs function, presented by (JEWSON; BRIX; ZIEHMANN, 2005). The payout is initiated when the strike value (k) of the index (x) is exceeded. Then, the payout increases based on the tick value (D) and respecting a maximum payout limit ($Pmax$). The maximum payout limit is a predetermined value at the beginning of the contract and can vary depending on the WTP of the water utilities and users. Since we are working with two different hazards, we used a combination of a long call and a short put with a different strike but the same tick (D) and limit ($Pmax$). Where the total payout is the minimum between the maximum payout and the amount proportional to the extent to which the strike is exceeded: beyond the strike for drought in equation 4.1 and above the strike for floods in equation 4.2.

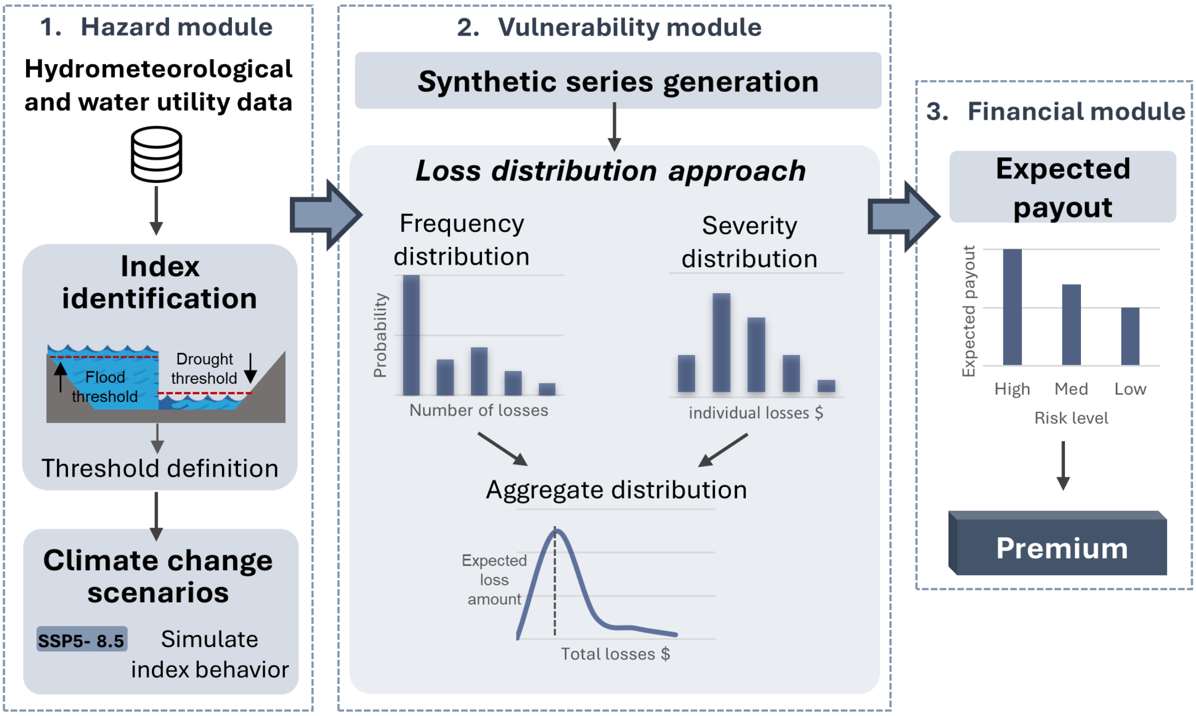


Figure 10 – The study description is divided into three steps: (1) the hazard module, in which it characterizes the index variable using hydrometeorological and water supply data as well as simulations with climate change scenarios, (2) the vulnerability module, in which it deals with economic losses based on event magnitude, and (3) the financial module, where it estimates the risk premium based on the expected payout.

Assuming that water utilities are interested in increasing financial protection against drought and flood-related losses, we have developed a multi-hazard index-based insurance scheme that assesses expected losses in current and future hydroclimatic scenarios. The methodology was divided into three modules shown in Figure 10, according to the methods by (RIGHETTO; MENDIONDO; RIGHETTO, 2007; MOHOR; MENDIONDO, 2017; GUZMáN; MOHOR; MENDIONDO, 2020; BENSO et al., 2023). The modules include (1) the hazard module, which characterizes the index variable, (2) the vulnerability module, which addresses the economic losses by event magnitude, and (3) the financial module, where the risk premium is estimated based on the expected payout.

$$Payout_{drought}(x) = min(Pmax, max(D(k-x), 0)) \tag{4.1}$$

$$Payout_{flood}(x) = min(Pmax, max(D(x-k), 0)) \tag{4.2}$$

4.2.1 Study case

The index-based multi-hazard insurance scheme was implemented in the Jaguari River Basin, the main contributor to the Cantareira Water Supply System (CWSS). The system includes four water-producing reservoirs, Jaguari-jacareí (connected by a channel), Cachoeira, and Atibainha. The Jaguari tributary contributes about 46% of the total water supplied by the CWSS (WHATELEY; CUNHA, 2007). Considered one of the largest public supply systems in the world, it is responsible for supplying water to 7.5 million people in the São Paulo Metropolitan Region SPMR (SABESP, 2020). The Jaguari basin is located in southeastern Brazil between the states of São Paulo and Minas Gerais (drainage area of 970 km^2). It lies upstream of the Jaguari-Jacareí reservoir, within the Piracicaba River Basin. The climate is humid subtropical, Cfa according to the Köppen climate classification, characterized by hot and wet summer (October to March) and dry winter (June to September) (ALVARES et al., 2013). The average annual precipitation and temperature are 1592 mm and 25ºC, respectively (RODRíGUEZ-LADO et al., 2007). The location map of CWSS and the representation of the reservoir are in the appendix B - Figure 16 a-b.

The region suffered from particularly dry years between 1999 and 2004, and more recently between 2014 and 2016 (WHATELEY; CUNHA, 2007; ESCOBAR, 2015; SOUZA et al., 2022). This drought event has exposed the SPMR fragility through fluctuation in water supply. The number was 8.8 million in early 2014 then was reduced to 5.5 million during the drought period between 2014 and 2016, and has returned to about 7.5 million as of today (DEUSDARá-LEAL et al., 2020). Despite the historical drought events, flood is also a hazard to consider in the region, due to the increasing intensity of the precipitation regime (MARENGO et al., 2020). In addition to its social relevance, the region has great economic importance, which is responsible for about 19% of the national Gross Domestic Product (GDP) (HADDAD; TEIXEIRA, 2015). For these reasons, we chose the region as a case study.

We used observed, remote sensing, and climate change data to set up the index-based multi-hazard insurance scheme for current and future scenarios. The observed precipitation data were obtained from the reanalysis products from Xavier's dataset and the ERA5 from 1980 to 2013 (XAVIER; KING; SCANLON, 2016; HERSBACH et al., 2020). The hydrological, reservoir and financial data were gathered from the Sanitation Company of São Paulo state - SABESP and covers the period from 1995 to the present (SABESP, 2004; SABESP, 2010; SABESP, 2014; SABESP, 2019; SABESP, 2020; SABESP, 2021). To assess the future scenarios, we used an ensemble mean over seven General Circulation Models (GCMs) from Phase 6 of the Coupled Model Intercomparison Project (CMIP6) conducted by (SONE et al., 2022b). The Shared Socioeconomic Pathway (SSP) considered here was the fossil-fuelled development scenario (SSP5-8.5) in the immediate (2015–2040), intermediate (2041–2070), and distant future (2071–2100). We have assumed the SSP5-8.5 as the worst-case scenario since it has sufficient emissions to produce a radioactive forcing of 8.5 Wm^{-2} by 2100 (O'NEILL et al., 2016).

