UNIVERSIDADE DE SÃO PAULO
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Spatial and time scales of human-water feedbacks facing drought risk in megacities: a socio-hydrological approach in São Paulo

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FELIPE AUGUSTO ARGUELLO DE SOUZA

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SPATIAL AND TIME SCALES OF HUMAN-WATER FEEDBACKS FACING DROUGHT RISK IN MEGACITIES: A SOCIO-HYDROLOGICAL APPROACH IN SÃO PAULO

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Advisor: Prof. Dr. Eduardo Mario Mendiondo

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ABSTRACT

SOUZA, F. A. A. **Spatial and time scales of human-water feedbacks facing drought risk in megacities: a socio-hydrological approach in São Paulo**. 2023. 122. Thesis – São Carlos School of Engineering, University of São Paulo, São Carlos, 2023.

The Sao Paulo Metropolitan Region hosts more than 20 million inhabitants, who are supplied by several water sources wherein the Cantareira System, one of the largest water supply reservoirs in the world, is capable to deliver more than 30m^3/s of water. The reduced rainfall observed in 2013 and 2014 triggered the most severe water crisis in its recent history and raised several questions about the hazard intensity, the decision makers' ability to handle with such events and the community role in reducing the water consumption when required. This thesis aims at investigating the interactions over time between water availability and human action in Sao Paulo to assess whether the crisis resulted from this drought event could have been avoided. First, historic records and key aspects related to drought risk management, such as hazard intensity, preparedness, exposure, vulnerability, disaster response and mitigation alternatives, are used to compare the 2013-2015 water crisis to the 1985-1986 drought, observed long ago, and contrast the evolution of those aspects so far. Therefore, the evidence suggests the greater hazard intensity and people's exposure to drought, in combination to both late water-saving policies' implementation and the dependency of several service areas on a single reservoir, culminated in the disaster experienced in 2013-2015. Second, a machine learning model is employed to address the community response to water saving policies and to outline a hypothetical storyline considering the early implementation of such policies. The model outputs suggest stronger significance on the contingency tariff rather than the bonus tariff. Therefore, the penalty tariff would be required two years in advance to promote water conservation of local users and prevent the Cantareira System from reaching the dead pool level. Third, the water allocation from the Paraiba do Sul River Basin is evaluated upon the scenarios of transboundary interactions between upstream – Sao Paulo State – and downstream – Rio de Janeiro State –within the context of the 2013-2015 water crisis. Those scenarios address the impacts of i) water allocations from the Paraiba do Sul River Basin to the Cantareira System through a tunnel concluded after the drought, and ii) updated operation rules of the Paraiba do Sul River Basins as a response to drought impacts within its basin observed in 2013-2015 as well. The three scenarios show that the impacts on water availability and hydropower production does not satisfy the two players at the same time and, therefore, put then in a game where hydroelectricity would be reduced for both states at any scenario, while the water transfers to Sao Paulo would be equivalent to the supply of 1 million people downstream in the three years. The three working fronts explore the two-way feedbacks between water availability and humans' behavior to better understand the coevolution of this coupled system in Sao Paulo and outline hypothetical storylines to improve the responses of futures drought events.

Keywords: Drought risk management, sociohydrology, transboundary river, game theory, machine learning model, water-saving policy evaluation.

RESUMO

SOUZA, F. A. A. **Escalas espaciais e temporais da interação homem-água frente ao risco de seca em megacidades: uma abordagem sócio-hidrológica em São Paulo**. 2023. 122. Tese – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2023.

