UNIVERSIDADE DE SÃO PAULO
Escola de Engenharia de São Carlos

# A tale of two cities:

# Public preferences for nature-based solutions and the effect of drought-related experiences on willingness to improve water security

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São Carlos

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# ABSTRACT

SONE, J. S. **A tale of two cities: public preferences for nature-based solutions and the effect of drought-related experiences on willingness to improve water security**. 2023. 145p. Tese (Doutorado) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2023.

Societal behavior and perceptions of water scarcity is expected to play a critical role in ensuring water security. Nonetheless, these drivers need to be better understood mainly because water scarcity-related experiences seem to influence public attitudes differently across countries. Thus, this thesis addresses: (i) how different experiences with water restrictions and rationing trigger people to invest in conversation measures and (ii) how public perception of nature-based solutions (NbS) affects preferences for this kind of measures to improve water watershed services. To explore these questions, water security is assessed in Campo Grande (CG) and the São Paulo Metropolitan Region (SPRM) by contrasting water demand with probabilistic levels of water availability under climate change and water demand scenarios. Then, a discrete choice experiment was used to investigate public preferences for measures to reduce the frequency and duration of future water shortages. These two sites and their respective supplying basins were chosen since their population has faced different restrictions and rationing efforts. In the **first chapter**, the foundation is laid for the problem statement and research questions. The results and methods are then divided into two parts: (i) water security under climate change and (ii) willingness to pay (WTP) to improve water security. This thesis' general conclusion is also presented in the third and last part. **Part I** starts with the respective methods adopted to assess future water security in the two basins feeding CG and the SPMR. The physically-based model SWAT+ was used to simulate the basins' hydrological response to three different Shared Socioeconomic Pathways (SSP): (i) SSP2-4.5 (medium forcing), (ii) SSP3-7.0 (medium-high forcing), and (iii) SSP5-8.5 (high forcing). An imbalance between availability and demand is the main driver of water insecurity in the Guariroba basin, which supplies CG. Due to a decrease in precipitation, water scarcity risk considerably increases in the future in the Jaguari basin, which supplies the SPMR. Even a reduction of 20% by 2070 in water demand is not enough to improve water security in both basins. This finding highlights the need of non-strutuctural measures such as NbS to safeguard future water supply. In **part II**, the material and methods adopted to design and implement the choice experiment in CG and the SPMR are described in detail, as well as the econometric models estimated to investigate public preferences and WTP for NbS to improve drinking water reliability. Water rationing experiences significantly influence public decision-making and WTP for NbS in both cities. Agroforestry is the most preferred solution in both cities although a considerable share is uncertain about the effectiveness of NbS. Protest motives are also explored in this part, and the main reason for nonparticipation is the lack of trust that the public authorities would invest the money in the measures. **Part III** provides an overview of the thesis outlining key findings and a general conclusion putting together all evidence contributing to answering this thesis' research questions. The findings indicate that there is public understanding for the need of environmental protection in watersheds feeding cities to achieve water security and support for NbS. The findings of this study provide important insights into relevant feedback between droughts and societal vulnerability and response inserted into the present-day Brazilian cultural, socioeconomic, and political context.

**Keywords**: Water Shortage; Drought Adaptation; Economic Valuation; Water Management.

## RESUMO

SONE, J. S. **Preferências por soluções baseadas na natureza e o efeito de experiências com secas na disposição a melhorar a segurança hídrica**. 2023. 145p. Tese (Doutorado) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2023.

O comportamento social e as percepções sobre a escassez de água têm um papel crucial na garantia da segurança hídrica para o abastecimento de água potável. No entanto, esses fatores precisam ser melhor compreendidos, especialmente porque as experiências relacionadas à escassez de água parecem influenciar as atitudes públicas de maneira variada em diferentes países. Portanto, esta tese tem como objetivo abordar os seguintes aspectos: (i) como diferentes experiências com restrições e racionamento de água motivam as pessoas a adotarem medidas de conservação e (ii) como a percepção pública sobre as soluções baseadas na natureza (SbN) afeta as preferências por esses tipos de medidas a fim de garantir a segurança hídrica. Para explorar essas questões, a segurança no abastecimento de água é avaliada em duas regiões, Campo Grande (CG) e Região Metropolitana de São Paulo (RMSP), contrastando a demanda de água com níveis probabilísticos de disponibilidade sob diferentes cenários de mudanças climáticas e demanda. Em seguida, um experimento de escolhas é utilizado para investigar as preferências públicas por medidas destinadas a reduzir a frequência e duração de futuros episódios de escassez hídrica. Essas duas localidades e suas respectivas bacias hidrográficas foram selecionadas devido às diferentes experiências com restrições de uso e racionamento de água enfrentados por suas populações. No **primeiro capítulo**, são estabelecidos os fundamentos para a formulação do problema e as questões desta pesquisa. Os resultados e metodologia são divididos em duas partes: (i) segurança hídrica sob mudanças climáticas e (ii) disposição para pagar (DAP) para melhorar a segurança hídrica. A conclusão geral desta tese é apresentada na terceira e última parte. A **parte I** se inicia abordando os métodos adotados para avaliar a segurança hídrica futura nas duas bacias que abastecem CG e RMSP. O modelo SWAT+ foi utilizado para simular a reposta hidrológica dessas bacias a três diferentes cenários de mudanças climáticas: (i) SSP2-4.5 (forçante média), (ii) SSP3-7.0 (forçante média-alta) e (iii) SSP5-8.5 (forçante alta). Observa-se que o desequilíbrio entre disponibilidade e demanda é o principal fator de insegurança hídrica na bacia do Guariroba, que abastece CG. Por outro lado, devido a uma diminuição na precipitação, o risco de escassez de água aumenta consideravelmente no futuro na bacia do Jaguari, que abastece a RMSP. Mesmo uma redução de 20% na demanda de água até 2070 não é suficiente para melhorar a segurança hídrica em ambas as bacias. Isso mostra que é necessário investir em medidas não estruturais, como as SbN, para garantir o suprimento da demanda futura. Na **parte II**, são apresentados primeiramente os materiais e métodos usados para a implementação do experimento de escolhas em CG e na RMSP, bem como os modelos econométricos estimados para investigar as preferências públicas e a disposição para pagar por soluções baseadas na natureza a fim melhorar a confiabilidade do abastecimento de água. Observa-se que as experiências com racionamento de água influenciam significativamente a tomada de decisão pública e a disposição para pagar por essas soluções em ambas as cidades. Nesse contexto, os sistemas de integração agricultura-floresta são a solução mais preferida em ambas as localidades, embora uma parcela considerável da população tenha dúvidas sobre a eficácia das SbN propostas. Nesta parte, também são explorados os motivos de protesto e a principal razão para a falta de disposição a pagar é a desconfiança de que as autoridades públicas não investiriam os recursos arrecadados nas medidas. A **Parte III**, fornece uma visão geral da tese, destacando as principais descobertas e uma conclusão geral que reúne todas as evidências que contribuíram para responder às questões desta pesquisa. As descobertas revelam uma compreensão pública da necessidade de proteção ambiental nas bacias hidrográficas que abastecem suas cidades para garantir a segurança do fornecimento de água e também apoio às soluções baseadas na natureza. Esses resultados fornecem reflexões importantes sobre interações relevantes entre secas, vulnerabilidade e resposta da sociedade, inseridos no contexto cultural, socioeconômico e político brasileiro atual.

**Palavras-chave**: Falta d'água; Adaptação à escassez hídrica; Valoração Econômica; Gerenciamento de Recursos Hídricos.

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# Chapter 1

# GENERAL INTRODUCTION

Large precipitation deficits propagate to all components of the hydrological cycle, triggering hydrological droughts (HUANG et al., 2017). This kind of drought may cause a decline in water supply and, along with increasing water demand, exacerbate water inequalities around the world and weaken the global economy. Furthermore, climate change is expected to worsen water-related issues due to an increase in frequency and magnitude of droughts worldwide (UNCCD - United Nations Convention to Combat Desertification, 2022); it will likely raise uncertainties about future water availability. Extreme weather events have globally increased by 7% from 2011 to 2013 (PAPALEXIOU; MONTANARI, 2019) and are expected to further increase by the end of the century (LEE et al., 2022). The assessment of climate change impacts on water resources is often related to some aspect of water security as water quantity and quality are the key variables that motivate scientific research and public policies. Expected changes in water quantity and quality due to climate change may increase the share of the global population that faces severe water scarcity by 35% (VLIET et al., 2021). In Brazil, for instance, 15 million people faced droughts in 2020 (OECD - Organisation for Economic Co-operation and Development, 2022). Therefore, there is an urgent need to implement appropriate measures to ensure future water security in this Anthropocene era of increasing change and uncertainty. For that, planing, management, and policy-making need to integrate environment and socioeconomic development based on evidence-informed decision-making.

Nature-based solutions (NbS) have emerged as a potential alternative to enhance water security by complementing grey infrastructure. For example, the adoption of afforestation and agroforestry can sustain water supply and mitigate drought by increasing infiltration and storage capacity (SONE et al., 2019; UN Environment-DHI; UN Environment; IUCN, 2018). The ultimate goal of NbS is to tackle social, economic, and environmental challenges by encompassing a set of actions to protect, conserve, restore, and sustainably use and manage natural or modified ecosystems while providing human well-being, ecosystem services, resilience and biodiversity benefit (United Nations Environment Programme, 2022). Therefore, prioritizing NbS over grey infrastructre measures can have not only environmental but also economic and social benefits (OLIVA; RASGUA, 2008). Despite the relevance, this kind of solution has still accounted for less than 1% of global infrastructure investment for water management by 2018 (CONNOR et al., 2018). Environmental and social impacts of NbS can be included into decision and policy-making processes by applying environmental non-market valuation through stated preferences methods, such as discrete choice experiments. This kind of study contributes to increasing public awareness of the importance of environmental assets, such as water provision. Policy-making would also benefit from a better understanding of how public experiences with water scarcity influence public decision to take and pay for water conservation measures based on nature. Interactions and feedback loops between society and drought impacts are not fully understood even though studies on the intertwined natural and social triggers have increased (e.g., Eamen, Brouwer and Razavi (2020), Jaeger et al. (2019), and Savelli et al. (2022)).

## 1.1 Water security and nature-based solutions

Water security is intricately tied to the availability of blue and green water resources. The former flows beneath and on the surface, and the latter represents the portion of precipitation that becomes soil moisture and eventually evaporates back into the atmosphere (i.e., blue and green water according to Falkenmark and Rockström (2006). The concept of water security emerged in the 1990s and was related to military and food security definitions; at that time, it was rarely associated with the environment (COOK; BAKKER, 2012). A more complete concept was further developed by the United Nations Water (UN-Water), stating that water security is the capacity to guarantee enough water with adequate quality for human activities, ecosystem preservation, and protection against climate risks (UN-Water, 2013). Within this context, analyses that incorporate water security have been proposed to assist decision-makers and water managers to overcome existing political, social, and economic challenges worldwide, as water provision has been significantly altered (FALKENMARK; WANG-ERLANDSSON; ROCKSTRÖM, 2019).

Water security has swiftly moved up the priority list for governments worldwide, even in some traditionally water-rich countries such as Brazil. Despite Brazil's privileged position regarding water availability, this resource is unevenly distributed across the country. This has led to local socioeconomic crises stemming from water scarcity, as reviewed by Gesualdo et al. (2021). A significant example occurred in 2021 when the National Water and Basic Sanitation Agency (ANA, Agência Nacional de Águas e Saneamento Básico in Portuguese) declared a critical water scarcity situation in five federal states. This alarming situation was triggered by the driest rainy season in 91 years in the Paraná River basin, a strategic region for the Brazilian hydropower generation, responsible for 23% of the total hydropower potential in Brazil (ANEEL - Brazilian Electricity Regulatory Agency, 2008). Thus, understanding the linkages between meteorological and hydrological droughts becomes paramount for future water management (MELO; WENDLAND, 2016). On the other hand, in the same year, an extratropical cyclone hit the Brazilian south coast and contributed to heavy storms in several cities in Southern state of Bahia (World Stock Market, 2021). As a result of severe flooding, authorities declared a state of emergency. Furthermore, a study by Marengo et al. (2020a) highlights the escalating occurrence of extreme rainfall in the São Paulo Metropolitan Region (SPMR). In 2020, the National Institute of Meteorology (Inmet) reported the second-highest daily rainfall volume since 1943. Thereby, to reduce the future impact of climate change on water availability and provision, it is crucial to understand its spatial and temporal variability, as well as people and economic assets vulnerability (FORMETTA; FEYEN, 2019). In the Brazilian river basins, water management still lacks economic valuation through willingness to pay approaches (PAIVA et al., 2020) even though water is officially recognized as a public good with economic value by the Brazilian Policy on Water Resources (Federal Law n. 9,433 enacted in 1997).

The concern with water security is not recent, and Brazil stands as a pioneer in reforestation to enhance water provision. Back in the 1860s, the rampant deforestation in Rio de Janeiro, the nation's capital at the time, seriously jeopardized the city's water sources. In response, an ambitious initiative to revive the forests was launched (DEAN, 1997), resulting in the planting of around 68,000 trees across a 180-hectare area between 1861 and 1873 (now part of the Tijuca National Park) (DRUMMOND, 1988). This scenario highlight the awareness of decision-makers about the importance and role played by land cover in water security. For example, reforestation can have a buffering effect on river flow and improve groundwater storage (VIGERSTOL et al., 2021). Later on, two Federal Laws were enacted to address the dual concerns of water supply and forest preservation: the Water Law (Law 24.643/34) and the Forest Code (Law 23.793/34), respectively. While the Forest Code has faced recent limitations (SOARES-FILHO et al., 2014), its legal framework remains pivotal in tackling soil degradation and encouraging the conservation and restoration of ecosystems. Nonetheless, the financial burden of adhering to these regulations remains an obstacle for rural landowners. Consequently, this has spurred the adoption of Payment for Watershed Services (PWS) programs, which have emerged as effective alternatives (RICHARDS et al., 2015) for landowners to align with the legal requirements. Such payment schemes are economic incentives to landowners to adopt conservation management practices aimed at enhancing the supply of freshwater. Besides the best management practices adopted within PWS programs, the use of nature-based systems has a great potential to safeguard water supply during the dry season and drought events. A Brazilian study found that restoring native forest vegetation in basins that contribute to the Cantareira water supply system would generate a net benefit of 69 million USD over 30 years (OZMENT et al., 2018). The Cantareira supplies water to approximately 7.2 million people in the São Paulo Metropolitan Region (SPMR), which is responsible for approximately 19% of the Brazilian Gross Domestic Product (GDP) (HADDAD; TEIXEIRA, 2015). The unprecedented drought that hit the SPMR in 2014-2015 (MELO et al., 2016; NOBRE et al., 2016) caused an estimated economic loss of 5 billion USD in 2014 (Munich Re, 2015), the fifth largest in the world by overall losses due to drought in that year.

Brazil has incorporated NbS in environmental policies but do not explicitly mention it in the National Policy on Water Resources, which provides a legal milestone in the Brazilian water resources management. Even worse, a more recent associated law enacted in 2020 (National Plan on Water Security) still relies on traditional grey infrastructure to ensure water security, lacking mechanisms to integrate water management and the environment such as NbS. Together Brazil and Indonesia could represent 50% of the world's climate mitigation potential by adopting NbS (GRISCOM et al., 2020). This is particularly critical as nearly two-thirds of climate mitigation potential in Brazil is related to avoiding deforestation (LEAVITT et al., 2021). In this context, setting aside part of lands to forest plantation (afforestation) and the integration of crop/livestock and forestry (agroforestry) are potential alternatives to improve water security while mitigating climate change impacts. Most importantly, policy-making can greatly benefit from insights and knowledge regarding public preferences for conservation measures and aspects of water security such as reduction of frequency and duration of water shortages. Brouwer et al. (2015) show that public experiences with water use restrictions significantly drive public WTP for water conservation measures, but these experiences appear to influence public attitudes differently across different countries possibly because experiences were more positive in some countries and watersheds and more negative in others. So, informing policymakers about public preference at local and country scales using non-market valuation approaches such as choice experiments is of utmost importance. Discrete choice experiment is a state preference method originally employed in the marketing and transport economics (e.g., Louviere and Hensher (1982) and Louviere and Woodworth (1983)), but it has been increasingly adopted in other fields such as the environment and agriculture.

When introducing NbS to improve water security such as (re)forestation in watersheds feeding urban areas, it is important to understand the drivers of public preferences and support for forest conservation. Existing studies in Brazil have found mixed evidence of public support for forest conservation and reforestation (BROUWER et al., 2022). Thus, public perception of NbS may significantly affect stated preferences for water security, especially together with water harvesting technologies, which are generally considered more suitable for and affordable in rainfall-rich places such as Brazil (United Nations Environmental Program, 2005). Moreover, perceptions of water security can vary across different stakeholders, highlighting the need for public elicitation. In this context, this research also contributes to addressing question 22 of the 23 unsolved problems in hydrology (BLÖSCHL et al., 2019) regarding the understanding of the trade-offs and synergies among societal interests in managing the water, food, and energy nexus while considering uncertainties associated with economic variables and climate change.

## 1.2 Problem statement, research questions and novelty

As far as it is known, this is an unprecedented study using a discrete choice experiment (DCE) to investigate public preferences for NbS, as well as how these preferences are affected by experiences with water restrictions and rationing and perceptions of NbS effectiveness. Tarfasa and Brouwer (2013) investigated public preferences for improving urban water quantity and quality, but no specific conservation measures were proposed. Public preferences for water supply improvements were also studied by Latinopoulos (2014), but no NbS were proposed. Anderson et al. (2022) contributed to our understanding on how perceptions of NbS effectiveness affect public preferences for measures in a grey-green spectrum but did not use stated preference/choice models to assess it. Others did not use either DCE or public experiences with water shortages (e.g., Tenaw and Assfaw (2022) and Wilson et al. (2021)). Here, there is interest in testing how different water shortage background conditions and public experiences with water use restrictions and rationing trigger people to invest in conservation measures in the basins supplying their cities with water. It is also aimed to test how public perceptions of NbS affect public preferences for measures to protect and conserve water-related watershed services and, hence, improve their water security. To do so, it is firstly fundamental to understand possible climate change impacts on water security and drivers of insecurity to better inform policy-making, as well as the general public. Information based on technical-scientific studies is of paramount importance to have effective policies and a society that takes better decisions. Several studies on climate change impacts on water security have been published worldwide (DAU; KUNTIYAWICHAI; ADELOYE, 2021; NATH; SCHUSTER-WALLACE; DICKSON-ANDERSON, 2022), demonstrating the relevance of such studies. Nonetheless, to the best of knowledge, this is the first study that compares future water security between two basins with different drought experiences and investments in measures to safeguard water availability. This study also provides the first assessment of water security in Campo Grande city, which will support policy and decision-making with technical-scientific information. Furthermore, few studies have assessed water security in Brazil using the new unmitigated climate change scenario from the Coupled Model Intercomparison Project phase 6 (CMIP6), the Shared Socioeconomic Pathway 3 with radiative forcing of 7.0 $Wm^{-2}$ (SSP3-7.0). This scenario fills a gap in CMIP5 forcing pathways and is of paramount importance for analyzing avertible impacts (O'NEILL et al., 2016).

Three research questions are specifically related to the aim of this thesis:

1. How vulnerable are the two main basins responsible for supplying Campo Grande and the São Paulo Metropolitan Region to climate change and what are the main drivers of water insecurity?

2. What are the public preferences for nature-based solutions aimed at enhancing water security?

3. How do different water shortage background conditions and experiences with water restrictions and rationing trigger people to invest in conservation measures?

4. What are the main motives for protesting against a payment scheme to finance nature-based solutions in the basins feeding the study cities with water?

## 1.3 Objectives

The purpose of conducting this research was to investigate, in a discrete choice experiment, public preferences for nature-based solutions to improve water supply reliability by reducing the frequency and duration of future water shortages in two cities with different water scarcity backgrounds: Campo Grande and the São Paulo Metropolitan Region. The specific objectives of this thesis are detailed below:

a) To assess future water security in Campo Grande and the São Paulo Metropolitan Region by analyzing the hydrological response to climate change scenarios of the two main basins responsible for supplying water to these cities: Guariroba and Jaguari River basins;

b) To evaluate how different water shortage background conditions and experiences with water use restrictions and rationing trigger people to invest in conservation measures;

c) To evaluate how public perception of nature-based solutions affects preferences to protect and conserve watershed services;

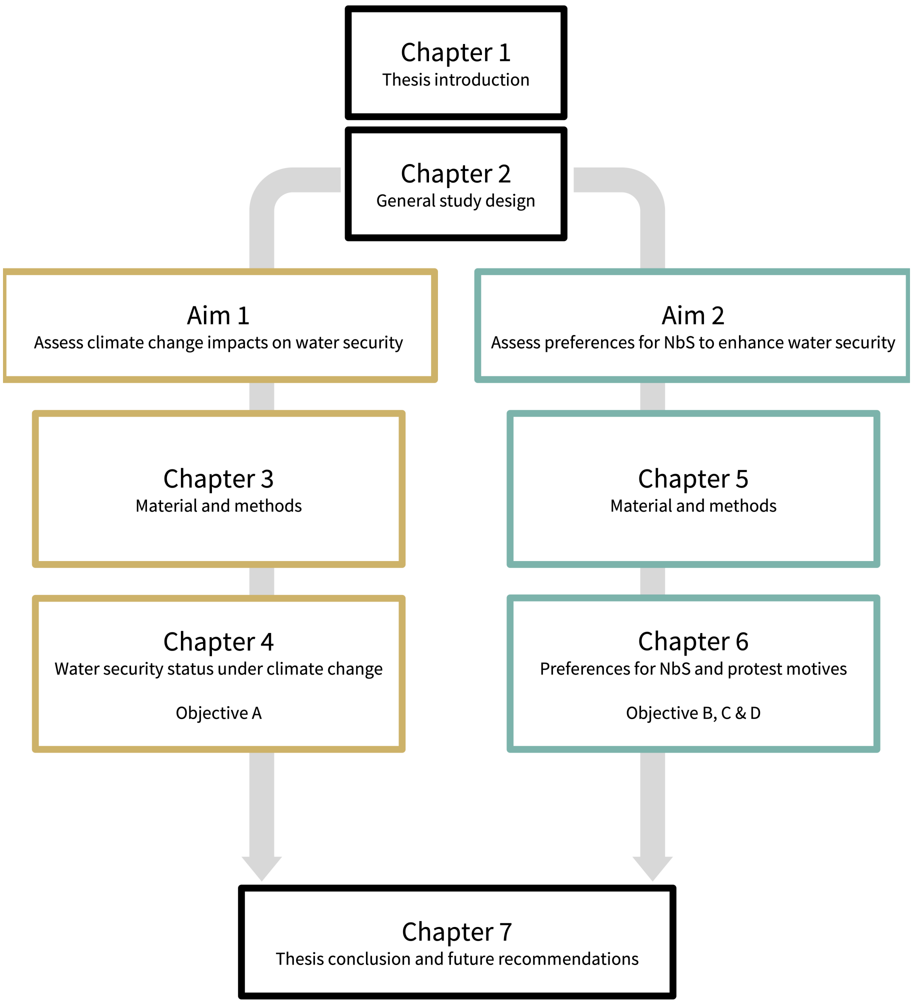
d) To assess the underlying motives of protest behavior against a payment scheme to implement conservation measures in the basins feeding the study cities with water.

## 1.4 Thesis outline

This thesis' topic was firstly introduced by laying the foundation for the subsequent research and discussion of the findings. The problem and research questions to which this work contributes were also stated. The **second chapter** is a general description and characterization of the study cities and their main respective basins, important to providing raw water. From this point, the thesis is divided into three parts: (i) water security assessment, (ii) public preferences for nature-based solutions (NbS), and the

(iii) general conclusion. **Part I** and **part II** starts with the material and methodological steps taken to fulfil this research objectives (**third and fifth chapters**). The **forth chapter** consists of the water security status under three climate change and two water demand scenarios, as well as the discussion of potential implications for water resources management under uncertainties. Water demand was contrasted with probabilistic levels of water availability to identify possible drivers. This chapter was aimed at setting a background understanding of current and future water security in the study basins to inform the policy framework proposed in the following part of this thesis. In **Part II** the **sixth chapter** focuses on unveiling public preferences, in a discrete choice experiment, for NbS to enhance water security attributes, such as a reduction in the frequency and/or duration of future shortages. In this chapter the influence of experiences with water use restrictions and rationing and expectations about their increase on public decision making were also analyzed. This chapter ends with a further investigation of the motives of protest behavior against the proposed framework to improve future water security. It is worth noting that the NbS proposed in this study was not meant to replace current grey/hard measures taken or others such as those adopted to reduce water loss in the distribution network, for example. Nature-based solutions and other green measures are complimentary and need to be implemented together with others in a way that maximize water-related ecosystem services and people's utility. The general conclusion of the carried out research is drawn in the **seventh chapter** in **Part III**. This study provides an answer to the driving questions stated in the general introduction, as well as recommendations and future research opportunities (Figure 1).

Figure 1 – Schematic diagram depicting the outline of the thesis structure and which sections are covering the stated objectives.

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# Chapter 2

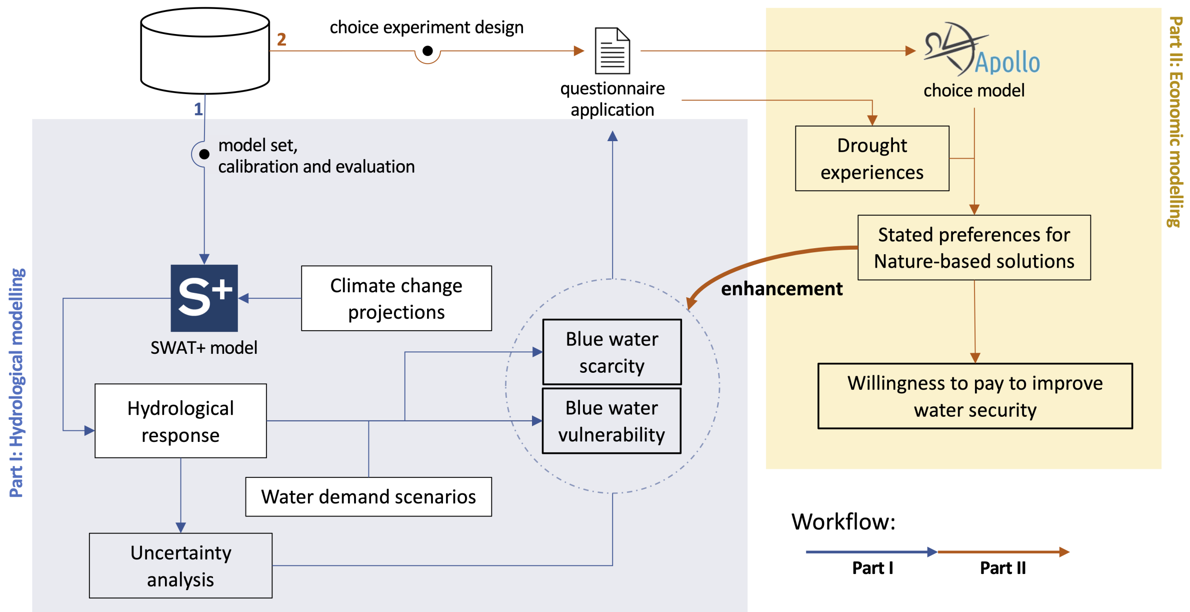
# GENERAL STUDY DESIGN

This study was carried out in two regions — Campo Grande city (CG) and the São Paulo Metropolitan region (SPMR) — where the population has had different experiences with water restrictions and rationing in the last 10 years. In 2022, the urban population living in CG (capital city of Mato Grosso do Sul) was estimated to be 898 thousand people (IBGE - Brazilian Institute of Geography and Statistics, 2023). The SPMR has an estimated population of nearly 21.5 million (Seade, 2023) distributed over 39 municipalities including the city of São Paulo (capital of the São Paulo State). Both urban areas are supplied by river basins in which they are not located. To test this thesis' hypotheses, future water security was firstly assessed by using the SWAT+ model to run the scenarios (SSPs) within the Coupled Model Intercomparison Project phase six (CMIP6) launched by the Intergovernmental Panel on Climate Change (IPCC) (further detail in Chapter 3). After better understanding climate change impacts on the main basins responsible for supply water to the two study regions, a choice experiment implemented in a questionnaire was carried out to elicit public preferences for nature-based solutions (NbS) aimed at enhancing their current water security status. For this purpose, a Mixed Multinomial Logit (MMNL) model was estimated using the Apollo package (HESS; PALMA, 2019) in R environment. Experiences with water restrictions and rationing efforts were also incorporated into the model to further understanding how people's background drives their willingness to participate in a payment scheme to improve their water security. The methodological steps taken in this thesis are depicted in Figure 2.

## 2.1 Study basins

Future water security was assessed in CG and the SPMR by simulating the hydrological response to climate change of the two most important basins for feeding their urban population with water: Guariroba and Jaguari River basins (Figura 3). The Guariroba River basin covers an area of 362 $km^2$ (560 m a.m.s.l.) and is in the rural area of the municipality of CG, entirely inserted in the Cerrado ecoregion. The Jaguari River basin

Figure 2 – General study design. The steps carried out in this study starts in Part I depicted in blue, followed by Part II in orange.

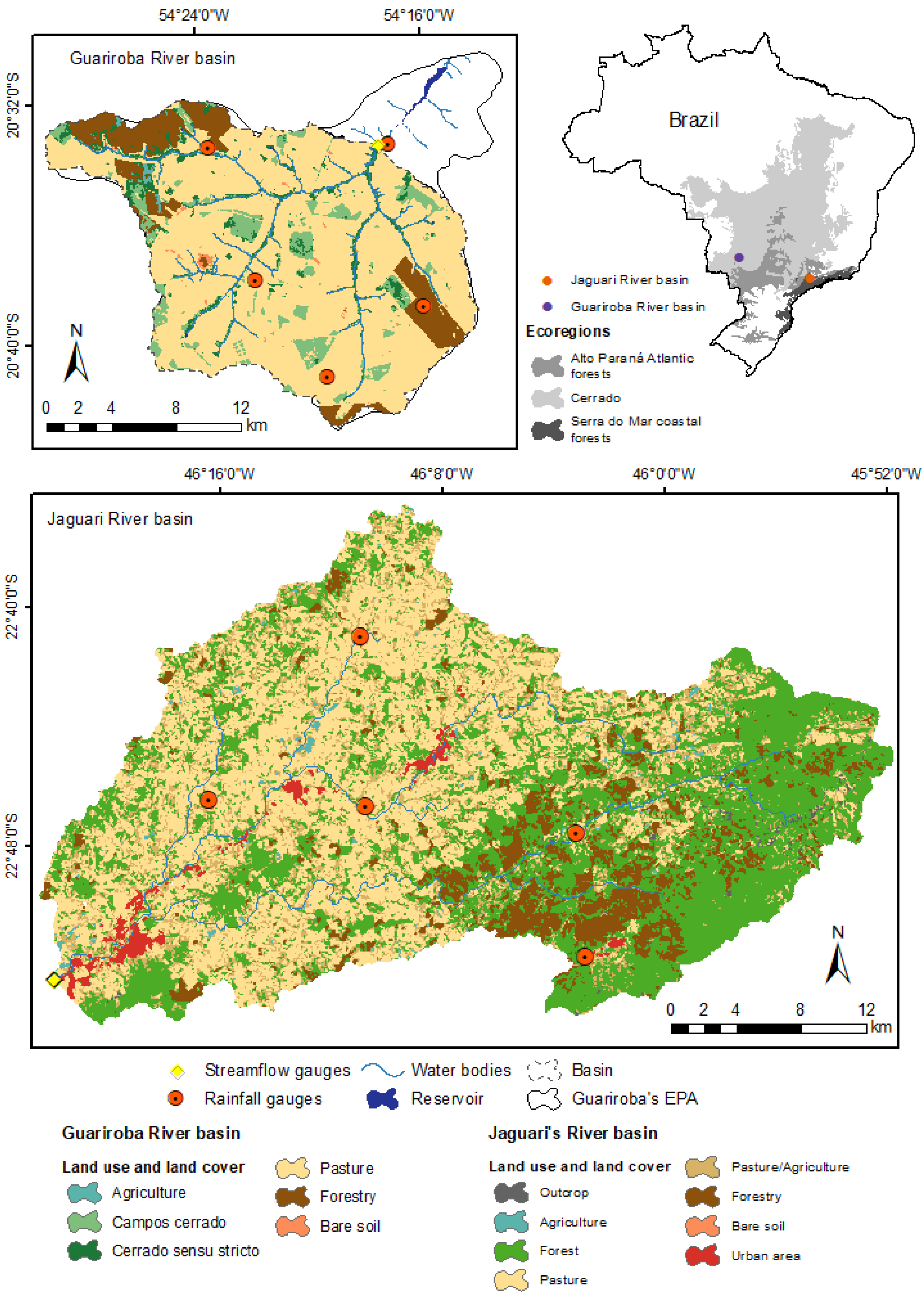



Source: Author.