4.2.2 Hazard module

The first step in developing the index-based insurance scheme is identifying an adequate index. Several climatic and hydrological indices were analyzed to characterize the correlation with the water utility reservoir level. An effective index, according to (BAUM; CHARACKLIS; SERRE, 2018), is transparent, publicly available, difficult to manipulate, and connected with financial risk. Precipitation, streamflow, Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Precipitation Index (SPI) are therefore possible indicators. Moreover, the candidates were evaluated both as individual measures and as cumulative values from monthly to annual aggregations. Our goal was to find an index that reflects both drought and flood conditions, thus we focused on the link between the candidate index and the reservoir level.

The importance of having a high correlation between the index variable and revenue financial risk is to reduce the basis risk. Basis risk is the difference between insurance payouts and actual losses, which could be higher or lower depending on the contract formulation. This risk is inherent to index insurance products, and it occurs when the payouts depend on an index that is not perfectly correlated with the actual losses (CLEMENT et al., 2018). For these reasons, in this study, we sought to find an index with a Pearson's correlation coefficient (c) greater than 0.7. The drought indices (SPEI and SPI), CDD, and CWD were poorly correlated with reservoir levels and discarded. Likewise, the precipitation and streamflow in singular measurements. However, the cumulative values of precipitation presented a substantially higher correlation. Hence, we define as an index the two-year accumulated daily precipitation (c= 0.76).

Following the index definition, the strike is typically set to one standard deviation above the estimated expected index and the most extreme historical value (JEWSON; BRIX; ZIEHMANN, 2005). However, we chose to customize the strike and followed the SABESP's reservoir operating regime as the basis for its definition (SABESP, 2021). The operating system consists of five Bands, ranging from normal to special. Band 4 is called "restriction", where the volume of the reservoir is between 30 and 20% of the total, and Band 5 - "special", with a volume less than 20% (ANA - Agência Nacional de Águas; DAEE - Departamento de Águas e Energia Elétrica, 2017). When the system is in Band 5, the withdrawal is half of the available in typical situations, severely impacting the supply of SPMR. See appendix B - Figure 16 c for more information. Therefore, the strike for drought was defined as when the reservoir enters constraint, Band 4. In the flood case, we assume that losses will occur when the reservoir level exceeds the maximum allowable value of 100%. The reservoir values have been translated into the index in order to adjust the payout function.

4.2.3 Vulnerability module

Vulnerability is a combination of social, economic, environmental, and cultural aspects that increase a unit's likelihood of being affected by a hazard. In this paper, however, the concept of vulnerability was restricted to economic losses caused by the occurrence of droughts and floods (UN - United Nations, 2015). The economic losses were calculated based on the relationship between the costs of supply and the corresponding water use. We followed the equation by (AUBUCHON; MORLEY, 2013), a function of the water price ($Price$), the water price elasticity (η), water demand (Q_0), and the percentage of water deficit to the regular demand above the Basic Water Requirements (BWR), equation 4.3. The assumed BWR value was based on the World Health Organization recommendation of 110 liters per person per day. The (η) is calculated by dividing the change in demand by the change in price. The water demand, the average consumption, the population served and the prices charged by the water supply company - SABESP, were calculated on the basis of the average values between 1995 and 2019. It is worth noting that for the future, the economic losses per day are held constant, although we acknowledge that this is a methodological limitation as water scarcity is a key driver of price elasticity (GARRONE; GRILLI; MARZANO, 2019).

$$Economic\ losses_{per\ day} = \frac{\eta}{1+\eta} * Price * Q_0 * \left[1 - \left(\frac{BWR}{Q_0}\right)^{\left(\frac{1+\eta}{\eta}\right)}\right] \tag{4.3}$$

We assume a value of economic losses per day as the tick value (D) of the payout equation for booth drought and flood hazard. Thus, the payout is proportional to the number of days the index is below (in the case of drought) or above (in the case of floods) the defined trigger. Before creating an insurance contract scheme, we need to estimate the probability of all possible outcomes to derive a premium. In order to estimate the probabilities of current and future expected losses, we need to simulate the index's behavior and assess its simulated economic losses and payouts. A long-time series is desirable for this, however, we have at our disposal only 30 years of data. We generated synthetic series for the historical and future scenarios to overcome this lack of longer observed time series. We applied the *PRSim.weather* (BRUNNER et al., 2021b), a synthetic weather generator that combines an empirical spatiotemporal model based on the wavelet transform and phase randomization with a parametric distribution of precipitation and temperature data. The *PRSim.weather* is finally run 100 times on a sample of 30 years of observed data (3000 years in total).

Proper drafting of contracts requires data on current and future expected losses, once the synthetic series is complete the distribution of payouts can be determined. The payout distribution methodology proposed in this work is based on a Loss Distribution Approach (LDA). The LDA is a statistical application known in actuarial science for quantifying the distribution of the frequency and severity of losses from operational risks (LI et al., 2011; HASHEMI; KHAN; AHMED, 2019; FUADI et al., 2020; SHEVCHENKO, 2011). The first step in LDA is to calculate the loss severity distribution, where we measure the severity of each loss in terms of economic impact. Then, in the second step, the loss frequency distribution is determined, which represents the frequency distribution of operational losses. Finally, the aggregated loss distribution was obtained by composing the loss frequency and severity distributions.

For risk contracts, the probability of payment distribution has an heavy tail, configuring high payments with a low probability of occurrence at the right end. In order to adjust this behavior and better indicate the price of risk at extremes, the Wang transformation can be used (WANG, 2002). This transformation adjusts the payout distribution by giving more weight to low-probability events. The distortion operator according to Wang (2002) is represented by λ, which is the market price of the risk, that represents the systematic risk of an insurance liability. The Wang transform will provide a "risk-adjusted" density function (Appendix B - Figure 17).

$$F^*(p) = \Phi(\Phi^{-1}(F(p)) + \lambda) \tag{4.4}$$

where $F(p)$ is the cumulative density function derived from observed payouts p, Φ is the standard normal cumulative density function, Φ^{-1} is the inverse normal cumulative function, λ is the market price of the risk, and $F^*(p)$ is the risk-adjusted cumulative density function.

4.2.4 Financial module

The contract is offered by the insurer at a price or premium (Pr), that can be estimated from the probability of the payment distribution. The value of Pr is a function of the expected payments ($E(p)$) plus the administrative fees (A), equation 4.5. Administrative fees in addition to the administrative cost itself, can also consider the opportunity costs, marketing, and return on investment (SMITH; WATTS, 2019), for this reason, they vary greatly depending on the magnitude and frequency of the insured risk.

$$Pr = E(p) + A = \sum p \cdot F^*(p) + A \tag{4.5}$$

Whether an index-based insurance scheme is offered by a public or a private system depends on the analysis of users' willingness to pay (WTP) and willingness to adapt

(*WTAdapt*). Therefore, we have divided the expected payouts into three risk categories: high, medium, and low. Categories were based on return periods of 100, 20, and 5 years respectively. They are a representation of policyholder risk aversion when relating the reservoir level for a given return period to the economic losses corresponding to the urban water supply deficit. This exercise assumes that the greater the risk aversion, the greater the WTP, and hence the value of the premium. Therefore, we propose a premium value per user of the urban water supply system, charged in the water tariff. Our proposal takes into account the three risk categories mentioned above, and for the purpose of this work, we assume a fixed population supplied of 3,312,000. In addition, the data presented here are in constant 2020 USD dollars, considering that 1.00 USD equals 5.15 BRL.

