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**MODEL CALIBRATION AND HYDRAULIC ASSESSMENT OF A WATER SUPPLY
MACROSYSTEM WITH DESALINATED WATER INTEGRATION.**

FORTALEZA

2026

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Advisor: Prof. Iran Eduardo Lima Neto, Ph.D.
Co-advisor: Prof. Bruno Melo Brentan, PhD.

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To God.

To my parents, Fátima and Raimundo.

To my brothers, Jean, Jeanny, Jane Mara,
Juliana and Jéssica.

To my wife, Sterlânia.

To my daughter, Ana Júlia.

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To God, for hope, mercy, and for being the meaning of my existence.

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“Every time you make a choice you are turning the central part of you, the part of you that chooses, into something a little different than it was before.” (Clive Staples Lewis, 1952).

RESUMO

Projetos e obras hidráulicas possuem elevada relevância para regiões caracterizadas por escassez de recursos hídricos, uma vez que modificações em suas estruturas, que são interligadas e interdependentes, podem gerar impactos adversos em todo o sistema. Nesse contexto, a modelagem e a calibração emergem como ferramentas fundamentais para a previsão de cenários e a proposição de melhorias nessas infraestruturas hídricas, especialmente em redes de distribuição de água, que envolvem múltiplos elementos e elevados níveis de complexidade. Destaca-se que a Região Metropolitana de Fortaleza, por apresentar alta densidade populacional e um regime climático marcado pela escassez hídrica, encontra-se particularmente suscetível a impactos associados a cenários de seca prolongada. A presente tese tem como objetivo principal discutir e analisar uma nova fonte de abastecimento de água, especificamente a dessalinização, e seus impactos sobre a rede de distribuição, por meio da proposição de um modelo calibrado do macrossistema e da simulação da injeção de água dessalinizada em diferentes cenários de crescimento da demanda hídrica. Para o desenvolvimento da calibração e de funções auxiliares, foram utilizados códigos implementados em MATLAB, enquanto o EPANET foi empregado para a modelagem hidráulica da rede. Os resultados obtidos evidenciam o caráter inovador da abordagem adotada e destacam a importância da previsão de cenários com base em modelos calibrados de sistemas de distribuição de água. Além disso, os resultados sugerem que, a longo prazo, o abastecimento de uma região densamente povoada pode apresentar limitações quando sustentado apenas por uma ou poucas fontes de suprimento. Ademais, conclui-se que a inserção de uma nova fonte de abastecimento na rede não garante, por si só, a equidade no atendimento aos requisitos hidráulicos mínimos e pode intensificar as desigualdades sociais no acesso à água.

Palavras-chave: Modelagem; Calibração; Sistema de distribuição de água; Dessalinização.

ABSTRACT

Hydraulic projects and infrastructures are of high relevance for regions characterized by water scarcity, since modifications in their structures, which are interconnected and interdependent, may generate adverse impacts throughout the entire system. In this context, modeling and calibration emerge as fundamental tools for scenario forecasting and for proposing improvements in these water infrastructures, especially in water distribution networks, which involve multiple elements and high levels of complexity. It is noteworthy that the Fortaleza Metropolitan Region, due to its high population density and a climatic regime marked by water scarcity, is particularly susceptible to impacts associated with prolonged drought scenarios. The present thesis aims to discuss and analyze a new water supply source, specifically desalination, and its impacts on the distribution network, through the proposal of a calibrated model of the macrosystem and the simulation of the injection of desalinated water under different scenarios of water demand growth. For the development of the calibration and auxiliary functions, codes implemented in MATLAB were used, while EPANET was employed for the hydraulic modeling of the network. The results obtained highlight the innovative nature of the adopted approach and emphasize the importance of scenario forecasting based on calibrated water distribution system models. Furthermore, the results suggest that, in the long term, the water supply of a densely populated region may present limitations when sustained by only one or a few supply sources. In addition, it is concluded that the introduction of a new water supply source into the network does not, by itself, guarantee equity in meeting minimum hydraulic requirements and may intensify social inequalities in access to water.

Keywords: Modeling; Calibration; Water distribution system; Desalination.

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LIST OF ABBREVIATIONS AND ACRONYMS

ARHE	Average Relative Hourly Error
BC	Before Christ
CAGECE	State Water and Wastewater Agency
DESAL	Seawater Desalination Plant Project
EA	Evolutionary Algorithm
ED	Electrodialysis
EPA	Environmental Protection Agency
FCV	Flow Control Valve
FMR	Fortaleza Metropolitan Region
HDI	Human Development Index
IBGE	Brazilian Institute of Geography and Statistics
INSA	National Institute of the Semi-Arid Region
I_r	Todini's resilience index
MAE	Mean Absolute Error
MED	Multi-Effect Distillation
MSF	Multi-Stage Flash
NSE	Nash-Sutcliffe Efficiency Coefficient
PBIAS	Percentual Bias
PRV	Pressure-Reducing Valve
PSO	Particle Swarm Optimization
R^2	Coefficient of Determination
RO	Reverse Osmosis
WDS	Water Distribution Systems
WTP	Water Treatment Plants

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1 INTRODUCTION

1.1 Contextualization

The Brazilian drylands climate is characterized by average annual precipitation of approximately 750 mm, combined with high potential evaporation rates that can reach about 2,500 mm per year. This unfavorable relationship between precipitation and potential evaporation results in a predominantly negative water balance, imposing important constraints on water resource availability (Montenegro & Montenegro, 2012; Campos et al., 2016). In some regions, these conditions are even more severe, with annual rainfall levels reaching values close to 400 mm. This situation is further aggravated by the fact that the region concentrates around 30 million inhabitants distributed over approximately 18% of the national territory (Silva et al., 2010; Silva et al., 2012). In addition, the presence of intermittent rivers, the spatial and temporal irregularity of rainfall, and the high interannual and seasonal variability intensify water scarcity, directly reflecting in socioeconomic impacts such as food insecurity and limited access to potable water.

Almost entirely inserted within this climatic context, the state of Ceará adopted, throughout the twentieth century, a structural strategy to address water scarcity based on the construction of small and medium-sized reservoirs. Estimates suggest the existence of between 25,000 and 30,000 units, with storage capacities ranging from 10 to 4,500 hm³ (Campos & Studart, 2008; Campos et al., 2016). This strategy, known as the reservoir-building policy, was initiated at the beginning of the last century and intensified during the 1950s and 1960s, a period in which knowledge of local hydrology was still limited (Pereira et al., 2025). This policy was grounded on the premise that increasing water supply constituted one of the primary mechanisms for mitigating the impacts of droughts (Campos, 2014). Despite its gradual implementation, the reservoir network played a fundamental role in strengthening regional water security. The expansion of these infrastructures was associated not only with financial incentives, but also with the intensification of droughts, climate change, and the continuous growth in water demand, factors that impose additional challenges to water resources management (Medeiros, 2003; Campos & Studart, 2008; Silveira et al., 2013).

Given the high density of reservoirs, the need for integrated and efficient river basin management becomes evident, encompassing both the operational aspects of these infrastructures and the mediation of conflicts associated with multiple water uses. Such

conflicts, present since the early stages of reservoir implementation and involving land expropriation processes and divergent socioeconomic interests, demonstrate that the challenges related to these works do not end after construction. On the contrary, a complex, continuous, and dynamic management process is initiated.

In the Fortaleza Metropolitan Region, these challenges are even more pronounced due to the high population density, estimated at approximately 2.5 million inhabitants, and the growth of water demands associated with urban and industrial expansion (IBGE, 2025). This combination, together with the intensification of drought periods, hinders water resource management and has required water abstraction from regions increasingly distant from the capital, thereby increasing the operational complexity of water supply systems (Raulino et al., 2021; Ballarin et al., 2023; Cataldi et al., 2025).

As a strategy to mitigate the increasing water stress in the Fortaleza Metropolitan Region, the Government of the State of Ceará has been investing in the construction of the largest desalination plant in the country, with a production capacity of 1 m³/s, which may be expanded in the future. The plant is expected to supply approximately 300,000 inhabitants, with a forecasted start of operation in 2026 and an investment of around R\$ 526 million for its construction and implementation. The facility will treat seawater through the Reverse Osmosis process, and the desalinated water will be directly injected into the water supply system through the existing Mucuripe and Aldeota reservoirs (CAGECE, 2023).

In view of the above, it becomes necessary to employ tools capable of identifying and quantifying the impacts that the injection of new water supply sources may have on the hydraulic and operational behavior of large-scale Water Distribution Systems (WDS), especially those located in areas of high urban density. Moreover, the scarcity of studies in the literature on this topic highlights the existence of a scientific gap and reinforces the need for more in-depth approaches.

1.2 Objectives

1.2.1 General Objective

The main objective of this thesis is to advance the hydraulic modeling of water distribution systems in urban areas, as well as to contribute to the discussion and analysis of new water supply sources and their impacts on the performance of WDS in regions facing difficulties in meeting water demand.

1.2.2 Specific Objectives

- To conduct an integrative review on the modeling and calibration of water distribution systems, with a focus on desalination.
- To analyze the calibration of large-scale networks using the PSO method applied to the Fortaleza water supply macrosystem.
- To evaluate the hydraulic, operational, and social impacts of injecting desalinated water into the calibrated network.
- To support decision-making by management agencies regarding the integration of new water supply sources.
- To contribute to societal understanding of the complexity and challenges of water supply systems.

1.3 Thesis Organization

More specifically, the study proposes three main contributions related to the complexity of modeling large-scale distribution networks and the presence of multiple hydraulic elements.

The present work is structured as follows: Chapter 1 presents the contextualization of the study, as well as its justification and objectives. Chapter 2 provides a literature review on the calibration and modeling of WDS, with emphasis on the potential hydraulic and operational impacts associated with the injection of desalinated water into these systems. Chapter 3 develops the calibration of a complex WDS microsystem in Fortaleza using the PSO method. Chapter 4 addresses the assessment of the impacts of desalination on the Fortaleza WDS microsystem through the simulation of future scenarios. It is noteworthy that these last three chapters are organized into sections comprising introduction, methodology, results, discussion and conclusions. Chapter 5 presents an integrated discussion of the results obtained in the three previous chapters. Finally, Chapter 6 presents some general conclusions and recommendations for future research.

2 HYDRAULIC CALIBRATION, MODELING, AND INTEGRATION OF DESALINATED WATER: A LITERATURE REVIEW

2.1 Introduction

In response to increasing water scarcity, rising demand, and the growing operational complexity of water supply systems worldwide, hydraulic modeling based on dynamic simulations has emerged as a fundamental tool for planning, operation, and scenario assessment in water distribution systems (WDS; Vörösmarty et al., 2010; Shao et al., 2023; Ferdowsi et al., 2024; Truong et al., 2025). These approaches enable the identification of areas susceptible to inadequate pressure heads and leakages, which compromise the quality of sanitation services, generate economic losses, and further reduce water availability (Marzola et al., 2021). Furthermore, the incorporation of sensors and monitored data into water supply systems allows the improvement of hydraulic models performance, as calibration reduces discrepancies between observed and estimated values through the adjustment of parameters such as pipe roughness, nodal demands, water quality-related properties, and the operational rules of pumps and valves (Meirelles et al., 2017; Zhao, 2022).

In light of unfavorable projections regarding the ability of conventional water resources to meet growing global water demand, many countries have turned to alternative water supply sources, with particular emphasis on seawater desalination (Elimelech et al., 2011; Salomons et al., 2023). Available data indicate that, by 2020, approximately 21,000 desalination facilities were in operation worldwide, distributed across at least 177 countries and territories (Jones et al., 2019; Eke et al., 2020; Katz et al., 2021). Furthermore, global desalinated water production in 2016 was roughly twice that recorded in 2008, while both the scale and the number of desalination plants increased at an average annual growth rate of 6.8% between 2010 and 2020 (Liu et al., 2016; Eke et al., 2020). In particular, countries located in arid and semi-arid regions of Southwest Asia, where approximately 65% of the world's most water-stressed nations are concentrated, have increasingly relied on desalination to meet their water demands and were pioneers in the large-scale adoption of this technology (D'Agostino et al., 2025). Because it does not depend on river flows, reservoir storage levels, or climatic variability, the widespread adoption of desalination in these water-scarce contexts underscores its potential as a so-called drought-proof water supply source (Dhakal et al., 2022).

Although desalination constitutes one of the main alternative water supply sources for regions facing water scarcity, and more than 62% of desalination plants currently in operation worldwide are intended for human consumption (Jones et al., 2019), it is essential to consider its technical, environmental, and social implications. From a technical perspective, several studies have reported changes in water quality following the introduction of desalinated water into supply systems, including increased concentrations of suspended particulate iron and the intensification of corrosion processes in iron pipes (Liu et al., 2013). There is also evidence that desalinated water can dissolve existing scale layers on the inner surfaces of distribution pipes, potentially increasing water pollution levels (Cai et al., 2023). Furthermore, the selection of pipe materials has a significant influence on the quality of seawater desalinated by reverse osmosis (Cai et al., 2023). From an environmental standpoint, major concerns relate to the generation and disposal of brine, inherent to desalination processes, which can alter the quality of receiving waters and cause adverse impacts on marine fauna and flora (Gupta et al., 2025). Another widely discussed issue is the high energy demand required for desalination plant operation, which may exceed the energy consumption of conventional water treatment technologies, thereby could contribute to increased greenhouse gas emissions associated with potable water production (Elimelech et al., 2011). From a social perspective, desalination raises geopolitical debates regarding water use and control, placing it within the domains of hydropolitics and hydrodiplomacy, as its impacts may affect different actors at both local and global scales and intensify political and economic tensions, as observed in contexts involving Israel, Palestine, and Jordan (Katz et al., 2021). In addition, studies suggest that due to the high financial investments and large land areas required for implementation, desalination may reinforce a logic of infrastructural neoliberalism, whereby facilities tend to primarily serve higher-income consumers, thereby exacerbating inequalities in water access among different social groups (O' Neill et al., 2024).

Accordingly, this study presents an exploratory and integrative literature review focused on hydraulic modeling and calibration of WDS, emphasizing their role in supporting the analysis of hydraulic and operational impacts associated with the integration of desalinated water into large-scale networks.

2.2 Materials and methods

An integrative literature review supported by bibliometric techniques was conducted to examine how hydraulic modeling and calibration have been applied to water distribution systems, with particular emphasis on identifying gaps and challenges related to the integration of desalinated water, system resilience, operational performance, and equity in large-scale networks. The review was primarily based on scientific articles indexed in the Scopus (Elsevier) and Web of Science Core Collection (Clarivate Analytics) databases, both of which are widely recognized as major international indexing platforms with high scientific relevance and impact in the academic community. The literature search relied on combinations of keywords associated with the main topics of the study, including “water distribution system”, “water distribution network”, “drinking water network”, “water supply system”, “hydraulic modeling”, “model calibration”, “pressure management”, “leakage”, “desalination”, “resilience”, “water equity”, and “optimization”.

Following data collection, the selected publications were initially classified according to their primary research themes. In particular, studies addressing desalination were first grouped into four major thematic categories, namely: technology, environment, economic and energy aspects, and social interests. Subsequently, the publications were further organized according to their predominant thematic focus, encompassing hydraulic modeling and calibration, pressure management and water loss analysis, desalination technologies, resilience of WDS, water equity, and optimization methods.

In a subsequent step, a complementary bibliometric analysis was conducted using the VOSviewer software, considering only articles indexed in the Scopus databases. This analysis aimed to identify thematic linkages, research clusters, co-authorship patterns, and emerging directions within the selected research areas. The thematic organization of the literature provided the basis for a structured and integrative synthesis of the current state of the art.

To visualize the thematic organization adopted in this study, a general bibliometric map of the literature was developed based on a keyword co-occurrence analysis using the VOSviewer software (version 1.6.20) and publications indexed in the Scopus (Elsevier) database. The filters applied to the database prioritized studies related to water supply and distribution systems, thereby reducing the inclusion of references that were not aligned with the core scope of the research. Figure 2.1 presents this bibliometric map and illustrates how

Based on Figure 2.1, derived from a time-unrestricted search in the Scopus database, the term “water distribution systems” occupies a central position in the bibliometric map, confirming its fundamental role within the analyzed field, and shows strong associations with terms such as “optimization”, “hydraulic models”, “leakage”, “epanet”, and “calibration”, among others. In contrast, the term “desalination”, although meeting the minimum threshold of eight occurrences adopted in the VOSviewer analysis, does not appear as a dominant cluster nor as a concept strongly integrated with the central nodes of the map. This pattern suggests that desalination has not yet been widely incorporated into the literature focused on the modeling and operation of WDS. This finding highlights a relevant gap in the state of the art and reinforces the need for further investigations adopting more integrated approaches that explicitly consider the technical, operational, and managerial impacts of desalination on the performance of these systems.

2.3 Results and discussion

2.3.1 Role of Hydraulic Modeling in Modern Water Distribution Systems

Hydraulic modeling of WDS consists of a mathematical representation of the network, enabling the simulation of water flow, estimating pipe flows and nodal pressures under different demand and operating conditions, and assessing the hydraulic and operational performance of the system (Walski et al., 2003). Although WDS date back to the Bronze Age (approximately 3200 - 1100 BC), the first formal records of hydraulic modeling applied to WDS emerged only in the late nineteenth century (Ormsbee, 2008). The initial milestone is attributed to the first systematic method of hydraulic analysis proposed by Spiess (1887), followed by the graphical method of Freeman (1892), the Camp and Hazen method (1934), the well-known Hardy Cross method (1936), and the Aldrich method (1937) (Mays et al., 2012; Mala-Jetmarova et al., 2015). The Hardy Cross method gained widespread recognition due to its computational feasibility and ease of iterative implementation, with its first computational application carried out in the analysis of the WDS of Palo Alto, California, in 1957 (Ormsbee, 2006). Following this advancement, several numerical methods were developed to improve robustness and computational efficiency, including the simultaneous node method (Martin & Peters, 1963), the simultaneous loop method (Epp & Fowler, 1970), the linear method or simultaneous pipe method (Wood & Charles, 1972; Tavallae, 1974), and

later the gradient method, also known as the simultaneous network method, proposed by Todini and Pilati (1988), which underpins the main hydraulic simulation tools used today.

Following advances in computational methods and algorithms, the next stage involved the creation of hydraulic simulation software packages for WDS (Mala-Jetmarova et al., 2015). During the 1960s and 1970s, numerous algorithms and software tools were developed within universities, such as KYPIPE and WADISO, leading in the 1980s to the emergence of commercial software packages. In 1993, the U.S. Environmental Protection Agency (EPA) released EPANET, developed by Lewis Rossman. EPANET subsequently became one of the most widely used software tools in both academic and professional applications, largely due to its free availability, comprehensive capabilities, and open architecture, which allow for extensions, adaptations, and integration with other tools (Ormsbee, 2006; Mala-Jetmarova et al., 2015). Since then, several other software platforms have been developed, including CWSnet (Guidolin et al., 2011), WATSYS, Synergi Water, HYDROFLO3, InfoWorks, DisNet, Netis, Archimede, Cross, Pipe Flow Expert, WNTR, WaterGEMS/WaterCAD, and WDNNetXL (Awe et al., 2019).

These algorithms, computational packages, and simulation software aim to represent the inherent complexity of WDSs, in which multiple factors can influence flow rates, pressures, and water quality throughout the pipe network. As these systems consist of predominantly buried infrastructure, composed of several interconnected elements, such as pipes, pumps, valves, reservoirs, and control devices, and are often affected deficiencies in maintenance practices, limited availability of reliable data, progressive material deterioration, and variability in operating conditions, the modeling of WDSs constitutes a complex and challenging task (Grigg, 2024). Effective management of these components, which convey water from the main distribution network to consumer service connections, requires models capable of simulating the hydraulic and operational behavior of the system under a wide range of scenarios. Such scenarios include pipe failures, leakage occurrence, network expansion and reconfiguration, maintenance forecasting and planning, sectorization processes, reductions in available pressure, operational strategies for pumps and reservoirs, as well as the transport and temporal evolution of chemical constituent concentrations throughout the network.

The scientific literature provides numerous examples of hydraulic modeling as a fundamental tool to support planning, operation, and decision-making in water supply systems. For instance, Joseph et al. (2024) employed logic-based and machine learning – based modeling approaches for leak detection in WDSs, demonstrating that these methods are

capable of identifying leakage events even under varying operational conditions, complex behavioral patterns, and the presence of outliers. The results indicated significant reductions in water losses and operational costs in case studies conducted on real-world networks in Australia. Trębicka (2023) used EPANET to simulate different hydraulic scenarios for a city in Poland, including network modernization and expansion scenarios. The results showed that network expansion was associated with reduced flow velocities and pipe discharges in specific sections due to demand redistribution and increased network connectivity. Conversely, the author highlighted that network expansion led to an increase in system reliability, underscoring the value of hydraulic modeling as a decision-support tool.

Olmuştur and Uysal (2025) investigated the implementation of a real-time pressure control strategy in a water distribution network of a city in Turkey, characterized by irregular rainfall patterns and high risks of extreme climatic events, similarly to dryland regions, aiming to reduce pressure levels, extend the service life of system components, and mitigate leakage-related water losses (Ceyhunlu and Cuma, 2025). Over a one-year operational period, the authors reported a 19% reduction in water losses. The network was modeled using EPANET, achieving differences of approximately 2% between simulated and measured values, which demonstrates the high reliability of the adopted hydraulic model. Brentan et al. (2024) analyzed the optimization of pump operation in a hypothetical water distribution networks, focusing on balancing energy efficiency and water quality preservation. Through hydraulic simulations and optimization strategies applied to a synthetic distribution network, the authors demonstrated that it is technically feasible to define operational schemes that simultaneously satisfy both criteria, highlighting the potential of hydraulic modeling to support operational decision-making. Finally, Mabrok et al. (2022) conducted a case study in Kuwait, which is characterized by extreme water scarcity comparable to dryland regions and a strong dependence on seawater desalination as its primary freshwater source, using EPANET to assess water quality in distribution networks, with particular emphasis on water age analysis. The authors emphasized the importance of considering multiple operational scenarios during the design phase, illustrating how hydraulic and water quality modeling can anticipate potential issues and support more robust planning decisions.

2.3.2 Hydraulic Calibration of Large-Scale Networks

To obtain a reliable and representative hydraulic model, it is essential to perform a calibration process. Calibration consists of the systematic comparison between field-monitored data and the results produced by the hydraulic model, followed by iterative adjustments of model parameters to minimize discrepancies between simulated and observed values. These adjustments aim to ensure that the model closely reproduces the actual behavior of the system, thereby increasing its reliability for operational scenario simulation and decision-support applications in WDS. The input parameters most commonly adjusted include pipe roughness, base nodal demands, water quality – related properties, and operational rules for pumps and valves. In turn, the output parameters used to evaluate model performance and support network monitoring primarily comprise flow rates, pressure heads, and concentrations of chemical constituents throughout the system.

The calibration of water distribution network models can be performed using different approaches, which are commonly classified into three main categories: iterative models (trial-and-error methods), explicit models (hydraulic simulation – based models), and implicit models (optimization-based models) (Savić et al., 2009). Iterative models require successive adjustments of unknown parameters at each iteration, largely guided by the experience and judgment of the user. This process involves multiple model executions until an acceptable calibration is achieved. Due to their low computational efficiency and strong dependence on the operator, this approach presents significant limitations and becomes impractical for large-scale networks, typically characterized by more than 500 pipes or service areas exceeding 20 km² (Bhave, 1988; Zanfei et al., 2020; Garzón et al., 2022).

Explicit models, in contrast, rely directly on the equations of mass and energy conservation to estimate calibration parameters, to prevent the need for iterative trial-and-error procedures (Ormsbee et al., 1986). However, this approach imposes important constraints, as it requires the number of parameters to be estimated to be equal to the number of available measurements. Moreover, measurement errors are not explicitly accounted for, which limits the quantification of uncertainties associated with the calibrated parameters and compromises the robustness of the results (Savić et al., 2009).

Finally, implicit calibration models employ optimization techniques to minimize one or more objective functions, typically defined based on the differences between field-measured variables and model-simulated variables. These models are referred to as “implicit” because the mass and energy conservation equations are embedded implicitly

within the hydraulic formulation of the problem (Savić et al., 2009; Zanfei et al., 2020). One of their main advantages is the flexibility in selecting decision variables, allowing for the simultaneous calibration of parameters such as pipe roughness, valve behavior, and nodal demands, while respecting predefined lower and upper bounds, which makes them particularly suitable for complex and large-scale networks.

