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

GABRIELA DE AZEVEDO REIS

RISK, VULNERABILITY AND IMPACT PERCEPTION: AN OVERVIEW CONSIDERING WATER SYSTEMS USING COLLABORATIVE METHODS AND MATHEMATICAL MODELLING

FORTALEZA
2023

GABRIELA DE AZEVEDO REIS

RISK, VULNERABILITY AND IMPACT PERCEPTION: AN OVERVIEW CONSIDERING WATER SYSTEMS USING COLLABORATIVE METHODS AND MATHEMATICAL MODELLING

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

Advisor: Prof. Dr. Francisco de Assis de Souza Filho.
Co-advisor: Prof. PhD. Donald Robert Nelson

FORTALEZA
2023

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

R31r Reis, Gabriela de Azevedo.
Risk, Vulnerability and Impact Perception : an Overview Considering Water Systems Using Collaborative Methods and Mathematical Modelling / Gabriela de Azevedo Reis. – 2023.
165 f. : il. color.

Tese (doutorado) – Universidade Federal do Ceará, Centro de Tecnologia, Programa de Pós-Graduação em Engenharia Civil: Recursos Hídricos, Fortaleza, 2023.
Orientação: Prof. Dr. Francisco de Assis de Souza Filho.
Coorientação: Prof. Dr. Donald Robert Nelson.

1. Vulnerabilidade à seca. 2. avaliação de riscos. 3. percepção de impacto. 4. lógica fuzzy. 5. análise de rede. I. Título.

CDD 627

GABRIELA DE AZEVEDO REIS

RISK, VULNERABILITY AND IMPACT PERCEPTION: AN OVERVIEW CONSIDERING WATER SYSTEMS USING COLLABORATIVE METHODS AND MATHEMATICAL MODELLING

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

Advisor: Prof. Dr. Francisco de Assis de Souza Filho.
Co-advisor: Prof. PhD. Donald Robert Nelson

EXAMINATION COMMITTEE

Prof. Dr. Francisco de Assis de Souza Filho (Advisor)
Federal University of Ceará (UFC)

Prof. PhD. Donald Robert Nelson (Co-advisor)
University of Georgia (UGA)

Prof. Dr. Eduardo Sávio Passos Rodrigues Martins
Federal University of Ceará (UFC)

Prof. Dra. Mariana Vella Silveira
Federal University of Ceará (UFC)

Prof. Dra. Iana Alexandra Alves Rufino
Federal University of Campina Grande (UFCG)

Prof. Dra. Rosa Maria Formiga-Johnsson
State University of Rio de Janeiro (UERJ)

AGRADECIMENTOS

Essa tese representa o documento final da minha formação acadêmica, após treze anos desde meu ingresso no curso de Engenharia Ambiental, em 2010. Agradeço às professoras e aos professores que me acompanharam durante todo esse primeiro ciclo.

Em especial, agradeço àquelas e àqueles do Departamento de Engenharia Hidráulica e Ambiental, com quem convivi durante todos esses anos, ainda que apenas por cumprimentos breves na escada e corredores. Agradeço especialmente à professora Ticiana, que sempre foi uma orientadora fora das formalidades de orientação.

Agradeço às professoras Iana, Rosa e Mariana e ao professor Eduardo por aceitarem analisar e discutir sobre esse trabalho. Agradeço também ao professor Don, que me acompanhou durante todo meu processo de especialização e me ajudou na formação do que ele mesmo chama: engenheira “renascentista”. Agradeço, em primeiro lugar, ao professor Assis. Mentor acadêmico, profissional, e de vida. Me ensinou hidrologia, modelagem, sociologia, estatística, filosofia, hidráulica, história da arte e mais uma infinidade de disciplinas que se possa imaginar. O mais importante: me ensinou valores e princípios.

Agradeço aos pontos de apoio do cotidiano, sem os quais o caminho haveria de ser infinitamente mais árduo. Agradeço meu time de doutorandas (que hoje já são doutoras!) e nossas sessões de trabalho e fofoca na nossa salinha virtual. Agradeço aos “colegas” (que hoje já são amigos!) do GRC. E agradeço, acima de tudo, o apoio incondicional de quem me aguenta todo os dias: minha mãe, Rosane, meu pai, Carlos, e meu amor, Isabela.

ABSTRACT

Drought events are a significant concern, and proactive strategies are required to mitigate their impact, such as the evaluation of vulnerabilities, risks and impacts. The participatory process in water resources planning and management is established in several nations, but vulnerability and risk analysis often remain one-sided. To effectively manage water resources, an interdisciplinary approach is necessary. This work provides different methods that comprehends the contribution of collaborators' knowledge and experience in order to asses vulnerabilities, risks and impacts in a drought scenario. The iSECA is a MCDM GIS-based index, characterized as a straightforward and accessible tool for quantifying vulnerability to drought caused by climate change, considering social, economic, and water management aspects. This model was applied to the Brazilian states of Ceará and São Paulo, identifying vulnerable locations and areas with water infrastructure that can improve local and regional adaptive capacity. The model results are clear and easy to understand and can serve as an indispensable tool for water management and drought planning. The methodology does not require fieldwork or extensive financial costs and can be applied at different scales for the development of plans such as drought and water security management. A typology of risks for water systems was developed through a collaborative process involving professionals with different experiences and expertise in water systems. The typology matrix classifies the types of structures of a water system against classes of risk to assist in risk assessment and decision-making. The typology is adaptable to different configurations of water systems and provides an important tool for water resource management. A fuzzy logic model is proposed to evaluate integrated risks of water systems using fuzzy logic and the typology of risks, which can handle qualitative information and quantify data. However, the data acquisition step is time-consuming and can exacerbate the lack of information, affecting the final results. Nonetheless, this approach can aid decision-making for water system management. Lastly, we evaluate the drought impact perception of stakeholders of the river basins committees in order to analyze how they behave can influence the water allocation and decision-making process through network analysis.

Keywords: Drought vulnerability, risk assessment, impact perception, fuzzy logic, MCDM, network analysis, typology of risk.

RESUMO

Eventos de seca são uma preocupação significativa, e estratégias proativas são necessárias para mitigar seu impacto, como a avaliação de vulnerabilidades, riscos e impactos. O processo participativo no planejamento e gerenciamento de recursos hídricos está estabelecido em várias nações, mas a análise de vulnerabilidade e risco muitas vezes permanece unilateral. Para gerenciar eficazmente os recursos hídricos, uma abordagem interdisciplinar é necessária. Este trabalho fornece diferentes métodos que compreendem a contribuição do conhecimento e da experiência dos colaboradores para avaliar vulnerabilidades, riscos e impactos em um cenário de seca. O iSECA é um índice baseado em SIG (Sistema de Informações Geográficas) MCDM (Tomada de Decisão Multicritério), caracterizado como uma ferramenta direta e acessível para quantificar a vulnerabilidade à seca causada pelas mudanças climáticas, considerando aspectos sociais, econômicos e de gestão da água. Esse modelo foi aplicado aos estados brasileiros do Ceará e São Paulo, identificando locais vulneráveis e áreas com infraestrutura hídrica que podem melhorar a capacidade adaptativa local e regional. Os resultados do modelo são claros e fáceis de entender e podem servir como uma ferramenta indispensável para o gerenciamento de água e o planejamento de secas. A metodologia não requer trabalho de campo ou custos financeiros extensos e pode ser aplicada em diferentes escalas para o desenvolvimento de planos, como o gerenciamento de secas e segurança hídrica. Uma tipologia de riscos para sistemas de água foi desenvolvida por meio de um processo colaborativo envolvendo profissionais com diferentes experiências e conhecimentos em sistemas de água. A matriz de tipologia classifica os tipos de estruturas de um sistema de água em relação às classes de risco para auxiliar na avaliação de riscos e tomada de decisões. A tipologia é adaptável a diferentes configurações de sistemas de água e fornece uma ferramenta importante para o gerenciamento de recursos hídricos. Um modelo de lógica difusa é proposto para avaliar riscos integrados de sistemas de água usando lógica difusa e a tipologia de riscos, que pode lidar com informações qualitativas e quantificar dados. No entanto, a etapa de aquisição de dados é demorada e pode agravar a falta de informações, afetando os resultados finais. No entanto, essa abordagem pode auxiliar na tomada de decisões para o gerenciamento de sistemas de água. Por fim, avaliamos a percepção de impacto da seca pelos stakeholders dos comitês de bacias hidrográficas, a fim de analisar como o comportamento deles pode influenciar a alocação de água e o processo de tomada de decisão por meio de análise de rede.

Palavras-chave: Vulnerabilidade à seca, avaliação de riscos, percepção de impacto, lógica fuzzy, MCDM, análise de rede, tipologia de risco.

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

1 INTRODUCTION

1.1 General background

Water systems are intricate socio-natural systems that involve various non-linear processes influenced by diverse stressors and actors. The fundamental purpose of these systems is to provide society with a natural resource, but the challenge lies in answering the questions: who needs this resource and how should it be provided? The former question pertains to the broad spectrum of society that demands water, including residents, tourists, shopkeepers, servers, industries, irrigators, ranchers, producers, and other users with varying demands. On the other hand, the latter question concerns the operational and functional aspects of the water system, which comprises engineered infrastructures designed to capture, store, transport, and distribute water, as well as operators, technicians, managers, and decision-makers. Every aspect of a water system has its unique characteristics and requirements, which contribute to the overall complexity of the system.

As populations grow and climate change risks and impacts get higher, the demand for water is increasing and the supply is becoming increasingly uncertain. In recent decades, water consumption has more than doubled population growth, exacerbating water stress scenarios across the planet (COSGROVE AND LOUCKS, 2015). Industrialized countries are contending with conflicts over water allocation, non-point source pollution, and extreme events like droughts. Meanwhile, less privileged countries are facing similar challenges, often compounded by insufficient infrastructure. Climate change events are a major obstacle for sustainable development, and vulnerability assessments and prioritization are essential for effective adaptation strategies (SUÁREZ-AMIÑANA et al., 2017; PRYSHLAK et al., 2014; VARGAS AND PANEQUE, 2017).

Drought events have significant impacts on the environment and human society, and managing these impacts requires efficient water resource management (MONTANARI et al., 2013). Post-hoc crisis management strategies are ineffective, and water resource managers must instead develop proactive strategies to mitigate the impacts of water scarcity. Developing drought management plans with proactive and risk-based management strategies is crucial and requires a comprehensive analysis of the vulnerability of the water system, based on social, technical, and scientific findings (PIENAAR AND HUGHES, 2017; WILHITE et al., 2014).

The participatory process in water resources planning and management is established in several nations, such as Brazil (BRASIL, 1997). It is related mainly to the management of river basins and water allocation decisions in states like Ceará. However, the elaboration of studies such as vulnerability and risk analysis remain, mostly, one-sided.

To provide decision makers with relevant information on complex systems, it is essential to develop risk assessment methods that rely on appropriate techniques and sufficient knowledge (RAE et al., 2012). In general, the first steps of a risk assessment method involve structuring the available information and knowledge at the local level to systematically model the risk at the system level (ZIO, 2018). However, limited information can increase uncertainty and hinder risk assessment outcomes. To address this challenge, qualitative data collection can be used to incorporate background knowledge provided by technicians and experts of the systems.

Zio (2018) emphasizes that risk assessment outcomes are dependent on the current state of knowledge and values assigned to the system. Therefore, it is necessary to identify what is at risk for the entire system, what the consequences of damage would be, and how severe the damage would be. Ensuring the safety of complex systems is a difficult task that demands knowledge, information, and adequate tools.

Basurto and Ostrom (2009) have suggested that typologies are valuable tools for avoiding the "panacea" analytical traps, where a single type of governance system is applied to all environmental problems, potentially compromising the governance of human-environment interactions (OSTROM, JANSSEN AND ANDERIES, 2007). Developing a typology of risks can provide accessible tools and knowledge that can be easily visualized during the risk assessment process, allowing for effective communication with decision makers as well as non-specialists involved in the evaluated system. Despite the increasing application of risk typologies to various areas, there is still a lack of typologies for risks in water resources systems. This is a significant challenge, considering the complexity of water resources systems, where risks may involve economic, social, climate, hydrological, structural engineering, and environmental aspects. Uncertainty is therefore comprised of various dimensions, including both random factors (i.e., natural randomness inherent to the system and its components) and epistemic factors (i.e., limitations of knowledge) (SKINNER, 2014).

Fuzzy logic is a valuable tool for situations where information is acquired through verbal, textual, or linguistic means, and there is a need to convert it into mathematical terms. Through the use of fuzzy logic, it is possible to develop computer programs and algorithms that construct inference systems by utilizing a set of linguistic rules that are supported by mathematical tools (TANSCHEIT, 2003). Furthermore, fuzzy logic can handle incomplete and imprecise data, which are commonly encountered in real-world issues and socio-natural systems (ZHANG et al., 2015; AMEYAW AND CHAN, 2016).

Water scarcity is increasingly becoming a critical challenge for the long-term sustainability of societies. Therefore, it is imperative to adopt an interdisciplinary approach and implement strategic and efficient measures for water management. Understanding the interplay between water systems and human systems is crucial, which has led to an increasing interest in socio-hydrological methods. These approaches aim to enhance the ability of communities to adapt and cope with water-related challenges by exploring the dynamics and co-evolution of these systems (NGUYEN et al., 2021).

The recognition of social aspects in water resources research is closely linked to the search for improved natural resources governance. Processes that seek adaptive governance rely on participatory methods (LEMOS et al., 2020). Advocates of participatory approaches argue that involving individuals and groups who are closely connected to the area or issue can improve information sharing, identification of challenges and solutions, build trust and credibility in scientific findings, and facilitate the integration of scientific knowledge into decision-making processes (KAINER et al., 2009).

The state and society have a continuous and interconnected relationship that involves various entities, such as councils, committees, forums, and networks. These entities play a crucial role in enabling social interactions between civil society and representatives of public authority. It is important to note that this connection does not imply the replacement of the state but rather recognizes the value of incorporating "expert knowledge", as well as “tacit knowledge” (SOUZA FILHO et al., 2022). When official records are not available or are inadequate, social perception can be a valuable resource for improving the modeling process (MARTINS et al., 2023). Thus, participation becomes a crucial aspect in ensuring the effectiveness of public policy, enabling interaction with the political system, resolving conflicts, and promoting democratic decision-making.

1.2 Rationale of the study

This dissertation has the main purpose of promoting discussions on vulnerability assessment as well as risk and impacts in water systems, mostly on drought scenarios, in order to contribute with innovative frameworks for water planning and management and water resources research. The discussion is also centered at the advantages of including participation throughout the methodologies. Overall, the dissertation is built based on the general hypothesis that the implementation of socio-hydrological approaches that integrate participatory methods and recognize the value of incorporating scientific and tacit knowledge throughout the assessment of vulnerability, risk and impacts on water systems can improve the effectiveness of water resources governance and promote sustainable decision-making processes. The discussion is mainly guided by trying to answer three questions elaborated through literature investigation and observing important gaps (summarized through section 1.1 General background and detailed through Chapters 3 DEVELOPMENT OF A DROUGHT VULNERABILITY INDEX USING MCDM AND GIS - STUDY CASE IN SÃO PAULO AND CEARÁ, BRAZILto 6).

The first question considers the need for assessing vulnerability to drought in order to identify who is more vulnerable to the impacts of droughts and where they are located. How can we assess drought vulnerability, considering the nuances of its concept, identifying who is vulnerable, and using a method that is simple to apply and easy to understand? The first of the four papers that composes this dissertation answers this question and is called “Development of a Drought Vulnerability Index Using MCDM and GIS - Study Case in São Paulo and Ceará, Brazil”.

The paper introduces an improved approach for assessing and categorizing drought vulnerability using a collaborative, GIS-based analysis and multi-criteria decision making (MCDM) model named iSECA, that offers technical and conceptual contributions and serves as a tool for developing drought management plans. iSECA is based on the IPCC definition of vulnerability, which includes sensitivity, exposure, and adaptive capacity. The model can be applied to regional and local scales using existing, secondary data, and can prioritize areas not covered by the majority of climate change vulnerability research.

The authors applied iSECA to two distinct regions in Brazil, Ceará and São Paulo, which have different biophysical and climatic characteristics as well as social and economic activities. The method is cost-effective, does not require extensive fieldwork, and uses indicators selected through brainstorming sessions and surveys with members of different River Basin Committees in São Paulo. iSECA is an accessible model that considers the complexity of diverse agents and aspects that affect the resilience of a water system, providing straightforward, logical steps, and easy-to-understand and visualize results. The results can contribute to drought management plans at national, state, or basin scales, making it possible to analyze the outcomes of drought-related public policies. In summary, iSECA is a versatile model with a broad range of applications, clear results, and a significant potential to contribute to the assessment of drought vulnerability and the development of effective drought management plans.

The second question revolves around risk analysis in water systems. Is it possible to develop a methodology that enables the execution of a risk analysis in water systems that can incorporate quantitative data and tacit knowledge of the system, making it more robust? The answer to the second question was structure into the second and third articles, as its complexity demanded two main steps of research: develop a framework for identifying the risks within a wide range of possible types of physical structures that a water system can present (discussed through second paper, called “4 DEVELOPMENT OF WATER SYSTEMS TYPOLOGY OF RISKS USING COLLABORATIVE METHODS”) and then, assessing these risks (present by the third paper, named “5 INTEGRATED RISK ASSESSMENT FOR WATER SYSTEMS INFRASTRUCTURE USING FUZZY INFERENCE AND COLLABORATIVE TYPOLOGY OF RISKS”).

As presented in section 1.1 General background, and after in Chapters 2 WHAT IS RISK?and 4 DEVELOPMENT OF WATER SYSTEMS TYPOLOGY OF RISKS USING COLLABORATIVE METHODS, risk typologies are efficient and necessary tools for assessing risk and are widely applied in distinct areas of research. However, literature lacks to present an existing typology of risk for assessing water systems. The development of a risk typology to identify the risks within the structures and then using a fuzzy logic-based approach to assess the risks can provide decision makers with relevant information for effective drought management planning. By incorporating qualitative data collection and a participatory process, the typology combined with the fuzzy inference model can systematically identify the risk at the structure level and provide accessible tools and knowledge that can be easily visualized during the risk assessment process, thereby facilitating effective communication with decision makers as well as non-specialists involved in the evaluated system. This approach will be particularly useful in water resource systems where risks may involve economic, social, climate, hydrological, structural engineering, and environmental aspects, and where uncertainty is comprised of various dimensions, including both random and epistemic factors.

Finally, the third question addresses the impacts of droughts and how it is perceived by distinct sectors of society. How different groups of interest perceived the impacts of drought events and how this distinction (if existing) affects the nuances of water planning and management? The fourth paper proposes to answer this final question by examining the impact perception of drought in the state of Ceará, Brazil. Firstly, it evaluates the qualitative perception of the impacts of the drought through a questionnaire answered by members of River Basin Committees. Secondly, network analysis theories are applied to the questionnaire data to develop mechanisms to identify conflicts and facilitate the mediation process. The diverse representation of the committees allows for capturing the different perspectives of the members, identifying interest groups, and understanding their behavior. The study aims to investigate the potential effect of interest group behavior on the process of negotiated water allocation and to facilitate the mediation of conflicts that may arise.

1.3 Objectives

The main objective of this dissertation is to provide water resources researchers, planners, managers and decision-makers with tools and solutions for vulnerability, risk and impacts on water systems considering drought scenarios and water infrastructure risks, as well as instigate discussions over the advantages of using participatory approaches and collaborative frameworks combined with mathematical modelling for these topics.

Additionally, in order to achieve the main goal, specific objectives were designed and concluded through the four papers that complete this dissertation. The specific objectives are:

1. Elaborate an index that calculates the vulnerability to drought considering local and regional scales;
2. Develop a typology of risks for a water system using a collaborative framework;
3. Use the typology of risks as database to develop a fuzzy logic model to assess risk;
4. Evaluate the perception of impacts to drought of members of river basin committees and develop mechanisms to identify conflicts and facilitate the process of mediation.

1.4 Structure of the dissertation

The structure of this work consists mainly of the aggregation of four papers concerning the assessment of risk, vulnerability, and impacts on a scenario of water systems in semi-arid regions or areas that have suffered with water scarcity crisis. Additionally, this document introduces the perspective of collaborative and participative frameworks concerning the evaluation of risk, vulnerability, and impacts of water systems. Participation enables representatives of society to express their opinions, thereby assisting in the decision-making process. On the other hand, collaboration occurs when participants actively engage with authors in the construction of the model/framework. These concepts are based on the definitions of ‘participation’, ‘collaboration’, and ‘participatory’ published by the Oxford English Dictionary (2004) and the Great Portuguese Dictionary Houaiss (2001).

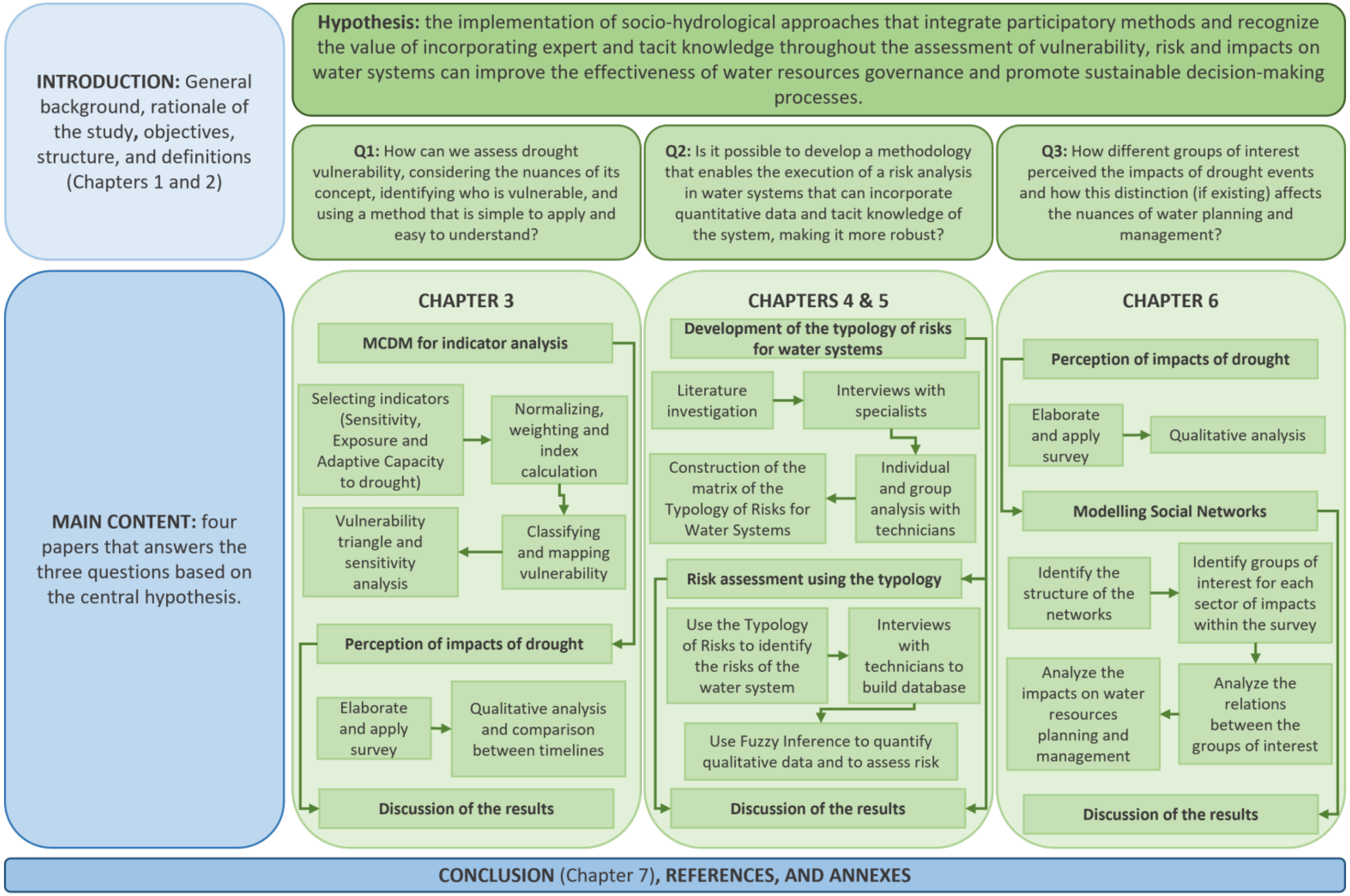
The first paper proposes an index to calculate the vulnerability to drought. The iSECA model quantifies drought vulnerability by applying Multi Criteria Decision Making techniques to calculate vulnerability indexes by weighting indicators of climatological, social, economic, and water management factors. GIS software maps and classifies vulnerability, producing a drought vulnerability index, including a vulnerability triangle and frequency curves. The model is a valuable tool for water management in drought prone regions, providing clear information for water managers and non-specialists.

The second paper elaborated a typology of risks of water systems using a collaborative framework, going through different steps that involves semi-structured interviews and focus groups. The typology was constructed considering the case study of a water system in Ceará where the collaborators choose the structures that composed the system. Then, applying the typology of risks and using the database created during its construction, the third paper concerns the development of a mathematical model that assess risk of water infrastructure using fuzzy logic.

Finally, the fourth paper firstly evaluates impact perception of drought through the answers of a questionnaire applied to members of River Basin Committees of Ceará. This first analysis is a qualitative evaluation and discussion of the main causes of impacts of the drought that initiated in 2012 in the state of Ceará, Brazil. The second assessment applies theories of network analysis using the database of the questionnaire’s answers. This assessment aims to develop mechanisms to identify conflicts and facilitate the process of mediation. The diversified representation of the committees will be able to capture the different views of the members and identify how they behave, thus identifying interest groups. The goal is to understand if the behavior of such groups can affect the process of negotiated water allocation and to understand the emergence of conflicts, facilitating their mediation process.

In order to assist in the understanding of the thesis structure, as well as to visualize how the hypothesis and research questions will be answered, the cognitive map presented in Figure 1 provides a structural summary, connecting the concepts, objectives, research questions, main content, and conclusion of the work as a whole.

Figure 1 - Cognitive map to summarize the overall structure and contents of the dissertation.



Source: Author.

2 WHAT IS RISK?

The clear definition of a water system is not a concept discussed in literature. Systems, in general, are defined according to the observer. Water systems can encompass the water infrastructure, the population that it supplies (and diverse social, political, cultural, and economic aspects that comes with it), and the environment that influences and is influenced by it. Therefore, water systems can be characterized as complex socio-natural systems due to the occurrence of diversified non-linear processes, influenced by distinct stressors and actors.

The main idea of a water system is to supply society with a natural resource, but the challenge relies on the questions: Whom are we supplying? How are we supplying them? The former question refers to the entirety of society who demands water: residents, tourists, shopkeepers, servers, industries, irrigators, ranchers, producers, and many other users that might be demanding water for whatever reason. The latter question represents the functionality and operation of the water system, composed by not only engineered infrastructures aimed to capture, store, transport, and distribute water, but also operators, technicians, managers, and decision-makers. Each aspect of a water system has its particularities and distinct demands, which builds a complexity amongst the entire system.

The continuous functioning of a water system is a fundamental factor of society's welfare. Such a complex system can be susceptible to damages that might have the potential to affect its overall function of supplying water in fair quantity and quality to society. An important characteristic of a supply system is the ability to operate satisfactorily under whichever climate and hydrologic conditions and possible future demands (HASHIMOTO et al., 1982). It is necessary to identify, for the entire system, what is at risk, what are the consequences of a damage and how severe is the damage. Guaranteeing the safety of such a system is a difficult task and demands knowledge and adequate tools.

This chapter covers definitions of risk and concepts that need to be understood in order to assess risk in a water system. Tools for assessing risks are also discussed, as well as states of the art concerning the study of risk.

2.1 Definitions

The concepts here discussed are not a consensus amongst the scientific and technical community. It is important to raise awareness to the discussion of the aspects concerning the study of risk, and it is fundamental to define the concept one is applying. When assessing risk, it is important to understand other definitions that are inherent to the concept of risk and/or are important aspects of the system that is being analyzed.

2.1.1 Risk

Etymologically, the word ‘risk’ arises from the Latin word ‘resicum’, that means danger that comes from an attempt. In Latin languages, the meaning evolved into both the possibility of loss and benefit, with the idea of a “chance” (GANOULIS, 2009). The International Risk Governance Council (IRGC) conceptualizes risk as an uncertainty about the severity of an adverse consequence of an event concerning a subject valued by society. This definition encompasses both positive and negative consequences. However, most organizations focus on the negatives outcomes (IRGC, 2017).

For risk analysis concerning engineered structures, risk mainly present a negative connotation, referring to loss, harm, damage, and/or disfunction. Zio (2018) affirms that risk deals with the “chance” that an event may occur and leave undesirable consequences for any subject. Ostrom and Wilhelmsen (2012) states that risk considers the probability of occurrence of an unwanted event with negative impacts. Kaplan and Garrick (1981) add to the analyze three fundamental questions: what is at risk?, how likely is it?, what are the impacts?.

The Society of Risk Analysis (SRA), a multidisciplinary association of scientists, had established a special committee to brainstorm a definition for the word ‘risk’. After four years of discussion, SRA decided that they could not publish one single definition of risk and recommended that every author use their own definition, as long as it is clearly explained (GANOULIS, 2009). Nonetheless, SRA (2018) states generally that a future activity is considered, e.g., the operation of a water system, and then the definition of risk is taken in relation to the consequences of given activity with respect to something that humans value, e.g., water.

In formal risk analysis, the definition of risk is often provided mathematically, aiming to assess risk through a quantitative approach. The most common mathematical tool used for the quantification of risk is the probabilistic analysis, particularly the subjectivistic theory of probability (ZIO, 2018). Risk is often considered as a composition of probabilities and consequences (BROOKS AND COOLE, 2020). According to Kaplan and Garrick (1981), one of the pioneer studies of quantifying risk using probabilistic analysis, it can be quantitatively defined as (1:

$$Risk = \{\langle s_i, p_i(f_i, c_i)\rangle\}, \qquad i = 1, \ldots, N+1 \tag{1}$$

where s represents the events varying for each scenario (from i to $N+1$) and p is the joint probability density function that represents the uncertainty of the frequency f of occurrence of each event and the consequences c of such event.

It is important to restate that the main goal of a water system is to provide water, in fair quantity and quality, to the population. If this main goal cannot be achieved, it means the system failed. There are various distinct factors that can affect, in different frequency and intensity, the total, partial, and punctual functioning of the system. Therefore, risks affecting a water system are heterogeneously distributed amongst its distinct components. Given the context of risk concepts discussions, for this entire study we can define that risk is the uncertainty of the occurrence, magnitude, and consequences of hazardous events that might negatively affect the functioning, at any level, of the water system. Additionally, in order to develop an efficient process of risk reduction, resilience strategies, local hazard, and vulnerability context should be considerate (WOOD et al., 2015).

2.1.2 Hazard

In order to study risk, it is necessary to understand from where the risk come from, i.e., the risk source. In this scenario, hazards are events or activities with the potential to cause harm, while harm is a damage caused on the system (SRA, 2018; GANOULIS, 2009). Hazards can occur in different shapes and sizes. Analyzing a water system, hazard can be an extreme climate event, a pollution load within the reservoir water, etc.

2.1.3 Uncertainty

In complex socio-natural systems, uncertainty is comprised of various distinct aspects. The dimensions of uncertainty can either be random (the natural randomness inherent to the system and its components) or epistemic (limitations of knowledge). The identification of uncertainties is a crucial part of the uncertainty management, which has an important role on the risk characterization process (SKINNER, 2014).

The epistemic versus random dimensions can also be explained as qualitative and quantitative definitions. Qualitatively, uncertainty is act of unknowing the true value or severity of future consequences of an event, as well as its occurrence. Quantitatively, uncertainty can be estimated by using subjective probability and possibility distributions (SRA, 2018). Bayesian methods are commonly used when dealing with uncertainty (HASHIMOTO et al., 1982).

2.1.4 Resilience

Holling (1973) defines resilience as the ability of a system to absorb changes and persist, and this concept started to receive a lot of attention in the areas relevant to the study of global environmental changes. For Timmerman (1981), resilience is a measure of the ability of a system or subsystem to absorb damage and recover in the face of a disaster.

Resilience appears in a contrast with stability. A system can appear to be unstable but be very resilient if it persists after severe stress due to its capacity to absorb variability, while a stable system may not have the ability to cope with large state variations (HOLLING, 1973; HASHIMOTO et al., 1982). According to Hashimoto et al. (1982), a resilient WATER SYSTEM should be able to recover from failure rapidly once it has occurred. Mainly four aspects then, compose resilience: robustness, redundancy, resourcefulness, and rapidity (ZIO, 2018).

The concept of resilience is added as an internal property of the system and a factor that can interfere with the level of vulnerability. Resilience is considered to have a connection with human actions and can be altered by anthropic activity, making the system more or less resilient. In several studies, resilience is treated as the capacity of the system to adapt to the stresses caused by external events, and this adaptive capacity can reduce the level of vulnerability of a system (ADGER, 2006; GALLOPÍN, 2006; FOLKE et al., 2004).

2.1.5 Vulnerability

Between the 1970s and 1980s, vulnerability studies appeared to be linked to resilience studies. The vulnerability appeared with a greater connection to the environmental system and the risk of hazardous events occurring. Liverman (1986) presents vulnerability as a two-dimensional concept, evaluating environment and society: where it is most vulnerable and who is most vulnerable. Vulnerability represents the susceptibility of a system to cope through a hazardous event (GANOULIS, 2009). In a water system, vulnerability can refer to the likely magnitude of a failure, if one occurs (HASHIMOTO et al., 1982).

Vulnerability also refers to structural changes in the system, considering internal and external factors, while resilience is an internal property of the system (GALLOPÍN, 2006). Due to the multidimensionality of the factors that contribute to the vulnerability, variables that can guarantee the complete success of the vulnerability indices have not yet been defined (SCHMIDTLEIN et al., 2008). Nonetheless, Reis et al. (2020) developed a drought vulnerability index using MCDM (Multicriteria decision-making) techniques and GIS tools. The study considered three aspects of vulnerability to drought: exposure, sensitivity, and adaptive capacity. The index considers climate, physical, social, and economic aspects, and evaluates the current conditions of the local water resources management.

2.1.6 Reliability

The reliability of a system is connected to its capacity to perform. It can be defined as the probability of a system to keep its performance with no failure occurrence during a given period, under a given hazard – that is, it does not fail (LEVESON, 2011; GANOULIS, 2009; HASHIMOTO et al., 1982). Reliability is often used in water resources planning and management and can sometimes be taken as the opposite of risk. However, reliability is not able to describe the severity or potential consequences of a failure – this can be measured and/or described through analysis of resilience and vulnerability (HASHIMOTO et al., 1982).

Safety and reliability are distinct properties, and it is possible that a system is reliable but unsafe, or even safe but unreliable. When there is a need to retrieve a system to a safe state in order to protect people, reliability and safety are in conflict. For some systems, safety is a mission. For others, it is a constraint (LEVESON, 2011).

2.1.7 Safety and Security

Safety and security are often considered two sides of the same coin. Both concepts aim for protection at some level within a process, activity, building, resource, or many other existing features. However, in literature, these concepts diverge when dealing with different types of hazards (GLESNER, GEYSMANS AND TURCANU, 2022).

Brooks and Coole (2020) defend that, despite safety and security having converging goals at the abstract level – to provide social wellness through the management of foreseeable risks –, they diverge at the technical and professional level. Safety actions are based on preventing the occurrence of non-malevolent adverse events, while security actions are planned according to malevolent occurrences, deliberately intended to adapt and circumvent defenses in order to cause harm. It provides the understanding that the main difference of such similar concepts lies in the intentional character of the hazard (GLESNER, GEYSMANS AND TURCANU, 2022; JORE, 2019).

The functioning of a system needs a defined objective. For example, the main objective of a water system is to provide water for a certain amount of people living at a given time and space, in satisfactory quantity and quality. The safety and security of its system must be planned in order to guarantee its objective, while risks are events that can somehow affect the accomplish of the main objective.

2.2 Analyzing risks

The analyzes of risk demands methodological steps and frameworks. Risk assessment methods are vastly explored in literature and applied in private and public organizations all around the world. Identifying and valuing risk is an essential process for decision makers and involves fundamental aspects in different sector of society: public health, natural disasters, investments, and so on. This section discusses different methods, approaches and frameworks of risk assessments focusing on water systems.

2.2.1 Risk assessment

Water is a fundamental natural resource for maintaining life, thus, a human right. Safety guarantees freedom from unaffordable harm, thus, also a human right (ZIO, 2018). Assuring the supply of water by guaranteeing the safety of a water system is a primary function for serving society’s welfare. Risk assessment is one of the most important steps to achieving this and ensuring water security.

A complete risk assessment assures technical and scientific support so that analysts and decision makers can identify the sources and consequences of potential hazards and describe risk, quantitatively, with a representation of uncertainties (ZIO, 2018).

The publication of the Risk Assessment in the Federal Government (NRC, 1983), also known as the “Red Book”, in the U.S.A., stablished definitions, concepts, guidelines, arrangements, and recommendations concerning risk assessment. Since then, environmental and natural resources agencies, such as the Environmental Protection Agency (EPA), has made efforts to improve the process of risk assessment. The “Red Book” report presented how risk assessment could fill the gap between results emerging from the research setting and their use in risk management and set limits do distinguish risk assessment and decision making as two different processes that should kept distinct. The process of assessing risk is a scientific activity limited by the available knowledge and the uncertainty inherent in risk, while the decision-making process based on risk is a political activity, with the outcomes of risk assessment being one type of input but never the sole basis for decision making (NRC, 2009; NRC, 1983). Zio (2018) defends that the assessment of the risk is, then, useful for making decisions such as on risk prevention and mitigation measures, prioritizing measures on different sources of risk, regulating and accepting risk, transferring risk through insurance. We can conclude that risk assessment is an important tool for guaranteeing rational decision making.

Despite the technical and scientific aspects of risk assessment, there is still uncertainty and there are still challenges to face. Accidents led by extreme events can have catastrophic consequences but are very unlikely to happen, so it is hard to have numeric or statistical information regarding all the potential events that bring risk to the object of analysis. One of the challenges is to quantify aspects that do not present numeric information, such as these unlikely but potentially disastrous events. A solution that we propose for this obstacle is to appeal to experts’ insights, that usually come as qualitative information, and then quantify it by using mathematical tools and solution such as fuzzy and Bayesian network inferences.

2.2.2 State of the Art: risk assessment for water systems

Cantos, Juran and Tinelli (2020) worked on a machine-learning-based risk assessment that assist the operation of a water distribution system by detecting the geolocation of high likelihood leaks. The method considers spatial flow pattern and the geolocation of previous leaks throughout the pipelines, inputting numerical values exclusively. As a machine-learning-based method, it requires real-time system monitoring by using complex sensor networks, representing a high-cost project. Water flow pattern is a highly common subject in different areas of study, such as water engineering, epidemic diseases, crops, sanitation, and even mining projects. For example, Guo et al. (2020) assessed the risk of water inrush in deep coal mines, with a team composed of experts on water resources, geography, geology, mine engineering, and geology. The authors identified that the risk of water inrush increases with de depth of coal mining and developed the risk assessment using data of grouting quantity, the loss of drilling fluid, gamma value, water temperature, average water absorption, distance between grouting loss points, water pressure on coal seam floor, and aquifuge thickness.

Mu et al. (2020) developed a risk assessment method in order to explore the seasonal risk of water-electricity nexus. The method uses indicators to quantify water consumption policy constraints and how it affects the water-electricity nexus. They prove that this nexus risk is highly seasonal, and the risk increases according to the watershed streamflow variability. There is a consensus among the water resources management literature that the higher is the variability, the higher is the challenge to manage water systems. Chen et al. (2019) also addressed the subject of water-electricity nexus, but with a different approach. The authors coupled water supply, hydropower generation and environment effects by using multi-dimensional models that encompass joint distributions and conditional expectation models, very similar to the risk analysis with Bayesian models' approach.

Following a distinct path, Lou et al. (2020) associates health risk assessment with drinking water systems. The authors studied the occurrence of nitrosamines in a drinking water system in China due to the use of disinfection products. The substance presents a potentially high health risk. Their method consisted of sampling water from different spots of the system periodically during a year in order to assess the spatial and temporal variability of occurrence of nitrosamines in the water. The authors, then, associated the data with cancer risk, concluding that the occurrence of nitrosamines in drinking water are related to cancer risk in children. Santos et al. (2020) also analyzed the occurrence of chemical substances in water systems and its risk towards the public health. The authors monitored the presence of pharmaceutically active compounds (PhACs) during one year in four Brazilian water sources. They found seasonal and social-economic variability, registering higher concentration of PhACs during winter and within areas of higher GDP and HDI. They recommend improvement on the drinking water treatment plants as the main solution to reduce risk of water contamination and, consequently, public health. Water contamination and public health represents the majority of studies that relate water and risk assessment. However, evaluating that this is not the scope of this thesis, studies with this approach will not be further discussed.