(970 $km^2$, 880 m a.m.s.l.) located in the upstream portion of the Jaguari-Jacareí reservoir comprises the Alto Paraná Atlantic Forest and Serra do Mar Coastal Forest ecoregions (Figure 3). Ecoregion characterizes a unit of a distinct combination of fauna and flora (OLSON et al., 2001). The Cerrado biome spans over 24% of Brazil's territory and stands as one of the world's biodiversity hotspots. Remarkably, it nurtures 43% of the country's water springs, as highlighted by Strassburg et al. (2017). Yet, the expansion of agriculture within the Cerrado has resulted in the clearance of nearly half of its native vegetation by 2010, as pointed out by Espírito-Santo et al. (2016). Nevertheless, there remains a dearth of comprehensive studies addressing the management of ecosystem services (ES) in this biome, despite the need of the food, water, and energy nexus. This knowledge gap persists largely due to the predominant focus of research on the southeastern region, primarily the Atlantic Forest biome (PARRON et al., 2019). The Atlantic Forest biome was once one of the World's largest and most biodiverse biomes, covering about 130 million hectares. It has faced significant degradation due to centuries of extensive agricultural expansion and deforestation. Consequently, the Atlantic Forest is currently placed among the top five biodiversity and conservation hotspots globally (MYERS et al., 2000). The significance of the Atlantic Forest is not solely environmental; it also holds economic importance. The states within this biome contribute to 70% of the Gross Domestic Product (GDP) and are home to 60% of the Brazilian population (RICHARDS et al., 2015).

Both basins play a key role in water supply and are part of a program of payment for ecosystem services to protect and conserve water ecosystem services, such as water

Figure 3 – Location of the studied basins. The Guariroba River basin (362 $km^2$) is in the Cerrado ecoregion, Midwestern Brazil. The Jaguari River basin (970 $km^2$) comprises two ecoregions in South-Eastern Brazil: the Atlantic and Coastal Forests.




Source: Author.

provision and soil erosion control. On one hand, the Guariroba basin currently supplies 34% of the total water demand of the urban area of Campo Grande (Águas Guariroba, 2020). On the other hand, the studied portion of the Jaguari basin is the main water source of the Cantareira Water Supply System (about 46%) (WHATELY; CUNHA, 2007). This system supplies water for approximately 7.2 million people in the São Paulo Metropolitan Region (SPMR) (SABESP, 2021), which is responsible for 19% of the national Gross Domestic Product (GDP) (HADDAD; TEIXEIRA, 2015). High deforestation rates and poor agricultural management practices led to the deterioration of water provision (RICHARDS et al., 2015). Due to the high socioeconomic relevance of both basins, local Payment for Watershed Services (PWS) programs were implemented to encourage the adoption of best management practices and native vegetation protection through financial incentives to local farmers.

### 2.1.1 Guariroba River basin

This basin was once one of the main raw water sources in CG, supplying approximately 50% of the city's water demand. High rates of deforestation of the native Cerrado vegetation contributed to a decrease in water supply and an increase in groundwater exploitation. Currently, the basin now supplies approximately 34% of the necessary potable water to meet the demand (Águas Guariroba, 2020). In order to safeguard and preserve this water source, the basin was designated as an Area of Environmental Protection (APA, *Área de Proteção Ambiental* from Portuguese) in 1995. Subsequently, the municipality of Campo Grande launched the "Manancial Vivo" PWS program in 2009, linked to the National Water and Sanitation Agency's (ANA, *Agência Nacional de Águas e Saneamento Básico* from Portuguese) "Produtor de Águas" program. The "Manancial Vivo" offers financial incentives to rural producers within the APA for adopting soil and water conservation practices, such as terracing and restoration of Permanent Protection Areas (APPs, *Áreas de Preservação Permanente* from Portuguese).

The climate of the region is categorized as a tropical savanna with a dry winter and a humid summer, following Köppen's classification. The predominant soil classes in the basin are Quartzarenic Neosols (93.5%), Hydromorphic Neossols (3.5%), and Red Latosols (3%). The topography of the basin is primarily flat, with an average slope of 3.7%. This characteristic, coupled with the sandy texture of the Neosols, favors the process of infiltration. Junior, Rodrigues and Oliveira (2019) found high infiltration rates in the basin, leading to consequently low generation of surface runoff. In the hydrological simulation the 2018 land use/cover was used. At that time, land use in the area consisted of pasture (73.8%), native Cerrado vegetation (riparian forests, cerrado *sensu stricto*, and *cerradão*) (15.2%), silviculture (eucalyptus) (10.1%), exposed soil (0.5%), and agriculture (0.3%).

### 2.1.2 Jaguari River basin

The study focused on the upper part of the Jaguari River basin with the monitoring gauge located in Extrema city, Minas Gerais, specifically the area upstream of the Jacareí Dam. This dam receives water from the Jaguari and Jacareí Rivers and its tributary. Given its hydrologic and socioeconomic roles in both the Cantareira Water Supply System and the SPMR, the municipality of Extrema implemented a PWS program called “Conservador de Águas” back in 2005. This initiative was born out of a pressing need to address the scarcity of natural vegetation, particularly riparian forests, as well as to counteract the inappropriate soil management practices often found in agricultural areas.

The climate is characterized by dry winters and mild summers, classified as Cwb in Köppen’s classification. The prevalent soil types within the basin include Red-Yellow Latosols (74.2%), Red-Yellow Argisols (21.6%), Haplic Cambisols (3.5%), and Lithic Neosols (0.7%). As used for the Guariroba hydrological model, 2018 land use encompassed pasture (36.9%), native Atlantic Forest vegetation (36.8%), a transitional zone between pasture and agriculture (15.1%, mosaics), silviculture (pine and eucalyptus) (8.8%), urban areas (1.4%), agriculture (0.7%), and exposed soil (0.1%).

# Part I

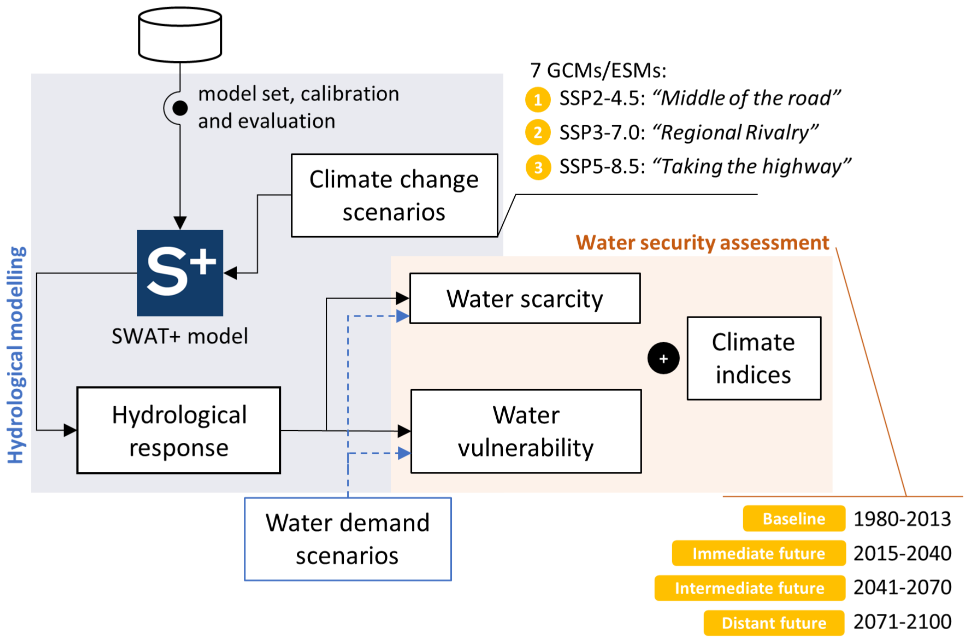
# Water security under climate change

# Chapter 3

# Material and methods: assessing water security

In this chapter, the methodology adopted to assess future water security is described in detail. This evaluation was based on the simulation of the basins' hydrological response to three future climate change projections forced by three pathways in the Scenario Model Intercomparison Project (ScenarioMIP) within the CMIP6. Projected streamflow was simulated by using the SWAT+ model to analyse water scarcity risk and vulnerability to not meeting future water demands. These analyses were supported by projected drought indices that directly affect water security and consumption behavior: (i) consecutive dry days (CDD) and (ii) the standardized precipitation-evapotranspiration index (SPEI). The following diagram (Figure 4) illustrates the main methodological steps.

Figure 4 – Study design for Part I of this thesis.

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## 3.1 Hydrological modelling

The semi-distributed physically-based SWAT+ model (revision 59.3) — Soil and Water Assessment Tool Plus (BIEGER et al., 2017) — was used to simulate the streamflow response to projected climate change scenarios by using the QSWAT+ (version 1.2.2) plugin, implemented in QGIS 3.4.11 (QGIS Development Team, 2019). The SWAT+ model is a restructured version of the Soil and Water Assessment Tool (SWAT) (ARNOLD; SRINIVASAN; WILLIAMS, 1998), which is used worldwide in hydrological studies (GASSMAN et al., 2007) on impacts of land use and land cover change on surface runoff, sediment yield, and water quality at a basin level. The SWAT+ makes spatial representation and hydrological processes more flexible by introducing the landscape units (LSU), which separate the lowland from the upland processes. The water balance drives all hydrological processes in the model (Equation 3.1), and water storage takes place through the soil layers and shallow and deep aquifers.

$$WB_f = WB_i + \sum (P_j - R_j - ET_j - D_j - RF_j) \times \Delta t \tag{3.1}$$

where $WB_f$ and $WB_i$ are respectively the final and initial soil water content (mm d$^{-1}$), and $P_j$, $R_j$, $ET_j$, $D_j$ and $RF_j$ are respectively the amount of rainfall, surface runoff, evapotranspiration, percolation, and return flow volume in mm d$^{-1}$.

SWAT+ simulations are constructed by dividing sub-basins into lumped hydrologic response units (HRUs), which consist of a homogeneous combination of land use, soil, and slope features (BIEGER et al., 2017; GASSMAN et al., 2007). The HRUs was delineated by using a percent of landscape unit threshold of 20% for land use, 10% for soil order, and 10% for slope according to Jha (2011) recommendations. The first threshold defines the minimum area of determined land use within a HRU; the minimum occurrence of soil and slope classes within each HRU are then set by the second and third thresholds, respectively. The HRUs that do not meet these minimal percentages are ignored and then reapportioned among the retained areas within each landscape by re-sampling until the threshold are reached. In this study, this procedure resulted in 376 and 467 HRUs in Guariroba and Jaguari basins, respectively.

Observed and remote sensing data (climatic and physiographic) were used to set up the models for both basins such as digital elevation model (DEM), vegetation cover, and meteorological and hydrological time series (Tables 7 and 8 in Appendix A). Additionally, gaps in observed precipitation data in both basins were filled using the Xavier's dataset (XAVIER; KING; SCANLON, 2016) until the end of 2015 (last year with available data); gaps starting from January 2016 were filled using ERA5 (HERSBACH et al., 2020). The baseflow recession constant, a groundwater parameter, was estimated using the *Baseflow filter* software (ARNOLD; ALLEN, 1999). For soil properties, pedo-transfer functions were adopted based on organic carbon, texture, and soil layer depth (SAXTON; RAWLS, 2006). The surface runoff was simulated by adopting the SCS Curve Number method (CN) as a function of antecedent soil moisture condition on a daily basis for both basins. Additionally, evapotranspiration process was estimated by using the Penman-Monteith equation (MONTEITH, 1965).

Prior to calibration, an automated global sensitivity analysis was carried out using the SWATCUP+ software (SWAT+ Calibration and Uncertainty Analysis Program, version 1.0.0), which regresses the Latin Hypercube generated parameters against the objective function values and the p-value is used to identify the significance of each parameter. Based on the sensitivity analysis, five and 11 streamflow-related parameters were respectively selected for the Guariroba and Jaguari basins (Tables 1 and 2). The lateral flow travel time (LAT_TTIME), slope length for lateral subsurface flow (LAT_LEN), percolation coefficient (PERCO), and the soil hydraulic conductivity (K) were the most sensitive parameters for both basins ($p\text{-}value < 0.05$). Seven parameters for the Guariroba basin and five for the Jaguari basin were also manually calibrated (Tables 1 and 2) to correspond to observed soil and land use classes, such as the maximum canopy index (CANMX) and the soil evaporation compensation factor (ESCO) (RODRIGUES; GUPTA; MENDIONDO, 2014; GLAVAN; PINTAR; VOLK, 2013).

The hydrological response of the Guariroba basin was simulated from 2011 to 2019, which the first year (2011) was used as model warm-up. The calibration period covered the most undisturbed condition from January 2015 to June 2019, and the evaluation period was from January 2012 to December 2014. For the Jaguari basin, the simulation of the hydrological response from 1991 to 2008 was used for model calibration and evaluation. The model warm-up was performed during the previous year (1990); the calibration period was from January 1991 to December 2000, and the evaluation period was from January 2001 to November 2008. The chosen parameters were automatic calibrated using the SWAT parameter estimator (SPE) available in the SWATCUP+ software, except the manually calibrated parameters that were set constant. The SPE, formerly SUFI-2 (ABBASPOUR; JOHNSON; GENUCHTEN, 2004; ABBASPOUR et al., 2007), allows multi-objective and behavioural optimizations combining stochastic calibration and uncertainty analysis.

Table 1 – Streamflow-related parameter default values, calibration changes and the parameters' uncertainty range for the Guariroba basin.

| SWAT+ parameter | Description | Default value | Calibrated value | Uncertainty range |
|---|---|---|---|---|
| ESCO | Soil evaporation compensation factor is the capacity of the model to extract the evaporative demand from soil layers | 0.950 | 0.400[a] | - |
| CANMX | Maximum canopy index is the maximum amount of water that can be trapped in the vegetation canopy (mm) | 1 | 25[a] | - |
| **LAT_TTIME** | Lateral flow travel time (day) | 0 | 2.759 | 1.865 – 3.368 |
| **LAT_LEN** | Slope length for lateral subsurface flow (m) | Varies by topography | Δ -23.16% | Δ -26.58 – 10.06% |
| SURLAG | Surface runoff lag coefficient lags a portion of the surface runoff release to the main channel (day) | 4 | 1[a] | - |
| **PERCO** | Percolation coefficient adjusts soil moisture for percolation to occur | 1 | 0.99 | 0.98 – 1 |
| EPCO | Plant water uptake compensation factor | 1 | 0.392 | 0.270 – 0.460 |
| ALPHA_BF | Baseflow recession constant (day) | 0.048 | 0.002[a] | - |
| RCHG_DP | Fraction of water percolation to deep aquifer | 0.05 | 0.01[a] | - |
| FLO_MIN | Water table depth for return flow to occur (m) | 5 | 8[a] | - |
| REVAP_MIN | Water table depth for "revap" or percolation to deep aquifer to occur (m) | 3 | 1[a] | - |
| **K** | Soil hydraulic conductivity (mm $h^{-1}$) | Varies by soil | Δ +157.83% | Δ 150.87 – 186.18% |

Note: [a] Parameters values manually changed from their default values. Parameters in bold were the most sensitive

Table 2 – Streamflow-related parameter default values, calibration changes and the parameters' uncertainty range for the Jaguari basin.

| SWAT+ parameter | Description | Default value | Calibrated value | Uncertainty range |
|---|---|---|---|---|
| ESCO | Soil evaporation compensation factor is the capacity of the model to extract the evaporative demand from soil layers | 0.950 | 0.750[a] | - |
| **CN2** | SCS runoff curve number for average moisture condition | Varies by vegetation | Δ +13.16% | Δ -10 – 35.49% |
| CANMX | Maximum canopy index is the maximum amount of water that can be trapped in the vegetation canopy (mm) | 1 | 15[a] | - |
| **LAT_TTIME** | Lateral flow travel time (day) | 0 | 173.84 | 100 – 180 |
| OVN | Manning's value for overland flow | Varies by vegetation | Δ +14.12% | Δ 6.22 – 43.29% |
| **LAT_LEN** | Slope length for lateral subsurface flow (m) | Varies by topography | Δ -5.30% | Δ -42.19 – 15% |
| **SLOPE** | Average slope steepness (m $m^{-1}$) | Varies by topography | Δ 2.96% | Δ -25 – 15% |
| SURLAG | Surface runoff lag coefficient lags a portion of the surface runoff release to the main channel (day) | 4 | 0.086[a] | - |
| **PERCO** | Percolation coefficient adjusts soil moisture for percolation to occur | 1 | 0.962 | 0.85 – 0.99 |
| ALPHA_BF | Baseflow recession constant (day) | 0.048 | 0.038[a] | - |
| REVAP | Groundwater "revap" coefficient regulates the water movement from the shallow aquifer to the root zone due to moisture deficit | 0.02 | 0.065 | 0.02 – 0.20 |
| RCHG_DP | Fraction of water percolation to deep aquifer | 0.05 | 0.100[a] | - |
| FLO_MIN | Water table depth for return flow to occur (m) | 5 | 4.204 | 4 – 8 |
| REVAP_MIN | Water table depth for "revap" or percolation to deep aquifer to occur (m) | 3 | 4.805 | 0 – 5 |
| **K** | Soil hydraulic conductivity (mm $h^{-1}$) | Varies by soil | Δ +87.39% | Δ 76.27 – 137.04% |
| Z | Soil depth | Varies by soil | Δ -6.68 | Δ -20 – 20% |

Note: [a] Parameters values manually changed from their default values. Parameters in bold were the most sensitive

The calibration and evaluation periods were analysed using the Pearson correlation coefficient (r), Kling-Gupta efficiency (KGE, Gupta et al. (2009)) — as the objective function — and the percent bias statistic (PBIAS, Gupta, Sorooshian and Yapo (1999)) (Figures 5 and 6). Model performance in the calibration and evaluation periods for both basins was satisfactory with Pearson's correlation exceeding 0.70. Values of KGE also indicated a relatively high correlation between observations and model simulations mainly for the Jaguari basin. The lower model's performance for the Guariroba basin — measured by KGE — corroborate the low *a-priori* expectation for this basin.The expected lower performance of the Guariroba's model may be due to the large number of gaps in observed precipitation data, which were filled with reanalysis data. Observed streamflow also exhibited considerable periods with missing data (Figure 5), which can have negative impacts in the calibration process.

Uncertainty in parameters is expressed as band and accounts for uncertainty in driving variables, conceptual model, parameters, and measured data. Uncertainty is quantified by the 95% prediction uncertainty (95PPU), calculated based on the propagation of the parameter uncertainties (2.5 and 97.5% percentiles) by using Latin Hypercube sampling. The generated uncertainty band was evaluated based on the percentage of observed data covered (p-factor) and its wideness (r-factor). Despite no hard values of these factors exist, values of a p-factor > 70% and an r-factor close to one are recommended (ABBASPOUR; JOHNSON; GENUCHTEN, 2004; ABBASPOUR et al., 2007). These scores indicate that most of the observations were captured in a small uncertainty envelop.

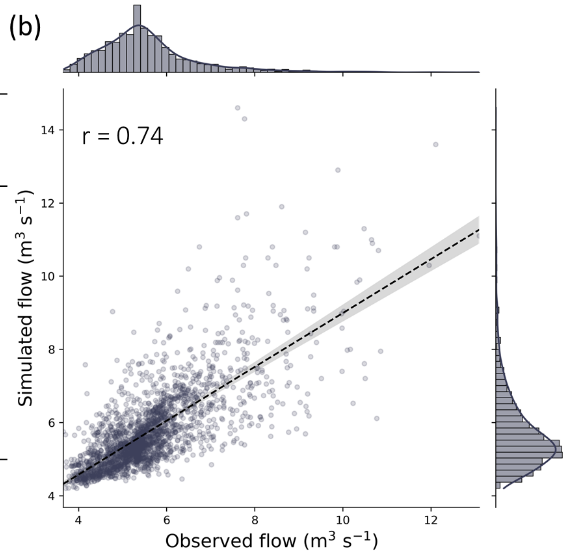
## 3.2 Future water security

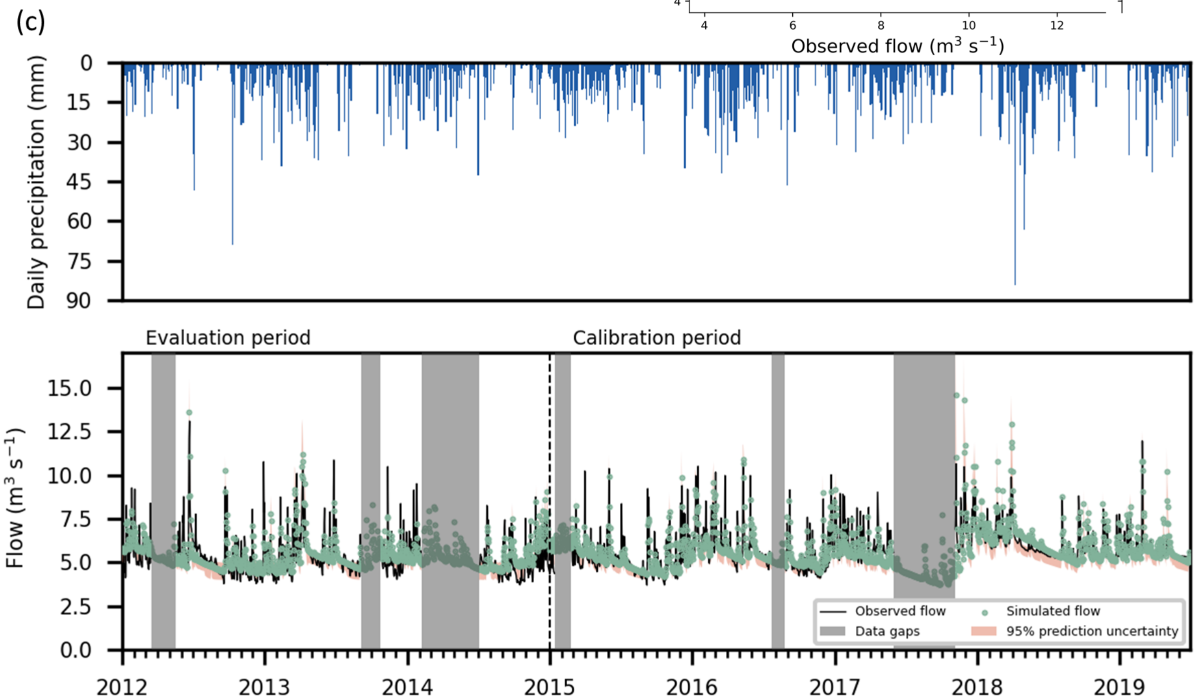
To assess future climate change impacts on water security by 2100, the basins' hydrological response to three climate projections was simulated using an ensemble mean over seven General Circulation/Earth System Models (GCMs/ESMs, variant ID r1i1p1f1) (Appendix B). The GCMs/ESMs were selected based on the availability of the climate variables required to run the SWAT+ model and a nominal resolution up to 100 km. The selected climate models are part of the Coupled Model Intercomparison Project phase 6 (CMIP6) (EYRING et al., 2016) within the Intergovernmental Panel on Climate Change (IPCC). Three Shared Socioeconomic Pathways (SSPs) (O'NEILL et al., 2016) were considered: (i) middle of the road scenario (SSP2-4.5, updated RCP4.5 pathway), (ii) regional rivalry scenario (SSP3-7.0), and (iii) fossil-fuelled development scenario (SSP5-8.5, updated RCP8.5 pathway) (see detailed description in Appendix B). The impacts of those scenarios were analysed considering the immediate (2015-2040), the intermediate (2041-2070), and the distant future (2071-2100).

Figure 5 – Observed and simulated daily streamflow during the calibration and evaluation periods (plot c) for the Guariroba River basin, as well as the correlation coefficient (plot b) and other metrics (plot a).

(a)

| Metrics | Calibration (2015-2019) | Evaluation (2012-2014) |
|---|---|---|
| KGE | 0.72 | 0.68 |
| PBias (%) | -2.31 | -3.40 |
| p-factor | 0.87 | 0.75 |
| r-factor | 0.77 | 0.74 |



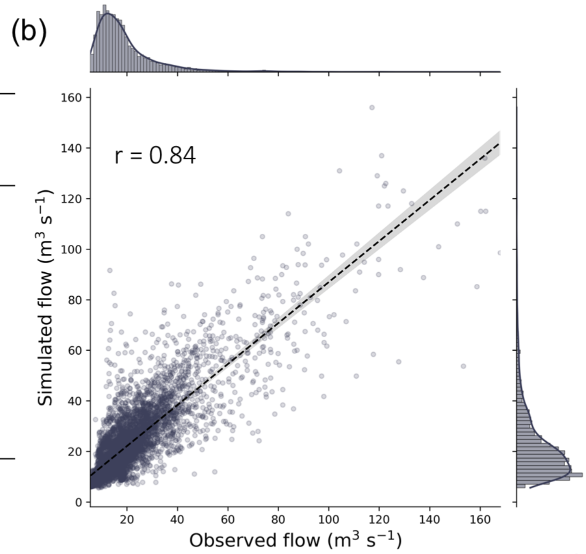



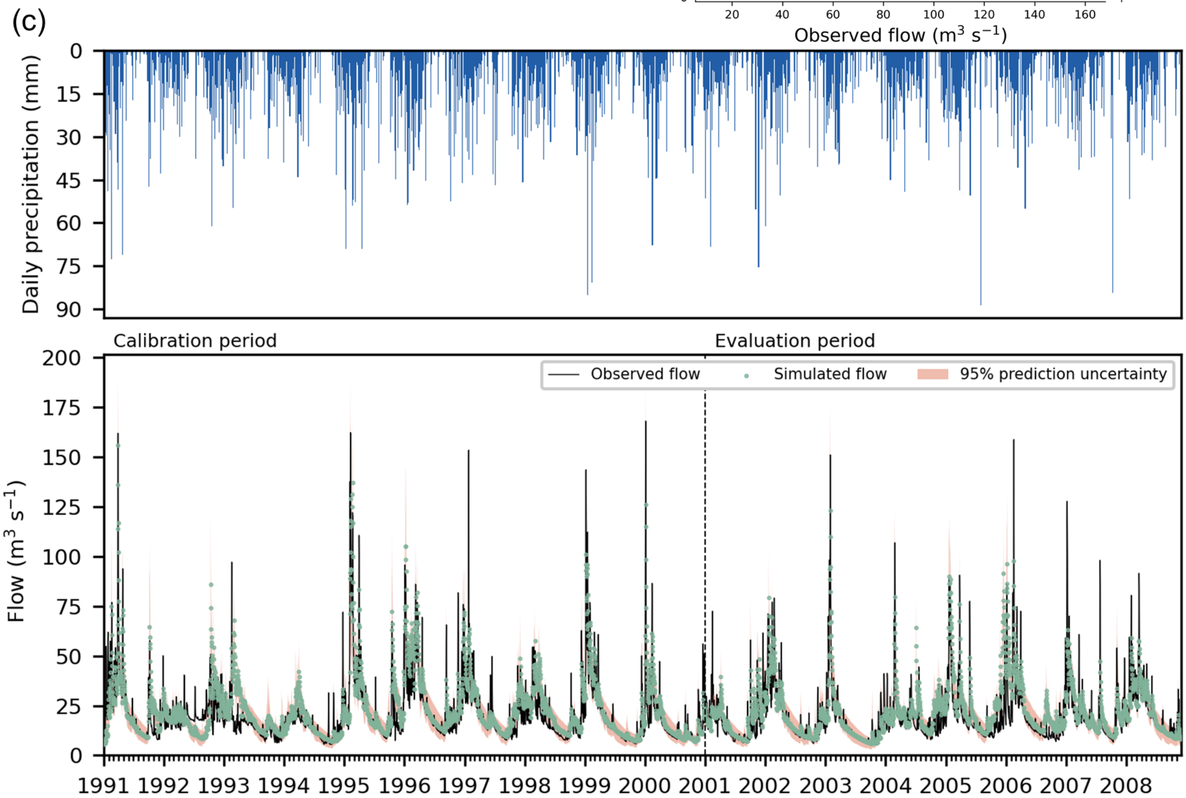

Note: KGE is the Kling-Gupta Efficiency, PBias is percent bias, p- and r-factor are the percentage of observed data enveloped by the 95% prediction uncertainty and the thickness of this envelop, respectively. The Pearson correlation (r) is provided in plot (b). Source: Author.

Figure 6 – Observed and simulated daily streamflow during the calibration and evaluation periods (plot c) for the Jaguari River basin, as well as the correlation coefficient (plot b) and other metrics (plot a).

(a)

| Metrics | Calibration (1991-2000) | Evaluation (2001-2008) |
|---|---|---|
| KGE | 0.83 | 0.77 |
| PBias (%) | -10.08 | -10.59 |
| p-factor | 0.80 | 0.79 |
| r-factor | 0.91 | 0.88 |




Note: KGE is the Kling-Gupta Efficiency, PBias is percent bias, p- and r-factor are the percentage of observed data enveloped by the 95% prediction uncertainty and the thickness of this envelop, respectively. The Pearson correlation (r) is provided in plot (b). Source: Author.

Since the seven CMIP6 models have different spatial resolutions, a first order conservative remapping was performed to regrid the model outputs to a common resolution of 2° x 1.5° for the ensemble construction. A multimodel ensemble outperforms any individual model by reflecting uncertainties inherent to climate models (DHAKAL;

KAKANI; LINDE, 2018; GLECKLER; TAYLOR; DOUTRIAUX, 2008). Nonetheless, further bias correction is required for regional studies to translate large-scale GCMs/ESMs to more representative scales. In this context, maintaining projected trends of future scenarios is still a challenge. Thus, the quantile delta mapping (QDM, Cannon, Sobie and Murdock (2015)) was employed to correct possible remaining systematic biases relative to observations in the historical baseline period (1980 to 2013). This method is based on quantile delta change (WILLEMS; VRAC, 2011; OLSSON et al., 2009) and detrended quantile mapping (BÜRGER et al., 2013). Firstly, the ensemble was further regrided to match the observed dataset of Xavier, King and Scanlon (2016) (0.25° x 0.25°), and future quantiles from the multimodel ensemble outputs were detrended. Then, the quantile mapping was applied to the detrended series, and the projected trends in quantiles were reintroduced (details on the technique is in Cannon, Sobie and Murdock (2015)).