The modeling of WDS applied to real and large-scale systems requires not only adequate data availability but also a thorough understanding of operational rules and a well-defined network topology. Furthermore, the large number of nodes and pipes, combined with the limited spatial and temporal coverage of monitored data, the presence of dynamic and complex operational rules, and the occurrence of inconsistent or inaccurate information, further increase the difficulty of obtaining a representative and reliable hydraulic model. In this context, the recent literature reports a growing number of studies that have addressed the calibration of WDS in real networks. Some of these works, published within the last five years and identified through the Scopus database, focus on the calibration of real-world water distribution networks and are summarized in Table 2.1.

Table 2.1 – Overview of recent studies on the calibration of real-world water distribution networks

References	Country	Calibration Method	Study Objective	Number of nodes	Diameter range (mm)	Network extension (km)	Points for calibration
Bouzari et al. (2025)	Algeria	Implicit	Water quality	-	90 to 1,200	246.8	11
Absalan et al. (2024)	Canada	Implicit		1,891	-	-	7
Costa et al. (2023)	Portugal	Implicit		-	-	5	5
Li et al. (2025)	China	Implicit	Planning / expansion	34,298	-	1,900	173
Abd et al. (2025)	Iraq	Implicit		17	110 to 225	23.3	33
Shi et al. (2024)	China	Implicit		-	800 to 6,000	234.07	12
Diaz-Ortiz et al. (2023)	Mexico	Implicit		147	-	-	7
Zhang et al. (2023)	China	Iterative (trial-and-error)		1,119	100 to 600	-	37
Kępa & Deska (2025)	Poland	Implicit	Operation / optimization	314	90 to 225	58.1	85
Mohammed et al. (2025)	Iraq	Implicit		1,092	100 to 500	379.79	4
Fernández – Guillamón et al.	Spain	Implicit		312	-	-	87

(2023)							
Chew et al. (2023)	Singapore	Implicit		11,796	15 to 1,400	331.4	36
Namtirtha et al. (2023)	India	Implicit		1,936	-	1,518	20
Zhao et al. (2022)	Australia	Implicit		-	80 to 1,400	77	8
Sidiropoulos et al. (2025)	Greece	Iterative (trial-and-error)	Leakage reduction	472	90 to 315	59.8	1
Galiatsatou et al. (2024)	Greece	Iterative (trial-and-error)		95	63 to 110	4.2	3
Leinæs et al. (2024)	Zambia	Implicit		652	-	-	23
Spizzo et al. (2023)	Italy	Implicit		5,793	150 to 600	406.6	-
Mekonnen (2023)	Ethiopia	Implicit		444	-	-	134
García et al. (2022)	Bahamas	Implicit		-	25 to 100	4.5	-
Ávila et al. (2022)	Ecuador	Iterative (trial-and-error)		832	59 to 581	65	1
Chew et al. (2022)	Singapore	Implicit		36,029	15 to 2,200	664.4	34
Negharchi et al. (2022)	Iran	Implicit		167	32 to 125	8	2
Seyoum et al. (2026)	United Kingdom	Implicit	General calibration	100	-	10.7	97
Pordal et al. (2023)	Iran	Implicit		±90	80 to 300	11.13	8
Song et al. (2022)	China	Implicit		625	200 to 1,400	118	4
Chen et al. (2022)	China	Implicit		-	-	870	60

Source: The autor.

The challenges associated with modeling and calibrating large-scale WDS become more pronounced when new and non-conventional water sources, such as desalinated water, are incorporated into the network.

2.3.3 Integration of Desalinated Water into Water Distribution Systems: Hydraulic and Operational Implications

In the face of increasingly critical water scarcity scenarios associated with climate change, desalination has emerged as a strategic alternative for countries with access to coastal zones. Desalination refers to the process of producing freshwater from saline sources,

including brackish water, seawater, and brine (Panagopoulos & Haralambous, 2020). However, despite technological advances and the growing adoption of desalination solutions, the impacts of introducing desalinated water into WDS, particularly from a hydraulic and operational perspective, remain insufficiently explored in the scientific literature.

In this context, Rouane et al. (2025) conducted a comprehensive review of the main desalination technologies, discussing their environmental impacts and future perspectives. The authors classify desalination technologies into five major groups: Reverse Osmosis (RO), Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), Electrodialysis (ED), and hybrid and polygeneration systems. Although RO is currently the most widely implemented and extensively discussed technology, a relevant knowledge gap persists regarding its hydraulic effects and operational integration within water distribution networks.

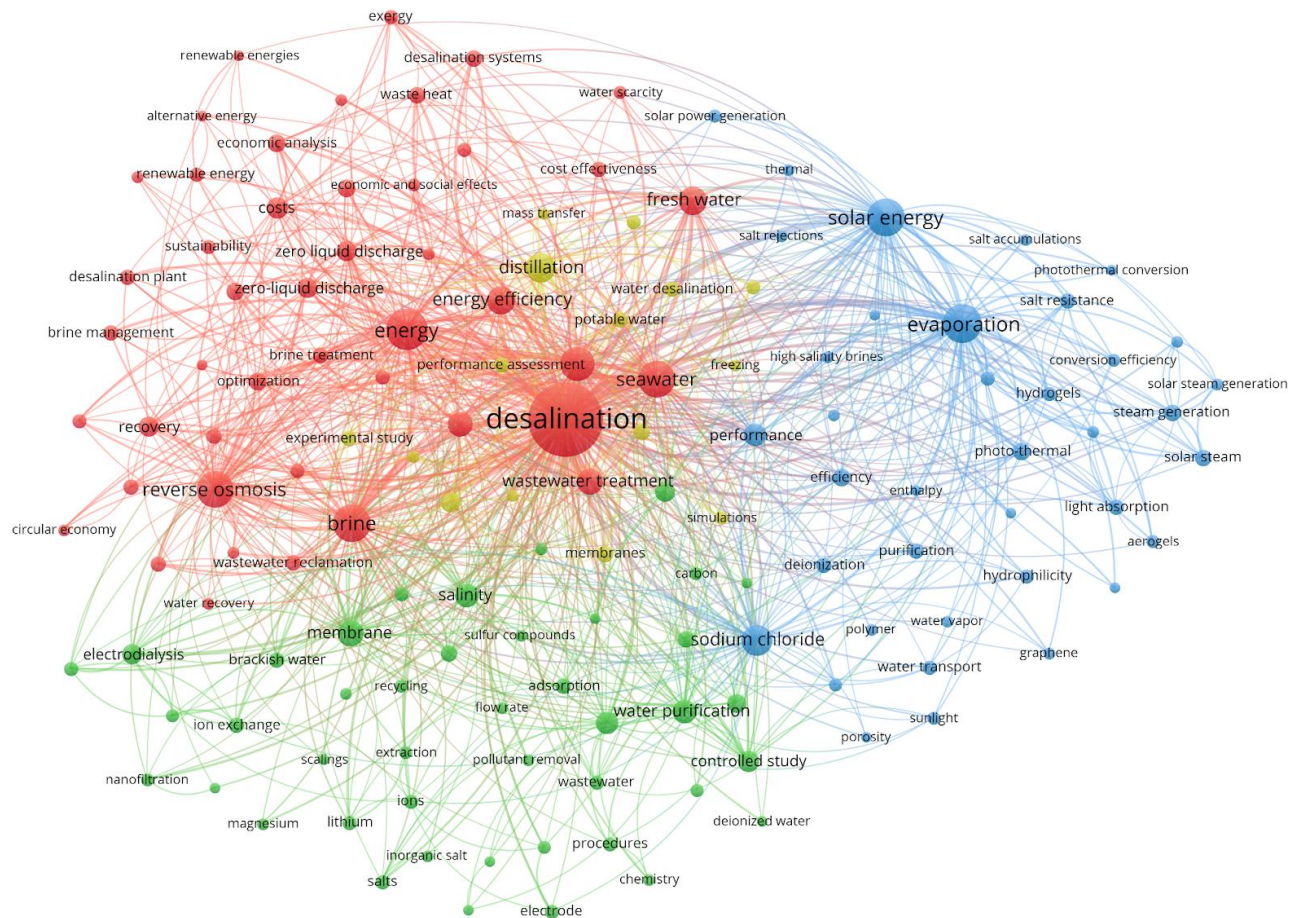
In parallel with technical and environmental discussions, the economic viability of desalination has also been the subject of debate. While desalination plants are traditionally regarded as having higher capital and operational costs compared to conventional water supply sources, Crookes (2018) demonstrated that, under specific institutional and management contexts, desalination can contribute to reducing water tariffs for consumers. The author further highlights that such reductions may expand access to potable water, including for low-income populations, reinforcing the need for integrated assessments that consider not only production costs but also the systemic effects of desalination on the operation, resilience, and overall performance of WDS.

A substantial body of literature has addressed the environmental impacts of desalination and their implications for distributed water quality, with particular emphasis on the adverse effects associated with brine discharge and the high energy demand of desalination processes. Panagopoulos and Haralambous (2020) conducted a comprehensive review of the environmental impacts of desalination and brine management, identifying several critical issues, including brine disposal and its association with localized changes in salinity and temperature, the presence of chemical residues, and adverse effects on marine ecosystems and organisms. In addition, the authors highlighted the high energy requirements of desalination and brine treatment processes, which, depending on the country's energy matrix, could be reliant on fossil fuels and may result in significant greenhouse gas emissions. Jones et al. (2019) similarly identified brine disposal as a critical challenge for desalination plants, noting that the global volume of brine produced substantially exceeds the volume of desalinated water, thereby increasing environmental risks related to hypersalinity and

chemical loading in receiving water bodies. Nassrullah et al. (2020), in turn, reviewed the state of the art of energy use in desalination and observed that current desalination processes operate close to their thermodynamic limits, implying that further reductions in energy consumption are inherently constrained and largely dependent on technological innovations or the integration of renewable energy sources.

To highlight the existence of a broad and well-established body of literature on desalination and its main negative impacts, particularly those related to brine management and high energy demand, Figure 2.2 presents a keyword co-occurrence map constructed from publications indexed in the Scopus database between 2020 and 2026, considering a minimum occurrence threshold of 35 terms. The map reveals the predominance and strong interconnectivity of keywords such as “brine”, “energy”, “energy efficiency”, and “reverse osmosis”, indicating that concerns regarding brine generation and management, as well as the energy requirements of desalination processes, represent central and recurring themes in the scientific literature. While these findings demonstrate the depth and robustness of research addressing the environmental and energy-related impacts of desalination, they also suggest that comparatively few studies explicitly examine how desalinated water influences pressure patterns, hydraulic stability, and operational reliability in large-scale water distribution networks.

Figure 2.2 – General bibliometric map of the literature on desalination using VOSviewer.



Source: The author.

Nevertheless, several open questions remain in the literature, particularly regarding the hydraulic effects of desalinated water within water distribution networks. These include how the introduction of desalinated water influences pressure and flow patterns throughout the network, especially in large-scale WDS; the impacts of intermittent desalination plant operation on hydraulic stability; the extent to which continuous pumping requirements and strategic storage influence energy performance and pressure dissipation; and the effects of desalinated water introduction on the spatial distribution of pressures within WDS.

Despite the limited number of studies directly linking desalination to WDS, it is possible to draw well-grounded inferences regarding this issue. One such inference is that, if the seawater desalination process itself already entails a high energy demand, the conveyance of desalinated water over long distances and toward storage reservoirs located at high elevations is likely to require even greater energy inputs for pumping operations (Araya et al.,

2018). In addition, such configurations may necessitate structural adaptations to the WDS, including the installation of additional pumping stations and transmission mains, in order to ensure adequate hydraulic performance and operational reliability. In this context, selecting desalinated water injection points located far from the coastline may introduce additional energy and operational challenges, particularly when motivated by the need to mitigate excessive pressure increases in areas close to the desalination plant. Consequently, from an operational perspective, there is a tendency to inject desalinated water into the distribution system at locations close to the desalination plant, which, in turn, leads to increased available pressures in the immediately surrounding areas (Rocha et al., in submission). As a result, pressure heterogeneity across the WDS is likely to increase, with regions farther from desalination plants exhibiting lower pressure levels than those observed in areas near the injection points. Such disparities may affect socially vulnerable populations, as desalination plants tend to be located in coastal regions characterized by strong economic attractiveness and generally associated with higher levels of socioeconomic development (Yılmaz & Terzi, 2021). In contrast, areas farther from the coastline may experience lower pressure levels and poorer service quality, thereby reinforcing socio-spatial inequalities in access to water supply services.

To reduce energy consumption associated with intensive pump operation in desalination processes or to enable periodic maintenance activities, several studies have suggested the adoption of intermittent operational schemes (Wu et al., 2024; Freire-Gormaly & Bilton, 2018). Such intermittency typically involves scheduled shutdowns during the operation of desalination systems. Freire-Gormaly and Bilton (2018) conducted experimental studies using reverse osmosis as the desalination technique and concluded that intermittent operation, combined with the use of antiscalants and permeate flushing, reduces membrane fouling, thereby preventing performance deterioration in the desalination process. However, the intermittent operation of pumping systems in pressurized pipelines may give rise to hydraulic transients, which are inherent to water flow processes and are characterized by pressure variations and the propagation of waves throughout the system (Capponi et al., 2025). The literature indicates that, in structurally complex water distribution systems, these natural transient phenomena may become more pronounced, resulting in localized pressure variations at specific points in the network that do not necessarily coincide with direct water injection locations or the immediate vicinity of supply sources (Starczewska et al., 2014; Bohórquez et al., 2020). Repeated pressure peaks over time may promote fatigue processes in pipes and

fittings, resulting in the formation of leaks which, in large-scale systems, pose increased challenges for detection and localization (Marsili et al., 2023).

One strategy to mitigate the effects of intermittency in the injection of desalinated water into WDS consists of the use of storage reservoirs, which are capable of supplying demand during periods when desalination production or water injection into the WDS is interrupted (Rashedi et al., 2025). In this configuration, water is stored during periods of desalination plant operation and subsequently used when production or injection is temporarily suspended. However, the proper management of water residence time in storage reservoirs is a critical factor for preserving water quality in distribution systems, since low renewal rates of the stored volume tend to increase water age and intensify risks to the quality of water supplied to the population, such as residual chlorine decay, microbial growth, and the presence of undesirable organisms (Geng et al., 2022).

2.4 Conclusions

This review examined the role of hydraulic modeling and calibration in water distribution systems, with particular emphasis on their application in assessing the hydraulic and operational impacts associated with the integration of desalinated water into real-world networks. The findings indicate that, over time, hydraulic modeling and calibration have become essential tools for planning, operation, and decision-making in water supply systems, enabling the analysis of scenarios related to pressures, flow rates, water losses, water quality, and energy performance.

Despite the extensive body of literature on desalination addressing technological, environmental, and energy-related aspects, this review identified notable gaps in the understanding of desalinated water injection and its hydraulic and operational effects on water distribution systems. Understanding the impacts of desalination is essential, as this technology continues to expand worldwide, particularly in regions experiencing severe water scarcity.

Evidence suggests that the injection of desalinated water tends to occur in areas close to desalination plants due to energy-related constraints, which may intensify the spatial heterogeneity of pressures across the network, resulting in higher pressure levels near injection points and lower values in more distant areas. In addition, the intermittent operation of desalination systems, which is often adopted, may give rise to hydraulic transients in

pressurized pipelines. These phenomena are inherent to water flow and may result in localized pressure variations which, over time, can contribute to fatigue processes and the occurrence of leakage. Even when storage reservoirs are used to mitigate the effects of intermittency, this solution requires careful management of water residence time in order to prevent water quality degradation, such as residual chlorine decay and microbial growth.

Overall, the findings reinforce that hydraulic modeling and calibration constitute central tools for understanding and mitigating the challenges associated with the integration of desalinated water into water distribution systems. Future studies should advance the development of integrated approaches that jointly and systematically consider hydraulic, operational, energy-related, and water quality aspects in large-scale systems applied to real urban contexts, while also integrating climatic conditions and water loss processes as key components of system performance.

3 KEY CALIBRATION STRATEGIES FOR MITIGATION OF WATER SCARCITY IN THE WATER SUPPLY MACROSYSTEM OF A BRAZILIAN CITY¹

3.1 Introduction

Water Distribution Systems (WDS) play a strategic role in addressing water deficits. Through effective design, operational control, and understanding of hydraulic parameters, it is possible to reduce losses throughout the system. These losses can reach yearly millions of cubic meters worldwide, with more severe impacts in developing countries (Dighade et al., 2014; Kizilöz, 2021). Moreover, the rapid population growth driven by urbanization intensification and the adverse effects of extreme climate events pose significant challenges to ensuring water supply for large urban centers (Greve et al., 2018; Rustam et al., 2024). These challenges are even more important in semi-arid regions, characterized by high temperatures and minimal annual precipitation. In such regions investments in water infrastructure are essential to meet multiple uses and ensure an adequate water supply (Campos et al., 2016; Pereira et al., 2024). Computational hydraulic simulation models are useful as management tools for water systems, enabling visualizing and predicting hydraulic and quality indicators, and enabling scenario anticipation.

Before using the results from hydraulic simulation, the calibration step is a key part of the process. It involves minimizing errors between monitored and calculated data by adjusting the input parameters of the hydraulic network model, often including pipe roughness, node base demand, water quality properties, and the operational rules of pumps and valves (Meirelles et al., 2017; Zhao, 2022). Calibration is frequently supported by optimization tools that adjust WDS model parameters to achieve optimal results, typically verified using pressure head, flow rate, and chemical concentration data. Reliable hydraulic models developed by various calibration and optimization methods can enhance WDS operations (Savic et al., 2009; Ferreira et al., 2022). Such models may help reduce energy costs (Maskit & Ostfeld, 2021), expand water supply with adequate pressure head (Zanfei et al., 2023), detect leaks, and pipeline obstructions (Nicolini et al., 2011; Salvino, 2015; Romero-Ben et al., 2023), and rehabilitate WDSs with fewer interventions and greater precision (Osorio et al., 2023).

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Calibration studies for WDS models are generally complex when applied to large-scale real networks (models with over 500 pipes and covering areas larger than 20 km², as classified by Garzón et al., 2022) due to limited data availability, operational rules complexities, network topology, and size uncertainties. These challenges lead many studies to focus on hypothetical or benchmark WDS models instead (Meirelles et al., 2017; Moasheri et al., 2021; Garzón et al., 2022; Farghadan et al., 2023). However, hypothetical WDS models introduce simplifications that may limit the application of proposed methodologies for real WDS calibrations. Real hydraulic model calibration presents various difficulties, including the large number of nodes and pipes to optimize, the limited distribution of monitored data, dynamic operational rules, and data errors or omissions that force researchers to disregard existing information (Savic et al., 2009; Chu et al., 2022). Furthermore, despite optimization methods, modelers' knowledge, sensitivity, and experience remain crucial in tasks such as parameter selection, anomaly identification, operational rule adjustments, network behavior analysis, and other aspects (Ostfeld et al., 2012).

Several WDS calibration methods are highlighted in the literature, particularly automatic approaches known for their precision and efficiency in real networks (Zhang et al., 2018; Zhao et al., 2022). These automatic calibration methods are broadly categorized into numerical and optimization-based approaches. Numerical approaches directly solve continuity and energy equations using numerical methods such as weighted least squares and singular value decomposition, making calibration complex and time-consuming for large-scale networks (Chu et al., 2020; Chu et al., 2022). On the other hand, optimization-based approaches reduce differences between simulated and observed results by adjusting decision variables through nonlinear hydraulic equations, a highly complex process (Zhang et al., 2018; Zhang et al., 2023). To address these challenges, Evolutionary Algorithms (EAs) have been employed due to their heuristic flexibility and ability to solve nonlinear, non-convex, and multimodal problems, making them particularly suitable for WDS calibration (Nicklow et al., 2010; Zhang et al., 2018).

Particle Swarm Optimization (PSO) is one of the AEs with strong applicability in WDS, as it is particularly effective due to its ability to converge quickly to solutions, making it highly practical for real WDS hydraulic models (Savic et al., 2009; Zhang et al., 2024). PSO is a random global quasi-optimal solution search algorithm to minimize the differences between monitored and simulated data. In addition, the method is inspired by the theory of swarm intelligence, which considers the exchange of information and the coevolution of

species in a colony, as observed in bird migrations or fish schooling behaviors (Meirelles et al., 2017; Minaee et al., 2019; Zhang et al., 2024). Over time, PSO and its more than 22 variants have been applied in WDS calibrations and other diverse hydraulic applications (Jahandideh-Tehrani et al., 2020).

This study evaluates the PSO method for calibrating real, large-scale WDS by focusing on the water supply macrosystem of a major Brazilian city with water availability challenges. The calibration process incorporated 48-hour monitoring data from 50 pressure head points and 40 flow rate points, as well as operational rules of 48 pressure head-reducing valves. This approach mirrors real-world complexities, contrasting with many studies that overlook such operational data. However, it also emphasizes that classical calibration alone is insufficient for accurate model performance. Inferring a priori knowledge about system behavior, such as operational constraints and infrastructure specifics, is crucial for improving calibration outcomes. Calibration was assessed using five hydraulic modeling indicators and comparative pre-and post-calibration graphs. The results demonstrated great hydraulic model improvement, enhancing its predictive capabilities and adaptability to various scenarios, such as integrating new water supply sources or responding to severe water crises.

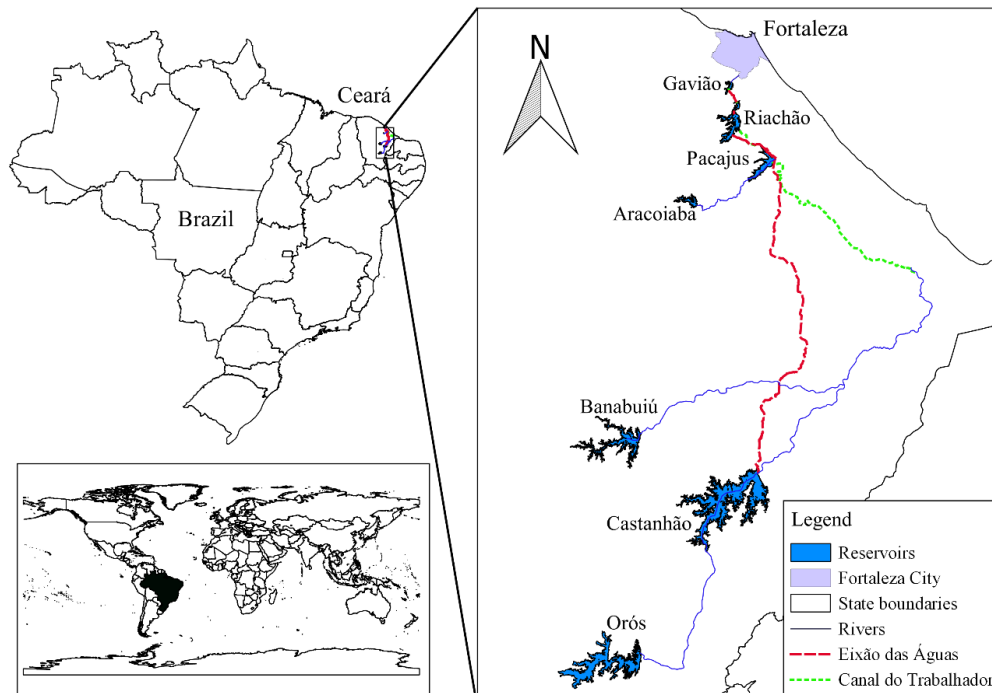
3.2 Materials and Methods

3.2.1 Study area

Fortaleza, the capital of Ceará state in Brazil, has approximately 2.5 million inhabitants and is located in the country's semi-arid Northeast region. This region is characterized by low annual precipitation (1338 mm), high evaporation rates (1435.2 mm), elevated temperatures (26 to 28 ° C), limited groundwater resources, intermittent rivers, and irregular rainfall patterns, resulting in water constraints throughout most of the year (Souza Filho, 2018; Mesquita et al., 2020; Walker et al., 2024). The city's water infrastructure includes two Water Treatment Plants (WTP Oeste and WTP Gavião) and eight reservoirs: Gavião, Pacoti, Riachão, Pacajus, Aracoiaba, Banabuiú, Orós, and Castanhão, with a combined storage capacity exceeding 11,000 hm³. These reservoirs are integrated through two major water supply systems: the "Canal do Trabalhador" and the "Eixão das Águas" (Silva et al., 2019). Together, the treatment plants have a maximum productivity of 15 m³/s, however during the multi-year 2012 - 2017 drought this capacity was reduced to 8.2 m³/s. In

response to the city's ongoing water scarcity challenges, Fortaleza began the development of a seawater desalination plant project (DESAL) with a projected production capacity of $1 \text{ m}^3/\text{s}$, which is expected to supply water to approximately 300,000 inhabitants (Uchôa et al., 2022; CAGECE, 2023). Figure 3.1 illustrates Fortaleza's water system.