During the research, it became clear that risk assessment through participatory approaches is still not explored, even though there is a consensus that participation increases the understanding of minor dynamics, that are crucial when making decisions and planning policies. In this tone, Wyrwoll et al. (2018) evaluated the use of causal modeling and participatory risk assessment to develop national policy on systemic water risks through the Risks and Options Assessment for Decision-Making (ROAD) framework. The method was applied to a district of Vietnam where national agricultural water reforms are being piloted. The authors provide insights on how to improve national level decision-making for systemic water risks. They defend that the participatory process work as a knowledge-transfer that improves the credibility of the overall decision-making process.

Dealing with water can represent innumerous aspects of ecological, social, engineering, and/or different other systems. All types of life maintenance, economic activities, and social well-being requires water with fair quality and quantity. The relationship between these variables generates systems with complex problems and management that cannot be solved with easy and fast solutions. Facing the studies presented above it is clear to see that water issues can appear in different ways, as well as their solutions.

2.3 Strategies of risk management

2.3.1 Building a typology of risks

Developing a typology of risks provides tools and knowledge that are easy do visualize during the process of risk assessment, and it can guarantee an accessible communication with not only the decision makers but also non-specialists that are inserted in the evaluated system. Distinct areas of research applied typology of risks, either as a product generated or as a step in a risk assessment approach.

For social, management, and business issues, Scharf et al. (2001) proposed a typology for work environments, considering aspects as work dynamic and hazards. The results of this study can be considered for working training, hazard awareness, and safe working practices. Overall, the results can assist risk management associated with safety and stability for employers and employees. DiStefano et al. (2003) externally replicated cluster analysis methods in order to find a classification of children good and misbehavior, for both practical and scientific purposes. This study was motivated by a lack of a uniform classification, which can compromise psychopathological diagnostics. The results can be applied to identify the "types" of children and anticipate the risks of misbehavior and psychopathologies for each "type", building a typology of risk of misbehavior in elementary school. Picard (2004) provided a model for analyzing risks associated with family enterprises, considering general risks present in all enterprises as well as those specific to family business. During the process, the authors defined a typology of risks, also considering the different contributions of each risk. Johansson, Denk, and Svedung (2009) decided to assess societal risks and safety management in Swedish local governmental level, analyzing the abilities of local governmental managers and institutions to cope with different threats to public's safety. The risk typology worked here as an identifier for management actions and decision-making. Manning, Birchmore, and Morris (2020) researched how existing complexity, uncertainty, and constantly emerging transitions affect food supply chains and how can comprehend and address risk. The authors developed a typology of risk in order to assist risk managers to more effectively visualize and rank supply chain risk.

Diverse health studies have used risk typologies to identify groups at risk. Desmond et al. (2005) presented a qualitative work, using ethnographic approach, which aimed to identify groups of populations at high risk of HIV according to local culture understandings. The study detected different social circumstances of risk associated with distinct types of people, as well as factors and social and economic conditions that affect the level of risk. Dohrenwend (2010) developed a typology of stressful situations that may present higher risks for people that suffer with PTSD. The typology consisted mainly in six characteristics of events that are considered most important in determining negative changes that may be uncontrollable: source, valence, unpredictability, magnitude, centrality, and tendency to exhaust the individual physically. Peacock et al. (2015) managed to develop a risk typology for groups of people with chronicle non-cancer pain that are in risk of aberrant behavior due to opioid medications. The authors concluded that the behaviors might be predicted for the distinct clusters of people that were created. Nonetheless, the authors emphasize the need of weighting risk factors, as they are not equally distributed and certain risks present interaction. Hunter (2017) developed a typology of groups of people according to their behavior towards risk exposures to hearing problems. Jang et al. (2018) clustered Asian Americans vulnerability to health access by developing a risk group typology. They generated three clusters based on the optimum entropy value: low, moderate, and high risk. People were grouped into these clusters according to its risk factors. Considering duration, intensity, and coverage, De Castro et al. (2018) built an epidemic risk typology using previous data from epidemic waves and risk factors.

Lastly, risk assessment is also a fundamental evaluation for studies covering environmental issues and natural disasters. Schwarz et al. (2009) developed a typology for empirical risk assessment and a typology for analytical risk assessment for buildings at risk of earthquakes in Antakaya, Turkey. In front of different vulnerability affecting factors (quality of maintenance and workmanship, building structure and material, particularities on the ground and elevation plan, regularity, Earthquake Resistant Design (ERD)), the authors assigned vulnerability classes to each building, ranging from A to F. The European Macroseismic Scale (EMS-98) provides the damage grades and the quantity of their occurrence. Galiana-Martin, Herrero, and Solana (2011) proposed a progressive multi-scale approach to assess the hazard and vulnerability of wildlands. The method encompasses three stages: a regional urban development model, a landscape character assessment, and a wildland typology. The latter according to distinct morphologies and different landscapes. The typology connected nine types of land cover with aspects of internal vulnerability (characteristics of the wildland itself) and external vulnerability (characteristics of the wildland unit location).

Skinner et al. (2014) developed a typology of potential uncertainties in Environmental Risk Assessments (ERAs) in order to provide managers an evidence-based guidance to identify and manage uncertainty during risk assessments. Amongst the distinct types and sources of uncertainty, the typology assists by providing categorizations with definitions of all potential types of uncertainties that might be encountered. Chang et al. (2018) developed an approach that identifies typologies of coastal communities according to their hazard vulnerability characteristics. Each community is described considering its vulnerabilities indicators, and then a cluster analysis is applied to the indicators in order to obtain the groups with higher vulnerability similarities. Käyhkö (2019) built a typology of responses to risks by examining responses of Nordic farmers facing the diverse effects of climate change and defended the inclusion of popular participation in adaptive management regarding climate changes.

Even though the step of identifying types of risk is being applied to different areas, there is a lack of typology of risks in water resources systems. It is a challenge considering the complexity of the functioning of a water resources system. The risks may involve economic, social, climate, hydrological, structure engineering, and environmental areas.

2.3.2 Risk assessing complex systems

A complex system can be defined as a system that encompasses networks composed by diverse and numerous components that interact with each other through nonlinear processes (SIMON, 1962). Still, complex systems tend to evolve through self-organization: they are neither completely random nor completely regular (SAYAMA, 2015). A wide range of complex systems can be found around us, from gene regulatory networks within a cell to the global climate, and, of course, water systems, as stated before.

Studies concerning social-ecological systems (SES) tend to focus on the relations between environmental and social aspects. Currently, the SES concept considers the dynamism and change of the systems, adding several multidisciplinary variables to understand its functioning (JOZAEI *et al.*, 2020; PARTELOW, 2018). It is fair to state that these aspects make it a complex system: full of risks, uncertainties and challenges for its management and planning. It is fair to say, also, that dealing with complex systems often happens when it comes to public management of resources such as water and energy, as it involves physical (natural), economic, social and cultural aspects, becoming a convoluted challenge for the decision-making process.

When it comes to risk assessment that aims to provide information for decision makers that are dealing with complex systems, it is imperative to assure that the method was developed through adequate techniques and sufficient knowledge (RAE et al. 2012). In that tone, the primordial steps of a general risk assessment method are to structure the information and knowledge available at a local level in order to systematic model the risk at system level (ZIO, 2018). The main obstacle at this stage is the usually limited information, increasing the uncertainty of the assessment outcomes. A solution to overcome this challenge is to incorporate the background knowledge provided by technicians and experts of the systems through qualitative data collection. According to Zio (2018), the risk assessment outcomes depend on the current state of knowledge and values assigned. The author concludes that the description of the risk intrinsic of a system is inherently conditional on the knowledge of that system.

3 DEVELOPMENT OF A DROUGHT VULNERABILITY INDEX USING MCDM AND GIS - STUDY CASE IN SÃO PAULO AND CEARÁ, BRAZIL

3.1 Introduction

Water demand tends to increase with population growth, and in conjunction with changing climate risks, a constant water supply can become increasingly uncertain. Over the last decades, the growth of water consumption more than doubled population growth (COSGROVE AND LOUCKS 2015). This increase in water demand combined with water scarcity will likely aggravate already existing water stress scenarios in various areas of the planet (SUÁREZ-AMIÑANA et al., 2017). For their part, industrialized countries contend with conflicts related to water allocation, non-point source pollution, and extreme events, including droughts (PRYSHLAK et al., 2014). Less privileged countries also face water uncertainty and scarcity due to similar factors, but which are often exacerbated by the lack of sufficient infrastructure. As a result, the negative impacts of climate change events are a major obstacle for sustainable development in these regions, though the magnitude of the challenge is unevenly distributed between and within countries. As a result, vulnerability assessment and prioritization are fundamental needs for scientific studies on climate change adaptation (VARGAS AND PANEQUE, 2017).

Drought events, depending on their frequency, intensity, and duration, amongst other physical aspects, cause a range of impacts on the environment and to human society. These impacts generate additional, secondary complexities for water resource management (MONTANARI et al., 2013). The subsequent uncertainty related to dependable water provision requires increased efficiency in planning and management (PIENAAR AND HUGHES, 2017). Responding to drought through post-hoc crisis management strategies is inefficient (WILHITE et al., 2014) and it is up to the water resource managers to develop and apply proactive strategies that mitigate the impacts of water scarcity. To do so effectively requires guidelines for the development of drought management plans, with proactive and risk-based management strategies (WILHITE et al., 2014), based on social, technical, and scientific findings. The vulnerability analysis of a water system is an essential contribution to the elaboration of such strategies.

Vulnerability is usually presented as an aggregate measure of human welfare, which assesses environmental, social, and economic susceptibility to potentially harmful disturbances. It is not a static measure, but rather, vulnerability varies through time and space according to political and social actions (BOHLE et al., 1994; HEWITT, 2013; THOMAS et al., 2016). Analyses therefore require a robust methodology to identify and categorize vulnerability, and a strong connection between researchers and decision-makers (TURNER et al., 2003). Since 2006, climate change vulnerability studies have increasingly focused on water resource management. Most of the publications stem from research in European and North American countries (NAZEMI et al., 2013; ACOSTA AND MARTÍNEZ, 2014; Asefa et al., 2014; CHANDA et al. 2014; GOHARIAN et al. 2016, MATEUS AND TULLOS, 2017; VARGAS AND PANEQUE, 2017; ZHANG et al., 2017; ANANDHI AND KANNAN, 2018), and there is a gap in South American research. Within Brazil, there is also a demand for increased research on water resources vulnerability, including the social components (WANG et al., 2014) since contemporary climate research focuses primarily on renewable energy systems, rather than water, and tends not to engage with the social aspects of vulnerability.

During the last couple of decades, a collaborative process of planning and management has been increasing amongst the water resources research community. Simonovic and Bender (1996) defend those participatory strategies help management to make well-informed decisions because it involves a wide range of important actors in the decision-making process. Collaborative models within water resources planning create linkages between social well-being of people, environmental management, and economic development. It is important to highlight the contributions of participation in water resources planning and management due to its complexity and uncertainty, as it covers: complex natural and human systems and conflict of multiple social, cultural, environmental, and economic interests (LANGSDALE et al., 2013).

The participatory process in water resources planning and management is established in several nations, such as Brazil (BRASIL, 1997). It is related mainly to the management of river basins and water allocation decisions in states like Ceará and São Paulo. However, the elaboration of studies such as vulnerability and risk analysis remain, mostly, one-sided.

This paper proposes an improved method to quantify and classify drought vulnerability through a multi-criteria decision making (MCDM), collaborative, and GIS-based analysis of exposure and sensitivity, and the adaptive capacity of a population to cope with drought. The iSECA model, and its innovations offer technical and conceptual contributions to, and serve as a tool for, the elaboration of drought management plans. The method is based on the IPCC definition of vulnerability, which includes the concepts of sensitivity, exposure, and adaptive capacity (IPCC, 2001) and can be applied to both regional and local scales by using existing, secondary data. Prioritizing areas not covered by the majority of climate change vulnerability research, the authors applied iSECA to two distinctive areas in Brazil: the states of Ceará and São Paulo. These states represent regions with different social and economic activities and dynamics, as well as different biophysical and climatic characteristics.

The method does not demand extensive fieldwork or substantial financial costs. The data can be obtained through local officials, publications, and online databases. The indicators used in this model were chosen through brainstorming sessions taken after the application of a survey amongst members of different River Basin Committees in São Paulo. They quantify meteorological, hydrological, and socioeconomic aspects of drought (ESLAMIAN AND ESLAMIAN, 2017). The differing characteristics between the two study areas demonstrates the value and relevance of iSECA for drought studies in other contexts. iSECA considers the complexity of diverse agents and aspects that interfere with the resilience of a water system by following straightforward, logical steps. The results are easy to understand and to visualize, making it accessible to decision-makers and the broader communities facing drought risks. The results of iSECA can contribute to drought management plans, on national, state, or basin scales. In sum, iSECA is an easy-to-build model, with a wide range of scalar applications and clear results, which makes it possible to analyze the outcomes of drought related public policies.

3.2 Background considerations

The notion that populations are differently vulnerable to natural hazards has been a focus of disaster research for many years. Hashimotto, Stedinger, and Loucks (1982) brought the definition of vulnerability and resilience to the study of water systems and Susmam et al. (1983) demonstrate that different groups within a society are at different levels of risk since they present varied capacities to absorb impacts and to recover. Several works present vulnerability as a dynamic between external (biophysical) and internal (socioeconomic) factors (BOGARD, 1988; DOW, 1992), adding that the degree of impact suffered from a harmful event is related to the regional risk and the social and economic conditions of the population affected (BOHLE et al., 1994; CUTTER, 1996).

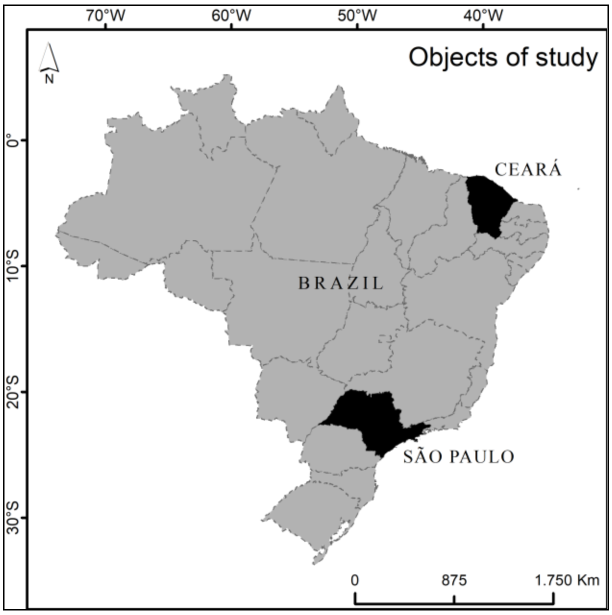
Given the evolution of the concept of vulnerability and its different interpretations by the various disciplines, there is not a technical consensus around a definition. Here, we define vulnerability to drought as a function of the level of exposure to physical climatic factors, sensitivity to drought impacts, and a population's ability to cope with these impacts (IPCC, 2001; ABRAHAM, 2006; FONTAINE, 2007). Exposure represents the magnitude, in time and space, of extreme climate events. Sensitivity is the degree of preparedness of a system and the capacity to absorb impacts without long-term harm or without presenting any significant change in its state. Lastly, adaptive capacity is the degree to which the adjustments and adaptations, in the form of actions, processes, or structures, can mitigate and minimize the potential impacts of climate change occurrences (IPCC, 2001; ABRAHAM, 2006).

Using an alternative methodology, Nazemi et al. (2013) measured the vulnerability of a Canadian water system based on potential variations in flow rate that represent a response to climate change. Goharian et al. (2016) combined the severity of the failures of a reservoir system in Salt Lake City, U.S., with a sensitivity analysis to climate change. Some works applied a reliability-resilience-vulnerability (RRV) analysis to asses climate change and climate events (such as droughts) impacts on water systems (ASEFA et al., 2014; CHANDA et al., 2014; MATEUS AND TULLOS, 2017; ZHANG et al., 2017). Anandhi and Kannan (2018) and Acosta and Martínez (2014) merged the IPCC structure of vulnerability with the Pressure-State-Impact-Response framework and with GIS techniques, respectively, to quantify water resources vulnerability to climate change. Vargas and Paneque (2017) developed an index to quantify vulnerability to drought at the river basin level. The studies mentioned here were developed through Europe and North America.

3.3 Study area

The iSECA method was applied in the states of São Paulo and Ceará, located in the southeast and northeast of Brazil, respectively (Figure 2). The areas were purposively chosen to test the applicability of the iSECA across different social and biophysical contexts. Both states, although located within the same western country, present divergent dynamics that guarantee the functionality of the method for different regions. São Paulo is the most populous and wealthiest state in Brazil, representing 32% of the national GDP (CRH / CORHI 2017). The state is located between 20º and 25º of latitude in the southern hemisphere and presents a primarily humid subtropical climate. The state of Ceará is located between 3º and 7º south latitude. It is a primarily semi-arid region, and its history is marked by recurrent severe and prolonged drought events.

Figure 2 - Location map highlighting the study area: States of São Paulo and Ceará, Brazil.



Source: Author.

3.3.1 Ceará

Ceará comprises a total area of 148,920 km² and approximately 9 million people. The annual average precipitation is less than 800 mm, which primarily falls between February and April. The latter part of the year is characterized by little to no precipitation. The annual average temperature in Ceará is about 26 ºC, with little seasonal variation. Ceará has an average surface water supply of 128 m³/s and an estimated water demand of 50 m³/s (INESP, 2008). A few essential biophysical characteristics of Ceará are its semi-arid climate, caatinga vegetation, the predominance of a crystalline basement, the occurrence of shallow soils – reducing its potential to store underground water, and the presence of intermittent rivers, combined with intense solar radiation and high evapotranspiration rates (INESP 2008). The state encompasses 184 municipalities, and its water bodies are divided into twelve hydrographic regions. Each region has a watershed committee that is responsible for its participative and integrated management of water resources (ARAÚJO, 2012). The most crucial water system of the state is the Jaguaribe-Metropolitano. It unites five out of the twelve hydrographic regions of the state through water transfer channels and reservoirs that have a water volume capacity of more than ten thousand hm³ (SILVA et al., 2017).

3.3.2 São Paulo

With an area of approximately 248,209 km² and a population of 43.35 million people, São Paulo is the most populous state in Brazil, representing 22% of the country's total population. The degree of urbanization of 96% (CRH/CORHI, 2017; MARTIRANI AND PERES, 2016). Sixteen percent of the population is classified as highly or very highly vulnerable, according to Index of Social Vulnerability of São Paulo (IPVS) (SEDAE, 2010). The annual average precipitation is about 1377 mm, with July being the driest and coldest month (15 ºC, 35 mm average) and January being the wettest and warmest month (22 ºC, 218 mm average) (CRH/CORHI, 2017). São Paulo has an average surface water supply of 3121 m³ / s and an estimated water demand of 443 m³ / s. It is divided into 22 hydrographic regions, with a management system similar to Ceará. Between 2013 and 2015, São Paulo faced a historic water crisis and the São Paulo Macrometropolis, with 30 million people, was the region most affected. The year 2014 recorded the lowest rainfall levels since the beginning of the monitoring of the historical series (CRH/CORHI, 2017). However, the water crisis should not be attributed only to climatic factors without considering the role of water managers (JACOBI, CIBIM AND LEÃO, 2015), as well as the socio-economic context of the state.

3.4 Methods

3.4.1 MCDM for indicator analyses

Management decisions within the water resources domain must account for a diversity of participants and perspectives, creating complexity and space for a variety of possibilities and scenarios. Multi-criteria decision making (MCDM) is an evaluation approach designed to deal with this type of complexity, in which alternative choices are analyzed by considering a set of multiple (and frequently conflicting) criteria (ISHIZAKA AND SIRAJ, 2017). MCDM integrates hierarchical division by weighting the aspects considered in analysis (indicators) and expert empowerment (LIN et al., 2019). These techniques can also be applied to quantify analyses that are commonly assessed qualitatively, such as vulnerability assessments. However, it is important to note that MCDM entails uncertainty, notably when the weighting process occurs subjectively based on the analyst experience, and models should be subject to sensitivity analysis (see item 3.4.5).

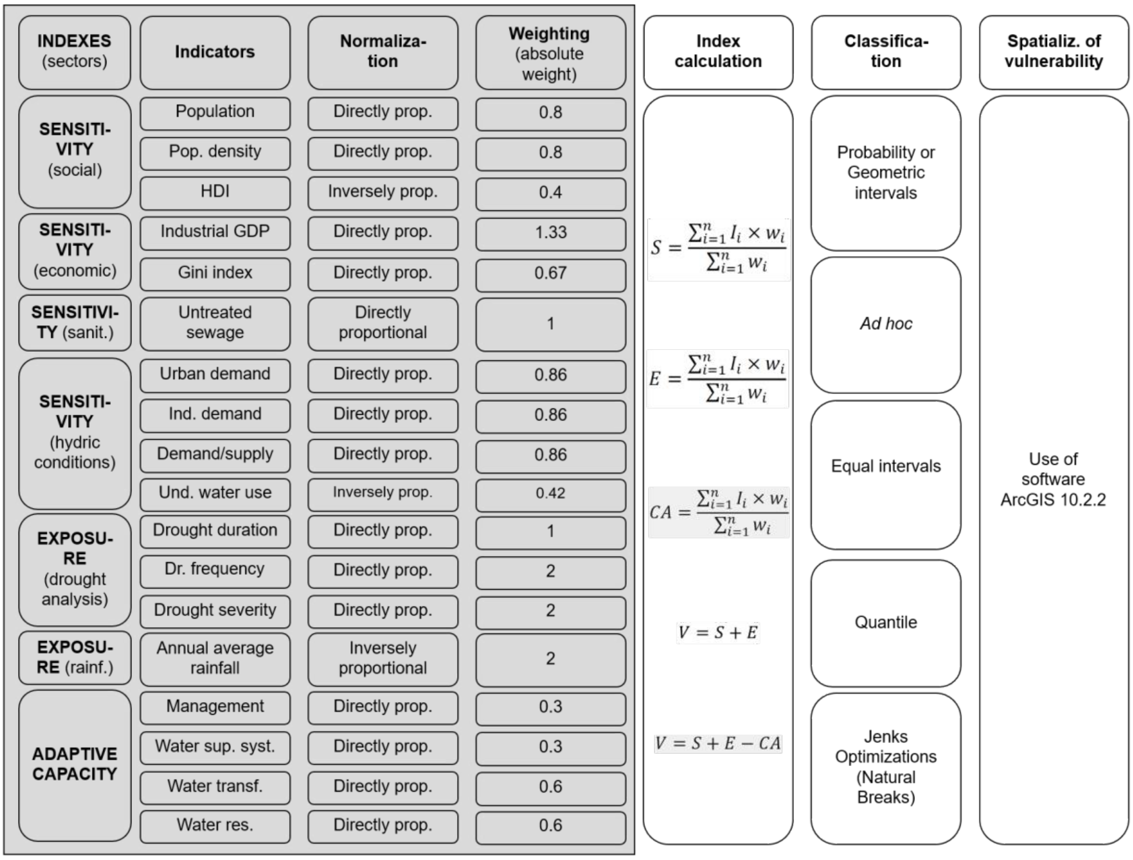
MCDM techniques are used for other types of water resources research. For example, Kim and Chung (2013) assessed the vulnerability to climate change and variability in South Korea using a suite of MCDM methods. Lin et al. (2019) presented a flood susceptibility analysis framework for a Chinese city based on an MCDM method that quantifies the potential flood scale and extent, all in a GIS platform. In Iran, Mostafazadeh et al. (2017) built eight structural management scenarios that were analyzed using spatial distribution and an MCDM technique to choose the best scenario. Overall, these techniques are easily adaptable to different contexts and scenarios, and they can also be found in a variety of other types of research applications (KUMLU AND TÜDES, 2019; MELA, TIAINEN AND HEINISUO, 2012; HÜLLE, KASPAR AND MÖLLER, 2011; TRIANTAPHYLLOU, 2000; OZERNOY, 1987).

For this study, the authors apply an MCDM approach in order to analyze indicators and build them into a unified index, making it possible to quantify vulnerability. Based on the concepts introduced by IPCC (2001), the method considers the vulnerability (V) of a given system as a combination of the sensitivity (S) and the exposure (E) to drought discounted by the adaptive capacity (CA) of the built infrastructure.

The index represents the relative vulnerability of the population within the system and its intrinsic conditions to cope with drought events. To represent S, the authors considered social and economic indicators, as well as sanitation conditions and water supply/demand of the system. E represents external climate conditions of the systems and was built based on historical rainfall patterns. Lastly, in order to quantify CA and to represent the structure of the system to deal with drought events, we considered management indicators as well as water infrastructure (such as canals and reservoirs).

The method follows a logical sequence of steps: selecting indicators, normalizing indicators, clustering indicators between sectors, weighting indicators and sectors, calculating indexes, classifying indexes, and spatializing indexes. The sequence is described in the following sections. The sectors, indicators, and index calculations are summarized in Figure 3.

Figure 3 - Method iSECA - details of sectors, indicators, and index calculations.



INDEXES (sectors)	Indicators	Normalization	Weighting (absolute weight)
SENSITIVITY (social)	Population	Directly prop.	0.8
	Pop. density	Directly prop.	0.8
	HDI	Inversely prop.	0.4
SENSITIVITY (economic)	Industrial GDP	Directly prop.	1.33
	Gini index	Directly prop.	0.67
SENSITIVITY (sanit.)	Untreated sewage	Directly proportional	1
SENSITIVITY (hydric conditions)	Urban demand	Directly prop.	0.86
	Ind. demand	Directly prop.	0.86
	Demand/supply	Directly prop.	0.86
	Und. water use	Inversely prop.	0.42
EXPOSURE (drought analysis)	Drought duration	Directly prop.	1
	Dr. frequency	Directly prop.	2
	Drought severity	Directly prop.	2
EXPOSURE (rainf.)	Annual average rainfall	Inversely proportional	2
ADAPTIVE CAPACITY	Management	Directly prop.	0.3
	Water sup. syst.	Directly prop.	0.3
	Water transf.	Directly prop.	0.6
	Water res.	Directly prop.	0.6

Index calculation

$$S = \frac{\sum_{i=1}^{n} I_i \times w_i}{\sum_{i=1}^{n} w_i}$$

$$E = \frac{\sum_{i=1}^{n} I_i \times w_i}{\sum_{i=1}^{n} w_i}$$

$$CA = \frac{\sum_{i=1}^{n} I_i \times w_i}{\sum_{i=1}^{n} w_i}$$

$$V = S + E$$

$$V = S + E - CA$$

Classification

- Probability or Geometric intervals
- *Ad hoc*
- Equal intervals
- Quantile
- Jenks Optimizations (Natural Breaks)

Spatializ. of vulnerability

Use of software ArcGIS 10.2.2

sanit. = sanitation; rainf. = rainfall; Pop. = population; Ind. = industrial; Und. = underground; Dr. = drought; sup. syst. = supply system; transf. = transference; res.= reservoir; prop. = proportional

Source: Author.

iSECA was developed for application at different spatial scales and was applied the model on both river basin and local (municipality) levels. To analyze the relative importance of adaptive capacities, the authors evaluated the model with and without the influence of adaptive capacity. Considering the more favorable hydrological situation in São Paulo, with higher annual rainfall average and the presence of various perennial rivers, the authors ran the model at the river basin level and without considering adaptive capacity. In Ceará, the model considered adaptive capacity and was applied at the local level. The authors also compared both sets of results with and without adaptive capacity to quantify the importance of water resources infrastructure and management in scenarios of high (São Paulo) and low (Ceará) water availability.

3.4.2 Application of survey

The survey was taken during 2017 in São Paulo and focused on the vulnerability perception of the state considering the water crisis faced during 2013-2015. The analysis of the perception of the impact of the water crisis consists of a survey and qualitative assessment of the acquired information. The data is composed of the experiences of active members of the São Paulo State River Basin Committees, representing Public State, Users and Civil Society. The strategy for the survey consists mainly of preparing and applying a questionnaire.

The questionnaire was designed to identify critical points in the various divisions that are directly or indirectly influenced by water availability. The main focus of the questionnaire is to assess critical points noticed during the water crisis that affected the State between 2013 and 2015.

In this way, the questionnaire mainly presents questions with objective answers. Questions are asked in the form of a statement, indicating some problem within a major sector. The respondent marks the level of impact according to their experience and observations made during the crisis period, considering the increasing scale of impact level: Irrelevant (0), Low (1), Medium (2), High (3), Very High (4), Potential (P), Not Assessed (NA). Potential impact may occur in the future although it has not yet been observed. The option “NA” if the respondent chooses not to respond to the question asked because he is not comfortable or does not have information. The questions were grouped according to the impacts of the drought on different sectors: the different uses of water and sanitation, the conflicts generated, the availability of water, communities, economic sectors and the environmental/recreational sectors.

The complete structure of the questionnaire is presented in Annex A of this document.

3.4.3 Index elaboration

Within each vulnerability component (Exposure, Sensitivity, Adaptive Capacity), indicators are categorized into sectors. Sensitivity is divided into four sectors: social aspects, economic aspects, sanitation, and water conditions. Sanitation considers the level of untreated sewage, which ends up being dumped into water bodies. With the increase of the organic load, the water bodies become unfit for human consumption and, consequently, in periods of drought, the number of alternative water sources is reduced. Drought has diverse impacts on the economic and social development of affected communities since water is a natural resource used in the means of production and the daily habits of the population. The precarious development of some communities represents poor preparation to deal with crises and emergencies (VEYRET, 2007). In this context, the social and economic aspects appear with weight 2 in the calculation of sensitivity. The authors considered population, quality of life, income distribution, and economic activity as indicators of both aspects. Finally, the supply and demand scenarios of the population located in the study areas were combined to represent the water conditions, which received triple the importance in the sensitivity analysis considering that the study is focused on the susceptibility to a scenario of water scarcity. Sanitation and water supply and demand data were obtained through the National Water Agency (ANA). Socio-economic data is from the national census and the Brazilian Institute of Geography and Statistic (IBGE).

To compute the exposure index, we used three indicators representing drought analysis, rainfall, and another alternative water source. This last indicator considers the exploitable groundwater potential of the aquifers of São Paulo, taking into account that the surface water sources are more vulnerable to droughts. The analysis of droughts represents the variability of the rainfall regime in the chosen area. The monthly precipitation average of each group was obtained, composing a time series of 36 years (1979 to 2014) in São Paulo and 106 years (1911 to 2017) in Ceará. In addition, the authors calculated the Standardized Precipitation Index (MCKEE, DOESKEN AND KLEIST, 1993) for the timescale of twelve months (SPI-12) for each group in order to identify the frequency and duration of droughts over the time series and to classify them according to their intensity. Rainfall data were collected from the ANA website.

Finally, the adaptive capacity index considered aspects of water management, water transfer, water reservoir capacity, and the situation of water systems. We considered that adaptive capacity can reduce vulnerability to drought, but it is not capable of canceling out sensitivity or exposure. Therefore, for the calculation of the vulnerability index in Equation (6), we considered a scale of 30% of the total adaptive capacity index. Hydrographic and water infrastructure data were obtained from the Water Resources Management Company of Ceará (COGERH) as a georeferenced database, making it possible to measure the length of the water channels and the maximum capacity of the reservoirs.

The calculation of the indexes proceeded as a multivariate analysis, including normalization and weighting of the indicators. The normalization process computed each indicator, with its different numeric scales and units, as a value varying mainly between 0 and 1, where 0 means low sensitivity, exposure or adaptive capacity, and values greater than 1 represent extreme conditions. This process occurred through the (*2* and the (3, where (2 was applied to indicators directly proportional to the index and (3 to indicators inversely proportional to the index. *Ii* represents the indicator, and *Xi* represents the variable. Min and Max are the minimum and maximum values that were fixed for each indicator.

$$I_i = \frac{X_i - Min}{Max - Min} \tag{2}$$

$$I_i = \frac{X_i - Max}{Min - Max} \tag{3}$$

Each index (sensitivity *S*, exposure *E*, and adaptive capacity *CA*) was divided into different sectors, composed by the indicators, with different weights, as described later in this paper and illustrated in Figure 3. Each indicator was also attributed a weight that represented said variable within its sector. The absolute weight (*wi*) is then computed through (4, where *SW* is the weight of the sector, and *IWi* is the weight of each indicator within the sector.

$$w_i = \frac{SW}{\sum_{i=1}^{n} IW_i} \times IW_i \tag{4}$$

The indexes (S, E, CA) are calculated by applying (5. Finally, the Vulnerability Index is calculated using (6 for the first analysis and (7 for the second analysis.

$$INDEX\ (S, E, or\ CA) = \frac{\sum_{i=1}^{n} I_i \times w_i}{\sum_{i=1}^{n} w_i} \tag{5}$$

$$V = S + E \tag{6}$$

$$V = S + E - CA \tag{7}$$

The weights were first applied to each sector within the indexes (S, E, CA) and then distributed amongst the indicators of their sectors. The weighting step proceeded with sessions of *brainstorming* with specialists on water resources management. The sensitivity analysis tested the robustness of the model, including the effects of the indicators and the given weights, and is described later in this paper in Section 5.4.5.

3.4.4 Classifying and mapping vulnerability

In order to assess the fit of classification methods, a chi-square test was used to test the adherence of the indexes to the normal distribution model. To avoid methodological bias, the classification scheme was based on five different methods. The Probability Method or The Geometric Intervals method were applied. The former was applied to the normally distributed data, where the intervals are established according to the mean and standard deviation of the distribution. The latter method was applied to data with asymmetric distributions, which creates geometric intervals by minimizing the sum of the squares of the number of elements in each class, so that the classes have approximately the same number of elements and that the difference between the classes is consistent. Second was the Ad Hoc Method, in which the authors used their empirical knowledge to define the classes. Third, for the Equal Intervals Method, intervals were defined with equal values (such as 0 to 0.25, 0.25 to 0.50, and so on). Fourth, in the Quantile Method each class was assigned the same number of elements, and there are no empty classes or disparities in the number of elements in the different classes. Finally, the Jenks Optimization Method, optimized the difference of values between classes and maximized the similarity of values in the same classes, based on the Best Variance Adjustment index (RAMOS et al., 2016). Geometric Intervals, Equal Intervals, Quantile, and Jenks Optimization were calculated through ArcMap® 10.2.2, and their specific methods are detailed by Ramos et al. (2016). The Probability method is the same as that utilized by the Institute of Research and Strategic Economics of Ceará (IPECE, 2016).

Classification methods divided the values into five classes for each index (sensitivity, exposure, adaptive capacity, and vulnerability): low, moderate, high, very high, or extreme. In order to synthesize the five methods, the final classification was made from the assignment of grades to each group according to their acquired classifications.

The final score (FS) was obtained from (8, where *GLi, GMi, GHi, GVHi*, and *GEi* represent the number of times each group was classified as low, moderate, high, very high and extreme and *LS, MS, HS, VHS,* and *ES* represent, respectively, the score of each class.

$$FS = GL_i \times LS + GM_i \times MS + GH_i \times HS + GVH_i \times SVH + GE_i \times ES \qquad (8)$$

The classification is georeferenced and spatialized using the ArcGIS software. This permits a visual and spatial representation of the final classification of drought vulnerability and identification of where and who is more vulnerable to the impacts of water scarcity.

3.4.5 Vulnerability triangle

The vulnerability triangle (VARGAS AND PANEQUE, 2017; LIU et al., 2013) graphically represents the three components of vulnerability (sensitivity, exposure, and adaptive capacity) by using the relative weight calculated with Equation (8). OI stands for the original index, and it can be replaced by the exposure (E), sensitivity (S), or adaptive capacity (CA) indexes. *RI* is the relative index, where *REI* represents the Relative Exposure Index, *RSI* is the Relative Sensitivity Index, and *RCAI* represents the Relative Adaptive Capacity Index.

$$RI = \frac{OI}{E + S + |-CA|} \times 100 \tag{9}$$

The authors used the tool to visualize and analyze the natural shape of drought vulnerability in both states. The vulnerability triangle represents the municipalities as points, and in Ceará, zone in which each point is located tells us if the municipality's vulnerability is more influenced by the sensitivity, exposure, or adaptive capacity index. The same approach was not used to analyze São Paulo’s results because that states vulnerability index considered two components (sensitivity and exposure) instead of three.

3.4.6 Sensitivity analysis

Since the model was built with multiple indicators and different weights to calculate the indexes, it is fair to assume that there is a level of uncertainty attached to the results. Therefore, in order to assess the robustness of the model and the reliability of the results computed from the indicators, the authors ran a sensitivity analysis.

The test analyzed three scenarios where the data suffered a variation of 5%, 10%, and 20% from its original values. To do so, we used the original and normalized data to generate three datasets of synthetic values through triangular distribution with α-β and α+β as minimum and maximum values, respectively, and α as the mode value. α represents the original value for each indicator in each object (city or river basin), and β is the limit value of variation (5%, 10%, 20%). For each variation scenario, the test generated one thousand synthetic values for each α represented. Then, the authors ran the model to obtain one thousand values of the vulnerability index. The sensitivity test permitted visualization of whether the model was sensitive or not to computation of data from different entry datasets, i.e., if iSECA can be used for different study objects with distinct behaviors, characteristics, and numeric values.

3.5 Results

This section presents the results for each study area and their interpretation. The authors highlight the results obtained from sensitivity, exposure, and adaptive capacity indexes and present the description of the aggregate vulnerability index with a georeferenced map for both states. Even though the analysis of Ceará uses the municipality scale, the map of vulnerability of Ceará also highlights the boundaries of the 12 main river basins of the state.

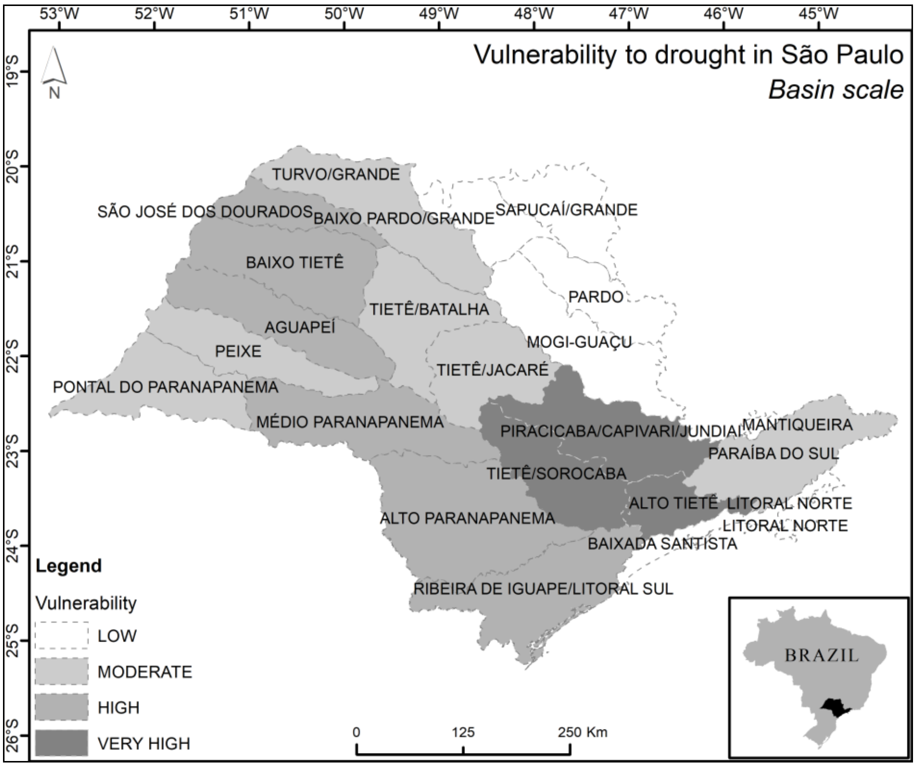
3.5.1 São Paulo

The values obtained for the exposure index fit within a range of 0.26 to 0.68, presenting a low amplitude. The results suggest that the state of São Paulo does not present tendencies of water scarcity. There were no occurrences of extended periods or high frequency of drought events during the period analyzed. The exposure values do not demonstrate much variation, in part, because the study area is not large and does not contain multiple climatic regions.

On the other hand, sensitivity values vary from 0.21 to 1.29. The maximum value, in the Alto Tietê region, is considerably higher than values for other basins, which only vary from 0.21 to 0.62. Alto Tietê encompasses the municipality of São Paulo and part of the Metropolitan Region of São Paulo (MRSP), which presents social and economic aspects distinct from the other regions. It was observed that, among the indicators utilized in the sensitivity calculation, the values of industrial production, population, and population density for the Alto Tietê unit exceeded the limit value of 1. The industrial activity should not be significantly impacted in periods of water scarcity since there is a lower relative water demand for this sector. It can be inferred, therefore, that the higher sensitivity of the MRSP, faced with a scenario of water scarcity, would be its substantial number of inhabitants and the spatial density of these inhabitants. However, due to a medium level of exposure, the vulnerability to drought of Alto Tietê is not as extreme as its sensitivity. Given these results, in assessing the water crisis that affected São Paulo in 2014, it is likely that water management efficiency was a key factor.