To examine the performance of the bias-corrected multimodel ensemble in simulating historical observations, the root-mean-square error (RMSE), overall percent bias (PBIAS), and mean squared error skill score ($SS_{mse}$, Wilks (2011)) were adopted. Skill scores are relative accuracy measures and were calculated using the MSE as the underlying accuracy statistics:

$$SS_{mse} = 1 - \frac{MSE_{ens}}{MSE_{clim}} \tag{3.2}$$

where $MSE_{ens}$ is the mean square error of the bias-corrected ensemble relative to the observed data (from Xavier, King and Scanlon (2016)) and $MSE_{clim}$ is the observations' variance of climatology of the current climatological standard normal period (1981–2010) (WMO - World Meteorological Organization, 2017), calculated as:

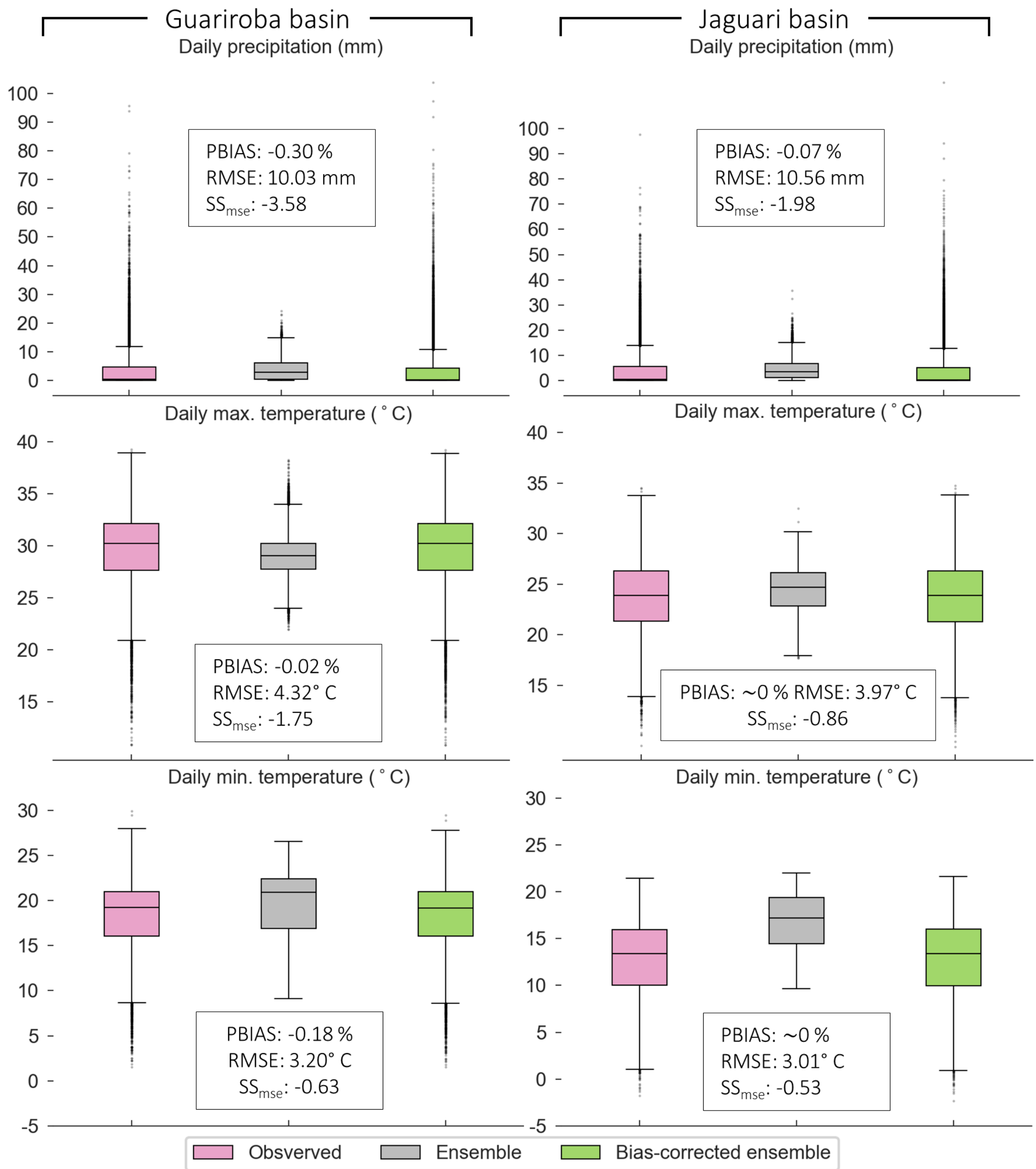
$$MSE_{clim} = (\frac{n}{n-1})^2 \times \frac{1}{n}\sum_{i=1}^{n}(x_{i,j} - \overline{x_j})^2 \tag{3.3}$$

where $x$ is monthly observations $i$ from period $j$ and $\overline{x}$ is long-term monthly mean considering all years in period $j$.

Prior to bias correction, the multimodel ensemble underestimated historical observations, poorly simulating extremes (Figure 7). Mainly for precipitation, the simulations from the ensemble alone failed to represent maximum extremes. It highlights the paramount importance of further bias correction in regional/local studies. After bias correction, the ensemble presented the same interquartile as the observed data, with similar maximum and minimum extremes. The corrected ensemble's mean square error ($MSE_{ens}$) presented slightly high deviation from the climatological variance ($MSE_{clim}$), exhibiting negative skill scores ($SS_{mse}$) for all variables as shown in Figure 7 (statistics measures for the other variables is presented in the Appendix B). For both basins, precipitation presented a worse skill score and, therefore, greater variability than the observed variance of climatology.

This variable is one of the main drivers of hydrological simulations and may account for a significant part of modelling uncertainty and bias. Possible uncertainties stemmed from the climate change projections were further discussed in the Discussion section. The climate scenarios for each variable are also presented in the Appendix B.

Figure 7 – Distribution of the projected precipitation and maximum and minimum temperature for the Guariroba and Jaguari basins, contrasting the historical periods of observed, multimodel ensemble, and bias-corrected ensemble. The metrics relate the observed (XAVIER; KING; SCANLON, 2016) and corrected ensemble's historical data.




Source: Author.

The baseline (1980 – 2013) and future water security (2015 – 2100) were assessed using the blue water scarcity and vulnerability indices proposed by Rodrigues, Gupta and Mendiondo (2014). The water-based framework contrasts the consumptive water uses with probabilistic levels of water provision. The water scarcity index (BW-Scarcity, Equation 3.4) indicates the impact of consumptive water uses on the median water availability while the water vulnerability index (BW-Vulnerability, Equation 3.5) expresses the possibility of water abstraction under drought conditions. Vulnerable time periods are represented by indices greater than 1, which indicates low water provision that drops below the minimum water required to meet water demand:

$$BW\text{-}scarcity = \frac{BW\text{-}footprint_{(x,t)}}{BW\text{-}provision_{(x,t)}(P_{50})} \tag{3.4}$$

$$BW\text{-}vulnerability = \frac{BW\text{-}abstraction_{(x,t)}}{BW\text{-}provision_{(x,t)}(P_{30})} \tag{3.5}$$

where BW-footprint represents the consumptive water use ($m^3$ $s^{-1}$) for human activities at the monitoring gauge of each basin and month of the year, and BW-abstraction corresponds to the sum of water permits for abstraction upstream the monitoring gauge stations ($m^3$ $s^{-1}$). Current consumptive water uses and permits were provided by the Institute of the Environment of Mato Grosso do Sul (IMASUL) and the Jaguari's water resources management plan (Consórcio Profill-Rhama, 2020a); $P_{50}$ and $P_{30}$ are respectively the 50th and 30th percentiles of BW-provision, computed as:

$$BW\text{-}provision = Q - EFR \tag{3.6}$$

where Q is the mean monthly streamflow in the Guariroba and Jaguari River ($m^3$ $s^{-1}$), and EFR is the fraction of streamflow maintained to meet the Environment Flow Requirements ($m^3$ $s^{-1}$). The Q95 an 7Q10 were considered as the EFR for the Guariroba and Jaguari basins, respectively. These low flow parameters are adopted by the states in which those basins are located.

Three future water demand scenarios were analyzed to assess the combined effects of climate change and strategies of water resources management in the basins: (i) increasing demand, (ii) current demand, and (iii) decreasing demand. The increasing demand illustrates a progressive growth in water demand of 40% by 2040, 50% by 2070, and 60% by 2100 from the basins' current demand. On the other hand, the decreasing demand represent a progressive reduction in water demand of 10% by 2040, 20% by 2070, and 30% by 2100 also from their current demand. In the current demand, water demand was considered as stable with insignificant variations throughout the future periods.

## 3.3 Drought indices

To support the analysis, two drought indices were computed for the baseline and future periods: consecutive dry days (CDD) (TANK; ZWIERS; ZHANG, 2009) and the standardized precipitation-evapotranspiration index (SPEI) (VICENTE-SERRANO; BEGUERÍA; LÓPEZ-MORENO, 2010). These indices are important for correlating the water security indices — based on the balance between water availability and demand — with the meteorological impacts — e.g., temperature — on water use and consumption during a drought situation. The CDD accounts for the maximum length of a dry spell, that is, consecutive days where precipitation is less than 1 mm. Higher number of consecutive dry days can affect ecosystem functioning, directly impacting water provision. The SPEI advances the standardized precipitation index (SPI) by including temperature to the calculation through a water balance between precipitation and potential evapotranspiration (PET). The PET was calculated using the Penman-Monteith method (MONTEITH, 1965). A threshold value of -1.5 was adopted according to the World Meteorological Organization (2012) for severely to extremely dry events ($-2 \leq$ SPEI $\leq -1.5$). Both indices were calculated at 1-month timescale.

# Chapter 4

# Water security in an uncertain future[1]

Assessing climate change impacts on water resources is often related to some aspect of water security as water quantity and quality are the key variables that motivate scientific research and public policies. Thus, future water security was assessed in two basins of paramount importance for urban water supply in Campo Grande (CG) and the São Paulo Metropolitan Region (SPMR): Guariroba and Jaguari River basins respectively (Figure 3. There are many studies in the Jaguari River basin (GESUALDO et al., 2019; DEUSDARÁ-LEAL et al., 2020; TAFFARELLO et al., 2016), mainly after the 2014/2015 water crisis that led to severe water restrictions and rationing in the SPMR (almost Day-Zero). In contrast, any study related to water security in the Guariroba basin was found, undermining decision making and policies to tackle climate change and safeguard water supply.

Here, the results of the water security assessment in the study basins are presented and their implications further discussed for the supplied cities. Scarcity and vulnerability indices higher than 1 respectively indicate that the median (50th percentile) and minimum water provision (30th percentile) does not meet the water demand. By analysing these two indices, periods that are more susceptible to water conflicts between different water sectors can be identified, such as the water supply. The indices computed for the future period (2015-2100) are contrasted with those for baseline (1980-2013) to evaluate the changes in water security due to climate change. Comparisons with the historical simulations from climate models during the baseline period is key to identify projected changes and trends. Following the next section, the water security results for each climate pathway considering the current and future water demand scenarios are shown. The standardized

[1] A modified version of this chapter has been published as: SONE, J. S.; ARAUJO, T. F.; GESUALDO, G. C.; BALLARIN, A. S.; CARVALHO, G. A.; OLIVEIRA, P. T. S.; WENDLAND, E. C. Water security in an uncertain future: contrasting realities from an availability-demand perspective. Water Resources Management, Springer, 2022. Disponível em: <https://link.springer.com/10.1007/s11269-022-03160-x>

precipitation-evapotranspiration index (SPEI) and the consecutive dry days (CDD) were also used for supporting the findings, as well as identifying possible drivers of water insecurity.

## 4.1 Historical and projected water security

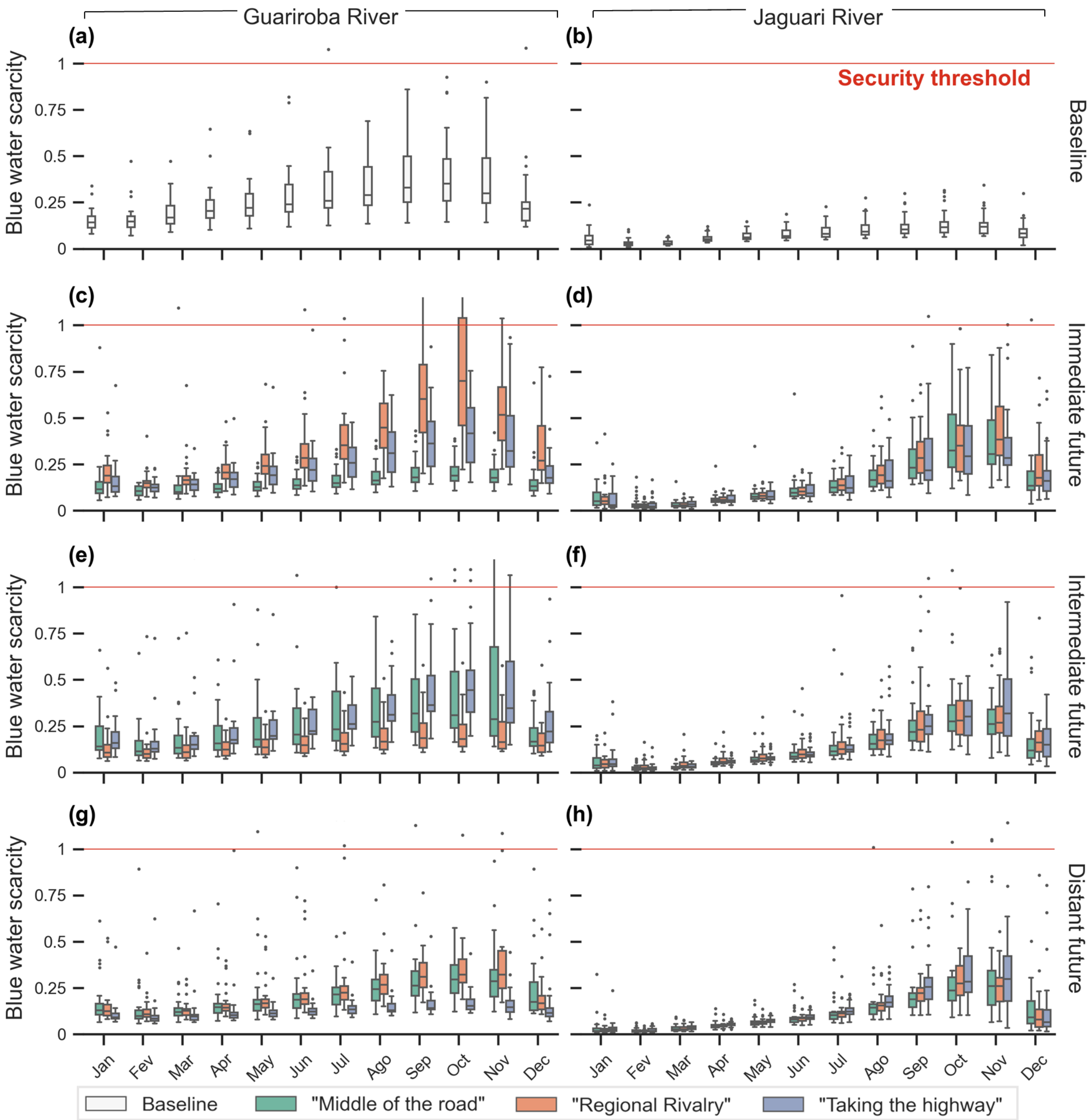
The scarcity and vulnerability indicators for the Jaguari and Guariroba basins presented a greater increase from the historical to future simulations (Figures 8 a,b and 19 a,b in the Appendix C). Water scarcity and vulnerability patterns are very alike, demonstrating that months with a higher risk of water scarcity are also those with greater vulnerability. As the current demand was considered for all evaluated scenarios, the increase in water insecurity mainly in the immediate and intermediate periods was due to a reduction of water provision rather than an increase in demand. Water availability was possibly affected by the projected decrease in the future precipitation during the rainy season from December to March (Figures 15 and 17 in the Appendix B). The water security indices indicate that this reduction in water availability was sharper in the Jaguari River from baseline to future periods. Moreover, evapotranspiration driving variables — e.g., net solar radiation and temperature — is expected to increase during the dry season (June to September) in the future periods, despite the projected increase in precipitation in these months. It is important to note that the water balance drives all hydrological processes in the SWAT+ model; therefore, precipitation and evapotranspiration play a major role in the simulation of hydrological response, detailed in the discussion section.

In all future periods, the climate change scenarios resulted in very similar monthly streamflow rates to the baseline for both basins (Figures 20 and 23 in the Appendix C). Conversely, an increase in extreme events of maximum streamflow was observed mainly in the SSP3-7.0 abd SSP5-8.5 scenarios during the rainy season. The monthly precipitation amount however tended to reduce in this period. Extreme events of minimum streamflow also showed a tendency to increase considering all scenarios during the dry season, mainly in the Guariroba basin. In the Jaguari basin, extremes of maximum monthly streamflow rates were prone to increase at the end of the century. Different from the findings of Gesualdo et al. (2019), changes in the distribution of the monthly streamflow rates were not noted in the Jaguari River; the highest streamflow rates occurred in February in the baseline and future periods for both basins. This is further elaborated in the discussion section.

### 4.1.1 Future water security under climate and water demand scenarios

The scarcity and vulnerability indicators in all climate projections showed higher insecurity levels from July to November (Figures 8 and 19 in the Appendix C), with the highest level in November in the Jaguari basin. Overall, the middle of the road and regional

Figure 8 – Water scarcity index considering the current water demand under three climate change scenarios (SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5 in light purple) over three evaluation periods: baseline (1980-2013), immediate future (2015-2040), intermediate future (2041-2070), and distant future (2071-2100). The red line indicates the security threshold over which characterizes median water provision below the required water demand. The immediate future is the most critical period, mainly under the SSP3-7.0 in both basins.



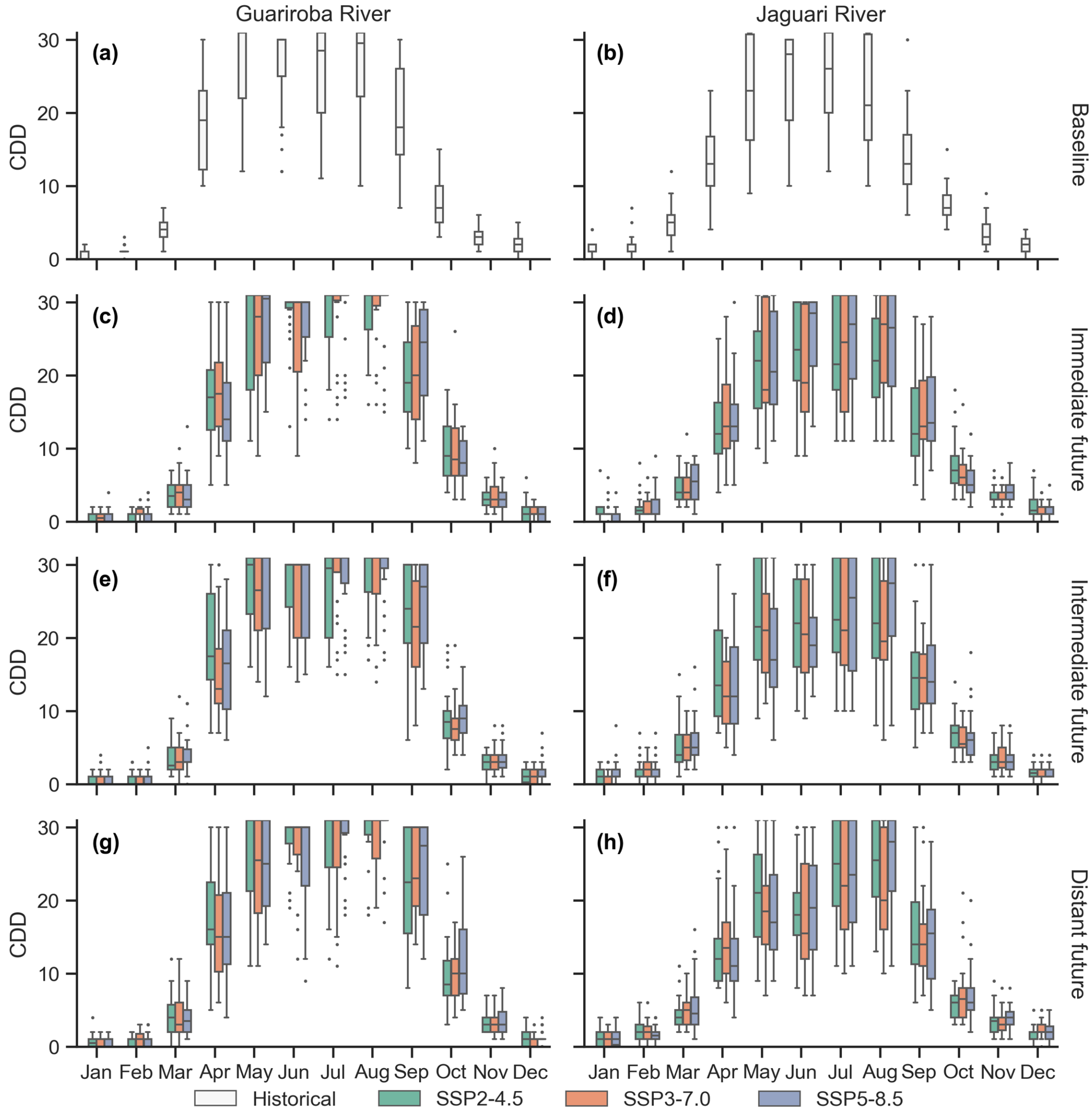

Source: Author.

rivalry scenarios (SSP2-4.5 and SSP3-7.0) for the Jaguari basin presented a similar pattern in the three future periods. The most pessimistic scenario — fossil-fuelled development (SSP5-8.5) — tended to present higher water insecurity in the intermediate and distant future periods (2041-2100). Nevertheless, possible severe drought events in the SSP2-4.5 and SSP3-7.0 were noted by the presence of outliers, which also represent a risk of future water shortages in these two climate pathways. On the other hand, the Guariroba River presented the worst levels of scarcity and vulnerability in the immediate future (2015–2040), considering the Regional Rivalry scenario. By the intermediate period, this and the most optimistic scenario presented similar median values. The water security indices tended to reduce by the end of the century in all climate scenarios in the Guariroba basin. In this period, median values were very similar to those from the baseline period, especially the SSP5-8.5 with lower indices.

The immediate and intermediate future periods (2015-2070) presented more critical indices and require special attention to the levels of water insecurity in both basins. Besides the current water demand, two alternative scenarios with progressive increase and decrease in water demand were also considered. As expected, future water security under the increasing water demand exacerbates the scarcity risk and vulnerability, mainly in the most critical months (i.e., dry season). With an increase of 60% in demand by 2100, October and November presented indices close or beyond the security threshold mainly under the SSP2-4.5 and SSP3-7.0 for the Guariroba River and the SSP5-8.5 for the Jaguari basin (Figures 21, 22, 24, and 25 in the Appendix C). It is worth noting that a decrease of 20% in demand did not suffice for improving water security in the intermediate periods.

The climate indices provided another perspective of meteorological conditions besides the hydrological response of the basins. Despite the observed decrease in the precipitation amount from December to March, median CDD during the summer (December-March) in both basins were very similar to those in the baseline period (Figure 9). Moreover, the distribution of CDD was very similar among the climate change scenarios during the summer. The Guariroba and Jaguari presented median consecutive dry days (CDD) of more than 20 days from May to August in the future periods, similar to historical simulation. In median terms, the SSP2-4.5 and the historical simulations were very alike for both basins. Nevertheless, shorter and longer CDD were respectively observed in the first and last months of the dry season considering the SSP5-8.5 for both basins. In the dry season, interquartile range and/or whiskers are narrower in the future periods for the Guariroba basin. Especially in the beginning (March-April) and ending of the dry season (October-November), whiskers are wider for both basins suggesting more uncertainty and increased risk of dry spells in these months. Mainly during August-September, CDD are longer in the more pessimistic climate scenario.

Figure 9 – Maximum consecutive number of days without rain (< 1 mm day$^{-1}$) within a month (CDD) over the baseline (1980-2013) and future periods: immediate (2015-2040), intermediate (2041-2070), and distant future (2071-2100). The CDD was computed considering three climate projections: SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5in light purple.




Source: Author.

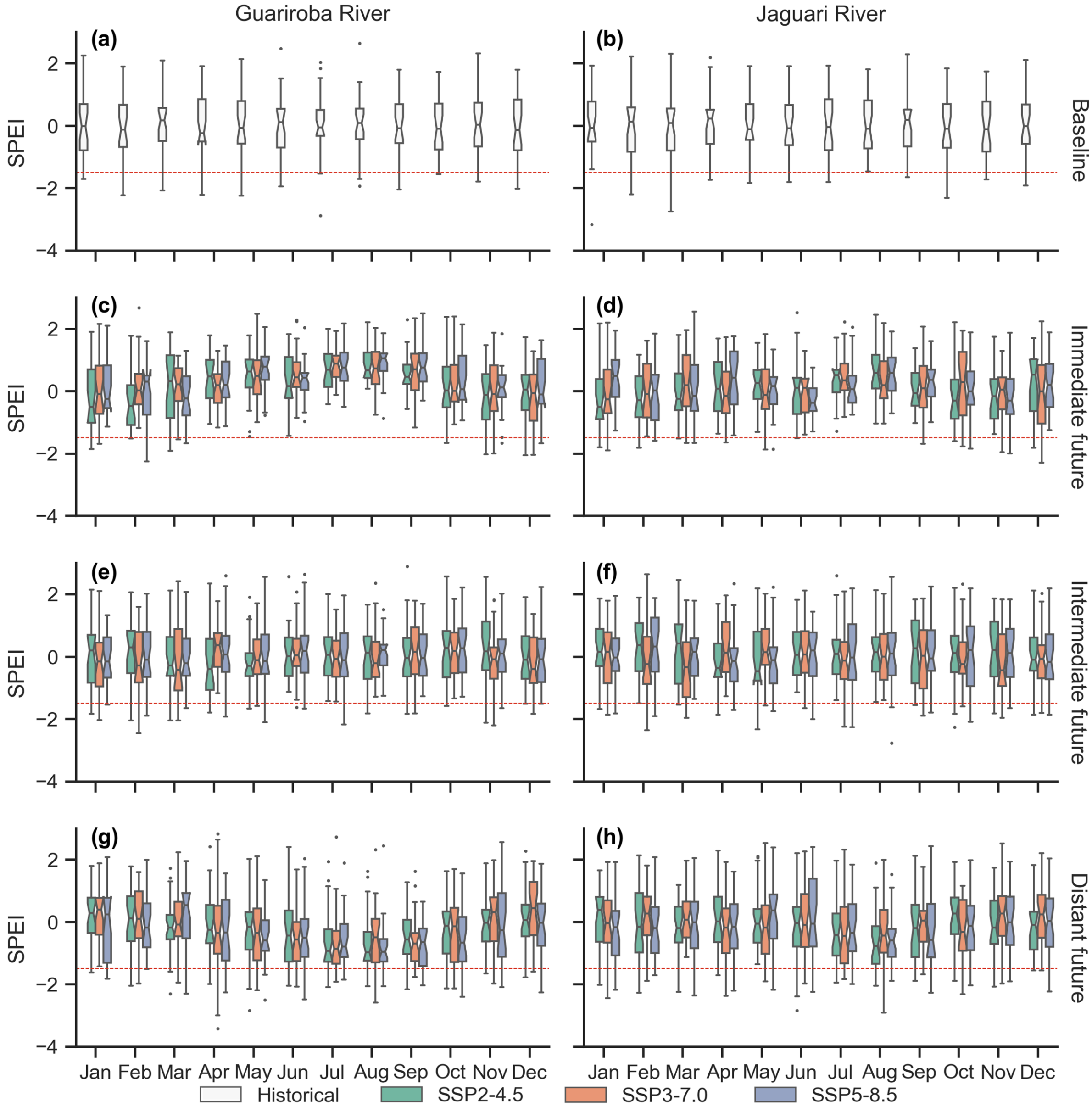
The study basins presented similar patterns of the standardized precipitation-evapotranspiration index (SPEI) throughout the future periods. A slight positive anomaly was noted during the dry season and a negative anomaly during the rainy season in the basins during the immediate future (Figure 10), corroborating the projected increase and decrease in precipitation during the dry and rainy seasons, respectively. The dry and rainy months also tend to become drier and wetter by 2100. The median SPEI values in the intermediate period is similar to baseline, with interquartile around near normal dry condition (-1 < SPEI < 1). By the end of the century, the basins are prone to face more severe droughts, with lower interquartile (25th) close to the threshold, even though an improvement in the water security indices from the immediate to the distant future was noted. Specifically in the Jaguari basin, interquartile range and whiskers are wider, corroborating the CDD index and suggesting more uncertainty in the distant future. The scarcity and vulnerability indicators are related to the basins' hydrological response and demand while those climate indices are strictly linked to climate variability. In the next section, the possible influence of the climate on water security, not captured by the water security indices, is discussed.

## 4.2 Discussion

The water security indices were computed considering the water demand upstream the reservoirs that provide water to supply part of the Campo Grande (CG) city and the São Paulo Metropolitan Region (SPMR). These cities already rely on interbasin water transfer to secure their water demand as they are not located in the study basins. Therefore, the scarcity and vulnerability indices unveil the susceptibility of their population to facing even more severe future water shortages as critical periods were identified without considering their demand. Mainly during the immediate and intermediate future, those indices were near or surpassed the security threshold during the dry season. The observed higher risk of water scarcity during these periods corroborates the experienced water rationing and restrictions by the aforementioned cities. The SPMR faced a severe drought period from 2013 to 2014 (MARENGO et al., 2015; NOBRE et al., 2016). This vulnerability frame is also observed in CG, in which people from at least 43 neighbourhoods faced water rationing during a dry spell in 2019 (G1, 2019), which also occurred in 2016. Water security in the Guariroba basin is particularly vulnerable due to a lack of studies and public monitoring and recording of past drought events that triggered restrictions and rationing efforts in CG. For instance, water resources experts from the Brazilian Academy of Sciences held authorities liable for a lack of transparency during the 2014/2015 drought in the Southeast region (BICUDO et al., 2015).

The Guariroba basin exhibited the worst water security indices by considering the current demand in the baseline period. This finding highlights the delicate balance between water availability and demand in this basin. Furthermore, this result indicates not only this imbalance but also a poor management of water permits to efficiently regulate water abstractions. Both basins currently have about 22% of their environmental flow requirement (EFR) compromised with water demand upstream the reservoir. The lower monthly water provision (monthly streamflow minus EFR) of the Guariroba River contributed to the highest scarcity and vulnerability indices in the future periods; the average Guariroba's streamflow fluctuates around its EFR (Q95) (Figure 5 and 20). This fact imposes challenges to always have available water to meet the demand while maintaining the EFR. Therefore,

Figure 10 – The precipitation-Evapotranspiration Index (SPEI) considers accumulated anomalies of precipitation and potential evapotranspiration in each month over the baseline (1980-2013) and future periods: immediate (2015-2040), intermediate (2041-2070), and distant future (2071-2100). The SPEI was computed considering three climate projections: SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5in light purple. The dotted red line indicates a threshold value of -1.5, below which represents severely to extremely dry conditions.