Figure 3.1 – Location and water system of Fortaleza City, emphasizing the multiple reservoirs and hydraulic works that contribute to the city's water security.



Source: The author.

3.2.2 Macrosystem of the Metropolitan Region of Fortaleza (MMF)

The water supply macrosystem model of Fortaleza comprises 479 junctions, one reservoir, and four tanks, resulting in 484 nodes. In addition, the model includes 393 pipes, 19 pumps, and 103 valves, resulting in 515 links. The total length of the pipes is 202.59 km and occupies an area of around 350 km^2 , with most of this extension composed of pipes more than 1000 mm in diameter (ranging from 50 mm to 1,900 mm), as shown in Table 3.1. The average topographic elevation of the hydraulic elements is 33.6 m, with the highest point at an elevation of 103.4 m and the lowest point at an elevation of just 7.5 m. The base demand of the 84 consumption nodes ranges from 0.37 to 868.3 L/s, according to information provided by the state water and sewage agency. In turn, the system is equipped with 48 pressure head-reducing valves governed by hourly operating rules.

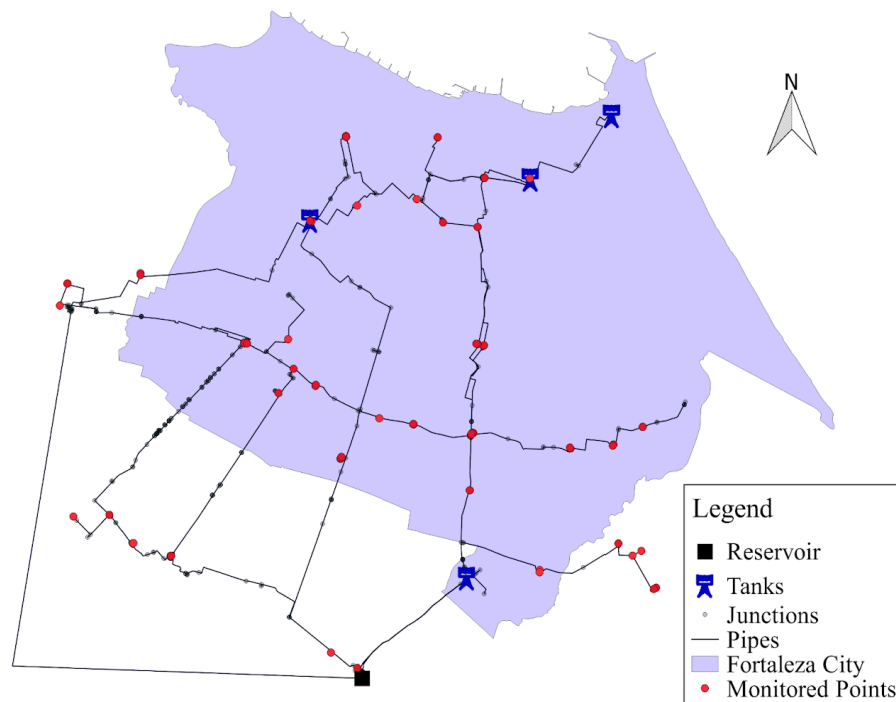
Table 3.1 – Pipes distribution in the analyzed network by diameter

Diameter	Number	Extension (km)
≤200 mm	61	1.73
200 a 400 mm	43	9.94
400 a 600 mm	105	46.19
600 a 1000 mm	107	60.06
≥1000 mm	77	84.67
Total	393	202.59

Source: The autor.

The water supply macrosystem model was provided by the State Water and Wastewater Agency (CAGECE) in a format compatible with EPANET 2.2 software. The schematic representation of this water distribution macrosystem model and the location of the monitored points are shown in Figure 3.2.

Figure 3.2 – Analyzed macrosystem, along with the locations of the monitored points.



Source: The autor.

3.2.3 Methodology

This study calibrated the proposed WDS model using observed pressure head and flow rate data provided by the State Water and Wastewater Agency (CAGECE) and performed an overall performance assessment. The calibration process was implemented using the EPANET–MATLAB toolkit (Eliades et al., 2016). The calibration relied on data from 50 pressure head monitoring points and 40 flow rate monitoring points, totaling 90 monitoring points, over two typical operational days, totaling 2,400 pressure head data points and 1,920 flow rate data points employed in the analysis. Modifications to valve operation rules are also implemented. The model's 48 pressure head-reducing valves, each with hourly operation rules, introduced a level of complexity to the calibration process, particularly due to the interactions between valve settings and pipe roughness, as variations in pressure regulation can influence flow distribution and, consequently, affect the calibration of roughness parameters. This complexity is addressed through manual adjustments in EPANET software during the calibration in collaboration with the state water and wastewater agency. These adjustments involved analyzing the operation rules through generated graphs and assessing their influence on network nodes. The valve operation rules are adjusted (e.g., increasing or decreasing pressure head control values) or, in some cases, removed to better match the observed monitoring point values while avoiding potential negative pressure heads at any network node during the modeled period. It's important to highlight that each pressure head-reducing valve has operation rules for each time step, meaning that 2,304 operation rules are analyzed. Any modification to a single rule impacted the network's behavior. Therefore, for each calibration iteration, these operation rules are considered, as it would not have been possible to achieve a minimally calibrated model without these adjustments. This highlights the complexity of calibrating large-scale hydraulic WDS models (Rathi et al., 2020).

Moreover, this study prioritized the calibration of the base demand factors, ranging from 0.1 to 4, before addressing the calibration of pipe absolute roughness (ϵ), ranging from 0.0001 mm to 15 mm. Therefore, the calibration process was conducted in the following sequence: (1) base demand and (2) absolute roughness. These variation ranges for both parameters were defined through an iterative calibration process involving several successive trials aimed at properly establishing the limits of variation for base demand and absolute roughness. Initially, preliminary ranges were assumed for each parameter. Based on the results obtained in each calibration attempt, it was evaluated whether the estimated values

approached the previously defined limits. When the results indicated excessive proximity to the limits or a tendency toward extrapolation, the ranges were adjusted and redefined for the subsequent simulation round. Thus, through successive tests and refinements of the variation ranges for base demand and absolute roughness, more consistent and representative limits were established for both variables used in the calibration process. After optimizing the objective function for base demand calibration, these values are updated in the hydraulic model, and the network conditions are checked for the presence of negative pressure heads. This sequence is chosen because base demand significantly influences flow rate behavior in hydraulic models, thereby affecting flow rates and hydraulic head losses. In addition, this parameter is more variable than roughness (Leinæs et al., 2024), introducing high uncertainty into the network, with any variation altering its behavior, making base demand a dominant factor in hydraulic networks (Hossain et al., 2021). Once the hydraulic model is adjusted, absolute roughness values are calibrated, updated in the hydraulic model, and verified for negative pressure heads within the network. In summary, the calibration process utilized in this study required pre-calibration operational adjustments to achieve a hydraulic model that closely represents real-world conditions.

The PSO method aims to minimize the objective function by iteratively changing and updating the position of particles within the search space, thereby seeking the best individual and collective positions. The objective function used in this study corresponds to the Mean Absolute Error (MAE). Thus, a particle “i” can be represented by two vectors: one representing the spatial position “ x_i ” and the other representing the search velocity “ v_i ”. Initially, the particles are randomly distributed, generating the first solution. Subsequently, the particles are moved so that those farther from the best solution converge toward it, storing the best position based on both individual and collective best-known position of the swarm (Kennedy and Eberhart, 1995; Meirelles et al., 2017; Anchieta et al., 2024). This iterative process is described by equations (3.1) and (3.2):

$$v_i^{t+1} = wv_i^t + c_1r_1 \frac{(x_i^t - l_i^t)}{\Delta t} + c_2r_2 \frac{(x_i^t - g_i^t)}{\Delta t} \quad (3.1)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \Delta t \quad (3.2)$$

Where “ i ” represents the particles of the swarm; “ r_1 ” e “ r_2 ” are the values of the random distribution, with values varying from 0 to 1; “ c_1 ” is the cognitive factor related to the information of the particle's best positions; “ c_2 ” is the social factor related to the information of the best positions experienced by the group; “ w ” is the inertia coefficient responsible for weighting the velocities of the particles; “ l_i^b ” represents the vector of the best local solution; “ g_i^b ” represents the vector of the best global solution or the swarm's best solution.

The results of the calibrated network are compared with the results of the pre-calibration network, using quantitative evaluation parameters and an overall performance assessment, in addition to a graphical analysis of the flow rate and pressure head behavior. The quantitative evaluation was conducted through the Mean Absolute Error (MAE), Average Relative Hourly Error (ARHE), Nash-Sutcliffe Efficiency Coefficient (NSE), Coefficient of Determination (R^2), and Percentual Bias (PBIAS). The MAE is calculated as the sum of the absolute difference between the monitored and modeled values, divided by the total number of data points. The ARHE evaluates the absolute difference between the monitored and modeled values, normalized by the monitored value and the number of simulated hours (48 hours). In this way, the ARHE considers the deviation of the monitored and modeled data for each hour of the simulation, thus allowing a more detailed analysis of the deviation behavior. The NSE evaluates the model's efficiency by comparing the squared difference between the monitored and modeled values with the squared deviation of the monitored values from their mean. Its range spans from 1 (perfect model representation) and $-\infty$ (the mean of observed data is a better predictor than the model itself). This metric is one of the main indicators of the accuracy of hydrological models, but it can also be applied in hydraulic modeling (Rahman et al., 2019). The R^2 reflects the proportion of variance explained by the model, representing the degree of alignment between observed and modeled values. It ranges from 0 (poor regression fit) to 1 (perfect regression fit), indicating how well the model predicts observed data (Rahman et al., 2019). The last indicator used was the PBIAS, which considers the trend of the mean modeled values in relation to the monitored values. For this indicator, the closer the value is to zero, the better the model performance. According to Moriasi et al. (2015), satisfactory PBIAS values depend on the variable being analyzed, with the most stringent threshold being $\pm 15\%$. Negative PBIAS values indicate that the model is overestimating the results, while positive PBIAS values suggest an underestimated model (Ghimire et al., 2024). Below is the list of equations used for the model indicators:

Table 3.2 – Relationship of Model Indicators and Their Equations

Indicators	Equations
Mean Absolute Error	$MAE = \frac{\sum_{i=1}^n abs(O_i - M_i)}{n.h}$
Average Relative Hourly Error (%)	$ARHE = \frac{\sum_{i=1}^n abs\left(\frac{O_i - M_i}{O_i}\right)}{n.h} \cdot 100$
Nash-Sutcliffe Efficiency Coefficient	$NSE = 1 - \frac{\sum_{i=1}^n (O_i - M_i)^2}{\sum_{i=1}^n (O_i - O_i^{mean})^2}$
Coefficient of Determination	$R^2 = \left(\frac{\sum_{i=1}^n (O_i - O_i^{mean})(M_i - M_i^{mean})}{\sqrt{\sum_{i=1}^n (O_i - O_i^{mean})^2 \cdot \sum_{i=1}^n (M_i - M_i^{mean})^2}} \right)^2$
Percentual Bias (%)	$PBIAS = \frac{\sum_{i=1}^n (O_i - M_i)}{\sum_{i=1}^n O_i} \cdot 100$

Source: The autor.

Where “ O_i ” are the observed or monitored data and “ O_i^{mean} ” is their respective mean; “ M_i ” are the values obtained from the modeling and “ M_i^{mean} ” is their respective mean; “ n ” is the number of observed or monitored nodes, and “ h ” is the number of hours used in the simulation.

3.3 Results and Discussion

The values of the five chosen indicators used to evaluate the calibration of roughness and base demands through pressure heads and flow rates are summarized in Tables 3.3 and 3.4. The results indicate that the calibration process successfully met the proposed

objectives. For pressure heads, 4 out of the 5 indicators demonstrated a better fit between the proposed model and the monitored data. Similarly, all 5 indicators for flow rates showed an improved alignment between the model and the observations.

Figure 3.3 shows an example of the typical average behavior of a monitored point for the pressure heads and flow rates of the analyzed WDS hydraulic model. Figure 3.3 shows the pressure head and flow rate scale presented in the Fortaleza microsystem and how well the calibrated model tracks the behavior of the monitored data over the 2-day period. It is important to note that, in Figure 3.3, the y-axis does not start at zero to enhance visualization.

Table 3.3 – General Results of the Calibration Indicators for Pressure heads

	MAE	ARHE	NSE	R²	PBIAS
Before Calibration	7.10 m	31.13%	0.597	0.623	2.64%
After Calibration	3.53 m	12.96%	0.873	0.879	3.38%

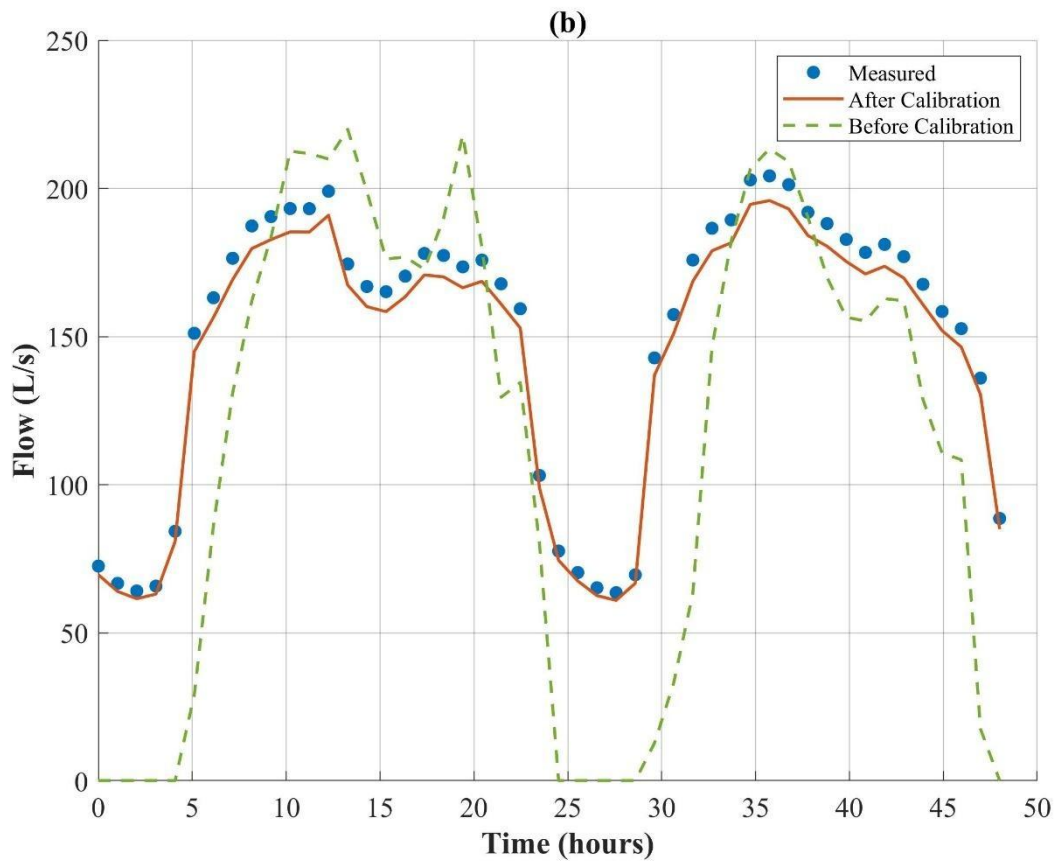
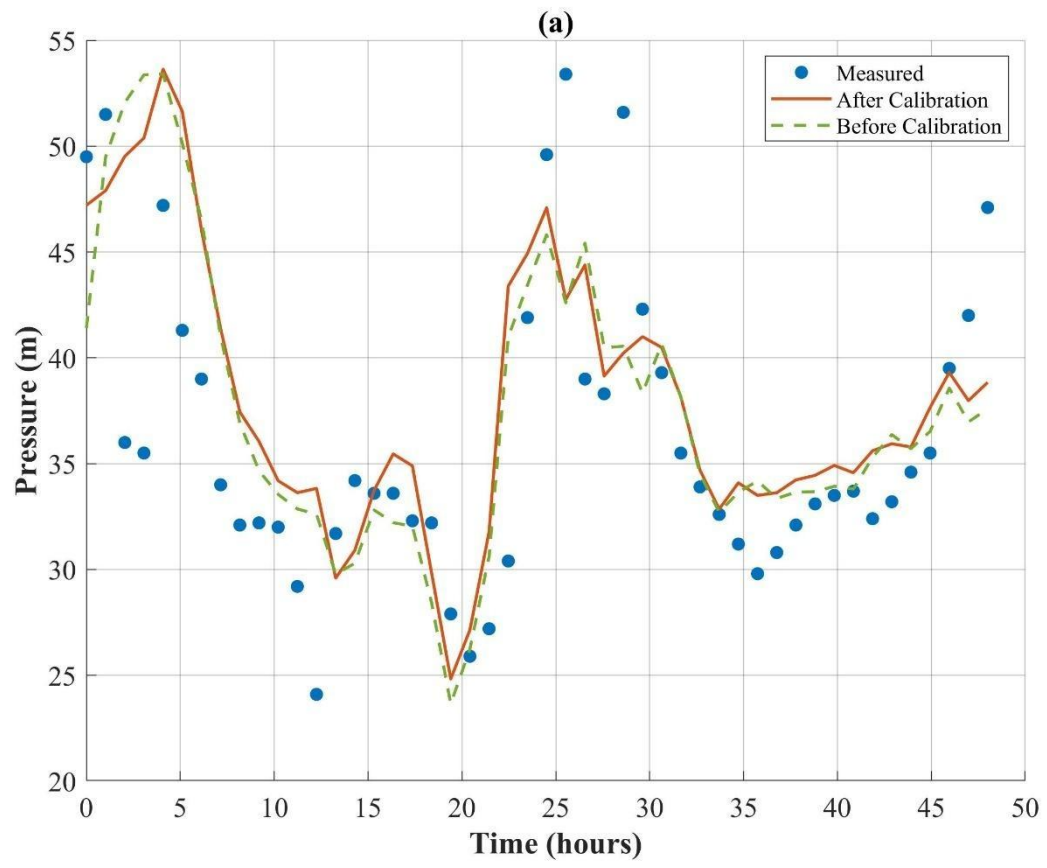
Source: The autor.

Table 3.4 – General Results of the Calibration Indicators for Flow rates

	MAE	ARHE	NSE	R²	PBIAS
Before Calibration	43.7 L/s	320.79%	0.754	0.780	11.80%
After Calibration	16.3 L/s	13.09%	0.965	0.965	1.06%

Source: The autor.

Figure 3.3 – Analysis of the typical average behavior of the network through a monitored point for pressure head (a) and flow rate (b).

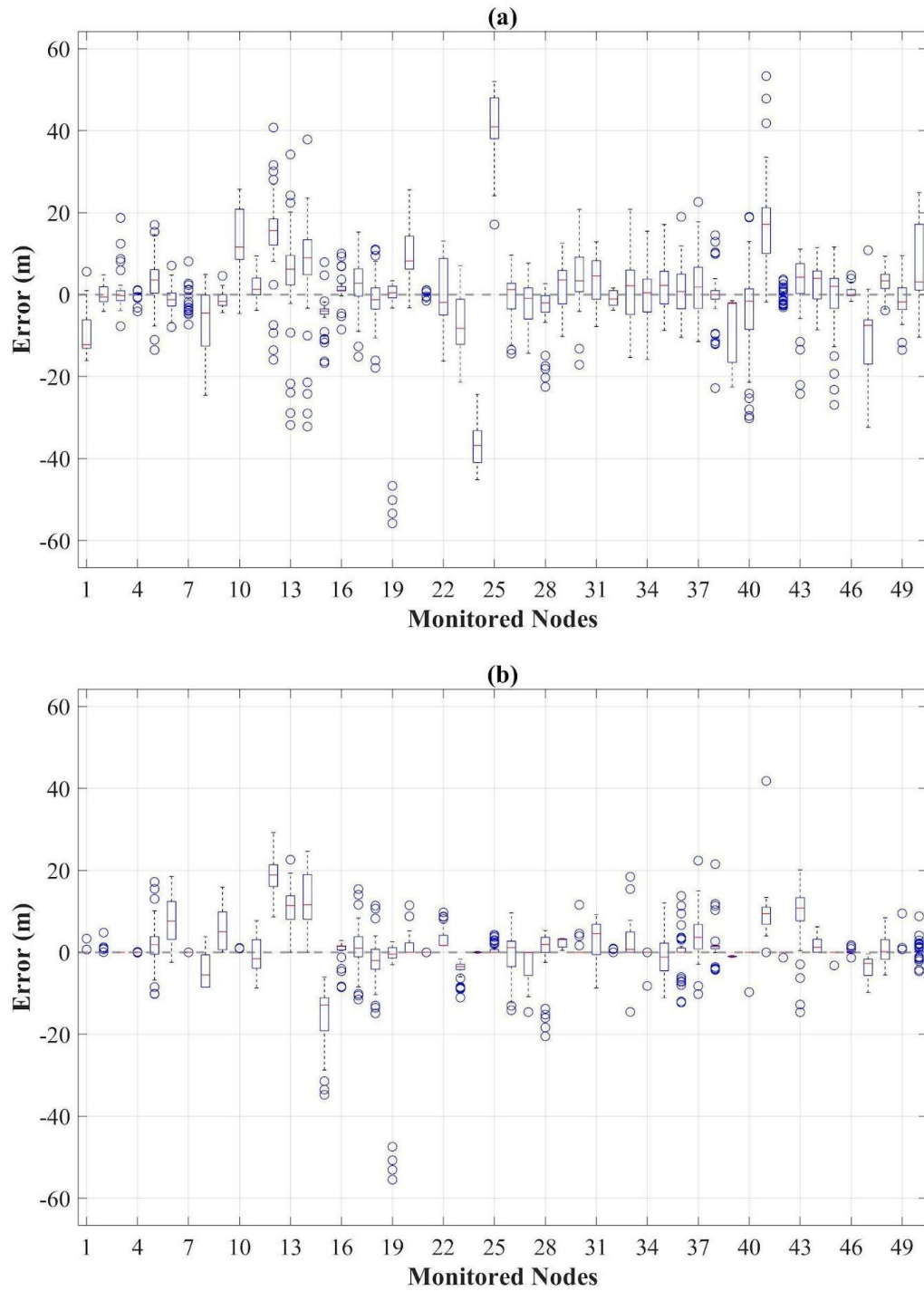


Source: The author.

Figures 3.4, 3.5, 3.6, and 3.7 show the behavior of the pipes and nodes represented by the Box&Whiskers diagram, which aims to represent the variability of the data and summarize various value distributions using the median, quartiles, minimum, maximum, and outliers (Farmani et al., 2005; Housh & Jamal, 2022). Figures 3.8, 3.9, 3.10, 3.11, 3.12, and 3.13 consist of scatter plots addressing the relationship between a set of binary data, representing the behavior of the evaluation parameters for each monitored point and its respective modeled value, allowing the visualization of the network's overall behavior.