Based on the results presented in Figure 4, an estimated that 64% of the state's population is living in a situation of very high vulnerability to drought. This corresponds to more than 30 million inhabitants. It is also estimated that the areas with very high vulnerability account for about 70% of the state's GDP and approximately 20% of the national GDP. Including adaptive capacity in São Paulo reduced vulnerability in most of the regions with an average of 29%. However, in Alto Tietê the inclusion of water resources infrastructure and management only reduced the vulnerability index value by 4%. This is explained in part by the fact that only 6% of the water system within the Alto Tietê region is considered satisfactory, i.e., capable of supplying water to the population with satisfactory quantity and quality.

Figure 4 - Map of vulnerability to drought - São Paulo, Brazil.



Source: Author.

The questionnaire applied in São Paulo in 2017 collected 85 answers amongst the 22 river basins. The answers pointed to water uses, sanitation, economic and environmental factors as the most vulnerable. In regions like Alto Tiete, with more urban characteristics, sanitation, water uses, water availability, and economic were, respectively, the most sensible spots. However, regions furthest from urban centers present a higher concern on the environmental and recreational factor. According to responders, these regions contemplate a variety of recreation activities involving water bodies, including luxury vacation condominiums. As the water reservoirs levels decreased and water pollution, consequently, increased, water managers were pressured concerning the safety of the population that enjoys the activities, including workers who got their income from such activities.

As a matter of comparison, we decided to add the answers of another questionnaire held in 2021, with similar approach: focused on the 2013-2015 São Paulo's water crisis, we looked for River Basin Committees members to answer an updated questionnaire. Table 1 exhibits the small differences of sector amongst the two questionnaires.

Table 1 - Comparison between the structure of the questionnaires taken in 2017 and 2021.

Sections	2017	2021
Water uses	x	x
Sanitation	x	x
Water availability	x	
Communities	x	x
Economic	x	x
Environmental and recreational	x	x
Influence of the media		x

Source: Author.

The main goal of this second questionnaire was to analyze if there was a difference in the answers' pattern. It has been reported in newspapers, during 2020 and 2021, that a new water crisis is affecting the state of São Paulo, amongst other regions in Brazil (FERRARI, 2020; MUNHOZ, 2020; VIECELI, 2021; VIEIRA, 2021). Besides the various impacts that a water crisis can generate, most of the focus during this new upcoming crisis is on the economic and electric sector. This fact can be due to the pandemic and post-pandemic social and economic situation in Brazil, which can be greatly affect by a national water crisis (MALAR, 2021; ROUBICEK, 2021). Therefore, the questionnaire of 2021 was taken during another water crisis but focused on the previous water crisis (2013-2015).

The new questionnaire received 46 answers and presented an overall increase of impact level on the water use and sanitation sectors. However, in the Alto Tietê region, the responders presented a higher concern with the economic impacts in 2021 than in 2017. In most regions, the environmental and recreational sector presented less concern in 2021. It is noticeable that there are differences in the results obtained between both questionnaires, which can lead to the conclusion that the current water crisis might have affected the perception of the previous water crisis. However, this analysis is limited by the fact that the structure of the new questionnaire presented a slight difference and half of the number of responders.

3.5.2 Ceará

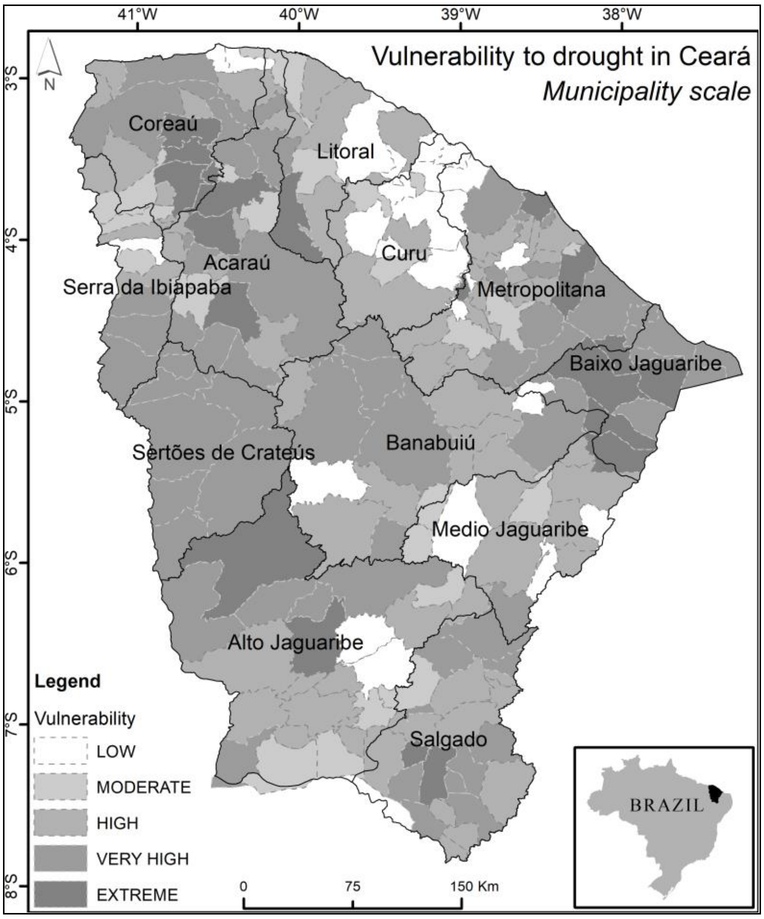
The sensitivity of the municipalities that encompass the major metropolitan area of Ceará were classified as extremely vulnerable, similar to São Paulo. This indicates the need for more attention to the social, economic, and sanitation characteristics of more populated areas in periods of drought, in addition to water supply and demand. The authors can also infer that densely populated locations tend to be more sensitive to drought. Additionally, the municipalities within the Baixo Jaguaribe basin present a higher sensitivity index. Even though it does not fall within the extremely vulnerable category, Baixo Jaguaribe presents the highest ratio between total demand and water supply. This basin has large irrigated regions and areas with intense shrimp farming activity. These activities have high water demand and may be responsible for the high ratio for most of the municipalities located within this basin.

The exposure index points to extreme situations of municipalities located at the western area of Ceará, highlighting the basins of Alto Jaguaribe, Sertões do Crateús, and Coreaú. The areas categorized with lower exposure include the municipalities located in the central coastal region of the state, in the basins of Metropolitana, Curu, and Litoral.

The adaptive capacity results highlight the significant influence of the integrated systems of interbasin water transfer in the state. The Jaguaribe-Metropolitano System is responsible for supplying the Metropolitan Region of Fortaleza (MRF), which includes the capital of Ceará, Fortaleza. The capital has a population of approximately 2.6 million people and is surrounded by intense industrial activity, including the Pecém Industrial and Port Complex. The system has a robust water channel network that integrates important and strategic reservoirs, such as Orós, Castanhão, and Banabuiú, through extensive water channels. Some regions within Coreaú and Acaraú basins also demonstrate higher adaptive capacity due to the concentration of water channels.

Drought vulnerability, as measured by the sensitivity, exposure, and adaptive capacity indexes, is shown in Figure 5. Most of the municipalities classified as low vulnerability are surrounded either by water channels or essential reservoirs. The municipalities located on the western side of Ceará are primarily classified as very high or extreme vulnerability. The central region of the state, known as "Sertão Central", is also classified as being very high vulnerability.

Figure 5 - Map of vulnerability to drought - Ceará, Brazil.

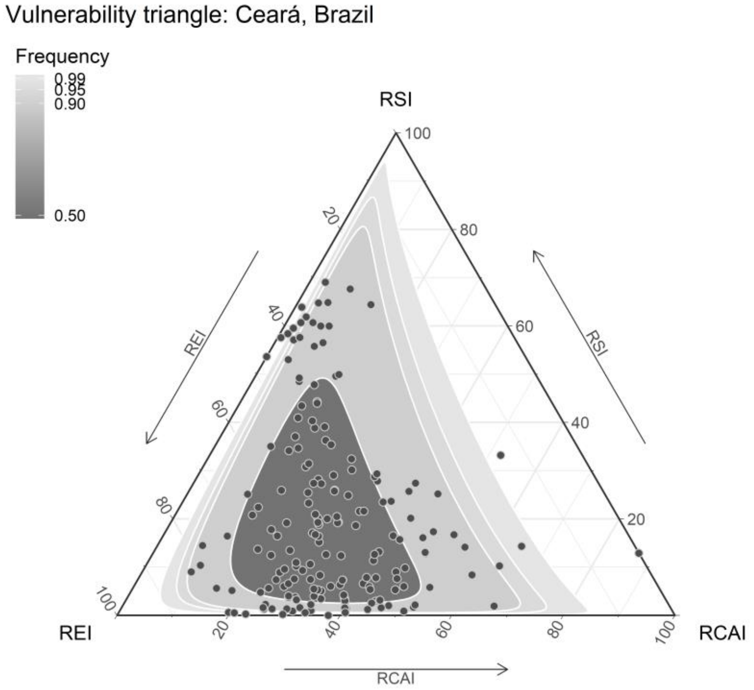


Source: Author.

In the Metropolitana basin, which is part of the MRF, there are occurrences of very high vulnerability. Some of these occurrences coincide with the critical situation of the municipal supply system. Fortaleza, however, presented a score of 60% of the total value possible for the adaptive capacity index. Nevertheless, the capital of Ceará was still classified as extremely vulnerable. Although Fortaleza has considerable water infrastructure to mitigate drought impacts, the capital of Ceará is still highly exposed to the effects of water scarcity. Including adaptive capacity only reduced 6% of Fortaleza's vulnerability, while the average reduction of the other municipalities was 19%. Additionally, 5 out of 12 cities of the Baixo Jaguaribe basin were classified as extremely vulnerable. This reflects the intense agricultural and shrimp farming activities that happen in this region.

Figure 6 presents the modified vulnerability triangles obtained through (9 for the state of Ceará. We improved the vulnerability triangle used by Vargas and Paneque (2017) and Liu et al. (2013) by adding frequency curves, based on confidence levels (50%, 90%, 95%, and 99%), which informs the zones that concentrate a given percentage of the municipalities. The curves were calculated according to Hamilton and Ferry (2018). Observing Figure 6, it is clear that exposure has the most influence on the vulnerability to drought in Ceará. These results are in line with the state's semi-arid climate and the historical occurrences of prolonged drought events, precipitated by lack of rainfall. Additionally, the low frequency of municipalities located in the adaptive capacity zone demonstrates that, even though the state of Ceará invests in the construction and management of water systems, its physical and institutional structures are not yet sufficient to significantly reduce drought vulnerability.

Figure 6 - Vulnerability triangle for the state of Ceará, Brazil.



Source: Author.

3.6 Discussion

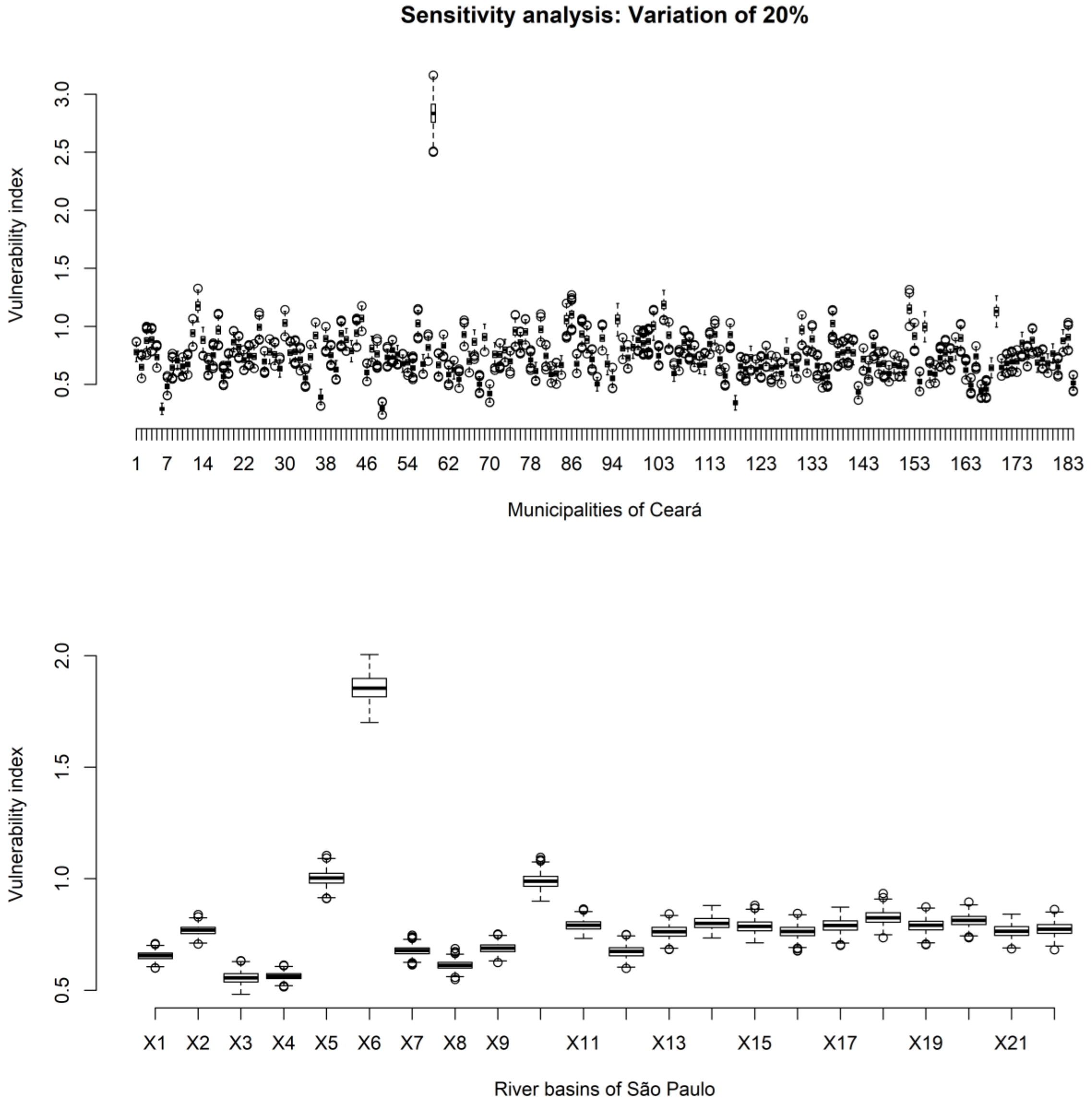
The model uses components that represent vulnerability to drought following the definition provided by IPCC (2001). iSECA makes it possible to quantify a complex concept using simplified MCDM techniques with a logical and easy to follow sequence of steps.

Additionally, it provides spatial visualization of the vulnerability diagnosis. Its comprehensive aspects facilitate the replication of the model and the comprehension of its outcomes, making it useful for water managers and non-specialists. It can be updated and run on a regular basis as a way to explore how changes in social characteristics and water infrastructure are influencing vulnerability.

Research regarding drought vulnerability in Brazil is mainly comprised of qualitative, social analyses (NELSON AND FINAN, 2009; LEMOS et al., 2016; SENA et al., 2018), and focused primarily in the Northeastern region where Ceará is located. Applying iSECA to São Paulo and Ceará fills part of the academic and technical gap of research on drought vulnerability in South America, identified by Wang et al. (2014). The different contexts in which the model was applied demonstrate the flexibility of the model to accommodate variable configurations and yet provide satisfactory results. iSECA also quantifies and highlights the importance of increasing adaptive capacities through water resources infrastructure and management for the reduction of drought vulnerability.

The sensitivity analysis validates the choice of indicators and their corresponding weights. Figure 7 presents the amplitude of the synthetic data generated for the worst-case scenario of variation (20%) of each object of study (municipalities in Ceará and river basins in São Paulo). Both graphs present satisfactory amplitude of variation, demonstrating the robustness of iSECA and its reliability to reapplication in different areas of study, with distinct datasets. The outlier objects in both graphs represent the city of Fortaleza, capital and most populous city of the state of Ceará, and the Alto Tietê river basin, where the Metropolitan Region of São Paulo is located with the largest population in Brazil.

Figure 7 - Sensitivity analysis of iSECA method considering a variation of 20% (worst-case scenario).



Source: Author.

Overall, the dataset required to apply iSECA is easy to acquire and to organize. Rainfall data are available through weather stations or public datasets such as the Climate Research Unit (CRU). Social and economic data are generally easy to obtain through a national census. Information regarding water systems, river basins, and water structures can be acquired with water management bodies and even with satellite images and processed with simple georeferencing and remote sensing techniques.

iSECA provided satisfactory and reliable results. Compared with similar works published by Vargas and Paneque (2017) and Liu et al. (2013), our model presents equally necessary and indispensable outcomes. However, iSECA demonstrated its adaptability to different spatial scales and its efficiency and accessibility by using fewer and simpler indicators and yet providing robust and comprehensive results.

3.7 Conclusion

The number of research projects addressing vulnerability to climate change has increased considerably increased during the last decade. In part, this is in response to the effects of extreme weather events, including droughts, facing populations around the globe. However, Latin American countries, e.g., Brazil, have not yet undertaken a significant level of research on vulnerability to climate change and its social aspects (WANG et al., 2014).

Using the IPCC (2001) definition of vulnerability to climate change, iSECA provided a logical and parsimonious model capable of quantifying vulnerability to drought. Using a solid and straightforward MCDM GIS-based structure, the model considers not only climate aspects but also social, economic, and water management features. In order to fill the science gap, iSECA was applied to Ceará and São Paulo, Brazilian states with very different climatic and social conditions. The application showed how the model can fit different spatial scales and regions with different social, economic, and climate aspects.

iSECA identified vulnerable locations, also pointing to the areas with water infrastructure that improves local and regional adaptive capacity. Historically, São Paulo has not suffered long periods of water scarcity nor high frequency of drought events. However, the Metropolitan Region of São Paulo (MRSP) corresponds to about 64% of the state's population and 20% of the national GDP and it was classified as very highly vulnerable due mainly to the complexity of its social and economic activities. Given the abundant water availability in the state, the 2013-2015 water crisis in São Paulo was significantly influenced by water management.

While water transportation in São Paulo is not as fundamental to vulnerability due to the higher number and spatial distribution of perennial rivers, the principal challenge for Ceará is to maintain the water supply to the Metropolitan Region of Fortaleza (MRF), a context with highly complex interactions of social, industrial, and economic intense activities. In this state, characterized by low water availability and limited spatial distribution of water sources, adaptive capacity through the development of infrastructure is key for maintaining the water supply. Despite the strong water resources infrastructure built to guarantee water transportation to the (MRF), the authors concluded that the water system is not yet sufficient to reduce the high vulnerability scenario of the state’s capital Fortaleza.

The model results are clear and easy to understand, and so can serve as an indispensable tool for water management and drought planning. The model outcomes are accessible for water managers and non-specialists. The vulnerability maps can identify the most and least vulnerable areas, facilitating the planning of priority actions to develop water management strategies. The vulnerability triangle combined with frequency curves is also useful as a graphical diagnosis to help visualize the most influential components of vulnerability. Additionally, the sensitivity analysis attested to the robustness of the model across applications.

iSECA does not demand fieldwork or extensive financial costs. The dataset for an application can easily be built with local official data, rainfall datasets, and information provided by a national census. The methodology is a simple solution for a complex matter. The model facilitates the indispensable use of vulnerability analysis for applied policies and the development of plans such as drought and water security management for different scales (national, state, or basin plans).

4 DEVELOPMENT OF WATER SYSTEMS TYPOLOGY OF RISKS USING COLLABORATIVE METHODS

4.1 Introduction

Water systems can be characterized as complex socio-natural systems due to the occurrence of diversified non-linear processes, influenced by distinct stressors and actors distributed amongst multiple layers. The continuous functioning of a water system is a fundamental factor of society's welfare. Such a complex system can be susceptible to damages that might have the potential to affect its overall function of supplying water in fair quantity and quality to society. An important characteristic of a supply system is the ability to operate satisfactorily under whichever climate and hydrologic conditions and possible future demands (HASHIMOTO et al., 1982).

According to Basurto and Ostrom (2009), typologies are useful tools when it comes to solving "panacea" analytical traps – when a single type of governance system is applied to all environmental problem, affecting the governance of human-environment interactions (OSTREM, JANSSEN AND ANDERIES, 2007). Developing a typology of risks provides tools and knowledge that are easy do visualize during the process of risk assessment, and it can guarantee an accessible communication with not only the decision makers but also non-specialists that are inserted in the evaluated system. Distinct areas of research applied typology of risks, either as a product generated or as a step in a risk assessment approach.

Distinct areas of research have developed typologies of risk: social, management, and business issues (SCHARF et al., 2001; PICARD, 2004), children education (DISTEFANO et al., 2003), governmental institutions (JOHANSSON, DENK AND SVEDUNG, 2009), food supply chains (MANNING, BIRCHMORE, AND MORRIS, 2020), public health (DESMOND et al., 2005; DOHRENWEND, 2010; PEACOCK et al., 2015; HUNTER, 2017; JANG et al., 2018; DECASTRO et al., 2018), and environmental issues and natural disasters (SCHWARZ et al., 2009; GALIANA-MARTIN, HERRERO AND SOLANA, 2011; SKINNER et al., 2014; CHANG et al., 2018; KÄYHKÖ, 2019). Despite not considering risk as a focus of their research, Studart et al. (2021), Kim and Swain (2017), Gleick and Heberger (2014), and Vlachos (2003) developed typologies concerning water governance-related conflicts, water crimes involving mismanagement and corruption of institutions as well as terrorism, warfare and terrorism conflicts involving water disputes, and water-related conflicts in the urban environment, respectively.

When it comes to risk assessment that aims to provide information for decision makers that are dealing with complex systems, it is imperative to assure that the method was developed through adequate techniques and sufficient knowledge (RAE et al., 2012). In that tone, the primordial steps of a general risk assessment method are to structure the information and knowledge available at a local level in order to systematic model the risk at system level (ZIO, 2018). The main obstacle at this stage is the usually limited information, increasing the uncertainty of the assessment outcomes. A solution to overcome this challenge is to incorporate the background knowledge provided by technicians and experts of the systems through qualitative data collection. According to Zio (2018), the risk assessment outcomes depend on the current state of knowledge and values assigned. The author concludes that the description of the risk intrinsic of a system is inherently conditional on the knowledge of that system.

Even though the step of identifying types of risk is being applied to different areas, and despite the timid development of water-related typologies, there is a lack of typology of risks in water resources systems. It is fair to say that there is little support for water-management-related typologies, and none considering water resources systems risks. It is a challenge considering the complexity of the functioning of a water resources system. The risks may involve economic, social, climate, hydrological, structure engineering, and environmental areas. In that scenario, uncertainty is comprised of various distinct aspects. The dimensions of uncertainty can either be random (the natural randomness inherent to the system and its components) or epistemic (limitations of knowledge) (SKINNER, 2014).

This paper aims to propose an innovative typology of risks for water systems developed through a collaborative process involving experts and technicians to support the risk assessment and the decision-making process both scientifically and technically. The typology, and its innovations, offer technical and conceptual contributions to, and serve as an initial tool for the assessment of risks within water systems. It is a tool that serves as an initial point, assisting in the early phase of risk analysis. It allows decision-makers to identify the components and interrelationships among the components of the water system.

The typology was built collaboratively with experts on water resources and technicians who works daily on water systems from the state of Ceará, in Brazil. The State has experienced frequent and severe drought events, that leads to significant migratory movements from rural areas to urban centers like Fortaleza, the capital of Ceará, and even São Paulo, located approximately 3,000 km away. Ceará has invested in both physical and institutional structures for water resource management, enhancing its ability to adapt to drought impacts and reduce vulnerability. The collaborative process of building the typology of risks strength the framework with scientific and tacit knowledge and provides a robust contribution for water systems managers. The typology of risks is flexible and adaptable, presenting itself as an initial important step for the water resources managers, where they can approximate the framework to the configurations and structures of their system.

4.2 Brief Background

As previously stated, water resources systems encompass multiple layers of complexity and uncertainty and its management involves the intersection of a complex socio-ecologic system with conflicting interests (LANGSDALE et al., 2013). During the last couple of decades, a collaborative process of planning and management has been increasing amongst the water resources research community. Simonovic and Bender (1996) defend those participatory and/or collaborative strategies help management to make well-informed decisions because it involves a wide range of important actors in the decision-making process. Collaborative models within water resources planning create linkages between social well-being of people, environmental management, and economic development. It is important to highlight the contributions of participation in water resources planning and management due to its complexity and uncertainty, as it covers: complex social-ecologic systems and conflict of multiple social, cultural, environmental, and economic interests (LANGSDALE et al., 2013).

The participatory process in water resources planning and management is established in several nations, such as Brazil (BRASIL, 1997). It is related mainly to the management of river basins and water allocation decisions in states like Ceará, which helps improve the ability of institutions to plan and to respond to extreme events (LEMOS et al., 2020). The evolution participatory and collaborative methods during the last couple of decades bring new challenges to the processes of water resources planning and management, pushing the development of new and innovative approaches (PALMER et al., 2013).

However, water resources systems analyses such as risk assessment are not amongst the aspects that rely on participatory and/or collaborative processes. In that tone, the risk assessment in a collaborative decision-support environment assumes proactive participation. Part of the job is to formulate different scenarios encompassing alternative solutions and to develop a system that improves based on feedback provided during the search for a socially desirable management decision (SIMONOVIC AND BENDER, 1996).

Table 2 presents introductory works concerning the water management through collaborative modeling. The researchers and plans were developed around the U.S., especially by the U.S. Army Corps of Engineers. It is clear that collaborative methods were emphasized in water management, but there is no accountability of risk assessment of water systems through collaborative and participatory approaches, nor the development of a typology of risks.

Table 2 - Diverse methods and frameworks for water management through collaborative modeling.

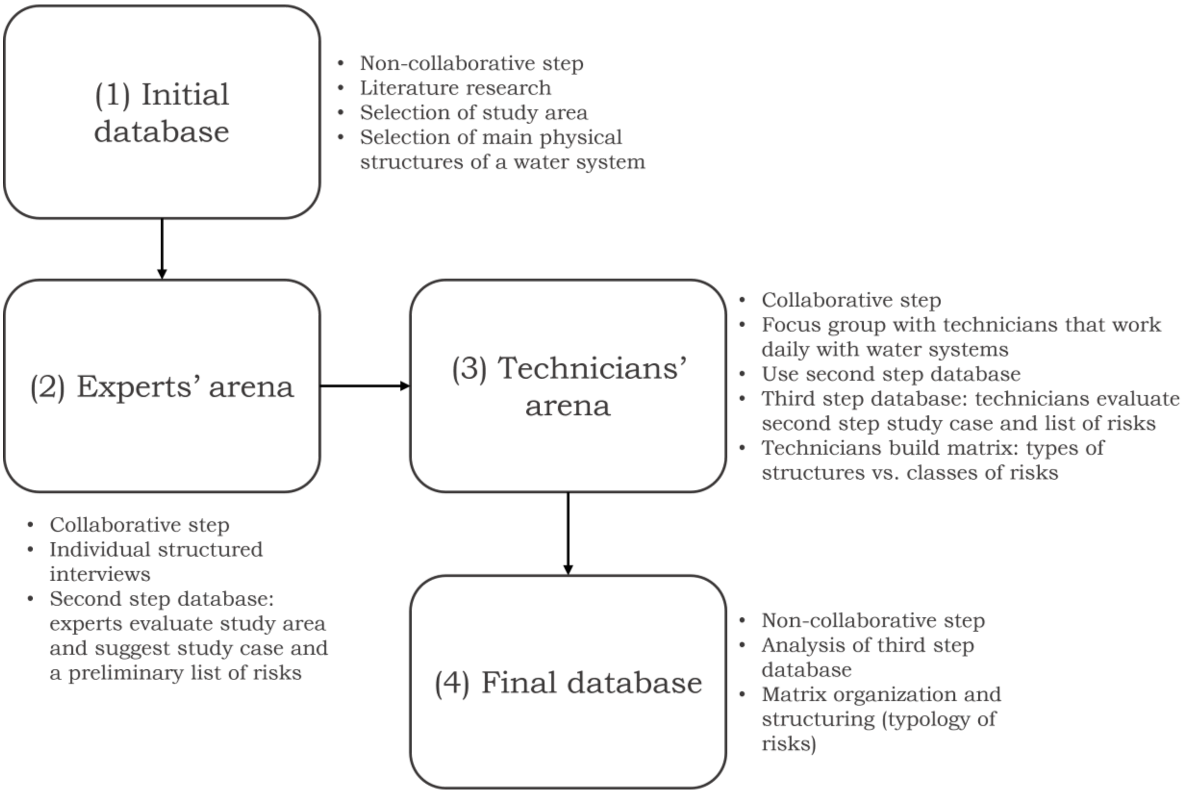
Method/framework/term	Description	Definitional work(s)
Collaborative Modeling for Decision Support	It was not defined as a new method, but as an integrated framework that includes related methods.	Bourget, 2011
Shared Vision Planning	Formulates water management by integrating three components: water planning, computer modeling, and structured public participation.	Werick and Whipple, 1995; Hagen, 2011
Mediated Modeling	Development of a model with the participation of stakeholders in order to mediate negotiation	van den Belt, 2004
Group Model Building	Aims to improve consensus, commitment, and team learning.	Vennix, 1996
Computer-Aided Negotiation (CAN)	Uses computer modeling or simulation to resolve disputes within negotiation.	McCrodden, 2011

Source: adapted from Langsdale et al., 2013.

4.3 Method

Aiming to reach the goal of building a collaborative typology of risk for water systems, our method consists of steps strategized in a way that the collaborators participate by choosing the features that will compose the system and then listing and evaluating its risks. The expected result is a typology of risks presented as a matrix of the types of structures of the system vs. the classes of risk. Our proposal goes through a four-steps process: (1) preliminary database; (2) experts' arena; (3) technicians' arena; (4) final database. The flow process and each step are represented by Figure 8 and detailed through the following sections of this paper.

Figure 8 - Steps of the method towards building a collaborative typology of risks concerning water systems.



Source: Author.

The first step consists of building an initial database encompassing a preliminary list of structures that compose a water system (reservoirs, canals, pumping stations, etc) to be evaluated. The second step is called expert's arena and involves individual structured interviews with academic professionals that are experts on water resources issues (including hydrology, hydraulics, water quality, and geotechnics). The experts were chosen according to their background knowledge of the study area. For this step, a total of six experts were interviewed. Then, the third step consists of a focus group that included sixteen technicians who work daily with water systems, selected according to their responsibilities in water resources management in the state of Ceará. It was considered the importance of representatives from different management regions, which include different strategic water structures for the State's supply. Lastly, the four step is the structuring of the results.

4.3.1 First step: initial database

To build the initial database, we resorted to a process of literature review in order to choose the study area and then define a list of the main physical structures of a water system. The study area here represents a State or similar area that has a context of water transfer between watersheds, presenting dense network of water structures that are fundamental for the functioning of social, economic, and environmental activities, amongst other important aspects. Additionally, the study case is a water system composed by different types of structures (reservoirs, canals, pumping stations, etc). This step is considered non-collaborative as it was developed prior to the participation of the collaborators.

4.3.1.1 Study area and study case

The Northeast region of Brazil (NEB) is characterized by shallow soils, high evaporation rates and present itself as a complex challenge to water resources management due to its high interannual and seasonal variability in precipitation (STUDART et al., 2021). The complexity increases as NEB is the most populated semiarid region of the planet (MARENGO et al., 2017). The state of Ceará, located in NEB (as seen in Figure 9), has 90% of its territory within the semiarid region of Brazil and part of its economy is dependent on agropastoral activities (SOUZA FILHO et al., 2006).

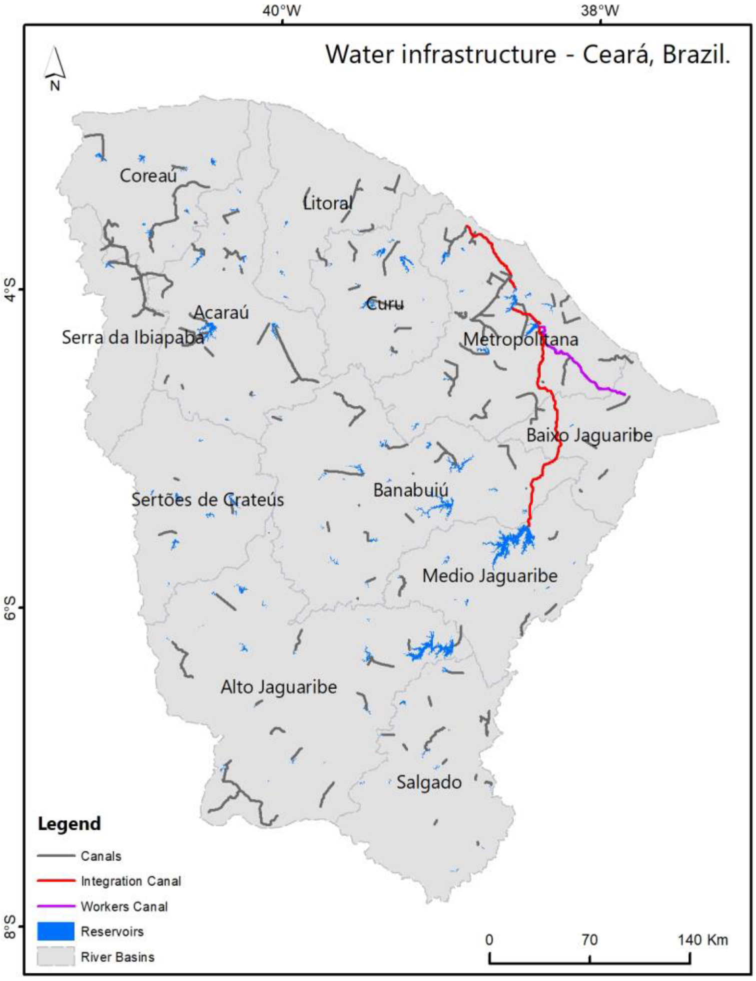
Figure 9 - Location map of the study area: State of Ceará, Brazil.

Source: Author.

Droughts are frequent events in the history of Ceará, marked by the occurrence of intense migratory flows from the most vulnerable population in rural areas to urban centers such as Fortaleza, the state capital, and even farther cities such as São Paulo. Throughout the last century, Ceará has invested on building physical and institutional structure concerning the management of water resources, increasing its capacity to adapt to the impacts of drought events and reducing its vulnerability (REIS et al., 2020).

Water management at Ceará is decentralized and participatory, with the presence of river basin committees (LOPES et al., 2020). The Brazilian State counts with twelve river basins and a rich network of canals and reservoirs built aiming to minimize drought impacts using water transfer strategies. Despite the existing structure (see Figure 10), Ceará is implanting an ambitious project of water transfer called “Malha D´Água” (Water Network). This project has the main goal of increasing its capacity to adapt to the impacts of drought by building even more connections between the river basins, creating more possibilities for water transfer strategies. Figure 10 presents the most important reservoirs and canals of Ceará, considering raw water management.

Figure 10 - Water infrastructure and river basins in Ceará, Brazil.



Source: Author.

Integration and Workers Canals are highlighted in Figure 10 due to the importance of these structures. Workers Canal was initially built aiming to guarantee water security to Metropolitana Basin, where the FMA is located (COGERH, 2009). FMA represents the greatest water demand in Ceará due to, mainly, its population density and various economic activities. Currently, Workers Canal transfer water to supply communities and diffuse uses throughout its length of 102 km. The function of guaranteeing water security to the Metropolitana basin now belongs to the Integration Canal, which transfers water from the largest reservoir of Ceará (Castanhão) to the FMA (COGERH, 2009).

Due to its management strategy of building water infrastructure to support water transfers during periods of drought, added to the climate conditions, we decided to choose Ceará as our study area. Nonetheless, our risk typology is build considering the water transfer processes that guarantees water security to FMA as the study case. In this scenery, the system known as Jaguaribe-Metropolitano, composed mainly by the Castanhão reservoir and the Integration Canal, is the most important system to transfer water to the Metropolitana river basin, where the FMA is located.

4.3.1.2 Defining the preliminary list of types of structures.

A preliminary list of types of structures is defined prior to the collaborative steps in order to assist the collaborators to understand and visualize the assessment. The definition of this list, for this study, means selecting components that will compose the study case system. The components, which we name here as ‘subsystems’, are physical structures that compose a water system: water canals, reservoirs, pumping stations, etc. We investigated literature related to water systems in Ceará in order to find references to support the choice of the preliminary list of structures.

Codes (2016) proposed a risk assessment using the Raw Water System of the Fortaleza Metropolitan Area (RWS/FMA), dividing it into eleven subsystems, containing reservoirs, canals, pumping stations, and tunnels. These subsystems encompass the physical structure used to transfer water from the largest reservoir of Ceará (Castanhão) to the FMA. We chose to use this work as a reference for the preliminary list due to its affinity with the case study chosen for our study.

4.3.2 Second step: experts’ arena

The second step consists of structured individual interviews with water resources experts. The goal of the expert’s arena is to acquire relevant information considering the study area and the study case in order to build an initial database to support the construction of our typology of risks. Therefore, we elaborate two main questions: 1) which subsystems should we consider on our study case? and 2) for each type of structure, what risks should we consider?

The first question lead us to a preliminary study case system, and the second question give us a preliminary list of risk per type of structure. We use the preliminary list of structures elaborated during step one. During the interviews, suggestions concerning the list of structures will be considered. The structured interview is presented in Annex B – Structured interview (Chapter 4).

4.3.3 Third step: technicians' arena

The third step is a focus group with technicians that work daily with water resources management in Ceará. This arena consists of three phases: 1) evaluation of second-step database: subsystems and types of structures; 2) individual evaluation of second-step database: list of risks; 3) building the typology of risks.

The material used for the development of the focus group is described in Table *3*.

Table 3 - List of materials for each phase of the 3rd step: focus group to build the typology of risk.

Phase	Material
1	- Map of Ceará and the water infrastructure selected during the second step printed as a poster; - Markers.
2	- Sheet for individual evaluation; - Pens.
3	- Panel; - Colored cardboards; - Markers.

Source: Author.

4.3.3.1 Evaluation of second-step database: subsystems and types of structures

This phase consists of evaluating the subsystems selected by the experts during the second step. The subsystems are illustrated in a map and the technicians are asked to add subsystems that have influence in the process of water transfer to guarantee water security to the FMA. Additionally, the technicians must evaluate if the list of types of structures encompasses the entirety of subsystems selected.

4.3.3.2 Evaluation of second-step database: list of risks

Each technician receives the list of risks of the second step and a sheet to fill answering two questions: 1) what is the risk? 2) which types of structures it affects? This phase aims to validate the risks that were listed by the experts and to add more risks that were not considered previously.

4.3.3.3 Building the typology of risks

The third phase consists of building the typology of risks. The authors build a panel to represent the matrix of the types of structures of the system vs. the classes of risk. Initially, the matrix is empty and will be filled by the technicians. The types of structure follow the list acquired during the second step. During the focus group, suggestions of other types of structure are welcome. Before the focus group, the authors brainstormed to decide the classes of risk.

The technicians are divided randomly into two different groups where they will discuss their individual evaluation of risks held in phase two and write the risks they listed and decided that should be at the matrix in cardboards (a risk for each cardboard). Each color of the cardboards represents a class of risk. In that way, each group will fill the cardboards by classifying the risk. Then, each group will place their cardboards in the matrix, according to the class of risk and type of structure. For example, the risk is “eutrophication”. The group then decides to classify it as a “water quality” risk and put it as a risk that happens in reservoirs (type of structure).

The final result expected is a list of risks classified and linked to its respective type of structure. The list is to be organized within the matrix of the types of structures of the system vs. the classes of risk. Therefore, the typology of risks is to be displayed as an easy to understand and visualize matrix.