Source: Author.

Guariroba's streamflow is at a great risk of violating the adopted EFR mainly during the drier months. This basin may undergo extreme drought events, especially by the end of the dry season (September-October), as represented by outliers below the lower whisker in Figure 20 (Appendix C). November already presented this vulnerability in the baseline simulations, so droughts may become more severe and extended, lasting longer.

Risk of water scarcity and vulnerability in both basins substantially increased by moving from the baseline to future periods, despite maintaining current water demand. This increase in water insecurity was due to a reduction in water provision, possibly triggered by a reduction of total monthly precipitation and an increase of maximum and minimum temperatures. In both basins, the projected increase in monthly precipitation during the dry season did not contribute to minimizing water scarcity risk and vulnerability during those months in the future scenarios. This shows rainfall seasonality might become more significant and distribution more heterogeneous, as also found by Almazroui et al. (2021). This increase during the dry season may be related to the bias correction applied even though the quantile delta mapping approach is less prone to inflate relative trends in precipitation. Cannon, Sobie and Murdock (2015) found an inflation of 1.2 times the raw GCM signal. Nevertheless, the fact that this higher amount of precipitation did not substantially improve water security indices during the dry season can be explained by analysing the other meteorological variables. Solar radiation and temperature also increased from the immediate to distant future periods, mainly during the dry season (Figures 16 and 18 in Appendix B). It consequently increases evapotranspiration rates. During the months with low precipitation, evapotranspiration is typically limited by the water stored in the more superficial soil layers (BUDYKO, 1974). By that, evaporation can be further exacerbated with the increase in solar radiation and can able to extract the evaporative demand from deeper soil layers.

The dimensions of water security permeate not only availability and demand, but also other variables that determine consumption patterns and alter hydrological fluxes. In the distant future, all climate scenarios suggested better water security indices compared with the other future periods (Figures 8g,h and 19g,h) even though the SPEI suggested that the dry season is becoming severely drier in both basins (lower interquartile closer to the threshold in Figure 10g,h). This finding may be related to the timescale at which the SPEI was computed. One-month SPEI better characterizes meteorological droughts and, consequently, has less impact on the hydrological response of the basins. With longer CDD and severely drier climate indicated by SPEI, the tendency of increased monthly precipitation during the dry season indicates more concentrated rainfall events separated by longer dry days (precipitation $< 1$ mm). Marengo et al. (2020b) drew a similar inference for the SPMR by finding an increase in extreme precipitation (from R20 to R100 mm) and also in CDD. Longer CDD and negative SPEI as 2100 approaches suggest more severe droughts during the dry season along with days with higher temperatures, increasing water demand and, consequently, exacerbating possible water crises. For example, a record maximum temperature registered in SPMR worsened the 2014/201 water crises (NOBRE et al., 2016).

Besides the technical and scientific information provided, it is worth noting the associated cascade uncertainties, of which each methodological step introduced its share. In the Material and Methods section the uncertainties from the calibration and validation of the hydrological models and from the construction and bias correction of the multimodel ensemble are discussed. Parameters of the hydrological models were calibrated based on the available observed data (e.g., streamflow, precipitation, and land use and cover), but confidence in model calibration on past observations is still a concern for climate change projections (VAZE et al., 2010; CORON et al., 2012; HUANG et al., 2020). Furthermore, the seven-model ensemble — selected to meet the requirements needed to conduct this research — has a limitation in size; therefore, future studies using more CMIP6 models are strongly encouraged as new models are expected to be launched. The selected climate models may also be related to differences found between the findings of Gesualdo et al. (2019) and this thesis. Those authors used an ensemble of 17 CMIP5 models, different from those used in this study (except the Norwegian model NorESM2, adopted in both studies). A larger ensemble composed by different models can offset changes with different sign and magnitude. A country-scale study is also of paramount importance to assess differences between CMIP5 and CMIP6 simulations of climate variables. Despite using the CMIP5 models, the study of Gesualdo et al. (2019) simulated the climate change impacts on water security using a conceptual model, which may also generate different hydrological response (DUETHMANN; BLÖSCHL; PARAJKA, 2020) hindering a robust comparison between studies.

### 4.2.1 Water management under climate uncertainties

Adaptive management is key to build a resilient water system to natural hydro-climatic variability, expected to be extended in the future. Climate change adaptation is not the only goal of water resources management, but also adaptation to non climate-related pressures in a particular water system (KUNDZEWICZ et al., 2008), such as high water withdrawals. In Brazil, EFRs, mainly Q95 and 7Q10, are instruments used to issue water permits and, therefore, regulate and manage water demands across water bodies in a basin. The already observed changes in frequency and distribution of climate extremes worldwide (PAPALEXIOU; MONTANARI, 2019) have weakened the use of historical series to determine a minimum required flow. Climate change challenges the stationarity assumption on which decision makers rely to manage water resources. Thus, a non-stationary probabilistic approach should be adopted to reduce risks and uncertainties in water resources planning and management (MILLY et al., 2008). Therefore, issuing water permits that reflect the current changes in annual and seasonal water flows is of utmost importance for improving and ensuring water security. A violation of EFRs threats the adequate functioning of ecosystems, shrinking the provision of water-related ecosystem services. In this context, implementing structural measures will not suffice to meet water demand, as learned from Korea's experience (LEE et al., 2022).

The dry season should be the core of water resources management to improve and guarantee water security. During this period, streamflow generally fluctuates around the EFR, increasing the risk of water shortages. In this case, there would not be enough water available to meet CG and the SPMR's water demand, considering that water withdrawals upstream the reservoir already corresponds to 20% of the EFRs. This challenging situation requires alternative conservation measures such as water harvesting technologies (VEMA et al., 2022) and nature-based solutions. Ozment et al. (2018) found that restoring native forest vegetation in the basins that contribute to the Cantareira system would generate a net benefit of 69 million USD over 30 years. Future research can also provide evidence of how land use and cover changes can impact water security and how best management practices can contribute to improve water security.

Water security transcends managing available water and how to equitably distribute it; it is inextricably linked to managing people, economy, and land use and land cover, requiring holistic management. Humans are an active part of this society-ecosystems nexus, but synergies (building resilience) and trade-offs (increasing vulnerability) of that interaction is still a challenge (FOLKE, 2006). To manage water under climate and non climate-related uncertainties, transdisciplinary collaboration (CUNDILL; CURRIE-ALDER; LEONE, 2019) and political will (DIELE-VIEGAS; HIPÓLITO; FERRANTE, 2021) are fundamental. In this context, water management in the Jaguari basin seems more robust, making the water system responsible to supply the SPMR more resilient than the one responsible to supply CG. The Guariroba basin lacks a more detailed and factual water plan for a better management, with diagnosis and prognosis that support future planning. The Jaguari's management plan, for instance, provides clear goals to improve water security based on water availability and demand projections (Consórcio Profill-Rhama, 2020a; Consórcio Profill-Rhama, 2020b), while the management plan for the Guariroba basin provides a defective diagnosis (Prefeitura Municipal de Campo Grande; Águas Guariroba S/A, 2008) hindering the improvement of water security inside and beyond its boundaries.

A sociohydrological drought currently hits Brazil. Apparently, the drought that hit the Brazilian Southeast and Midwest in 2014 still persists. Naumann et al. (2021) found that precipitation is below the 1981-2010 average in the last five years (2016-2021) near the Cantareira system. This study and others (NASA Earth Observatory, 2021; ANA - National Water and Basic Sanitation Agency, 2021) identified a multi-annual drought since 2019 in the whole Paraná River basin, which comprises the studied basins. The prolonged impacts of the hydrological droughts started in 2014 have impacted the society and economy by causing dust bowls (Phys.org, 2021; G1, 2021b), episodes of water rationing, restrictions and disruptions (G1, 2021a; The New York Times, 2021), and reduced agricultural yield (GETIRANA; LIBONATI; CATALDI, 2021). Additionally, soil moisture in the Paraná basin is extremely low due to below-average rainfall in the last years (NAUMANN et al., 2021; MELO et al., 2016). Soil water content is the largest reservoir able to maintain water flow during the season with low precipitation (e.g., (LOON; HUIJGEVOORT; LANEN, 2012)) and, therefore, the supply for human activities and ecosystem functioning. Yet, this variable is often neglected or underestimated in water budget studies, mainly due to a lack of ground-based data.

## 4.3 Summary and conclusions

Here, the impacts of three climate change and water demand scenarios on water security of two distinct basins in Brazil were investigated: Guariroba and Jaguari River basins. They are strategical for the water supply system of Campo Grande e the São Paulo Metropolitan Region. The assessment of their future water security allowed us to identify water security drivers despite their differences in climate and water demand. Higher vulnerability and water scarcity risk are expected in the immediate (2015-2040) and intermediate future (2041-2070) as a projected decrease in water availability was observed during these periods. The findings of this study indicate that water insecurity stems from an imbalance between water availability and demand, mainly in the Guariroba River basin. Even considering a reduction scenario of 20% in water demand, both basins presented critical vulnerability levels in the immediate and intermediate future. It reveals the urgent need for effective measures to tackle the water availability-demand imbalance, possibly exacerbated in the future.

The months with higher susceptibility to water shortages in both basins were from September to November considering the current demand in the baseline period. It indicates a weakness in meeting the basins' demand with the historical water availability during the dry season. From the baseline to the future periods, a significant increase in water scarcity risk and vulnerability was noted due to a reduction in water provision, mainly in the Jaguari River basin. The climate indices support the hypothesis of more intense and concentrated rainfall (i.e., heavy rainfall events separated by longer dry days).

How projected climate change scenarios impact the hydrological fluxes at a basin scale and what probably triggered those changes from the climate perspective were demonstrated. Recent opposing extreme weather episodes (e.g., drought in the Midwest and Southeast while flooding in the North region) brings up the need of building a water system for anticipation, preparedness, and resilience. Besides, the use of natural systems can be adopted to improve water security mainly during the dry season. Further studies will contribute to better understand the impacts of nature-based solutions on water security and public preferences and willingness to pay for them.

## 4.4 Data availability

The data used in this study, which includes the multimodel ensemble and projected streamflow, are available at the Zenodo repository. These data are also part of the first effort to build a national dataset that allow for climate change studies in Brazil. Part of the data available at the Zenodo repository also composes part of the Climate Change Dataset for Brazil (CLIMBra, Ballarin et al. (2023)), which consist of an ensemble of 19 bias-corrected CMIP6 projections based on the SSP2-4.5 and SSP5-8.5 scenarios. CLIMBra paves the way for the development of high-quality research on climate change-related impacts on several study fields in Brazil.

# Part II

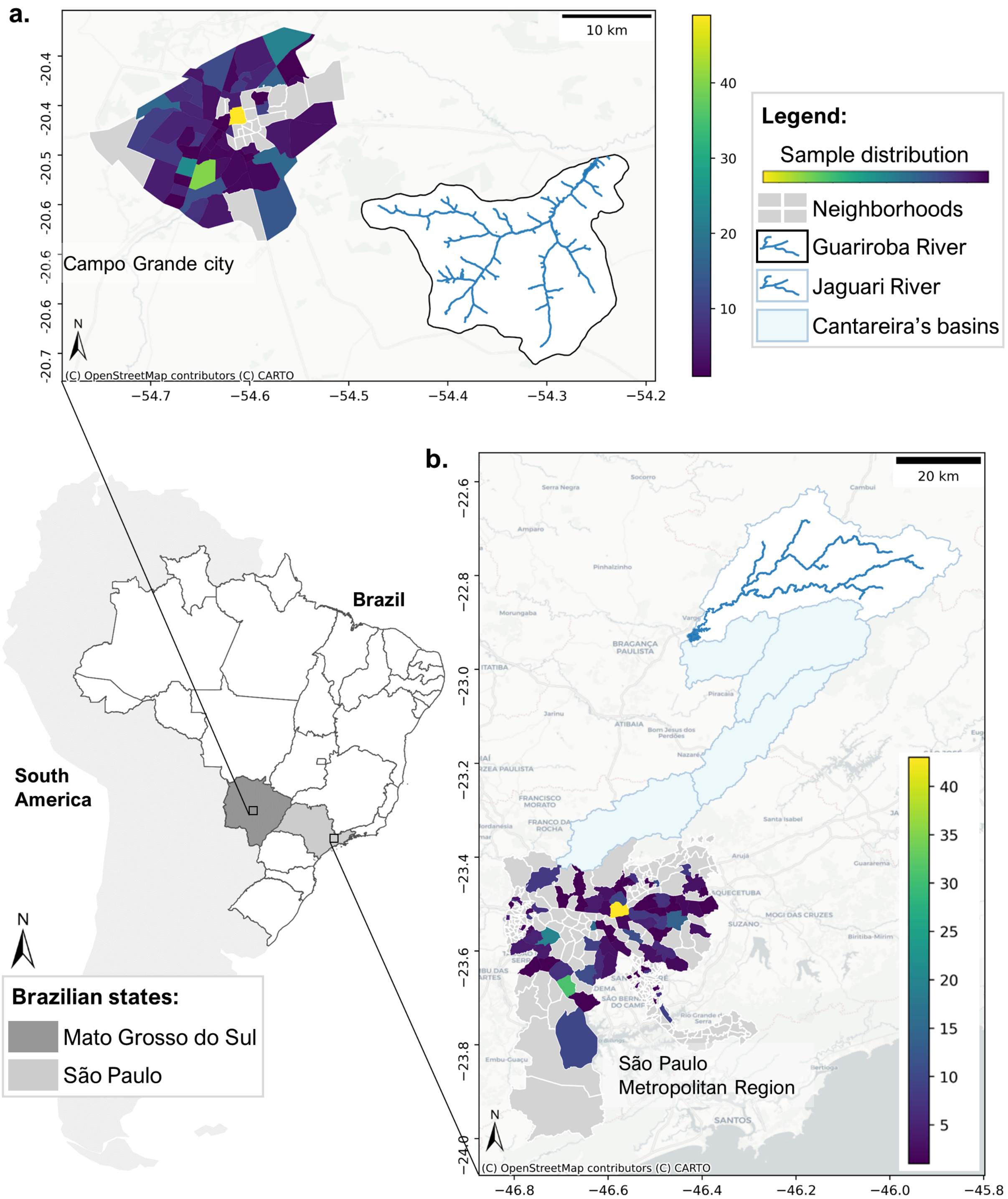
# Willingness to improve water security

# Chapter 5

# Material and methods: assessing preferences for measures to improve water security

A field survey was conducted in Campo Grande city (CG) and the São Paulo Metropolitan Region (SPMR) in November 2021. A total of 870 people were interviewed through the random street-intercept method by a specialized company. As described in detail in Chapter 2 and highlighted in Chapter 4, these two cities have experienced different levels of water use restrictions and rationing over the last years, and this is why they are particularly interesting for the scope of this study. Here, water use restrictions are considered as limitations to water availability in terms of volume and/or time when it can be used while rationing is understood as a temporary suspension of water supply. Eight hundred valid responses were obtained (400 in each study site, Figure 11), a no response rate of 9%. In the SPMR, the four main cities supplied by the Cantareira water supply system were the focus: São Paulo, Guarulhos, Osasco, and Santo André. Pedestrians were randomly selected as they passed by the interviewer to answer the questions in the questionnaire. The respondents consist of residents in the urban area of the cities under study and connected to the public water supply system. Before implementing the main survey, the questionnaire was pretested using a sample of 25 respondents in the city of São Paulo, using the same random street-intercept procedure. The pretest resulted in a limited number of modifications of the questions and improvements in the discrete choice experiment (DCE) design. Respondents were asked to confirm their consent in participating in the survey by signing a consent form (Appendix D) before answering the questions. All survey research protocols were reviewed and approved by the Brazilian Research Ethics Board (approval no. 5113450).

Figure 11 – Survey map with the sample distribution and the location of the study sites and the main water supply basins: Campo Grande city and the Guariroba River basin (plot a) and the São Paulo Metropolitan Region and the Jaguari River basin (plot b).




Source: Author.

To help minimize bias and ensure representativeness, gender and household income were used as control measures. The 2010 Brazilian census (IBGE - Brazilian Institute of Geography and Statistics, 2011) was adopted as a reference for statistical information.

## 5.1 Discrete choice experiment design

A questionnaire was designed to investigate willingness of CG and the SPMR's residents to pay (WTP) for conservation measures, as well as their experiences with past drought events. The questionnaire was divided into four parts: (i) respondents' general water use characteristics, (ii) their water shortage experiences, (iii) their WTP for water conservation measures, and (iv) their sociodemographic background characteristics. The first section included questions about household water consumption and drinking water sources. The second section contained attitudinal questions about water-saving measures and questions about water shortage experiences such as past water use restrictions and rationing episodes. In the third part, a discrete choice experiment (DCE) was developed to test whether the respondents are willing to pay for the implementation of conservation measures to improve their future water security. The last section collected information about, among others, respondents' age, education level, household composition and income. The final version of the questionnaire can be found in the Appendix E.

A choice experiment is a stated preference method to estimate public preferences for new products, technologies, or policy programs (LOUVIERE; HENSHER, 1982; LOUVIERE; WOODWORTH, 1983). In this part, it is aimed to elicit public preferences for specific measures to be implemented over a time horizon of 10 years to reduce the frequency of future water shortages and the duration of future water supply interruptions. Thus, the good on offer, for which respondents were asked to pay, was improved water supply reliability or water security through the implementation of nature-based solutions (i.e., agroforestry and water harvesting) and water harvesting (structural measure) in the river basins feeding the cities under study. To financially support the necessary investments in these specific measures and guarantee the public benefits from improved water security, respondents were informed that an extra monthly payment on top of their household water bill would be required for the next 10 years. It was also emphasized that they could choose the *status quo* alternative (current situation), and doing it would imply no extra costs; consequently, no new measures would be implemented in the basins to ensure their future water security.

The alternative scenarios were composed of four attributes (Table 3) differing in the level of (i) future water shortages frequency on average, (ii) how long future water supply interruption will last on average, (iii) water conservation measures to be implemented in the basins, and (iv) additional charge on households monthly water bill. To create unique hypothetical alternatives, these four attribute levels were arranged using a Bayesian D-efficient design (SÁNDOR; WEDEL, 2001) as the respondents are not able to answer all possible combinations (i.e., a full factorial design). Optimal designs maximize the expected Fisher information, which depends on the parameters of the multinomial logit model (MNL, McFadden (1974)) for the case of this study. A Bayesian efficient design allows the specification of a prior preference distribution to reduce the sensitivity related to the accuracy of the guess of the true parameters before conducting the experiment. In this study, *a-priori* information gathered from the pretest of the entire questionnaire was used to estimate a simple MNL model. As mentioned, the pretest was carried out in the SPMR and yielded 100 observations from the 25 individuals interviewed. The parameters estimated by the MNL model ($\beta$s) were used to specify an appropriate prior distribution and therefore minimize the $D_B$-error. The final optimal design was generated using the modified Fedorov algorithm, an adaptation of the classical Fedorov exchange algorithm (FEDOROV, 1972). This algorithm swaps alternatives from an initial design with candidate alternatives to minimize the $D_B$-error. The routine and algorithms are implemented in the *idefix* package (TRAETS; SANCHEZ; VANDEBROEK, 2020), which was used in R environment.

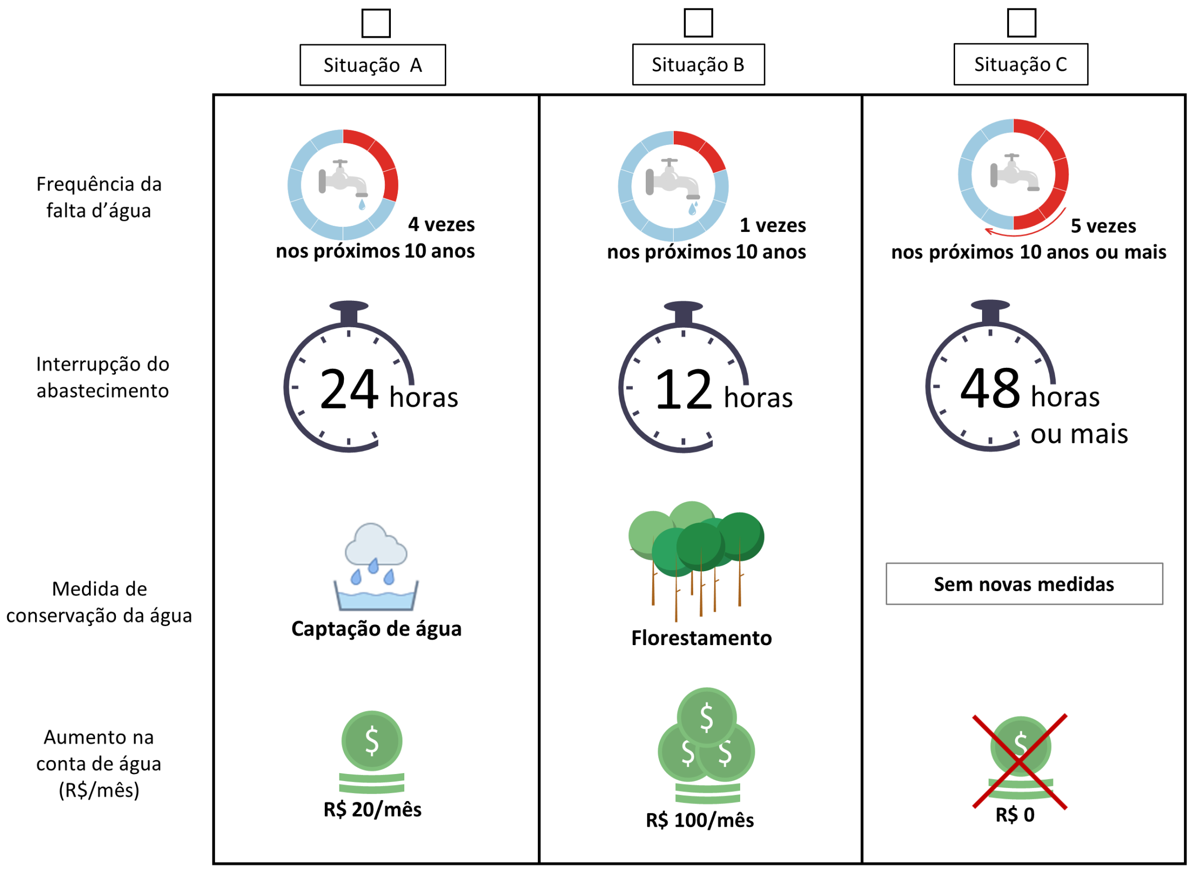
Table 3 – Description of the attributes and their levels in the choice experiment.

| Attributes | Attribute levels |
|---|---|
| Frequency of future water shortages | Once in the next 10 years<br>Twice in the next 10 years<br>Four times in the next 10 years<br>Five times in the next 10 years or more (*status quo*) |
| Duration of future water supply interruptions | 12 hours<br>24 hours<br>36 hours<br>48 hours or longer (*status quo*) |
| Water conservation measures | Agroforestry<br>Afforestation<br>Water harvesting<br>No new measures (*status quo*) |
| Increase in monthly water bill | 100 BRL<br>50 BRL<br>20 BRL<br>0 BRL (*status quo*) |

Fifty-six hypothetical alternatives were generated and combined to unique choice tasks. Each choice task consisted of two alternative scenarios (Situations A and B in Figure 12) from these 56 generated alternatives and the *status quo* alternative (Situation C in Figure 12). The inclusion of this latter *status quo* (SQ) alternative is instrumental to be able to estimate welfare measures that are consistent with demand theory (BATEMAN et al., 2002) and not to force respondents to choose one of the hypothetical alternatives (scenarios). Thus, the final design comprised 28 different choice tasks, which were later divided into seven blocks of four tasks. These blocks were randomly assigned to each respondent, given that each respondent would be assigned only one of the seven blocks. In each block the first choice task was shown again at the end (i.e., choice task 5) without telling respondents to test choice consistency and potential preference learning (BROUWER et al., 2010). It means that each respondent therefore answered five choice tasks (cards like the one in

Figure 12). Respondents gained important market experience by answering multiple times to consider their WTP a higher water bill for the three measures over the next 10 years. These multiple choice tasks contribute to reducing possible hypothetical bias in the choice experiment. This type of bias arises in stated preference studies when respondents report a WTP that exceeds what they would actually pay using their own money.

Figure 12 – Illustration of a choice card used in the survey in Portuguese, the respondents' mother tongue.




Source: Author.

Following the choice experiment, respondents who were not willing to pay (nonparticipants) were asked questions about their underlying reasons. Nonparticipants are those who consistently chose the SQ alternative in all five choice tasks. The answers to these questions were subsequentially used in the analysis to identify and distinguish between the so-called 'protest response' in the literature (e.g., Brouwer and Martín-Ortega (2012), Dziegielewska and Mendelsohn (2007), García-Llorente, Martín-López and Montes (2011)) and true or legitimate zero responses (e.g., because respondents indicate not to be able to afford to pay extra for their water bill due to income constraints). Protesters are those who demonstrate an objection to the valuation process itself, and the inclusion of protest responses can bias preferences and estimates of WTP (HALSTEAD; LULOFF; STEVENS, 1992). This is why is very important to identify protest responses within the sample. Therefore, a mixed multinomial logit model (MMNL, Hensher and Greene (2003) and

Train (2002b)) was estimated for CG and the SPMR using a truncated sample without protesters. The estimation process is further explained in the next section.

## 5.2 Choice modeling

The choice experiment technique is based on the characteristic theory of utility (LANCASTER, 1966), which says that any good can be described as its attributes and the values that these take. So, public preferences for NbS to improve water supply reliability are modeled in terms of McFadden's random utility model (RUM) (MCFADDEN, 1974). Given that many attributes are unobservable or observable only with an error, the utility function ($U_{ijt}$) is broken down into a deterministic (observable $V_{ijt}$) and a stochastic part (error term $\varepsilon_{ijt}$). Suppose a respondent chooses one of the $k$ alternatives related to different water conservation measures and its consequential reduction in the frequency of future water shortages and duration of water supply interruption as:

$$U_{ijt} = V_{ijt} + \varepsilon_{ijt} \qquad \forall j \in k \tag{5.1}$$

The deterministic part of the utility function was specified to be linear in parameters including a alternative-specific constant (ASC). DCEs are attribute-based and $V_{ijt}$ for individual $i$ for good $j$ in choice task $t$ is estimated as a linear function of its attributes $X_{ijt}$ and potential explanatory variables $Z_{ijt}$ (TRAIN, 2002a):

$$V_{ijt} = ASC + \beta_i X_{ijt} + \alpha_i Z_{ijt} \tag{5.2}$$

where $ASC$ is the alternative-specific constant for the SQ alternative (*status quo* =1; alternative = 0). The $ASC$ captures the average effect on utility of all factors that are not included in the model, considered here as a specific parameter capturing a bias toward the current situation (SQ). The $X_{ijt}$ and $Z_{ijy}$ are the vectors of observed attribute and explanatory variables (e.g., alternatives' attributes and socioeconomic characteristics) of each respondent $i$ in choice task $t$; and $\varepsilon_{ijt}$ is the vector of error terms that capture individual- and alternative-specific influencing factors on utility. The error is assumed to be independently and identically distributed (IID) and follow an extreme-value type I distribution (i.e., homoscedastic error terms).

As the observed utility of each choice set is due to the selection of the most preferred alternative (i.e., utility maximisation problem), the mixed logit probability of an individual $i$ preferring alternative $j$ over other alternatives $k$ in the choice task $t$ is expressed as:

$$\pi_{ijt} = \int \frac{\exp(\beta_i X_{ijt} + \alpha_i Z_{ijt})}{\sum_{j \in D} \exp(\beta_i X_{ikt} + \alpha_i Z_{ikt})} \Delta(\beta_i | b) \, d\beta_i \qquad \forall j \in D_{it} \tag{5.3}$$

where $\beta$ coefficients vary across respondents ($\beta_i$) with density $\Delta(\beta_i|b)$, which represents the mean and covariance of $\beta$ in each sample (CG and the SPMR). Treating parameters as random requires the use of maximum likelihood algorithm, which searches a solution by simulating draws from distributions with given means and standard deviations. These choice probabilities were approximated by simulating the log-likelihood with 1,500 pseudo-Monte Carlo draws for both CG and the SPMR samples. This technique provides an unbiased and consistent estimator of the actual individual choice probabilities. The models were set using the Apollo package in R Studio (HESS; PALMA, 2019); the quasi-Newton hill-climbing technique known as the Broyden-Fletcher-Goldfarb-Shanno (BFGS) was employed to estimate the models.

To account for heterogeneous preferences among respondents, the alternative specific constant (ASC), frequency of future water shortages, duration of future water supply interruption, and the three proposed practices were modelled as being randomly distributed across respondents. The first three attributes follow normal distribution while the practices follow a uniform distribution as recommended by Bhat (2003). The proposed conservation measures were included as dummies using dummy coding. The frequency and duration of future water shortages and cost (increment in water bill) were included in the model as continuous variables.

Since the models may fail to explain the sources of heterogeneity, three dummies related to public experiences with droughts and expectations were interacted with the SQ ASC . The first dummy indicates whether individuals think water shortage episodes will increase. The second and third dummies are related to recent experiences with water use restrictions and/or rationing, distinguishing between 2021-2019 (most recently) and 2010-2018 (recently). Additionally, a dummy for those who have experienced restrictions over the last 10 years and for those who experienced rationing were each interacted with the frequency attribute. It was also tested whether uncertainty about the perceived effectiveness of nature-based solutions (i.e., agroforestry and afforestation) is influencing public preferences for these two proposed measures. Lastly, low household income per capita ($<$ 50th percentile) was interacted with the ASC attribute.

## 5.3 Modeling protest behavior

To further understand the protesters' decision process, a probit model with sample selection (VEN; PRAAG, 1981) was estimated for each study site using Stata (version 17). This model assumes that there is an underlying relationship (latent equation) such that only the binary results are observed (probit equation):

$$y_j^* = x_i\beta + u_{1j} \tag{5.4}$$

$$y_j^{probit} = (y_j^* > 0) \tag{5.5}$$

where $x_i\beta$ is a vector of coefficients for the covariates included in the probit equation and $u_{1j}$ is a random error term. However, the dependent variable ($y_j$) is only observed if:

$$y_j^{selection} = (z_j\gamma + u_{2j} > 0) \tag{5.6}$$

The selection equation is completely observed, but only part of the sample is available for the outcome equation. In other words, it is only possible to identify whether the respondents protest if they decided to not participate in the framework for investing in the three proposed measures by consistently choosing the SQ alternative in all choice cards. Thus, there are two dependent decision variables simultaneously estimated: (i) *Protest* as the binary outcome for whether the respondent is a protester (Protest = 1) or a true bidder (Protest = 0) and (ii) *Nonparticipation* (Nonparticipation = 1, which includes protesters and true bidders) as a binary selection variable.

The coefficients of the covariates ($z_j\gamma$) included in the selection equation (Nonparticipation) should include at least one regressor not included in the probit equation (Protest), so-called exclusion restriction, which would affect the probability of not willing to pay but not the probability of being a protester. Therefore, the monthly household income as a socioeconomic variable and the expectations of increasing water shortages in the future as a variable accounting for a sociohydrological perspective were included in the model. It was considered that income only affects the decision to participate (true zero WTP) and not as an underlying reason for protesting, as well as expectations that water shortages will increase in the future.