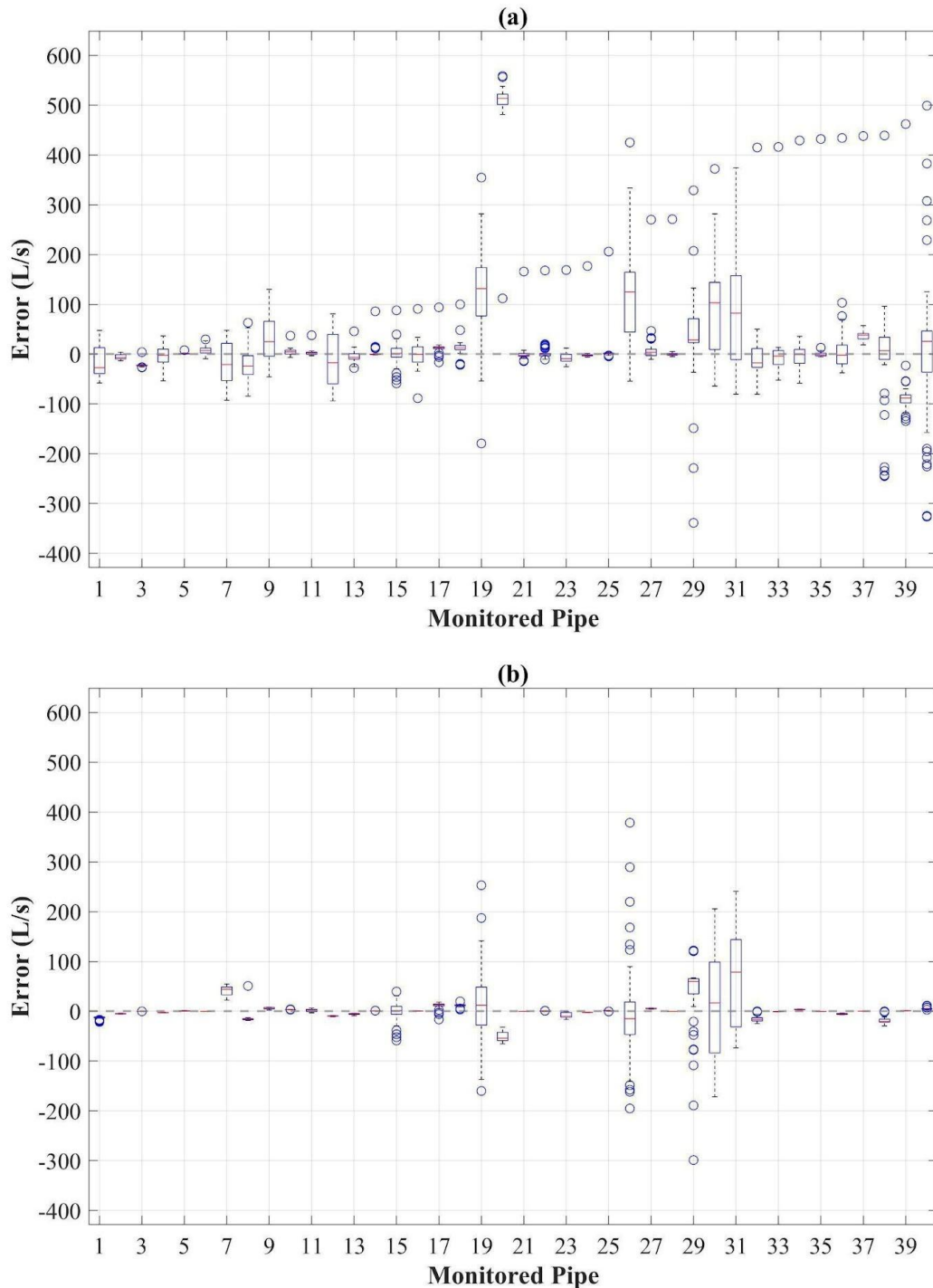
Figures 3.4 and 3.5 show the improvement in the hydraulic model after calibration, considering the error between the monitored and calculated data. The Box & Whiskers diagram for the MAE demonstrates a reduction in the number of outliers and a clustering of values closer to zero on y-axis after calibration. In Figure 3.4, monitored points 24 and 25 highlight the reduction in pressure head errors after calibration. Similarly, in Figure 3.5, shown a reduction of outliers above 300 L/s after calibration, a value that corresponds to nearly 30% of the highest monitored value for flow rates. For both pressure head and flow rate, the MAE was reduced by over 50%. Furthermore, considering the maximum allowable error of 2 m for pressure heads, as defined by the Water Research Center (1989), the calibrated model achieves approximately 60% of pressure heads within this limit, while before calibration, compared to only 33% prior to calibration.

Figure 3.4 – Box & Whiskers of the MAE for pressure heads (a) before calibration and (b) after calibration



Source: The author.

Figure 3.5 – Box & Whiskers of the MAE for flow rates (a) before calibration and (b) after calibration

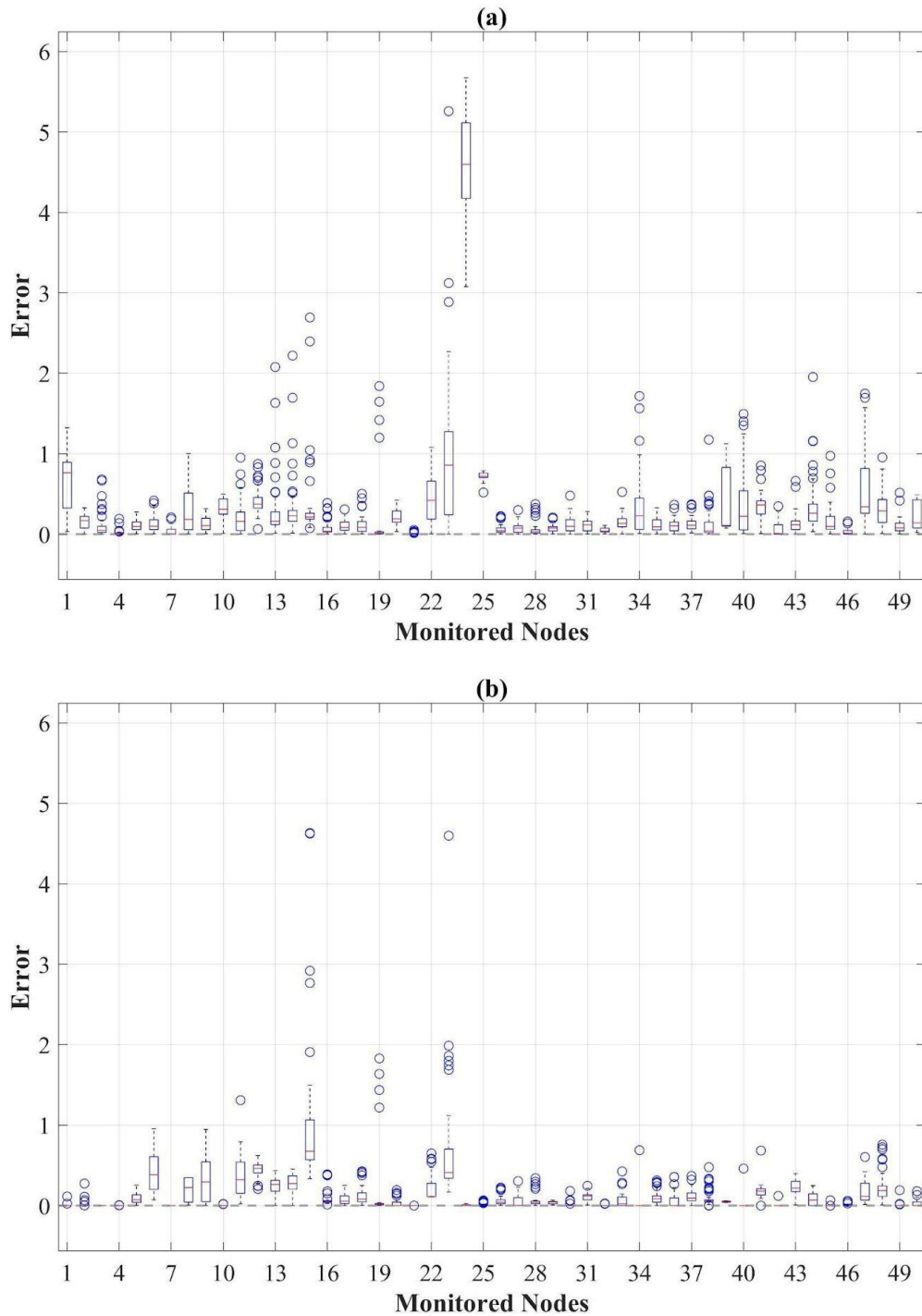


Source: The author.

As the ARHE represents the average relative hourly error, this indicator reflects the behavior of the errors in hourly pressure heads and flow rates, allowing for a more detailed analysis of the parameters considered. Figure 3.6 shows the reduction in the number of relative errors above 1 for pressure heads after calibration compared to before. Similarly,

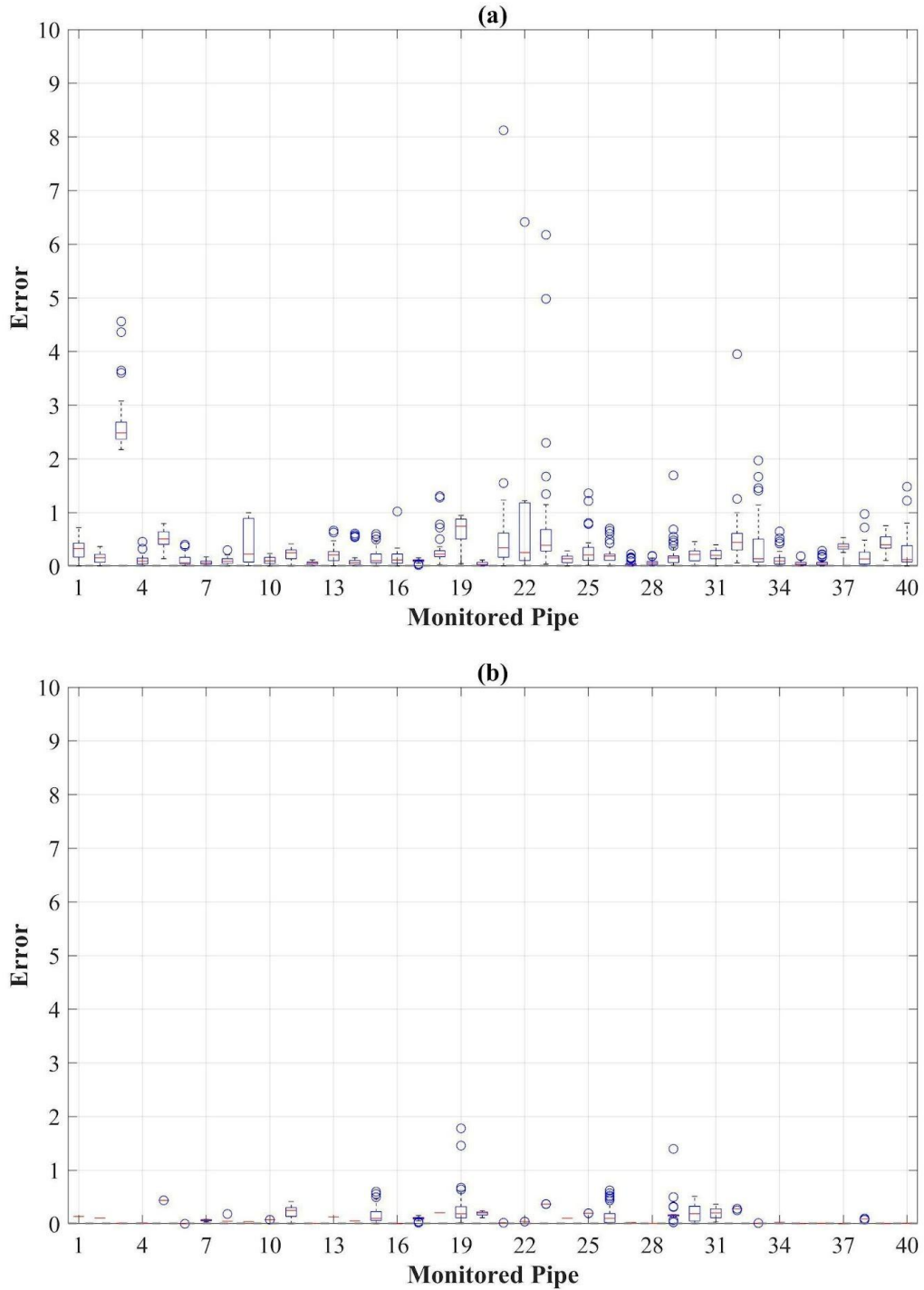
Figure 3.7 highlights how much calibration reduced in flow rate relative errors, which decreased from a maximum of approximately 8 before calibration to below 2 after calibration. Therefore, the improvement is more noticeable for the flow rates, as the reduction is higher than 95%.

Figure 3.6 – Box & Whiskers of the ARHE for pressure heads (a) before calibration and (b) after calibration



Source: The author.

Figure 3.7 – Box & Whiskers of the ARHE for flow rates (a) before calibration and (b) after calibration

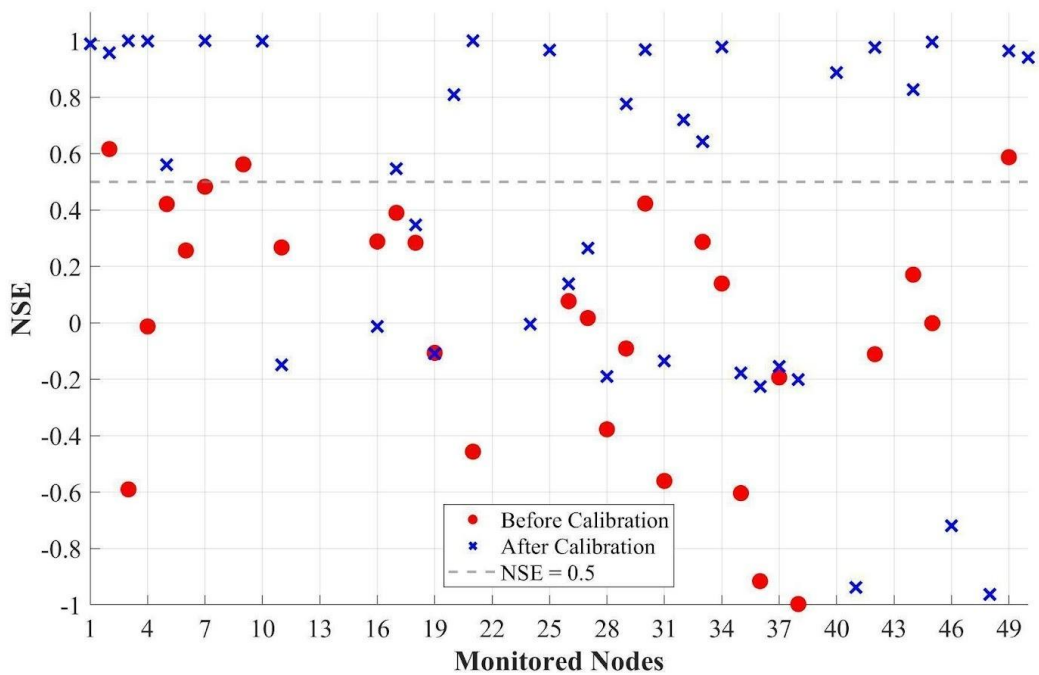


Source: The author.

The NSE and R^2 showed similar results, indicating that the calibration adequately represents the monitored values. The NSE and R^2 for pressure head are 0.87, and for flow rate,

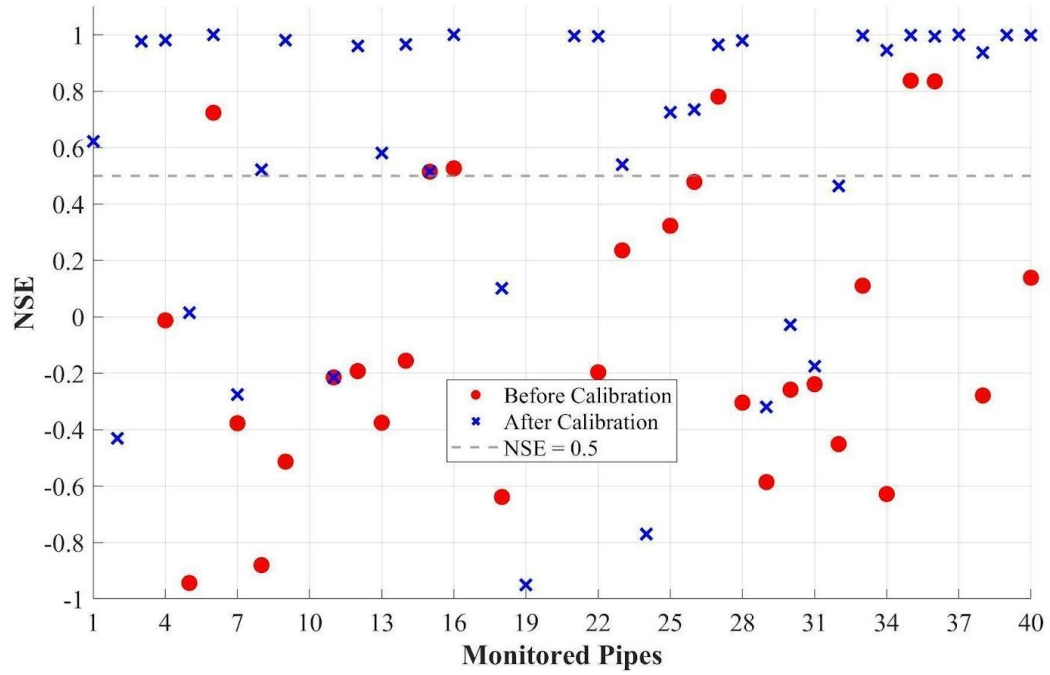
it is 0.96 after calibration. That is, values above 0.5 are considered acceptable for a model, and values above 0.8 indicate a very well-adjusted model (Rahman et al., 2019). Through Figures 3.8, 3.9, 3.10, and 3.11, it is possible to see the increase in the number of pipes and nodes above 0.5, with the most significant increase observed in Figure 3.8, where there are only 3 nodes above $NSE = 0.5$ before calibration, and after calibration, there are 22 nodes above this mark. For R^2 , this increase in the number of values close to 1 is also visible in the graph, where a significant number of points near 0 can be seen before calibration. In comparison with the work by Kapelan et al. (2007), which calibrated a hydraulic model of a WDS of a small town in the UK using 672 observed pressure heads and resulting in $R^2 = 0.999$, this work utilized more than three times the amount of observed pressure heads (2,400) and obtained an R^2 of 0.87, indicating a hydraulic model close to ideal, despite the large number of observed data. It is important to note that the scale of Figure 3.8 had to be expanded because some values before calibration were quite divergent (with small NSE values), and it would not have been possible to view the graph in detail.

Figure 3.8 – NSE plot for pressure heads before and after calibration

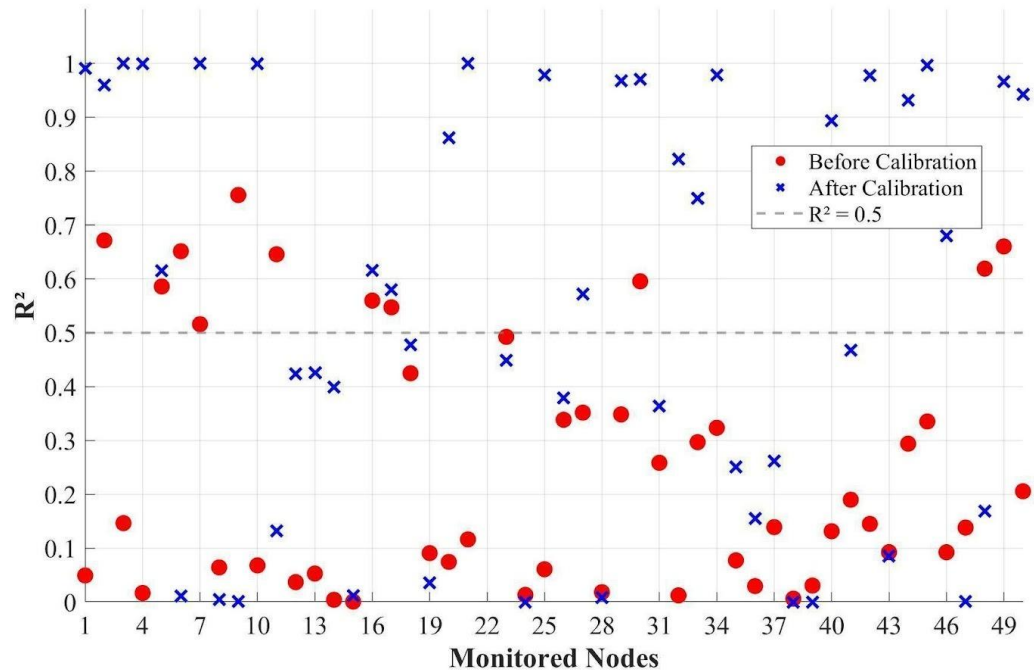


Source: The author.

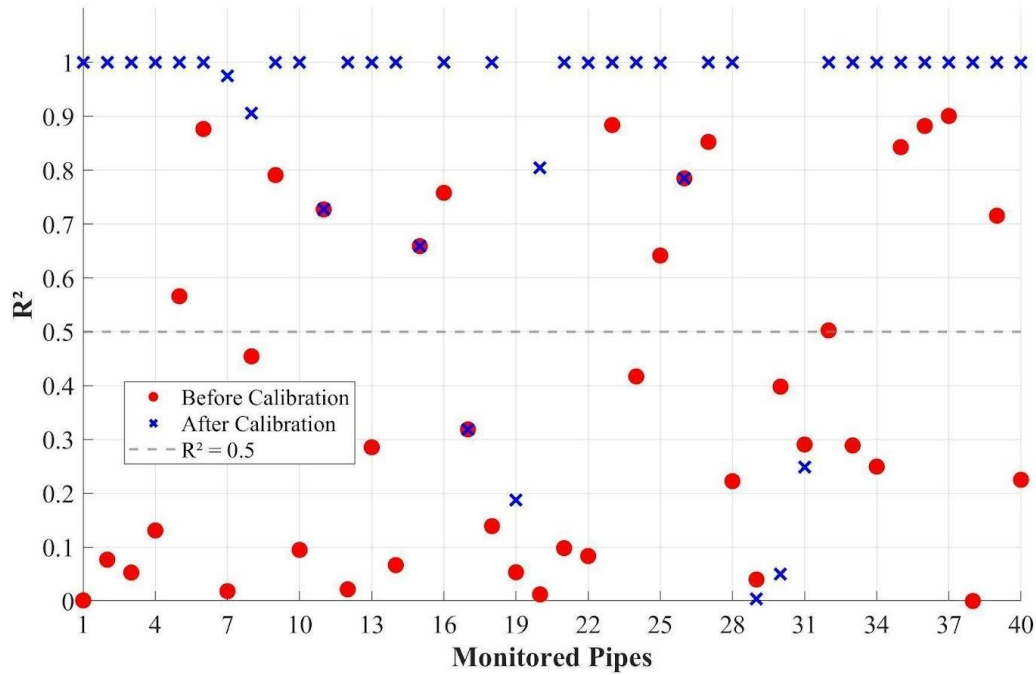
Figure 3.9 – NSE plot for flow rates before and after calibration



Source: The author.

Figure 3.10 – R^2 plot for pressure heads before and after calibration

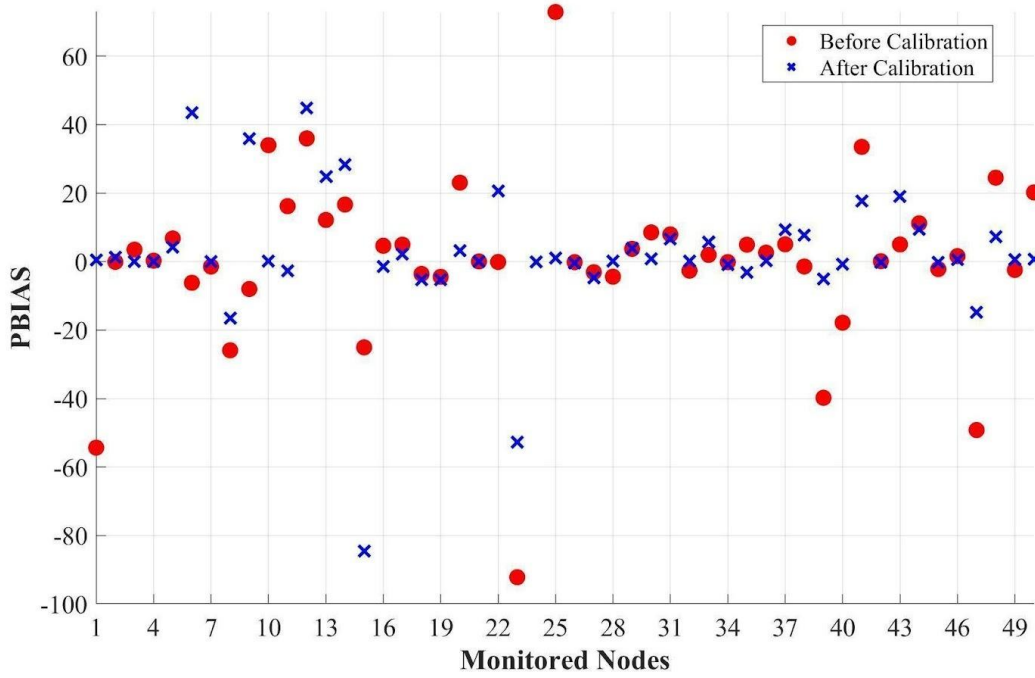
Source: The author.

Figure 3.11 – R^2 plot for flow rates before and after calibration

Source: The author.