4.3.4 Fourth step: final database

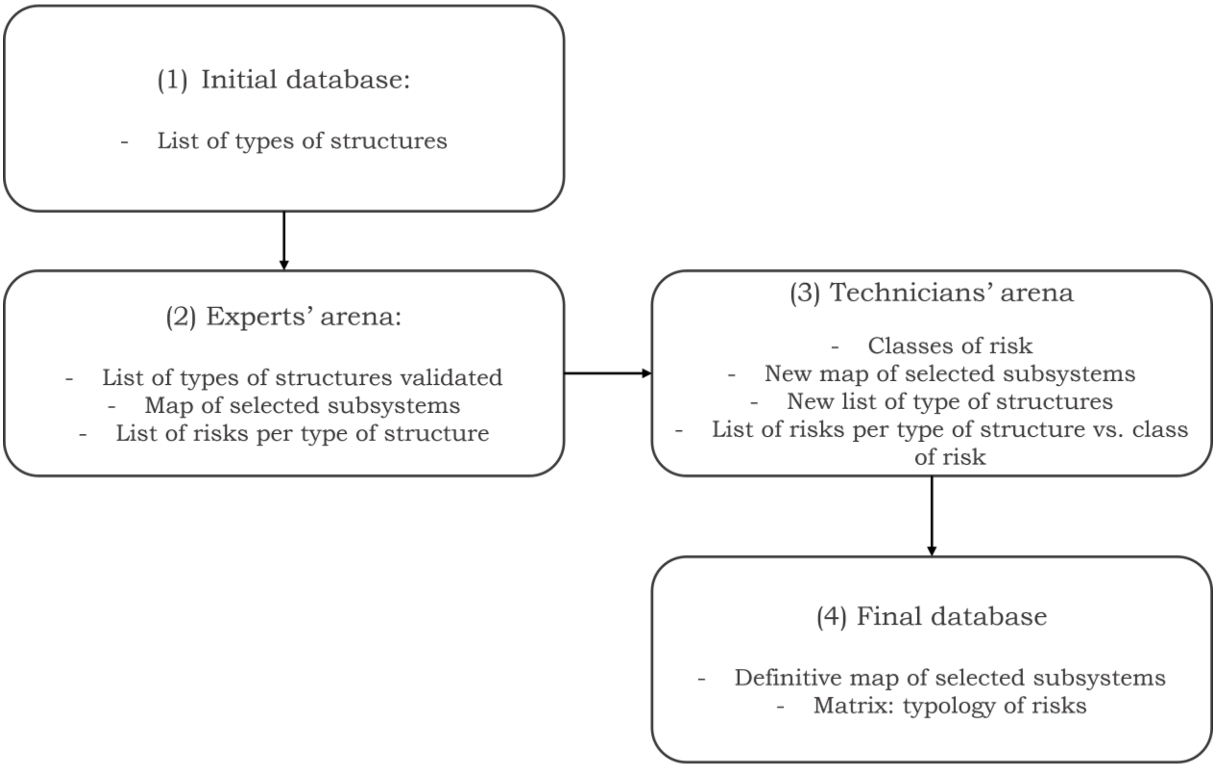
The last step consists simply of organizing the data acquired and designing the matrix of the typology. The fourth step is considered non-collaborative because it is developed solely by the authors, without the direct participation of the collaborators.

4.4 Results and Discussion

As stated previously, the main goal of this study is to propose a typology of risks concerning water systems using a collaborative method. In order to do so, the authors selected the Brazilian State of Ceará as the study area. The typology is built around a study case that encompasses a water system marked by numerous water transfer operations and that, therefore, provide a dense network of water infrastructure. In our study case, the climate aspects of the NEB semiarid (high evaporation rates and precipitation variability) increases the level of complexity for the water management process and decision making.

The process to elaborate this study counts with different steps in its method. To easy the comprehension of the results, Figure 11 exhibits the results obtained during each step of the method (expressed previously by Figure 8).

Figure 11 - Summary of the results according to its respective step based on the method process.



Source: Author.

4.4.1 Types of structures

Initially, the authors listed types of structures in order to represent the usual components of a water system. This list is fundamental to build the typology of risks as the typology delivers risks according to the water structure. The list of types of structures was then modified during the experts' arena and the technicians' arena. Table 4 summarizes the process of listing the types of structure in each step of the method.

Table 4 - Lists of types of structures for each method step.

	1st step: initial database	2nd step: Experts' Arena	3rd step: Technicians' Arena	4th step: final database
Types of structures	- Reservoirs - Canals -Tunnels - Pumping stations - Perennialized rivers	- Reservoirs - Canals -Tunnels - Pumping stations - Perennialized rivers -Siphons	- Reservoirs - Canals -Tunnels - Pumping stations - Perennialized rivers -Siphons -Water wells	- Reservoirs - Canals -Tunnels - Pumping stations - Perennialized rivers -Siphons -Water wells

Source: Author.

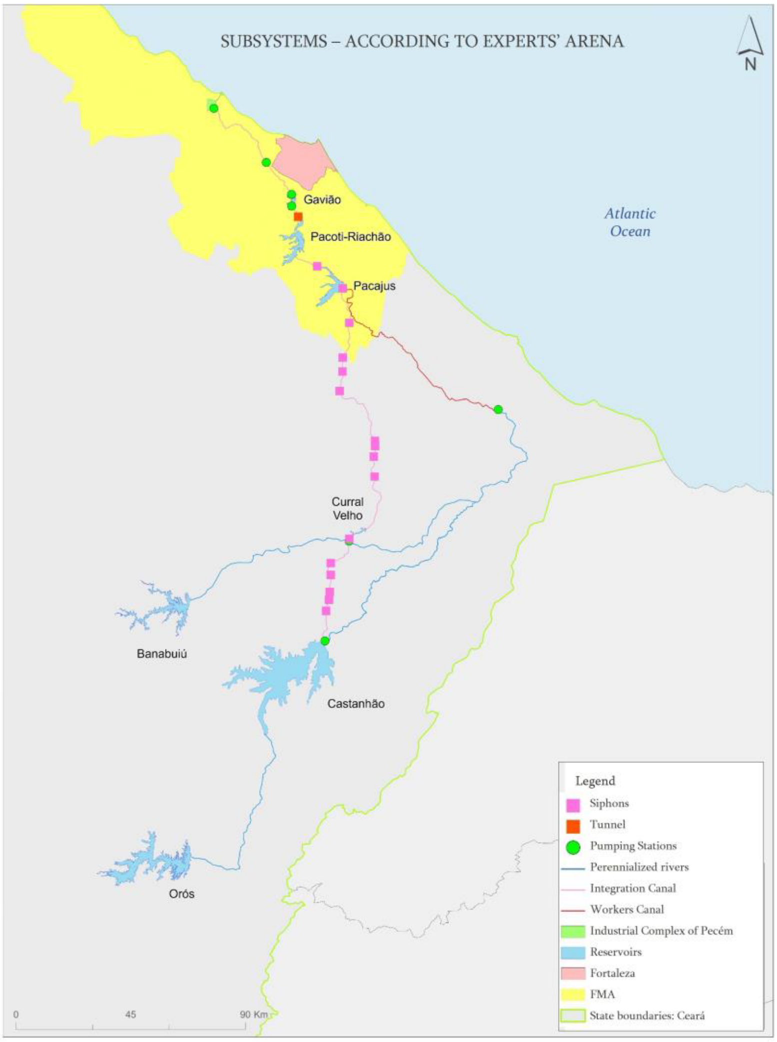
Reservoirs are artificial barred by dams to store water and control the water flow. Depending on the size and volume capacity, a reservoir can store water from months to years. Canals are artificial waterways. In water systems, canals usually function in order to transfer water from a river to another, or a reservoir to another or even to transfer water between river basins that are distant from each other. The process of water transfer generally uses the gravity in its favor to force the water flow. Depending on the topography, pumping stations, siphons or tunnels are necessary. Siphons are tubular devices usually applied to overpass obstacles such as streams and rivers. Tunnels can be constructed in order to open a passage for the canal through mountains or rock masses. Water wells are artificial excavations used to obtain underground water. Lastly, perennialized rivers are intermittent rivers artificially turned into perennial rivers due to the operationalization of water stored in reservoirs.

The process of listing different types of structure with the collaboration of experts in water resources and technicians of water management provide a wide vision of possible configurations that a water system can build. This process diversifies the study and provide robustness and flexibility to the typology so it can be applied to different and varied water systems.

4.4.2 Map of subsystems

The generation of maps concern to the second and third steps. During the second step, known as the Experts' Arena, the collaborators pointed subsystems that are relevant to the process of water transfer to the FMA. This was an important step to achieving the typology of risks as the study case revolves around guaranteeing water security to the FMA by evaluating the risks concerning the processes of water transfer. According to the experts' notes, the first map was elaborated, containing the subsystems illustrated by Figure 12.

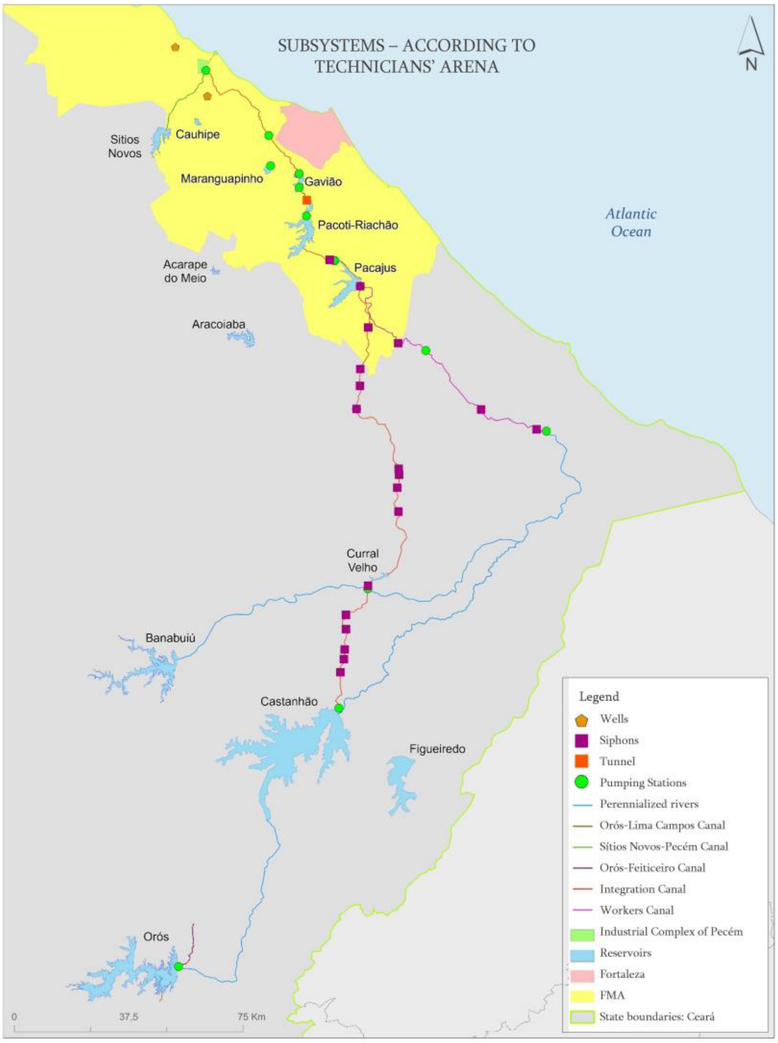
Figure 12 - Map of the subsystems produced during the Experts' Arena.



Source: Author.

Figure 12 was used as a starting point at the Technician's Arena, that evaluated the map and suggested modifications concerning the subsystems that have influence on the process of water transfer to guarantee water security at the FMA. As a result, Figure *13* illustrates the complete system used as the study case, drawn with the collaboration of both the experts and technicians. It is possible to see more siphons and pumping stations, as well as the addition of three canals. Lastly, two points of well-systems were added.

Figure 13 - Map of the subsystems produced during the Technicians' Arena



Source: Author.

The validation of the subsystems increases the reliability of the study, as it considers structures that have influence on the water transfer to FMA. The process of validation also contributes to an increased reliability in the analysis (Source: Author.

).

Figure 14 - Process of map validation at the Technicians' Arena. (a): The authors present the map elaborated during Experts' Arena. (b), (c) and (d): the collaborators interact with the authors to propose modifications and to validate the map.

(a) *(b)*

(c) *(d)*

Source: Author.

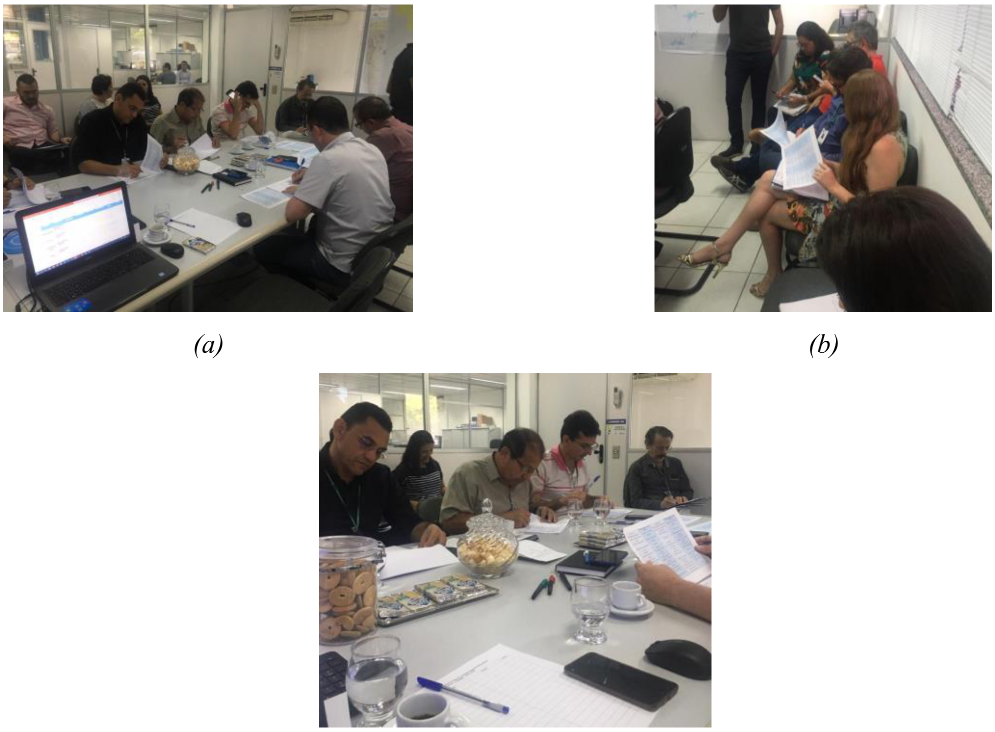
4.4.3 List of risks

The list of risks initiated at the Experts' Arena and increased during the Technicians' Arena. It is important to state that these lists were not yet divided into classes of risks – this step represents the third phase of the third step (Building the typology of risks at the Technicians' Arena). Therefore, initially the list of risks is organized into types of structures, which changes from the Experts' Arena to the Technician's Arena.

Another addition of the Technicians' Arena is the category of "External Pressures". This category does not represent any physical structure of a water system. However, it appears as external aspects that may interfere on a water system, such as climate, population dynamics and political dynamics that can affect water management.

The process of listing risks during the Experts' Arena happened through individual structured interviews. Collaborators from the Technicians' Arena listed risks during an individual process, answering two questions: 1) what is the risk? 2) which types of structures it affects? Source: *Author.* registered this process.

Figure 15 - Collaborators from the Technicians' Arena listing risks individually.



(a) *(b)*

(c)

Source: Author.

The list of risks is presented by Table *5*, differing the risks listed during the Experts' Arena (general characters) and the Technicians' Arena (*italic characters*). Both columns Wells and External pressures were added by the Technicians' Arena, as seen previously at Table 4 and explained on the first paragraph of this section. The structures of a water system have particularities that can affect the level of the risk. For example, the types of risks of dams (reservoirs) differ depending on the material they were built with (earthen dam, concrete dam etc.). The same complexity happens with tunnels and canals. The types of risks are different according to the geological aspect of where the tunnel was built, if it has coating or not and other physical aspects. Considering the goal of this study – to build a typology of risks for water systems to support decision making and risk assessment processes -, some risks may seem more general, but this facilitates the adaptability of the final product to different water systems in the most diverse configurations.

Table 5 - List of risks according to the types of structure*.

Reservoirs	Canals	Tunnels	Siphons
Contamination by input of nutrients	Illegal withdrawal	Geological features	When the obstacle is a watercourse: structure vulnerable to large floods
Proliferation of exotic species (mussels)	Collapsible soils	Dimensioning of the transversal section	Sabotage/Vandalism/Terrorism
Piping (Internal Erosion)	Foundation collapse	*Tunnel collapse*	System bottleneck (happens when the siphon flow capacity is smaller than the canals)
Overtopping	Transversal section		Absence of extra operating cell
Contamination by urban transport	Displacement of coating material		*Degradation of structures*
Risk of contamination by waste disposal (dump)	Contamination by urban transport		
Sabotage/Vandalism/Terrorism	Risk of contamination by waste disposal (dump)		
Eutrophication	Sabotage/Vandalism/Terrorism		
Proliferation of macrophytes	Eutrophication		
Structural failure increased - equipment failures: landfill, foundation, spillway/sluice gates, water intake, abutments	Proliferation of macrophytes		
Moral hazard (operator)	Proliferation of exotic species (mussels)		
Differences in the specific weight of structures: Roller-Compacted concrete + earthen dam – different settlement	Rupture		

Table 5 - List of risks according to the types of structure – continued.

Reservoirs	Canals	Tunnels	Siphons
Foundation Settlement	Infiltration		
Slide failure at dam	Structural failure increased - equipment failures		
Concrete failure (dam)	Floodgates: transient		
Spillway obstruction	Operational risk: canal “reservoir” – regulate flow and “reserved volume”		
Dead storage	Settlement		
Fish mortality	Slowing canals		
Proliferation of green algae	*Proliferation of green algae*		
Proliferation of cyanobacteria	*Proliferation of cyanobacteria*		
Unviability of the source for water supply	*Contamination by Domestic Sewage*		
Bed silting	*Failure to activate the gates (canals)*		
Lack of proper maintenance	*Breakdown of canal structure due to low water pressure*		
Contamination by Domestic Sewage	*Bed silting*		
	Lack of proper maintenance		
	Valve sticking		
Pumping stations	**Perennialized rivers**	**Wells**	**External pressures**
Oscillations in electrical circuits	Illegal withdrawal	*Eutrophication*	*Migration of population*
Water hammer/Transient flow	Sabotage/Vandalism/Terrorism	*Proliferation of green algae*	*Irregular occupation of the margins*
Height hydraulic variation	*Fish Mortality*	*Overheating of the motors/pump*	*Political interference*
Piping sizing	*Pollution by Invasive Species*	*Pumping failure*	*Discontinuity of programs*
Degradation of pipes	*Pollution by Nutrients*	*Absence of extra operating cell*	*Little variation in water tariff*

Table 5 - List of risks according to the types of structure – conclusion.

Pumping stations	**Perennialized rivers**	**Wells**	**External pressures**
Lack of maintenance	*Contamination by Domestic Sewage*	*Transient flow*	*Cost of electric energy*
Sabotage (of the structure and transmission lines)	*Contamination by solid waste disposal (dump)*	*Pump cavitation*	*Uncontrolled construction of small reservoirs*
Theft attempts	*Eutrophication*	*Settlement Caused by Pumping*	*Drought*
Facility foundation (leakage from pumps can result in particle entrainment and soil collapse, affecting infrastructure)	*Unviability of the source for water supply*	*Lack of proper maintenance*	*Flood*
Unplanned dead storage capacity of reservoir		*Stopping electronic machinery and equipment due to aging*	
Pump cavitation		*High corrosion stage in the hydromechanical structures*	
Power surge		*Unplanned dead storage capacity of reservoir*	
Power generator inoperative			
High corrosion stage in the hydromechanical structures			
Eutrophication			
Proliferation of green algae			
Overheating of the motors/pump			
Pumping failure			
Absence of extra operating cell			
Stopping electronic machinery and equipment due to aging			
Pipeline rupture			

* The *italic characters* represent the modifications/additions made during the Technician's Arena. General characters represent the risks initially listed during the Expert's Arena.

4.4.4 Classes of risks

The classes of risks were stated previously to the Technicians' Arena by the authors through a brainstorming section. The authors considered technical and physical aspects that influence the entire functioning of the water system, as well as each subsystem solely. The chosen classes of risks are: hydraulic risks, electromechanical risks, hydrological risks, geotechnical risks, operational risks, and water quality risks. A class called "Others" was also created in order to encompass undefined risks.

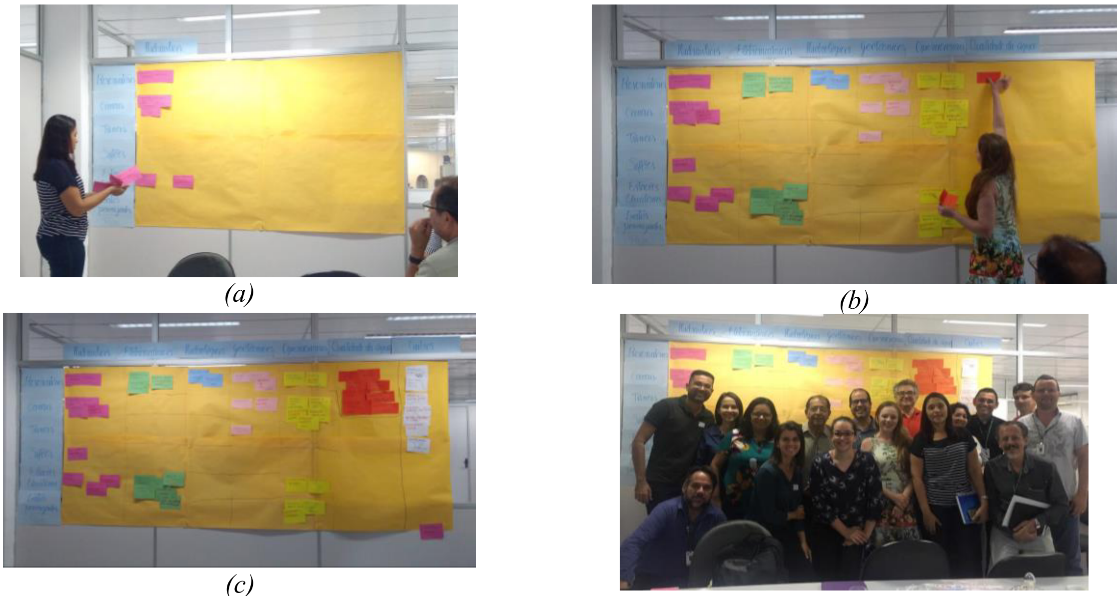
Hydraulic risks concern the malfunctioning of hydraulic accessories, as well as the interruption or accident involving hydraulic functions of a water system. Analogously, electromechanical risks refer to the malfunction of electromechanical accessories, such as pumps and floodgates. Hydrologic risks refer mainly to the occurrence of extreme climate events, but also consider aspects that affect the water balance of the system or a single structure, such as a reservoir. Geotechnical risks consider mainly the influence that soils, rocks, massifs or likely physical features can have on the structures of the water system. Operational risks refer to the general functioning of a system that relies on planning and management actions. Lastly, water quality considers aspects that have a negative impact on the water quality of the system. The column that lists "others" risk consists of risks that did not fit into a class of risk and that does not refer directly to a type of structure, but to the entire system as a whole.

4.4.5 Typology of risks: the matrix

The construction of the matrix of the types of structures of the system vs. the classes of risk occurring during the last phase of the third step, at the Technicians' Arena. The collaborators were randomly divided into two groups and asked to argue with their respective groups about the risks they listed individually. Then, each group should explain risk by risk and allocate each risk at the matrix, filling it completely.

The matrix was physically built as a panel and the collaborators used colored cardboards to classify and attach the risks at the matrix. Figure 16 registered the process. Once the matrix was built, the authors collected the information to organize and design the matrix called as the Typology of Risk for Water Systems, represented by Table 6.

Figure 16 - Construction of the matrix of the typology of risks. (a) and (b): Collaborators inserting risks as colored cardboard at the matrix. (c): the completed matrix. (d): Authors and collaborators celebrating the completion of the Technicians' Arena.



(a)

(b)

(c)

(d)

Source: Author.

Table 6 - Typology of Risk for Water Systems.

	Hydraulic	Electromechanical	Hydrologic	Geotechnical
Reservoirs	Overtopping	Corrosion in the hydromechanical structures	Drought	Piping (Internal Erosion)
	Spillway obstruction	Hydromechanical structures inoperative	Bed silting	Foundation Settlement
Canals	Bed silting			Infiltration
	Displacement of coating material			Collapsible soils
	Floodgates: transient			Settlement
Tunnels				Tunnel collapse
Siphons	Degradation of structures	Corrosion in the hydromechanical structures		
Pumping Stations	Water hammer/Transient flow	Corrosion in the hydromechanical structures		
	Pump cavitation	Hydromechanical structures inoperative		
	Height hydraulic variation	Oscillations in electrical circuits		
		Power generator inoperative		
		Stopping electronic machinery and equipment due to aging		
		Overheating of the motors/pump		
Perennialized Rivers				
Wells			Drought	

Table 6 - Typology of Risk for Water System (continued).

	Operational	Water quality	Others
Reservoirs	Unplanned dead storage	Proliferation of exotic species	Political interferences
	Illegal withdrawal	Contamination by waste disposal (dump)	Outdated water billing rate
	Sabotage/Vandalism/Terrorism	Eutrophication	High energy billing rate
	Migration of population	Contamination by input of nutrients	Discontinuity of water management programs
	Failure in activating the gates	Proliferation of macrophytes	
	Lack of proper maintenance	Fish mortality	
		Proliferation of cyanobacteria	
		Irregular occupation of margins	
Canals	Illegal withdrawal		
	Sabotage/Vandalism/Terrorism		
	Lack of proper maintenance		
	Height hydraulic variation		
	Migration of population		
	Failure in activating the gates		
	Insufficient water transfer		

Table 6 - Typology of Risk for Water System (conclusion).

	Operational	Water quality	Others
Tunnels			
Siphons		Proliferation of macrophytes	
Pumping Stations	Height hydraulic variation Oscillations in electrical circuits Water hammer/Transient flow Lack of proper maintenance	Proliferation of macrophytes	
Perennialized Rivers	Illegal withdrawal Lack of proper maintenance Insufficient water transfer Uncontrolled construction of small reservoirs	Proliferation of macrophytes Irregular occupation of margins	
Wells	Lack of proper maintenance	Contamination by waste disposal (dump) Contamination by input of nutrients	

Source: Author.

Initially, a type of risk (such as “vandalism”, or “corrosion”) can fit more than one type of structure as well as more than one class of risk. It is important to understand the meaning of each risk computed in the Typology. Annex C – Description of the risks from the Typology of Risk (Chapter 4) presents the list of risks of the Typology in alphabetic order.

The Typology was overall built with the collaboration of experts with experience in researching water systems and technicians that work daily operating water systems. These aspects bring robustness to the results.

It is important to emphasize the capacity of the Typology of Risks to adapt to the diverse possibilities of configuration of a water system. The arrangement of the Typology as a matrix of types of structure vs. class of risk provides flexibility and adaptability when applying to different water systems. However, it should be considered that the Typology was built by agents with knowledge and experience with water systems from semiarid and tropical regions. This may require further adaptation process for water systems located at regions with notable climate difference that deals with thaw and snow, for example.

4.5 Conclusion

Water systems present various non-linear processes, affected by different aspects that include socioeconomic situations, going through external physical factors and management of complex infrastructures. The malfunctioning of infrastructures in a water system due to multiple external physical factors can lead to various socioeconomic impacts.

Despite the application of risk identification in various areas, there remains a lack of typology for risks in water resources systems. This gap is particularly challenging due to the complexity of water resources systems, which encompass economic, social, climate, hydrological, structural engineering, and environmental risks. Uncertainty within these systems can arise from natural randomness or limitations in knowledge.

To address this issue, this paper proposed an innovative typology of risks for water systems developed through collaboration with experts and technicians. The aim is to support risk assessment and decision-making processes scientifically and technically. This typology provided both conceptual and technical contributions, serving as an initial tool for risk analysis and enabling decision-makers to identify components and interrelationships within the water system. The typology was collaboratively constructed with water resource experts and technicians who work directly with water systems in the state of Ceará, Brazil. The collaborative process of building the typology of risks incorporates scientific and tacit knowledge, providing a robust contribution for water systems managers. This flexible and adaptable typology serves as an important initial step for water resources managers, allowing them to tailor the framework to their specific system configurations and structures.

Even though the typology of risk delivered here can be adaptable, it should not be seen as a universal and inflexible tool. The typology is flexible and can assist researchers, managers and decision makers to initially comprehend their systems and then to structure a more robust and organized risk assessment. In conclusion, the typology of risk provided facilitates the process of water systems risk assessment and was built through an innovative collaborative process, with validation of the method and offering an increased robustness of the results.

5 INTEGRATED RISK ASSESSMENT FOR WATER SYSTEMS INFRASTRUCTURE USING FUZZY INFERENCE AND COLLABORATIVE TYPOLOGY OF RISKS

5.1 Introduction

Ensuring a consistent and reliable water supply is a fundamental requirement for any community. One of the primary responsibilities in managing water resources is to maintain an uninterrupted supply system. Consequently, safeguarding the infrastructure of the water system is crucial and must be supported (SITZENFREI et al., 2011). The susceptibility of a water supply system is influenced by social and climate changes (REIS et al., 2020). There are multiple potential hazards associated with the various activities that constitute a water supply system.

Water security is a fundamental concern for ensuring adequate and high-quality water supply to support society and ecosystems (GREY AND SADOFF, 2007; UNU, 2013; TORATAJADA AND FERNANDEZ, 2018). The scarcity of water due to water insecurity can lead to explosive situations, and water use conflicts may arise when water availability is limited (SILVA et al., 2017; REED, 2017). Providing water during times of scarcity and cost optimization are crucial aspects of water systems operations (GAD AND ABD-ELAAL, 2016), which require maintenance and hazard monitoring. Continued operation of the system must be ensured by preserving infrastructure and functions, such as through risk assessment. As stated previously in the Chapter 4 of this work, distinct areas of research applied typology of risks, either as a product generated or as a step in a risk assessment approach.

Socio-natural systems, particularly water systems, are intricate and characterized by various non-linear processes. To effectively manage these systems, it is imperative to conduct a thorough analysis of system vulnerability and risk. Information related to socio-natural systems can be either qualitative or quantitative in nature. The infrastructure of water systems comprises various subsystems, such as reservoirs, channels, and pumping stations. Often, obtaining information from local operators and workers about specific subsystems can be challenging and may be limited to verbal or textual communication, with little insight into the frequency of failures. Therefore, incorporating linguistic information is crucial in conducting a comprehensive risk assessment. In recent years, collaborative models have been utilized in water resources planning to establish a link between social-economic development and environmental management. These models aim to mitigate conflicts over natural resources, like water, and reduce the uncertainty surrounding complex systems by collecting information from various stakeholders with diverse social, cultural, environmental, and economic interests (LANGSDALE et al., 2013).

The complexity of modern systems necessitates risk assessment methodologies that can simultaneously and consistently evaluate both qualitative and numerical aspects in a flexible manner. For risk to be considered in a public policy management plan, it must be calculable; otherwise, it becomes merely a measure of uncertainty (VEYRET, 2007). Uncertainty in risk assessment can stem from either random sources, such as the inherent natural randomness of the system and its components, or epistemic sources, such as limitations in knowledge (SKINNER, 2014). To ensure that the risk assessment methods used to inform decision-makers dealing with complex systems are adequate, it is crucial to employ appropriate techniques and sufficient knowledge (RAE et al., 2012). A key initial step in the risk assessment process is to organize the available information and knowledge at the local level to systematically model the risk at the system level (ZIO, 2018). However, a major challenge at this stage is the limited information available, which can increase uncertainty in the assessment outcomes. One potential solution to this challenge is to incorporate the expertise of technicians and system experts through qualitative data collection. Zio (2018) asserts that the outcomes of risk assessment depend on the current level of knowledge and the values assigned to the system, highlighting that the description of the inherent risks of a system is inherently conditional on the knowledge available about that system.

Evaluating the risks associated with water infrastructure systems is critical for ensuring a reliable water supply, maintaining water security, promoting socio-economic development, and safeguarding human and environmental health and quality of life. Responding to risk is a crucial aspect of critical infrastructure protection (YU et al., 2018). Risk can be defined in many ways, but it typically refers to the probability of an adverse event with negative consequences (OSTROM AND WILHELMSEN, 2012). This definition can be further refined by considering three main factors: what is at risk, the likelihood of occurrence, and the potential impacts (KAPLAN AND GARRICK, 1981).

In order to perform a comprehensive safety assessment of a system, it is essential to consider the various ways in which the system can fail or be compromised, as well as the potential impacts of such failures (WASHINGTON et al., 2019). When assessing a supply system, control measures should be established based on a prioritization of risks associated with potential hazards or dangerous events. To assess the risks associated with each hazard, it is necessary to use two scales: one to measure the probability of the hazardous event occurring, and another to measure the severity of the event's potential consequences for society (VIEIRA AND MORAIS, 2005).

Fuzzy logic is useful in situations where information is acquired through verbal, textual, or linguistic means, and it is necessary to convert it into mathematical terms. By utilizing fuzzy logic, it is possible to create algorithms and computer programs that construct inference systems through a collection of linguistic rules that are supported by mathematical tools (TANSCHEIT, 2003). Fuzzy logic is also capable of handling incomplete and imprecise data, which are often encountered in socio-natural systems and real-world issues (ZHANG et al., 2015; AMEYAW AND CHAN, 2016).

The objective of this paper is to develop a mathematical model that is capable of understand linguistic data and present results as discrete values to evaluate the risks of water systems. This model should be capable of running risk assessments for water systems, considering water structures as subsystems of the global systems and, therefore, providing the state of risk of each peace that composes a water system. The results can contribute to water planning and management and facilitate the process of decision-making.

The chosen strategy is to apply a fuzzy inference model for conducting an integrated risk assessment of a water system according to the typology of risks developed in Chapter 4, considering also the same water system chosen to develop the typology. The magnitude of the risks provided by the typology of risks were obtained through semi-structured interviews with technicians that work daily on the system’s management and operation, and through interpolation amongst similar structures. This strategy intends to mathematically incorporate tacit knowledge within the process of risk assessment, in order to pursue a decrease of uncertainty and to build a robust model validated by collaborators. The use of fuzzy inference is adequate for qualitative data input, making it possible to model the data acquired from the interviewees. The model transforms qualitative information into a fuzzy set and subsequently into numerical values to quantify qualitative information. The collaboration of system management and operation agents ensures the model's robustness.

It is fair to state that our model differs from previous works that have used fuzzy arithmetic instead of fuzzy inference, thus not incorporating linguistic information. While fuzzy set theory has limited representation in risk assessment studies, numerous studies have employed fuzzy sets in water resource studies (GOMES, 2011; SANTOS, 2012; SALES, 2014). Additionally, this model and its results can contribute to the state of art of risk assessment for water systems literature by providing an innovative framework to evaluate risks through collaboration and participation.

5.2 Background conceptualization

The term "fuzzy" refers to imprecise or nebulous concepts and describes the incomplete knowledge of analyzed systems. It differs from conventional logical reasoning and was introduced to scientific literature in Zadeh's "Fuzzy Sets" manuscript in 1965. Fuzzy sets theory has become popular in system modeling, where categories with uncertain boundaries, subjective properties, or imprecise attributes are considered. Kaufmann and Gupta (1988) argue that fuzzy logic uses mathematical formulations to express human intuitive processes. It can translate specialized knowledge into computable numerical data and express the ambiguity of human thought. Fuzzy inference systems use rules to model qualitative aspects of human knowledge and reasoning processes. These systems are useful in decision-making problems with imprecise information and have real-world applications.

According to Boente et al. (2016), the increasing use of fuzzy logic is due to its ability to provide a more realistic representation of problems by incorporating larger amounts of data, allowing for more precise mathematical evaluation of results. Compared to other tools, fuzzy logic is better at representing complex situations that involve uncertainty and inaccuracies in the real world. As a result, fuzzy logic has become a fundamental tool in various areas of knowledge, including human-machine systems (ZAHABI AND KABER, 2019), dam safety and stability (HAGHSHENAS et al., 2016; AYDEMIR AND GUVEN, 2017), risk assessment and consequences associated with hydropower projects and industrial plants (ISLAM AND NEPAL, 2016; KARIMPOUR et al., 2016; ABDO AND FLAUS, 2016; TRIPATHI AND SHRESTHA, 2017), and determining irrigation requirements based on climatological parameters (MOUSA et al. 2014), among other applications.

Nasiri et al. (2007) developed a new fuzzy multiple-attribute decision support system for water resources management issues, which prioritizes alternative solutions based on improvements in the water quality index (WQI). By utilizing fuzzy logic, the authors integrated qualitative and quantitative information in the same framework, even when the probability distributions of the data are unknown. However, the framework may be sensitive to overestimating risk values. Similarly, Xu and Qin (2014) created a decision support system for an urban water distribution system by using trapezoidal-shaped fuzzy sets to describe uncertain information. Lee et al. (2009) employed fuzzy logic to evaluate risks in a small drinking water supply system, translating qualitative data into risk probabilities. While this method requires prior knowledge and experience with the system, fuzzy logic was able to quantify qualitative information and identify risks in the system.

The use of qualitative information alongside quantitative data without altering the existing framework is becoming increasingly necessary across various fields. Fuzzy set theory and fuzzy logic approaches have been employed in multiple studies to meet this demand. However, a gap exists in the literature concerning the aggregation of qualitative and quantitative data for risk assessment of water supply systems. Therefore, there is a need for a new method that integrates both types of data for a comprehensive analysis of the subsystems that make up a water supply system. We emphasize the importance of the Risk-fuzzy model, which utilizes triangular and trapezoidal-shaped fuzzy sets, and how it can be adapted and enhanced for other systems.

5.3 Method

The method covers the process of data acquisition and data processing. The information consists of risks' magnitude and was acquired through interviews and semi-structured interviews with technicians and experts that have previous experience concerning structures of the system. Data processing occurs through the Fuzzy Logic Toolbox library of MATLAB® software, while the sensitivity analysis went through using RStudio. As stated previously, the study area of this analysis comprehends the same system used in Chapter 4 and represented by

Figure *13* and includes 56 subsystems.

5.3.1 Data acquisition

In order to acquire data, a structure for semi-structured interviews was used and can be seen at Annex D – Structure for semi-structured interviews (Chapter 5). The structure consists of a sheet designed for marking the magnitude (possibility of occurrence and severity of impacts) for each risk listed for each type of structure according to Table *6*. The values from 0 to 3 or 4 represent the scale: Very unlikely; Unlikely/Minimal impact; Not very likely/Moderate impact; Likely/High impact; and very likely/Critical impact. This scale is going to be better explained in the following sections of this chapter.

This structure is supposed to cover all the 56 subsystems of the study case. Interviews were also held aiming to fulfill lack of information in any subsystem. Additionally, interpolation of data was used in similar structures also to fulfill lack of information.

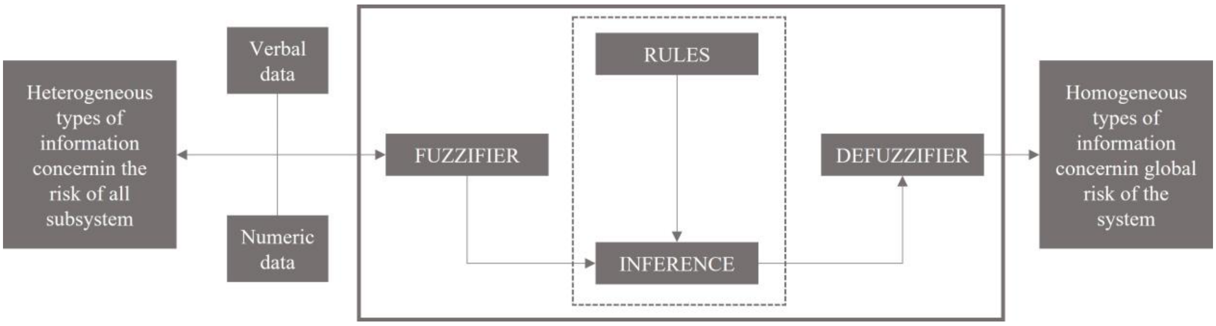
5.3.2 Fuzzy inference process

The assessment of risks was carried out from two different viewpoints. Firstly, a subsystem-based approach was employed, which involved the evaluation of all risks within each water subsystem. Secondly, a global system-based approach was adopted, which integrated all the risks of the subsystems under analysis. To achieve the desired risk values, the "Risk-fuzzy" model was developed, which operates on a pre-defined scale. This model is capable of handling qualitative data, and its outputs are expressed in a uniform quantitative format.

5.3.2.1 Input data and fuzzification

The construction of a fuzzy inference system involves three fundamental operations, as shown in Figure 17. The rules can be either provided by experts or extracted from numerical data. The fuzzifier operation activates the rules that apply to the fuzzy input set. In the inference step, fuzzy sets are mapped, and the activation and combination of rules are determined. Finally, the fuzzy output set undergoes the defuzzifier operation, which yields a precise output (CODES, 2016).

Figure 17 - Design of the fuzzy inference system.



Source: adapted from Codes (2016).

During the fuzzification stage, the fuzzy set determined the degree of pertinence for each linguistic variable. The three linguistic variables used were: possibility of occurrence (input or condition), severity of impact (input or condition), and risk (output or consequence). This set configures the rules of the model, which results in a matrix of risk. It means that the risk is classified according to the linguistic values of the possibility of occurrence (PoO) and the severity of impact (SoI). The rules and the matrix of risk are illustrated at Table 7.

Table 7 - Rules of the Risk-fuzzy model and the matrix of risk.