# Chapter 6

# Public preferences for nature-based solutions and the effect of drought-related experiences on willingness to improve water security[1]

Several drought periods have hit the São Paulo Metropolitan Region as the 2014/2015 episode mentioned in the General Introduction (Chapter 1). In 2019, another important drought event unveils the vulnerability frame in the SPMR. Below average rainfall in 2019 along with the low water level in reservoirs were exacerbated by an increase in water consumption since people began to stay at home most of their time during the COVID-19 pandemic (SABESP, 2021). Safe water supply was only maintained in this year due to investments in the integrated water supply system, according to the report. This vulnerability to droughts is also observed in Campo Grande city. Chapter 4 highlights that water scarcity may become more frequent and last longer even under the most optimistic climate change scenario in Campo Grande. Even considering a decreasing demand scenario, vulnerability to water scarcity is still high at least until the mid-century in both study areas. To address this issue, nature-based solutions (NbS) have emerged as a potential approach to be encouraged and embedded into policies' framework aimed at improving water security. Nonetheless, human behavior and public perceptions regarding water availability and supply are expected to play a key role in improving the effectiveness of such policies, but these drivers have to be better understood.

[1] Partial results contained in this chapter have been accepted for an in-person presentation at the 2023 Conference of the European Association of Environmental and Resources Economists (EAERE) and the 2023 Simpósio Brasileiro de Recursos Hídricos (SBRH). The EAERE Conference was held in Limassol, Cyprus, on June 27 – 30, 2023. The 2023 SBRH will be held in Aracaju, State of Sergipe – Brazil, on November 19–24, 2023.

Here the results of the discrete choice experiment (DCE) carried out in November 2021 are presented, and public preferences for nature-based solutions to improve future water supply reliability are discussed. The interest was in highlighting how different water shortage background conditions and public experiences with water use restrictions and rationing can trigger people to invest in conservation measures in the basins supplying their cities with water. It is also elaborated on how public perceptions of NbS affect public preferences for measures to protect and conserve water-related watershed services.

## 6.1 Households socio-hydrological characteristics

The socioeconomic characteristics of the two samples (Table 4) show a good overall representativeness, compared with the 2010 official Brazilian census and statistical information from the state of São Paulo for 2023 (IBGE - Brazilian Institute of Geography and Statistics, 2011; Seade, 2023). By contrasting the official statistical records with the characteristics of the two samples, the levels of education may be somewhat misrepresented. A substantially smaller share of respondents with no education or incomplete primary education compared with the census can be observed in both study sites. Conversely, the share of respondents with secondary or higher education is slightly higher than that reported in the official records. It is important to point out that those differences may be due to the lack of more recent socioeconomic information collection. The national population census was carried out in August 2022, but only partial results have been released preventing us from obtaining updated household information. Thus, the official information used here as a reference may not reflect actual education levels in the studied cities. The education level of the sampled population may have increased since 2010, corroborating samples with a smaller share with no or incomplete primary education and a higher share with secondary or higher education.

Turning to sociohydrological characteristics, a share of 86% and 98% think tap water is the most important water source in CG and the SPMR households, respectively. Nonetheless, 38% of the SPMR respondents indicated that they also use other drinking water sources while almost all respondents from CG (95%) rely only on tap water (Table 4). A share of 37% in the SPMR also rely on bottled water. These results corroborate the fact SPMR residents have faced more water shortage events than those in CG, and this vulnerability scenario can contribute to more people relying on multiple water sources, such as bottled water. It is worth noting that the consumption of bottled water can also be influenced by other factors as purchase power. Around three quarters (72%) of the SPMR respondents faced at least one episode of water restriction in the last decade, compared with about a quarter (24%) from CG. Furthermore, nearly two thirds of the sampled population from the SPMR (66%) also faced water rationing, a share which is nearly 1.5 times higher than in CG. Nearly half of the SPMR households (48%) faced not only water

Table 4 – Household characteristics across the two samples in the city of Campo Grande and the São Paulo Metropolitan Region (SPRM).

| Description | Campo Grande | SPMR |
|---|---|---|
| *General sociodemographic characteristics* | | |
| Average age (years) (st. dev.) | 39 (14) | 41 (12) |
| Share male respondents (%) | 40.0 | 40.8 |
| Share with no education or incomplete primary education (%) | 6.5 | 0.5 |
| Share completed primary school (%) | 13.2 | 7.5 |
| Share completed secondary or higher education (%) | 74.2 | 88.5 |
| Average household size (persons) (st. dev.) | 3 (2) | 3 (1) |
| Average monthly income per person (thousand BRL) (Q1–Q3) | 1.5 (0.6–1.8) | 2.1 (1.0–2.6) |
| *Sociohydrological characteristics* | | |
| Share using tap water as the only source of drinking water (%) | 94.5 | 62.0 |
| Average daily water consumption per person (liters) (Q1–Q3) | 170 (66.7–232) | 158 (66.7–175) |
| Average ratio of monthly water bill to monthly income (%) (Q1–Q3) | 5.4 (2.7–7) | 2.7 (1.3–3.2) |
| Share facing water restrictions in the past (%) | 24.0 | 72.3 |
| Of whom facing water restrictions (%): | | |
| • in 2021 | 36.5 | 20.1 |
| • between 2016 and 2020 | 29.1 | 40.8 |
| • 1–5 times in the last 10 years | 89.5 | 73.4 |
| • every year for the last 10 years | 6.3 | 16.3 |
| • that last on average up to a week | 91.7 | 68.8 |
| • that last more than a month | 1.0 | 28.0 |
| Share facing water rationing in the past (%) | 45.8 | 66.0 |
| Of whom facing water rationing (%): | | |
| • in 2021 | 37.2 | 28.8 |
| • between 2016 and 2020 | 42.1 | 49.6 |
| • 1–5 times in the last 10 years | 89.1 | 71.2 |
| • every year for the last 10 years | 7.1 | 16.3 |
| • that last on average up to a week | 95.2 | 85.3 |
| • that last more than a month | 0.5 | 13.6 |
| Share facing both water restrictions and rationing (%) | 4.9 | 47.9 |
| Share taking water saving measures at home (%) | 80.3 | 92.3 |
| Share storing water at home in anticipation of water shortages (%) | 30.2 | 68.5 |

**Note:** The average exchange rate in November 2021, when the survey was implemented, was 0.18 USD for 1 BRL (IMF - International Monetary Fund, 2021).

restrictions but also rationing efforts, a share which is nearly 10 times higher than in CG. When analyzing longer duration, a considerable share of SPMR experienced water shortage effects that lasted longer than a month, especially water use restrictions (28%). This might explain the much higher share of respondents storing water at home in anticipation of future water shortages, more than 2 times higher in the SPMR than in CG.

Finally, most respondents believe that the number of dry years has increased over the last 10 years (72% in CG and 78% in SPMR) and therefore the number of water shortage episodes (86% in CG and 79% in SPMR). This also corroborates the considerable share of respondents who believe that climate change is real in both study sites. Respondents in both samples think that first of all water companies (69% in CG and 89% in SPMR) and second of all the local municipal government (30% in CG and 22% in

SPMR) are responsible for safeguarding their water supply. Interestingly, a share of 11% and 22% in CG and the SPMR respectively believe that the responsibility is shared among all actors, including foremost water companies and the local government. Regarding the proposed measures, most respondents from both cities believe the proposed measures — agroforestry, afforestation, and water harvesting technologies — will contribute to reducing the frequency of future water shortages (about 63%), and nearly half of them are convinced that the measures will be implemented. It is worth noting that a considerable share doubts the measures will actually be implemented. A similar scenario was observed when asked whether they think the nature-based solutions (agroforestry and afforestation) are effective compared with water harvesting. Around half of the respondents in the SPMR (58%) think NbS are effective compared with water harvesting, whilst almost the other half (42%) does not know or is uncertain. In CG, a share of 42% thinks NbS are effective in comparison with water harvesting while a quarter stated they do not know how effective NbS are compared with water harvesting. Even though most people believe NbS are effective, the results show a considerable share is still uncertain about the effectiveness of nature-based solutions compared with conventional grey infrastructure.

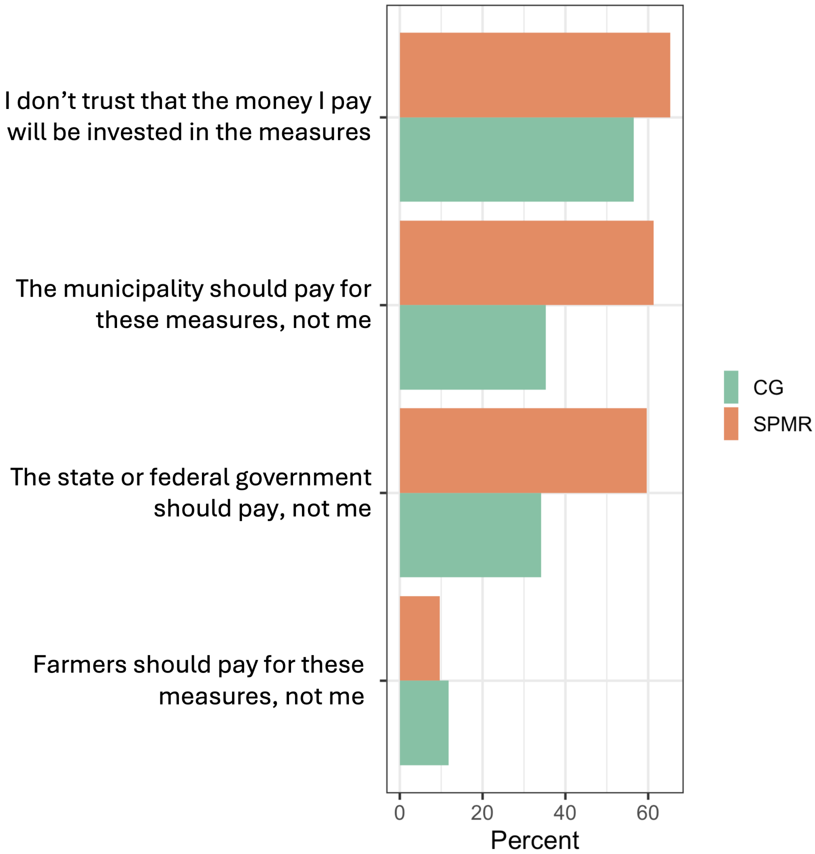
## 6.2 Choice consistency check and (non)participation rates

The hypothetical alternatives in the choice experiment presented a slight selection bias as choices at both study sites were equally distributed between the two alternatives. Respectively in CG and the SPMR, the first alternative was chosen in 23% and 28% and the second in 19% and 26% of the occasions. Also, respondent choices at both study sites were consistent as 91% of the respondents chose the same alternative in cards 1 and 5. The choice consistency observed is higher than in other studies that showed remarkably high percentages (e.g., Brouwer et al. (2010), Tarfasa et al. (2017)). As expected, no significant differences were noted when regressing consistent and inconsistent choices on levels of the choice attributes probably due to the very low inconsistent choices.

Nearly two-thirds (64%) in the SPMR sample were willing to pay extra for the conservation measures to improve their water security. Otherwise, more than half of the respondents in CG were not willing to pay (nonparticipation rate of 56%) and consistently chose the status quo (SQ) alternative in all five choice tasks. From an economic point of view, legitimate or 'true' zero bidders are those who either cannot afford to pay or do not prefer the good on offer. A share of 5% and 13.5% are respectively legitimate bidders in the SPMR and CG. Thus, those who showed either positive or zero WTP respectively corresponds to 69% and 57.5% in the SPMR and CG. Considering the entire sample, around 16% stated that their income is too low to pay extra on top of their current water bill in both the SPMR and CG. Additionally, those who are simply not interested in paying extra to safeguard future water supply correspond to 16% in the SPMR and 11% CG.

Still, a share 31% and 42.5% were considered protesters in the SPMR and CG samples, respectively. The most common protest reason at both study sites is that respondents lack trust that their money will be spent on the proposed measures (63% in the SPMR and 56% in CG when only considering the protesters share, Figure 13). A similar protest response was also found when investigating public preferences for forest conservation in Brazil (BAKAKI; BERNAUER, 2016). A large share in the SPMR also considers that it is government's responsibility to pay for the implementation of the proposed measures while a smaller share thinks alike in CG. Around 10% in both samples believe farmers should pay for the proposed measures.

Figure 13 – Share of protest responses in Campo Grande (CG) and the São Paulo Metropolitan Region (SPMR) considering only protesters in the sample. Please note that percentages exceeded 100% because respondents could choose more than one alternative.




Source: Author.

## 6.3 Preferences for conservation measures and improvements in water security

A mixed multinomial logit (MMNL) model was estimated for each study site to investigate the effect of experiences with water scarcity on choice behavior for water security improvement. Given the very consistent choices in both samples, the fifth choice (i.e., the repeated choice task) was included in the model, better reflecting the respondents' preferences. Besides, the protesters were removed from both samples; thus, all legitimate bidders and participants willing to pay respectively yielded 1,150 and 1,380 observations for the CG and SPMR models. As expected, the cost coefficient is negative and highly significant ($p < 0.01$) in both samples (Table 5); the higher the increase in the respondents' water bill the less likely they will choose an alternative scenario. Household monthly income has also significant effect on public WTP. In both cities, households with low monthly income (i.e., equal to or less than the median household income) have higher likelihood of opting for the SQ option ($p < 0.01$). The alternative specific constant (ASC) is negative and significant in the SPMR, suggesting that the SPMR respondents refuse the SQ and are willing to pay to improve their water security. The insignificant ASC in CG may be due to the considerable frequency with which the SQ was chosen (28% in CG). Insignificant ASC also indicates that the specified model for CG adequately captures systematic unobserved components that are relevant for the decision-making regarding WTP for conservation measures. Substantial taste heterogeneity ($p < 0.01$) is also observed in both cities (ASC $\sigma$) and corroborating the considerable amount of people not willing to pay.

The frequency and duration of future water shortages are as expected negative (Table 5); the respondents will less likely choose an alternative that offers higher frequency and longer duration of future water shortages. Duration of future water supply interruption is highly significant ($p < 0.01$) in the SPMR. This corroborates the fact that the SPMR respondents have experienced much more frequent and longer water restrictions and rationing episodes (Table 4). Nonetheless, frequency in both cities and duration in CG did not have a significant effect on utility. Consequently, these insignificant parameters are not playing any role in the respondents' decisions. This finding shows that, when choosing an alternative, a reduction in frequency and duration of future water shortages was neglected by most respondents since their decision was probably based on the idea that the decrease in the frequency and/or duration of water shortages are not tangible and/or immediate (WEBER, 2006). Specifically in CG, this negligence may be due to fewer episodes of water restrictions and rationing experienced (Table 4). To explain underlying reasons behind the negligence, an interaction between frequency and whether respondents experienced water restrictions and rationing at least once over the last 10 years was included in the model (*Frequency* = 1, Table 4). A significant effect of experiences with water use restrictions on utility ($p < 0.01$) was found in CG, but not in the SPMR. Individuals who have faced water use restrictions at least once will more likely choose an alternative scenario with lower frequency, indicated by the negative interaction coefficient. This supports the hypothesis of fewer experiences with restrictions and rationing contributing to the negligence of the frequency and duration parameters. Furthermore, duration in both sites and frequency in the SPMR have significant standard deviation ($\sigma$), indicating significant preference heterogeneity in reducing the frequency or duration of future water restrictions and rationing. This may suggest that there is no public consensus on which attribute

Table 5 – Estimated coefficients of the Mixed Multinomial Logit model for the two study sites.

| Variables | Campo Grande | | São Paulo M. R. | |
|---|---|---|---|---|
| | est. | rob. s.e. | est. | rob. s.e. |
| ASC $\mu$ | 0.3435 | 0.4952 | -1.6381$^{*}$ | 0.9825 |
| ASC $\sigma$ | -24.4732$^{***}$ | 4.3119 | 7.6664$^{***}$ | 1.6273 |
| *Choice attributes* | | | | |
| Frequency of water shortages $\mu$ | -0.0294 | 0.0917 | -0.2173 | 0.2044 |
| Frequency of water shortages $\sigma$ | -0.0710 | 0.0552 | 0.5729$^{***}$ | 0.1516 |
| Duration of supply interruption $\mu$ | -0.0076 | 0.0129 | -0.0592$^{***}$ | 0.0157 |
| Duration of supply interruption $\sigma$ | 0.0922$^{***}$ | 0.0147 | -0.1494$^{***}$ | 0.0221 |
| Agroforestry $\mu$ | 6.1653$^{***}$ | 1.3246 | 5.0247$^{***}$ | 1.1839 |
| Agroforestry $\sigma$ | -1.3412 | 0.9287 | -1.0784 | 1.6899 |
| Afforestation $\mu$ | 3.7291$^{***}$ | 1.3121 | 2.2980$^{***}$ | 0.7294 |
| Afforestation $\sigma$ | 4.1514$^{***}$ | 1.2608 | 4.6741$^{***}$ | 1.3149 |
| Water harvesting $\mu$ | 4.4782$^{***}$ | 1.1486 | 1.4682$^{**}$ | 0.6867 |
| Water harvesting $\sigma$ | 3.1261$^{***}$ | 0.8201 | 6.7137$^{***}$ | 1.3328 |
| Monthly payment (BRL) | -0.0145$^{***}$ | 0.0039 | -0.0882$^{***}$ | 0.0122 |
| *Covariates* | | | | |
| ASC × low household income per capita | 0.8499$^{***}$ | 0.1543 | 0.9298$^{***}$ | 0.1918 |
| Frequency × experienced restrictions over the last 10 yrs | -0.5033$^{***}$ | 0.1448 | -0.0426 | 0.1693 |
| Frequency × experienced rationing over the last 10 yrs | 0.1193 | 0.1127 | -0.0392 | 0.1612 |
| NbS × uncertain about NbS effectiveness | 0.2550 | 0.3766 | -0.0741 | 0.3811 |
| ASC × faced last restrictions/rationing most recently | 0.1276 | 0.0841 | -0.4361$^{***}$ | 0.1130 |
| ASC × faced last restrictions/rationing recently | -1.0460$^{***}$ | 0.0692 | -0.8000$^{***}$ | 0.1390 |
| ASC × think water shortages will increase | -1.4038$^{***}$ | 0.1065 | -0.5799$^{***}$ | 0.1060 |
| *Model summary statistics* | | | | |
| Log-likelihood | -779.22 | | -854.87 | |
| Adjusted $\rho^2$ | 0.37 | | 0.42 | |
| Number of observations | 1,150 | | 1,380 | |
| Inter-individual draws | 1,500 | | 1,500 | |

**Note:** *est.* and *rob. s.e.* are respectively the estimates and the robust standard errors. Households with monthly income less than or equal to the median were considered as low income. NbS stands for nature-based solutions (either agroforestry or afforestation). Most recent episodes of water use restrictions and/or rationing correspond to the period between 2019 and 2021 while the recent episodes correspond to the 2010-2018 period; $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, and $^{***}$ $p < 0.01$.

should be prioritized for improvement.

Regarding the proposed measures, the three coefficients are positive and highly significant ($p < 0.01$, except water harvesting in the SPMR having $p < 0.05$) in both samples (Table 5). When looking at the coefficients' magnitude, a much larger estimate for the agroforestry was noted in comparison with afforestation and water harvesting. The magnitude difference between agroforestry and afforestation is highly significant in both CG and the SPMR ($p < 0.01$). The difference between agroforestry and water harvesting is also significant in CG ($p < 0.05$) and the SPMR ($p < 0.01$). On the other hand, the magnitude differences between afforestation and water harvesting are not statistically different in any study city. It suggests an overall public preference for agroforestry over the other two in both cities. Moreover, there is no significant taste heterogeneity in the most preferred measure, suggesting that there is a consensus on the preference for agroforestry. This measure allows for sustainable agricultural production while also improving and preserving ecosystems. This may be the underlying reason behind public preference for agroforestry. A study comparing agroforestry systems with other conventional cropping systems found that agroforestry improved water infiltration into the soil and reduced soil erosion, with rates similar to native vegetation (SONE et al., 2019). Considering the other least preferred measures (afforestation and water harvesting), high and significant taste heterogeneity ($p < 0.01$) was observed.

High and significant taste heterogeneity was found in preferences for afforestation and water harvesting. To further investigate what may be influencing people's decision to support the NbS proposed (i.e., agroforestry and afforestation), a dummy representing the respondents' uncertainty about the effectiveness of the proposed NbS was introduced into the model to interact with the agroforestry and afforestation coefficients. Nonetheless, neither significant positive nor negative influence of this perception on preferences was found for either agroforestry or afforestation, despite the considerable uncertainty about NbS effectiveness. There is a need for future research to investigate influencing factors other than perceived effectiveness of proposed solutions to deterioration of watershed services and, therefore, water insecurity. It is hypothesized that the perception about the need to move beyond conventional grey infrastructure measures (e.g., water harvesting technologies) to tackle the water insecurity issues might be affecting public decision-making. Furthermore, afforestation may be seen as a competing alternative to agricultural activities, stimulating the conflicting individual's interest in both food production and water supply. These hypotheses may explain the high variance for those two measures. In fact, it is worth noting that the role played by NbS in watershed water fluxes is not clear and well disseminated in the society. Even among scientists, the effect of reforestation/afforestation is still a complex and challenging gap, with diverging evidence published worldwide (e.g., Dijke et al. (2022), Anache et al. (2019) and Filoso et al. (2017)).

### 6.3.1 Effect of experiences with restrictions and rationing on choice behavior

Public experiences with water restrictions and rationing and expectations regarding future water shortages were interacted with the status quo ASC (Table 5). Most recent experiences with water restrictions and/or rationing (2021-2019) is significant and negative in the SPMR ($p < 0.01$), but not in CG. That is, SPMR individuals who have faced water restrictions and/or rationing between 2019 and 2021 are more likely to choose one of the hypothetical alternatives over the SQ. This finding is substantiated by the fact that the SPMR was hit by one of the worst dry spells during the period from 2020 to 2021 (SABESP, 2021); this scenario does not apply to the CG region. This fact may also explain why experiences from this period are not significantly influencing respondents' choices in CG. Last experienced episodes of water restrictions and rationing between 2010 and 2018 are significantly affecting public decision to support and pay for measures to improve their water security in both cities. The negative sign of this coefficient indicates that those who faced recent last restrictions and rationing efforts (2010-2018) in both cities are willing to improve their water security condition, more likely choosing one of the hypothetical alternatives. During this period, the almost "Day Zero" water crisis arose in the SPMR and the watersheds responsible for water supply in the Metropolitan Region in 2014-2015. The finding suggests that public experiences with water scarcity plays a key role in the decision to support and pay for NbS to improve their water security. There is also evidence that corroborate the significant effect of drought experiences in this period on CG individuals' decision. Water crises occurred in 2016 in CG, putting at least 43 neighborhoods into water rationing efforts. Nevertheless, related information is only found in newsletters. Any official record and monitoring of past drought events were found in CG, unveiling a troubling vulnerability to water scarcity as discussed in the Section 4.2 of Chapter 4.

In both study sites, not only most respondents think droughts have increased in the last 10 years, but also most of them expect that water shortages will increase in the future (86% in CG and 79% in the SPMR). Furthermore, this expectation is strongly influencing people's decision to pay for NbS, more likely choosing one of the hypothetical alternatives over the status quo (significant and negative coefficient in Table 5, $p < 0.01$ in both cities). This finding shows that public decisions about investing in conservation measures to improve their current water security may be dependent not only on their experiences with drought events but also their expectations that water scarcity events will increase.

## 6.4 Understanding protest motives

A probit model with sample selection was estimated for each study site to better understand the motives of protesting during the survey in November 2021. The results are presented in Table 6. The $\rho$ coefficient was highly significant in CG and the SPMR ($p < 0.01$), indicating that the residuals from the probit (*Protest*) and selection equation (*Nonparticipation*) for each study site are correlated. This confirms that the probit model with sample selection is preferred over two separate models since the decision to protest is not random and the two subsamples have different characteristics. The constant term in the selection equation (nonparticipation = 1) is statistically significant in CG ($p < 0.05$), implying the presence of unobserved heterogeneity influencing the decision of whether to participate or not. Nevertheless, latent heterogeneity does not appear to have significant impact on the decision of protesting among the respondents in CG. In the SPMR, both constant coefficients are not statistically significant.

The characteristics of the respondents and household significantly affect the likeli-

Table 6 – Probit model with sample selection to explain protest decisions and those who consistently chose the *status quo* alternative in all choice cards (Nonparticipants).

| Decision | Variables | Campo Grande | | São Paulo M.R. | |
|---|---|---|---|---|---|
| | | est. | rob. s.e. | est. | rob. s.e. |
| **Protest** | Restrictions or rationing experiences | -0.3049$^{**}$ | 0.1476 | -0.8083$^{***}$ | 0.2948 |
| | Think NbS are not effective | -0.1009 | 0.1643 | 0.5388$^{***}$ | 0.1592 |
| | Age | 0.0024 | 0.0051 | 0.0114$^{*}$ | 0.0060 |
| | Other water sources besides tap water | -0.2250 | 0.4299 | -0.1003 | 0.1663 |
| | Water bill-household income ratio | -2.7368$^{**}$ | 1.2604 | 0.1088 | 3.6609 |
| | Constant | 0.2082 | 0.2927 | -0.3488 | 0.3582 |
| **Nonparticipation** | Restrictions or rationing experiences | -0.2328$^{*}$ | 0.1393 | -1.0804$^{***}$ | 0.2829 |
| | Think water shortages will increase | -0.2558$^{*}$ | 0.1494 | -0.1123 | 0.1287 |
| | Think NbS are not effective | 0.2916$^{*}$ | 0.1571 | 0.6822$^{***}$ | 0.1374 |
| | Age | 0.0074 | 0.0048 | 0.0105$^{*}$ | 0.0058 |
| | Other water sources besides tap water | -0.0588 | 0.3725 | 0.0276 | 0.1562 |
| | Water bill-household income ratio | -2.6559$^{*}$ | 1.4053 | 3.1012 | 3.0821 |
| | Monthly household income | -0.0001$^{***}$ | 0.00002 | -0.0001$^{***}$ | 0.00002 |
| | Constant | 0.6363$^{**}$ | 0.2733 | 0.2105 | 0.3814 |
| | $\rho$ | 0.9402$^{***}$ | 0.0746 | 0.9901$^{***}$ | 0.0169 |
| | Log-pseudolikelihood | -374.02 | | -295.51 | |

**Note:** $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, and $^{***}$ $p < 0.01$.

hood of serial nonparticipation (consistently choosing the SQ alternative) and protesting. Older individuals have a significant likelihood ($p < 0.10$) of serial nonparticipation and protesting in the SPMR (Table 6). Nonetheless, this coefficient did not demonstrate a significant influence on neither nonparticipation nor protesting among the respondents in CG. As expected, monthly household income exerts a significant influence in decision-making ($p < 0.01$ in both cities), supporting the results of the MMNL models; households with higher monthly income are more likely to accept paying for conservation measures (nonparticipation = 0) to enhance water reliability. Conversely, households with lower income levels present reduced likelihood of participating in the proposed scheme and, therefore, paying extra on top of their monthly water bill (legitimate zeros). In the SPMR, the ratio between monthly water bill and household income does not influence the decision of nonparticipation and protesting. In CG, households with higher ratio are more likely to express true zero willingness to pay ($p < 0.05$). Also in CG, individuals with higher water bill-household income ratio unexpectedly have higher likelihood of participation in the proposed scheme ($p < 0.10$). This significant effect is probably due to the relatively low water bill paid in comparison to household income. Notably, the majority of respondents have a ratio of less than 6% (see Figure 26 in Appendix F). The crucial finding here is that having a higher water bill-household income ratio does not affect the likelihood of protesting. In other words, CG respondents with higher ratio who consistently chose the SQ alternative in all five tasks are more likely to be legitimate bidders (true zero WTP).

In both cities, individuals who have faced water use restriction and/or rationing exhibit a higher likelihood of participating in the proposed scheme for investing in conservation practices to improve future water security ($p < 0.10$ in CG and $p < 0.01$ in the SPMR). This finding corroborates the MMNL results (Chapter 6) and substantiates the hypothesis that the decision to participate is influenced by prior experiences with water scarcity. The study of Meyerhoff and Liebe (2006) also shows that those who are more concerned with environmental problems have a reduced likelihood of protesting. However, expectation that water shortages will increase is only affecting participation in the proposed scheme in CG ($p < 0.10$). It was expected that this coefficient would affect decision-making in both cities, as indicated by the MMNL models. Turning to protest decisions, even though individuals with such experiences may be a serial nonparticipant, they have reduced likelihood of protesting ($p < 0.05$ in CG and $p < 0.01$ in SPMR). This finding suggests that individuals facing water scarcity are more inclined to support and participate but not protest against conservation initiatives to improve their current water security status. Possible serial nonparticipation in this case is more likely due to insufficient means to afford paying extra.

The statistically significant positive coefficient associated with public opinion regarding the ineffectiveness of nature-based solutions (NbS) (i.e., agroforestry and afforestation) compared with rainwater harvesting demonstrates a positive correlation with individuals' decision to not participate in the scheme ($p < 0.10$ in CG and $p < 0.01$ in the SPMR, Table 6). This finding together with the overall preference for agroforestry system indicated by the MMNL models (Table 5 discussed in Chapter 6) demonstrate that the type and perceived effectiveness of conservation measures play a key role in influencing individuals' decision to participate in water conservation programs and policies designed to improve water security. Thus, understanding these factors is vital for designing and implementing effective water conservation strategies aimed at enhancing water security. It is important to highlight that, despite this significant coefficient's influence on the decision to participate, a considerable share of the respondents is uncertain about the effectiveness of NbS. The broader societal understanding of NbS effects on hydrological flows in watersheds is still developing, but society can acknowledge the benefits derived from ecosystem services (BUIJS et al., 2008). Upon examining protest motives in the SPMR, the respondents' perception of the ineffectiveness of NbS is significantly and positively correlated with protesting. This effect was not significant in CG although a higher share thinks NbS is not effective in CG (33.5%), compared with the SPMR share (8.5%). So, it does not exhibit very clear and consistent evidence of the impact of perceived ineffectiveness of NbS on protest behavior across the two cities.

One of the main contributions of this study is the incorporation of a social dimension (i.e., public preferences) into strategies aimed at ensuring water security such as nature-based solutions. The findings from the probit and MMNL models (discussed in detail in Chapter 6) corroborate. Both models indicate a significant effect of experiences with water restrictions and rationing on willingness to support and pay for measures to improve water security. Expectations that water shortages will increase also play a significant role in public decision of paying, albeit probit only shows this effect in CG. When it comes to this study's second aim, the probit models show that the perceived ineffectiveness of NbS in comparison with water harvesting is affecting people's decision to support and pay for them although the MMNL models does not indicate a significant influence of this perception on public preferences for a specific measure. This study's findings have the potential to not only inform water conservation policy-making with public preferences for conservation practices but also understand the intertwined effect of expectations and experiences with water scarcity events on public decisions to invest in solutions to safeguard their future water supply. Insights from this study can also contribute to strategies for encouraging stakeholders' participation in the policy-making at the local, state, and federal levels by better understanding people's motivations.