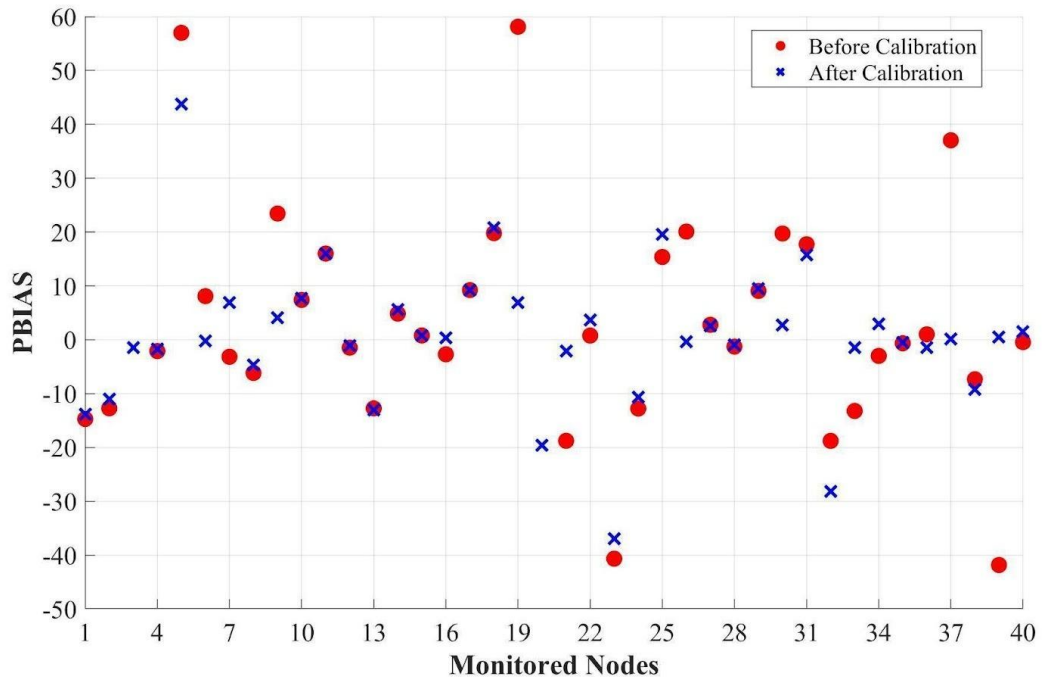
For the PBIAS, an adverse behavior was observed, as the value for pressure head increased after calibration, while for flow rate, the reduction was predominant, as shown in Tables 3.3 and 3.4. This increase in PBIAS for pressure heads can be justified by the PBIAS equation itself, where the summation of the difference between observed and monitored data considers the sign of these subtractions. Thus, for the PBIAS value after calibration in pressure heads to be higher than before calibration, it may indicate a slight tendency toward greater underestimation. Nevertheless, the PBIAS values after calibration can still be considered very good, as they are below 10%, and also satisfactory according to the $\pm 15\%$ threshold proposed in the literature (Moriassi et al., 2007; Moriassi et al., 2015). In Figure 3.12, it is emphasized that the graph had to be enlarged to view more details, as before calibration, the PBIAS values were significantly lower than the others. This highlights the improvement of the PBIAS indicator after calibration.

Figure 3.12 – PBIAS plot for pressure heads rates before and after calibration



Source: The author.

Figure 3.13 – PBIAS plot for flow rates before and after calibration



Source: The author.

It is also worth highlighting that several adjustments were made to the operating rules of the pressure head-reducing valves, including the removal of some rules and the hourly

modification of certain valve operation rules. Moreover, for each modification made to the operating rules, it was necessary to check the consistency of the hydraulic model. These verifications involved modifying the valve operation rules, base demand factors, and absolute roughness values of the hydraulic model, followed by running the EPANET simulation for a 48-hour period and checking for possible negative pressure heads at any point in the 484 nodes every hour. These analyses confirm that reaching the hydraulic model used in the calibration requires meticulous interventions by the modeler (Ostfeld et al., 2012). As a result, several modifications and preliminary calibrations were made to arrive at the final calibrated model, highlighting the inherent complexity of calibrating real, large-scale WDSs. The progress of this calibration process for both pressure heads and flow rates demonstrates the evolution of the indicator results alongside their respective calibration versions. For each version, the valve operation rules, the calibrated parameters, or the number of monitoring points were modified. For instance, from version 1 to version 2, the pressure head monitoring points were reduced from 57 to 56 due to inconsistent data at one point, in addition to changes made to the pressure head values of some valves. This procedure was repeated until version 8, which resulted in the final configuration of this study.

The exclusion of certain monitoring points was also evaluated, based on their poor performance according to the adopted indicators, as well as the resulting changes in indicator values. After excluding only 6 pressure head monitoring points based on the worst MAE results, leaving 44 monitoring points, it was observed that the evaluation parameters for the calibrated model presented the following results: MAE = 2.59 m; ARHE = 10.25%; NSE = 0.94; $R^2 = 0.94$; and PBIAS = 1.84%. When the same procedure was performed excluding only 6 flow rate monitoring points based on the worst MAE results, leaving 34 monitoring points, the following results were presented: MAE = 6.34 L/s; ARHE = 11.06%; NSE = 0.99; $R^2 = 0.99$; and PBIAS = -0.11%. Therefore, all indicators showed improvements in the results after the removal of just 6 monitoring points. Even with this removal, this work presents the number of monitored points used in the calibration as higher than that found in most of the analyzed literature, thus highlighting that the entire calibration process and the amount of data used in this work resulted in a consistent hydraulic model (Meirelles et al., 2017; Zarei et al., 2022; Sabbaghpour et al., 2012; Jadhao & Gupta, 2018; Zanfei et al., 2020).

It is important to highlight that several innovative techniques for calibrating water supply networks have been developed, such as graph-based metamodels (Zanfei et al., 2023) and artificial neural networks (Meirelles et al., 2017), among others. However, the decision to

calibrate the Fortaleza macrosystem using more traditional strategies from the literature was driven by the complexity of working with a real, dynamic system in collaboration with the state water and wastewater agency responsible for its management. Given the Brazilian context of increasing water demand and the impacts of climate change on water resources (Ballarin et al., 2023), particularly in the largest metropolis of the Brazilian semi-arid region, which frequently experiences drought events (Pereira et al., 2024), this calibrated network represents a critical tool. It will support the state water and wastewater agency in evaluating the impacts of introducing new water sources, operational changes, and climate change scenarios, as well as increasing demand on the network's performance. Furthermore, as new supply sources are incorporated, periodic recalibration of the network becomes necessary to account for changes in hydraulic conditions, particularly variations in pipe roughness. In this context, calibration should be understood as a continuous process, ensuring that the model remains representative of the system over time and capable of reliably supporting planning and operational decision-making.

3.4 Conclusions

This study conducted a calibration of the absolute roughness (ϵ) and base demand multiplication factors of a large-scale real Water Distribution System (WDS) located in a metropolitan area of Brazil, facing water risks. The calibration process involved 50 pressure head monitoring points and 40 flow rate monitoring points over a 48-hour period. Additionally, the hydraulic model considered the operating rules of several pressure head-reducing valves within the network, highlighting the inherent challenges of real WDSs and underscoring the importance of the modeler in calibrating large-scale hydraulic models with operational rules. The PSO method was used as the algorithm to minimize the objective function.

Moreover, the calibration development included adjustments to the valve operation rules, analyzing generated graphs and the influence of these rules on the network nodes. Modifications such as increasing, reducing, or eliminating pressure head control values were made to meet the monitored points and avoid negative pressure heads. In total, 2,304 operation rules were evaluated, with each adjustment directly impacting the network behavior. These adjustments were essential for obtaining a minimally calibrated model, highlighting the complexity of calibrating large-scale WDS hydraulic models.

The results indicated that the calibrated model showed good performance for the five indicator parameters used, which were evaluated for both the entire network and each monitored point. Specifically, MAE values were 3.53 m for pressure head and 16.3 L/s for flow, ARHE values were 12.96% for pressure head and 13.09% for flow, NSE values were 0.873 for pressure head and 0.965 for flow, R^2 values were 0.879 for pressure head and 0.965 for flow, and PBIAS values were 3.38% for pressure head and 1.06% for flow. Notably, 60% of the pressure head errors are below 2 m. The exclusion of certain monitoring points was also evaluated, specifically those that exhibited the worst performance according to the selected indicators, as well as the resulting increase in indicator values. The study includes a large number of monitoring points, highlighting the robustness of the calibration for a complex hydraulic model.

Finally, this study is expected that this work will contribute to improvements in the water distribution system of Fortaleza City by using the calibrated model for operation scenario analysis and network modifications. Moreover, it will support the analysis by the managing entities of the WDS on the impact of integrating new water supply sources into the network. Additionally, as new sources are incorporated and hydraulic conditions evolve, periodic recalibration of the model becomes necessary to account for factors such as changes in pipe roughness. In this sense, calibration should be treated as a continuous process, ensuring that the model remains representative of the system over time.

4 HYDRAULIC IMPACTS AND INEQUITIES OF DESALINATED WATER INTEGRATION INTO A BRAZILIAN SEMIARID WATER SUPPLY MACROSYSTEM²

4.1 Introduction

Brazilian drylands have a recurrent history of droughts. Despite this, the region is home to around 28 million inhabitants, making it one of the most populated semi-arid regions in the world (INSA - Instituto Nacional do Semiárido, 2022). This is due to several strategies developed to adapt to and mitigate the effects of these events. For instance, over the past 120 years, an extensive network of reservoirs has been constructed. This vast reservoir network, along with public policies proposed by the government, farmers, civil society, and the private sector, has improved living conditions during droughts (Lima Neto et al., 2011; Rabelo et al., 2022; Pereira et al., 2025).

However, the region, especially its largest city, Fortaleza, which has 2.57 million inhabitants, the highest gross domestic product in the region, and the highest population density among capitals in Brazil, now faces new challenges to ensure water security (IBGE, 2025). These include the impacts of climate change, anthropogenic pollution, and a sharp increase in water demand (Raulino et al., 2021; Ballarin et al., 2023). For instance, droughts have become increasingly frequent, especially in Brazil (Cataldi et al., 2025), and pose challenges to ensuring water consumption in cities with unplanned urban growth (Xu et al., 2025), leading to the search for new strategies and alternative water sources to mitigate climate-related impacts (Shemer, et al., 2023).

More recently, between 2012 and 2018, the state of Ceará, whose capital is Fortaleza, experienced a multi-year drought considered the worst in terms of rainfall deficits over the past century (Wiegand et al., 2021; Rocha et al., 2024). During this period, the low levels of water reservoirs prompted the expansion of resources and the development of strategies aimed at identifying alternative water sources (Pereira et al., 2025). These included the use of groundwater and the potential desalination of seawater, in order to ensure adequate quantity and quality of water for human consumption, both for present and future generations (Pereira et al., 2021; Seigerman et al., 2024). These challenges may trigger water conflicts not

² Article submitted: ROCHA, J. S.; UCHÔA, J. G. S. M.; BRENTAN, B. M.; NETO, I. E. L. Hydraulic Impacts And Inequities Of Desalinated Water Integration Into A Brazilian Semiarid Water Supply Macrosystem. **Journal of Water Resources Planning and Management**, in submission.

only in Fortaleza but also across the state of Ceará and neighboring states, due to a network of hydraulic infrastructure for interbasin water transfers designed to meet the growing demand in the Fortaleza metropolitan region (Medeiros, 2020).

Therefore, understanding the impact of new water sources for the Fortaleza region is crucial for efficient water resource management in Brazil. One such source currently under evaluation is the Seawater Desalination Plant Project (DESAL), which will have an initial maximum production capacity of 1 m³/s. The plant is expected to meet the water demand of approximately 300,000 inhabitants and begin operations in 2026 (CAGECE, 2023). Indeed, desalination is increasingly promoted in coastal regions, with projections suggesting that the global population relying on desalination could triple from 2015 to 2050 (Gao et al., 2017). Among large desalination plants using the reverse osmosis method, notable examples include the Sorek I plant in Israel, with a capacity of 7.22 m³/s; the Umm Al Quwain facility in the United Arab Emirates, with 7.89 m³/s; and the Ras Al-Khair plant in Saudi Arabia, reaching 11.99 m³/s (Janowitz et al., 2025). In this context, the DESAL plant is expected to occupy a prominent position on the global stage, becoming the largest desalination facility in Brazil (Pereira et al., 2021). If its capacity were hypothetically expanded to 2.5 m³/s by 2030, it could potentially become the largest desalination plant in the Western Hemisphere, surpassing the Carlsbad plant in the United States, which currently has a capacity of 2.10 m³/s (Petersen et al., 2019). In addition, DESAL, although it presents an energy consumption comparable to that of the São Francisco River transposition, an important water supply source for the state of Ceará, can offer additional energy benefits, especially when integrated with renewable sources, contributing to greater system efficiency and sustainability (Pereira et al., 2026).

However, despite the increasing number of desalination plants worldwide to address water scarcity (Richter et al., 2013; Alodah, 2023; Estrela-Segrelles et al., 2024), this alternative water source requires careful attention and monitoring of the quality of water entering the distribution system. Issues such as 'red water', pipe corrosion, and adverse changes in the chemical parameters of the water can turn this water supply solution into a potential problem and may compromise public acceptance (Zhao et al., 2021). A common environmental concern associated with desalination is the discharge of high-concentration brine (Banerjee et al., 2025). Indeed, most studies on the impacts of desalination plants have focused on the effects of their brine discharges on the marine environment to identify suitable locations for their installation (e.g., Roberts et al., 2010; Vishnupriyan et al., 2021).

Preliminary studies by the State Water and Wastewater Agency (CAGECE) have suggested that the proposed plant in Fortaleza will not compromise water quality, aligning with findings reported in the literature (Pereira et al., 2021, 2024). However, no analysis has yet examined the broader implications for the water – energy nexus, specifically, the balance between energy efficiency, water production, social acceptance, and environmental sustainability, which are key factors for the effective implementation of desalination systems (Gude, 2016; Chu et al., 2021).

Thus, it becomes essential to analyze and understand the hydraulic impacts resulting from the injection of desalinated water into the infrastructure of the water distribution macrosystem, especially given the scarcity of studies specifically focused on hydraulic analysis and the assessment of uncertainties in distribution networks supplied by desalination plants (Rashedi et al., 2025). One factor considered in the design of DESAL was its location, chosen to minimize transmission and distribution costs (Dweiri et al., 2018). However, its potential effects on the spatial distribution of pressures and flows within the Fortaleza macrosystem remain unknown. Such changes could exacerbate leakage rates (Khan, 2021), which already account for approximately 46% of system losses (SNIS, 2022).

In addition, integrating DESAL into a complex water supply network like that of the Fortaleza metropolitan region also requires careful consideration of social and political impacts, since the Northeast region of Brazil, where Fortaleza is located, is one of the most unequal in terms of access to water (Cetrulo et al., 2020; Jesus et al., 2023). Any negative impacts from DESAL could heighten public dissatisfaction and opposition to the technology (Gude, 2016). This is particularly important because desalination is an energy-intensive process, reaching up to 4 kWh/m³ (Voutchkov, 2018), which results in a larger carbon footprint compared to conventional treatment technologies (Khan, 2021). Moreover, it requires constant maintenance, has operational constraints (such as operating only at pre-established flow rates), and may impact the broader water supply macrosystem (El-Fadel, 2005; Smith et al., 2018; Moreno-Silva et al., 2024).

Some studies have linked water distribution networks with the injection of desalinated seawater; however, they provide limited detail regarding the hydraulic impacts on the network. Rashedi et al. (2025) proposed a two-stage optimization approach applied to a case study in Iran. The first stage involved quantifying and locating pumping stations between desalination plants and water storage reservoirs. The second stage consisted of designing and

planning a water distribution network that considers multiple consumers, incorporating mechanisms for water sharing, trading, and fair allocation. The results indicated a significant reduction in water scarcity and a more balanced distribution among users. However, the study did not explicitly address the hydraulic conditions of the network, such as the pressure head at consumption points following the implemented adjustments.

Moreover, Pérez et al. (2020) discussed and quantified the impacts of the abrupt increase in water demand associated with tourism activities in Ibiza, Spain, a situation comparable to mass tourism in cities such as Fortaleza during seasonal periods. The authors highlighted the necessity of employing desalination to meet this additional demand, emphasizing the financial and operational impacts of this solution, including increased water production costs and the requirement for expanded water infrastructure. Furthermore, they noted that losses in the distribution network exacerbate this scenario, particularly in aging and vulnerable systems. Besides, Carvalho et al. (2020) analyzed water consumption patterns in Fortaleza and developed predictive models based on socioeconomic, demographic, and household variables. The approach aimed to support decision-making regarding the expansion of water supply capacity, including alternative sources such as desalination. However, the study was limited to the analysis of water demand and did not consider the operational conditions of the distribution network or simulate the technical impacts of integrating new sources, such as the planned desalination plant for the city.

Some preliminary studies have assessed the potential effects of DESAL on the Fortaleza macrosystem, but these were based on an uncalibrated distribution network. Recent advances by Rocha et al. (2025), in collaboration with CAGECE, have improved this. After calibrating the system using hourly data from 50 pressure head monitoring points and 40 flow rate monitoring points, they achieved Nash - Sutcliffe efficiency (NSE) values above 0.80 for both flow and pressure head. These improvements now enable a more reliable evaluation of the impacts of DESAL on the Fortaleza macrosystem, thereby supporting evidence-based decision-making by the local government to mitigate potential risks associated with the project.

With a calibrated model of the Fortaleza macrosystem and technical data provided by CAGECE, it is now possible to assess the impact of pressure changes in the distribution network. The loss rate in the water distribution system in the region is estimated at around 46%, according to official data (SNIS, 2022); an increase in pressure could exacerbate these losses. It is also necessary to evaluate whether the DESAL injection points in the network can

effectively distribute water throughout the region. Although the plant is located in a wealthier area of the city, which typically has higher water demand, structural and operational adjustments may still be required to optimize distribution (Lopes et al., 2024).

Finally, the economic viability of DESAL's operation and maintenance must be considered, particularly given that desalination is sensitive to electricity prices, which in Brazil often vary with hydrological conditions (and are typically higher during dry periods, when reservoir levels are low). Thus, this study aims to assess the impacts of DESAL on the Fortaleza macrosystem, to generate actionable insights to support efficient water resource management in the region. Such understanding requires integrating policy choices with complex social, economic, technical, and environmental processes (Sahin et al., 2015) and can inform the implementation of other desalination plants worldwide.

4.2 Materials and Methods

4.2.1 Study area

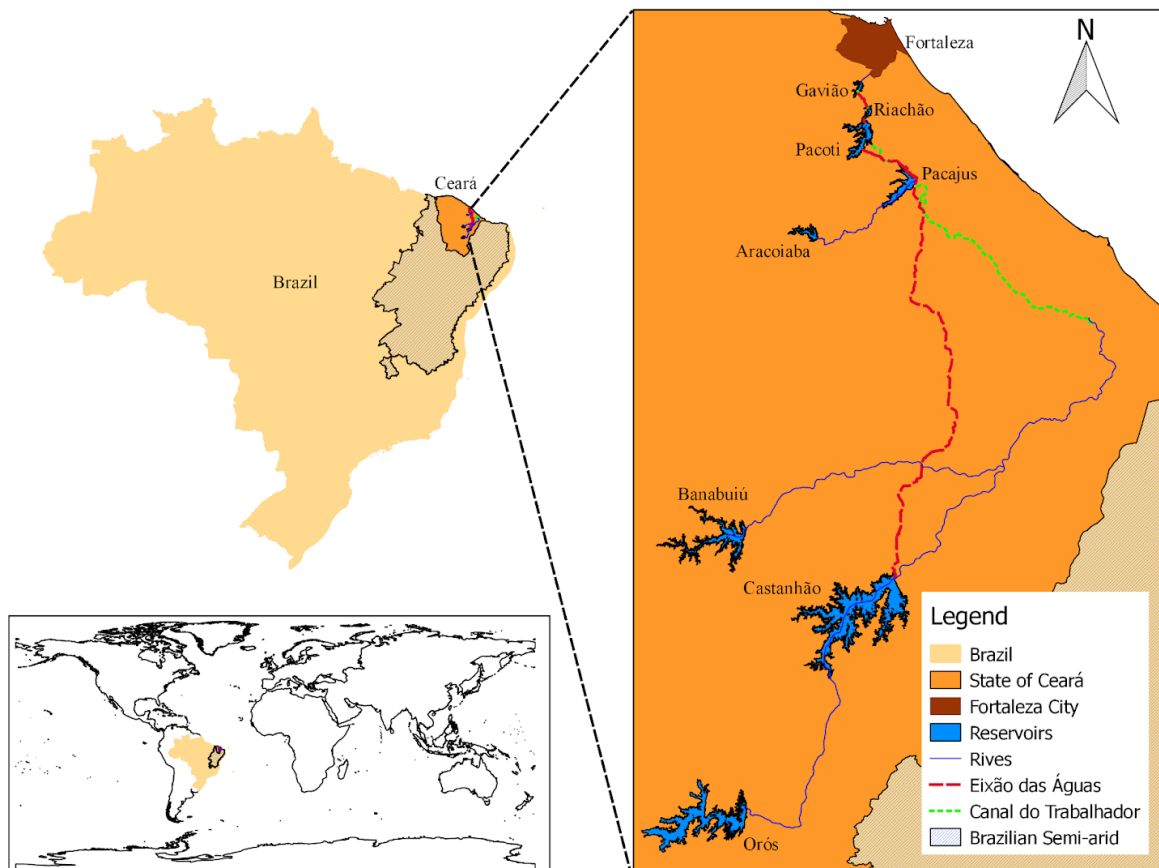
The city of Fortaleza is the capital of the Ceará state, located in the Northeast region of Brazil. With a coastline along the Atlantic Ocean, Ceará benefits from a strategic location that supports the development of ports and fosters important commercial and technological relations for the local economy (Carvalho, 2021). On the other hand, approximately 98% of Ceará's territory lies within a semi-arid climate zone, characterized by low annual rainfall, high evaporation rates, elevated temperatures, and limited groundwater availability. These conditions make water scarcity a persistent issue, frequently addressed in the state's public policies (Souza Filho, 2018). Additionally, most of the region's watercourses are intermittent, and rainfall is highly irregular. In response to these challenges, the Ceará state has adopted the construction of numerous reservoirs as its main strategy for coping with drought periods (Walker et al., 2024).

Fortaleza's water supply system consists of two Water Treatment Plants (WTP Oeste and WTP Gavião) and eight main reservoirs: Gavião, Riachão, Pacoti, Pacajus, Aracoiaba, Banabuiú, Castanhão, and Orós. Together, these reservoirs possess a combined storage capacity exceeding 11,000 hm³, with Castanhão (6,700 hm³), Orós (1,940 hm³), and Banabuiú (1,600 hm³) reservoirs alone accounting for approximately 55% of the state's total water storage capacity (Santos et al., 2024). The reservoirs are interconnected through natural

watercourses and artificial canals, such as the Eixão das Águas and the Canal do Trabalhador (see Figure 1), with the objective of ensuring water supply to the Fortaleza Metropolitan Region (FMR). Together, the Water Treatment Plants have a maximum production capacity of 15 m³/s. However, during the prolonged drought that occurred between 2012 and 2017, this flow was reduced to 8.2 m³/s (Rocha et al., 2025).

The city of Fortaleza has an estimated population of approximately 2.5 million inhabitants, distributed over an area of more than 312 km², making it the Brazilian capital with the highest population density (IBGE, 2025). The municipality is divided into 121 neighborhoods, with a markedly uneven population distribution, ranging from about 1,000 to 76,000 residents per neighborhood. The southern, southeastern, and northwestern zones contain the most densely populated areas. The western zone of the city serves as the main industrial hub, with an average water consumption of approximately 1.4 m³/s. This same region also includes neighborhoods with high population density and a significant presence of informal settlements, such as Pirambú, which is recognized as one of the largest favelas in Latin America (Carvalho et al., 2020). Figure 4.1 illustrates the location and system that brings water to the FMR.