4.3 Results and Discussion

The results provide an average premium per person under the multi-year and multi-risk contract of an index-based insurance scheme considering the climate change drivers analyzed by the simulations presented here. The drought and flood insurance coverage set a combination of three risk categories (high, medium, and low), each assessed using 3000 years of synthetic precipitation time series. The stochastic simulation successfully reproduced the observed statistical characteristics of the precipitation time series. The seasonal and daily distribution characteristics as well as the temporal correlation characteristics, and the non-stationary are accurately captured by the simulations, see appendix B - Figure 18. The simulations are presented in Figure 11, where the gray is the Synthetic series space, the red is the drought condition, and the blue is the flood condition. In the future period, the climate change scenario resulted in an increase in extreme events of both floods and droughts in the immediate future (2015-2040). Similar results were reported for the same period by (SONE et al., 2022b), which the authors found the period critical in terms of ensuring water security in the region. In the intermediate and distant future (2071-2100), the scenario suggested concentrated precipitation events separated by prolonged dry days. (MARENGO et al., 2020) reported an increase in extreme precipitation and Consecutive Dry Days (CDD) for the SPMR. These results suggest a heterogeneous distribution of precipitation, although this could be overcome by changes in reservoir operations to deal with this variability. Furthermore, in Figure 12 we can analyze the violin graph of the maximum, average, and minimum of the synthetic series. We have observed that the minimum distribution has its highest density in the historical period below the drought threshold. On the contrary, in future scenarios, the highest density is above the threshold, indicating a lower probability of drought conditions. Similar behavior occurs in the distribution of maximums, where future scenarios show a lower probability of flood conditions compared to historical simulations. The behavior shown in Figure 12 can be seen as a limitation of future scenarios since these have been bias-corrected. The bias correction method can deteriorate trends and/or relative changes projected by the models and as a consequence hamper the understanding of climate change effects (MAURER; PIERCE, 2014).

The relationship between the utility costs of supply and the corresponding water use results in an average daily loss of USD 150,530.00. We calculate the loss value through the LDA for each day that the reservoir is below trigger (for drought) and under trigger (for flood), represented by the red and blue lines respectively in Figure 11. In figure 13 we have the optimal annual premium for each period, i.e., historical and future, for different insurance coverage levels, i.e., low, medium, and high. Considering the drought risk over the historical period for the three coverage levels, the optimal premium value is of USD 1.08, 1.65, and 2.01 for each water user per day and the respective coverage level. These values correspond to 1.8, 2.8, and 3.5 percent of the average annual fee paid into the water bill per user. For the flood risk, the optimal premium value is one-third compared to drought risk, USD 0.38, 0.49, and 0.58 for low, medium, and high. This behavior, reflected in the premium value, was to be expected since the risk of flood is lower than the risk of drought.

In various scenarios, higher coverage levels are associated with more expensive premiums due to their restriction to events with a lower probability of recurrence. Specifically, in the case of drought risk, transitioning from historical simulations to the immediate future leads to a substantial reduction in premium values. For each of the low, medium, and high coverage levels, premium values decrease by 84%, 82%, and 76%, respectively. Similarly, flood risk exhibits a comparable reduction in premiums, with decreases of 96%, 60%, and 55% for the respective coverage levels. hese significant changes in premium values can be attributed to future scenario simulations. It is important to note that the CMIP6 GCMs (Coupled Model Intercomparison Project Phase 6 General Circulation Models) lack a clear relationship between the model spread around the mean during the reference period and the magnitude of simulated sub-regional climate change in the future period (ALMAZROUI et al., 2021a). Furthermore, it is worth mentioning the uncertainties associated with the ensemble used in this study, as it is limited in size and has a spatial resolution of 2°×1.5°(SONE et al., 2022b). Future studies should consider using a combination of single GCMs instead of relying solely on ensemble approaches to provide a more comprehensive understanding of premium variations and their relationship to projected climate changes. This approach may offer insights into the uncertainties associated with different GCMs and improve the accuracy of risk assessment in insurance pricing models.

In the simulations, the flood risk decreases towards the end of the century and reaches values close to zero, so that in the intermediate and distant future the premium is only available for the high coverage level. (ALMAZROUI et al., 2021b) reported Brazil as a hotspot region for increased hot and dry events. This could explain the trend towards lower insurance premium values for flood risk in the intermediate and distant future. Similar

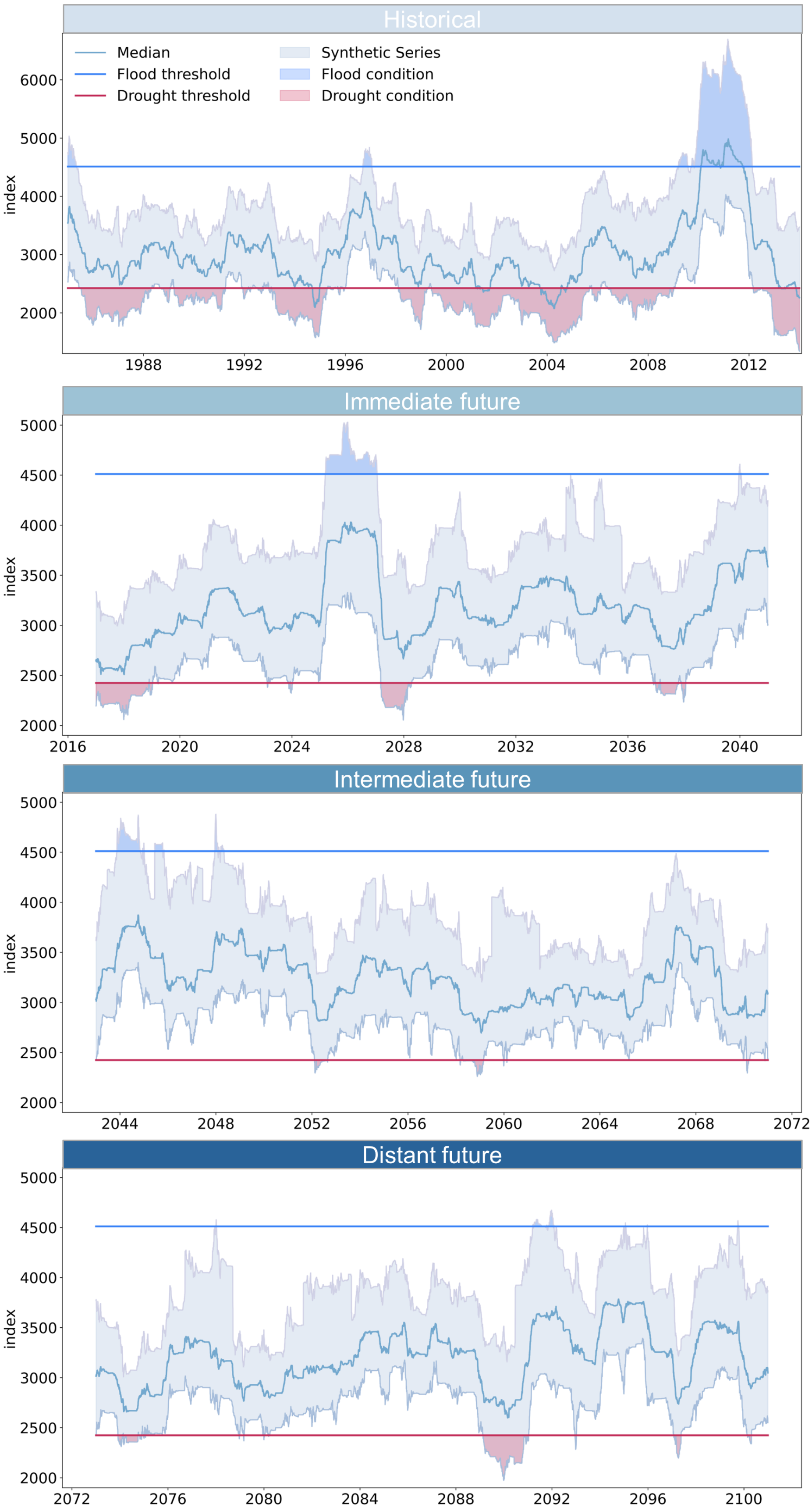


Figure 11 – Synthetic series simulation for drought and floods assessment, for the historical and future periods