		Possibility of Occurrence				
		Very unlikely	**Unlikely**	**Not very likely**	**Likely**	**Very likely**
Severity of Impact	**Minimal impact**	Negligible	Negligible	Negligible	Minimal	Moderate
	Moderate impact	Negligible	Negligible	Minimal	Moderate	High
	High impact	Negligible	Minimal	Moderate	High	Critical
	Critical impact	Minimal	Moderate	High	Critical	Critical

Source: Author.

The rules apply to each variable according to the discrete values presented at Table 8. The degree of membership shows how much of that discrete value represents a particular variable. This concept of fuzzy inference appears after the defuzzification process, as the output of the model.

Table 8 - Pertinence values according to the rules of the model.

Pertinence function for PoO	**Pertinence function for SoI**	**Pertinence function for Risk**	**Discrete numeric value [1]**
Very unlikely	-	Negligible	10
Unlikely	Minimal impact	Minimal	20
Not very likely	Moderate impact	Moderate	40
Likely	High impact	High	60
Very Likely	Critical impact	Critical	80

[1] For a degree of 100% of pertinence to the corresponding fuzzy set.
Source: Author.

5.3.2.2 Risk assessment

The inference rules were applied to each subsystem, followed by the defuzzification step, to obtain a numerical value of the risk. These rules were used to correctly manipulate the fuzzy sets, which were defined by the intersection of the Possibility of occurrence and Severity of impacts variables.

In the defuzzification process, the centroid method (also known as the "center of gravity method") was utilized. This method calculates the geometric center of the composite area that represents the fuzzy output term, which is the union of all rule contributions. The resulting risk value falls within the interval of [10, 80], which is part of the discourse universe [0, 100]. It could also be expressed as a percentage.

We assumed that all subsystems had equal levels of importance and that the quality of the risk information was the same across all subsystems. To combine the outputs of the activated fuzzy rules from all subsystems, we applied the union aggregation operator (as shown in (10). The aggregation of rules results in a fuzzy set, which was then defuzzified to obtain numerical values, as described in the previous step.

$$\mu_{(A \cap B)}(x) = max\left(\mu_{(A)}(x), \mu_{(B)}(x)\right) \tag{10}$$

5.3.2.3 Sensitivity analysis

The input dataset used in this model consists of subjective choices, which means that there is a broad range of possible values that can be chosen for the antecedent variables. To account for this variability and assess the sensitivity of the model, Monte Carlo Simulation was used to generate three different scenarios.

In Scenario 1, 1000 random sets of possible input values were generated for the Possibility of Occurrence and Severity of Impact variables, ranging from +10% to -10% of their initial value. These values correspond to a change in the degree of pertinence to two fuzzy sets, 25% and 75% of the initial simulated value.

In Scenario 2, antecedent variables were computed using triangular confidence intervals. The upper vertex of the confidence interval was set to equal the initially simulated antecedent variable, while the lower left and right vertices corresponded to variations ranging from -10% to +10% of their value for the Possibility of Occurrence and from -12.5% to +12.5% of their value for the Severity of Impacts. Similar to Scenario 1, 1000 random sets of possible input values were generated for each antecedent variable.

In Scenario 3, antecedent variables were computed using trapezoidal confidence intervals. The upper vertices of the confidence interval were set to the same values as those of the initially simulated antecedent variables, but with a variation of -10% for the upper left vertex and +10% for the upper right vertex of the Possibility of Occurrence. Similarly, the lower left and right vertices corresponded to variations of -10% and +10% for the Possibility of Occurrence and -12.5% and +12.5% for the Severity of Impacts of the initially simulated antecedent variables. Again, 1000 random sets of possible input values were generated for each antecedent variable.

These scenarios were generated to assess the sensitivity of the model to changes in the degree of pertinence and confidence intervals of the antecedent variables.

5.4 Results and discussions

The proposed methodology for integrated risk assessment of a water system infrastructure, using the Risk-fuzzy program, was applied to the system chosen by the technicians and experts during the elaboration of the typology of risks exhibited in Chapter 4.

The initial evaluation of the Possibility of Occurrence and Severity of Impacts variables was carried out by assigning discrete numerical values based on the proposed scales by the interviewers. These values were assigned a degree of pertinence of 100% to one of the input fuzzy sets. For those subsystems that were lacking information, we decided to input similar values to similar structures.

However, since the input data is qualitative in nature, there is a certain margin of confidence that must be considered due to the uncertainties and inaccuracies associated with subjective choices. The fuzzy methodology allows for the establishment of intermediate values in such cases, which enables the evaluation of data with a higher degree of precision. Similarly, the level of risk obtained through the model is not limited to the first definition but may vary depending on the input data and its degree of pertinence to the fuzzy sets.

Table 9 presents the actual values of the Risk variable for each of the subsystems. The subsystems have risk values categorized between moderate and high, indicating that these water units might need attention and priorities on maintenance and operation.

Table 9 - Subsystems risks and pertinence function.

ID	Subsystem type	Subsystem	Subsystem risk	Pertinence Function
1	**Reservoir**	Lima Campos	45,30	High
2		Orós	41,06	High
3		Castanhão	40,50	High
4		Figueiredo	41,06	High
5		Banabuiú	40,06	High
6		Curral Velho	41,06	High
7		Pacajus	45,00	High
8		Pacoti Riachao	45,00	High
9		Gaviao	45,00	High
10		Aracoiaba	45,00	High
11		Acarape do meio	45,00	High
12		Maranguapinho	45,00	High
13		Cauhipe	45,00	High
14		Sitios Novos	45,00	High
15	**Canal**	Integracao	50,00	High
16		Trabalhador	50,00	High
17		Sitios Novos - Pecem	45,07	High
18	**Tunnel**	Vale - Metropolitana	31,02	Moderate

Table 9 - Subsystems risks and pertinence function (conclusion).

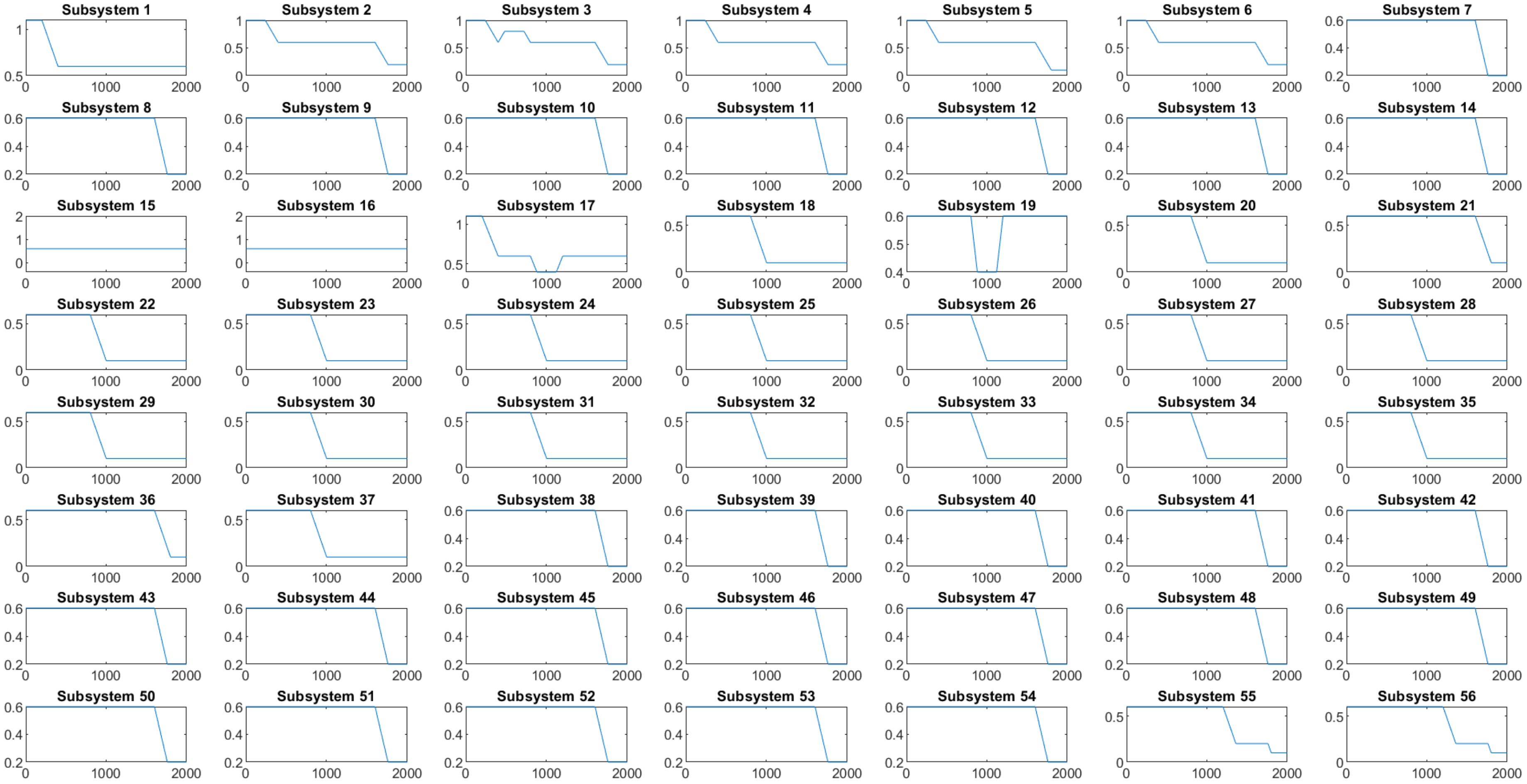
ID	Subsystem type	Subsystem	Subsystem risk	Pertinence Function
19	**Siphons**	Livramento	50,00	High
20		Novo	31,02	Moderate
21		Formoso	43,96	High
22		Santa Rosa	31,02	Moderate
23		Corcunda	31,02	Moderate
24		Banabuiu	31,02	Moderate
25		Palhano	31,02	Moderate
26		Boa Vista	31,02	Moderate
27		Mao Ruiva	31,02	Moderate
28		Melancias	31,02	Moderate
29		Pirangi (Eixao)	31,02	Moderate
30		Serrote	31,02	Moderate
31		Juazeirinho	31,02	Moderate
32		Marambaia	31,02	Moderate
33		Rio Choro	31,02	Moderate
34		BR-116	31,02	Moderate
35		Macacos	31,02	Moderate
36		Umburanas	43,96	High
37		Pirangi (Trabalhador)	31,02	Moderate
38	**Pumping stations**	EB Oros	45,00	High
39		EB Castanhao	45,00	High
40		EB Banabuiu	45,00	High
41		EB Itaicaba	45,00	High
42		EB Pirangi (Eixao)	45,00	High
43		EB Pirangi (Trabalhador)	45,00	High
44		EB Pacajus	45,00	High
45		EB 1	45,00	High
46		EB 2	45,00	High
47		EB Pacoti	45,00	High
48		EB Gavião	45,00	High
49		EE 0	45,00	High
50		EE1	45,00	High
51		EE 2	45,00	High
52		EE 3	45,00	High
53		EB Maracanau	45,00	High
54	**Perennialized rivers**	Perennialized rivers	45,00	High
55	**Wells**	Pecem	38,56	Moderate

56	Taiba	38,56	Moderate

Source: Author.

It is fair to assume that the obtained output values for the subsystems do not exclusively belong to one specific fuzzy set. This can be evaluated by observing Figure 18.

Figure 18 - Pertinence curves for each subsystem.



Subsystem 1
Subsystem 2
Subsystem 3
Subsystem 4
Subsystem 5
Subsystem 6
Subsystem 7
Subsystem 8
Subsystem 9
Subsystem 10
Subsystem 11
Subsystem 12
Subsystem 13
Subsystem 14
Subsystem 15
Subsystem 16
Subsystem 17
Subsystem 18
Subsystem 19
Subsystem 20
Subsystem 21
Subsystem 22
Subsystem 23
Subsystem 24
Subsystem 25
Subsystem 26
Subsystem 27
Subsystem 28
Subsystem 29
Subsystem 30
Subsystem 31
Subsystem 32
Subsystem 33
Subsystem 34
Subsystem 35
Subsystem 36
Subsystem 37
Subsystem 38
Subsystem 39
Subsystem 40
Subsystem 41
Subsystem 42
Subsystem 43
Subsystem 44
Subsystem 45
Subsystem 46
Subsystem 47
Subsystem 48
Subsystem 49
Subsystem 50
Subsystem 51
Subsystem 52
Subsystem 53
Subsystem 54
Subsystem 55
Subsystem 56

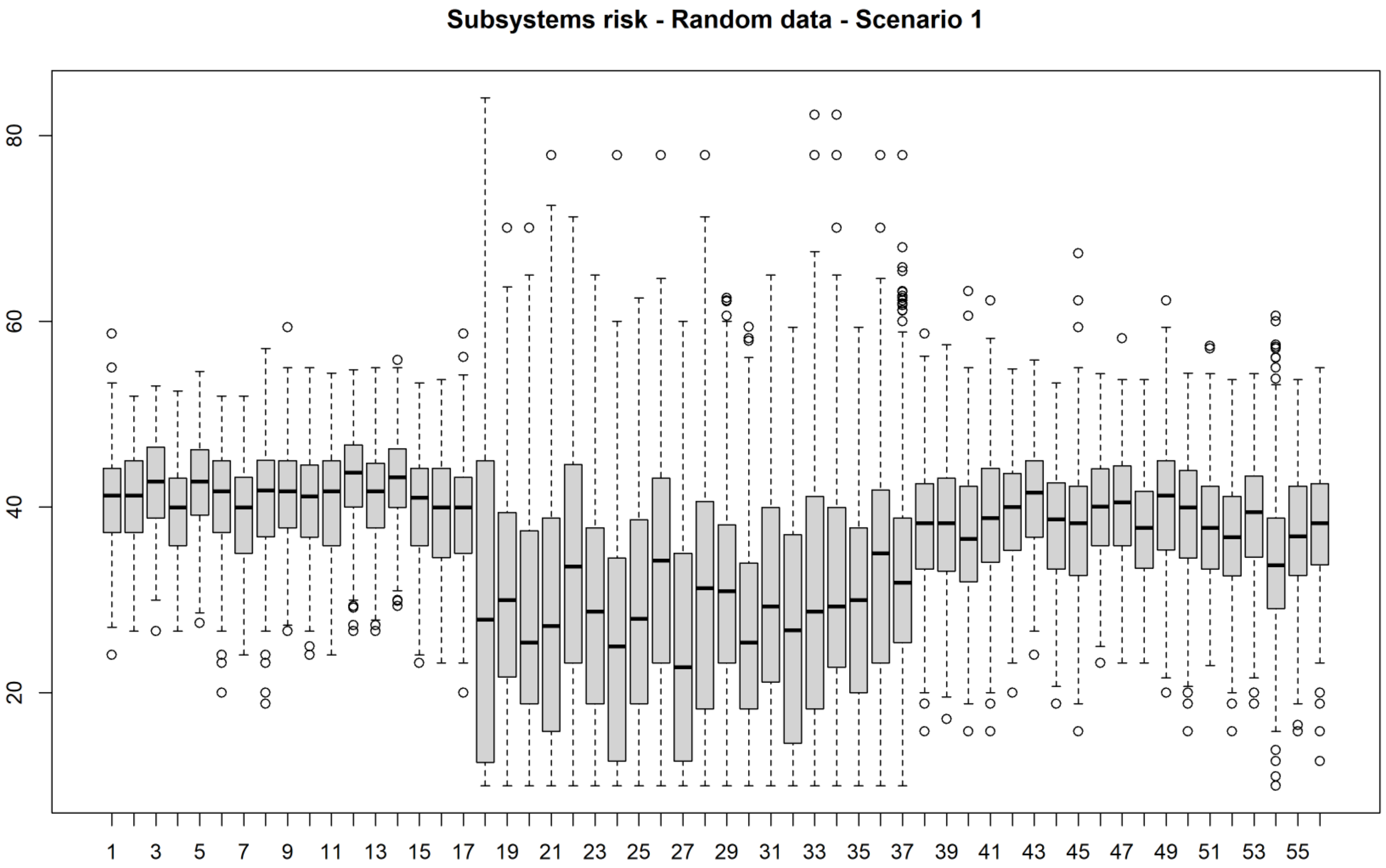
Source: Author.

The global risk of the system provided by the Risk-Fuzzy model was R = 43.72. According to the suggested scale, this value corresponds to the fuzzy set classified as high. It is possible to observe a few types of subsystems (or types of structures) that present higher values of risk, such as reservoirs, canals and pumping stations.

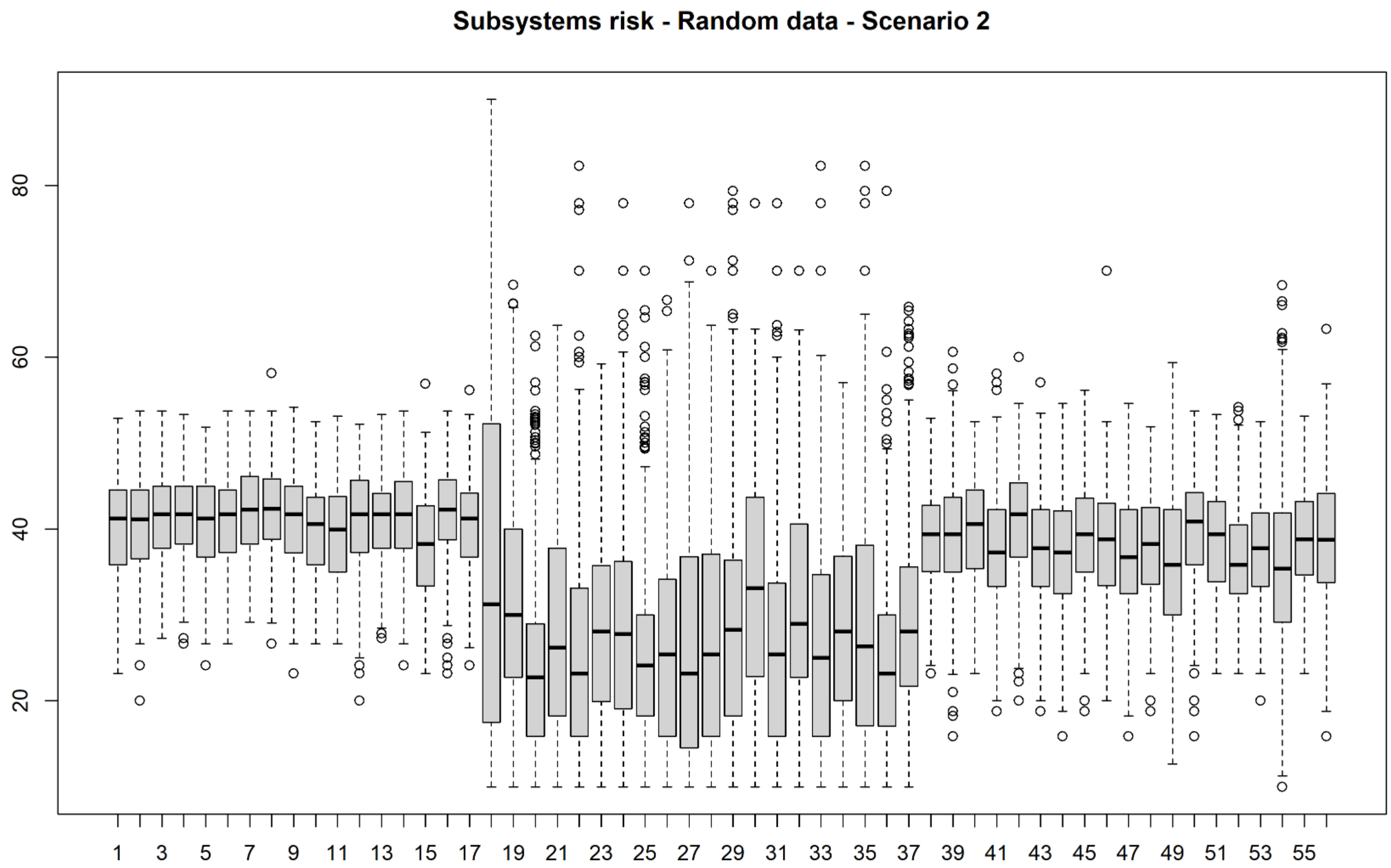
It is also possible to observe that a lot of subsystems belonging to the same type of structures resulted on equal values of risk. This might be mainly related to the lack of information acquired during the interviews, specially for types of structure with a lot of "repetitive" subsystems, such as siphons and pumping stations. The process of data acquisition is tiring for the interviewers once there are a lot of subsystems with a repetitive list of risks to be evaluated. This scenario leads to an uncertainty concerning the mathematical efficiency of the model. Therefore, we opted to run a sensitivity analysis to evaluate the behavior of the model.

In our analysis, we conducted simulations for three scenarios, each comprising 1000 random sets. The PoO and SoI values of all variables were varied independently. Figure *19* illustrates the results of our risk sensitivity analysis for each subsystem across the three scenarios. Firstly, we observed that Scenario 3 (Figure *19*a) had the lowest amplitude value in most of the subsystems analyzed, suggesting that it had the most favorable risk conditions compared to the other scenarios. It is also important to point that the subsystems 18 to 37 represent the tunnel and the siphons and are notably the subsystems with wider amplitude from the three scenarios of the sensitivity analysis. Considering that the pumping stations, which are the other type of structure with repetitive results of risk, presented an acceptable behavior on the sensitivity analysis (subsystems 38 to 53), we can assume that the dystrophy concerning the tunnel and the siphons are not related to the data acquisition process. We can infer, then, that the cause of this dystrophy might be related to the low number of risks concerning both type of structures. The typology accounted for the tunnel and the siphons one and three risks each, respectively. In conclusion, it is recommended to review these types of structures with the collaborators that participated during the elaboration of the typology, as well as review the data acquisition process concerning the type of structures that encompasses a higher number of subsystems, such as siphons and pumping stations.

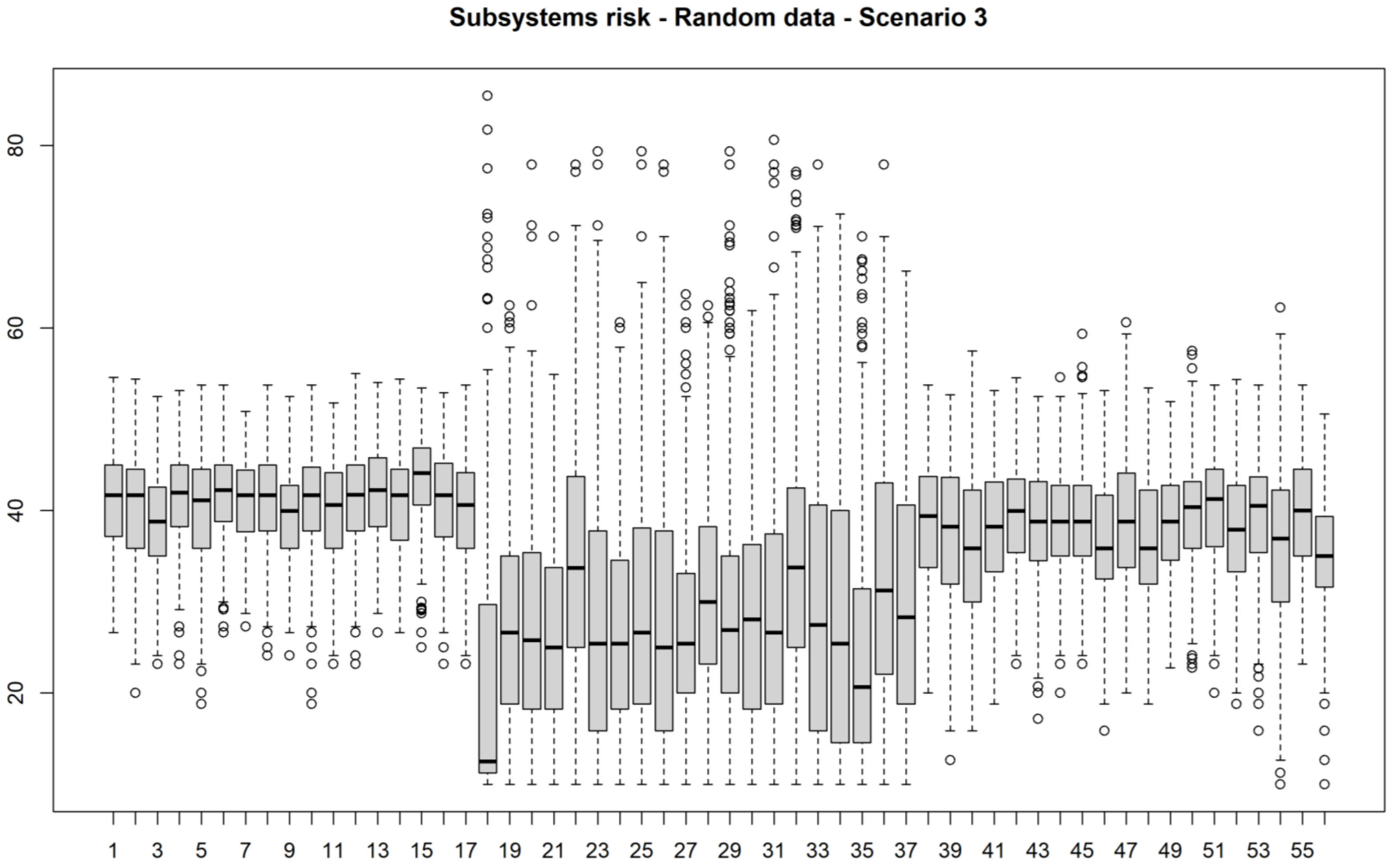
Figure 19 - Risk sensitivity analysis for each subsystem, considering the three different scenarios: (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.



(a)


Subsystems risk - Random data - Scenario 2
80
60
40
20
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
45
47
49
51
53
55

(b)



(c)

Source: Author.

The Risk-fuzzy model was applied to the water infrastructure system in Ceará, Brazil, and demonstrated sufficient robustness to support similar applications in other raw water systems. The system can be divided into subsystems, such as water transportation, storage, and pumping stations, each of which has its own unique risks that can impact the overall system. By conducting an integrated risk analysis, this model can evaluate the risks of the water system and its hierarchical levels, based on the defined components and their respective risk lists. Qualitative information can also be used to evaluate risks that lack exact probability and can only be assessed based on the possibility of occurrence.

However, it should be noted that while the Risk-fuzzy model conducts an integrated risk analysis, it does not currently account for cascading effects and causal relationships between the risks and different components. A Bayesian Network model can contemplate that effect and might be a solution once the risk is quantified through a fuzzy modelling process.

5.5 Conclusion

Ensuring water security requires a dependable supply of water that meets the required quantity and quality standards for most of the time. To achieve this, a fundamental prerequisite is the existence of water supply system infrastructure, which includes reservoirs, channels, pumping stations, etc. In order to ensure uninterrupted operation of the system, it is crucial to preserve the infrastructure and its functions. This can be achieved through a rigorous risk assessment process, which is essential even when there is limited information on the frequency of failures in water systems. While qualitative information may be used in such assessments, it is imperative to quantify the risks to avoid uncertainties.

In the face of challenges, the authors employed fuzzy inference to conduct an integrated analysis of water infrastructure risks. Fuzzy logic was selected as the primary method due to its capacity to handle qualitative information and apply a mathematical framework to quantify the data. The authors developed a model by performing four key activities: fuzzification of input data, analysis of inference rules, aggregation of risks, and defuzzification. This model enabled the analysis of a complex system that could be broken down into several subsystems.

The approach proved to be a useful tool for evaluating integrated risks and demonstrated flexibility in allowing for the inclusion or exclusion of subsystems and risk types in a straightforward manner. This adaptable framework can be applied to water systems of various scales and accommodates incoming data provided through different confidence intervals. The input data were evaluated based on their ability to have degrees of relevance to either one or two fuzzy sets in both antecedents (Possibility of Occurrence and Severity of Impact). Various scenarios were simulated to test the approach, including those with discrete numerical values. In all of the application scenarios, the water system exhibited risks falling within the moderate and high risk classes for both fuzzy sets.

This study introduces a methodological framework that can be applied to assess the risks of water systems, regardless of their size, with little or no quantitative data available. The framework considers all aspects of the water system and can help to identify its weak spots and vulnerabilities. By providing an effective tool for risk assessment, the model contributes to the process of ensuring water security. It is fair to state that a main disadvantage of the method is the data acquisition step. The process of acquiring information is exhausting and time-consuming, and depending on the number of subsystems, it can exacerbate the lack of information. As a consequence, this can even affect the final results.

Furthermore, we recommend taking into account the characterization of the typology of risks and reapplying the model. It can also be considered to review the data acquisition process in order to minimize the lack of information. This approach can further improve the accuracy of risk assessment and aid decision-making for water system management.

6 WHO ARE THE STAKEHOLDERS?

6.1 Introduction

The increasing population size results in a higher demand for water, which creates a fragile equilibrium for maintaining a steady water supply, and this is further complicated by the added uncertainties posed by climate change risks. In the past few decades, the increase in water consumption has outpaced population growth, resulting in a more significant strain on water resources (COSGROVE & LOUCKS 2015). This combination of increased demand and limited availability of water is likely to worsen existing water stress in many parts of the world (SUÁREZ-AMIÑANA et al. 2017). Additionally, developed nations are grappling with challenges related to water allocation, non-point source pollution, and extreme events like droughts, which further exacerbate the situation. For their part, industrialized countries contend with conflicts related to water allocation, non-point source pollution, and extreme events, including droughts (PRYSHLAK et al. 2014).

This complex dynamic that relates society and water balance brought an increase in the interest in interdisciplinary approaches when it comes to water research during the last few decades. This increase is driven mainly by the need to comprehend water related societal challenges (WESSELINK et al., 2017). Water researchers are, in response, focusing on building interdisciplinary approaches to order to understand water problems, make predictions, and produce information on which society makes future decisions (BAKKER, 2012; KREUGER et al., 2016). Scientists refer to this new movement in water research as 'socio-hydrology' and defend that it is clear that the actions of society are having a significant and escalating impact on hydrology in numerous countries (SILVAPLAN, 2012). As a result, water is increasingly becoming a crucial constraint on the long-term viability of society. Therefore, it is crucial to adopt an interdisciplinary approach and implement strategic and efficient measures for water management. The significance of comprehending the interplay between water systems and human systems has led to an increasing interest in socio-hydrological methods. These approaches aim to enhance the ability of communities to adapt and cope with water-related challenges by exploring the dynamics and co-evolution of these systems (NGUYEN et al., 2021).

The advance of the social aspects within water resources research goes hand in hand with the search for improvement in the governance of natural resources. Processes that seek adaptive governance rely on participatory methods. Supporters of participatory approaches argue that collaborating with individuals and groups who are closely involved in the area or issue can improve sharing of information, identification of challenges and solutions, build trust and credibility in scientific findings, and facilitate the integration of scientific knowledge in decision-making processes (KAINER et al., 2009).

Integrated water resources management models, such as the one used in Brazil, counts with organizations composed by stakeholders that represent society at the river basin level, encompassing water users, civil society members, and officials from various administrative units that either fall within or overlap with the river basin (MEDEMA et al., 2008). Lemos et al. (2020) reinforces the understanding that the quality of social interactions amongst the stakeholders, such as inclusivity, exclusivity, bridging, or bonding, along with effective systems for knowledge transfer and learning, participation, and collaboration, play a crucial role in improving adaptive capacity and resilience. Additionally, the emphasis on democracy and participation increases the connection between governance and knowledge and the trust between state and society.

Having a clear understanding of the rules governing interactions, establishing boundaries, and identifying connections among stakeholders is essential for successful collaborative water resources planning and management. This understanding should encompass the broader ecosystem in which stakeholders operate, including their interests, knowledge, and relationships. The interactions between stakeholders often give rise to the formation of social networks, which play a crucial role in facilitating the exchange of knowledge, mobilization of resources, and resolution of conflicts. However, the analysis of these networks and stakeholder interactions at the basin level is currently lacking in terms of comprehending influences, interests, and levels of participation (ROJAS et al., 2020).

Given the presented context, it is fair to conclude that it is necessary to understand the interests of the stakeholders, their behavior and how it affects water resources planning and management layers such as the process of decision making and the occurrence of conflicts.

Therefore, this paper proposes mechanisms to identify groups of interests amongst stakeholders' social networks and the process of analysis, in a way to assist visualizing and understanding behavior and conflicts, facilitating the process of mediation and management. The research uses the Brazilian state of Ceará as the study case and considers a context of a long-term drought that has initiated in 2012 and still causes impacts in several regions of the State. The analysis considers the perception of the stakeholders that compose the river basin committees on the impacts of the drought. We believe that the diversified representation of the committees will be able to capture the different views of the stakeholders and identify how they behave, thus identifying interest groups. We also assume that the social networks resulting from the stakeholders' perception will be able to support an analysis of how they cluster and whether stakeholders identify with the grouping imposed on them through the creation of committees. The goal is also to understand if the behavior of such groups can affect the process of negotiated water allocation and to understand the emergence of conflicts, facilitating their mediation process. Network analysis will be used to comprehend this problem. Solutions should be sought based on the behavior of interest groups, not just individual agents, through the creation of convergence mechanisms. It is understood that from these points, the conflict mediation process can be facilitated, assisting in negotiated water allocation and other aspects of water resources planning and management.

6.2 Where are stakeholders inserted?

The relationship between state and society can be seen as a continuous and interconnected process that involves various entities, such as councils, committees, forums, and networks. These entities play a crucial role in enabling social interactions between civil society and representatives of public authority. However, it is important to note that this connection does not imply the replacement of the state. Instead, it recognizes the value of incorporating "expert knowledge", as well as “tacit knowledge” (SOUZA FILHO et al., 2022). When official records are not available or are inadequate, social perception can be a valuable resource for improving the modeling process (MARTINS et al., 2023). Collaborative water governance has emerged as a promising approach to address the challenges associated with water management, combining formal collaborative governance methods with the principles of water governance, aiming to put them into practical action and emphasizing the importance of stakeholders working together to achieve common goals in managing water resources (ANSELL & GASH, 2008; EMERSON et al., 2012; HOLLEY, 2015; HARRINGTON, 2017; ROJAS et al., 2020). It encourages a bottom-up approach that incorporates local knowledge, promotes inclusivity and transparency, and relies on participatory processes to facilitate collaboration and consensus-building. These processes foster the sharing of responsibility and wider contributions from stakeholders at all levels, ultimately leading to the development of a shared vision and plan for future water management (CONNICK & INNES, 2003; ROJAS et al., 2020). Participation becomes, then, a crucial aspect in ensuring the effectiveness of public policy, enabling interaction with the political system, resolving conflicts, and promoting democratic decision-making.

According to Engle and Lemos (2010), the decentralized governance structures of the Brazilian water reform, as represented by the river basin committees and the stakeholders representing different groups of society through these institutions, may have a positive correlation with adaptive capacity. However, achieving both equality in decision-making and access to knowledge may involve tensions and tradeoffs. The implementation of governance, as well as the expansion of democratic participation, can face obstacles such as pre-existing power relationships, entrenched bureaucracies, and insufficient resources. These factors can impede successful implementation. Institutions dynamics, among other aspects, can lead to path dependencies that hinder the flexibility and decision-making capabilities of members in river basin committees, thus creating a negative impact on them (ENGLE, 2011).

In Brazil, the water management is allegedly decentralized, democratic and participative. However, the federal level holds substantial authority in implementing policies, while states have a significant role in managing water, resolving conflicts, and shaping the policy landscape for river basins (ENGLE AND LEMOS, 2010). The Brazilian system of participatory water management involves a tri-party arrangement among the stakeholders, which are previously divided into state and federal government, users, and organized civil society organizations. This arrangement is represented by river basin committees that are responsible for making decisions related to water allocation, project development, and conflict-resolution, and is predetermined through national legislation (BRASIL, 1997). Yet, the federal law provides states with considerable flexibility in designing and implementing specific aspects of the reform, such as the formation and constitution of the basin committees and other governance mechanisms. This includes the representation of stakeholders within councils, the implementation of bulk water charging, the level of agency, and technical support. According to Engle and Lemos (2010), this situation results in each state having its institutional structure and, therefore, the degree of implementation of the law may vary significantly within the broad principles of the law. The diversity of the river basin committees' influence and authority creates the possibility of studying governance approaches across different basins. This is important for evaluating how these approaches may shape the process of water allocation negotiation and resolving conflicts.

Understanding the formal and informal rules that govern interactions within a system, defining boundaries, and identifying connections and relationships among stakeholders are important steps in achieving an efficient frame of collaborative water resources planning and management (STRINGER et al., 2017, ROJAS et al., 2020). This understanding should encompass the comprehension of the ecosystem which the stakeholders are inserted, including their interests, knowledge, and relationships, among other factors, which is essential for the successful implementation of any collaborative framework considering water resources planning and management (BODIN & CRONA, 2009; PRELL et al., 2009; PRELL et al., 2010; STEIN et al., 2011; FLIERVOET et al., 2016; FLIERVOET et al., 2017).

It is also necessary to understand that stakeholder interactions often give rise to the formation of social networks (OGADA et al., 2017). Research highlights the pivotal roles played by these networks in facilitating the exchange of knowledge and information, the mobilization and utilization of resources, and the resolution of conflicts (CRONA & BODIN, 2006). However, the analysis of these networks and the interactions between stakeholders in terms of influences, interests, and participation at the basin level has been limited (OGADA et al., 2017, ROJAS et al., 2020).

In Ceará, a semi-arid state located at the northeastern region of Brazil (NEB), river basin committee members in different basins reported encountering similar types of conflicts related to water, including access to water, water quantity, water quality, water allocation, and governance (STUDART et al., 2021). According to the authors' research, water allocation conflicts were particularly prevalent and arose from issues such as water transfer between basins diversion, which generated disagreements among water users and uses. River basin committee members identified governance conflicts as common in river basins, with a significant focus on the inadequate coordination between environmental and water management institutions, as well as between different water management bodies. Other governance challenges mentioned by members included low levels of interest from water users in participating in river basin committees' meetings, as well as limited autonomy and power struggles within the committees (STUDART et al., 2021).

6.3 Network analysis

A complex network is characterized by the presence of non-trivial elements. It is a distribution of arcs arriving in and leaving out different nodes, that can or cannot be clustered, depending on their connections. A complex network can be considered the most adequate tool to represent a social network using graphs. Social networks encompass individuals (or a similar structure that can be individualized, such as institutions) that have some degree of connection and/or influence (SCOTT, 2017; GABARDO, 2015).

An example of application is to identify who is the most influential individual within a given group. When there is a need to propagate a message, it is more efficient to deliver an information to this individual than to deliver the same information to a less influential individual. A network analysis can also indicate how the message is going to be widespread or even accepted between the other members of the group.

Network analysis rely on graphs to understand its functioning. Graphs are a mathematical abstraction used to represent a complex network and is composed by edges and nodes. Individuals are represented by nodes and their connections by the edges. The construction of a graph counts with metrics and attributes that aim to reduce subjectivity concerning the analysis of a complex network. The degree of a node is a simple metric that represents its number of connections. It is useful to identify individuals that are more connected or have more influence within a network (GABARDO, 2015).

In complex networks, it is often possible to observe communities or groups organized into different clusters. This organization happens according to their similarity or even proximity. Modularity (Q) is a metric to identify clusters within a complex network through the analysis of the connections between nodes. Modularity was created to compare the links within the obtained communities to theoretical random connections. This concept is based on the notion that if there is a natural and random expected division of the network, the connections within a community must exceed the expected theoretical value, while exhibiting opposite behavior for connections between communities (CHANG et al., 2012). This metric can be calculated through (11, where A_{ij} represents the affiliation matrix, while the second term calculates the probability of an arc is between the nodes i and j, and m represents the quantity of arcs in a graph. k_i is the degree of the node i and k_j is the degree of the node j.

$$Q = \frac{1}{4m} \sum_{i,j} (A_{ij} - \frac{k_i k_j}{2m}) \qquad (11)$$

The modularity metric is a scale that ranges from zero to one. A value close to one suggests a robust community structure within the network, while a value near zero indicates a nearly random distribution of within-community edges.

6.4 Method

The method process initiated with a data acquisition stage that consisted of an application of an online questionnaire amongst members of the twelve River Basins

Committees of Ceará. According to the results of the questionnaire, the authors are then able to go through a qualitative analysis to comprehend the impacts of the drought. Then, the network analysis aims to identify and evaluate clusters that may or may not have influence in the perception or even in the decision-making process of water management and water allocation amongst the River Basin Committees.

6.4.1 Data acquisition

The process of data acquisition counts with the application of an online questionnaire. The target audience are the members of the twelve River Basin Committees of the state of Ceará. The main goal of the questionnaire is to identify how the respondents perceived the most significant impacts during the drought, as well as the actions of response to drought managed by the public institutions.

The questionnaire is primarily designed to collect objective responses and is divided in two main sections: the first covers the impacts of drought and the second evaluates the response actions.