## 6.5 Summary and conclusions

Sustainable and effective efforts to improve water security are undermined because interactions and feedback loops between society and drought events are not fully understood, nor are they used to inform policymaking. To contribute to this, 800 people in Campo Grande city (CG) and the São Paulo Metropolitan Region (SPMR) were interviewed to carry out a choice experiment consisting of an increase in water bill to implement conservation practices in the basins responsible for the population's water supply. Most people showed either positive or zero willingness to pay (WTP) in CG (58%) and the SPMR (69%). Experiences with water use restrictions and rationing significantly influence public decision-making and WTP for nature-based solutions (NbS), especially most recent episodes (2019-2021) in the SPMR and recent ones (2010-2018) in CG. When investigating protest behavior, experiences with water restrictions and rationing influence people's decision to participate in the payment scheme to invest in NbS. People from the SPMR are also less likely to protest. The protest behavior analysis corroborates the results obtained from the MMNL models, indicating the findings detailed in this chapter are robust.

There is public understanding for the need of environmental protection in watersheds feeding the cities with water to achieve water security. Agroforestry is the most preferred NbS in both CG and the SPMR. The uncertainty about the effectiveness of NbS is not impacting public preferences for a specific solution, but the perceived ineffectiveness plays an important role in the respondents' decision to participate in the proposed payment scheme in both cities. Moreover, the belief in the ineffectiveness of the afforestation and agroforestry measures significantly influences protest behavior in the SPMR. Thus, public water scarcity backgrounds and experiences with water shortages positively impact their decision to support and pay for nature-based solutions in the basins feeding their cities with water in order to enhance water security.

The findings from this study should be generalized to other regions and countries with caution. As covered in the General Introduction (Chapter 1), public perceptions can vary across countries and regions as they are dependent on experiences with water scarcity. Here, it is demonstrated how these experiences can affect public decision and support for NbS, which can inform policy-making mainly in developing countries where non-market valuation studies through stated preference methods are scarce.

# Part III

# Thesis conclusion

# Chapter 7

# General conclusions

This study brings together a climate change impact assessment and an elicitation of public preferences to enhance water supply reliability and, therefore, water security in Campo Grande and the São Paulo Metropolitan Region. To the best of knowledge, this is an unprecedented study using the new unmitigated climate change scenario (SSP3-7.0) from CMIP6 and incorporating the adoption of nature-based solutions (NbS) into a discrete choice experiment as measures for the conservation of watershed services. Turning to the **first research question** (Section 1.2 in Chapter 1), the assessment of climate change impacts on water security shows an increase in the risk of water scarcity and vulnerability, mainly until the mid-century. Even when analyzing the historical period, the imbalance between water availability and demand becomes evident. These findings indicate a water supply reliability is already vulnerable to meeting the increasing demand — which is already observed and widely discussed by authorities — and climate change can further exacerbate water insecurity. This first part of the thesis takes us to the investigation of public support and preferences for alternatives to improve water security and safeguard water supply, nature-based solutions (**second research question**). This unprecedented study incorporated afforestation and agroforestry systems (nature-based solutions) into the discrete choice experiment design, contrasting it with water harvesting technologies (a very common grey infrastructure).

Agroforestry is the most preferred measure to be implemented and tackle drinking water insecurity in both Campo Grande and the São Paulo Metropolitan Region. There was no statistically significant difference between preference for afforestation over water harvesting or vice-versa. There is also no significant effect of uncertainties about the perceived ineffectiveness of agroforestry and afforestation on preferences for these two nature-based solutions. The findings support the hypothesis that there is public support and preference for solutions that tackle socioeconomic and environmental challenges while also provide ecosystem services (e.g., water provision), despite uncertainties about their effectiveness is still a concern. Moving from the measures to the actual improvements in drinking water reliability, there is an overall preference for the reduction of duration over frequency of future water shortages. Nevertheless, there is no significant effect of reducing frequency or duration on the utility of the Campo Grande residents. This also corroborate the hypothesis that water scarcity background and experiences influence people's preferences. In Campo Grande, where people have faced less frequent and severe water restrictions and rationing efforts in comparison with the São Paulo Metropolitan Region, the respondents neglected these two attributes of water supply reliability (i.e., frequency and duration).

The **third research question** tries to fill the gap in better understanding interactions and feedback loops between society and extreme events (i.e., droughts). Experiences with water use restrictions and rationing significantly influenced people's decision to support and pay for the proposed measures to improve the current water security status in Campo Grande and the São Paulo Metropolitan Region. Both most recent (2019-2021) and recent episodes (2010-2018) of restrictions and rationing are influencing public preferences and willingness to pay. Specifically in Campo Grande, only recent episodes are impacting public willingness to participate in the proposed payment scheme. This corroborates the last cases of water shortage reported in the news. Related to that, individuals who face at least one episode of water restrictions in Campo Grande have their utility increased with the reduction in the frequency of future water shortages. The expectation that droughts will increase was also keystone of public decision-making.

Since a considerable amount of protest response was observed, people's motives and underlying behavior were further investigated in the **forth research question**. The main reason behind protesting is the lack of trust that the money will be invested in measures to improve water security. Besides, the respondents think the different levels of the government should pay because the taxes they pay already suffice. The probit model results corroborate those of the MMNL and showed that experiences with restrictions and rationing are also influencing protest behavior. Those who have endured restrictions and rationing efforts are more prone to not protesting. Particularly in the São Paulo Metropolitan Region, individuals who think nature-based solutions are ineffective in comparison to water harvesting are also more likely to protest. This relationship was not observed in Campo Grande. This finding not only supports the hypothesis that experiences with restrictions and rationing influence public decision to pay but also robustly indicates that these experiences are intrinsically related to protesting.

## 7.1 Further research and recommendations

During the journey of conducting this research, limitations and new hypothesis and ideas came up. Regarding the climate change impacts assessment, there are persistent challenges ahead related to moving beyond grid resolution and dynamically downscaling the global models to support and inform water resources management at a basin scale. Another limitation is related to the number of available models for the construction of the ensemble at that time. The ideal is to incorporate into the multimodel ensemble as many models as possible to overcome systematic errors. It is also beyond the scope of this thesis, but investigating the impact of how model parameterization and uncertainties are communicated affect the decision-making of policymakers. When investigating public preferences for nature-based solutions, a concern arose. In the analyses it is not possible to separate water supply disruptions due to infrastructure problems from water shortages due to decreased water availability. This turned out to be a limitation in this study. On the other hand, there is great potential to continue investigating preferences and willingness to pay for nature-based solutions to improve a wide range of watershed services at a national scale. This kind of studies is of paramount importance for informing policy making and having effective strategies to tackle water insecurity and increase the resilience of basins to climate change impacts. Furthermore, local-scale studies on the influence of NbS on the basin's hydrological response to improve water security are of paramount importance. The NbS potential to improve water security is very context-specific, and local/regional hydro-climatic characteristics should be considered.

When discussing the implications of this work throughout this thesis, it was unavoidable to question about programs of Payment for Watershed Services (PWS). Preference and willingness to pay elicitation is keystone to carry out enhancements in the format of these programs in Brazil. An economic valuation is fundamental to better reflect participants expectations on the payments received, which are sometimes only incentives. This prospective study will also allow for the establishment of a robust water market. In Brazil these program are rarely evaluated in the means of ensuring the effectiveness of the implemented practices and the impact on the target objectives. A cost-benefit analysis can contribute to better allocating investments and ensuring the benefits provided by PWS programs.

The considerable amount of respondents with uncertainties related to the effectiveness of nature-based solutions unveils an urgent need to strengthen the bridge between science and society. It is important for promoting environmental education and raise awareness of the threats on water security and the role of environmental conservation. Some actions can be taken: (i) continuously monitor water and drought-related variables, (ii) make scientific findings available to the general public using adequate visual, format, and language, and (iii) promote public debate and engagement in decision and policy-making.

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# Appendices

# APPENDIX A

# SWAT+ input data

The content presented in this appendix consists of the input data type and source used to set and calibrate the SWAT+ model for the Guariroba River basin (Table 7) and the Jaguari River basin (Table 8).

Table 7 – Input data source for the Guariroba River basin.

| Data type | Description | Resolution | Source |
|---|---|---|---|
| Digital Elevation Model | IKONOS image | 10 m | HEroS/UFMS |
| Soil order | - | 1:160,000 | Grande and Águas Guariroba S/A (2008) |
| Soil characteristics | Soil depth, texture, and organic matter<br>Hydrological group<br>Other soil parameters estimated by pedo-transfer functions | Typical soil profile | Anache et al. (2015)<br>Sartori, Neto and Genovez (2005)<br>Saxton and Rawls (2006) |
| Land use and land cover | Land use and land cover in 2014 | 30 m | MapBiomas[a] |
| Streamflow | - | Daily | HEroS/UFMS |
| Climate | Precipitation | Daily | HEroS/UFMS, Xavier, King and Scanlon (2016), and ERA5[b] |
| | Maximum and minimum temperature | Daily | Xavier, King and Scanlon (2016) and ERA5 |
| | Wind speed at 2 m | Daily | |
| | Relative humidity | Daily | |
| | Surface net downward shortwave radiation | Daily | |

Note: HEroS is the Laboratory of Hydrology, Erosion, and Sediment at the Federal University of Mato Grosso do Sul. [a] MapBiomas Project is a multi-institutional initiative to generate annual land cover and use maps using automatic classification processes applied to satellite images. The complete description of the project can be found at <http://mapbiomas.org>. [b] ERA5 reanalysis replaces the ERA-Interim global climate data (HERSBACH et al., 2020)

Table 8 – Input data source for the Jaguari River basin.

| Dados | Descrição | Resolução | Fonte |
|---|---|---|---|
| Digital Elevation Model | Shuttle Radar Topography Mission (SRTM) | 30 m | USGS - United States Geological Survey |
| Soil order | Soil Map of the São Paulo State | 1:250,000 | Oliveira et al. (1999) |
| | Soil Map of the Minas Gerais State | | Amaral et al. (2004) |
| Soil Characteristics | Soil depth, texture e organic matter | Typical soil profile | Alkimim (2009) |
| | Hydrological group | | Sartori, Neto and Genovez (2005) |
| | Other soil parameters estimated by pedo-transfer functions | | Saxton and Rawls (2006) |
| Land use and land cover | Land use and land cover in 2000 | 30 m | MapBiomas[a] |
| Streamflow | - | Daily | SABESP |
| Climate | Precipitation | Daily | SABESP, Xavier, King and Scanlon (2016), and ERA5[b] |
| | Maximum and minimum temperature | Daily | Xavier, King and Scanlon (2016) |
| | Wind speed at 2 m | Daily | |
| | Relative humidity | Daily | |
| | Surface net downward shortwave radiation | Daily | |

Note: SABESP is the São Paulo Basic Sanitation Company (from Portuguese *Compania de Saneamento do Estado de São Paulo*). [a] MapBiomas Project is a multi-institutional initiative to generate annual land cover and use maps using automatic classification processes applied to satellite images. The complete description of the project can be found at <http://mapbiomas.org>

# APPENDIX B

# Climate models and projections

This appendix provides additional information on the General Circulation/Earth System models that composes the multimodel ensemble, as well as further detail on the performance of bias correction and projected changes in the meteorological and hydrological variables. First, it is provided below some characteristics of the models from the Coupled Model Intercomparison Project phase 6 (CMIP6) used to compute the ensemble (Table 9). Each scenario adopted is detailed in Table 10.

Table 9 – Climate models (r1i1p1f1) considered for the multimodel ensemble.

| Institutions | CMIPs | Spatial resolution | Reference |
|---|---|---|---|
| CMCC | CMCC-ESM2 | 1.3°x 0.9° | Lovato, Peano and Butenschön (2021) |
| EC-Earth | EC-Earth3 | 0.7°x 0.7° | EC-Earth Consortium (2019) |
| INM | INM-CM4-8 | 2.0°x 1.5° | Volodin et al. (2019a) |
| INM | INM-CM5-0 | 2.0°x 1.5° | Volodin et al. (2019b) |
| MPI | MPI-ESM1-HR | 0.9°x 0.9° | Schupfner et al. (2019) |
| MRI | MRI-ESM2-0 | 1.1°x 1.1° | Yukimoto et al. (2019) |
| NCC | NCC-NorESM2-MM | 0.9°x 1.25° | Bentsen et al. (2019) |

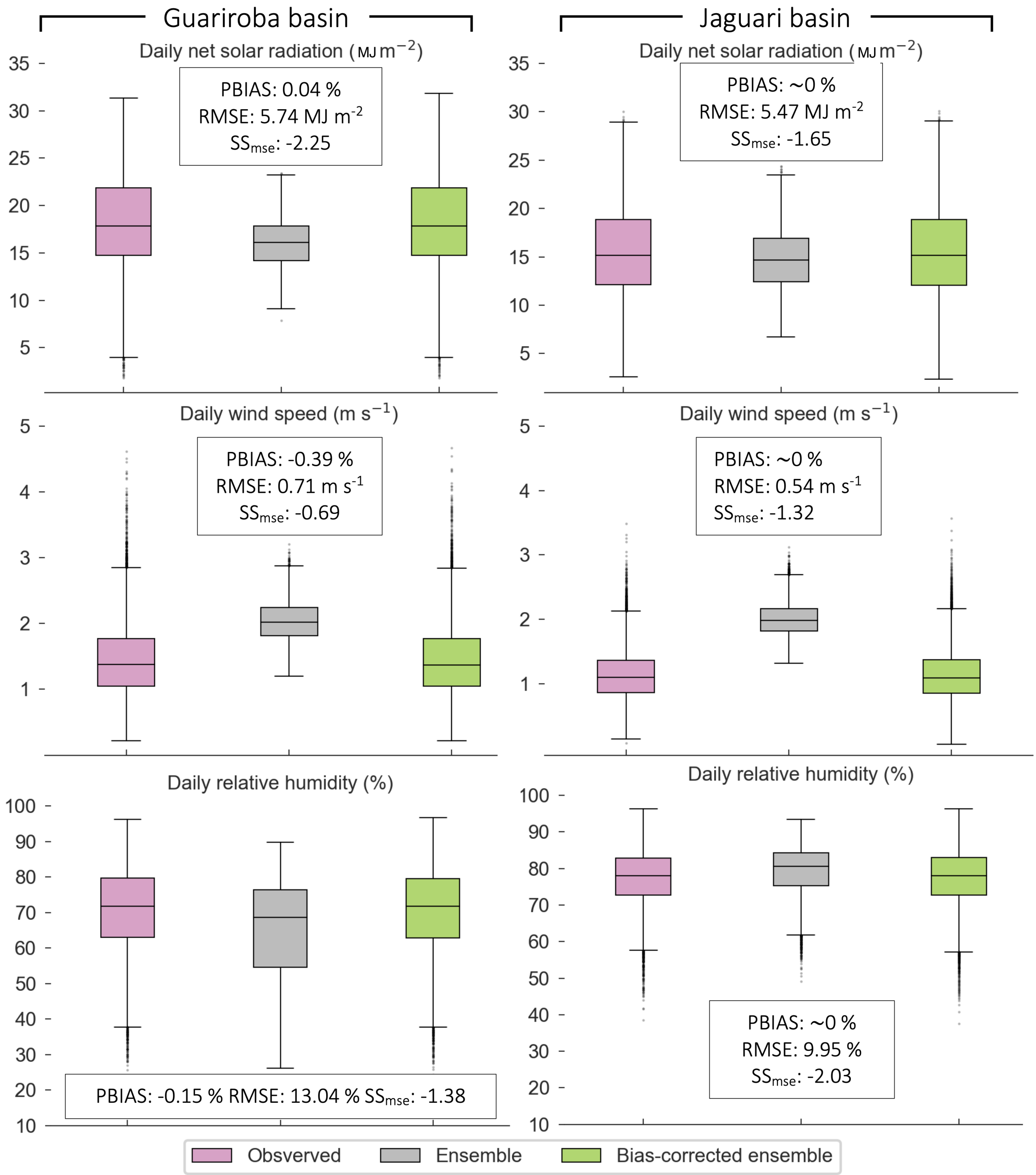
Note:CMCC stands for Centro Euro-Mediterraneo sui Cambiamenti Climatici (Italy), EC-Earth is the EC-Earth Consortium (Europe), INM is the Institute for Numerical Mathematics (Russia), MPI is the Max Planck Institute for Meteorology (Germany), MRI is the Meteorological Research Institute (Japan), and NCC is the Norwegian Climate Center (Norway).

Table 10 – Description of the three shared socioeconomic pathways adopted in this study.

| Scenario name | Forcing category | Description |
|---|---|---|
| Middle of the road (SSP2-4.5) | Medium | This scenario represents the medium part of the range of future pathways and updates the Representative Concentration Pathway 4.5 (RCP4.5 from CMIP5). It assumes trends to continue their historical patterns without substantial deviations and combines intermediate societal vulnerability with intermediate forcing level, resulting in a warming of about 2.7°C by 2100. Land use change and aerosols are not extreme compared with other SSPs. |
| Regional rivalry (SSP3-7.0) | High | This scenario assumes a prioritization of regional security by countries and represents the medium to high end of future pathways. It is similar to forcing in the SSP2-4.5. This scenario is a better exploration of possible baseline in a world that fails to enact climate policies and to invest in education or health. It lies in between the worst (SSP5-8.5) and more reasonable scenario (SSP2-4.5), resulting in a warming of 3.6°C. Substantial land use change and near-term climate forcers (NTCF) emissions are considered, allowing an analysis of sensitivity of regional climate to land use and aerosols. |
| Fossil-fuelled development (SSP5-8.5) | High | This scenario represents the high end of the future pathways, with emissions sufficient to produce a radiative forcing of 8.5 W $m^{-2}$ by 2100. It updates the RCP8.5 from CMIP5, which is the worst no-policy baseline scenario, even though they are not directly comparable. This SSP scenario has higher $CO_2$ concentrations but lower methane concentrations compared with RCP8.5, reaching 4.4°C by 2100. This scenario assumes relatively optimistic trends for human development with an energy intensive, fossil-based economy. |

Below details on the evaluation of the bias-corrected ensemble are provided for the variables not included in the main text (Figure 14) The projected climate change impacts on all meteorological variables used in this study are shown in two parts. **Part B.1** and **Part B.2** corresponds to the results for the Guariroba River (Figures 15 and 16) and Jaguari River basins (Figures 17 and 18), respectively.

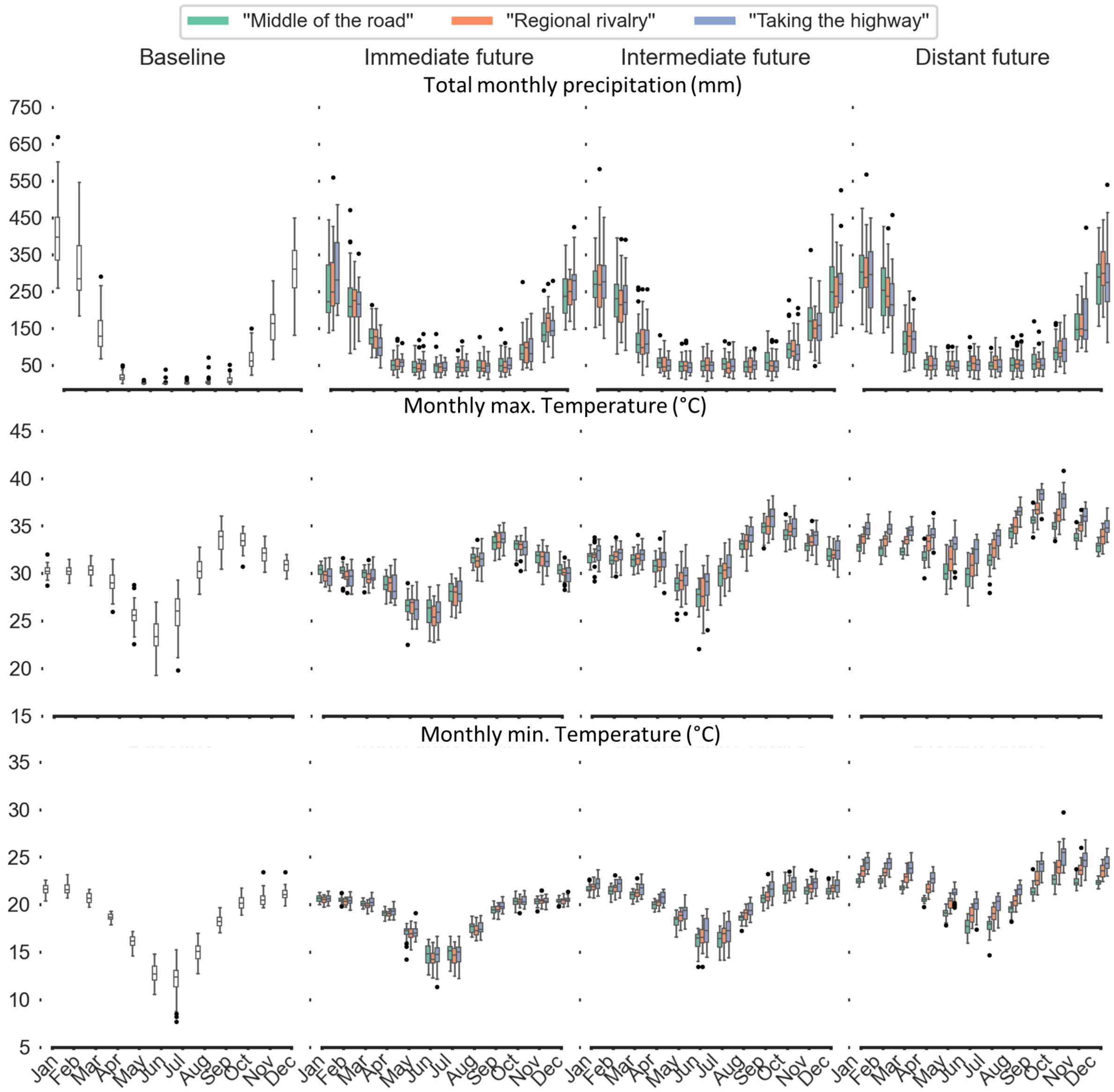
Figure 14 – Distribution of the projected daily net solar radiation ($MJ\ m^{-2}$), wind speed ($m\ s^{-2}$), and relative humidity (%) variables for the Guariroba and Jaguari basins in the observed/historical period.




Source: Author.

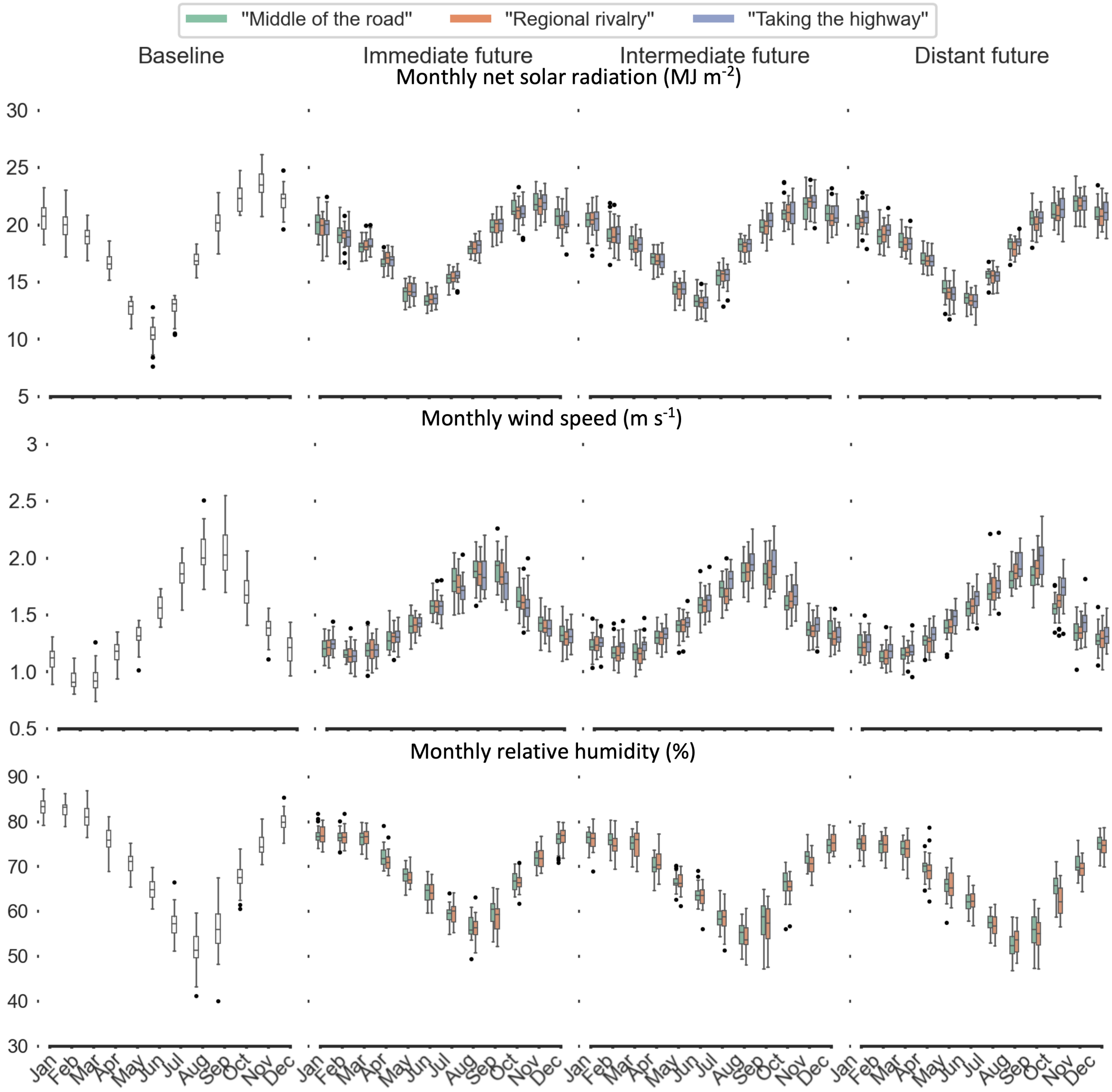
## B.1 Guariroba River basin

Figure 15 – Boxplots of the main meteorological variables under the Middle of the Road (SSP2-4.5), Regional Rivalry (SSP3-7.0), and Taking the Highway scenarios (SSP5-8.5) for the Guariroba River basin: monthly precipitation ($mm$) and monthly maximum and minimum temperature (°$C$).




Source: Author.

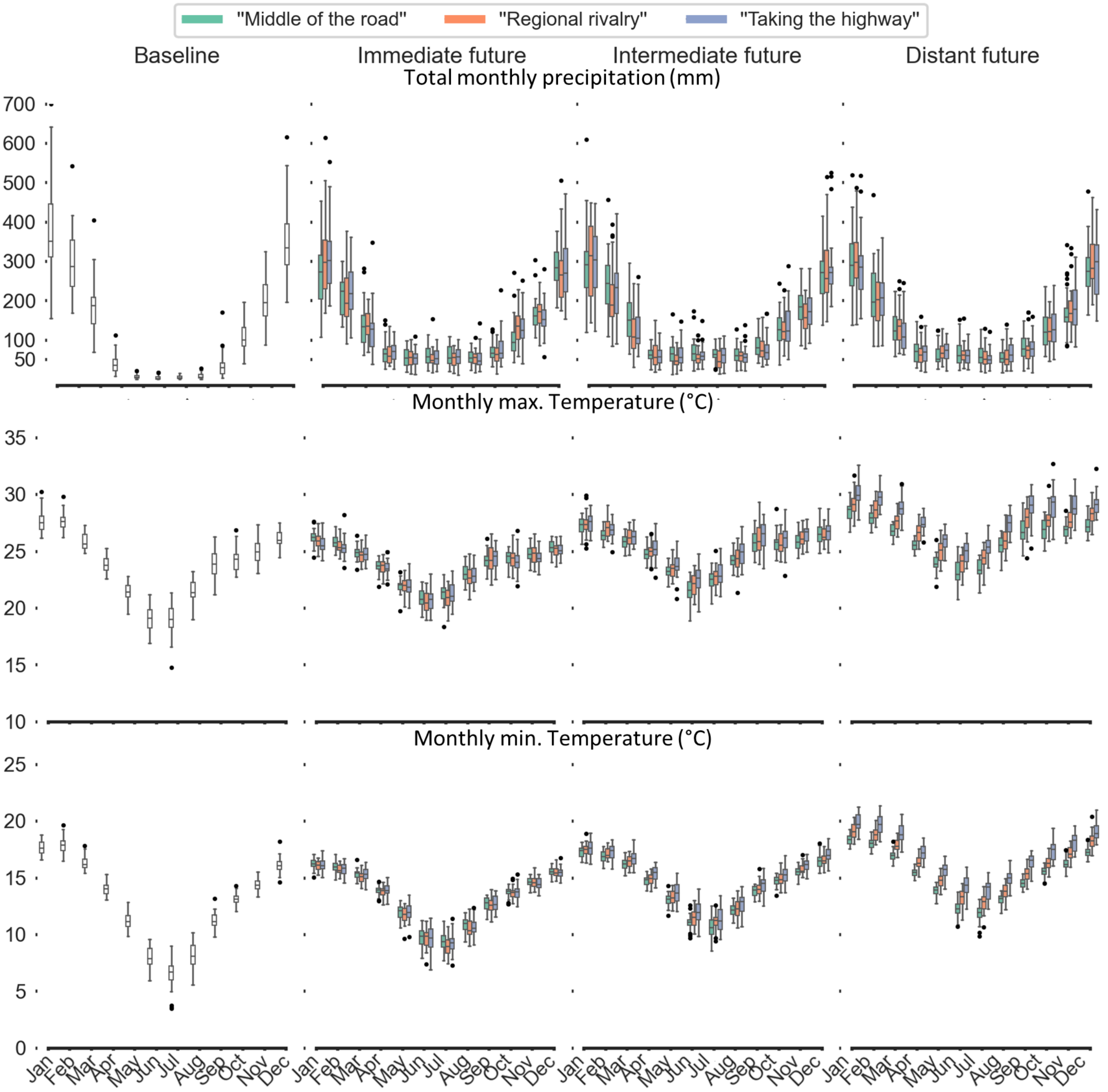
Figure 16 – Boxplots of the three other meteorological variables under the Middle of the Road (SSP2-4.5), Regional Rivalry (SSP3-7.0), and Taking the Highway scenarios (SSP5-8.5) for the Guariroba River basin: monthly net solar radiation ($MJ\ m^{-2}$), monthly wind speed ($m\ s^{-1}$), and monthly relative humidity (%).




Source: Author.