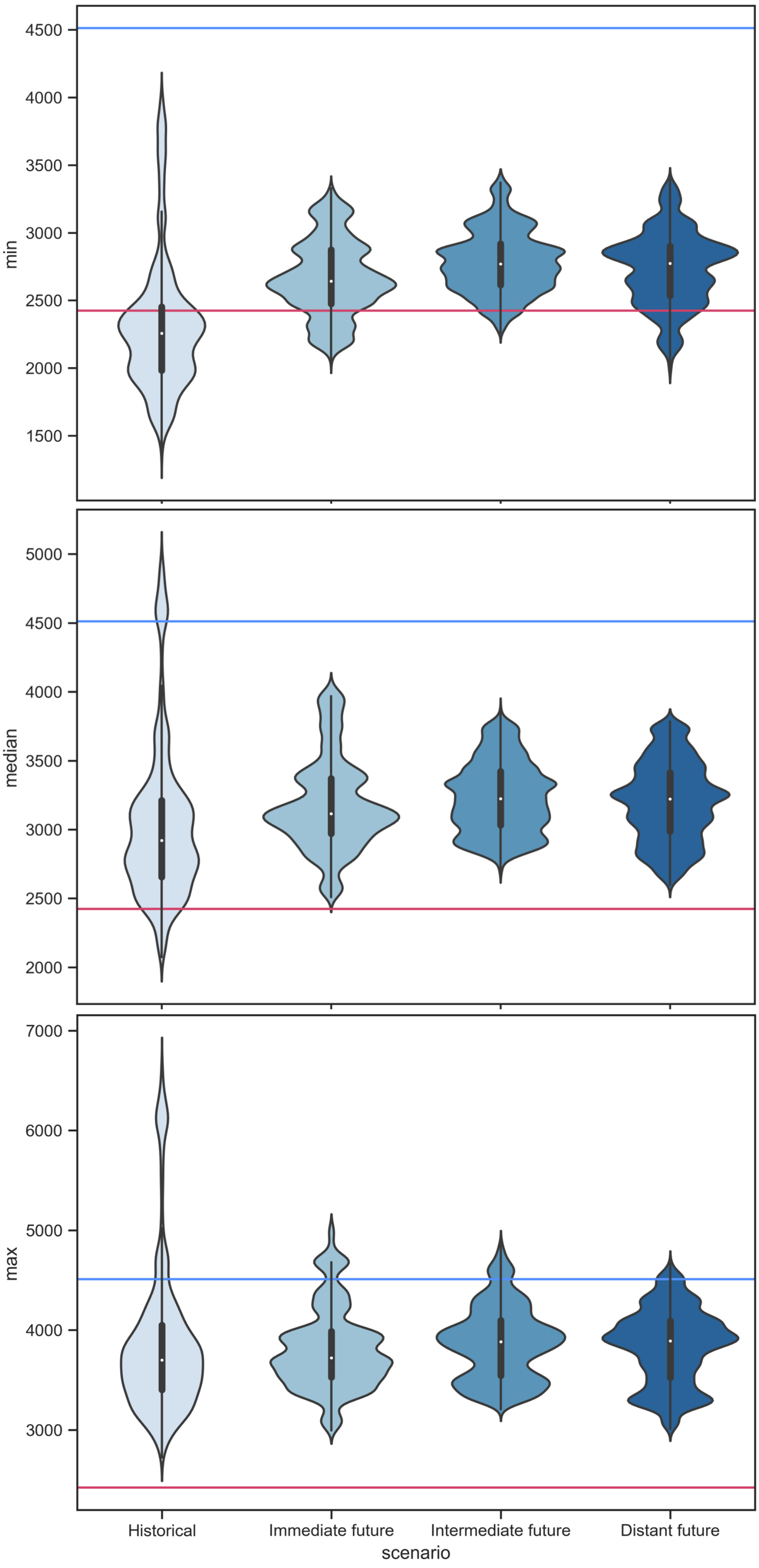


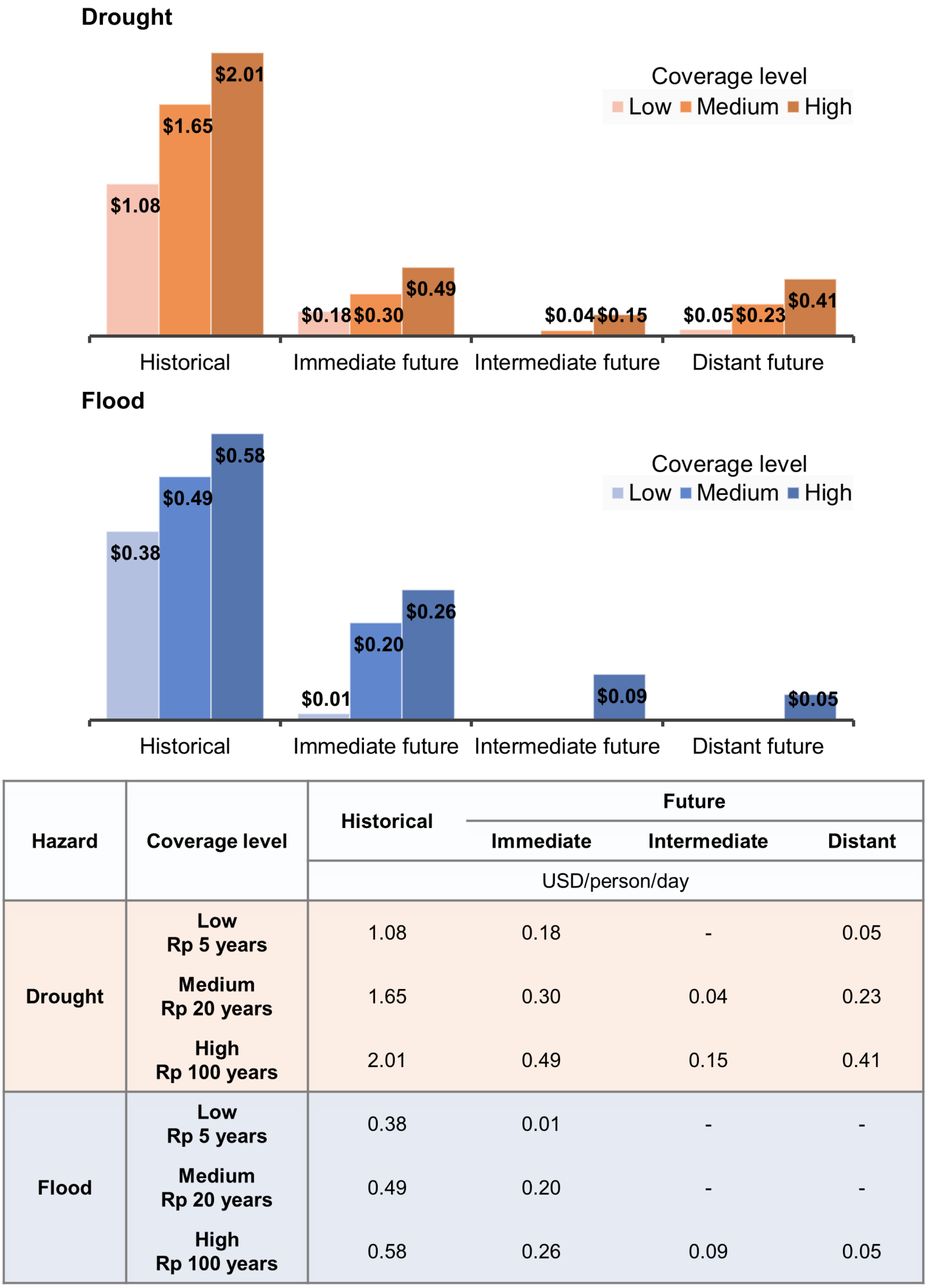
Figure 12 – Violin plot of Minimum (min), Median, and Maximum (max) distribution of precipitation (mm) synthetic series for Historical and future periods. The red line represents the drought threshold and the blue line is the flood threshold