Figure 4.1 – Location of Ceará state in relation to Brazil, and details of the water transfer system to supply the water demand of the FMR



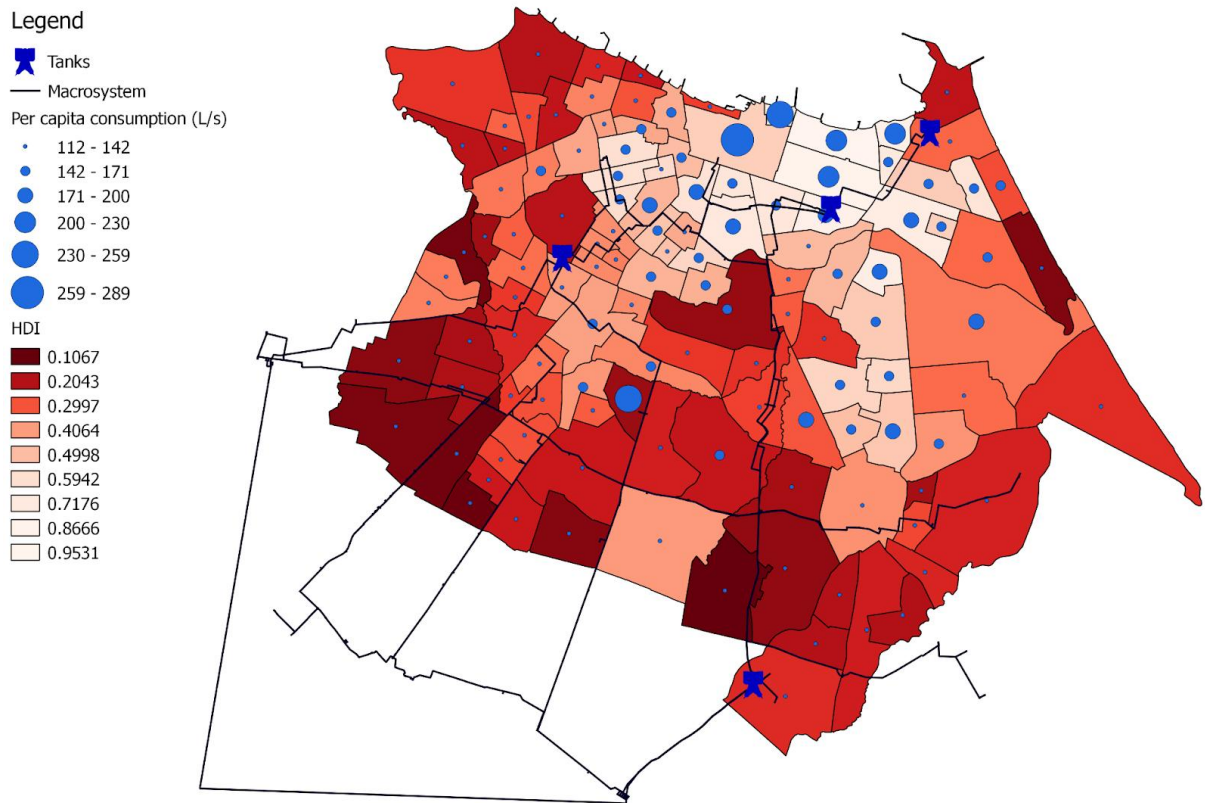
Source: The author.

Fortaleza city exhibits significant per capita water consumption disparities among its neighborhoods. Figure 4.2 illustrates the relationship between the Human Development Index (HDI) and per capita consumption across the municipality's neighborhoods. In general, areas with higher HDI also tend to display higher per capita consumption values. A slight deviation from this pattern can be observed in the Raquel de Queiroz neighborhood, which presents a relatively low HDI but a high per capita consumption. This difference may be explained by the presence of facilities with high water demand in the area, such as the Hospital Universitário do Ceará, a sports complex with an Olympic-size swimming pool, a school, and another small healthcare unit. These facilities indicate that, within a relatively small area, there are significant water-demand points that may contribute to the elevated per capita consumption observed in the neighborhood. The socioeconomic differences are particularly pronounced. Among the neighborhoods with the highest HDI are Meireles (0.953), Aldeota (0.866), Dionísio Torres (0.859), and Mucuripe (0.793). In contrast, Conjunto Palmeiras (0.106), Parque Presidente Vargas (0.135), Canindezinho (0.136), and Parque Genibaú (0.138) present the lowest indices. Notably, Meireles records an HDI higher than that

of countries such as Belgium (0.951), Ireland (0.949), and Finland (0.948), whereas the lowest-HDI neighborhoods in Fortaleza rank below countries like South Sudan (0.388), Somalia (0.404), and Niger (0.419) (Nations U., 2025).

The neighborhoods with the highest per capita water consumption are Centro (288.6 L/s) and Praia de Iracema (248.0 L/s), while the lowest values are observed in Parque Presidente Vargas (112.2 L/s) and Parque Genibaú (113.3 L/s). The two reservoirs that will receive water from the desalination plant (DESAL) are located in high-HDI neighborhoods with elevated per capita consumption, Aldeota (209.3 L/s) and Mucuripe (207.4 L/s). By contrast, neighborhoods farther from the DESAL injection points exhibit significantly lower consumption rates, such as Parque Presidente Vargas (112.2 L/s), Parque Genibaú (113.3 L/s), and Canindezinho (114.4 L/s). Placed within the historical context of infrastructure's central role in drought management (Mitroi et al., 2025), our analysis raises the question of whether DESAL merely increases overall water availability or also contributes to more equitable water access across the metropolitan region of Fortaleza.

Figure 4.2 – Map of the relationship between the Human Development Index (HDI) and per capita consumption (in L/s) by neighborhoods in the city of Fortaleza (Prefeitura Municipal de Fortaleza, 2014)



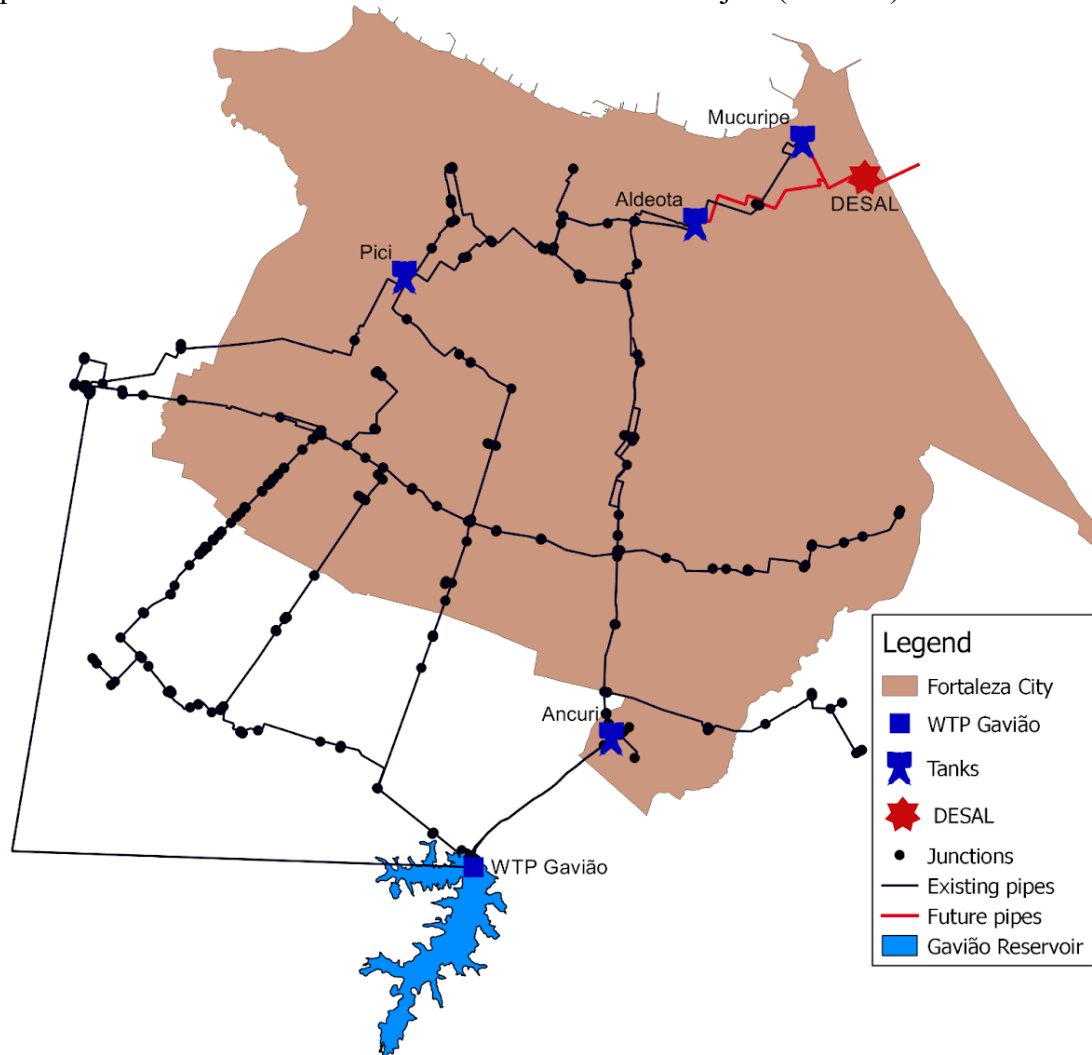
Source: The author.

4.2.2 Macrosystem of the Fortaleza Metropolitan Region (FMR) with the Seawater Desalination Plant Project (DESAL)

The Fortaleza's water supply macrosystem hydraulic model consists of 484 nodes, which include 479 junctions, a single reservoir (Gavião), and four elevated storage tanks (Mucuripe, Aldeota, Pici, and Ancuri). The network is composed of 515 links, incorporating 393 pipelines, 19 pumping stations, and 103 valves. Collectively, the pipelines extend over 202.59 km and cover an area of approximately 350 km². A substantial portion of this network is comprised of pipes with diameters exceeding 1000 mm. The system's hydraulic components are distributed across an average topographic elevation of 33.6 meters, with elevation extremes ranging from 7.5 m to 103.4 m. The base demand across the 84 consumer nodes varies significantly, from 0.37 to 868.3 L/s, based on data provided by CAGECE. Additionally, the system includes 48 pressure-reducing valves that operate according to pre-defined hourly control schedules. Pipe absolute roughness values range from approximately 0.0001 mm to 15 mm, with a mean of 6.2 mm and a median of 1.45 mm (Rocha et al., 2025). Furthermore, future DESAL facilities are planned for the eastern coast of Fortaleza, where

desalinated water will be introduced into the macrosystem through the Mucuripe and Aldeota tanks, as illustrated in Figure 4.3.

Figure 4.3 – Macrosystem details of the Fortaleza Metropolitan Region (FMR) and implementation site of the Seawater Desalination Plant Project (DESAL)



Source: The author.

4.2.3 Assessment of the impact of DESAL on the FMR Macrosystem

This study evaluates the hydraulic impact of injecting flows from the future seawater desalination plant of Fortaleza (DESAL) into the water supply macrosystem of the Fortaleza Metropolitan Region (FMR). The analysis is conducted using the hydraulic model calibrated in the EPANET software, as developed by Rocha et al. (2025). The year 2017 is used as the base year for calibration, as it provides the most comprehensive pressure and flow data for the network and is considered a representative year (the COVID-19 pandemic

significantly altered demand dynamics in subsequent years). The operational effects of introducing desalinated water are simulated over a 48-hour period.

In this context, ten operational scenarios are defined, divided into two groups of five. The distinction between the five scenarios within each group lies in the proportion of the total DESAL flow allocated between the Mucuripe and Aldeota reservoirs, as detailed in Table 4.1.

1) Addition (five scenarios): In this group, the DESAL flow is directly added to the system, without any adjustment to the production of the Gavião WTP. In the hydraulic model, two nodes are introduced into the network, each connected to its respective storage tank and assigned a negative base demand, thereby representing the inflow of desalinated water.

2) Compensation (five scenarios): In this group, the progressive increase in DESAL injection is accompanied by a proportional reduction in the outflow from the Gavião WTP, so that the total injected volume remains constant. This reduction is represented in the model by a flow control valve (FCV).

In both groups, the five scenarios vary according to the injection percentages of DESAL's total flow into the two tanks designated to receive the desalinated water (see Table 1). It was assumed that the Mucuripe reservoir would receive 40% of the total DESAL flow, while the Aldeota reservoir would receive the remaining 60%, as specified by CAGECE. Table 4.1 presents a detailed description of the scenarios simulated for the year 2017.

Table 4.1 – Scenarios analyzed for the incorporation of DESAL to the Fortaleza water distribution macrosystem

Input flow by sector (m³/s)

Scenarios	DESAL's total			Reduction from Gavião WTP		
	2025-2029	2030-2044	2045-2050	2025-2029	2030-2044	2045-2050
S0	0.0	0.0	0.0	0.0	0.0	0.0
S1 - Addition	0.2	0.5	1.0	0.0	0.0	0.0
S2 - Addition	0.4	1.0	2.0	0.0	0.0	0.0
S3 - Addition	0.6	1.5	3.0	0.0	0.0	0.0
S4 - Addition	0.8	2.0	4.0	0.0	0.0	0.0
S5 - Addition	1.0	2.5	5.0	0.0	0.0	0.0
S1 - Compensation	0.2	0.5	1.0	-0.2	-0.5	-1.0
S2 - Compensation	0.4	1.0	2.0	-0.4	-1.0	-2.0
S3 - Compensation	0.6	1.5	3.0	-0.6	-1.5	-3.0
S4 - Compensation	0.8	2.0	4.0	-0.8	-2.0	-4.0
S5 - Compensation	1.0	2.5	5.0	-1.0	-2.5	-5.0

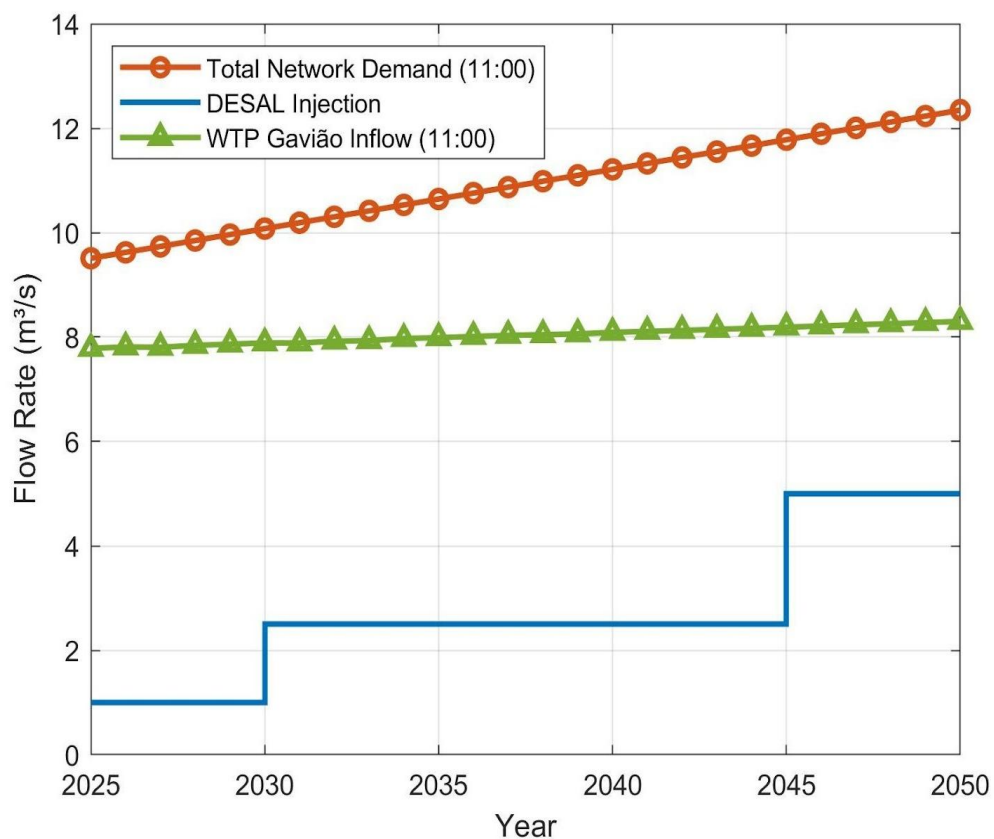
Source: The autor.

For the 2025–2050 period, the same structure of operational scenarios and the injection percentages for the two reservoirs (40% for Mucuripe and 60% for Aldeota) are maintained. However, the network demands are progressively adjusted to reflect population growth over the years. Population projections are carried out using the arithmetic method, based on official census data. From these projections, annual demand increase factors are calculated by dividing the estimated population of each year by the population in 2017. These factors are then applied to the base network demands, resulting in scenarios with a gradual increase in domestic consumption. In addition, the planned increases in DESAL's injection capacity over the years, as reported by the State Water and Wastewater Agency (CAGECE), are incorporated. Until 2029, the injected flow was kept at 1 m³/s; between 2030 and 2044, this value increased to 2.5 m³/s; and from 2045 to 2050, it was further increased to 5 m³/s.

Figure 4 presents the total network demand during the peak hour (11:00 a.m.), the flow rate supplied by the WTP Gavião at the same time, and the evolution of the DESAL injection over the years.

Still on Figure 4.4, the behavior of WTP Gavião stands out. In the hydraulic model, the WTP Gavião was represented as a fixed-level reservoir, a condition that allows the system to supply the flow required to meet the demand imposed in each simulation year. Thus, as the projected consumption increases due to population growth, the WTP's contribution also rises to maintain the hydraulic balance of the network and ensure service continuity. This approach is consistent with the simulation logic described in EPANET, in which constant-level reservoirs act as unlimited supply sources, automatically adjusting their discharge according to the evolution of demand (Rossman, 2000).

Figure 4.4 – Projected Total Demand, DESAL Injection, and WTP Gavião Inflow (2025–2050)



Source: The author.

The evaluation of pressure head results at critical nodes is carried out for the period from 2025 to 2050, considering two main analytical dimensions: (i) temporal analysis within each scenario, examining the annual evolution of pressure and identifying significant

trends and changes; and (ii) comparative analysis across scenarios, using the baseline scenario (S0) as the reference. This methodology enables an integrated assessment capable of revealing both the internal evolution of each scenario and the structural differences between them.

Another method employed to evaluate the hydraulic behavior of the network under the introduction of DESAL water was the Todini resilience index (Todini, 2000). This index quantifies the ability of a looped water distribution network to withstand failures, demand variations, or stress conditions by assessing the available energy balance within the system. Practically, resilience is associated with the surplus head available at each node relative to a minimum required piezometric head. The Todini index typically ranges from 0 to 1, with values closer to 1 indicating networks with a greater capacity to maintain service delivery under adverse operating conditions. However, it may assume negative values when design requirements are not met, as highlighted by Maiolo et al. (2018). In this study, a minimum required head of 10 m was adopted, in accordance with Brazilian technical standards. The index was calculated for the hours of minimum and maximum demand in each analyzed scenario. The following equation presents the variables used to compute the Todini resilience index (I_r):

$$I_r = \frac{\sum_{i=1}^{n_n} q_i^* (h_i - h_i^*)}{\sum_{r=1}^{n_r} Q_R H_R + \sum_{j=1}^{n_p} P_j / \gamma - \sum_{i=1}^{n_n} q_i^* h_i^*} \quad (4.1)$$

Where “ γ ” is the specific weight of water; “ Q_R ” e “ H_R ” are the discharge and hydraulic head, respectively, associated with each reservoir “R”; and “ n_r ” is the number of reservoirs in the system. Likewise, “ n_p ” denotes the number of pumps, and “ n_n ” the number of nodes. In addition, “ h_i ” is the hydraulic head at node “i”, “ h_i^* ” is the minimum hydraulic head required for adequate service (10 m), “ q_i^* ” is the design demand at node “i”, and “ P_j ” represents the power supplied to the network by pump “j”.

Furthermore, a potential reduction in water demand resulting from education policies and conscious consumption practices implemented over the years in the city of Fortaleza is simulated. Based on the study by Vidal-Lamolla et al. (2024), it is estimated that the monthly demand reduction achieved through such measures ranges from 8.1% to 15.6%. In this study, the maximum value (15.6%) is adopted, considering that, in light of climate

change and water scarcity, it is likely that policies and educational actions are effectively implemented in the city to encourage consumption reduction. Although Vidal-Lamolla et al. (2024) applied their study to a fictitious network with a population significantly smaller than that of Fortaleza, the research demonstrated that non-tariff measures might be more effective in reducing water use than merely increasing tariffs. Moreover, Tortajada et al. (2019) conducted a study on water consumption reduction strategies in five Spanish cities, finding that such measures could lead to reductions of up to 25% in domestic water use. Consequently, these reduction percentages (15.6% and 25%) are adopted in the present study.

4.3 Results and discussion

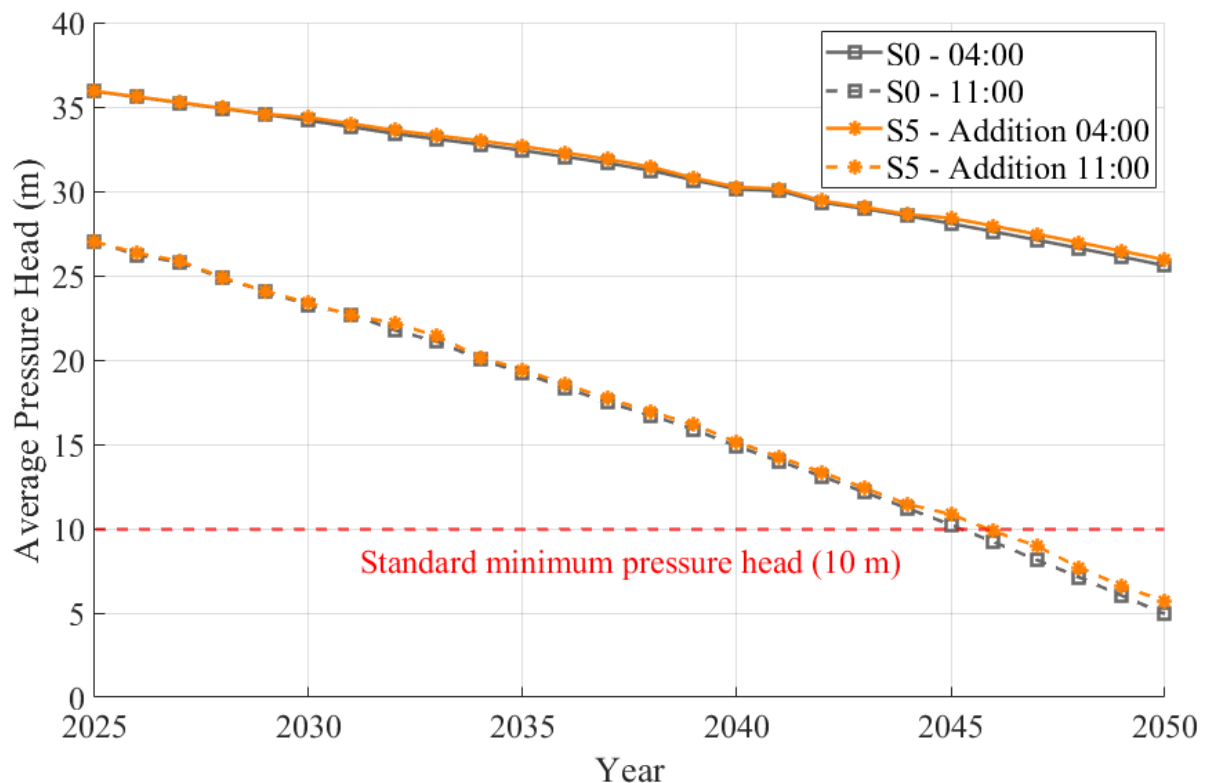
Figure 4.5 shows the behavior of the macrosystem in the baseline scenario at peak (11:00) and off-peak (04:00) consumption hours between 2025 and 2050. In 2025, the pressure head differed by about 10 m between the two hours, and this gap widened to nearly 20 m by 2050. This pattern highlights the strong variability in Fortaleza's water supply network, driven by domestic consumption linked to daily routines: low demand during nighttime rest (04:00) and elevated demand at 11:00, coinciding with work breaks, meal times, and higher temperatures. Similar patterns, with minimum values at night and higher values during the day, have also been observed in other studies (Price et al., 2022; Sánchez et al., 2022; Mazzoni et al., 2023).

Such large daily fluctuations in pressure head cause stress on the network and may contribute to its deterioration over time, resulting in potential leaks and the intrusion of untreated or contaminated water (Marsili et al., 2023; Jara-Arriagada, 2021). Furthermore, a gradual reduction in average pressure head over time can be observed, driven by the increase in demand associated with population growth. The reduction is especially pronounced during peak hours: between 2025 and 2050, the pressure head at 11:00 drops by more than 20 m. This sharper decline during peak demand indicates that, without new water sources, population growth will exacerbate pressure losses at critical times, thus jeopardizing the assurance of adequate minimum pressure head levels (≥ 10 m) according to Brazilian standards across the network.