The first section comprises statements highlighting issues within major sectors impacted by drought: the impact of drought on water uses, sanitation, conflicts, water availability, quality of life, economic sectors, and environmental/recreational sectors. Respondents are required to assess the level of impact based on their observations and experiences during the crisis period using a rating scale that increases in severity from Irrelevant (0) to Low (1), Medium (2), High (3), and Not Assessed (NA). The NA option is for respondents who choose not to answer the question due to a lack of information or discomfort.

The second section provides a list of possible actions that may or may not have been taken into action and the respondents are asked to evaluate each of them as Very Efficient, Efficient, Not Very Efficient, Inefficient, Not implemented in the river basin, and Not Assessed.

The complete structure of the questionnaire is presented in Annex E – Questionnaire applied in Ceará (Chapter 6) of this document.

6.4.2 Qualitative analysis

The first step of this study is to conduct a qualitative analysis to ascertain the impacts of drought on different sectors across the river basins of Ceará. Specifically, the study will identify the sectors that were most affected by the drought and evaluate the effectiveness of various actions that were taken in response to the drought, focusing on the perceptions and experiences of members of the river basin committee. The data obtained from the questionnaire will be analyzed to identify key themes and patterns related to the impacts of drought and the effectiveness of various response actions. The findings of this study will provide valuable insights into the impacts of drought on different sectors to each river basins and will help to inform future drought response strategies in Ceará.

6.4.3 Modelling the social network

The complex network analysis here consists mainly of identifying communities (i.e., groups of interest or clusters). From this point, it is possible to understand the behavior of the agents and how they dance between the different interests exposed in the questionnaire. Then, we will be able to infer if and how this dance might affect the process of water allocation and the generation and solution of conflicts. The prominent aspect of devising a social network resides in its inherent capacity to offer a vast array of information, surpassing the mere process of clustering. Beyond identifying agent clusters, it unravels intricate internal relationships and quantifies degrees of influence. Such comprehensive insights into the network structure illuminate its potential for a deeper understanding of social dynamics and individual behaviors.

Community detection in complex networks shares similar objectives with clustering techniques, as both seek to group together nodes that exhibit similar attributes and are closely connected to each other. In essence, the identified communities can be thought of as clusters within the network. The primary goal of community detection algorithms is to group nodes with high interconnectivity, thereby demonstrating a certain degree of dissimilarity or independence from nodes outside the community. The optimization process of aggregating communities uses modularity as the main matric ((11, from section 6.3 Network analysis) (ROCHA, 2021).

Optimizing modularity in complex networks is a challenging task, which has resulted in the development of various algorithms to overcome its inherent complexity (ROCHA, 2021). The *Louvain* algorithm is a technique that utilizes modularity to optimize the partitioning of large networks. Its primary aim is to identify hierarchical structures within such networks. To achieve this, the algorithm repeatedly exchanges nodes between communities, assessing the impact on modularity at each step until no further improvement is possible. Following this, the communities are collapsed into latent nodes, and the edge weights between these and other observed and latent nodes are identified. This process gives rise to a "multi-level" structure (BLONDEL et al., 2008; GATES et al., 2016; CHRISTENSEN et al., 2020).

There are also approaches to detect communities in a network that are based on node similarity measures. These approaches use a measure of similarity between nodes to identify cohesive communities within the network. The *Walktrap* algorithm is an example of such an approach, which uses a distance measure based on random walks and applies a hierarchical agglomerative clustering method. In this algorithm, a random walker moves from one node to another in the network, selecting the next node by randomly choosing a neighbor of the current node. The algorithm assumes that random walks tend to get trapped within communities and uses this property to detect communities. The distance measure is based on the probability of reaching a third node through a random walk from two nodes in the same community. The algorithm calculates this distance for all nodes and constructs a hierarchical community structure based on the similarities between them (PONS AND LATAPY, 2005; GAN et al., 2007; CHRISTENSEN et al., 2020; ROCHA, 2021). The Euclidean distance was elected for this process, and similarity for the construction of the network and clusters is represented by (12, where *d* represents the distance and *S* the similarity.

$$S = \frac{1 - d}{\max{(d)}} \tag{12}$$

Researches comparing both algorithms did not observe significant differences between them. Yet, both algorithms were consistently efficient on medium to large complex networks (HALVERSON AND FLEMING, 2015; CHRISTENSEN et al., 2020; TOTH et al., 2022). Considering these statements, the algorithms *Louvain* and *Walktrap* were evaluated to run the complex network analysis for this study. For the development of this study, we applied the R package *igraph*, which encompasses the algorithms for both methods: *Louvain* and *Walktrap* (CSARDI AND NEPUSZ, 2006). Through a comparative analysis of *Louvain* and *Walktrap* statistical results, the authors concluded that the *Louvain* algorithm demonstrated superior suitability for the study's objective. Consequently, the social networks to be analyzed herein will solely encompass those generated through the *Louvain* algorithm.

6.5 Results and discussions

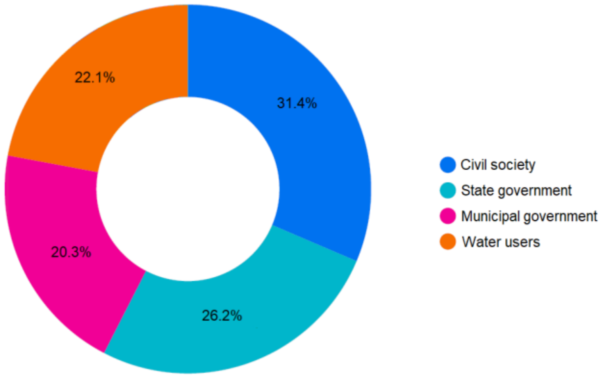
This section presents the results obtained both from the questionnaire answers and the complex network analysis as well as the authors' interpretation. The results are exhibited in two different parts: the first one encompasses the qualitative analysis of the questionnaire, while the second part covers the complex network analysis.

6.5.1 Qualitative analysis of the perception of the impacts

The federal law has established the representation of the river basin committees as a tri-party arrangement between government, water users and civil society. In Ceará, the State Water Act defines the composition of the river basin committees as 30% from civil society, 30% from water users, 20% from state government and 20% from municipal government.

In this study, a sample of 172 distributed amongst the twelve river basin committees of Ceará responded to the questionnaire, representing a population of 420 potential respondents. The sample was drawn to gather insights and make inferences about the larger population. That being said, Figure 20 represents the composition of questionnaire responses. Civil society and municipal government are fairly represented amongst the respondents. However, the representation of water users (22.1% instead of 30%) and state government (26.2% instead of 20%) are slightly unbalanced. It is important to consider for the entire analysis.

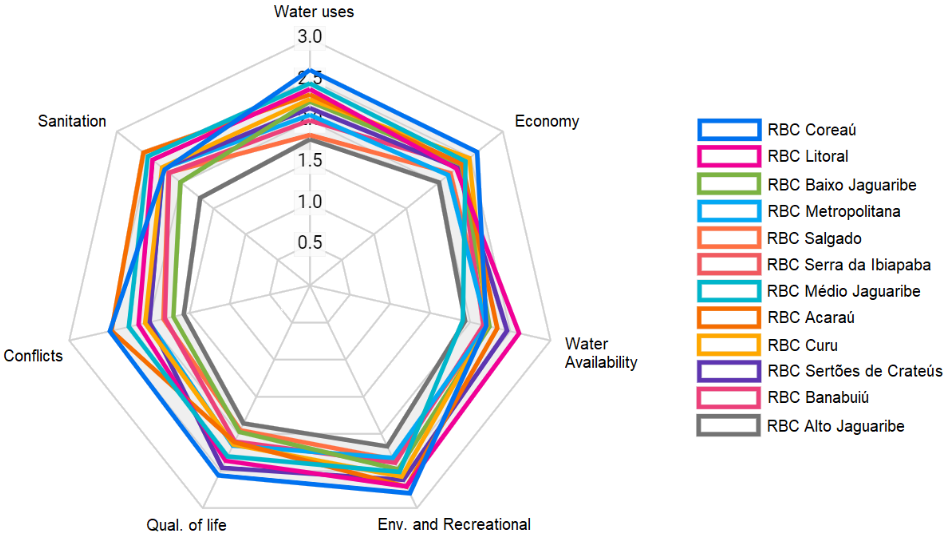
Figure 20 - Composition of questionnaire responses on the perception of drought impacts.



Source: Author.

Figure 21 summarizes the average responses of each river basin committee for the first section of the questionnaire, considering the perception of the impacts to the drought initiated in 2012 at Ceará. According to the graph, the curves closer to the center are closer to zero (the value that represents irrelevant impact), and the closer the curves are to the outer edge of the graph, the closer they are to three (the value that represents high impact). The grey curve that represents RBC Alto Jaguaribe illustrates that this RBC has the lowest average of perceived impacts in the State, highlighting only the environmental/recreational sector. It can be noticed that in other RBCs, the averages are more varied, standing out in some sectors and presenting lower impacts in others. For example, RBC Litoral presents a significant average of perceived impacts in the water availability and environmental/recreational sectors, while presenting a more reduced average in the conflicts sector. On the other hand, other regions, such as RBC Coreaú, present considerable averages of perceived impacts in almost all sectors.

Figure 21 - Graphical summary of the first section of the questionnaire (perception of impacts on various sectors).



Source: Author.

Nonetheless, still observing

Figure 21, it is fair to infer that all the RBCs from Ceará have suffered severe impacts during the drought period initiated in 2012, as the radar graph shows that the averages lie between the values of 1.5 (low to medium impact) and 3 (high impact).

The second section of the questionnaire covers the possible actions taken by the public institutions during the drought. Figure 23 exhibits the list of actions and the results of their perceived average efficiency (1 being Inefficient and 4 Very Efficient).

Figure 22 – (a) Evaluation of the possible actions taken by public institutions during the drought.

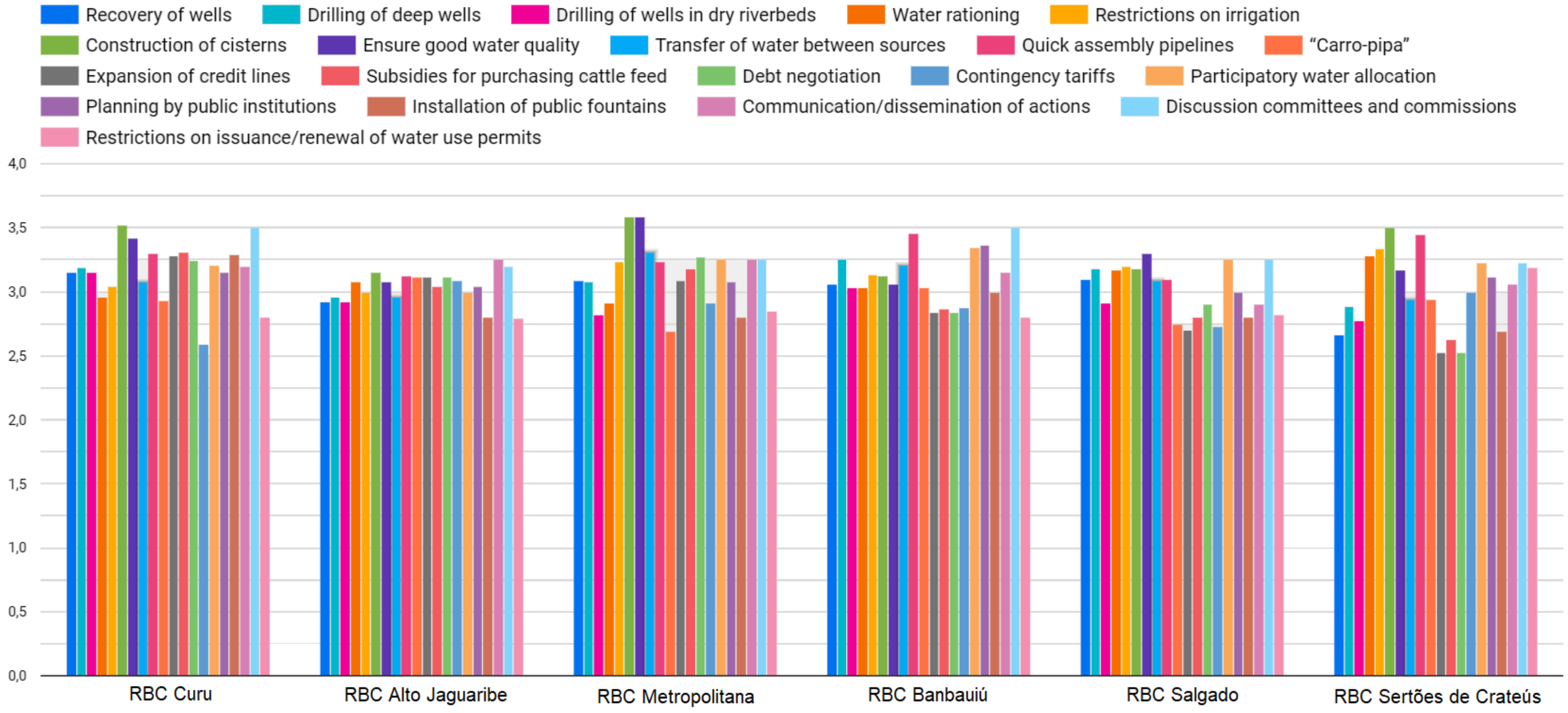
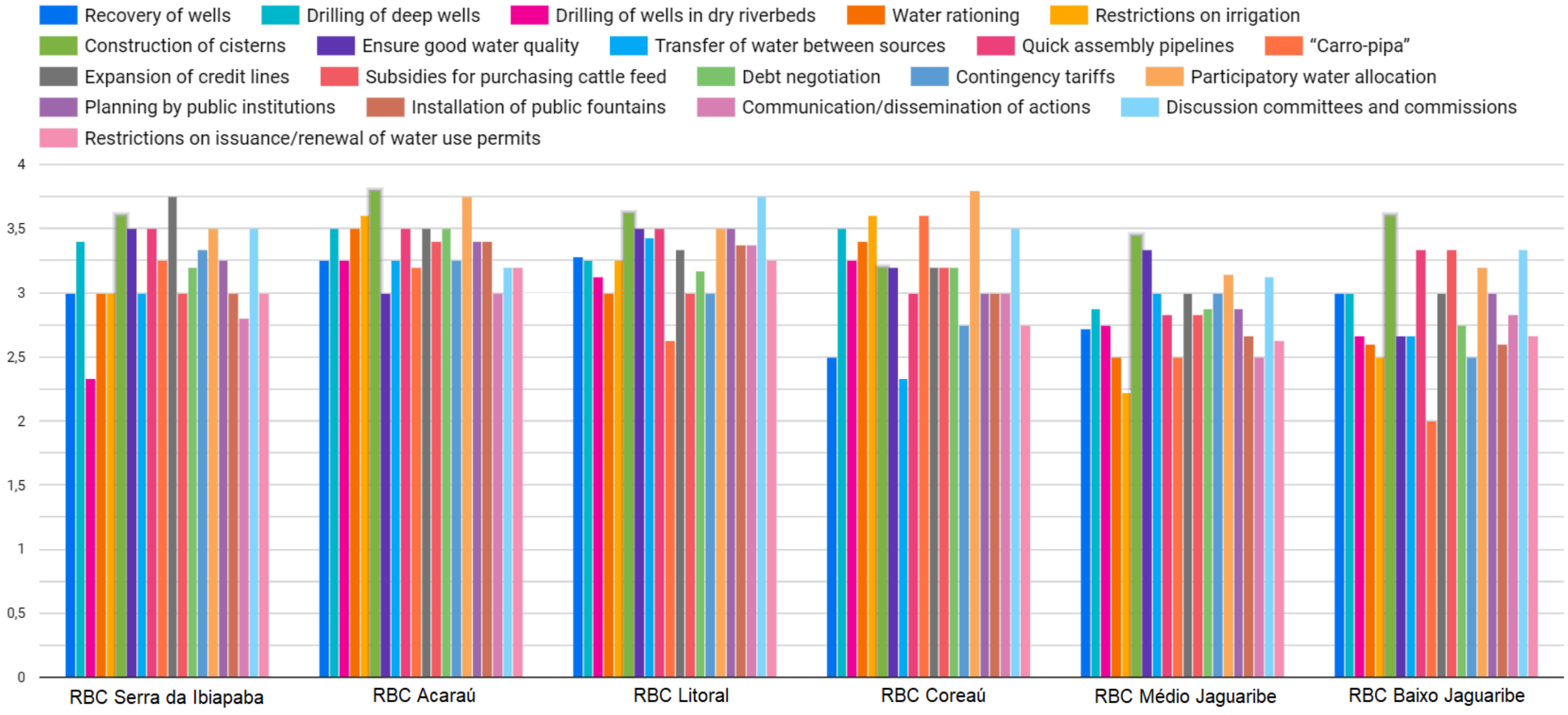


Figure 23 – (b) Evaluation of the possible actions taken by public institutions during the drought.



Source: Author.

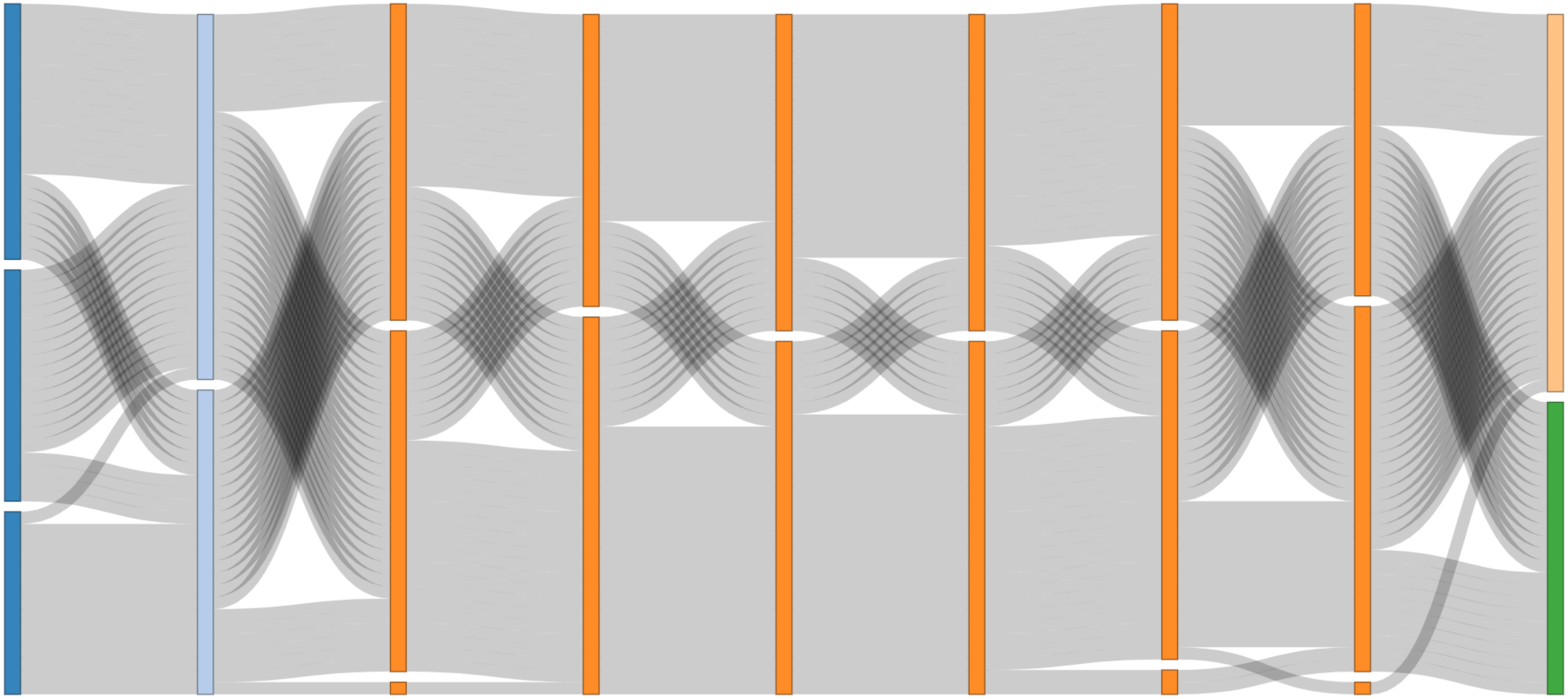
Observing Figure 23 (a) and Figure 23 (b), a few actions are initially highlighted by their efficiency in various river basins. The construction of cisterns are rated higher than 3.5 (Efficient to Very Efficient) in eight of the twelve river basins committees. This information is validated by the famous federal programs of construction of cisterns in the semi-arid region of NEB than began during the early 2000s. The construction of cisterns throughout the NEB have improved the adaptive capacity of the population in the semi-arid region with regards to dealing with frequent and severe droughts, as well as recognizing the important role of northeastern women in the survival of their families (NOGUEIRA et al., 2022; MORAES AND ROCHA, 2013).

Participatory water allocation is considered at least Efficient in each one of the twelve river basins. This result is probably related to the ability of solving conflicts that a democratic management may have. Additionally, this result converges to the analysis this paper proposes. Aligned to this, the creation of committees and commissions to discuss issues and solutions during the drought period is also highlighted. Despite not every action being highlighted in the graph, it is possible to notice that there is no action below the value of 2 (Not very efficient) in any of the river basins.

6.5.2 Network analysis

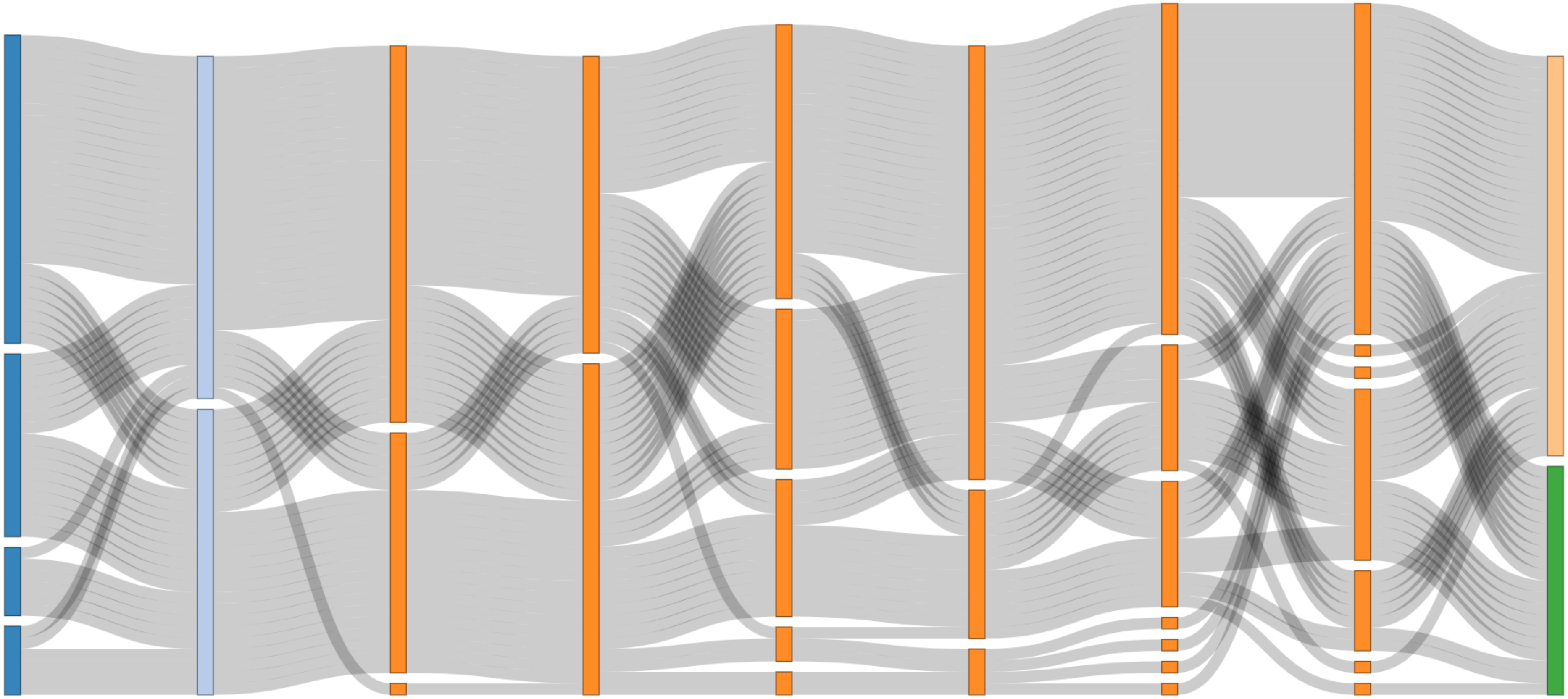
The preliminary evaluation of the results encompassed the generation of social networks utilizing both the *Louvain* and *Walktrap* algorithms. To facilitate an in-depth analysis, Sankey graphs and boxplots were employed as visual aids. Initially, Figure 24 illustrates the “dance” of the agents amongst the different clusters of perception according to the *Louvain* algorithm, whilst Figure 25 represents the *Walktrap* algorithm. Comparing both figures, it is possible to observe how *Walktrap* introduced redundant clusters, resulting in the emergence of isolated agents and demonstrating an increased sensitivity to generate new clusters, which may impact on the results. Additionally, Figure 26 presents the boxplots concerning the distance between nodes for each sector and each algorithm, where each box represents a cluster and n represents the quantity of data within each cluster. The low *n* values for the surplus *Walktrap* boxes reinforces the assumption of the increased sensitivity to generate clusters, creating communities with little data or representation.

Figure 24 - Sankey graph of the Louvain algorithm concerning the different sectors of the questionnaire and the distribution of the agents' perception. Each set of bars represent a different sector, and its divisions concerns the clusters generated. The grey arrows represent the “dance” of the agents amongst the different clusters of perception.



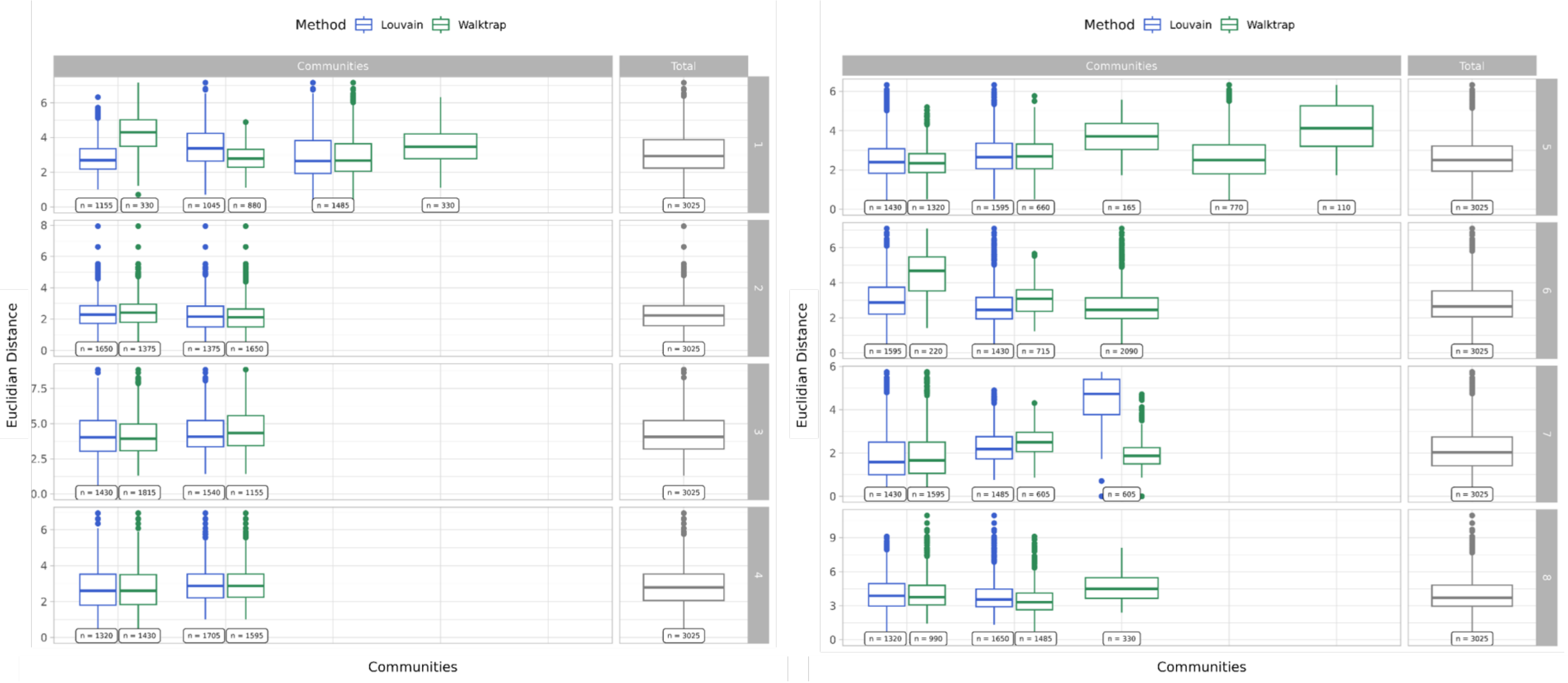
Source: Author.

Figure 25 - Sankey graph of the Walktrap algorithm concerning the different sectors of the questionnaire and the distribution of the agents' perception. Each set of bars represent a different sector, and its divisions concerns the clusters generated. The grey arrows represent the “dance” of the agents amongst the different clusters of perception.



Source: Author.

Figure 26 - Boxplots concerning the distance between nodes for each sector and each algorithm. Each box represents a cluster and *n* represents the quantity of data within each cluster.



Source: Author.

Given that it was observed that the Walktrap algorithm introduced redundant clusters, resulting in the emergence of isolated agents and limited data within the clusters. Consequently, our primary interest lies solely in examining the social networks constructed by the Louvain algorithm. Therefore, Figure *27* to Figure 34 illustrate the social networks as the result of this study. Certain stakeholders appear to have a higher degree of influence and it varies according to the sector of the questionnaire, as evidenced by their greater number of connections and greater centrality within the network. Clusters of respondents who share similar perspectives on the impacts of drought and potential solutions for water allocation were identified, suggesting that there may be commonalities in their experiences or backgrounds.

Figure 27 - Level of perceived impact on water uses.

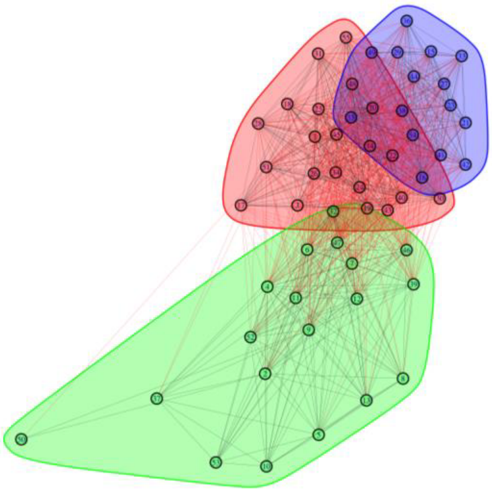


Figure 28 - Level of perceived impact on sanitation.

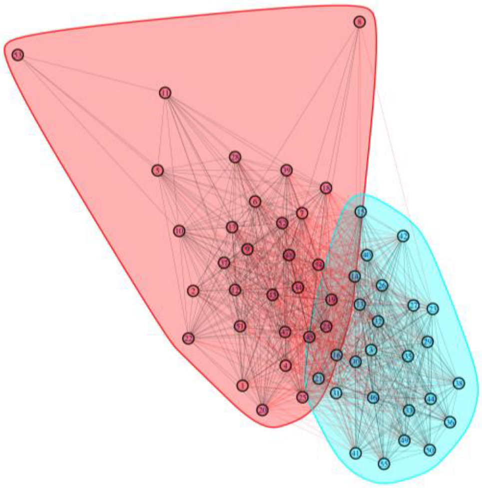


Figure 29 - Level of perceived impact on conflicts.

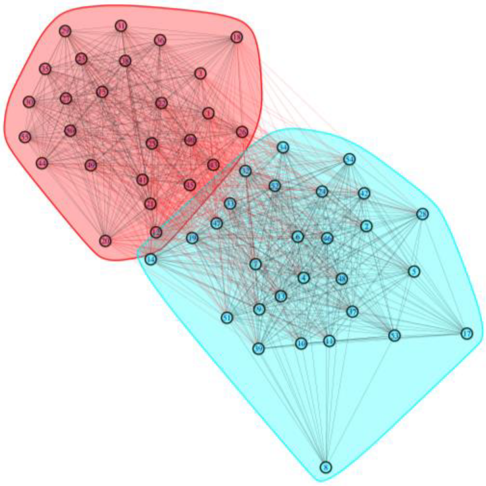


Figure 30 - Level of perceived impact on water availability.

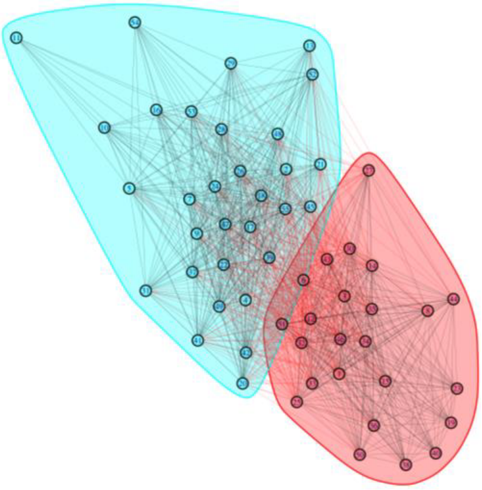


Figure 31 - Level of perceived impact on quality of life.

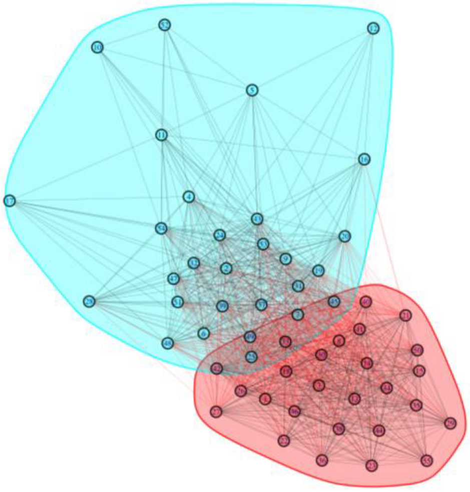


Figure 32 - Level of perceived impact on economy.

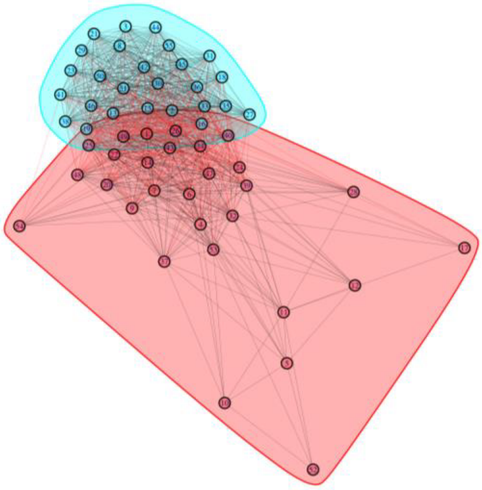


Figure 33 - Level of perceived impact on environment/recreational sectors.

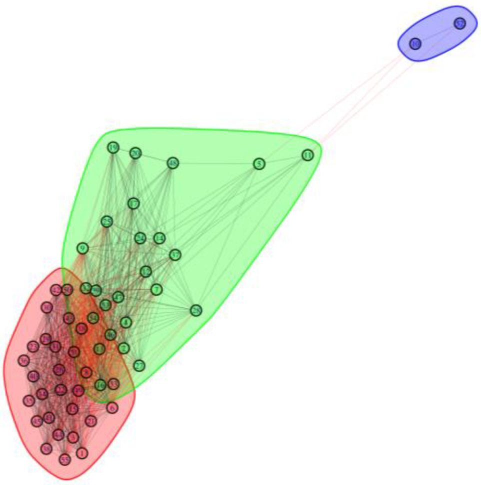
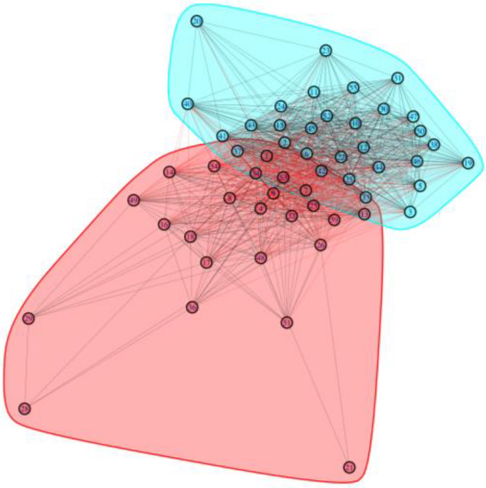


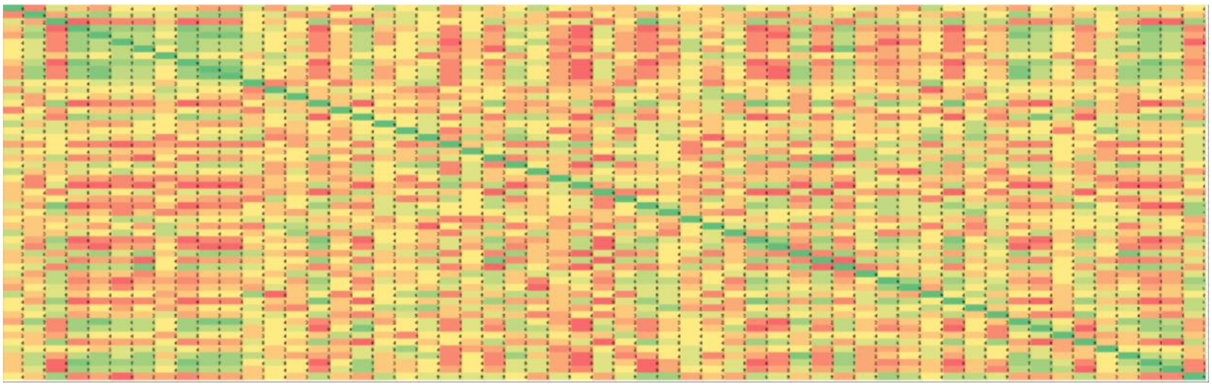
Figure 34 - Level of perceived impact on the actions to respond to the impacts.



Analyzing the networks, it is possible to conclude that the stakeholders do not present an “obvious” behavior, where they would group according to the tri-party arrangement predetermined through national legislation, which is the division between state and federal government, users, and organized civil society organizations.

Additionally, we decided to address a matrix of similarity for each sector between the stakeholders throughout the networks. Each matrix was built by analyzing if each stakeholders’ agent is in the same cluster of the other agents, assigning the value of 1 if yes (represented by darker green) and the value of 0 if it is not (represented by darker red). Figure 35 illustrates the result of summing up the matrixes of each sector. The higher frequency of warmest colors suggests that the stakeholders’ agents do not tend to stay in similar clusters throughout the different sectors, reinforcing the idea that their behavior is heterogeneous and diverge from what is expected according to the tri-party definition.

Figure 35 - Matrix of similarity between the stakeholders amongst all sectors' networks.



Source: Author.

The heterogeneity of the networks pointing to the direction of “unexpected” behavior of the stakeholders also enriches the discussion of how it could affect distinct aspects of participatory water resources planning and management, such as the occurrence of conflicts and the process of negotiation of water allocation. Stakeholders’ agents are humans with different interests, principles, and motivations. Unlike hydrological models, the human behavior might be hard to model and predict. Adding this challenge to a predefinition of classes (the tri-party legal definition), where it is assumed who each stakeholder represents and how they behave, it is necessary to shed light on this subject in order to comprehend unexpected and non-sectorized conflicts, as well as to elucidate and harmonize decisions regarding the participatory allocation process. Such understanding will reinforce the notion of adaptive and participatory governance, enhancing the perception of societal inclusiveness and decision-making, and rendering water resources management and planning more effective and robust.

6.6 Conclusion

The increasing global population and the challenges posed by climate change have led to a growing demand for water resources, straining the delicate balance of maintaining a steady water supply. Participatory methods and adaptive governance are crucial in improving the management of water resources, as they foster collaboration, knowledge sharing, and integration of scientific findings in decision-making processes. Integrated water resources management models, exemplified by Brazil's approach, involve stakeholder organizations that represent various societal interests at the river basin level. Effective social interactions, knowledge transfer, and participatory processes enhance adaptive capacity and resilience. Understanding stakeholder interests, behavior, and their effects on decision-making processes and conflicts is essential for successful water resources planning and management. Network analysis can aid in identifying interest groups, visualizing behavior patterns, and facilitating conflict mediation. By focusing on the collective behavior of interest groups, rather than individual actors, solutions can be developed to support negotiated water allocation and other aspects of water resources management.