behavior occurs for drought risk, although the risk is more meaningful than flood risk, it remains very low in the intermediate future and increases slightly towards the end of the century. This result agrees with (ALMAZROUI et al., 2021b), where under the high emission scenario SSP5-8.5 there is a drastic increase in heat waves by the end of the twenty-first century.

The risk management fee (premium fee) can be implemented in water bills as a new strategy to pool risk between users and utilities and prevent them from being exposed to surcharge fluctuations. The Premium rates have a linear relationship with the high, medium, and low coverage levels, therefore, insurance uptake is unlikely to be affected by the coverage levels. The coverage level in the case described here is assumed based on the willingness to pay (WTP) and the level of risk aversion of the water users. It is known that water users who have faced water restrictions and rationing in the past are more likely to WTP for prevention and adaptation measures (SONE et al., 2022a). Thus, we can assume that the water users in SPMR could be more WTP for index-based insurance as they have faced many water restrictions over the last 20 years. The results revealed that utilities and users were exposed to a wide range of hydrological and climate-related financial risks, particularly in recent years. A variety of factors could contribute, including climate change, which alters the frequency and intensity of droughts-related events, and the growing population and demand in the region. During the 2013 to 2015 drought, the water utility company (SABESP) saw its net profit reduction of about USD 409 million per year (GUZMáN; MOHOR; MENDIONDO, 2020). From the water utility's and users' perspectives, a multi-year multi-risk index-based insurance scheme with premiums below the average reduction in revenue would be beneficial. Through insurance as a financial instrument, water utilities could help improve the financial risk and management of water resources. This leads to greater financial stability for the water utility and, in the long term, to lower feed for water users (BAUM; CHARACKLIS; SERRE, 2018).

4.4 Conclusion

We simulated a multi-year and drought and flood index-based insurance for the Cantareira Water Supply System for current and future periods. We found that two-year lag accumulated precipitation was the highest correlated index variable and reflected a daily direct loss of approximately USD 150,000.00 due to drought and flood in the distribution reservoir. Our results show that the premiums have a linear relationship with the coverage levels. The higher the coverage level, the higher the premium fee. At the present, each person should pay an annual amount (premium) of USD 1.08, 1.65, and 2.01 to obtain drought coverage for Low, medium, and high coverage levels, respectively. For flood coverage, the values are USD 0.38, 0.49, and 0.58 for the same coverage levels. For future simulations, the immediate future presents the highest premium values for both



Hazard	Coverage level	Historical	Future		
			Immediate	Intermediate	Distant
		USD/person/day			
Drought	**Low** **Rp 5 years**	1.08	0.18	-	0.05
	Medium **Rp 20 years**	1.65	0.30	0.04	0.23
	High **Rp 100 years**	2.01	0.49	0.15	0.41
Flood	**Low** **Rp 5 years**	0.38	0.01	-	-
	Medium **Rp 20 years**	0.49	0.20	-	-
	High **Rp 100 years**	0.58	0.26	0.09	0.05

Figure 13 – Premium values, USD per person per day, for drought and flood hazards in historical and future periods

flood and drought risks. This value declines further in the intermediate future, with the same trend for flood risk at the end of the century, and a small increase in the distant future for drought risk.

Our results suggest that drought-flood-related financial risks can be the management by water utilities and users to reduce the financial impact of drought and flood on the water users via index-based insurance. We also find evidence that premiums have a linear relationship with coverage levels. The alternative, nonlinear, will not be feasible or sustainable for insurance scheme management, since both private and public contract insurance schemes are linear. As disruptions are difficult to remedy on a short-run basis, index-based insurance has the potential to significantly reduce the costs of managing financial risk. Given that extreme weather events will become more frequent and intense in the future, we recognize the critical importance of financial tools to mitigate losses as an additional solution for water resources management.

Chapter 5

GENERAL CONCLUSIONS

Resilience assumes a critical role in a climate-change world characterized by multiple spatial and temporal scales, as it addresses the fundamental objectives of water security: ensuring sufficient and clean water for human consumption and economic activities while mitigating risks associated with droughts and floods. Aligned with this, the hypothesis of this thesis was that the implementation of risk pooling mechanisms and index-based insurance as adaptive strategies in Brazil's catchments would yield substantial improvements in water security and resilience. These strategies were anticipated to reduce the impact of extreme events, enhance the capacity to manage water shortages, guide the formulation of effective adaptation plans, and mitigate long-term economic losses resulting from such events. The findings of this research support the hypothesis, demonstrating the necessity for Brazil to strategically plan and implement appropriate water infrastructure and non-structural measures for effective water resource management. Among these measures, risk pooling emerges as a viable strategy to mitigate the impacts of widespread droughts by facilitating the sharing of loss risks among regions outside identified drought similarity regions. Moreover, index-based insurance exhibits the potential to effectively manage water shortages and significantly reduce financial risks for water utilities and users in the face of extreme events, such as droughts and floods.

The first specific objective of this thesis was to review and analyze water security in Brazil, considering the impacts of extreme events, water shortages, and the progress of national water security policies. In Chapter 2, the aim was to fulfill this objective by elucidating the challenges faced by different regions and the need for comprehensive water management policies. While the recent water crisis in the major metropolitan areas of Brazil has driven discussions on water security, it is crucial to extend these efforts beyond the urban centers and address the urgent need for progress in regions such as the North and Northeast, where a significant portion of the population faces substantial water inequalities. Recognizing the significance of addressing water inequality, integrating river basins, and fostering participative management, this thesis underscored the importance of these factors in ensuring water security. Furthermore, the study highlighted the potential of environmental policies, specifically the National Policy for Payment for Environmental Services, in supporting climate change adaptation and sustainable water resource management. In addition to these policy considerations, the thesis emphasized the necessity of investments in drinking water supply, sanitation, and water reuse, coupled with the development of integrated risk management strategies.