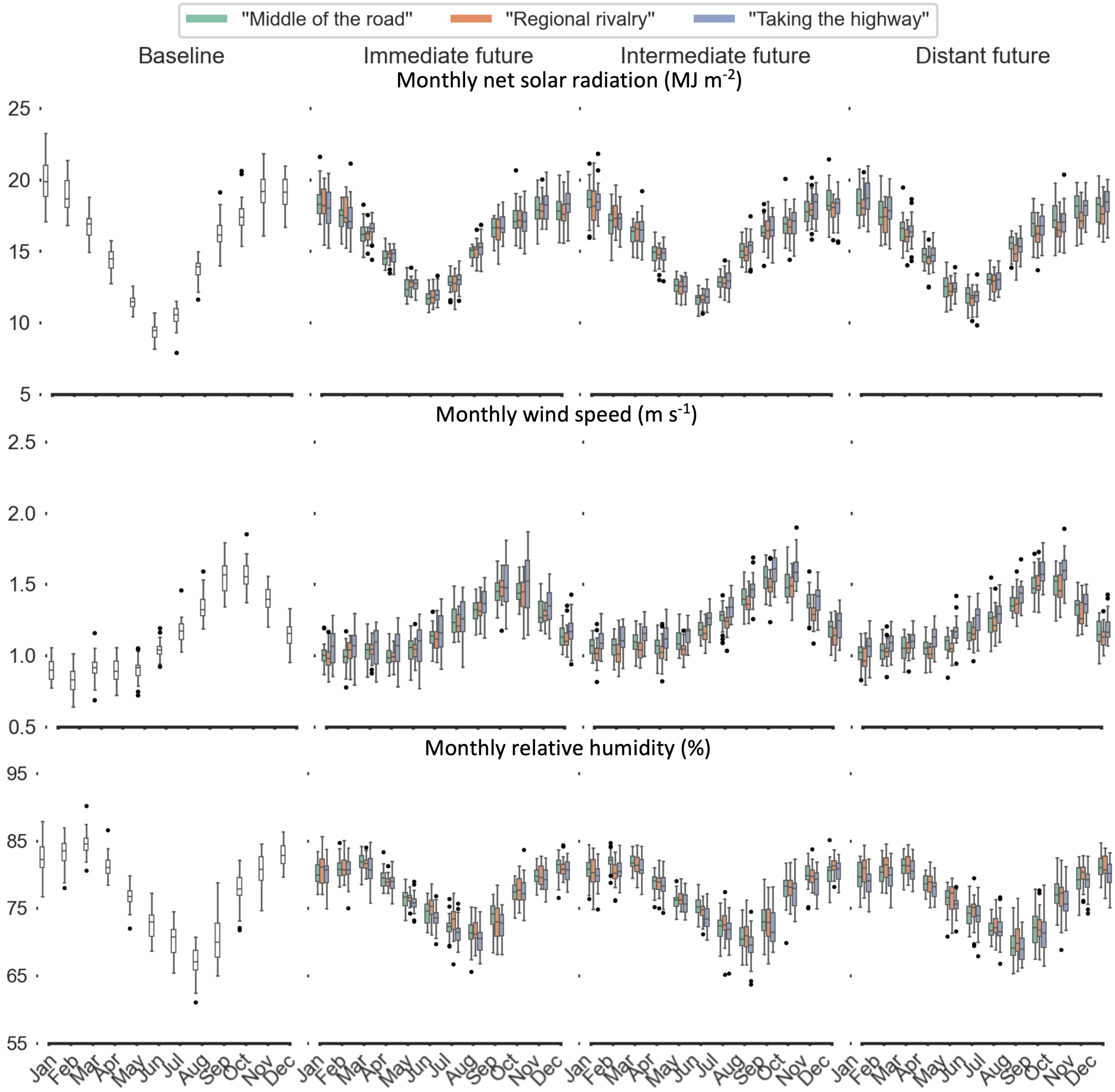
## B.2 Jaguari River basin

Figure 17 – Boxplots of the main meteorological variables under the Middle of the Road (SSP2-4.5), Regional Rivalry (SSP3-7.0), and Taking the Highway scenarios (SSP5-8.5) for the Jaguari River basin: monthly precipitation ($mm$) and monthly maximum and minimum temperature ($°C$).




Source: Author.

Figure 18 – Boxplots of the three other meteorological variables under the Middle of the Road (SSP2-4.5), Regional Rivalry (SSP3-7.0), and Taking the Highway scenarios (SSP5-8.5) for the Jaguari River basin: monthly net solar radiation ($MJ\ m^{-2}$), monthly wind speed ($m\ s^{-1}$), and monthly relative humidity (%).



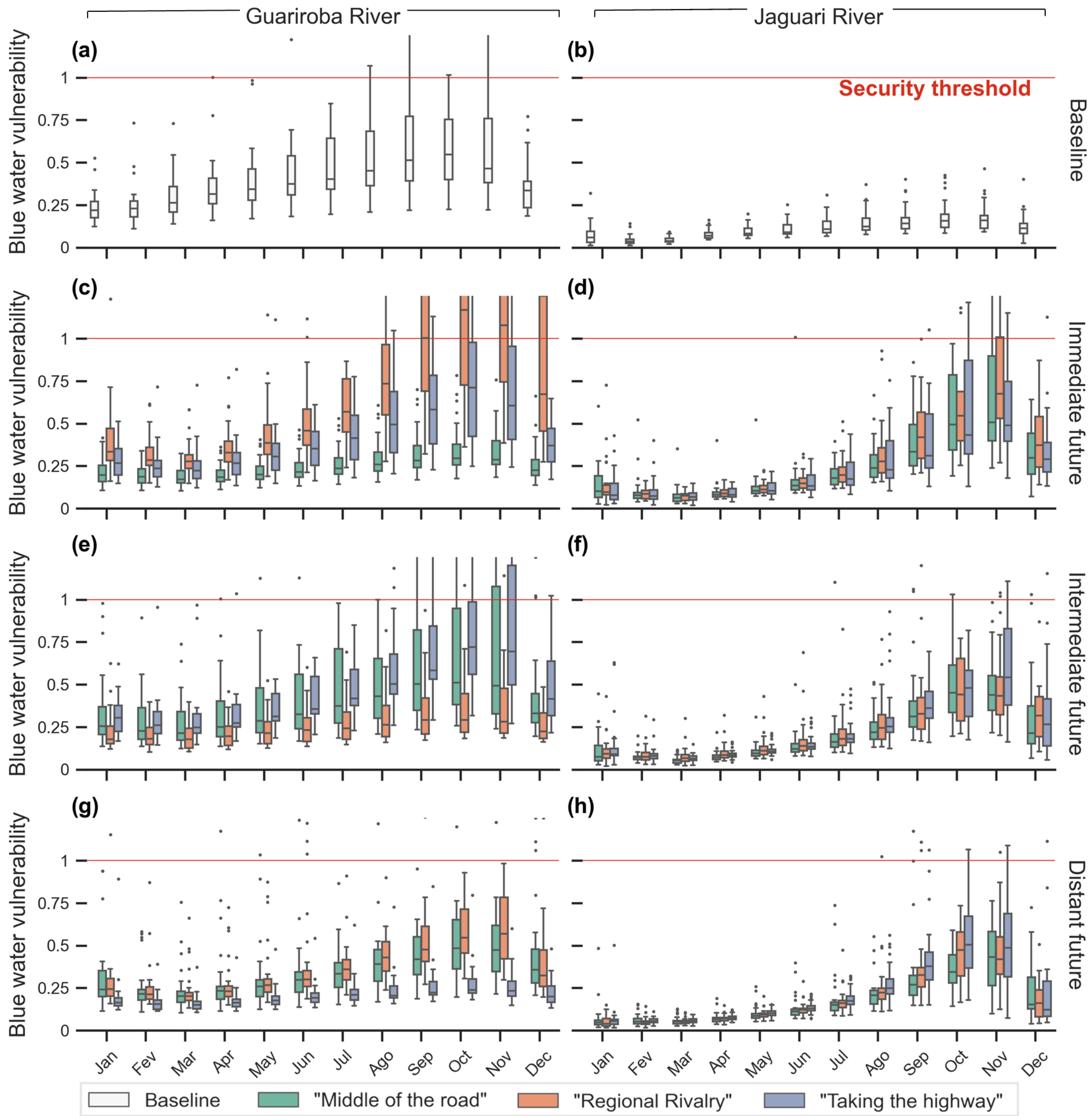

Source: Author.

# APPENDIX C

# Water scarcity and vulnerability under climate and water demand scenarios

This appendix provides additional information on the projected changes in streamflow and the compound effects of climate change and alternative demand scenarios on the water security indices. The vulnerability indices are firstly presented for both study basins, Guariroba and Jaguari, not included in the main text (Figure 19). Climate change impacts on streamflow of the Guariroba and Jaguari RIvers are depicted in **Part C.1** (Figure 20) and **Part C.2** (Figure 23), respectively. Subsequently, information about the effects of climate change and water demand scenarios on the water scarcity (Figure 21 for the Guariroba basin and Figure 24 for the Jaguari basin) and vulnerability (Figure 22 for the Guariroba basin and Figure 25 for the Jaguari basin) indices is provided.

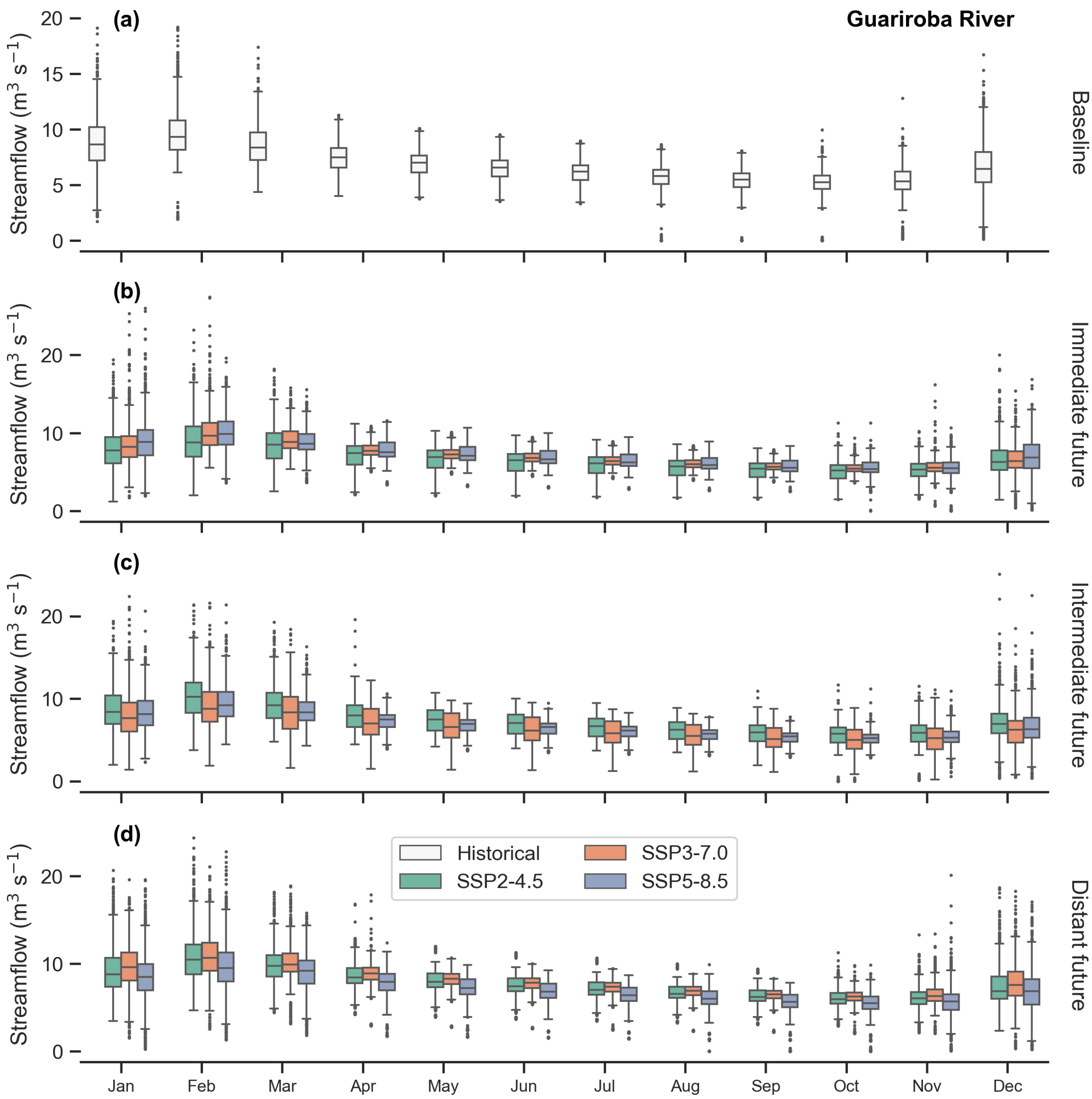
Figure 19 – Water vulnerability index considering the current water demand under three climate change scenarios (SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5 in light purple) over three evaluation periods: baseline (1980-2013), immediate future (2015-2040), intermediate future (2041-2070), and distant future (2071-2100). The red line indicates the security threshold over which characterizes minimum water provision below the required water demand. For the immediate future, the SSP3-7.0 scenario represents more vulnerability to the required water provision for consumptive demand.




Source: Author.

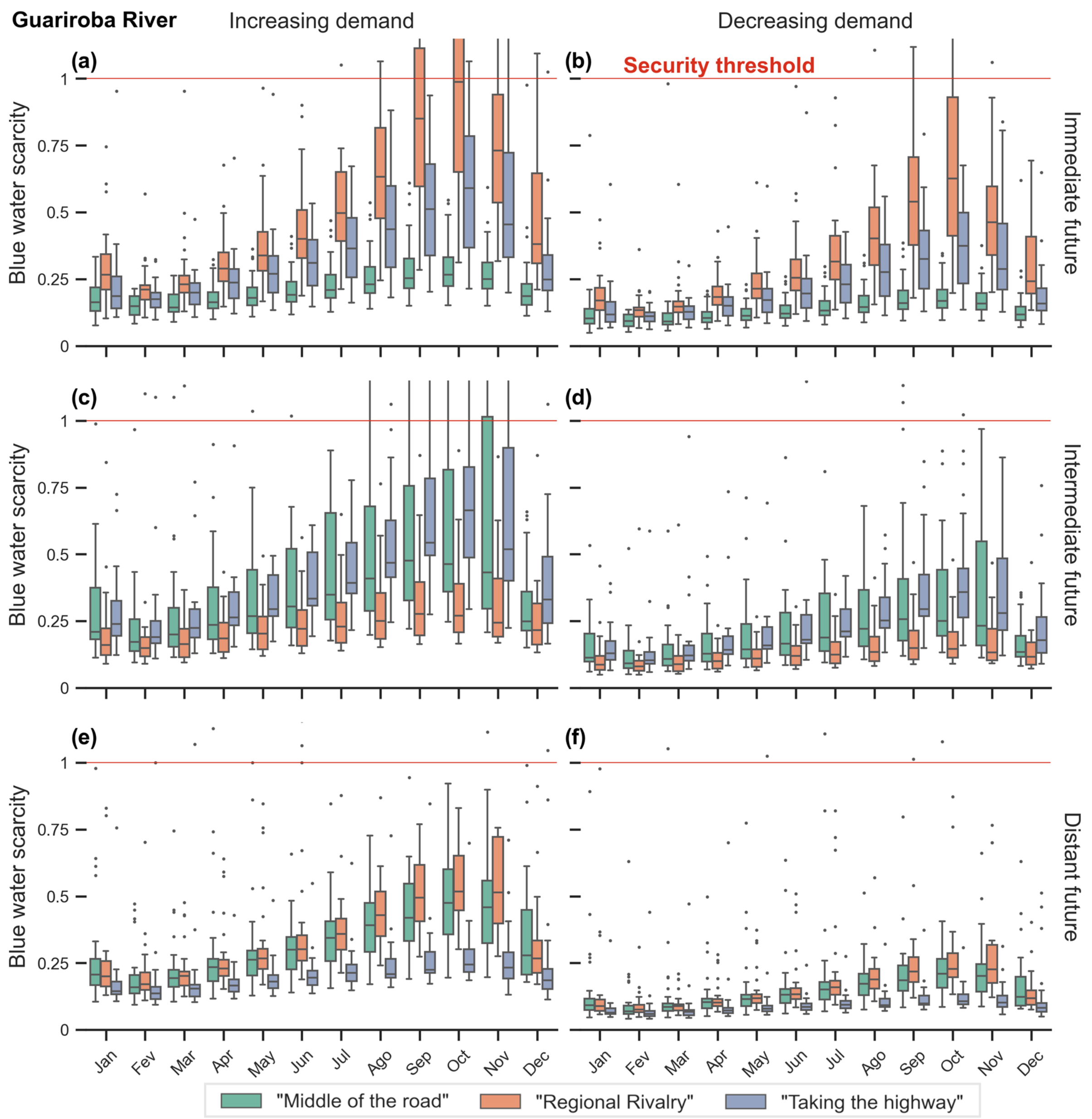
## C.1 Guariroba River basin

Figure 20 – Projected future streamflow in boxplots for the Guariroba River basin under the historical simulations and three climate change scenarios: SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5 in light purple. The projected monthly streamflow was evaluated according to four periods: Baseline (1980-2013), immediate (2015-2040), intermediate (2041-2070), and distant future (2071-2100).



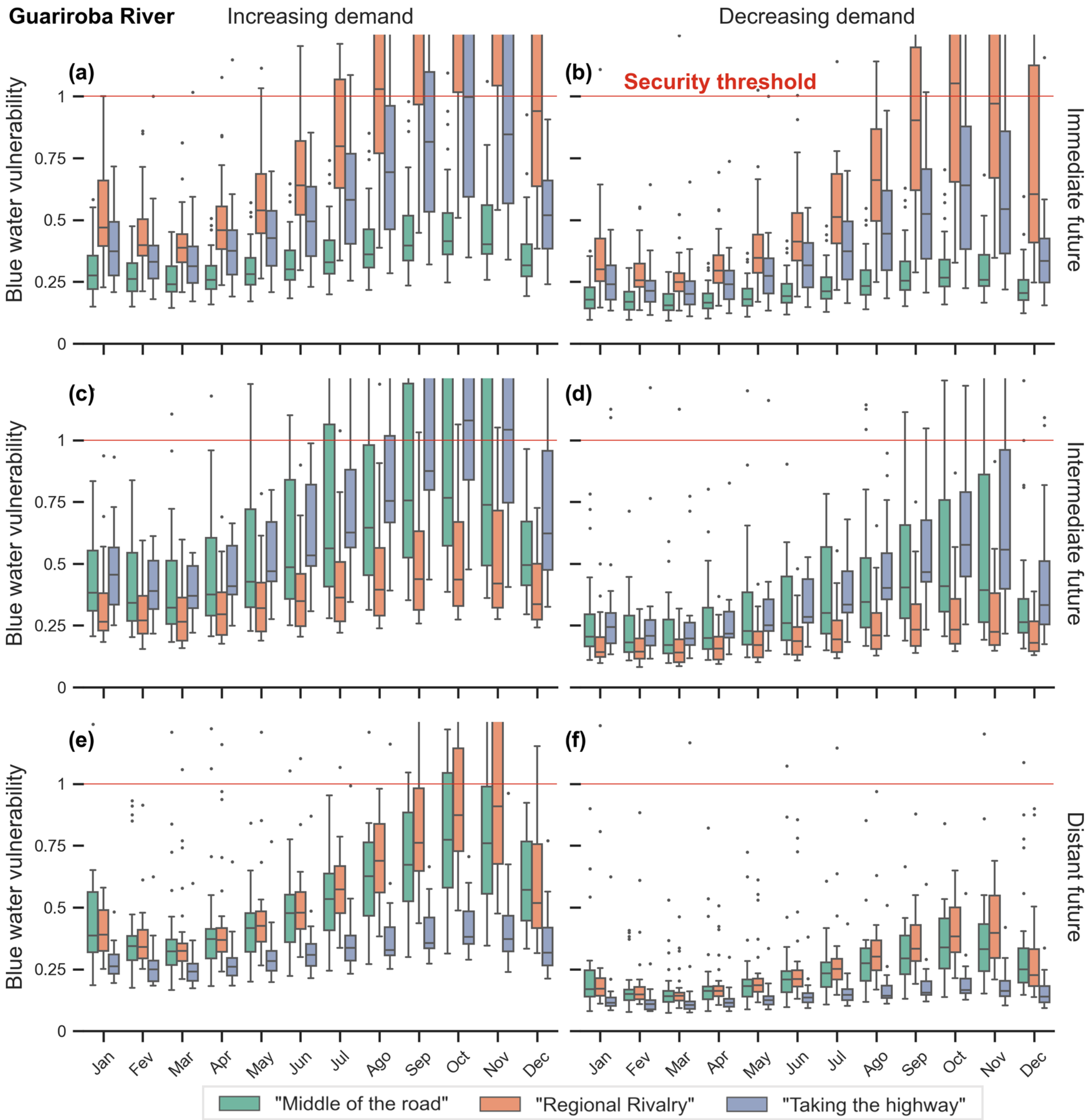

Source: Author.

Figure 21 – Water scarcity index considering increasing and decreasing water demand scenarios under the three climate change projections (SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5 in light purple). An increase of 50% by the intermediate future in water demand led to water scarcity indices higher than the security threshold mainly from September to November under the Regional Rivalry (immediate future) and Middle of the Road scenarios (intermediate future).




Source: Author.

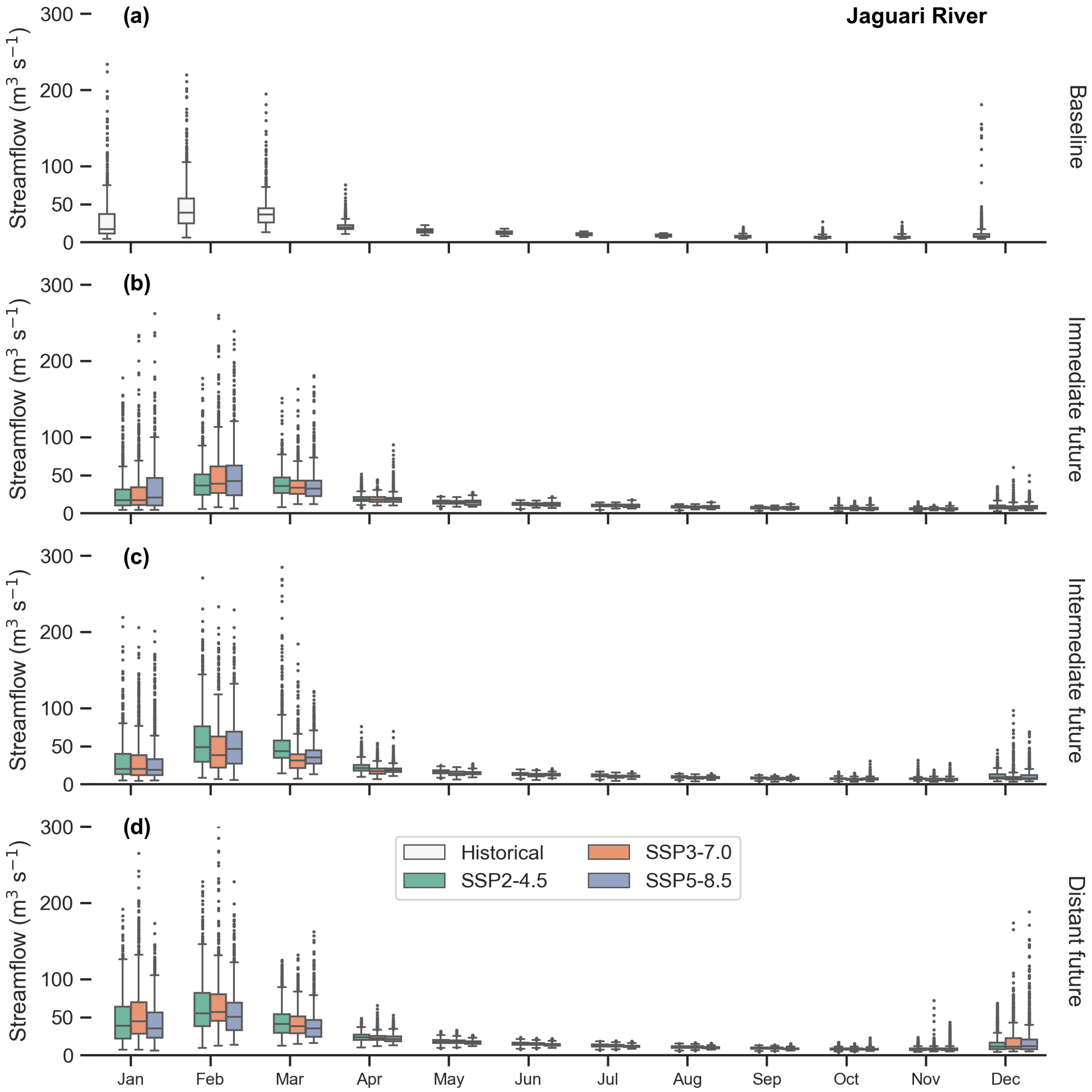
Figure 22 – Water vulnerability index considering increasing and decreasing water demand scenarios under the three climate change projections (SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5 in light purple). Even a progressive decrease in water demand did not decrease the higher vulnerability during the immediate and intermediate future.




Source: Author.

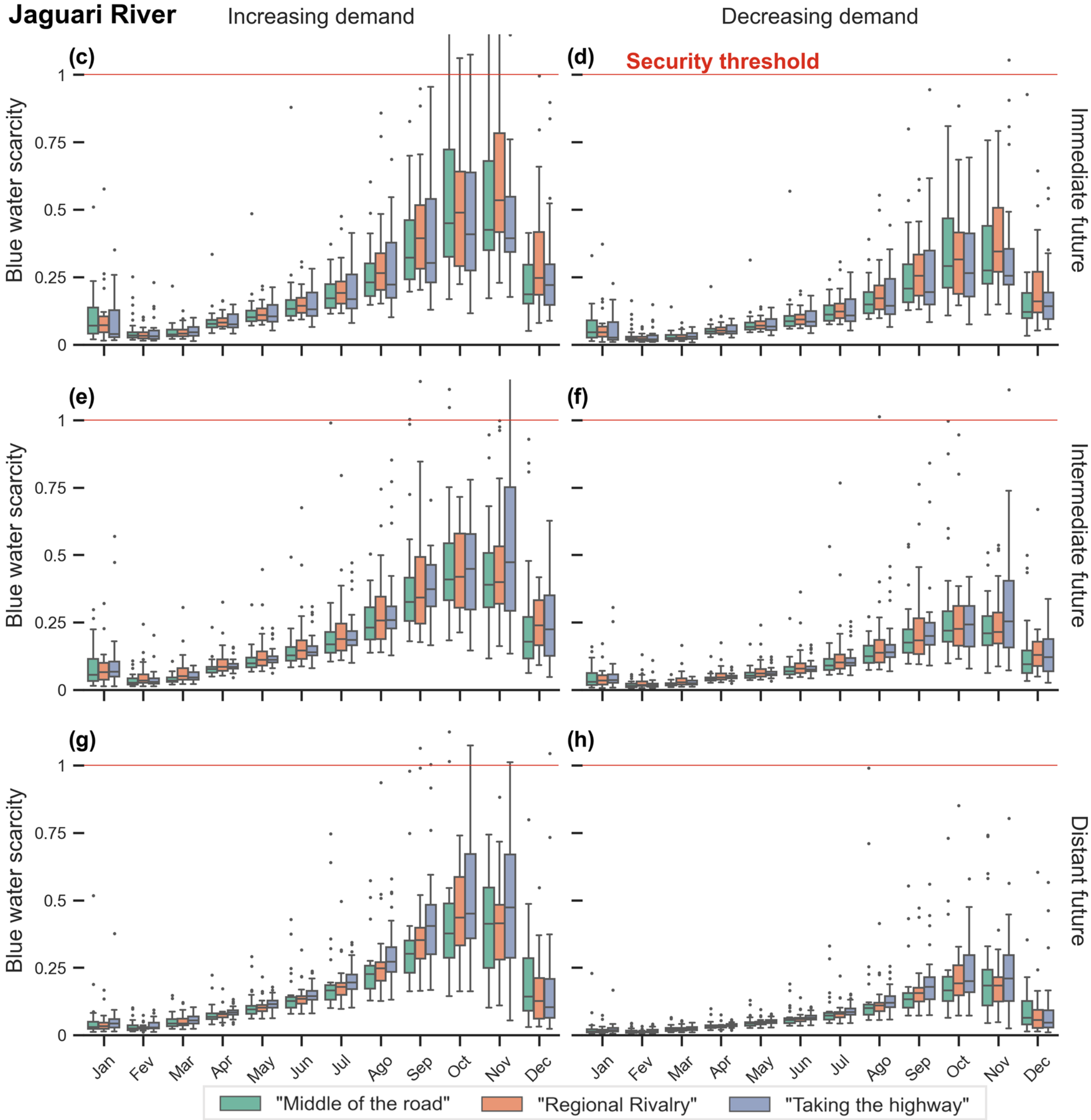
## C.2 Jaguari River basin

Figure 23 – Projected future streamflow in boxplots for the Jaguari River basin under the historical simulations and three climate change scenarios: SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5 in light purple. The projected monthly streamflow was evaluated according to four periods: Baseline (1980-2013), immediate (2015-2040), intermediate (2041-2070), and distant future (2071-2100).



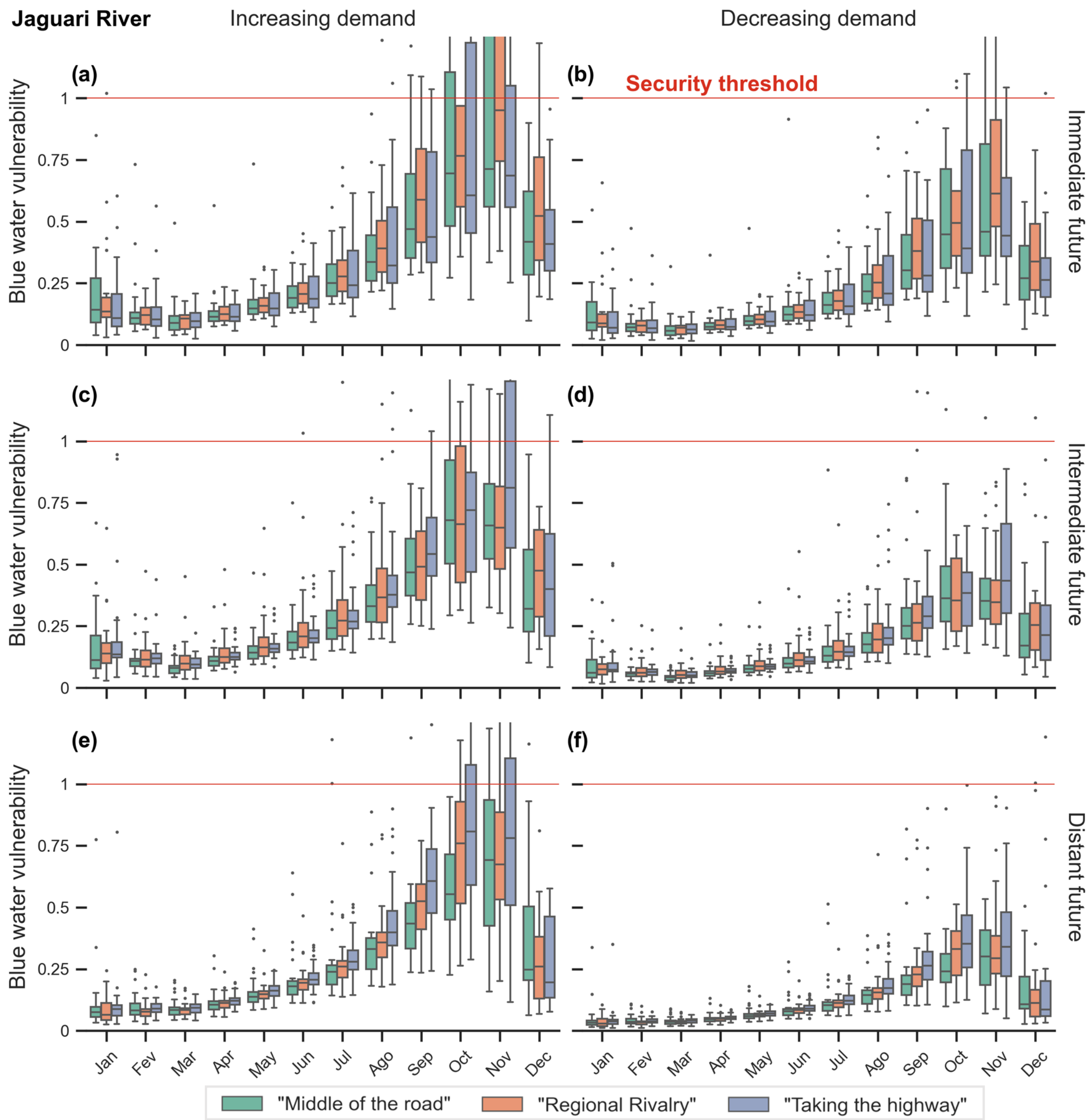

Source: Author.