A Região Metropolitana de São Paulo abriga mais de 20 milhões de habitantes que são abastecidos por diversas fontes de água, onde o Sistema Cantareira, um dos maiores sistemas de reservatórios de abastecimento de água do mundo, é capaz de fornecer mais de 30m³/s de água. A redução das chuvas observada em 2013 e 2014 desencadeou a mais grave crise hídrica de sua história recente e levantou diversas questões sobre a intensidade do evento, a capacidade dos tomadores de decisão para lidar com tais eventos e o papel da comunidade na redução do consumo de água quando necessário. Desta maneira, esta tese objetiva investigar as interações ao longo do tempo entre a disponibilidade de água e a ação humana, em São Paulo, para avaliar se a crise decorrente do evento de seca poderia ter sido evitada. Primeiro, revisita-se registros históricos e compara-se a crise hídrica de 2013-2015 com a seca de 1985-1986 para avaliar a evolução de aspectos-chave relacionados ao gerenciamento de risco de seca, como intensidade do evento, preparação, exposição, vulnerabilidade, resposta ao desastre e ações de mitigação. Assim, as evidências observadas sugerem que a maior intensidade do evento e a maior exposição das pessoas à seca, em combinação com a implementação tardia de políticas de redução do uso da água e a dependência de várias áreas de abastecimento em um único reservatório culminaram no desastre ocorrido em 2013-2015. Na sequência, um modelo de aprendizado de máquina aborda a resposta da comunidade às políticas de redução do uso de água para avaliar a eficácia de cenários hipotéticos que consideram a implementação precoce de tais políticas. O modelo sugere mais importância da tarifa de contingência, que aumenta o valor cobrado dos consumidores por não reduzir o uso de água, em relação à tarifa bônus, que reduz a conta de água dos consumidores que voluntariamente diminuem seu consumo. Assim, os resultados apontam que as políticas de redução de consumo seriam necessárias com dois anos de antecedência para promover a conservação da água dos usuários locais e evitar que o Sistema Cantareira atingisse o nível do volume morto. Por fim, as interações transfronteiriças da bacia do Rio Paraíba do Sul entre montante – Estado de São Paulo – e jusante – Estado do Rio de Janeiro – são exploradas no contexto da mesma crise hídrica de 2013-2015. A construção de cenários aborda os impactos de i) alocações de água da Bacia do Rio Paraíba do Sul para o Sistema Cantareira através de um túnel, que fora concluído apenas após o evento de seca, e ii) as novas regras de operação dos reservatórios, que foram atualizadas em resposta aos impactos da seca observada em 2013-2015. Os cenários mostram que os impactos na disponibilidade de água e na produção de energia hidrelétrica não satisfazem os dois jogadores ao mesmo tempo e, portanto, colocá-los-iam em cenários onde a hidreletricidade seria reduzida para ambos os estados, enquanto a transferência de água para São Paulo seria equivalente ao abastecimento de 1 milhão de pessoas a jusante. Os três estudos exploram os feedbacks bidirecionais entre a disponibilidade de água e as respostas humanas para melhor entender a coevolução desse sistema em São Paulo e avaliar cenários hipotéticos com intuito de estimar as melhores respostas para futuros eventos de seca.

Palavras-chave: Gestão de risco de secas, sócio hidrologia, rios transfronteiriços, teoria dos jogos, aprendizado de máquina, políticas consumo de água.

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LIST OF ABBREVIATIONS

SPMR – São Paulo Metropolitan Region

SABESP - *Companhia de Saneamento Básico de São Paulo* (water utility of São Paulo)

PCJ - Piracicaba, Capiravari and Jundiaí rivers

EWS - Early Warning Systems

CEMADEN - Brazilian Centre for Monitoring and Early Warning of Natural Disasters

SCS – Soil Conservation Service

SPI – Standardized Precipitation Index

SDI – Streamflow Drought Index

GIS – Geographic Information System

IBGE – Brazilian Institute of Geography and Statistics

DEM – Elevation Model files

XG Boost – Extra Gradient Boost

FP – False Positives

FN – False Negatives

TP – True Positives

TN – True Negatives

SA – Service Area

SHAP - SHapley Additive exPlanation

PbSRB – Paraíba do Sul River Basin

GoF – goodness-of-fit

NSE – Nash-Sutcliffe Efficiency criterion

KGE – Kling-Gupta Efficiency

ANA – National Water and Sanitation Agency

BRL – Brazilian currency

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1 GENERAL INTRODUCTION

The growth of cities triggers several challenges that require sophisticated and creative solutions, since every region of the planet has its own particularity. Meeting the demands for water is one of these main challenges and has affected many megacities, where water availability has not evolved at the same rate of demands, while reduced rainfall led to drought propagation, such as some cases in the United States, Mexico, India, South Africa, Australia, and even Brazil.