Our comprehensive review showed a pressing need for strategic planning, development, and understanding of adaptation measures to address existing and future challenges in water resources management. In light of this, we emphasized the significance of adopting an integrated management approach that encompasses all regions of Brazil, taking into account their unique characteristics and vulnerabilities. Thus, the second specific objective of this thesis was to introduce a framework to identify the vulnerable regions in Brazil accounting for spatially compounding droughts. In Chapter 3, we presented a novel approach to investigating the spatial connectedness of hydrological droughts, which extends beyond the confines of our study area and can be applied to diverse regions worldwide. Our findings revealed that the semi-arid and densely populated areas in the South and Southeast regions of Brazil are particularly prone to severe and widespread droughts. By identifying regions with similar drought patterns and spatial dependencies, our research provided valuable insights for drought management strategies and facilitated the development of risk pooling mechanisms.

In Chapter 3, the study also underscored the distinct characteristics of droughts in different regions, with significant implications for sectors such as food production, energy generation, and water supply. In line with our third specific objective, we aimed to recommend the first adaptation measure, a network of risk pool regions based on the identified vulnerable drought regions. This recommendation seeks to enhance resilience and guide the implementation of future adaptation plans to mitigate the impacts of hydrological extremes. We propose that catchments outside the same similarity region form risk pools, as they are less likely to simultaneously experience drought events. Importantly, our findings emphasize the necessity of considering spatial and temporal aspects of drought and incorporating climate change projections for effective disaster risk reduction and long-term water resource management.

The second adaptation measure proposed in this thesis aligns with the fourth specific objective, which focuses on the proposition of index-based insurance as a viable strategy for mitigating and preventing long-term financial losses in water supply systems when confronted with extreme events. Specifically, our investigation concentrated on the Cantareira Water Supply System and simulated multi-year drought and flood index-based insurance scenarios, presented in chapter 4. Through our analysis, we determined that the most highly correlated index variable for this system was the accumulated precipitation with a two-year lag. This variable effectively captured the cumulative impact of drought and flood events on the distribution reservoir, resulting in substantial daily losses. The findings revealed a direct relationship between premiums and coverage levels, with higher coverage necessitating higher premium fees. To facilitate practical implementation, the research provided specific premium amounts corresponding to different coverage levels, both for the present and future periods. Ultimately, our study concluded that index-based insurance has the potential to effectively manage financial risks associated with droughts and floods in water supply systems. By reducing the costs associated with risk management, this approach offers a viable solution for water resource management amidst the escalating frequency and intensity of extreme weather events. The findings of this research provide valuable insights for the development and implementation of index-based insurance programs to enhance the resilience of water supply systems and ensure their sustainable operation in the face of climatic uncertainties.

Overall we can conclude that the thesis meets its general objective of proposing risk pooling and index-based insurance as adaptation measures to improve water security and resilience in catchments under changes in Brazil. We identified the spatially compounding drought-vulnerable regions, recommended risk pool regions, and explored the potential of index-based insurance for the Cantareira Water Supply System. The study highlighted the importance of these strategies in enhancing water security, managing extreme events, and mitigating economic losses. It emphasized the need for comprehensive water management policies, adaptive measures, and financial tools to address the challenges posed by climate change and ensure the long-term sustainability of water resources in Brazil.

Limitations of this research should be acknowledged to provide directions for future studies. Firstly, the implementation of risk pooling mechanisms and index-based insurance as adaptation measures was primarily explored at the conceptual level. Further research is required to assess the practicality, feasibility, and effectiveness of these strategies in real-world contexts, considering factors such as legal frameworks, institutional arrangements, and stakeholder engagement. Additionally, the analysis focused on specific case studies, such as the Cantareira Water Supply System, and may not fully capture the diversity of water systems and regions in Brazil. Future studies should include a broader range of case studies to provide a more comprehensive understanding of the applicability and limitations of these adaptation measures across different contexts. Furthermore, the socioeconomic and equity implications of risk pooling and index-based insurance should be further explored to ensure that these measures do not inadvertently exacerbate existing inequalities and vulnerabilities within the water sector.

Future research endeavors could expand upon the approach of analyzing spatially compounding droughts and extend it to the realm of spatially compound floods. While this thesis primarily focused on drought events, understanding the spatial patterns and dependencies of flood events is equally crucial for comprehensive water resource management and resilience-building. By incorporating the concept of spatially compound floods, in addition to combining the investigation with droughts, future research can provide valuable insights into the interconnectedness of hydrological extremes and develop more holistic strategies to address the challenges posed by climate change. Moreover, considering climate change models in future studies would provide a forward-looking perspective on water security and resilience. Climate projections can offer valuable information about potential changes in precipitation patterns, temperature, and extreme weather events, allowing for a more accurate assessment of future risks and vulnerabilities. Integrating climate change scenarios into the analysis of spatially compounding droughts and floods can enhance the understanding of how these events may evolve under different climate change trajectories, thus enabling the development of robust adaptation measures and policies.