This paper proposed the use of mechanisms and analysis to identify interest groups within stakeholders' social networks in order to understand behavior, conflicts, and facilitate mediation and management processes. The study focuses on the state of Ceará in Brazil, which has been experiencing a long-term drought since 2012. By considering the perceptions of stakeholders in river basin committees regarding the drought's impacts, the research aims to capture different viewpoints, identify behavior patterns, and interest groups. Social network analysis was employed to analyze clustering and stakeholders' identification with committee-imposed groupings. The goal was to assess how the behavior of these groups influences the process of negotiated water allocation and the emergence of conflicts, facilitating their mediation.

The method revolves around the generation of social networks and the definition of clusters through the optimization of modularity. Initially, we opted to use the *Louvain* algorithms instead of the *Walktrap* due to its sensitivity to generate surplus clusters that could impact the analysis of the results. Once the networks were generated, we were able to identify its heterogeneity and how it relates to the behavior of the stakeholders. The patterns differs to the classes imposed by the tri-party legal system used in Brazil, which may indicate that the stakeholders do not behave as they were "designated".

The outcomes of the heterogeneity and unexpected behavior of the stakeholders have the potential do affect the framework of the participatory process of management and planning of water resources, implying the occurrence of misunderstood conflicts and affecting the process of negotiated allocation of water. The stakeholders involved in water resource management are diverse individuals with their own unique interests, principles, and motivations. Unlike hydrological models that focus on natural processes, modeling and predicting human behavior can be challenging. Furthermore, the predefined classes based on a tri-party legal definition, which assume how each stakeholder should behave, may not capture the complexity of real-world dynamics. Therefore, it is crucial to gain a deeper understanding of this subject in order to grasp unexpected conflicts that transcend traditional sector boundaries. This understanding will also help in elucidating and reconciling decisions related to participatory allocation processes.

By shedding light on the complexities of human behavior and stakeholder dynamics, we can promote adaptive and participatory governance. This approach enhances the perception of inclusiveness in societal decision-making, making water resource management and planning more effective and resilient.

7 OVERALL DISCUSSION AND CONCLUSION

This dissertation discussed the complexity of water systems and the challenges of managing them in the face of increasing demand and uncertainty, particularly in the context of climate change. Drought events are a major concern and require proactive strategies to mitigate their impacts, such as risk assessment methods and typologies of risks. Fuzzy logic is a useful tool for handling incomplete and imprecise data in these complex systems. The participatory process in water resources planning and management is established in several nations, but vulnerability and risk analysis often remain one-sided.

To effectively manage water resources, an interdisciplinary approach is necessary, which has led to increasing interest in socio-hydrological methods. These methods aim to enhance the ability of communities to adapt and cope with water-related challenges by exploring the dynamics and co-evolution of water systems and human systems. The recognition of social aspects in water resources research is closely linked to the search for sustainable development, and effective water management requires understanding the interplay between water systems and human systems.

The iSECA model is a simple and accessible tool for quantifying vulnerability to drought caused by climate change, considering social, economic, and water management aspects. It was applied to the Brazilian states of Ceará and São Paulo, identifying vulnerable locations and areas with water infrastructure that can improve local and regional adaptive capacity. The model results are clear and easy to understand and can serve as an indispensable tool for water management and drought planning. The methodology does not require fieldwork or extensive financial costs and can be applied at different scales for the development of plans such as drought and water security management.

A typology of risks for water systems was developed through a collaborative process involving professionals with different experiences and expertise in water systems. The typology matrix classifies the types of structures of a water system against classes of risk to assist in risk assessment and decision-making. The typology is adaptable to different configurations of water systems and provides an important tool for water resource management, filling a gap in risk assessment for water resources.

Chapter five emphasizes that water security requires dependable infrastructure and a rigorous risk assessment process. A fuzzy logic model is proposed to evaluate integrated risks of water systems using fuzzy logic, which can handle qualitative information and quantify data. However, the data acquisition step is time-consuming and can exacerbate the lack of information, affecting the final results. To improve accuracy, the data acquisition process should be reviewed. Nonetheless, this approach can aid decision-making for water system management.

The method described through Chapter 6 focuses on generating social networks and defining clusters using modularity optimization. Louvain algorithms were chosen over Walktrap due to their sensitivity in generating excess clusters that could impact analysis. The generated networks revealed heterogeneity and unexpected behavior among stakeholders, which deviated from the predefined classes in Brazil's tri-party legal system. This suggests that stakeholders do not necessarily adhere to their designated roles. These findings have implications for the participatory process of managing and planning water resources, potentially leading to misunderstood conflicts and affecting negotiated water allocation. Understanding the complexities of stakeholder behavior and dynamics is crucial for addressing conflicts that go beyond traditional sector boundaries and promoting adaptive and participatory governance. This approach enhances inclusiveness in decision-making, improving the effectiveness and resilience of water resource management and planning.

Overall, this dissertation provides valuable tools, frameworks, and insightful discussions that contribute to the understanding and improvement of participatory processes in water resource planning and management. The research delves into the complexities of identifying, measuring and assessing vulnerability and risks concerning water systems. We discussed stakeholder dynamics, identifies unexpected behaviors, and proposes methods to optimize cluster formation in social networks. By shedding light on these issues, the dissertation enhances the ability to design and implement more effective and inclusive participatory governance in water resource management. The findings and recommendations presented in this study have the potential to inform and transform the way water resources are planned, managed, and allocated, leading to more resilient and sustainable outcomes.

REFERENCES

ARAÚJO, B.A.M. **Water allocation in Ceará**: diagnosis and challenges. Tese apresentada ao Programa de Pós-Graduação em Engenharia Civil, do Departamento de Engenharia Hidráulica e Ambiental, da Universidade Federal do Ceará, como requisito parcial à obtenção do título de Doutor em Engenharia Civil. Fortaleza-CE. 2012.

ABDO, H.; FLAUS, J. M. Uncertainty quantification in dynamic system risk assessment: a new approach with randomness and fuzzy theory. **International Journal of production research**, London, v. 54, n. 19, p. 5862-5885, mai. 2016. Disponível em: http://doi.org/10.1080/00207543.2016.1184348. Acesso em: 8 jan 2022.

ABRAHAM, J.S. **Assessing drought vulnerability**. Dissertation presented at the University of Arizona, as requisite to achieve the degree of Doctor in Civil Engineering. Tucson-AZ. 2006.

ACOSTA, I.R.; MARTÍNEZ, M.J.M. Assessment of surface runoff vulnerability to climate change in the Lerma-Chapala basin, Mexico. J. **Water Resour. Plann. Manage**., Reston, VA, v. 140, n. 12, p. 584-602, 2014.

ADGER, W.N. Vulnerability. **Global Environmental Change**, Elsevier, v. 16, p. 268-281, 2006. Disponível em: http://doi.org/10.1016/j.gloenvcha.2006.02.006. Acesso em: 8 jan 2022.

AMEYAW, E.E.; CHAN, A.P.C. A Fuzzy Approach for the Allocation of Risks inPublic–Private Partnership Water-Infrastructure Projects in Developing Countries. **J. Infrastruct. Syst**., Reston, VA, v. 22, n. 3, p. 4016-4035. 2016. Disponível em: http://doi.org/10.1061/(ASCE)IS.1943-555X.0000297. Acesso em: 15 set. 2021.

ANANDHI, A.; KANNAN, N. Vulnerability assessment of water resources – translating a theoretical concept to an operational framework using systems thinking approach in a changing climate: Case study in Ogallala Aquifer**. Journal of Hydrology,** Elsevier, v. 557, p. 460-474, 2018.

ANSELL, C.; GASH, A. Collaborative Governance in Theory and Practice. **J. Public Adm. Res. Theory**, v. 18, p. 543–571, 2008.

ASEFA, T.; CLAYTON, J.; ADAMS, A.; ANDERSON, D. Performance evaluation of a water resources system under varying climatic conditions: reliability, resilience, vulnerability and beyond. **Journal of Hydrology,** Elsevier, v. 508, p. 53-65. 2014.

AYDEMIR, A.; GUVEN, A. Modified risk assessment tool for embankment dams case study of three dams in Turkey. **Civil Eng. Env. Systems**, Reston, VA, v. 34, n. 1, 2017. Disponível em: http://doi.org/10.1080/10286608.2017.1300794. Acesso em: 17 ago. 2022.

BAKKER, K. Water: political, biopolitical, material. **Soc Stud Sci**, California, v. 42, p. 616–623, 2012.

BASURTO, X.; OSTROM, E. Beyond the Tragedy of the Common. Economia delle fonti di energia e dell'ambiente. v. 1, 2009 Fascicolo, pp. 1000–1026. Disponível em: http://doi.org/ 10.3280/EFE2009-001004. Acesso em: 17 ago. 2022.

BLONDEL, D.V.; GUILLAUME, J.L.; LAMBIOTTE, R.; LEFEBVRE, E. Fast unfolding of communities in large networks. **J. Stat. Mech.** 2008. Disponível em: http://doi.org/10.48550/arXiv.0803.0476. Acesso em: 02 fev. 2021.

BRASIL. Lei nº 9.433, de 8 de janeiro de 1997. Institui a Política Nacional de Recursos Hídricos, cria o Sistema Nacional de Gerenciamento de Recursos Hídricos, regulamenta o inciso XIX do art. 21 da Constituição Federal, e altera o art. 1º da Lei nº 8.001, de 13 de março de 1990, que modificou a Lei nº 7.990, de 28 de dezembro de 1989. Diário Oficial [da] República Federativa do Brasil, Brasília, DF, 8 jan. 1997. Disponível em <http://www.planalto.gov.br/ccivil_03/leis/L9433.htm>. Acesso em: 19 de setembro de 2021.

BOGARD, W.C. Bringing social theory to hazards research: conditions and consequences of the mitigation of environmental hazards. **Sociological Perspectives**, North America, v. 31, n. 2, p. 147–168, 1988.

BOHLE, H.G.; DOWNING, T.E.; WATTS, M.J. Climate change and social vulnerability. **Global Environmental Change,** London, v. 4, n. 1, p. 37–48, 1994.

BODIN, O.; CRONA, B. The role of social networks in natural resource governance: What relational patterns make a difference? **Glob. Environ. Chang.**, London, v. 19, p. 366–374, 2009.

BOENTE, A.N.P.; RIBEIRO, L.O.M.; DORIA, F.A.M.A.; COSENZA, C.A.N. A importância da intermodalidade/multimodalidade no transporte de cargas no brasil: uso da lógica fuzzy como ferramenta de aferição [The importance of the intermodality/multimodality on the transport of cargoes in Brazil: the use of fuzzy logic as an admeasurement tool]". In: **XVII Congresso Nacionais de Excelência e Gestão, Anais...**, 1-14. 2016.

BOURGET, E. (Org.) **Converging Waters**: Integrating Collaborative Modeling With Participatory Processes to Make Water Resources Decisions. 2011. IWR Maass-White Series, Institute for Water Resources, U.S. Army Corps of Engineers, Alexandria, Virginia.

BROOKS, D.J.; COOLE, M. Divergence of Safety and Security. In: Bieder, C., Pettersen Gould, K. (eds) **The Coupling of Safety and Security**. SpringerBriefs in Applied Sciences and Technology(). Springer, Cham. 2020. Disponível em: http://doi.org/10.1007/978-3-030-47229-0_7. Acesso em 05 mai. 2021.

CANTOS, W.P.; JURAN, I.; TINELLI, S. Machine-Learning–Based Risk Assessment Method for Leak Detection and Geolocation in a Water Distribution System. **J. Infrastruct. Syst.**, v. 26, n.1, 2020. Disponível em: http://doi.org/10.1061/(ASCE)IS.1943-555X.0000517. Acesso em 05 mai. 2021.

CAPELO NETO, J.; BRITO, C. R. F.; VIANA, A. G. **Plano de contingência e emergência**. Fortaleza: Universidade Federal do Ceará (UFC), 2014. 209 p. 1 CD-ROM.

CHANDA, K.; MAITY, R.; SHARMA, A.; MEHROTRA, R. Spatiotemporal variation of long-term drought propensity through reliability-resilience-vulnerability based Drought Management Index. **Water Reour. Res**., Reston-VA, v. 50, p. 7662-7676, 2014.

CHANG, S. E.; YIP, J. Z. K.; CONGER, T.; OULAHEN, G.; MARTELEIRA, M. Community vulnerability to coastal hazards: Developing a typology for disaster risk reduction. **Applied Geography**, v. 91, p. 81–88, 2018. Disponível em: http://doi.org/10.1016/j.apgeog.2017.12.017. Acesso em 05 mai. 2021.

CHANG, Y. T.; LEAHY, R.M.; PANTAZIS, D. Modularity-based graph partitioning using conditional expected models. **Physical Review E - Statistical, Nonlinear, and Soft Matter Physics**, [S. l.], v. 85, n. 1, p. 1–17, 2012. Disponível em: http://doi.org/10.1103/PhysRevE.85.016109. Acesso em 18 ago. 2021.

CHEN, L.; HUANG, K.; ZHOU, J.; DUAN, H.F.; ZHANG, J.; WANG, D.; QIU, H. Multiple-risk assessment of water supply, hydropower and environment nexus in the water resources system. **Journal of Cleaner Production**, JCLP 122057, 2019. Disponível em: http://doi.org/10.1016/j.jclepro.2020.122057. Acesso em 18 ago. 2021.

CHRISTENSEN, A. P.; GARRIDO, L. E.; GUERRA-PEÑA, K.; GOLINO, H. Comparing community detection algorithms in psychological data: A Monte Carlo simulation. **PsyArXiv**. 2020. Disponível em: http://doi.org/10.31234/osf.io/hz89e. Acesso em 05 mai. 2021.

CRONA, B.; BODIN, O. What You Know is Who You Know? Communication Patterns Among Resource Users as a Prerequisite for Co-management. **Ecol. Soc**., v. 11, n. 7, 2006.

CSARDI, G.; NEPUSZ, T. The igraph software package for complex network research. **InterJournal Complex Systems**, [S. l.], v. Complex Sy, n. 1695, p. 1695, 2006.

CODES, R.A. **Proposta Metodológica de Avaliação Integrada de Riscos na Infraestrutura de Sistemas Hídricos por Meio do Programa Risco-Fuzzy** – Estudo de Caso: Sistema de Aporte de Água Bruta para a Região Metropolitana de Fortaleza. Tese apresentada ao Programa de Pós-Graduação em Engenharia Civil, do Departamento de Engenharia Hidráulica e Ambiental, da Universidade Federal do Ceará, como requisito parcial à obtenção do título de Doutor em Engenharia Civil. Fortaleza-CE, 2016.

COGERH - COMPANHIA DE GESTÃO DOS RECURSOS HÍDRICOS. **Canal do Trabalhador e sua Função Social ao longo de seus 102 km**. Fortaleza, Ceará. 2009. Disponível em: <https://portal.cogerh.com.br/canal-do-trabalhador/>. Acesso em 05 mai. 2021.

CONNICK, S.; INNES, J.E. Outcomes of Collaborative Water Policy Making: Applying Complexity Thinking to Evaluation. **J. Environ. Plan. Manag**., Reston-VA, v. 46, p. 177–197, 2003.

COSGROVE, W.J.; LOUCKS, D.P. Water management: current and future challenges and research directions. **Water Resources Research**., Reston-VA, v. 51, p. 4823-4839, 2015.

CRH – Water Resources State Council/ CORHI – **Water Resources State Plan Committee** (2017) São Paulo Water Resources State Plan 2016-2019, São Paulo.

CUTTER, S.L. Vulnerability to environmental hazards. **Progress in Human Geography**, v. 20, n. 4, p. 529-539, 1996.

DE CASTRO, D. B.; SAMPAIO, V. S.; DE ALBUQUERQUE, B. C.; PINTO, R. C.; SADAHIRO, M.; DOS PASSOS, R. A.; BRAGA, J. U. Dengue epidemic typology and risk factors for extensive epidemic in Amazonas state, Brazil, 2010-2011. **BMC Public Health**, v. 18, n. 1, p. 1–10, 2018. Disponível em: http://doi.org/10.1186/s12889-018-5251-x. Acesso em 22 set, 2022.

DESMOND, N.; ALLEN, C. F.; CLIFT, S.; JUSTINE, B.; MZUGU, J.; PLUMMER, M. L.; ROSS, D. A. A typology of groups at risk of HIV/STI in a gold mining town in north-western Tanzania. **Social Science and Medicine**, v. 60, n. 8, p. 1739–1749, 2005. Disponível em: http://doi.org/10.1016/j.socscimed.2004.08.027. Acesso em 22 set, 2022.

DISTEFANO, C.; KAMPHAUS, R.; HORNE, A.; WINSOR, A. Behavioral adjustment in the U.S. elementary school: cross-validation of a person-oriented typology of risk. **Journal of Psychoeducational Assessment**, v. 21, p. 338–357, 2003. Disponível em: http://doi.org/10.1177/073428290302100403. Acesso em 22 set, 2022.

DOHRENWEND, B. P. Toward a typology of high-risk major stressful events and situations in posttraumatic stress disorder and related psychopathology. **Psychological Injury and Law**, v. 3, n. 2, p. 89–99, 2010. Disponível em: http://doi.org/10.1007/s12207-010-9072-1. Acesso em 22 set, 2022.

DOW, K. Exploring differences in our common future(s): the meaning of vulnerability to global environmental change**. Geoforum,** Vienna, v. 23, n. 3, p. 417–436, 1992.

EMERSON, K.; NABATCHI, T.; BALOGH, S. An Integrative Framework for Collaborative Governance. **J. Public Adm. Res. Theory**, Amsterdam, v. 22, p. 1–29, 2012.

ENGLE, N.L. Adaptive capacity and its assessment. **Glob Environ Chang**, London, v. 21, n. 2, p. 647–656, 2011. Disponível em: http://doi.org/10.1016/j.gloenvcha.2011.01.019. Acesso em 22 set, 2022.

ENGLE, N.L.; LEMOS, M.C. Unpacking governance: building adaptive capacity to climate change of river basins in Brazil. **Glob Environ Chang**, London, v. 20, n. 1, p. 4–13, 2010. Disponível em: http://doi.org/10.1016/j.gloenvcha.2009.07.001. Acesso em 07 set., 2020.

ESLAMIAN, S.; ESLAMIAN, F.A. **Handbook of Drought and Water Scarcity**: Principles of Drought and Water Scarcity, Taylor & Francis Group, 2017.

FERRARI, M. **Cantareira atinge pior nível desde fim da crise hídrica em SP e acende alerta**. CNN Brasil, Caderno Nacional. 2020. Disponível em: <https://www.cnnbrasil.com.br/nacional/cantareira-atinge-pior-nivel-desde-fim-da-crise-hidrica-em-sp-e-acende-alerta/>. Acesso em 20 de novembro de 2021.

FLIERVOET, J.M.; GEERLING, G.W.; MOSTERT, E.; SMITS, A.J.M. Analyzing Collaborative Governance Through Social Network Analysis: A Case Study of

RiverManagement Along theWaal River in The Netherlands. **Environ.Manag.,** Amsterdan, v. 57, p. 355–367, 2016.

FLIERVOET, J.M.; VAN DEN BORN, R.J.; MEIJERINK, S.V. A stakeholder's evaluation of collaborative processes for maintaining multi-functional floodplains: A Dutch case study. **Int. J. River Basin Manag**, Amsterdan, v. 15, p. 175–186, 2017.

FONTAINE, M.M. **Assessing vulnerability to natural hazards**: an impact-based method and application to drought in Washington State. Dissertation presented at the University of Washington, as requisite to achieve the degree of Doctor in Civil Engineering. pp. 165. 2007.

FOLKE, C.; CARPENTER, S.; WALKER, B.; SCHEFFER, M.; ELMQVIST, T.; GUNDERSON, L.; HOLLING, C.S. Regime shifts, resilience, and biodiversity in ecosystem management. **Annu. Rev. Evol. Syst**., v. 35, p. 557-581, 2004. Disponível em: http://doi.org/10.1146/annurev.ecolsys.35.021103.105711. Acesso em 07 set., 2020.

GAD, A.A.M.; ABD-ELAAL, A.E.M. Practical guidelines for a reliability-based design of building water supply systems, **Urban Water Journal**, v. 13, n. 2, p. 94-107, 2016. Disponível em: http://doi.org/10.1080/1573062X.2014.993995. Acesso em 07 set., 2020.

GALIANA-MARTIN, L.; HERRERO, G.; SOLANA, J. A wildland-urban interface typology for forest fire risk management in mediterranean areas. **Landscape Research**, v. 36, n. 2, p. 151–171, 2011. Disponível em: http://doi.org/10.1080/01426397.2010.549218. Acesso em 07 set., 2020.

GALLOPÍN, G.C. Linkages between vulnerability, resilience, and adaptive capacity. **Global Environmental Change**, v. 16, p. 293-303, 2006. Disponível em: http://doi.org/10.1016/j.gloenvcha.2006.02.004. Acesso: 02 mai. 2021.

GAN, G.; MA, C.; WU, J. Data Clustering: Theory, Algorithms, and Applications. **ASA-SIAM Series on Statistics and AppliedProbability**, SIAM, Philadelphia, ASA, Alexandria, VA, 2007. Disponível em: http://doi.org/10.1137/1.9780898718348. Acesso em 07 set., 2020.

GANOULIS, J. **Risk analysis of water pollution**. Wiley-VCH, Weinheim, Germany. 2nd ed. 320p. 2009.

GLESNER, C.; GEYSMANS, R.; TURCANU, C. Two sides of the same coin? Exploring the relation between safety and security in high-risk organizations, **Journal of Safety Research**, v. 82, 2022, p. 184-193. Disponível em: http://doi.org/10.1016/j.jsr.2022.05.010. Acesso em 07 set., 2020.

GLEICK, P.H., HEBERGER, M. Water Conflict Chronology. In: **The World's Water.** Island Press/Center for Resource Economics, Washington, DC, pp. 173–219. 2014. Disponível em: http://doi.org/10.5822/978-1-61091-483-3_11. Acesso: 02 mai. 2022.

GOHARIAN, E.; BURIAN, S.J.; BARDSLEY, T.; STRONG, C. Incorporating potential severity into vulnerability assessment of water supply systems under climate change conditions. **J. Water Resour. Plann. Manage**., Raston-VA, v. 142, n. 2, 2016.

GOMES, V. U. **Aplicação da teoria fuzzy em um modelo bidimensional de transporte de massa, para estudar o risco fuzzy em rios urbanos, sujeitos a lançamentos de agentes poluentes** [Application of diffuse theory in a two-dimensional mass transport model to study diffuse risk in urban rivers subject to releases of polluting agents]. 2011. Dissertation. Universidade Federal do Ceará, Fortaleza, Brazil, 2011.

GREY, D.; SADOFF, C.W. Sink or swim? Water security for growth and development. **WaterPolicy,** v. 9, n. 6, p. 545–571, 2007. Disponível em: http://doi.org/10.2166/wp.2007.021. Acesso em 22 ago. 2022.

GUO, Y.; DONG, S.; HAO, Y.; LIU, Z.; YEH, T.C.J.; WANG, W.; YAOQUAN GAO, Y.; LI, P.; ZHANG, M. Risk Assessments of Water Inrush from Coal Seam Floor during Deep Mining Using a Data Fusion Approach Based on Grey System Theory. **Complexity.** Volume 2020, Article ID 8205370, 12 pages. Disponível em: http://doi.org/10.1155/2020/8205370. Acesso em 22 ago. 2022.

HAGEN, E. New Approaches in the Potomac River Basin and Beyond – Pioneering Work in the Development of Shared Vision Planning. In: **Converging Waters**: Integrating Collaborative Modeling With Participatory Processes to Make Water Resources Decisions. IWR Maass-White Series, E. Bourget (Org.) Institute for Water Resources, U.S. Army Corps of Engineers, Alexandria, Virginia, pp. 35-58. 2011.

HAGHSHENAS, S. S.; LASHTEH, M. A.; POURKAZEN, P. The Risk Assessment of Dam Construction Projects Using Fuzzy TOPSIS (Case Study: Alavian Earth Dam). **Civil Engineering Journal**, Raston-VA, v. 2, N. 4, 2016. Disponível em: http://doi.org/10.28991/cej-2016-00000022. Acesso em: 13 jun. 2021.

HALVERSON, M. J.; FLEMING, S. W. Complex network theory, streamflow, and hydrometric monitoring system design. **Hydrology and Earth System Sciences**, [S. l.], v. 19, n. 7, p. 3301–3318, 2015. Disponível em: http://doi.org/10.5194/hess-19-3301-2015. Acesso em: 13 jun. 2021.

HAMILTON, N.E.; FERRY, M. ggtern: Ternary Diagrams Using ggplot2. **Journal of Statistical Software,** v. 87, n. 3, p. 1-17, 2018.

HARRINGTON, C. The political ontology of collaborative water governance. **Water Int.**, v. 42, p. 254–270, 2017.

HASHIMOTO, T.; STEDINGER, J. R.; LOUCKS, D. P. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. **Water Resources Research**, v. 18, n. 1, p. 14–20, 1982. Disponível em: http://doi.org/10.1029/wr018i001p00014. Acesso em: 13 jun. 2021.

HEWITT, K. Environmental disasters in social context: Toward a preventive and precautionary approach. **Natural Hazards**, v. 66, n. 1, p. 3–14, 2013.

HOLLEY, C. Crafting Collaborative Governance: Water Resources, California's Delta Plan, and Audited Self-Management in New Zealand. **Environ. Law Rep. News Anal.**, v. 45, p. 1–14, 2015.

HOLLING, C.S. Resilience and stability of ecological systems. **A. Rev. Ecol. Systems**, v. 4, p. 1-23, 1973.

HÜLLE, J.; KASPAR, R.; MÖLLER, K. Multiple criteria decision-making in management accounting and control –State of the art and research perspectives based on a bibliometric study. **Journal of Multi-Criteria Decision Analysis**, v. 8, p. 253–265, 2011.

HUNTER, A. Attitudes, Risk Behavior, and Noise Exposure among Young Adults with Hearing Problems: Identifying a Typology. **Seminars in Hearing**, v. 38, n. 4, p. 332–347, 2017. Disponível em: http://doi.org/10.1055/s-0037-1606327. Acesso em 12 ju. 2022.

INESP – Institute of Studies and Research for the Development of the State of Ceará. **Water Pact**: Current Scenario of Water Resources in Ceará. 2008. Fortaleza, Brazil.

IPCC (Intergovernmental Panel on Climate Change). **Climate change 2001**: impacts, adaptation, and vulnerability. Contribution of working group II to the third assessment report of the intergovernmental panel on climate change. 2001 Cambridge University Press, Cambridge

IPECE – Instute of Economic Research and Strategy of Ceará. **Municipal Alert Index**: IMA. 2016. Fortaleza, Brazil.

IRGC - International Risk Governance Council. **Introduction to the IRGC Risk Governance Framework, revised version**. Lausanne: EPFL International Risk Governance Center. 2017. Disponível em: https://irgc.org/risk-governance/irgc-risk-governance-framework/. Acesso em: 04 fev. 2021.

ISHIZAKA, A.; SIRAJ, S. Are multi-criteria decision-making tools useful? An experimental comparative study of three methods. **European Journal of Operational Research**, v. 264, p. 462-471, 2018.

ISLAM, M. S.; NEPAL, M. A Fuzzy-Bayesian Model for Risk Assessment in Power Plant Projects. **Procedia Computer Science**, v. 100, n. 1, 2016. Disponível em: http://doi.org/10.1016/j.procs.2016.09.259. Acesso em 14 jul. 2022.

JACOBI, P.R.; CABIM, J.; LEÃO, R.S. Water crisis at Paulista Macrometropolis and civil society answers. **Estudos Avançados**, v. 29, n. 84, p. 27-42, 2015.

JANG, Y.; PARK, N. S.; YOON, H.; HUANG, Y. C.; RHEE, M. K.; CHIRIBOGA, D. A.; KIM, M. T. The risk typology of healthcare access and its association with unmet healthcare needs in Asian Americans. **Health and Social Care in the Community**, v. 26, n. 1, p. 72–79, 2018. Disponível em: http://doi.org/10.1111/hsc.12463. Acesso em 14 jul. 2022.

JOHANSSON, A.; DENK, T.; SVEDUNG, I. The typology for allocations of societal risk and safety management tasks at the local governmental level – Framing the current directions in Sweden. **Safety Science**, v. 47, p. 680–685, 2009. Disponível em: http://doi.org/10.1016/j.ssci.2008.09.008. Acesso em 14 jul. 2022.

JORE, S.H. The Conceptual and Scientific Demarcation of Security in Contrast to Safety. **Eur J Secur Res, v.** 4, p. 157-174, 2019. Disponível em: http://doi.org/10.1007/s41125-017-0021-9. Acesso em 14 jul. 2022.

JOZAEI, J.; MITCHELL, M.; CLEMENT, S. Using a resilience thinking approach to improve coastal governance responses to complexity and uncertainty: a Tasmanian case study, Australia, **Journal of Environmental Management**, v. 253, 2020. Disponível em: http://doi.org/10.1016/j.jenvman.2019.109662. Acesso em 14 jul. 2022.

KAINER, K.A.; DIGIANO, M.L.; DUCHELLE, A.E.; WADT, L.H.O.; BRUNA, E.; DAIN, J.L. Partnering for greater success: local stakeholders and research in tropical biology and conservation. **Biotropica**. v. 41, n.5, p. 555–562, 2009. Disponível em: http://doi.org/10.1111/j.1744-7429.2009.00560.x. Acesso em 11 mai. 2021.

KAPLAN S, GARRICK B. On the quantitative definition of risk. **Risk Analysis**, v. 1, p. 11-27, 1981. Disponível em: http://doi.org/10.1111/j.1539-6924.1981.tb01350.x. Acesso em 14 jul. 2022.

KARIMPOUR, K.; ZARGHAMI, R.; MOOSAVIAN, M.A.; BAHMANYAR, H. New Fuzzy Model for Risk Assessment Based on Different Types of Consequences. **Rev. IFP Energies nouvelles**, v. 71, n. 17, 2016. Disponível em: http://doi.org/10.2516/ogst/2014044. Acesso em 11 mai. 2021.

KAUFMANN, A.; GUPTA, M. M. **Fuzzy mathematical models in engineering and management science**. Amsterdam: Elsevier Science Publishers B. 1988.

KÄYHKÖ, J. Climate risk perceptions and adaptation decision-making at Nordic farm scale– a typology of risk responses. **International Journal of Agricultural Sustainability**, v. 17, n. 6, p. 431–444, 2019. Disponível em: http://doi.org/10.1080/14735903.2019.1689062. Acesso em 11 mai. 2021.

KIM, K., SWAIN, A. Crime, Corruption, Terrorism and Beyond: A Typology of Water Crime. **Springer, Cham**, pp. 95–111, 2017. Disponível em: http://doi.org/10.1007/978-3-319-50161-1_5. Acesso em 11 mai. 2021.

KIM, Y.; CHUNG, E.S. Assessing climate change vulnerability with group multi-criteria decision making approaches, **Climatic Change,** v. 121, p. 301–315, 2013.

KREUGER, T.; MAYNARD, C.; CARR, G.; BRUNS, A.; MUELLER, E.N.; LANE, S.N. A transdisciplinary account of water research. **Wiley Interdiscip Rev Water,** v. 3, p. 369–389, 2016.

KUMLU, K.B.Y.; TUDES, S. Determination of earthquake-risky areas in Yalova City Center (Marmara region, Turkey) using GIS-based multicriteria decision-making techniques (analytical hierarchy process and technique for order preference by similarity to ideal solution), **Natural Hazards**, v. 96, p. 999–1018, 2019.

LANGSDALE, S.; BEALL, A.; BOURGET, E.; HAGEN, E.; KUDLAS, S.; PALMER, R.; TATE, D.; WERICK, W. Collaborative modeling for decision support in water resources:

Principles and best practices. **Journal of the American Water Resources Association**, California, v. 49, n. 3, p. 630-638, 2013.

LARSON, S.; ALEXANDER, K.S.; DJALANTE, R.; KIRONO, D.G.C. The Added Value of Understanding Informal Social Networks in an Adaptive Capacity Assessment: Explorations of an Urban Water Management System in Indonesia. **Water Resour. Manag**., London, v. 27, p. 4425–4441, 2013.

LEE, M.; MCBEAN, E.A.; GHAZALI, M.; SCHUSTER, C.J.; HUANG, J.J.; Fuzzy-Logic Modeling of Risk Assessment for a Small Drinking-Water Supply System, **J. Water Resour. Plann. Manage.**, Raston-VA, v. 135, n. 6, p. 547-552, p. 2009. Disponível em: http://doi.org/10.1061/(ASCE)0733-9496(2009)135:6(547). Acesso em 21 out. 2022.

LEMOS, M.C.; LO, Y.J.; NELSON, D.R.; EAKIN, H.; BEDRAN-MARTINS, A.M. Linking Development to Climate Adaptation: Leveraging Generic and Specific Capacities to Reduce Vulnerability to Drought in NE Brazil. **Global environmental change**, London, v. 170, n. 39, 2016.

LEMOS, M.C.; PUGA, B.P.; FORMIGA-JOHNSSON, R.M.; SEIGERMAN, C.K. Building on adaptive capacity to extreme events in Brazil: water reform, participation, and climate information across four river basins. **Regional Environmental Change**, London, v. 20, n. 53, 2020. Disponível em: http://doi.org/10.1007/s10113-020-01636-3. Acesso em 21 out. 2022.

LEVESON, N.G. **Engineering a safer world: Systems thingking applied to safety**. The MIT Press, Massachusetts, 555p. 2011.

LIVERMAN, D.M. The vulnerability of urban areas to technological risks: An overview of US and European experience. **Cities**, v. 3, n. 2, p. 142–147, 1986. Disponível em: http://doi.org/10.1016/0264-2751(86)90053-3. Acesso em 21 out. 2022.

LIN, L.; WU, Z.; LIANG, Q. Urban flood susceptibility analysis using a GIS-based multi-criteria analysis framework, **Natural Hazards**, v. 97, p. 455–475. 2019.

LUO, Q.; BEI, E.; LIU, C.; DENG, Y.L.; MIAO, Y.; QIU, Y.; LU, W.Q.; CHEN, C.; ZENG, Q. Spatial, temporal variability and carcinogenic health risk assessment of nitrosamines in a drinking water system in China. **Science of the Total Environment**, v. 736, 2020. Disponível em: http://doi.org/10.1016/j.scitotenv.2020.139695. Acesso em 16 jul. 2021.

LIU, X.; WANG, Y.; PENG, J.; BRAIMOH, A.; YIN, H. Assessing vulnerability to drought based on exposure, sensitivity and adaptive capacity: a case study in middle Inner Mongolia of China. **Chin Geogr Sci**, China, v. 23, n. 1, p. 13–25, 2013.

MALAR, J.P. **Brasil, Europa e China têm crises energéticas com causas diferentes**; entenda. CNN Brasil, Caderno Business. 2021. Disponível em: <https://www.cnnbrasil.com.br/business/brasil-europa-e-china-tem-crises-energeticas-com-causas-diferentes-entenda/>. Acesso em 20 de novembro de 2021.

MANNING, L., BIRCHMORE, I., & MORRIS, W. Swans and elephants: A typology to capture the challenges of food supply chain risk assessment. **Trends in Food Science and**

Technology, v. 106, p. 288–297, set. 2020. Disponível em: http://doi.org/10.1016/j.tifs.2020.10.007. Acesso em 11 ago. 2022.

MARENGO, J.A., TORRES, R.R., ALVES, L.M. Drought in Northeast Brazil—past, present, and future. **Theor. Appl. Climatol**, v. 129, p. 1189–1200, 2017. Disponível em: http://doi.org/10.1007/s00704-016-1840-8. Acesso em 11 ago. 2022.

MARTINS, L.F.; STUDART, T.M.C.; PONTES FILHO, J.D.; PORTO, V.C.; SOUZA FILHO, F.A.; COSTA, F.R.S. Flash Flood Reconstruction and Analysis—A Case Study Using Social Data. **Climate,** v. 11, n. 20, 2023. Disponível em: http://doi.org/10.3390/cli11010020. Acesso em 18 jul. 2023.

MARTIRANI, L.A.; PERES, I.K. Water crisis in São Paulo: News coverage, public reception and the right to information. **Ambiente & Sociedade**, v. 19, n. 1, p. 1-20, 2016.

MATEUS, M.C.; TULLOS, D. Reliability, Sensitivity, and Vulnerability of reservoir operations under climate change. **J. Water Resour. Plann. Manage**., v. 143, n. 4, 2017.

MCCRODDEN, B. Reflections of Computer-Aided Dispute Resolution (CADRe) on the Roanoke. In: **Converging Waters**: Integrating Collaborative Modeling with Participatory Processes to Make Water Resources Decisions. IWR Maass-White Series, E. Bourget (Org.) Institute for Water Resources, U.S. Army Corps of Engineers, Alexandria, Virginia, pp. 35-58. 2011.

MEDEMA, W.; MCINTOSH, B.S.; JEFFREY, P.J. From premise to practice: a critical assessment of integrated water resources management and adaptive management approaches in the water sector**. Ecol Soc**, v. 13, n. 2, p. 29. 2008.

MELA, K.; TIAINEN, T.; HEINISUO, M. Comparative study of multiple criteria decision-making methods for building design. **Advanced Engineering Informatics**, v. 26, p. 716-726. 2012.

MONTANARI A, YOUNG G, SAVENIJE HHG, HUGHES D, WAGENER T, REN LL, KOUTSOYIANNIS D, CUDENNEC C, TOTH E, GRIMALDI S, BLÖSCHL G, SIVAPALAN M, BEVEN K, GUPTA H, HIPSEY M, SCHAEFLI B, ARHEIMER B, BOEGH E, SCHYMANSKI SJ, DE BALDASSARRE G, YU B, HUBERT P, HUANG Y, SCHUMANN A, POST DA, SRINIVASAN V, HARMAN C, THOMPSON S, ROGGER M, VIGLIONE A, MCMILLAN H, CHARACKLIS G, PANG Z, BELYAEV V. Panta Rhei – Everything flows: Change in hydrology and society – the IAHS scientific decade 2013-2022. **Hydrological Sciences Journal**, v. 58, n. 6, p. 1256-1275, 2013.

MORAES, A.F.J.; ROCHA, C. Gendered waters: the participation of women in the 'One Million Cisterns' rainwater harvesting program in the Brazilian Semi-Arid region, **Journal of Cleaner Production**, v. 60, p. 163-169, 2013. Disponível em: http://doi.org/10.1016/j.jclepro.2013.03.015. Acesso em 18 jul. 2023.

MOSTAFAZADEH, R.; SADODDIN, A.; BAHREMAND, A.; SHEIKH, V.B.; GARIZI, A.Z. Scenario analysis of flood control structures using a multi-criteria decision-making technique in Northeast Iran, **Nat Hazards**, v. 87, p. 1827–1846, 2017.

MOUSA, K. A.; CROOCK, M. S.; ABDULLAH, M. N. Fuzzy based Decision Support Model for Irrigation System Management. **International Journal of Computer Applications**, v. 14, n. 9, 2014. Disponível em: http://doi.org/10.5120/18230-9177. Acesso em 18 mai. 2020.

MU, M.; ZANG, Z.; CAI, X.; TANG, Q. Seasonal risk assessment of water-electricity nexus systems under water consumption policy constraint. **Environ. Sci. Technol.,** 2020. Disponível em: http://doi.org/10.1021/acs.est.0c00171. Acesso em 18 mai. 2020.

MUNHOZ, F. **Seis anos após crise hídrica, represas de SP estão com nível elevado de água**; Folha de São Paulo, Caderno Agora. 2020. Disponível em: https://agora.folha.uol.com.br/sao-paulo/2020/02/seis-anos-apos-crise-hidrica-represas-de-sp-estao-com-nivel-elevado-de-agua.shtml. Acesso em 20 de novembro de 2021.

NASIRI, F.; MAQSOOD, I.; HUANG, G.; FULLER, N. Water Quality Index: A Fuzzy River-Pollution DecisionSupport Expert System, **J. Water Resour. Plann. Manage**., Raston-VAN, v. 133, n. 2, p. 95-105, 2007. Disponível em: http://doi.org/10.1061/(ASCE)0733-9496(2007)133:2(95). Acesso em 20 nov. 2021.

NATIONAL RESEARCH COUNCIL (NRC): Committee on the Institutional Means for Assessment of Risks to Public Health. **Risk Assessment in the Federal Government**: Managing the Process. Washington (DC): National Academies Press (US). 1983.

NATIONAL RESEARCH COUNCIL (NRC): Committee on Improving Risk Analysis Approaches Used by the U.S. EPA. **Science and Decisions**: Advancing Risk Assessment. Washington (DC): National Academies Press (US). 2009.

NAZEMI, A.; WHEATER, H.S.; CHUN, K.P.; ELSHORBAGY, A. A stochastic reconstruction framework for analysis of water resource system vulnerability to climate-induced changes in river flow regime. **Water Resources Research**, California, v. 49, p.291-305, 2013.