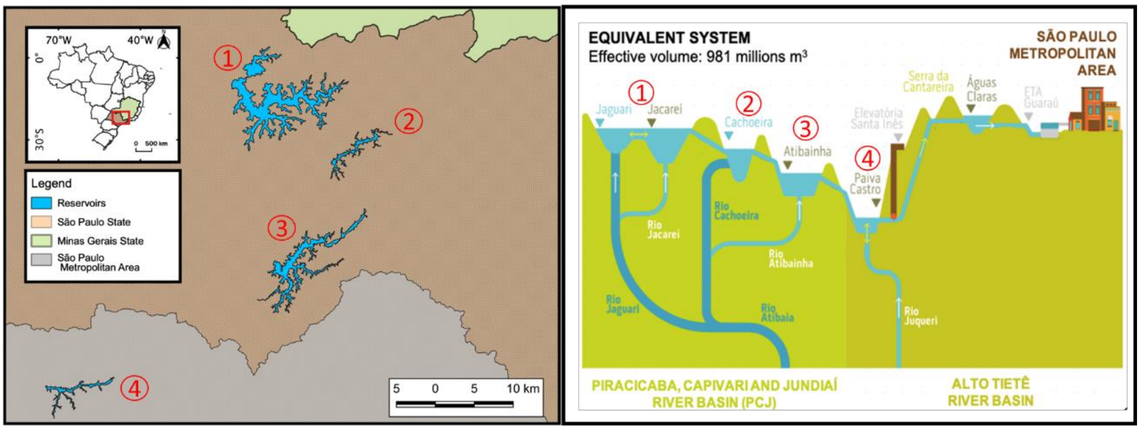

Figure 1.1: Location of the Cantareira Reservoirs and the representativeness of the supply infrastructure that delivers water to the São Paulo Metropolitan Region. Right-hand side figure was adapted from ANA (2017).

In urban centers, water insecurity can occur because of several factors. At the hydrological level, threats are identified when water availability is reduced because of changes in precipitation regimes and deterioration of water quality. In the political field, these water scarcity signs are evidenced by the dispute over the right to use water resources. In the socio-demographic sphere, the challenge is due to the increase in population and corresponding demand. From an anthropic point of view, not only the population is changing but the way they consume the resources available. In addition, the economic development triggers the evolution and expansion of activities that consume more and more energy and water. In summary, different perspectives focuses on different elements separately, but they are interconnected through direct or indirect mechanisms.

Table 1.1: Cantareira System, its reservoirs and municipalities served, ANA (2010)

REGIÃO METROPOLITANA DE SÃO PAULO		
SISTEMA	PRINCIPAIS MANANCIAIS	SEDES URBANAS ATENDIDAS
Cantareira	Represas Jaguari, Jacareí, Atibainha, Cachoeira e Paiva Castro	Barueri; Caieiras; Cajamar; Carapicuíba; Francisco Morato; Franco da Rocha; Guarulhos; Osasco; São Caetano do Sul; São Paulo

As example, the São Paulo Metropolitan Region (SPMR) experienced the worst water crisis in its history between 2013 and 2015, when the local authorities, the water utility and the water consumers were forced to shift their patterns of consumption in order to avoid the emptiness of the largest water source in South America, the Cantareira System, represented by the five reservoirs presented in Figure 1.1. The reservoirs that form the Cantareira System (see Table 1) receives water from the PCJ (Piracicaba, Capiravari and Jundiaí rivers) River Basin allocation, and from the Alto Tietê River Basin.