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APPENDIX A

Supplementary material of chapter 3

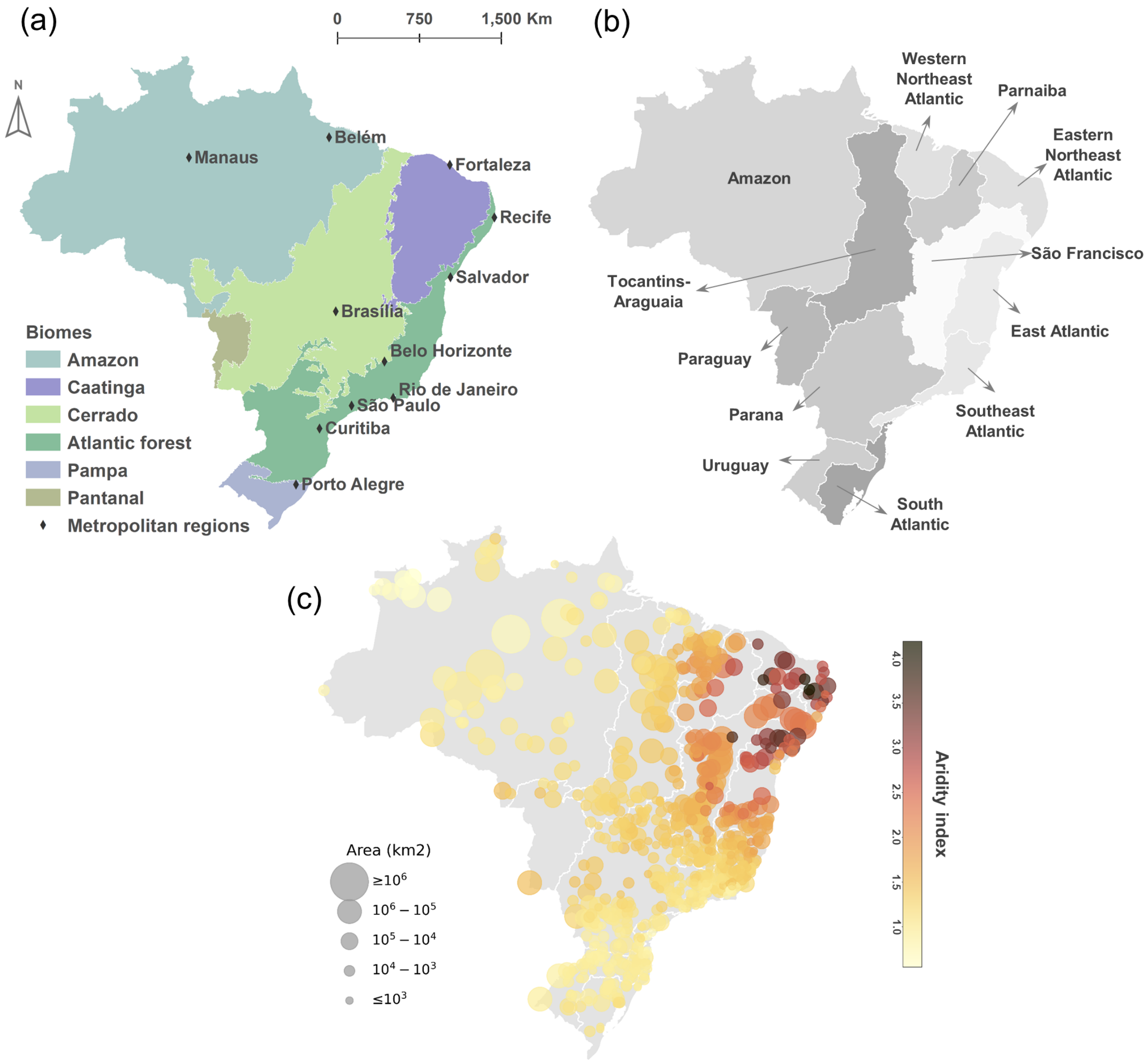


Figure 14 – (a) Brazilian biomes and the main metropolitan regions, (b) 12 hydrographic regions, and (c) CABra's catchments, colored according to their aridity index and scaled by area.

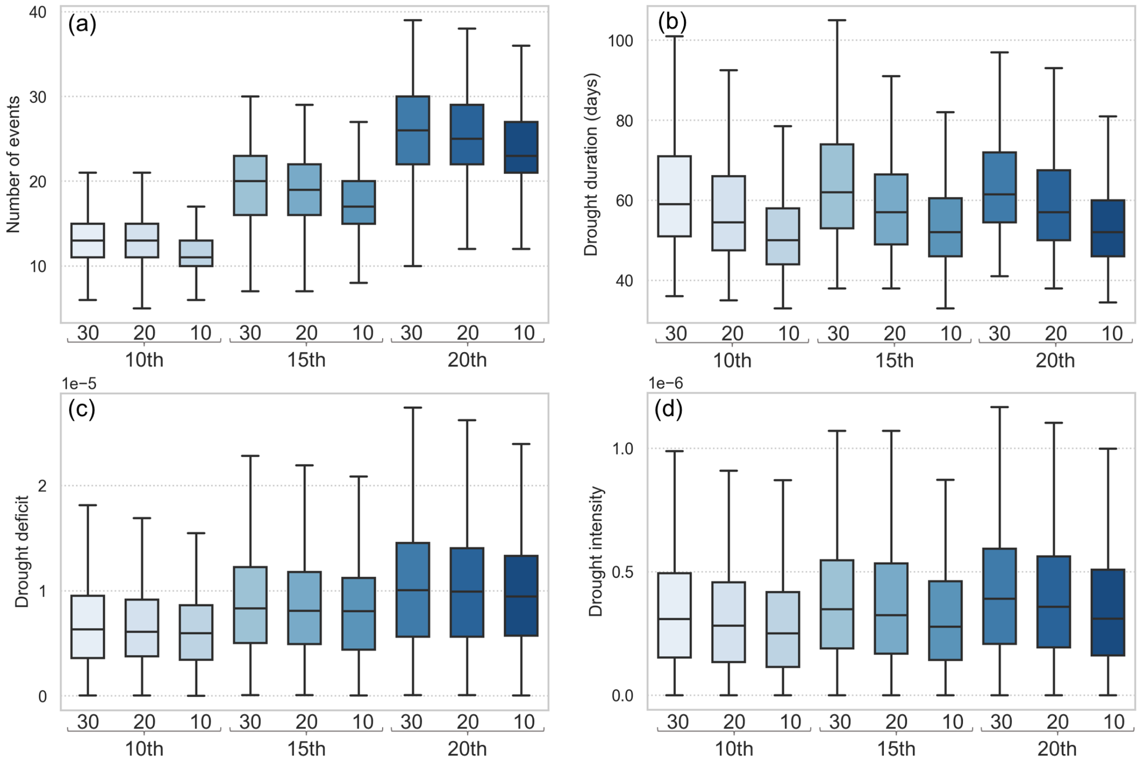
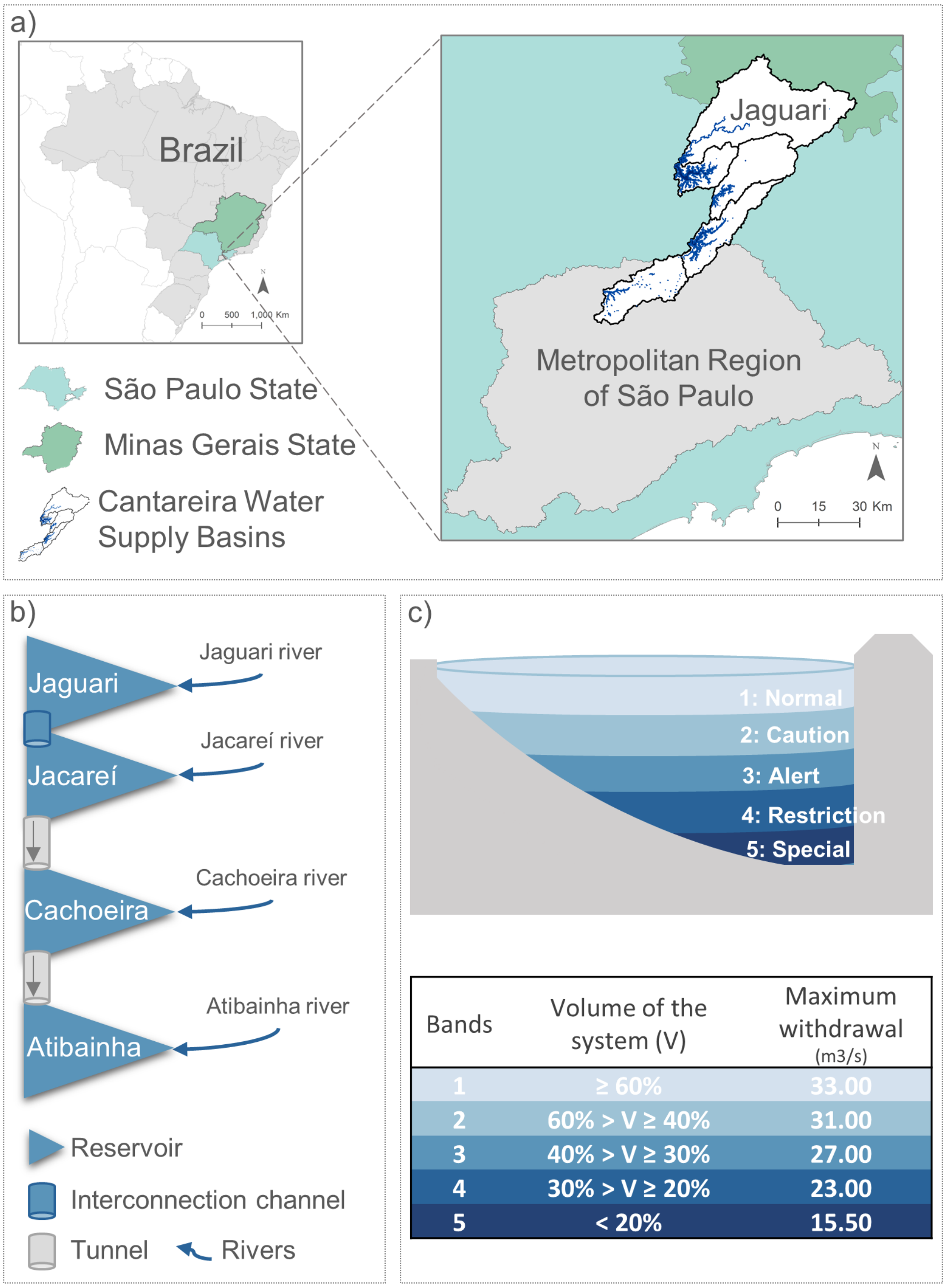