NELSON, D.R.; FINAN, T.J. Praying for Drought: Persistent Vulnerability and the Politics of Patronage in Ceará, Northeast Brazil. **American Anthropologist**, Athens, v. 111, n. 3, p. 302. 2009.

NGUYEN, D.C.H.; NGUYEN, D.C.; LUU, T.T.; LE, T.C.; KUMAR, P.; DASGUPTA, R.; NGUYEN, H.Q. Enhancing Water Supply Resilience in a Tropical Island via a Socio-Hydrological Approach: A Case Study in Con Dao Island, Vietnam. **Water**, v. 13, p. 2573, 2021. Disponível em: http://doi.org/10.3390/w13182573. Acesso em 20 nov. 2021.

NOGUEIRA, D.; MESQUITA, P.; CAVALCANTE, L.; RODRIGUES FILHO, S.; SAITO, C. Rainwater Harvesting as a Strategy for Adapting to Climate Change and Building Women's Autonomy in Brazilian Semiarid. **Géneros**, v. 11, n. 1, 2022. Disponível em: http://doi.org/10.17583/generos.6673. Acesso em 20 nov. 2022.

OGADA, J.O.; KRHODA, G.O.; VEEN, A.V.D.; MARANI, M.; VAN OEL, P.R. Managing resources through stakeholder networks: Collaborative water governance for Lake Naivasha basin, Kenya. **Water Int.,** v. 42, p. 271–290, 2017.

OSTROM, E.; JANSSEN, M.A.; ANDERIES, J.M. Going beyond panaceas. **PNAS**, v. 104, n.39, p. 15176-15178, 2007. Disponível em: http://doi.org/10.1073/pnas.0701886104. Acesso em 20 nov. 2022.

OSTROM, L.T., WILHELMSEN, C.A. **Risk Assessment**: Tools, techniques, and their applications. 2012. Wiley, New Jersey.

OZERNOY, V. A framework for choosing the most appropriate discrete alternative multiple criteria decision-making method in decision support systems and expert systems. **Lecture Notes in Economics and Mathematical Systems**, p. 56–64. 1987.

PALMER, RN.; CARDWELL, HE.; LORIE, M.; WERICK, W. Disciplined planning, structured participation, and collaborative modeling – applying shared vision planning to water resources. **Journal of the American Water Resources Association**, v. 49, n. 3, p. 630-638, 2013.

PARTELOW, S. A review of the social-ecological systems framework: applications, methods, modifications, and challenges. **Ecology and Society**, v. 23, n. 4, p. 36. Disponível em: http://doi.org/10.5751/ES-10594-230436. Acesso em 20 ago. 2022.

PEACOCK, A.; DEGENHARDT, L.; LINTZERIS, N.; LARANCE, B.; CAMPBELL, G.; NIELSEN, S.; BRUNO, R. Opioid therapy for chronic non-cancer pain: Does typology of risk predict aberrant behaviour? **Drug and Alcohol Dependence**, v. 156, p. 173–174, 2015. Disponível em: http://doi.org/10.1016/j.drugalcdep.2015.07.471. Acesso em 20 ago. 2022.

PICARD, R.G. A Typology of Risk in Family Media Enterprises, **Journal of Media Business Studies**, 1:1, 71-83, 2004. Disponível em: http://doi.org/10.1080/16522354.2004.11073421. Acesso em 20 ago. 2022.

PIENAAR, G.W.; HUGHES, D.A. Linking hydrological uncertainty with equitable allocation for water resources decision-making. **Water Resour Manage,** California, v. 31, p. 269-282, 2017.

PRELL, C.; HUBACEK, K.; REED, M. Stakeholder Analysis and Social Network Analysis in Natural Resource Management. **Soc. Nat. Resour.**, v. 22, p. 501–518, 2009.

PRELL, C.; REED, M.; RACIN, L.; HUBACEK, K. Competing structure, competing views: The role of formal and informal structures in shaping stakeholder perceptions. **Ecol. Soc.**, v. 15, n. 34, 2010

PRYSHLAK, T.T.; SAWYER, A.H.; STONEDAHL, S.H.; SOLTANIAN, M.R.; AL, R.E.T. Water demand management in times of drought: What matters for water conservation. **Water Resources Research**, California, v. 51, p. 125-139, 2014.

RAMOS, P.A.; MARCATO JUNIOR, J.; DECANINI, M.M.S.; PUGLIESI, E.A.; OLIVEIRA, R.F.; PARANHOS FILHO, A.C. Quantitative and qualitative evaluation of data classification methods for choropleth mapping. **Revista Brasileira de Cartografia**, v. 68, n. 3, p. 609-629, 2016.

RAE, A.; MCDERMID, J.; ALEXANDER, R. In **Proceedings of PSAM 11 and ESREL 2012**, 2012, 2292-2301.

REED, D. In search of a mission. In: Reed D. (ed) **Water, security and U.S. foreign policy**. WWF and Routledge, New York, p. 3–34, 2017.

REIS, G.A., DE SOUZA FILHO, F.A., NELSON, D.R., ROCHA, R.V., SILVA, S.M.O. Development of a drought vulnerability index using MCDM and GIS: study case in São Paulo and Ceará, Brazil. **Nat Hazards**, v. 104, p. 1781–1799, 2020. Disponível em: http://doi.org/10.1007/s11069-020-04247-7. Acesso em 20 ago. 2022.

ROCHA, R.V. **Bayesian Networks and Network Science Applied to Water Resources**: Streamflow Analysis and Forecast Incorporating the Non-Stationarity. Dissertation, Federal University of Ceará. 2021.

ROJAS, R.; BENNISON, G.; GÁLVEZ, V.; CLARO, E.; CASTELBLANCO, G. Advancing Collaborative Water Governance: Unravelling Stakeholders' Relationships and Influences in Contentious River Basins. **Water**, v. 12, p. 3316, 2020.

ROUBICEK, M. **Como a crise elétrica ameaça a retomada da economia. Nexo Jornal. Caderno Expresso**. 2020. Disponível em: https://www.nexojornal.com.br/expresso/2021/08/29/Como-a-crise-el%C3%A9trica-amea%C3%A7a-a-retomada-da-economia. Acesso em 20 de novembro de 2021.

SALES, R. J. M. **Aplicação da lógica fuzzy no modelo de Streeter-Phelps para analisar o risco de contaminação das águas de rios, considerando múltiplos processos e múltiplos lançamentos** [Application of fuzzy logic in the Streeter-Phelps model to analyze the risk of river water contamination, considering multiple processes and multiple releases.] 2014. Dissertation. Universidade Federal do Ceará, Fortaleza, 2014.

SANTOS, S. H. L. **Aplicação da teoria fuzzy em modelos de transporte de massa para o cálculo do risco na concessão de outorga para lançamento de efluentes em rios** [Application of fuzzy theory in mass transport models for the calculation of risk in the granting of effluent release in rivers]. 2012. Dissertation. Universidade Federal do Ceará, Fortaleza, 2012.

SANTOS, A.V.; COUTO, C.F.; LEBRONA, Y.A.; MOREIRA, V.R.; FOUREAUX, A.F.S.; REIS, E.; SANTOS, L.V.S.; ANDRADE, L.H.; AMARALA, M.C.S.; LANGEA, L.C. Occurrence and risk assessment of pharmaceutically active compounds in water supply systems in Brazil. **Science of the Total Environment**, 2020, Disponível em: http://doi.org/10.1016/j.scitotenv.2020.141011. Acesso em 20 ago. 2022.

SAYAMA, H. **Introduction to the Modeling and Analysis of Complex Systems.** Open SUNY Textbooks, Milne Library, State University of New York, Geneseo, NY. 2015. 498p.

SCHARF, T.; VAUGHT, C.; KIDD, P.; STEINER, L.; KOWALSKI, K.; WIEHAGEN, B.; RETHI, L.; COLE, H. Toward a Typology of Dynamic and Hazardous Work Environments, **Human and Ecological Risk Assessment**, v. 7, n. 7, p. 1827-1841, 2001. Disponível em: http://doi.org/10.1080/20018091095429. Acesso em 20 ago. 2022.

SCHMIDTLEIN, M.C.; DEUTSCH, R.C.; PIEGORSCH, W.W.; CUTTER, S.L. A Sensitivity Analysis of the Social Vulnerability Index. **Risk Analysis**, v. 28, n. 4, p. 1009-1114, 2008. Disponível em: http://doi.org/10.1111/j.1539-6924.2008.01072.x. Acesso em 20 ago. 2022.

SCHWARZ, J.; ABRAHAMCZYK, L.; LANGHAMMER, T.; LEIPOLD, M.; GENES, M. C.; BIKCE, M.; KACIN, S. Building Typology For Risk Assessment: Case Study Antakya (Hatay). In: WCCE – ECCE – TCCE Joint Conference: **EARTHQUAKE & TSUNAMI**, 2009, Istanbul, Turkey.

SEDAE – State System of Data Analysis Fundation (2010) **Paulista Social Vulnerability Index 2010 edition**. São Paulo.

SENA, A.; FREITAS, C.; SOUZA, P.F.; ALPINO, T.; PEDROSO, M.; CORVALAN, C.; BARCELLOS, C.; CARNEIRO, F. Drought in the Semiarid Region of Brazil: Exposure, Vulnerabilities and Health Impacts from the Perspectives of Local Actors. **PLoS currents** (10). 2018.

SILVA, S.M.O.; SOUSA FILHO, F.A.; AQUINO, S.H.S. Risk assessment of water allocation on water scarcity period: the case of Jaguaribe–Metropolitan System. **Eng Sanit Ambient**, São Paulo, v. 22, n. 4, p. 749-760, 2017.

SIMON, H.A. The architecture of complexity. **Proceedings of the American Philosophical Society**, v. 106, n. 6, p. 467–482, 1962.

SIMONOVIC, S.P.; BENDER, M.J. Collaborative planning-support system: an approach for determining evaluation criteria. **Journal of Hydrology**, Amsterdam, v. 177, p. 237-251, 1996.

SITZENFREI, R., MAIR, M., MÖDERL, M., RAUCH, W. Cascade vulnerability for risk analysis of waterinfrastructure. **Water Science & Technology**, California, v. 64, n. 9, p. 1885-1891, 2011. Disponível em: http://doi.org/10.2166/wst.2011.813. Acesso em 20 ago. 2022.

SIVAPALAN, M.; SAVENIJE, H.H.G.; BLÖSCHL, G. Socio-hydrology: a new science of people and water. **Hydrol Process**, v. 26, p. 1270–1276, 2012.

SKINNER, D. J. C.; ROCKS, S. A.; POLLARD, S. J. T.; DREW, G. H. Identifying Uncertainty in Environmental Risk Assessments: The Development of a Novel Typology and Its Implications for Risk Characterization. **Human and Ecological Risk Assessment**, v. 20, n. 3, p. 607–640, 2014. Disponível em: http://doi.org/10.1080/10807039.2013.779899. Acesso em 20 ago. 2022.

SOUZA FILHO, F.A.; STUDART, T.M.C.; PONTES FILHO, J.D.; MARTINS, E.S.P.R.; AYRIMORAES, S.R.; PESSOA, C.A.P.; ROLIM, L.Z.R.; ARAUJO JUNIOR, L.M.; SILVA, S.M.O.; CARVALHO, T.M.N.; AQUINO, S.H.S. Integrated proactive drought management in hydrosystems and cities: building a nine-step participatory planning methodology. **Natural Hazards**, v. 115, p. 2179–2204, 2023. Disponível em: http://doi.org/10.1007/s11069-022-05633-z. Acesso em 19 jun. 2023.

SOUZA FILHO, F. A., SUN, L. MONCUNILL, D.F., MOURA, A.D., ZEBIAK. An operational downscaling prediction system for Northeast Brazil and the 2002-04 real time forecasting evaluation. **Journal of Climate**, v. 19, p. 1990-2007, 2006.

SRA - The Society of Risk Analysis. The Society of Risk Analysis Glossary, updated August 2018. **The Society of Risk Analysis**. Available at https://www.sra.org/risk-analysis-overview/risk-analysis-glossary/. Access: 04 fev. 2021.

STEIN, C.; ERNSTSON, H.; BARRON, J. A social network approach to analyzing water governance: The case of the Mkindo catchment, Tanzania. **Phys. Chem. Earth** Parts A/B/C, v. 36, p. 1085–1092, 2011.

STRINGER, L.C.; REED, M.S.; FLESKENS, L.; THOMAS, R.J.; LE, Q.B.; LALA-PRITCHARD, T. A New Dryland Development Paradigm Grounded in Empirical Analysis of Dryland Systems Science. **Land Degrad. Dev**., v. 28, p. 1952–1961, 2017.

STUDART, T.M.C.; CAMPOS, J.N.B. SOUZA FILHO, F.A.; PINHEIRO, M.I.T.; BARROS, L.S. Turbulent waters in Northeast Brazil: A typology of water governance-related conflicts, **Environmental Science & Policy**, v. 126, 2021, p. 99-110, Disponível em: http://doi.org/10.1016/j.envsci.2021.09.014. Acesso em 19 jun. 2023.

SUÁREZ-ALMIÑANA S, PEDRO-MONZONÍS M, PAREDES-ARQUIOLA J, ANDREU J, SOLERA A. Linking Pan-European data to the local scale for decision making for global change and water scarcity within water resources planning and management. **Science of the Total Environment**, v. 126, n. 13, p. 603–604, 2017.

SUSMAN P, O'KEEFE P, WISNER B. Global disasters, a radical interpretation. In: Hewitt K (ed) **Interpretations of Calamity for the Viewpoint of Human Ecology**. Allen & Unwin, Boston, MA, p. 263-283, 1983.

TANSCHEIT, R., 2003. Sistemas Fuzzy [Fuzzy systems]. In: **VI Simpósio Brasileiro de Automação Inteligente (SBAI)**, Bauru, Brazil. Anais de Minicursos... São Paulo: Sociedade Brasileira de Automática (SBA), 35 p.

TIMMERMAN, P. **Vulnerability, resilience and the collapse of society**: Environmental monograph no. 1. Toronto: Institute for Environmental Studies, 1981, 46p.

THOMAS T, JAISWAL RK, GALKATE R, NAYAK PC, GHOSH NC. Drought indicators-based integrated assessment of drought vulnerability: a case study of Bundelkhand droughts in central India. **Natural Hazards**, v. 81, n. 3, p. 1627–1652, 2016.

TORTAJADA, C.; FERNANDEZ, V. Towards global water security: a departure from the status quo? In: **World Water Council** (ed) Global Water Security: Lessons Learnt and Long-Term Implications, Espace Gaymard, Marseille, France, 1-20. 2018.

TOTH, C.; HELIC, D.; GEIGER, B.C. Synwalk: community detection via random walk modelling. **Data Mining and Knowledge Discovery**, v. 36, p. 739–780, 2022. Disponível em: http://doi.org/202310.1007/s10618-021-00809-w. Acesso em 19 jun.

TRIANTAPHYLLOU E. **Multi-criteria decision making methods**: A comparative study, Ed. Springer, US. 2000.

TRIPATHI, E. P.; SHRESTHA, E. S. K. Risk assessment of boot hydropower projects in Nepal using fuzzy logic approach. **Journal of Advanced College of Engineering and Management**, v. 3, n. 1, 2017. Disponível em: http://doi.org/10.3126/jacem.v3i0.18965. Acesso em 19 jun 2021.

TURNER BL, KASPERSON RE, MATSON PA, MCCARTHY JJ, CORELL RW, CHRISTENSEN L, ECKLEY N, KASPERSON JX, LUERS A, MARTELLO ML, POLSKY C, PULSIPHER A, SCHILLER A. A framework for vulnerability analysis in sustainability science. **PNAS**, v. 100, n. 14, p. 8074-8079, 2003.

UNU - United Nations University, 2013. **Water security & the global water agenda**: A UN-Wateranalytical brief. United Nations Institute for Water Environment and Health, United NationsEconomic and Social Commission for Asia and the Pacific, Canada.

VAN DEN BELT, M. **Mediated Modeling**: A System Dynamics Approach to Environmental Consensus Building. Island Press, Washington, D.C. 2004.

VARGAS, J.; PANEQUE, P. Methodology for the analysis of causes of drought vulnerability on the River Basin scale. **Nat Hazards**, v. 89, p. 609–621, 2017.

VENNIX, J.A.M. **Group Model Building**: Facilitating Team Learning Using System Dynamics. John Wiley, Chichester. 1996.

VEYRET, Y. **Risks**: the man as the agressor and victim. Contexto, São Paulo. 2007.

VIECELI, L. **Piora da crise hídrica impacta planos de empresas e ameaça economia até 2022**. Folha de São Paulo, Caderno Mercado. 2021. Disponível em https://www1.folha.uol.com.br/mercado/2021/09/piora-da-crise-hidrica-impacta-planos-de-empresas-e-ameaca-economia-ate-2022.shtml. Acesso em 20 de nov. 2021.

VIEIRA, B.M. **Apesar de chuvas acima da média, reservatórios de SP estão 9 pontos percentuais abaixo do nível pré-crise hídrica de 2013**. G1, Caderno São Paulo. 2021. Disponível em: https://g1.globo.com/sp/sao-paulo/noticia/2021/11/04/apesar-de-chuvas-acima-da-media-reservatorios-de-sp-estao-9-pontos-percentuais-abaixo-do-nivel-pre-crise-hidrica-de-2013.ghtml. Acesso em 20 de nov. 2021.

VIEIRA, J.M.P.; MORAIS, C. **Planos de segurança da água para consumo humano em sistemas públicos de abastecimento. Instituto Regulador de Águas e Resíduos** [Water safety plans for drinking water in public supply systems]. Minho University. Lisbon: SIG – Sociedade Industrial Gráfica, 2005. 161 p.

VLACHOS, E., 2003. Towards a typology of water-related conflicts in the urban environment. **Water Sci. Technol**. v. 47, p. 205–210. Disponível em: http://doi.org/10.2166/wst.2003.0399. Acesso em 19 jun 2021.

XU, T.Y.; QIN, X.S. Integrating Decision Analysis with Fuzzy Programming: Application in Urban Water Distribution System Operation. **J. Water Resour. Plann. Manage.**, v. 140, n. 5, p. 638-648, 2014. Disponível em: http://doi.org/10.1061/(ASCE)WR.1943-5452.0000363. Acesso em 19 jun. 2021.

WANG B, PAN SY, KE RY, WANG K, WEI YM. An overview of climate change vulnerability: a bibliometric analysis based on Web of Science database. **Nat Haz**, v. 74, p. 1649-1666, 2014.

WASHINGTON, A.; CLOTHIER, R.; NEOGI, N.; SILVA, J.; HAYTHURST, K., WILLIAMS, B. Adoption of a Bayesian Belief Network for the System Safety Assessment of Remotely Piloted Aircraft Systems. **Safety Science**, v. 118, p. 654-673, 2019. Disponível em: http://doi.org/10.1016/j.ssci.2019.04.040. Acesso em 19 jun. 2021.

WERICK, W.; WHIPPLE JR., W. **National Study of Water Management During Drought**: Managing Water for Drought, Institute for Water Resources, Alexandria, Virginia. IWR Report 1994-NDS-08. 1995.

WESSELINK, A.; KOOY, M.; WARNER, J. Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines. **WIREs Water**, v. 4, p. 1196, 2017. Disponível em: http://doi.org/10.1002/wat2.1196. Acesso em 19 jun. 2021.

WILHITE, D.A.; SIVAKUMAE, M.V.K.; PULWARTY, R. Managing drought risk in a changing climate: The role of national drought policy. **Weather and Climate Extremes**, v. 3, p. 4-13, 2014.

WOOD, N. J.; JONES, J.; SPIELMAN, S.; SCHMIDTLEIN, M. C. Community clusters of tsunami vulnerability in the US Pacific Northwest. **Proceedings of the National Academy of Sciences**, v. 112, n. 17, p. 5354–5359, 2015. Disponível em: http://doi.org/10.1073/pnas.1420309112. Acesso em 9 dez. 2021.

WYRWOLL, P. R.; GRAFTON, R. Q.; DANIELL, K. A.; CHU, H. L.; RINGLER, C.; LIEN, L. T. H.; KHOI, D. K.; DO, T. N.; TUAN, N.D. A. Decision-Making for Systemic Water Risks: Insights From a Participatory Risk Assessment Process in Vietnam, **Earth's Future, v.** 6, p. 543–564, 2018. Disponível em: http://doi.org/10.1002/2017EF000777. Acesso em 9 dez. 2021.

YU, F.; LI, X.Y.; HAN, X.S. Risk response for urban water supply network using case-based reasoning during a natural disaster. **Safety Science**, v. 106, p. 121-139, 2018. Disponível em: http://doi.org/10.1016/j.ssci.2018.03.003. Acesso em 9 dez. 2021.

ZADEH, L. A., 1965. **Fuzzy sets**. Information and control, New York, v. 8, n. 3, p. 338-353. Disponível em: http://doi.org/1016/S0019-9958(65)90241-X. Acesso em 9 dez. 2021.

ZAHABI, M.; KABE, D. A fuzzy system hazard analysis approach for human-in-the-loop systems. **Safety Science**, v. 120, p. 922-931, 2019. Disponível em: http://doi.org/10.1016/j.ssci.2019.08.029. Acesso em 9 dez. 2021.

ZHANG, L.; WU, X.; QIN, Y.; SKIBNIEWSKI, M. J.; LIU, W. Towards a Fuzzy Bayesian Network Based Approach for Safety Risk Analysis of Tunnel-Induced Pipeline Damage. **Risk Analysis, v.** 36, n. 2, p. 278–301, 2015. Disponível em: http://doi.org/10.1111/risa.12448. Acesso em 9 dez. 2021.

ZHANG, C.; XU, B.; LI, Y.; FU, G. Exploring the relationships among Reliability, Resilience, and Vulnerability of water supply using many-objective analysis. **J. Water Resour. Plann.** Manage., v. 143, n. 8, 2017.

ZIO, E. The future of risk assessment. **Reliability Engineering and System Safety**, Amsterdam, v. 177, p. 176–190, mar. 2018. Disponível em: http://doi.org/10.1016/j.ress.2018.04.020. Acesso em 9 dez. 2021.

Annex A – Questionnaire applied in São Paulo (Chapter 3)

INTERVIEWEE DATA

1. Name of Respondent

2. Email

3. What is your organization?

( ) Department of Water Resources
( ) DAEE
( ) SABESP
( ) OTHER

4. In case of another, which one?

5. River Basin that will be focused on in the questionnaire response

( ) Various Basins
( ) Mantiqueira
( ) Paraíba Do Sul
( ) Litoral Norte
( ) Pardo
( ) Piracicaba/Capivari/Jundiai
( ) Alto Tietê
( ) Baixada Santista
( ) Sapuca/Grande
( ) Mogi-Guaçu
( ) Tietê/Sorocaba
( ) Ribeira De Iguape/Litoral Sul
( ) Baixo Pardo/Grande
( ) Tietê/Jacaré
( ) Alto Paranapanema
( ) Turvo/Grande
( ) Tietê/Batalha
( ) Médio Paranapanema
( ) São José Dos Dourados
( ) Baixo Tietê
( ) Aguape
( ) Peixe

( ) Pontal Do Paranapanema
6. List regions in case you have checked "multiple regions"

For each item in the next questions:

Consider the scale of impacts: Irrelevant (0), Low (1), Medium (2), High (3), Very High (4), Potential (P), Not Assessed (NA). Potential impact may occur in the future although it has not yet been observed.

IMPACT ON USER SECTORS
7. Impact on the Different Water Uses
( ) Irrigation
( ) Urban Supply
( ) Industry
( ) Hydroelectric Production
( ) Navigation
( ) Aquatic Ecosystems
( ) Fisheries
( ) Other uses
8. In case of evaluating other uses, which one was added?
9. Impact on the Sanitation Sector
( ) The interruption of water supply to cities
( ) Increased water treatment costs for uses (urban, industrial, irrigation...)
( ) Loss of revenue with reduced billed water
( ) Unfavorable public perception of the sanitation company
( ) Financial losses in the sanitation company
10. List Other relevant impacts on Sanitation (if necessary)

CONFLICTS
11.
( ) Allocative conflicts
( ) Physical or symbolic violence in conflicts
( ) Weakening of water resources management organizations

( ) Reaction regarding the legitimacy of the decision-making process on allocation in the dry period
( ) Criticizes the quality of drought management and planning decisions
( ) Institutional ruptures / Conflicts between Institutions
( ) Lack of equity in the allocation of water between uses and regions
( ) Lack of economic efficiency in the allocation of water between uses and regions
( ) Conflict between the sanitation service provider and the sector's regulatory institution
( ) Conflict between water users and prosecutors
( ) Conflict between water users and environmental regulatory institution
12. List Other Conflicts (if necessary)

WATER AVAILABILITY

13. Impact on Water Supply
( ) Reduction of water stocks
( ) The interruption of the water supply for some use
( ) Water quality in water bodies degraded by drought (eutrophication, organic load...)
( ) Increased employee costs and time to implement drought plan
( ) Increased need for data / information required to monitor and implement drought mitigation plan
( ) Acquisition/transfer costs to access new water supply sources
( ) Costs to increase the efficiency of water use in the operation of mancias and water transfer works
( ) Unfavorable public perception of water resources management bodies
( ) Shortage of equipment and other water-related services (eg contractors to repair/drill wells)
( ) Water Reuse Intensification
( ) Intensification in the construction of wells
( ) Use of seawater desalination
14. List Other relevant impacts on the offer (if necessary)

COMMUNITIES

15. Impact Communities
( ) Reduction in population income

( ) Increased unemployment level due to drought
( ) Drinking water of inferior quality (ie bad taste and odor)
( ) Indoor and public landscaping stressed or dead
( ) Contamination in the network as a result of lower pressures
( ) Reduced quality of life
( ) The loss of human life (eg diarrhea)
( ) Reduction in firefighting capacity
( ) Physical and mental stress (population)
( ) Major political conflict
( ) Reduction or modification of recreational activities
( ) Uneven distribution of drought impacts among social groups
( ) Changes to population growth trends (most likely during a prolonged drought)
( ) Increased awareness of water conservation
( ) Change in water use behavior to conserve water
( ) Re-evaluation of social values (priorities, needs, rights) in order to adapt to drought

16. List Other relevant impacts on Communities (if necessary)

ECONOMIC

17. Economic Impact

( ) Reduction in the production of wealth in the municipality (GDP)
( ) Land prices (Decrease)
( ) Subsidence of land as a result of depletion (lowering) of groundwater
( ) Economic loss in farmers
( ) Economic loss in the tourism sector
( ) Disruption of the industrial production chain
( ) Reduction of economic development
( ) Increase in food prices
( ) Reduction in hydroelectricity production

18. List Other relevant impacts on the Economy (if necessary)

ENVIRONMENTAL AND RECREATIONAL

19. Environmental and Recreational Impact

( ) Increased risk of frequency and severity of forest fires

( ) Stress in aquatic and riverine ecosystems

( ) Lower lake/reservoir levels reducing recreational activities

( ) Increased susceptibility to plant diseases

( ) Reduction of runoff at springs (sources)

( ) Stress for fish and other wildlife

( ) Low water quality in rivers and / or lakes / reservoirs

Annex B – Structured interview (Chapter 4)

Interviewee:

Area of expertise: (   ) Hydrology (   ) Hydraulics (   ) Water Quality (   ) Geotechnics

Date: __ / __ / ____

QUESTION 1)

Considering the process of water transfer to guarantee water security to the FMA and considering the water infrastructure of the State of Ceará, which subsystems should we consider on our study case?

QUESTION 2)

For each type of structure, what risks should we consider?

a) Reservoirs

b) Canals

c) Tunnels

d) Pumping stations

Annex C – Description of the risks from the Typology of Risk (Chapter 4)

Table 10 - Description the risks from the Typology of Risks in alphabetic order.

RISK	DEFINITION
Degradation of structures	Degraded general structures, such as concrete (by natural process or accelerated by adverse conditions)
Drought	Climate event that reduces the average precipitation of a region
Tunnel collapse	Landslide inside the tunnel
Bed silting	Settlement of solid particles in the bed of a river, canal or reservoir.
Collapsible soils	Unsaturated soil that are susceptible to a considerable rearrangement of particles upon wetting, reducing drastically its volume
Contamination by input of nutrients	Presence of nutrients above the self-depuration capacity of the water body
Contamination by waste disposal (dump)	Presence of solid waste and/or landfill leachate above the self-depuration capacity of the water body
Corrosion in the hydromechanical structures	Degraded metallic structures, such as pipes and pumps components (by natural process or accelerated by adverse conditions)
Discontinuity of water management programs	Discontinuity of the application of programs for better public management in the water resources sector
Displacement of coating material	Decoupling of the plates that cover and protect the canal structure
Eutrophication	Water body enriched with nutrients and organic matter
Failure in activating the gates	Failure in the opening operation of the floodgates, in canals or reservoirs
Fish mortality	Death of large numbers of fish in a reservoir
Foundation settlement	Disruption of the foundation due to unequal compression of the soil
Height hydraulic variation	Variation in the height of the water column
High energy billing rate	Increase of energy tariff due to external reasons

Table 7 - Description the risks from the Typology of Risks in alphabetic order – continued.

Hydromechanical structures inoperative	Malfunctioning of structures that compromise the operation of the system as a whole
Illegal withdrawal	Withdrawal of water made with illegal canals, pipes or pumps
Infiltration	Downward movement of water into structures or soil
Insufficient water transfer	The volume of water being transfered is not wnough to attend demands
Irregular occupation of margins	Irregular properties built along the margins of reservoirs or rivers
Lack of proper maintenance	Scarcity of maintenance of structures in general
Migration of population	Movement by humans (communities, populations) from one region to another, affecting water demand and, therefore, water management
Oscillations in electrical circuits	Fluctuation in electrical current
Outdated water billing rate	Outdated water tariff due to external reasons
Overheating of the motors/pumps	Damage caused in the pumps due to overload and overheat
Overtopping	Reservoir water flows over the dam
Pipping (Internal erosion)	Infiltration and water flow within the structure of a dam or canal
Political interference	External interference on the public water planning and management motivated by political reasons
Power generator inoperative	Malfunctioning of the power generator during an electric surge
Proliferation of cyanobacteria	Increase in the number of cyanobacteria beyond the capacity of the ecosystem
Proliferation of exotic species	Increase in the number of exotic species beyond the capacity of the ecosystem
Proliferation of macrophytes	Increase in the number of macrophytes beyond the capacity of the ecosystem
Pump cavitation	Formation of small "bubbles" on the water due to pressure reduction, causing damage to metal structures
Sabotage/Vandalism/Terrorism	Human actions that compromise equipment, structures and water quality such as robbing electric equipment or poisoning water

Table 7 - Description the risks from the Typology of Risks in alphabetic order – conclusion.

Spillway obstruction	Physical obstacle blocking the passage of water through the spillway
Stopping electronic machinery and equipment due to aging	Malfunctioning of structures that compromise the operation of the system as a whole due to aging
Uncontrolled construction of small reservoirs	Construction of unplanned small reservoirs to satisfy individual necessities
Unplanned dead storage	Unplanned reduction of the volume of a reservoir
Water hammer/Transient flow	Pressure surge through waves caused by the sudden stop or change of direction movement of a volume of water.

Annex D – Structure for semi-structured interviews (Chapter 5)

Table 11 - Structure for semi-structured interviews.

		Possibility of occurrence					Severity of the impact			
		0	1	2	3	4	0	1	2	3
(Name of the) Reservoir	Fish Mortality									
	Pollution by Invasive Species									
	Pollution by Nutrients									
	Contamination by Domestic Sewage									
	Contamination by solid waste disposal (dump)									
	Contamination by urban transport									
	Eutrophication									
	Proliferation of green algae									
	Proliferation of cyanobacteria									
	Unviability of the source for water supply									
	Compromise of concrete structure in the upstream and downstream facings									
	Sliding of the reservoir structure									
	Reservoir overtop									
	Obstruction of the auxiliary spillway									
	Settlement (of a structure foundation)									
	Infiltration / poor drainage									
	Piping failure									
	Bed silting									
	Unplanned dead storage capacity of reservoir									
	Dry water source									
	Lack of proper maintenance									
Tunnel	Tunnel collapse									
(Name of the) Siphon	Transient flow									
	Degradation of structures									
	Absence of extra operating cell									

Table 8 - Structure for semi-structured interviews (continued).

		Possibility of occurrence					Severity of the impact			
		0	1	2	3	4	0	1	2	3
(Name of the) Canal	Fish Mortality									
	Pollution by Invasive Species									
	Pollution by Nutrients									
	Contamination by Domestic Sewage									
	Contamination by solid waste disposal (dump)									
	Contamination by urban transport									
	Eutrophication									
	Proliferation of green algae									
	Proliferation of cyanobacteria									
	Failure to activate the gates (canals)									
	Slowing canals									
	Transient flow									
	Settlement (of a structure foundation)									
	Infiltration / poor drainage									
	Breakdown of canal structure due to low water pressure									
	Piping failure									
	Bed silting									
	Lack of proper maintenance									
	Transient flow									
	Bed silting									
	Valve sticking									
(Name of the) Pumping station	Eutrophication									
	Proliferation of green algae									
	Overheating of the motors/pump									
	Pumping failure									
	Absence of extra operating cell									
	Transient flow									
	Pump cavitation									
	Settlement Caused by Pumping									
	Lack of proper maintenance									
	Stopping electronic machinery and equipment due to aging									
	High corrosion stage in the hydromechanical structures									
	Unplanned dead storage capacity of reservoir									
	Power generator inoperative									
	Pipeline rupture									
	Absence of extra operating cell									

Table 8 - Structure for semi-structured interviews (conclusion).

		Possibility of occurrence					Severity of the impact			
		0	1	2	3	4	0	1	2	3
(Name of the) Well	Eutrophication									
	Proliferation of green algae									
	Overheating of the motors/pump									
	Pumping failure									
	Absence of extra operating cell									
	Transient flow									
	Pump cavitation									
	Settlement Caused by Pumping									
	Lack of proper maintenance									
	Stopping electronic machinery and equipment due to aging									
	High corrosion stage in the hydromechanical structures									
	Unplanned dead storage capacity of reservoir									
Perennialized Rivers	Fish Mortality									
	Pollution by Invasive Species									
	Pollution by Nutrients									
	Contamination by Domestic Sewage									
	Contamination by solid waste disposal (dump)									
	Eutrophication									
	Unviability of the source for water supply									

Annex E – Questionnaire applied in Ceará (Chapter 6)

INTERVIEWEE DATA

1. Interviewee's name:

2. Email:

3. Which River Basin Committee (RBC) do you participate in?

( ) RBC Acaraú
( ) RBC Coreaú
( ) RBC Curu
( ) RBC Sertões de Crateús
( ) RBC Serra da Ibiapaba
( ) RBC Litoral
( ) RBC Metropolitana
( ) RBC Alto Jaguaribe
( ) RBC Médio Jaguaribe
( ) RBC Baixo Jaguaribe
( ) RBC Salgado
( ) RBC Banabuiú

4. What is your sector in the River Basin Committee?

( ) Municipal public power
( ) State public power
( ) Civil Society
( ) Water user (human consumption)
( ) Water user (irrigation)
( ) Water user (industry)
( ) Water user (aquaculture)
( ) Water user (fishing)
( ) Water user (livestock)
( ) Water user (other uses)

For each item in the next questions:

Read the statements about the impacts of drought on user sectors and mark the degree of impact that best describes the situation experienced during the drought that started in 2012, according to your perceptions and experiences.

Consider the following impact scale:

Irrelevant (0), Low (1), Medium (2), High (3), and Not Assessed (NA).

5. IMPACTS OF DROUGHT ON WATER USES

( ) Irrigated agriculture
( ) Dryland agriculture
( ) Urban water supply
( ) Rural water supply
( ) Livestock
( ) Industry
( ) Aquatic Ecosystems
( ) Fishing
( ) Fish farming
( ) Recreation
( ) Tourism
( ) Other uses

If any other use has been assessed, please indicate below.

6. SANITATION IMPACTS

( ) Water supply interruption for urban areas
( ) Water supply interruption for rural communities
( ) Increase in water bills for consumers
( ) Worsening of water quality offered
( ) Lower pressures in water supply networks
( ) Use of alternative water sources for supply
( ) Other

If there is any sanitation impact not listed above, please indicate it below.

7. IMPACTS OF DROUGHT ON THE OCCURRENCE OF CONFLICTS

( ) Human consumption vs. irrigation
( ) Human consumption vs. industrial use
( ) Human consumption vs. fish farming in the reservoir
( ) Human consumption vs. fishing
( ) Human consumption vs. shrimp farming
( ) Upstream uses vs. downstream irrigation
( ) Public irrigation vs. private irrigation
( ) Conflicts related to water distribution in cities
( ) Conflicts due to water transfers
( ) Conflicts related to water quality
( ) Conflicts between water users and state institutions (Public Prosecution, Police, water management agencies, environmental agencies)
( ) Conflicts between water users and environmental interests
( ) Conflicts regarding the renewal or issuance of water use permits during drought
( ) Conflicts due to the price of water
( ) Conflicts related to decision-making on water allocation
( ) Conflicts due to non-compliance with allocation agreements by users
( ) Conflicts due to illegal diversion or withdrawal of raw water

Is there any other drought-related conflict not listed above? If yes, please describe it.

If conflicts have been recorded, please cite the water system (dam, spring, pipeline, well, etc.) with the highest occurrence.

8. IMPACTS OF DROUGHT ON WATER SUPPLY:

( ) Intensification of well construction
( ) Use of seawater desalination
( ) Use of desalination systems in wells and installations in municipalities
( ) Expansion of rainwater harvesting systems
( ) Exclusive use of reservoirs for human consumption
( ) Diversification of water sources to meet demand

(   ) Reduction in water storage
(   ) Disruption of water supply for some use
(   ) Decline in the quality of available water.

If there is any other impact of drought on water supply that has not been listed, please describe it below.

9. IMPACT OF DROUGHT ON QUALITY OF LIFE:

(   ) Migration of affected population
(   ) Increase in poverty
(   ) Compromised food security of affected families
(   ) Increase in diseases
(   ) Intensification of conflicts over water
(   ) Physical and mental stress on the population
(   ) Change in behavior towards water use
(   ) Change in values to adapt to the drought
(   ) Interruption of public services (health, education)
(   ) Decrease in income of the population

Is there any other impact on quality of life that has not been listed? If affirmative, please describe it below.

10. IMPACTS OF DROUGHT ON THE ECONOMY

(   ) Economic loss in the agricultural sector
(   ) Economic loss in livestock farming
(   ) Economic loss in the industrial sector
(   ) Economic loss in the trade and services sector
(   ) Economic loss in fishing
(   ) Decrease in land prices
(   ) Change in economic activities (e.g. replacing agriculture with shrimp farming)
(   ) Slowdown in municipal economic growth
(   ) Increase in food prices

( ) Unemployment in urban areas
( ) Unemployment in rural areas
( ) Increase in household expenses due to the purchase of water
( ) Unemployment in urban areas

Are there any other economic impacts of drought not listed above? If so, please list below.

11. IMPACTS OF DROUGHT ON THE ENVIRONMENT AND RECREATIONAL / LEISURE ACTIVITIES

( ) Increased forest fires
( ) Disappearance of rivers, lakes, and lagoons
( ) Reduced flow of springs
( ) Reduction in vegetation coverage (forests, trees, shrubs)
( ) Death of fish
( ) Death of wildlife
( ) Degradation of basin areas
( ) Poor water quality in rivers, lakes, and reservoirs
( ) Restriction of recreational activities in lakes, rivers, and reservoirs

Are there any other relevant environmental or recreational impacts? If so, please describe them.

Now, we would like you to evaluate some of the measures and responses implemented to minimize or solve the problems caused by the drought that began in 2012. In this question, there is a different form of evaluation, as we are not evaluating the impacts, but the effectiveness of the measures adopted. Therefore, the evaluation to be made should include one of the following response options:
Very Efficient, Efficient, Not Very Efficient, Inefficient, Not implemented in the river basin, and Not Assessed.

12. EVALUATION OF ACTIONS/RESPONSES TO DROUGHT PROBLEMS:

(   ) Participatory water allocation
(   ) Establishment of committees and commissions to discuss drought-related issues
(   ) Planning of response actions by public institutions
(   ) Drilling of deep wells
(   ) Drilling of wells in dry riverbeds and reservoirs
(   ) Recovery of wells
(   ) Construction of quick assembly pipelines
(   ) Transfer of water between sources (reservoirs, rivers, canals)
(   ) Operation “carro-pipa” (water truck delivery)
(   ) Water rationing
(   ) Contingency tariffs on water use
(   ) Restrictions on irrigation
(   ) Restrictions on issuance/renewal of water use permits
(   ) Installation of public fountains in urban areas
(   ) Actions to ensure good water quality
(   ) Communication/dissemination of actions to be implemented by public institutions
(   ) Construction of cisterns
(   ) Expansion of credit lines
(   ) Debt negotiation
(   ) Subsidies for purchasing cattle feed

Were there any other measures not listed? If so, please describe them below.

What do you think could have been done to better address the negative effects of drought in your basin?