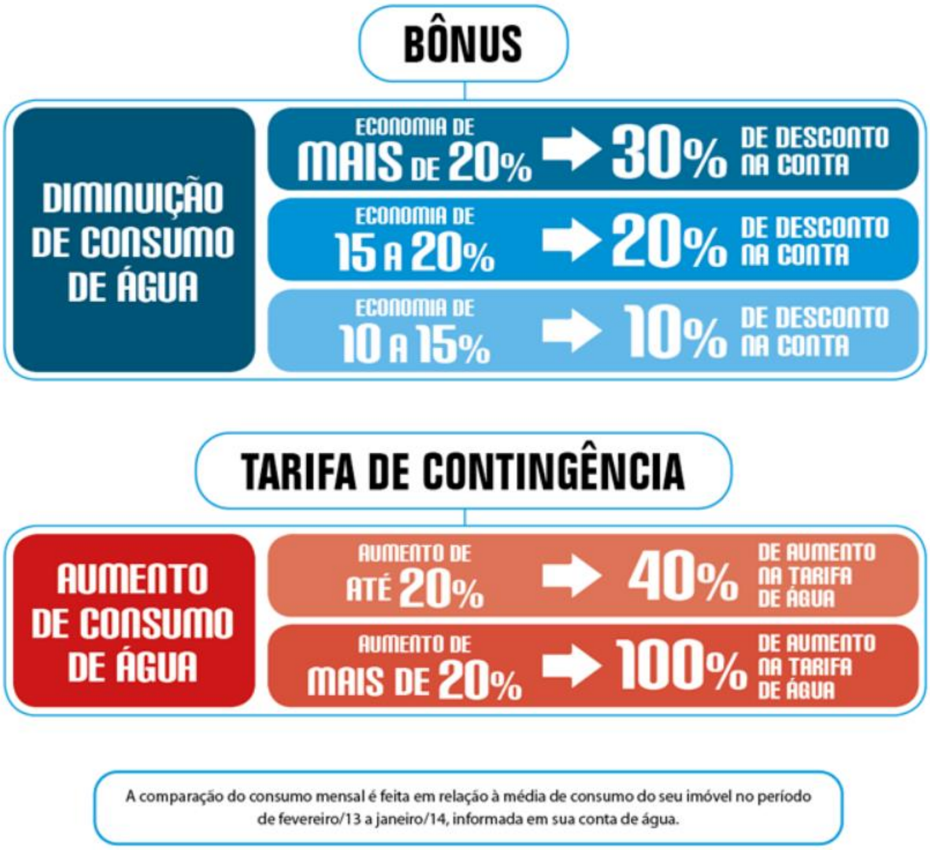

Figure 1.2: Showcases the two tariffs implemented to promote water use reduction between 2014 and 2015 (SABESP, 2020). The blue policy is named Bonus Tariff because discounts were given to consumers who reduced their consumption at one of the three ranges. The red policy is named the Contingency (or Penalty) Tariff, because consumers were charged when consumption increased.

These events not only drew attention of Brazilian authorities and researchers, but also of the international community. During that period, the region suffered low rainfalls and, consequently, very low inflows were observed, what led the reservoirs to reach storage levels below the historical average and drove the SMPR to the worst drought recorded. Meanwhile, some policies were implemented to reduce the demands of the population until the reservoirs reach acceptable levels, such as the two tariff policies presented in Figure 1.2.