As the scenarios within the Compensation group exhibited significant reductions in network pressures, including low and even negative pressure values, the comparison was restricted to scenario S0 (without the injection of desalinated water from DESAL) and the

scenarios of the Addition group, specifically scenario S5 - Addition, which presented more favorable pressure conditions in the network. Accordingly, Figure 4.5 illustrates a slight increase in pressures over the years for scenario S5 - Addition compared to S0, as was already expected based on the analyses conducted for the year 2017. The increases in pressure proved to be more pronounced in the later years under consideration, particularly between 2045 and 2050, when the DESAL injection reaches its maximum flow rate (5 m³/s). Despite the increase in pressures at the two time periods analyzed in scenario S5 - Addition, it is observed that, as in scenario S0, the average pressures during peak consumption hours fall below the minimum required threshold (10 m) around the year 2045. This finding indicates that, even under maximum DESAL injection, the rise in water demand in the later years, driven by population growth, reduces average peak-hour pressures to a degree that compromises the maintenance of adequate pressure levels necessary to ensure the full functionality of the distribution network.

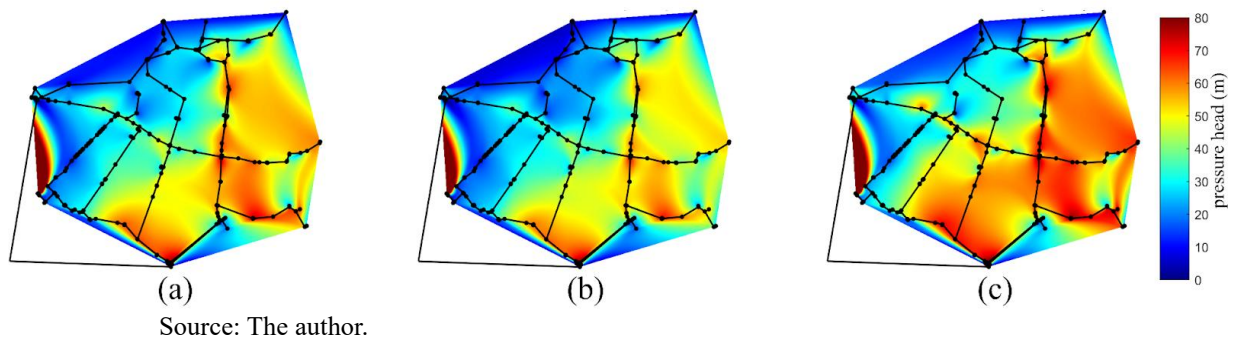
Figure 4.5 – Average pressures at peak (11:00) and off-peak (04:00) consumption hours between 2025 and 2050 in the baseline scenario



Source: The author.

Figure 4.6 presents the average pressure heads throughout the network over the year 2017, considering three conditions in baseline scenario: the overall average, the average at peak demand (11:00), and the average at off-peak demand (04:00). It is important to note that these maps are based on interpolated discrete point data, representing spatial averages by area derived from a macrosystem approach that does not explicitly account for the finer-scale distribution network. In the scenario without the injection of desalinated water, the highest pressure heads are concentrated near the Gavião WTP (to the south, see Figure 3) and in the pipelines adjacent to the Mucuripe, Aldeota, and Ancuri tanks (to the east, see Figure 3), whereas the lowest pressure heads are located at the network extremities as well as in the central and western regions of the figures. Certain areas exhibit persistently low pressure heads (< 10 m), regardless of the time of consumption, which may compromise demand satisfaction and indicate that, in the current configuration, some regions already face supply issues. Conversely, some areas present consistently high pressure heads over time or a wide range of pressure head variation, indicating increased susceptibility to leakage and pipeline due to stress and the progressive wear of hydraulic structures. Regions exhibiting high pressure head values are predominantly concentrated in neighborhoods with low HDI, such as Aeroporto, Alto da Balança, Aerolândia, Passaré, Barroso, Paupina, and Ancuri. This pattern may indicate the potential occurrence of leaks in these areas. In contrast, the lowest pressure head values are observed in neighborhoods such as São Gerardo, Presidente Kennedy, Bonsucesso, and Vila Peri, among others. (Van Zyl et al., 2007; Doss et al., 2024).

Figure 4.6 – Network pressures under the baseline scenario (S0). (a) 48-hour average pressures, (b) average pressures at peak demand (11:00), and (c) average pressures at off-peak demand (04:00) in 2017



Figures 4.7 and 4.8 illustrate the nodal differences between the baseline scenario (S0) and all other scenarios. It should be noted that these results are based on interpolated

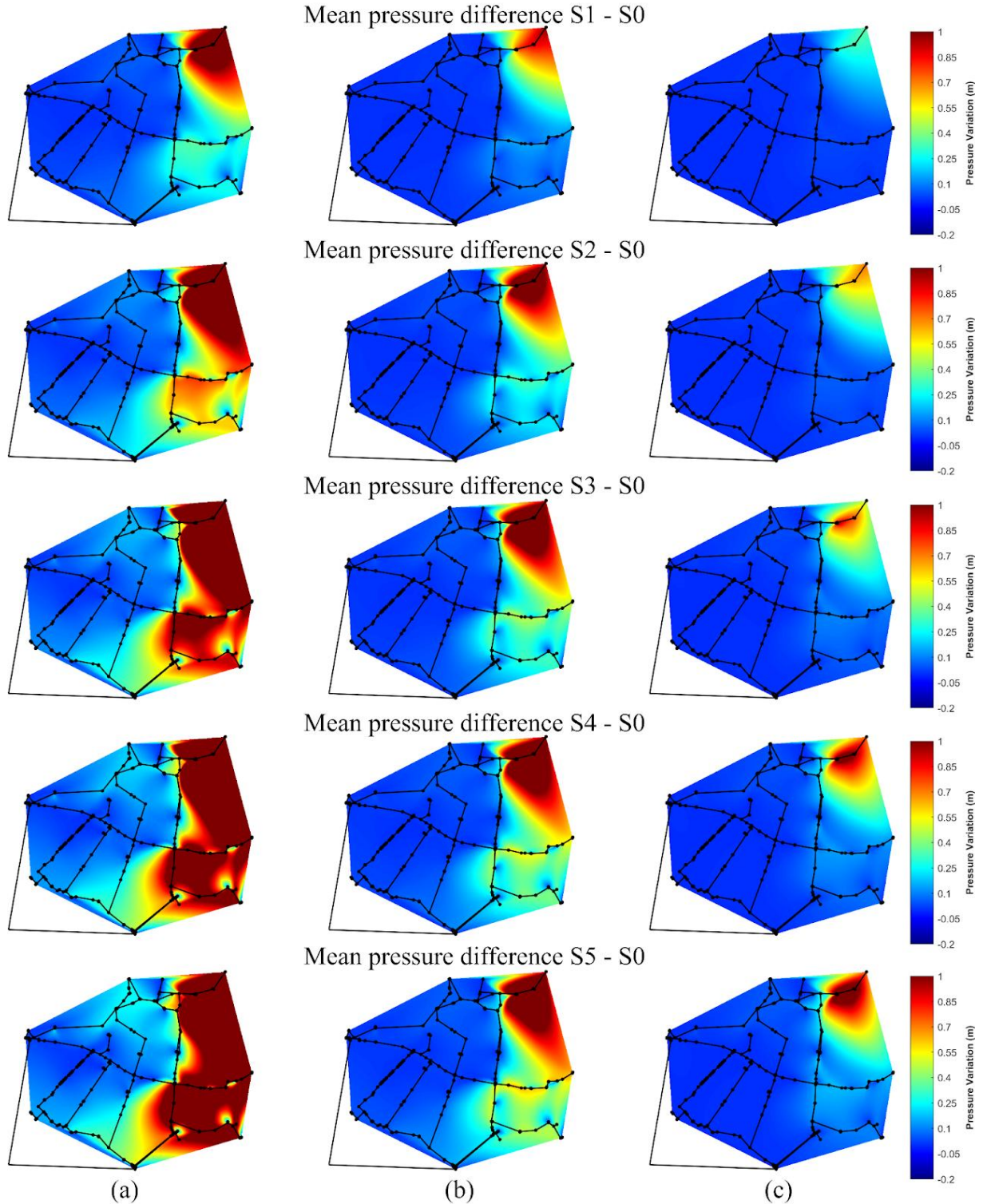
discrete nodal data, representing spatial averages derived from a macrosystem approach, with limited representation of the finer-scale distribution network. Figure 4.7 compares the scenario S0 with the Addition group scenarios, while Figure 4.8 presents the same analysis for the Compensation group scenarios. It is noteworthy that the scale of Figures 4.7 and 4.8 was defined in order to make the variations of increase and decrease perceptible, with the maximum observed increments exceeding 1 m. These figures show how the pressure behavior in the network changes when incorporating water from the Fortaleza desalination plant across the different scenarios, supporting evaluation and decision-making on DESAL's implementation. Neighborhoods such as Aldeota, Dionísio Torres, and Cocó exhibit the highest pressure head increases across all analyzed scenarios, which can be largely attributed to their proximity to the injection points of the desalination system.

In Figure 4.7, the largest changes in average pressure (48-hour values) occur near the Aldeota and Mucuripe tanks, the two reservoirs that will receive DESAL water, and in the eastern part of the supply system. These same areas already exhibit high pressure heads without the DESAL (see Figure 4.6); therefore, simply increasing water injections without any compensation from the Gavião WTP or operational changes in the system could make them even more susceptible to leaks. Besides, because leakage flow rate is proportional to pressure head, this would also increase overall system losses (van Zyl et al., 2017; Uchôa et al., 2023). Given that desalination is energy-intensive, losing this water through leakage could also undermine public trust, particularly since the cost of water is likely to rise due to the expenses associated with DESAL implementation, potentially amplifying impacts on consumer goods dependent on water. Therefore, the results presented here can help stakeholders anticipate and mitigate the challenges of desalination integration, ultimately contributing to greater social acceptance and trust (Gude, 2016; Liu et al., 2022).

Pressure increases are most pronounced in low-lying regions closer to the sea, while areas with existing low pressures remain unchanged or decline slightly, particularly during off-peak demand (04:00). Even in regions that showed the largest increases in average pressures and during peak demand hours (11:00), reductions were observed during the low-demand period (04:00). Overall, these results indicate an increase in the pressure head amplitudes throughout much of the analyzed network. Price et al. (2022) noted that such pressure variations can lead to pipe leaks, and an effective way to mitigate these high pressure heads is through the use of Pressure-Reducing Valves (PRVs). Moreover, Jara-Arriagada and

Stoianov (2021) estimated that it is possible to reduce pipe burst occurrences by 18% to 30% through the reduction of average pressure heads.

Figure 4.7 – Difference in network pressures between DESAL addition scenarios and the baseline (S0). (a) 48-hour average pressures, (b) average pressures at peak demand (11:00), and (c) average pressures at off-peak demand (04:00) in 2017



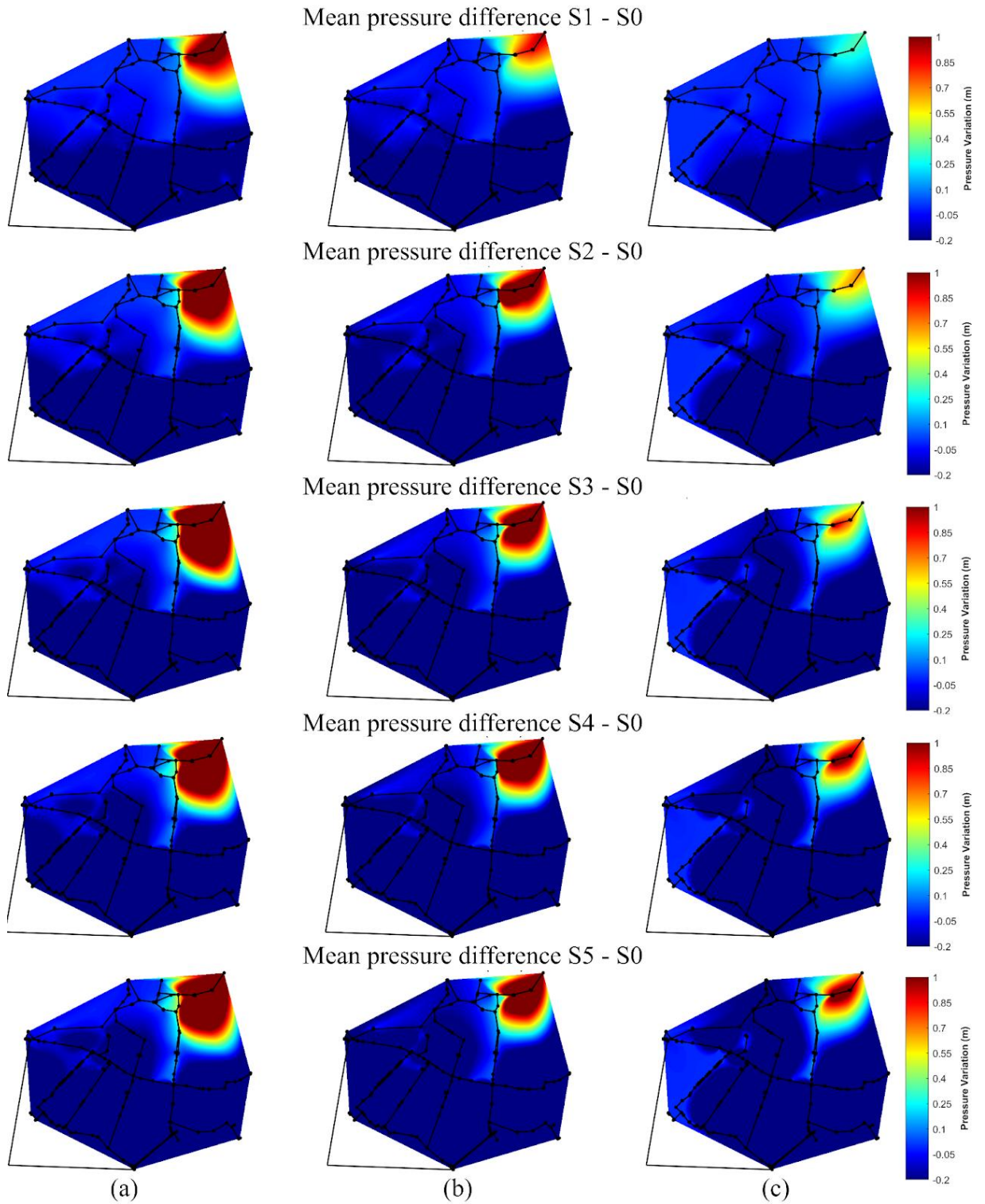
Source: The author.

When comparing the Compensation group scenarios with the baseline scenario (Figure 4.8), the highest pressures remain concentrated near the Aldeota and Mucuripe tanks, the injection points for DESAL water. In contrast, in the remainder of the network, there was predominantly a reduction in pressure head, or, in some sections, only a slight increase relative to scenario S0. Unlike the Addition group, the Compensation scenarios are not limited to the simple addition of DESAL waters at these two tanks. As the volume injected by the plant increases, the contribution from the WTP Gavião reservoir, the main supply source of the system, is simultaneously reduced. Thus, the purpose of this group of scenarios is to balance the participation of the different water sources within the network. In this context, the observed behavior, with only minor increments in pressure head, was already expected.

Nevertheless, the decline in pressure head across most of the network highlights the fundamental role of WTP Gavião in sustaining system pressure levels, given that it represents the largest water input to the network. As a result of this redistribution, the Compensation scenarios exhibit significant problems of insufficient pressure head and even negative pressure heads at several nodes, a condition already observed in scenario S0.

Critical pressure heads (< 10 m) or negative values pose substantial risks of pathogen intrusion where soil contamination sources exist, such as leaking sewer pipelines (Besner et al., 2011; Shao et al., 2019). Furthermore, as illustrated in Figure 4.8 and Figure 4.2, water supply failures due to insufficient pressure head occur predominantly in regions with a low HDI. This situation underscores a common pattern in developing countries, where low-income populations face more severe challenges related to water scarcity, either through greater physical effort or additional financial costs to secure access to water, compared with wealthier regions (Majuru et al., 2016). In this context, the implementation of DESAL risks perpetuating centralized, supply-side responses to water scarcity, rather than promoting decentralized, demand-side strategies that consider the social and cultural capacity to respond to drought and rising water demand (Green, 2019).

Figure 4.8 – Difference in network pressures between DESAL compensation scenarios and the baseline (S0). (a) 48-hour average pressures, (b) pressures at peak demand (11:00), and (c) pressures at off-peak demand (04:00) in 2017



Source: The author.

Table 4.2 summarizes the main differences between the Addition and Compensation scenarios for 2017, consistent with the patterns shown in Figures 4.6 – 4.8. In the Addition scenarios (S1 – S5), the mean absolute deviations relative to the baseline

scenario (S0) remain relatively small, both for the overall average and for peak (11:00) and off-peak (04:00) periods, indicating that the addition of water from the DESAL plant has a limited impact on the network-wide pressures. However, maximum values and the top-10 averages show notable peaks, particularly in S3 and S4, suggesting that some nodes experience extreme variations well above the network average and may represent critical points for pressure management.

In contrast, the Compensation scenarios show larger deviations across all metrics, which increase more sharply as DESAL's contribution grows. This highlights that the simultaneous reduction of the WTP Gavião contribution causes a significant redistribution of pressure head, amplifying both temporal variability (between minimum and maximum consumption periods) and spatial variability (among different nodes in the network). Maximum values and top-10 averages further reveal particularly vulnerable nodes, where pressure differences reach several tens of meters.

Overall, the Addition scenarios produce relatively homogeneous impacts, whereas the Compensation scenarios amplify localized effects, increasing the risk of insufficient or even negative pressures. From an operational perspective, this suggests that implementing Compensation scenarios requires special attention to the identification of critical nodes, continuous monitoring, and possible hydraulic interventions, such as control valves, pump reinforcement, or adjustments in tank operations, in order to prevent supply failures and maintain system stability.

Table 4.2 – Mean absolute deviations between the baseline (S0) and other scenarios in 2017

Scenarios	48-hour average pressures (m)	Average pressures at off-peak demand (m)	Average pressures at peak demand (m)	Maximum Value (m)	3rd Quartile (m)	Average of the top 10 with the highest pressure (m)
S1 - Addition	0.120	0.018	0.051	3.35	0.078	3.33
S2 - Addition	0.235	0.036	0.106	5.69	0.165	5.66
S3 - Addition	0.369	0.055	0.145	47.23	0.209	44.26
S4 - Addition	0.393	0.072	0.159	47.66	0.270	43.63
S5 - Addition	0.418	0.089	0.173	15.99	0.347	15.39
S1 - Compensation	0.279	0.134	0.299	16.46	0.262	12.56
S2 - Compensation	0.490	0.337	0.630	13.55	0.422	12.56
S3 - Compensation	0.719	0.554	0.740	47.18	0.638	33.02
S4 - Compensation	0.851	0.772	0.943	19.88	0.788	19.86
S5 - Compensation	0.985	0.894	1.022	24.41	0.912	24.39

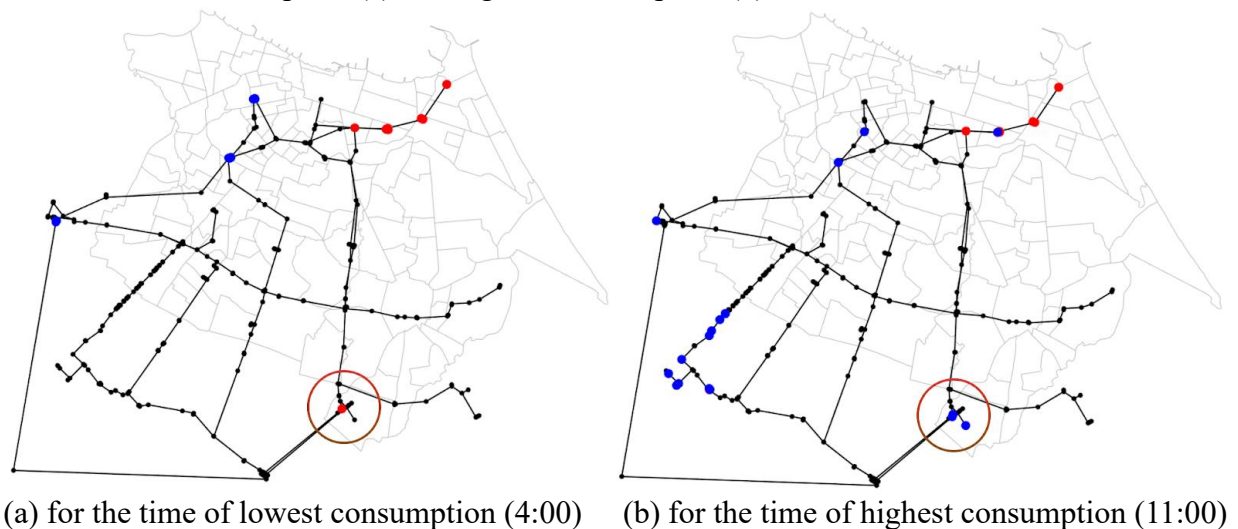
Source: The autor.

To better highlight the nodes with the largest deviations relative to scenario S0, Figure 4.9 presents the location of those that recorded the greatest reductions (in blue) and the greatest increases (in red) in pressure over the years, during both minimum and maximum consumption hours. The spatial distribution of these nodes confirms that pressure increases tend to occur near the injection points (located in neighborhoods with higher Human Development Index values), while the most pronounced reductions are concentrated in nodes farther from these water entry points. This spatial configuration of pressure variations underscores the unequal impacts of injection within the network. On the one hand, areas close

to injection points benefit from more favorable hydraulic conditions; on the other, peripheral sectors experience progressive pressure deficits, particularly during peak consumption periods. These disparities highlight the need for complementary operational strategies, such as the installation of pressure-regulating valves, reinforcement of peripheral mains, consumer awareness initiatives, or even the implementation of decentralized injection points, in order to reduce inequalities in supply quality (Khan, 2021; Moossa et al., 2022). The results also reinforce the understanding that the network topology and the socioeconomic distribution are interlinked and must be considered in an integrated manner in water planning and design. Such a perspective underscores the importance of approaches that ensure not only hydraulic efficiency but also equity in access to adequate water conditions across the urban system (Araújo et al., 2024).

Additionally, it is observed that, in the region highlighted in Figure 4.9, there is a node that, at different times of day, exhibits both the greatest reduction (at 04:00) and the greatest increase (at 11:00) in pressure. This behavior indicates a high amplitude of variation throughout the day, rendering this region particularly vulnerable to additional stress on the pipelines and, consequently, more susceptible to potential failures (Jara-Arriagada, 2021; Marsili et al., 2023)

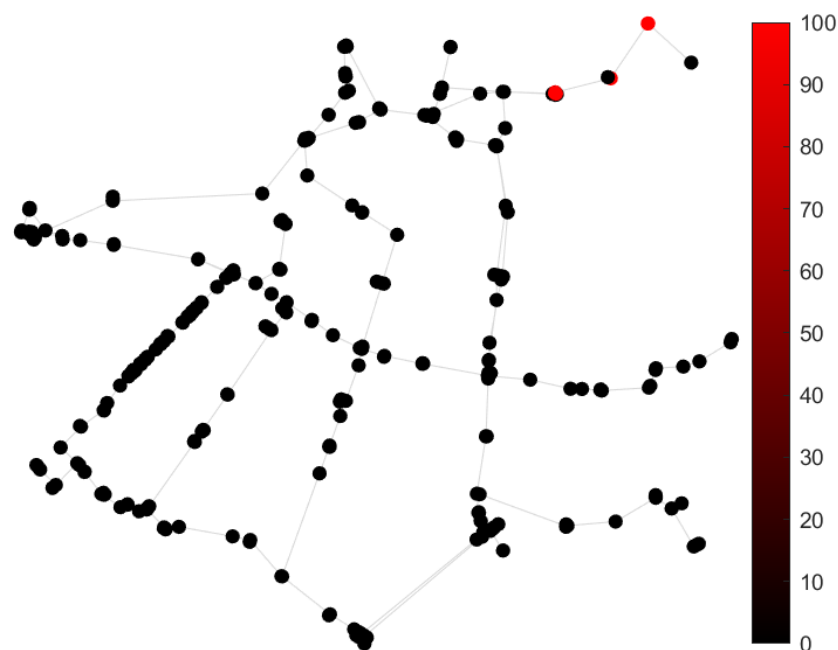
Figure 4.9 – Map highlighting the nodes with the largest (in red) and smallest (in blue) relative variations in pressure compared to the baseline scenario (S0) over the years for the time of lowest consumption (a) and highest consumption (b)



Source: The author.