Figure 15 – Sensitivity analysis of threshold (10th, 15th, and 20th percentile) and moving window (10, 20, 30 days) choice on (a) number of drought events, (b) drought duration (days), (c) drought deficit (mm), and (d) drought intensity (mm)

APPENDIX B

Supplementary material of chapter 4



Bands	Volume of the system (V)	Maximum withdrawal (m3/s)
1	≥ 60%	33.00
2	60% > V ≥ 40%	31.00
3	40% > V ≥ 30%	27.00
4	30% > V ≥ 20%	23.00
5	< 20%	15.50

Figure 16 – (a) location of the Cantareira Water Supply System (CWSS) Basins and the Jaguari Basin, (b) Schematic representation of water-producing reservoir of CWSS, and (c) Schematic representation of reservoir bands and the operating system.

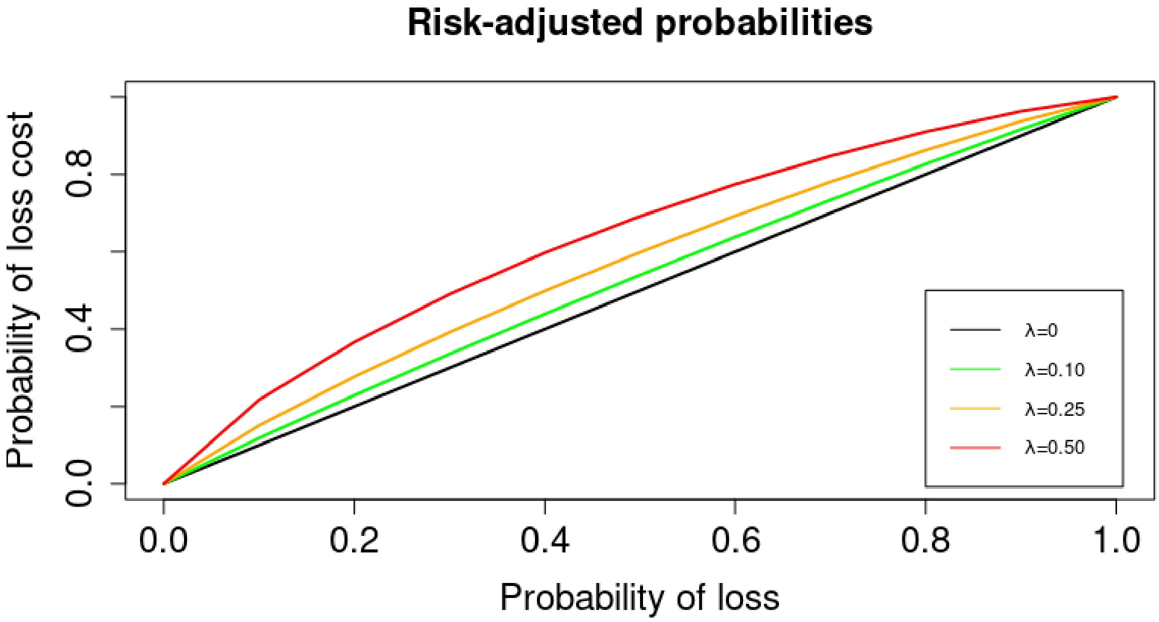


Figure 17 – Risk adjusted probabilities using different values of market risk λ

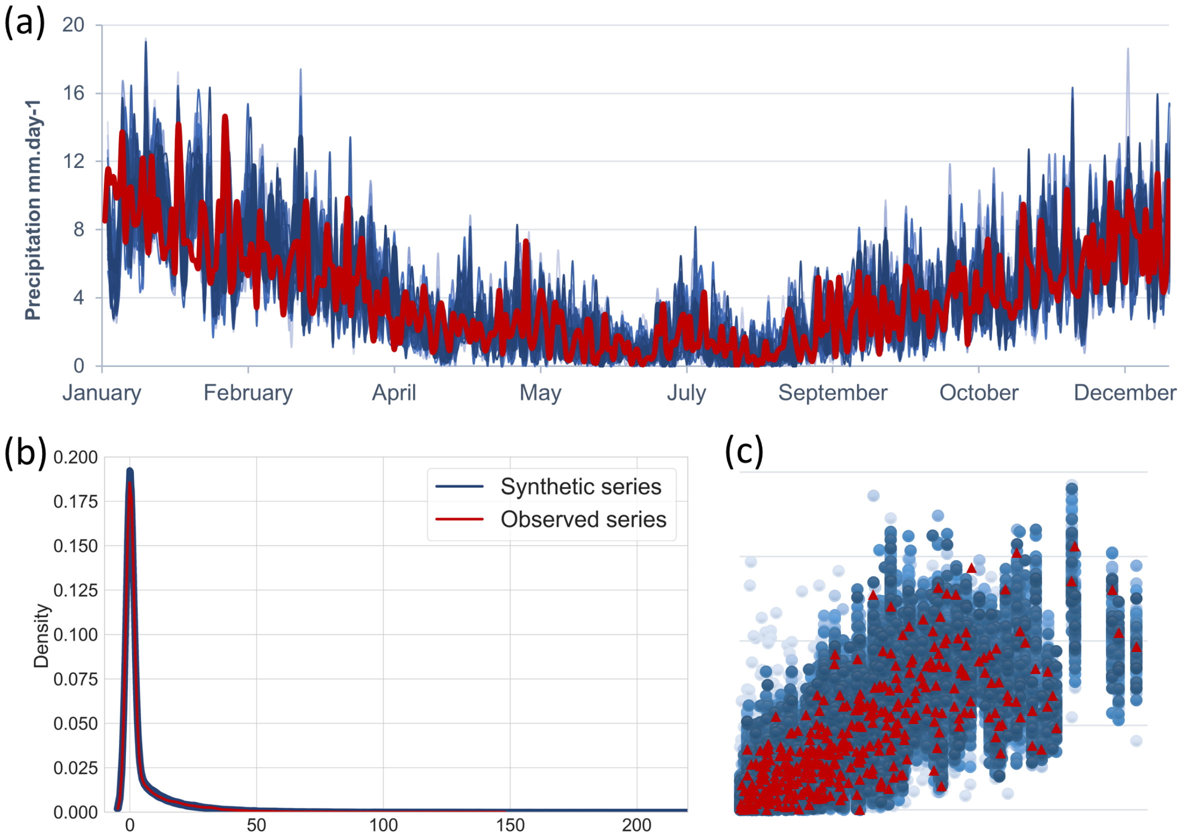


Figure 18 – Comparison of observed and stochastically generated time series (Synthetic): (a) Annual precipitation (b) density and (c) scatterplot plots. The red line in (a) and (b) represents the observed time series, while the blue lines represent the synthetic series; in (c), the red triangles represent the observed time series, while the blue circles represent the synthetic series.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