Figure 24 – Water scarcity index considering increasing and decreasing water demand scenarios under three climate change projections (SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5 in light purple). By 2100, an increase of 60% in water demand under the taking the highway scenario (boxplots in light purple) led to water scarcity indices higher than the security threshold mainly in October and November.




Source: Author.

Figure 25 – Water vulnerability index considering increasing and decreasing water demand scenarios under three climate change projections (SSP2-4.5 in green, SSP3-7.0 in orange, and SSP5-8.5 in light purple). A decrease of 20% in demand by 2070 (intermediate future) was not enough for improving water vulnerability to safe levels as observed during the baseline period




Source: Author.

# APPENDIX D

# Term of Free and Informed Consent

In this appendix the Term of Free Consent is presented in Portuguese (Brazil), as approved by the Ethics Board and then handed in to the interviewees.

## D.1 Termo de Consentimento Livre e Esclarecido (TCLE)

Esta entrevista é parte de uma pesquisa independente realizada pela Universidade de São Paulo e pela Universidade Federal de Mato Grosso do Sul e foi avaliada e aprovada pelo Comitê de Ética em Pesquisa (CEP) em 18 de novembro de 2021 (**CAAE 51992421.1.0000.5422**), número do parecer de aprovação: **5.113.450**.

Os resultados dessa pesquisa serão utilizados para informar os tomadores de decisão e responsáveis pela formulação de políticas públicas sobre a segurança hídrica da sua região. Assim, é importante que você responda da forma mais verdadeira possível. Todas as suas respostas serão tratadas de forma completamente confidencial e não serão compartilhadas com mais ninguém. Entrevistaremos uma amostra representativa de centenas de residências familiares na sua região. Os dados serão processados de maneira que não será possível chegar até você ou sua família. Espera-se que você esteja disposto a dedicar de 15 a 20 minutos para preencher este questionário. Ao aceitar participar desta pesquisa, o(a) senhor(a):

1. Assinalará a alternativa “Sim” para aceitar participar da pesquisa, o que corresponderá à assinatura deste Termo de Consentimento Livre e Esclarecido, redigido conforme a Resolução CNS 466/2012;

2. Responderá ao questionário.

3. Autorizará o uso de suas respostas para produção e publicação de trabalhos técnico-científicos sob condição de sigilo e privacidade.

## GARANTIAS LEGAIS:

i **O senhor(a) será esclarecido(a)** sobre a pesquisa em qualquer aspecto que desejar.

ii **O senhor(a) é livre para se recusar a participar**, retirar seu consentimento ou interromper sua participação a qualquer momento. **Sua participação é voluntária** e o(a) senhor(a) pode decidir encerrar sua participação a qualquer momento sem precisar especificar a razão de sua decisão. Sua decisão em não participar da pesquisa não acarretará em nenhum tipo de constrangimento, penalidade ou dano.

iii O senhor(a) possui garantia ao **direito à indenização** diante de eventuais danos comprovadamente decorrentes da pesquisa.

iv **Sua identidade será tratada com respeito**, assegurando e garantindo o **sigilo e confidencialidade** dos seus dados pessoais, ou seja, seu nome não será registrado e qualquer outro dado ou elemento que possa identificá-lo(a) será mantido em sigilo. Todos os dados obtidos na pesquisa serão utilizados exclusivamente com finalidades científicas.

v O senhor(a) tem direito a **01 (uma) via deste Termo de Consentimento Livre e Esclarecido** assinada pelo pesquisador.

## DESCONFORTO, RISCOS E BENEFÍCIOS:

i Sua participação pode envolver **riscos de desconforto** em relação ao tempo gasto para responder o questionário **e de constrangimento** em responder alguma pergunta que não se sinta à vontade em responder. Sua privacidade será respeitada conforme previsto nas garantias mencionadas acima.

ii Sua participação também pode envolver **risco de vazamento de dados** coletados.

iii **Não há benefícios diretos** aos participantes desta pesquisa.

## ACOMPANHAMENTO E ASSISTÊNCIA:

i São garantidos esclarecimentos adicionais e informações sobre o estudo e suas consequências pelas pessoas que acompanharão e conduzirão as entrevistas.

ii Os pesquisadores garantem que este termo será cumprido e que responderão a quaisquer questões colocadas pelo(a) participante através dos contatos:

a. Jullian Souza Sone: **julliansone@usp.br**

b. Prof. Dr. Edson Wendland: **ew@sc.usp.br**

c. Prof. Dr. Paulo Tarso Sanches de Oliveira: **paulo.t.oliveira@ufms.br**

d. **O Comitê de Ética em Pesquisa com Seres Humanos da Faculdade de Zootecnia e Engenharia de Alimentos da Universidade de São Paulo** (CEPH/FZEA/USP) para dúvidas ou denúncias relacionadas à ética da pesquisa e localiza-se na Av. Duque de Caxias Norte, 225, Jd. Elite, CEP 13635-900, Pirassununga – São Paulo, telefone (19) 3565-6759, e-mail: cepfzea@usp.br

**DECLARAÇÃO DE VONTADE:**

Tendo sido informado(a) dos objetivos da pesquisa acima de maneira clara e detalhada, sanado minhas dúvidas, **declaro meu livre consentimento em participar**, estando totalmente ciente de que minha participação é voluntária e não há nenhum valor financeiro a receber ou a pagar pela minha participação. Eu entendo que sou livre para aceitar ou recusar e que posso interromper minha participação a qualquer momento. Eu estou ciente de que o pesquisador se responsabilizará por efeitos adversos ou quaisquer outros danos comprovadamente causados pela minha participação nesta pesquisa, considerando possíveis ressarcimentos e indenizações. O pesquisador me certificou de que todos os dados coletados nesta entrevista serão confidenciais. **Eu concordo que esses dados sejam usados para os propósitos desta pesquisa** e assino este termo em duas vias, uma das quais foi-me entregue.

| | |
|---|---|
| ................................ | ................................ |
| Assinatura do participante | Assinatura do pesquisador |

# APPENDIX E

# Choice Experiment questionnaire

The content in this appendix comprises the questionnaire and the discrete choice experiment carried out in November 2021. The document is presented as used in the survey, in Portuguese (Brazil), mother tongue of the interviewees.

*Esta entrevista é parte de uma pesquisa independente realizada pela Universidade de São Paulo e pela Universidade Federal de Mato Grosso do Sul. Os resultados gerados poderão contribuir para melhorar a segurança hídrica da sua região.*

*Todas as suas respostas serão tratadas de forma completamente confidencial e não serão compartilhadas com mais ninguém. Os resultados serão protegidos de maneira que não será possível chegar até você ou sua família. Sua participação nessa pesquisa é completamente voluntária e levará no máximo 20 minutos.*

*Gostaríamos que você se comprometesse a não divulgar as ideias que lhe serão apresentadas e nem reproduzisse o conteúdo exposto nesta pesquisa. Você pode acessar o Termo de Consentimento Livre e Esclarecido aqui.*

Você concorda?

☐ 1 – Sim.

☐ 2 – Não. *<ENCERRAR>*

## 1. Bloco Água

*Agora vamos falar sobre água.*

1.1. Pensando nas diversas formas de cobranças pelo consumo da água, qual frase melhor se enquadra no sue perfil?

☐ 1 – Recebo a conta de água pelo correio ou via digital, através de e-mail ou aplicativo de celular.

☐ 2 – A conta de água é inclusa no valor do aluguel que pago todo mês de forma que consigo identificar o valor referente ao consumo de água.

☐ 3 – A conta de água é inclusa na taxa de condomínio onde moro de forma que consigo identificar o valor referente ao consumo de água.

☐ 4 – A conta de água é inclusa no meio de outras diversas cobranças de forma que não consigo identificar o valor referente ao consumo de água. *<ENCERRAR>*

1.2. Quais as principais fontes de água potável, ou sejam água para beber ou utilizar para cozinhar em sua residência? Se possui várias fontes, por favor, classifique suas escolhas em ordem de maior utilização, considerando que o 1º lugar é o que você mais utiliza.

☐ 1 – Água encanada.

☐ 2 – Poço privado.

☐ 3 – Poço público.

☐ 4 – Cisternas.

☐ 5 – Água engarrafada, e.g., água mineral (litros).

☐ 6 – Outro. Por favor, especifique:

1.3. (Se código 5 na Q1.2.) Você disse que consome água mineral engarrafada para beber e cozinhar. Qual o tipo de garrafa/galão que você costuma comprar?

☐ 1 – Garrafa de 500 ml.
☐ 2 – Garrafa de 1 litro.
☐ 3 – Garrafa de 1,5 litros.
☐ 4 – Galão de 5 litros.
☐ 5 – Galão de 10 litros.
☐ 6 – Galão de 20 litros.
☐ 7 – Outros. Por favor, especifique: ……………………………………………….................

1.4. (Se códigos 1, 2 e 3 na Q1.3.) Quantas garrafas você consome por dia?

☐ 1 – Até 2 garrafas.
☐ 2 – De 3 a 6 garrafas.
☐ 3 – De 7 a 10 garrafas.
☐ 4 – Mais de 10 garrafas.

1.5. (Se códigos 4, 5 e 6 na Q1.3.) Quanto tempo costuma durar um galão na sua casa?

☐ 1 – Uma semana.
☐ 2 – Duas semanas.
☐ 3 – Três semanas.
☐ 4 – Um mês.
☐ 5 – Um mês e meio.
☐ 6 – Dois meses.
☐ 7 – Mais de dois meses.

1.6. (Se código 5 na Q1.2.) Qual o valor máximo que você aceita pagar por um(a) [galão/garrafa] de água mineral, que você costuma comprar?

R$ ............................

1.7. Qual o valor médio mensal que você costuma pagar pelo consumo de água em sua residência? Você pode usar uma conta de água caso a tenha de fácil acesso. Se você não sabe o valor exato, por favor, nos informe seu melhor palpite.

R$ ............................

**2. Experiências de escassez hídrica**

*Agora vamos ler um texto e gostaríamos que você prestasse bastante atenção.*

> Gostaria de informá-lo sobre a situação a água em(na) [**Campo Grande/Região Metropolitana de São Paulo**]. A área onde você vive tem tido secas que têm causado a redução do nível de água do [**Rio Guariroba/Rio Jaguari**] e do seu reservatório. Por isso, tem acontecido restrições no uso da água em sua residência e/ou racionamento de água.
>
> Com as mudanças climáticas é esperado que as secas aumentem e, com isso, diminua ainda mais o volume de água disponível.

2.1. Nos últimos 10 anos, aumentaram os períodos de seca na região em que você vive?

☐ 1 – Sim.
☐ 2 – Não, os períodos de seca não apresentaram piora nos últimos anos.
☐ 3 – Não, o número de anos com períodos de seca diminuiu.
☐ 4 – Não sei.

2.2. Você acredita que a a falta d'água irá aumentar em sua cidade nos próximos 10 anos?

☐ 1 – Sim.
☐ 2 – Não.
☐ 3 – Não sei.

2.3. Você acredita em mudanças climáticas?

☐ 1 – Sim, acredito que as mudanças climáticas são reais.
☐ 2 – Não acredito que mudanças climáticas estejam ocorrendo.

2.4. Você já vivenciou situações de falta d'água que causaram restrições de uso ou racionamento?

☐ 1 – Sim, restrições no uso da água, por exemplo, a proibição em atividades não essenciais como lavar veículos, prédios e calçadas.
☐ 2 – Sim, racionamento de água, por exemplo quando falta água em determinados dias ou horários.
☐ 3 – Não.

2.5. (Se código 1 na Q2.4.) Em qual ano foi a última vez que você vivenciou **restrições** de uso de água em sua residência?

☐ 1 – Neste ano (2021).
☐ 2 – Entre 2019 e 2020.
☐ 3 – Entre 2016 e 2018.
☐ 4 – Entre 2013 e 2015.
☐ 5 – Entre 2010 e 2012.
☐ 6 – Outro. Por favor, especifique: …………………………………………………………………
☐ 7 – Me lembro de ter vivenciado restrições de uso ou racionamento de água, mas não sei qual ano foi a última vez.

2.6. (Se código 2 na Q2.4.) Em qual ano foi a última vez que você vivenciou **racionamento** de água em sua residência?

☐ 1 – Neste ano (2021).
☐ 2 – Entre 2019 e 2020.
☐ 3 – Entre 2016 e 2018.
☐ 4 – Entre 2013 e 2015.
☐ 5 – Entre 2010 e 2012.
☐ 6 – Outro. Por favor, especifique: …………………………………………………………………
☐ 7 – Me lembro de ter vivenciado restrições de uso ou racionamento de água, mas não sei qual ano foi a última vez.

2.7. (Se código 1 na Q2.4.) Com que frequência você tem vivenciado **restrições** de uso de água em sua residência?

☐ 1 – Uma vez nos últimos 10 anos.
☐ 2 – De 2 a 5 vezes nos últimos 10 anos.
☐ 3 – De 6 a 9 vezes nos últimos 10 anos.
☐ 4 – Todos os anos nos últimos 10 anos.

2.8. (Se código 2 na Q2.4.) Com que frequência você tem vivenciado **racionamento** de água em sua residência?

☐ 1 – Uma vez nos últimos 10 anos.
☐ 2 – De 2 a 5 vezes nos últimos 10 anos.
☐ 3 – De 6 a 9 vezes nos últimos 10 anos.
☐ 4 – Todos os anos nos últimos 10 anos.

2.9. (Se código 1 na Q2.4.) Qual foi a maior duração das **restrições** de uso de água que você lembra ter vivenciado nos últimos 10 anos?

☐ 1 – Algumas horas, menos que um dia.
☐ 2 – Um dia.
☐ 3 – De 2 a 5 dias.
☐ 4 – Uma semana.
☐ 5 – De 2 a 3 semanas.
☐ 6 – Um mês.
☐ 7 – De 2 a 6 meses.
☐ 8 – Mais de 6 meses.

2.10. (Se código 2 na Q2.4.) Qual foi a maior duração de **racionamento** de água que você lembra ter vivenciado nos últimos 10 anos?

☐ 1 – Algumas horas, menos que um dia.
☐ 2 – Um dia.
☐ 3 – De 2 a 5 dias.
☐ 4 – Uma semana.
☐ 5 – De 2 a 3 semanas.
☐ 6 – Um mês.
☐ 7 – De 2 a 6 meses.
☐ 8 – Mais de 6 meses.

2.11. Você faz algo para economizar água em sua casa?

☐ 1 – Não.
☐ 2 – Sim, eu:

☐ 2.1 – tomo banho mais curtos.
☐ 2.2 – reduzo o uso da máquina de lavar.
☐ 2.3 – tenho vaso sanitário com economia de água ou dou descarga com menor frequência.
☐ 2.4 – lavo meu carro com menor frequência.
☐ 2.5 – rego meu jardim/plantas com menor frequência.
☐ 2.6 – Outro. Por favor, especifique: ..................................................................

2.12. Você possui caixa d'água em sua residência para armazenar água em situações em que não há fornecimento?

☐ 1 – Sim. ☐ 2 – Não

2.13. Em situações de restrições e racionamento de água, você armazena água por outro meio em residência?

☐ 1 – Sim, tenho uma cisterna.
☐ 2 – Sim, armazeno água em baldes ou outros recipientes.
☐ 3 – Sim, compro água engarrafada.
☐ 4 – Outro. Por favor, especifique: ......................................................................
☐ 5 – Não.

2.14. Na sua opinião, quem é responsável em sua região por garantir que todas as famílias sempre tenham água suficiente em suas casas? Você citou que possui mais de um responsável por garantir água suficiente a todos. Por favor, classifique suas escolhas em ordem de importância, considerando que o 1º lugar é o que você considera mais importante.

☐ 1 – A Prefeitura.
☐ 2 – O Governo do Estado.
☐ 3 – O Governo Federal do Brasil.
☐ 4 – As companhias de abastecimento público.
☐ 5 – Outro. Por favor, especifique: ......................................................................

## 3. Experimento de escolhas

*Agora vamos ler um outro texto e gostaríamos que você prestasse bastante atenção.*

De acordo com estudos atuais, existe a possibilidade de **faltar água** na sua casa em **5 dos próximos 10 anos**. Ou seja, ano sim outro não você e sua família podem ter restrições e racionamento de água que poderão durar até 48 horas (2 dias). A ideia desta pesquisa é apresentar algumas medidas de **conservação de água** para que isso não aconteça. Estamos interessados em saber se **você está disposto(a) a pagar um valor a mais na sua conta de água atual para garantir que você continue recebendo água em quantidade suficiente em sua casa no futuro.**

Vamos apresentar 3 medidas de conservação da água que serão adotadas nas terras agrícolas na bacia do [**Rio Guariroba/Rio Jaguari**].

- Opção 1: **integrar a agricultura + pecuária + plantação de florestas** para o aproveitamento e uso consciente

- Opção 2: **florestamento da região** em áreas que não são florestadas

- Opção 3: **Captação da água da chuva** para que os produtores rurais possam armazenar a água da chuva ao invés de usar a água dos rios, que então, pode ser usada para abastecer a água para as famílias, como a sua.

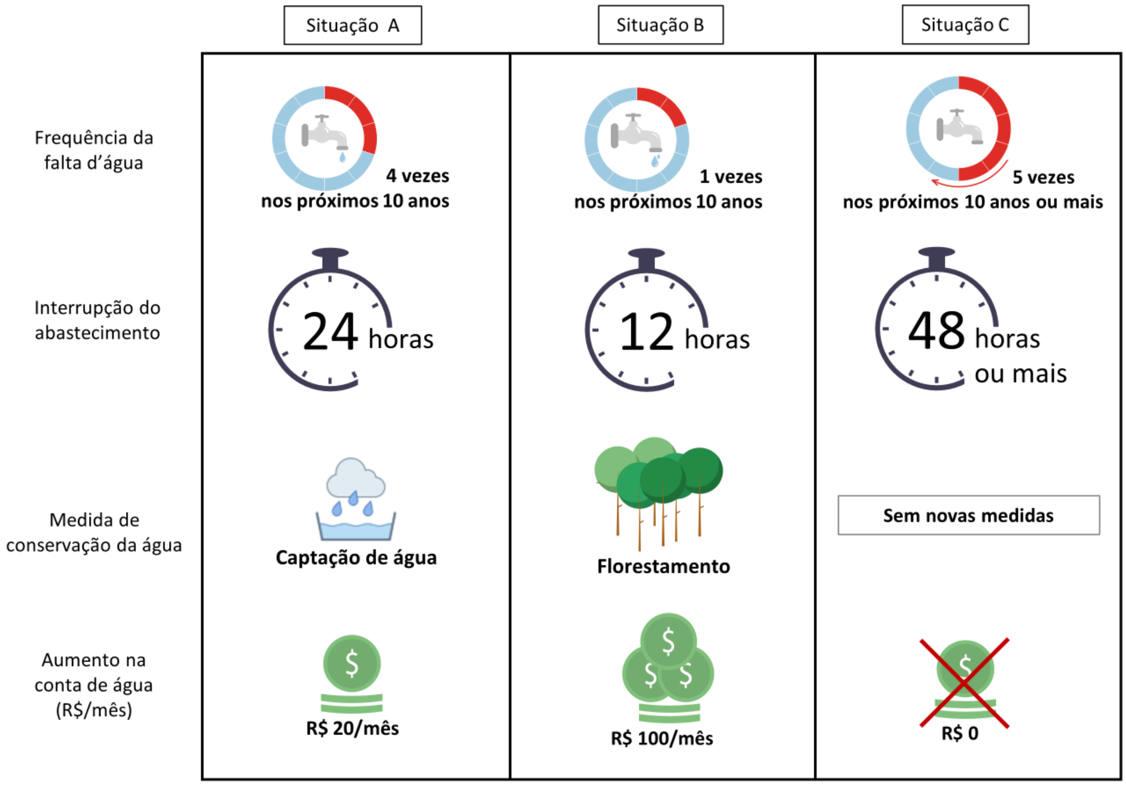
Aplicando essas medidas, a frequência da falta d'água no futuro pode reduzir de 5 para 4, 2 ou até 1 nos próximos 10 anos. E, a duração dessas possíveis restrições de uso ou racionamento de água também pode diminuir de 2 dias (48 horas) para 1 dia e meio (36 horas), 1 dia (24 horas) ou somente 12 horas. Os custos de implementação dessas medidas para redução da frequencia e duração das restrições e racionamentos futuros serão divididos igualmente entre todos os usuários abastecidos pelo manancial do [**Rio Guariroba/Rio Jaguari**]. Isso significa que você e sua família também pagariam um valor a mais na sua fatura de água mensal nos próximos 10 anos.

*Agora, antes de começar, vamos fazer um exercício com um exemplo de cartão com 3 situações: A, B e C. <MOSTRAR O CARTÃO AO RESPONDENTE>*
*Na situação A temos a medida de captação da água da chuva, que poderá reduzir a falta d'água para 4 dos próximos 10 anos e diminuir o tempo de falta de água para até 24 horas.*
*Na situação B temos o florestamento, que pode reduzir a falta d'água para 2 dos próximos 10 anos e diminuir o tempo de falta de água para até 12 horas.*
*Escolhendo a situação A você aceita pagar R$ 20 reais a mais na sua conta de água todo mês nos próximos 10 anos. Na situação B, o valor que você aceita pagar a mais todo mês na sua conta nos próximos 10 anos é de R$ 100 reais.*

*Na opção C não há nenhuma taxa adicional para pagar na sua conta de água e, assim, nada será feito para a conservação de água. Com isso você aceita a possibilidade de enfrentar a falta d'água em 5 dos próximos 10 anos com restrições e racionamento de água que pode durar 48 horas ou mais.*

Nesse exemplo de cartão, qual situação você prefere?

☐ 1 – Situação A. ☐ 2 – Situação B. ☐ 3 – Situação C.




3.1. Olhando para este cartão, qual situação você prefere?

☐ 1 – Situação A.
☐ 2 – Situação B.
☐ 3 – Situação C.

3.2. Olhando para este cartão, qual situação você prefere?

☐ 1 – Situação A.
☐ 2 – Situação B.
☐ 3 – Situação C.

3.3. Olhando para este cartão, qual situação você prefere?

☐ 1 – Situação A.
☐ 2 – Situação B.
☐ 3 – Situação C.

3.4. Olhando para este cartão, qual situação você prefere?

☐ 1 – Situação A.
☐ 2 – Situação B.
☐ 3 – Situação C.

3.5. Olhando para este cartão, qual situação você prefere?

☐ 1 – Situação A.
☐ 2 – Situação B.
☐ 3 – Situação C.

3.6. (Se código 3 nas Q3.1., Q3.2., Q3.3., Q3.4. e Q3.5.) Por que você escolheu a situação em que não há pagamento de nenhum valor em todos os cenários apresentados?

☐ 1 – Não posso pagar a mais pela minha conta de água, minha renda é muito baixa.

☐ 2 – Eu não pago meu consumo de água pela fatura. Quero pagar a mais por outro meio.

☐ 3 – Não estou interessado em pagar a mais para assegurar o abastecimento de água da minha casa.

☐ 4 – Prefiro comprar água engarrafada, ao invés de pagar uma fatura de água mais cara.

☐ 5 – Estou interessado em outras fontes de água para assegurar o abastecimento de água da minha casa.

☐ 6 – Não confio que o valor pago será investido em medidas de economia de água.

☐ 7 – O Município deve pagar por essas medidas, não eu.

☐ 8 – O Estado ou Governo Federal deve pagar por essas medidas, não eu.

☐ 9 – Os proprietários rurais que residem na bacia devem pagar pelas medidas, não eu.

☐ 10 – Não acredito que a frequência de falta d'água irá aumentar no futuro e que minha família enfrentará mais restrições de uso da água.

☐ 11 – Outra razão. Por favor, especifique: ..................................................

3.7. Qual é o valor máximo que você está disposto a pagar a mais na sua conta de água mensal para ter medidas conservação e garantir que não falte água em sua residência?

R$ .............................

3.8. Em uma escala de 0 a 10, o quanto você acha que realmenre pagaria o valor mencionado?

| | **Não tenho certeza se pagaria** 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | **Tenho certeza de que pagaria** 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Pagaria o valor de taxa de conservação | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

3.9. O quanto você acredita que as medidas de conservação da água poderão ajudar para diminuir a frequência da falta d'água?

| | **Não acredito em nada** | **Não acredito** | **Não acredito e nem desacredito** | **Acredito** | **Acredito muito** |
|---|---|---|---|---|---|
| As medidas irão ajudar para diminuir a falta d'água | ☐ | ☐ | ☐ | ☐ | ☐ |

3.10. O quanto você está convencido de que as medidas de conservação da água serão realmente realizadas para melhorar o abastecimento de água no futuro com o pagamento da taxa na mensalidade da conta de água?

| | **Nada convencido** | **Pouco convencido** | **Não estou convencido nem duvido** | **Convencido** | **Muito convencido** |
|---|---|---|---|---|---|
| As medidas irão ajudar para diminuir a falta d'água | ☐ | ☐ | ☐ | ☐ | ☐ |

3.11. Comparado à captação de água, na sua opinião, quão efetivas são as medidas de florestamento e integração lavoura, pecuária e floresta em reduzir a frequência e duração de futuras situações de falta d'água?

☐ 1 – Não efetivas.
☐ 2 – Pouco efetivas.
☐ 3 – Efetivas.
☐ 4 – Muito efetivas.
☐ 5 – Não sei

## 4. Informações socioeconômicas

4.1. Você se considera:

☐ 1 – Homem.
☐ 2 – Mulher.
☐ 3 – Outro. Por favor, especifique: ........................................................................

4.2. Qual a sua idade?

............. anos.

4.3. Você nasceu nessa região?

☐ 1 – Sim.
☐ 2 – Não

4.4. (Se Campo Grande ou São Paulo capital) Em qual área você mora?

| | |
|---|---|
| ☐ 1 – Norte. | ☐ 4 – Oeste. |
| ☐ 2 – Sul. | ☐ 5 – Centro. |
| ☐ 3 – Leste. | ☐ 4 – Oeste. |

4.5. (Se Região Metropolitana de São Paulo) Em que cidade você mora?

☐ 1 – Guarulhos.
☐ 2 – Osasco.
☐ 3 – Santo André.

4.6. Qual bairro você mora?

..............................................................................................................................................

4.7. Quem normalmente toma as decisões financeiras importantes na sua casa?

☐ 1 – Apenas eu tomo essas decisões.
☐ 2 – Apenas outra(s) pessoa(s) toma(m) as decisões.
☐ 3 – Eu juntamente com outra(s) pessoa(s) que mora junto comigo tomamos as decisões.

4.8. Qual o seu grau de escolaridade?

☐ Analfabeto/Ensino fundamental incompleto.
☐ Ensino fundamental.
☐ Ensino médio.
☐ Ensino técnico/profissional após o ensino médio.
☐ Ensino superior (bacharel ou equivalente).
☐ Pós-graduação (mestrado ou doutorado).
☐ Outro. Por favor, especifique: ..............................................................................

4.9. Você ou algum membro da sua família está profissionalmente envolvido na agropecuária (cultivo de plantas e criação de animais) ou envolvido na silvicultura (produção, exploração e manutenção de florestas)?

☐ Sim, na agropecuária. Por favor, especifique como: ..........................................
☐ Sim, na silvicultura. Por favor, especifique como: ............................................
☐ Não.

4.10. Você ou algum membro da sua família está profissionalmente envolvido no setor da água? Por exemplo, tratamento de água ou esgoto, abastecimento público, ou etc.

☐ Sim. Por favor, especifique como: .....................................................................
☐ Não.

4.11. Quantas pessoas, incluindo você, moram em sua residência?

.................. pessoa(s).

4.12. Quantas crianças ou adolescentes, menores que 18 anos, moram em sua residência?

.................. criança(s) ou adolescente(s).

4.13. Quantas pessoas, incluindo você, possui renda na sua família?

................. pessoa(s)

4.14. Quanto é, em média, a renda total líquida da sua família após deduções, tais como impostos, taxas etc.?

R$ .............................

☐ Prefiro não responder, mas posso indicar um intervalo onde a renda familiar se encontra:

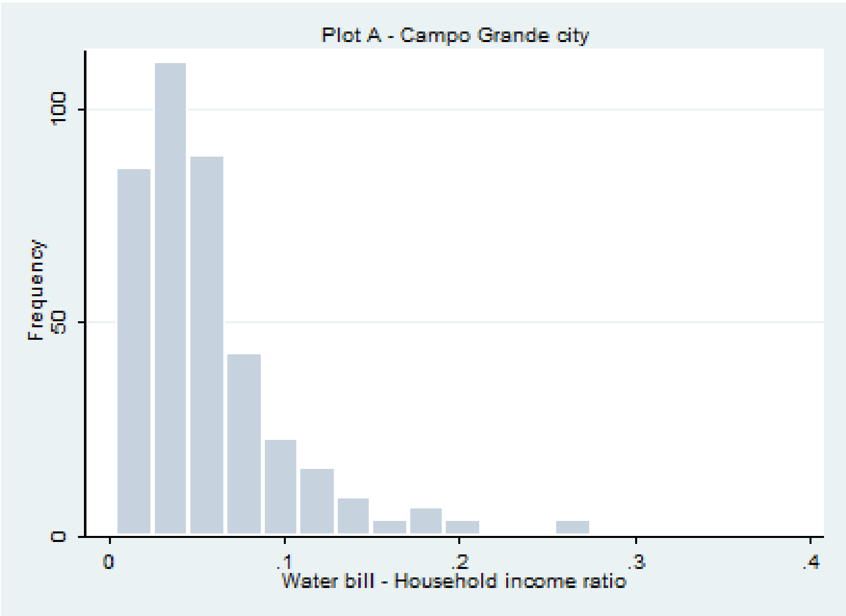
| | |
|---|---|
| ☐ Até R$ 1.100,00 | ☐ R$ 12.501,00 a R$ 15.000,00 |
| ☐ R$ 1.101,00 a R$ 2.000,00 | ☐ R$ 15.001,00 a R$ 17.500,00 |
| ☐ R$ 2.001,00 a R$ 3.000,00 | ☐ R$ 17.501,00 a R$ 20.000,00 |
| ☐ R$ 3.001,00 a R$ 4.000,00 | ☐ R$ 20.001,00 a R$ 22.500,00 |
| ☐ R$ 4.001,00 a R$ 5.000,00 | ☐ R$ 22.501,00 a R$ 25.000,00 |
| ☐ R$ 5.001,00 a R$ 7.500,00 | ☐ R$ 25.001,00 a R$ 30.000,00 |
| ☐ R$ 7.501,00 a R$ 10.000,00 | ☐ Acima de R$ 30.000,00 |
| ☐ R$ 10.001,00 a R$ 12.500,00 | |

# APPENDIX F

# Frequency distribution of Water bill-household income

This appendix presents the ratio of monthly water bill to monthly household income (i.e., the amount paid for drinking water compared with the total amount earned within a household) (Figure 26).

Figure 26 – Frequency distribution of the ratio monthly water bill–household monthly income for the Campo Grande sample.




Source: Author.

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