Figure 4.10 reinforces the interpretations presented in the previous analyses by illustrating the percentage distribution of the combined contributions from the two reservoirs across the network nodes. It is observed that only three nodes simultaneously receive water from both sources, and these are the same nodes that, as shown in Figure 4.7, 4.8 and 4.9, exhibit the greatest pressure variations over the years. This direct correspondence between contribution patterns and pressure variation patterns confirms that the most pronounced increases occur near the injection points, highlighting the structural influence of these entry points on the network's hydraulic behavior. Moreover, this behavior is not limited to the scenario with DESAL operation; equivalent analyses conducted for the scenario without DESAL reveal the same trend, indicating that it is an inherent characteristic of the system's topology. Another relevant aspect is that these results demonstrate the predominantly localized nature of the intervention provided by DESAL: although certain sectors near the injection points benefit from improved hydraulic conditions, most of the network receives no direct contribution, which limits the spatial extent of the positive effects. Thus, Figure 4.10 not only presents the spatial logic of the source contributions but also reinforces the understanding that the configuration of the network decisively conditions the distribution and variability of pressures, underscoring the need for integrated approaches to planning and operational management.

Figure 4.10 – Spatial map of the combined proportional contribution (0–100%) of water from the Mucuripe and Aldeota DESAL injection reservoirs to the network nodes



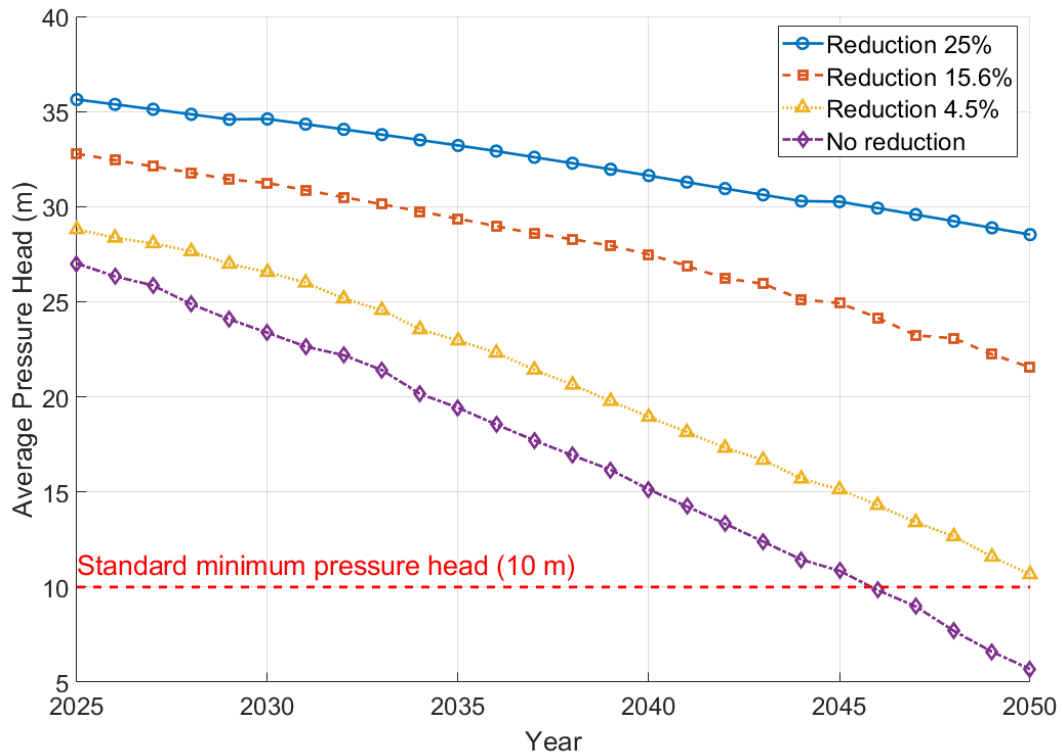
Source: The author.

The results of Todini's resilience index (I_r) show that the simulated network, corresponding to the year 2017, which was also the year used for the calibration of the system, presents I_r values ranging approximately from 0.32 to 0.48 across the analyzed scenarios. These results indicate a moderate capacity of the network to absorb hydraulic failures or variations in operating conditions. According to Todini (2000), values near 0.20 are typically associated with networks of low resilience, which tend to show limited ability to withstand adverse conditions such as hydraulic failures or increased demand. Since all simulated scenarios exhibit I_r values above this threshold, the findings suggest that there is sufficient energy surplus in the system to satisfy demand requirements and maintain minimum pressure levels even under perturbations. Although the obtained values do not indicate a high level of resilience, they show that the network retains a reasonable capability to accommodate failures and continue operating within acceptable performance limits. When calculating the Todini index for the year 2025, negative values were observed across all analyzed scenarios, ranging around -2 and reaching approximately -3 at certain hours. These results indicate that, given the current demand levels and even with the inclusion of the DESAL facility, the network operates without sufficient energy surplus to withstand potential failures or variations in operating conditions. This reveals an energetically deficient system, unable to maintain minimum pressure levels when subjected to perturbations. If the system already exhibits negative resilience values in 2025, it is reasonable to assume that, in future years, as demand continues to grow, this condition will further deteriorate, increasingly compromising the network's ability to meet operational requirements.

Figure 4.11 illustrates the evolution of average pressure head in the water supply network between 2025 and 2050, considering different demand-reduction scenarios resulting from rationalization policies and conscious consumption. A continuous decline in average pressures is observed across all scenarios, directly reflecting population growth and the consequent increase in demand. In the scenario without demand reduction, the most critical situation arises: pressures head decrease sharply, falling below the minimum regulatory threshold of 10 m around 2045. This result highlights the infeasibility of ensuring proper network operation within this horizon, even with the additional inflow of water from DESAL, which proves insufficient to maintain pressures at acceptable levels. The scenario with a 4% reduction shows slightly better performance, remaining close to the minimum threshold up to 2050. This indicates that even modest water-saving measures can improve minimum pressure

head conditions by extending the period before critical situations occur. The 15.6% reduction scenario, as estimated by Vidal-Lamolla et al. (2024), exhibits an intermediate pattern, maintaining safer pressure head levels throughout the time series, though still trending toward the regulatory limit after 2050. This suggests that medium-impact rationalization policies may delay, but not eliminate, the risk of insufficient pressure in the long term. By contrast, the 25% reduction scenario, consistent with Tortajada et al. (2019), presents the most favorable outcomes, with average pressures head consistently above the regulatory threshold throughout the analyzed period. This behavior demonstrates that only robust demand-rationalization strategies are capable of offsetting population growth and ensuring adequate network operation, overcoming the limitations imposed even with the contribution of DESAL. Therefore, the analysis makes clear that consistent public policies focused on education and the rational use of water are indispensable to maintain minimum operational conditions in the supply network. Moreover, the results suggest that the inflow of water from DESAL, when considered in isolation, may not be enough to fully ensure compliance with the minimum pressure head required by regulation under all evaluated conditions. Nevertheless, the proposed injection of desalinated water into the macrosystem constitutes a strategically important complement to the existing supply structure, contributing to the diversification of water sources, alleviating pressure on Fortaleza' s traditional systems, and reducing reliance on surface supplies that are more susceptible to climatic variability.

Figure 4.11 – Demand reductions in scenarios in the face of rationalization education in water use for scenario S5 – Addition (11:00)



Source: The author.

Recent studies indicate that while the capital and operating costs of desalination plants have decreased, the technology remains highly energy-intensive and considerably more expensive than conventional water sources (Green, 2019), particularly for developing countries such as Brazil. Depending on the energy mix, desalination can also lead to substantial greenhouse gas emissions (Darre, 2018). To mitigate this, studies have proposed integrating solar power systems to meet the energy demands of desalination plants (Ghenai et al., 2018). The Brazilian Northeast, characterized by consistently high solar irradiation, holds significant potential for solar energy generation (Cunha, 2022). However, the lack of affordable renewable energy during nighttime remains a challenge, which could be alleviated by advances in energy storage technologies (Andrade, 2025). Targeted investments are therefore essential to reduce the high energy footprint of DESAL in the region.

Future studies should investigate strategies to minimize both social and environmental impacts, such as pressure variations affecting local users and greenhouse gas emissions, through simulations using the hydraulic model developed in this study. Such efforts would enable a balanced assessment of each alternative, supporting the design of scientifically sound, economically viable, and environmentally sustainable water supply

schemes for local region (Alsarayreh et al., 2020; Hendrickson et al., 2023; Sayed et al., 2023).

4.4 Limitations

In collaboration with CAGECE, this study utilized the most up-to-date information to assess the impact of DESAL on Fortaleza's water supply macro-system. To conduct the analysis, some simplifications were necessary. First, we assumed that the distribution of demand across neighborhoods remains constant and that demand growth is uniform across the region. Second, we assumed that no additional water sources would be incorporated into the macrosystem. Third, the arithmetic method was used for population projection, which may not be the most appropriate given the city's demographic conditions. Fourth, still regarding population growth, this study adopted a uniform demographic growth for the entire city, which may not represent the population growth behavior of neighborhoods. Fifth, the analyses were performed for 48 hours (2 days) of simulation, making the analysis time-restricted. Finally, we assumed that the macrosystem itself remains unchanged throughout the study period. Future work should address these limitations. In addition, model calibration should be understood as a continuous process, as it is influenced by factors such as the evolution of pipe roughness over time and the incorporation of new water supply sources, which can alter the hydraulic behavior of the system. In this context, the internal roughness of pipes is directly influenced by changes in water quality, as variations in physicochemical composition may intensify processes such as scaling or corrosion. The introduction of new sources, such as desalinated water, can alter these characteristics over time, affecting the roughness coefficient and, consequently, the hydraulic behavior of the system. Therefore, it is essential to account for these variations in predictive analyses in order to incorporate potential future changes in the network's operational conditions. Nevertheless, this study provides an initial step toward understanding the role of DESAL in Fortaleza's macrosystem, with implications for other cities considering desalination projects.

4.5 Conclusions

This study evaluated the hydraulic impact of injecting desalinated water (DESAL) into the water supply macrosystem of the Metropolitan Region of Fortaleza (RMF). The

analysis was conducted using a previously calibrated hydraulic model of a large, real-world Water Distribution System (WDS) located in a Brazilian metropolitan area that faces water risks and droughts. The assessment considered projected demand growth and DESAL inflows for the period from 2025 to 2050.

The hydraulic analysis encompassed ten operational scenarios, divided into Addition and Compensation groups. In the Compensation scenarios, the reduction of flows from the Gavião Water Treatment Plant (WTP) was represented in the model through a flow control valve (FCV). This approach simulated the operational rules governing the integration of the new source (DESAL) and the rebalancing of contributions from existing sources, thereby highlighting the inherent challenges of managing large WDSs and the complexity of ensuring system stability when incorporating new water supply sources. The development of Compensation scenarios, which involved reducing the largest water input to the network (Gavião WTP), resulted in significant pressure redistribution. In contrast to the Addition scenarios, which produced relatively homogeneous impacts, the Compensation scenarios amplified localized effects, increasing the risk of insufficient or even negative pressures at already vulnerable nodes. The scenario analysis showed that, both in the baseline scenario (S0) and in the other scenarios (S1–S5), average pressures fall below the regulatory minimum threshold of 10 m around 2045, particularly during peak consumption hours (11:00). The results indicated that the additional DESAL inflow, on its own, is insufficient to ensure compliance with the minimum hydraulic pressure requirements mandated by regulation in the long term. However, the analysis suggests that the implementation of robust demand management strategies can offset population growth and maintain average pressures consistently above 10 m throughout the entire study period (2025–2050).

Finally, this work is expected to contribute to improvements in the water distribution system of Fortaleza by employing the model for the analysis of long-term operational scenarios and network modifications. Moreover, it will support decision-making by WDS management entities regarding the impact of integrating new supply sources into the network, underscoring the necessity for DESAL to be accompanied by consistent public policies focused on education and rational water use in order to preserve the minimum operational conditions of the supply system.

5 GENERAL DISCUSSION OF THE RESULTS

This thesis presents a relevant contribution to the advancement of knowledge in large-scale WDS modeling and calibration, with a focus on the incorporation of desalinated water and the assessment of its hydraulic and operational impacts. The results highlight the importance of using rigorously calibrated models for the proper representation of the system's hydraulic components, including pipes, nodes, valves, reservoirs, pumps, operational rules, and demands, as well as for analyzing system performance under the introduction of a new source and multiple operational scenarios under conditions of progressively increasing demand. The following section presents the discussion of the integrated results from the three contributions proposed in this study.

The literature review presented in Chapter 2, in addition to providing a solid theoretical foundation and historical contextualization of WDS modeling, brings together recent applications developed in regions with climatic characteristics similar to those of the Metropolitan Region of Fortaleza, some of which employed the same modeling tool (EPANET) adopted in Chapters 3 and 4. Studies such as those by Olmuştur and Uysal (2025) and Mabrok et al. (2022), although conducted on different continents, were carried out in areas marked by significant water scarcity and demonstrate that hydraulic modeling, beyond being contemporary and widely applicable, should be incorporated as an essential tool for forecasting, planning, and operational improvement of water systems. These works reinforce that modeling should not be regarded merely as a technical advantage, but rather as a strategic necessity for regions facing similar challenges related to water availability. Mabrok et al. (2022), in particular, conducted their study in a region with a high dependence on desalinated water. Although they did not directly examine the hydraulic or operational implications resulting from the injection of this water into the distribution network, the authors highlight concerns related to water quality aspects. In this context, both the study and the analyzed region serve as relevant references for identifying potential challenges associated with incorporating desalination as a supply source in the Metropolitan Region of Fortaleza, especially with regard to indirect impacts on hydraulic performance and the operational management of the distribution system.

It is observed that the calibration carried out in Chapter 3 using the PSO method (a type of implicit method) is consistent with the predominance of approaches adopted over the past five years in studies involving the calibration of large-scale real networks, according to a survey conducted in the Scopus database, as presented in Table 2.1 of Chapter 2. This trend toward the use of implicit methods in the calibration of large systems highlights their

flexibility in defining and selecting decision variables, as demonstrated in the application to the Metropolitan Region of Fortaleza network, in which base demand and absolute roughness were adopted as decision variables, as described in Chapter 3. Furthermore, the possibility of establishing minimum and maximum bounds for these variables helps restrict the search process to technically plausible ranges, preventing the exploration of unrealistic values or those outside operational standards. In this way, computational performance is optimized, processing time is reduced, and the calibration procedure becomes more efficient, robust, and consistent conditions that are essential in networks with a large number of nodes and pipes, whose structural and operational complexity requires methods capable of handling a high number of parameters and multiple variables.

Still with reference to Table 2.1, three studies stand out for presenting a significant number of calibration points associated with networks containing a large number of nodes: Li et al. (2025), Rocha et al. (2025), and Mekonnen (2023). Li et al. (2025) conducted the calibration process on two networks, one of which is a large-scale system supplying approximately 1.2 million inhabitants. In that study, the authors compared two nodal demand calibration methods applied to the same networks, evaluating the errors obtained and the processing time required by each approach. Rocha et al. (2025), in turn, applied the PSO algorithm to simultaneously calibrate base demand and absolute roughness in a supply macrosystem serving approximately 2.57 million people. The study also incorporated 2,304 operational rules distributed over 48 hours for 48 pressure-reducing valves and constitutes Chapter 3 of the present work. Mekonnen (2023), on the other hand, carried out a hydraulic diagnosis aimed at future network expansions and upgrades, including pressure and flow calibration in a system serving approximately 25,854 inhabitants. Although all three studies present a substantial volume of data and monitoring points, relevant differences exist in their adopted approaches. The works by Li et al. (2025) and Mekonnen (2023) focus, respectively, on methodological comparison for demand calibration and on diagnostic assessment for improvement planning. Rocha et al. (2025), however, simultaneously incorporates structural calibration and complex operational adjustment in a large-scale macrosystem whose population scale is significantly higher than that of the other studies analyzed, more than twice that of Li et al. (2025) and nearly one hundred times that of Mekonnen (2023). In this context, potential calibration errors in a system of such magnitude tend to produce impacts that extend beyond the technical sphere, reaching social, economic, and institutional dimensions associated with water security. Thus, the work by Rocha et al. (2025) presents an

element of originality by integrating structural parameter calibration with detailed operational rules, broadening the traditional scope of analyses centered solely on demand or hydraulic diagnosis, as discussed in Chapter 2. In this way, it highlights the potential of hydraulic modeling as a tool to support the management and governance of large-scale critical infrastructure.

When comparing the parameters used to evaluate calibration, it becomes evident that the three studies adopt different levels of depth. In Case 2 of Li et al. (2025), the analysis focuses mainly on relative demand error and processing time. Mekonnen (2023) employs classical statistical indicators, such as R^2 and NSE, which are appropriate for diagnostic validation of the network. Rocha et al. (2025), in contrast, apply a broader set of metrics, including MAE, ARHE, NSE, R^2 , and PBIAS, assessed for both pressure and flow, along with before-and-after calibration comparisons, as described in Chapter 3. In addition to these statistical indicators, the authors also employ graphical evaluation methods, particularly box plots, to analyze the distribution and dispersion of simulated and observed values, providing a complementary visual assessment of model performance. This more comprehensive evaluation enhances the consistency of the results and strengthens the reliability of the model for applications in large-scale systems.

There is a clear and complementary relationship between Chapters 3 and 4 of this work. While Chapter 3 focuses on the development and calibration of the hydraulic model, establishing its technical foundation and validating its reliability, Chapter 4 uses this previously calibrated framework to simulate and evaluate different scenarios involving the injection of desalinated water into the macrosystem, including demand projections. In this way, Chapter 3 demonstrates the practical applicability of the model as a decision support tool for future operational and planning strategies. In addition, the results and discussion presented in Chapter 4 are aligned with the gaps and strategies previously identified, indicating that the injection of desalinated water is consistent with the predictions and inferences discussed in Chapter 2, as it influences the spatial distribution of pressures and reveals differences in hydraulic performance across distinct areas of the network. Nevertheless, the proposed injection of desalinated water into the macrosystem constitutes a relevant strategic complement to Fortaleza's traditional water supply system, helping to reduce dependence on surface sources that are more vulnerable to climatic variability. Furthermore, desalination represents a water supply alternative aligned with international trends, as discussed in Chapter

2, which highlights the consistent expansion of this technology in recent years in response to water scarcity scenarios.

Specifically, Chapter 4 indicates that the localized injection of desalinated water into two reservoirs located in areas with higher HDI tends to increase pressure gains in these regions when compared to more peripheral areas. However, regardless of the location selected for injection, improvements in pressure conditions are expected in the area directly supplied. In addition, as illustrated in Figure 4.3, the current system already includes traditional sources that inject significant flow rates into areas distant from the future desalinated water injection zone. In this context, introducing desalination in a region that does not directly receive these conventional sources may contribute to a more distributed and less spatially concentrated supply configuration. Considering that WDS macrosystems are complex, interconnected, and interdependent structures, the introduction of new supply sources such as desalinated water goes beyond simple changes in local flow rates. As a looped network, the injection of new flows triggers a system-wide redistribution of pressures and flows, adjusting the hydraulic and operational behavior of the entire system to maintain mass and energy balance. As discussed in the conclusions of Chapter 2, this dynamic leads to significant variations in the spatial and temporal heterogeneity of pressures, highlighting that any localized modification affects the overall stability, hydraulic compliance, and resilience of the network as a whole.

6 GENERAL CONCLUSION AND RECOMMENDATIONS

This thesis was structured around three specific objectives: (1) to develop an integrative and exploratory literature review focused on hydraulic modeling and WDS calibration, with emphasis on their role in supporting the analysis of hydraulic and operational impacts associated with the integration of desalinated water into large-scale networks; (2) to calibrate the water distribution macrosystem of the Fortaleza Metropolitan Region based on hourly data from 50 pressure monitoring points and 40 flow monitoring points, considering two typical operational days; and (3) to assess, through the calibrated model, the impacts of desalinated water injection from hydraulic and operational perspectives, identifying the vulnerabilities and potentials of this increase in water supply for Fortaleza and its metropolitan region. In the three preceding chapters, each of these objectives is addressed in the form of an independent article, while in the final chapter the same calibrated model presented in the previous chapter is employed.

The first paper presented a relevant approach by confronting the specialized literature on the topic, integrating WDS and desalination as closely related themes, since desalination has been increasingly consolidated as an alternative source of water supply. It also provided a comprehensive analysis of the recent literature on water distribution system modeling and calibration based on real-world case studies. Despite the scarcity of studies that simultaneously address WDS and the hydraulic impacts of desalination, the first article made it possible to establish important inferences regarding these potential effects, namely: the intensification of spatial pressure heterogeneity within the network, with a tendency toward pressure reduction at points farther from the desalination plant; the intermittent operation of the plant, which may give rise to hydraulic transients, natural phenomena inherent to water flow, potentially leading to localized pressure variations that, over time, may contribute to structural fatigue and an increased incidence of leaks; and the use of storage tanks, which may lead to longer water detention times, favoring water quality degradation, particularly with respect to the reduction of free residual chlorine. This article raises relevant questions and justifies the importance of the two subsequent papers, while also highlighting the existing gap in the literature.

The second paper presented a practical application, based on a real-world case study, of the calibration of base demand and absolute roughness for a water distribution macrosystem in a region characterized by water scarcity and high population density, which imposes a high level of operational stress on the WDS. This study addressed the inherent complexity of calibrating a network with 479 junctions, 1 reservoir, 4 tanks, 393 pipes, 19 pumps, and 103 valves. The calibration method employed was PSO, which proved appropriate for the analyzed scenario, using 2,400 pressure data points and 1,920 flow data points, in addition to considering the various operational rules existing in the network, thus characterizing a large-scale and complex system. Despite the computational challenges and the complexity of the macrosystem, the calibration of base demand and absolute roughness resulted in a model with good performance according to the adopted indicators, such that 60% of the pressure errors were below 2 m. This paper provided a calibrated model for the analysis of operational scenarios and network modifications, as well as for the assessment of the impacts of integrating new water supply sources, as applied in the subsequent paper.

The third and final paper used the calibrated model from the second paper to analyze the hydraulic and operational impacts on the WDS of the Fortaleza Metropolitan Region, in addition to addressing some of the gaps identified in the first paper. The

desalination plant proposed for the city has two water injection points into the WDS, with an initial capacity of 1 m³/s. In this study, ten operational scenarios of the plant were proposed, five scenarios considering only the addition of water from the plant to the network and five scenarios considering injection compensation, that is, as the flow rate of desalinated water increases, a corresponding reduction occurs in the flow rates from another water supply source. The analysis also considered future projections of water demand up to the year 2050, evaluating how these scenarios impact network pressures and to what extent, under progressively increasing demand, the WDS would be able to meet minimum pressure requirements. The results indicated that, even with the addition of desalinated water, the system's average pressures tend to fall below the regulated minimum limit from 2045 onwards, especially during peak demand periods. The findings show that desalination alone is not sufficient to ensure long-term hydraulic performance, requiring the adoption of effective demand management strategies and public policies focused on rational water use to maintain minimum system operating conditions. This final paper closes the gaps identified in the first paper and expands the understanding of desalination as a strategic tool to address water scarcity.

As recommendations, each paper presents its own considerations.

The first paper was based exclusively on the literature indexed in the Scopus (Elsevier) and Web of Science Core Collection (Clarivate Analytics) databases, considering publications up to the year 2026. As a recommendation for future work, it is suggested to expand the search scope to include other relevant databases, as well as to incorporate complementary sources beyond scientific articles, such as technical reports, institutional documents, and specialized news, in order to capture reports of problems and challenges associated with the integration of desalination into WDS.

The second paper evaluated the impact of desalination on the water supply macrosystem of Fortaleza based on recent data, adopting some methodological simplifications. Uniform growth of demand and population across the entire city was assumed, along with maintenance of the system configuration throughout the analysis period, absence of additional water supply sources, and simulations restricted to a 48-hour time horizon. Furthermore, the arithmetic method was used for population projection, which may not accurately represent local demographic dynamics. In addition, other calibration methods could also be employed for this case. Despite these limitations, the study represents a relevant

initial step toward understanding the role of desalination in Fortaleza's water supply system, serving as support for future investigations and as a reference for other cities considering this supply alternative.

In the third paper, the hydraulic and operational aspects of desalinated water injection were analyzed, with particular focus on the behavior of network pressures under different operational scenarios. However, other relevant parameters could also be investigated, such as flow rates, free residual chlorine concentrations, and water age. The inclusion of these aspects would allow a more comprehensive characterization of the impacts of desalination on the performance of the distribution system. Furthermore, the literature consistently points to the energetic impacts associated with desalination plants, especially with regard to pump operation. In this sense, it is also recommended to evaluate energy consumption and pumping station operation strategies across the different analyzed scenarios.

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