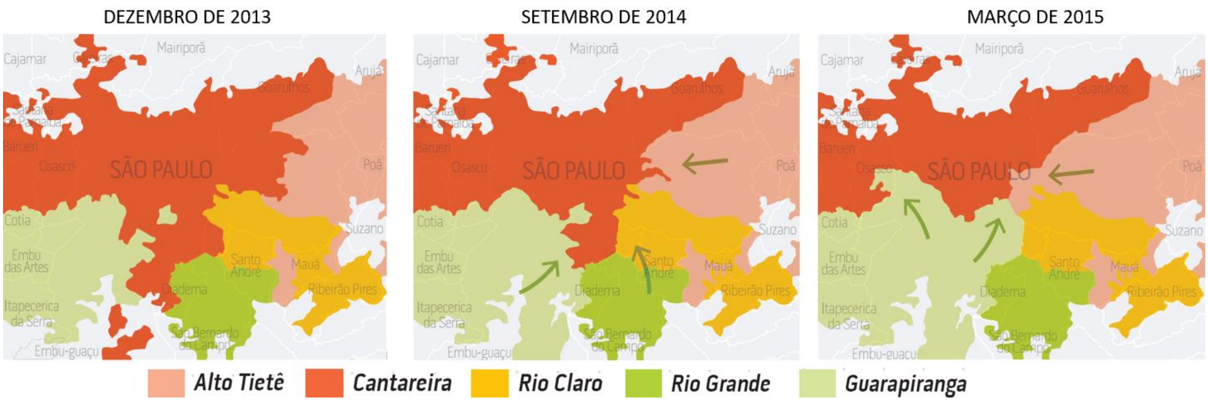

Figure 1.3: Shows the reduction of Cantareira Coverage between 2013 and 2015 to reduce withdrawals from the reservoirs (ANA, 2017)

Beside the Cantareira System, The Brazilian Atlas of Urban Water Supply (ANA, 2010) highlights the existence of other 7 main systems responsible to deliver water to 31 out of 39 SPMA's municipalities and other isolated systems. The responsible for the reservoir operations and water supply within the SPMR is the *Companhia de Saneamento Básico de São Paulo* – SABESP, a company established in 1973 from the junction of other companies, classified as a joint-stock company and semi-public corporation.

The existing literature concluded that the 2013-2015 water crisis was a consequence of low inflows into the Cantareira reservoirs because of a reduction in precipitation between 2013 and 2014. This reduction was forecasted by Fearnside (2005), who warned that deforestation in Amazon Forest could result in reduced rainfall in the Southeastern region of Brazil. Other authors (Baptista, 2017; Puga, 2018) also highlighted the negligence of local authorities, because some previous reports warned about the possible collapse in the water supply system (ANA, 2010a, 2010b). Therefore, some policies were implemented in order to promote water use reduction to ensure the water availability in the region. Puga

(2018) identified the bonus and penalty tariffs as pricing policies created by the water utility to stimulate voluntarily reduction, the pressure reduction in pipelines to reduce the leakages and, lastly, the allocation of water from other reservoirs to the regions previously supplied by the Cantareira System (ANA, 2017).

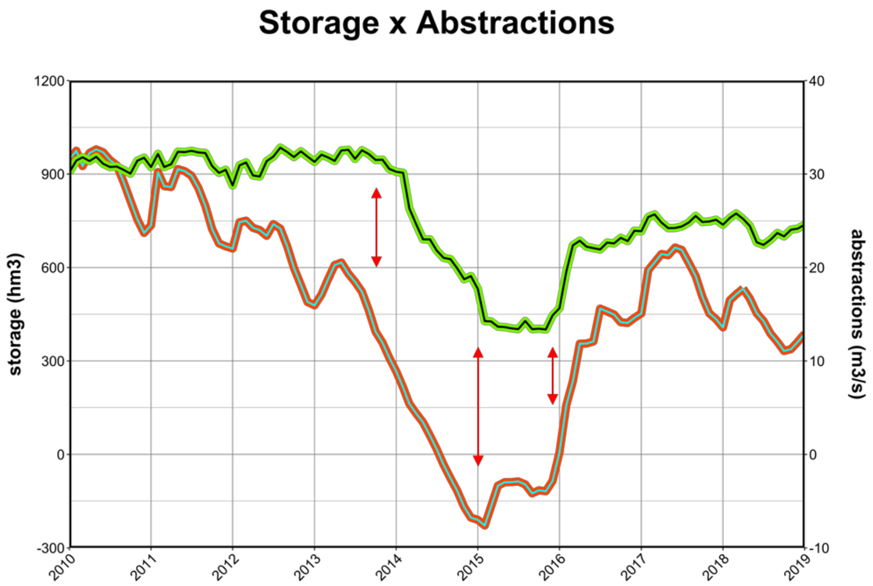

Figure 1.4: Presents the interactions between water availability and water consumption, where the red line is the storage at the Cantareira System and the green line is water abstractions from the System. The red arrows highlight the parallel decreasing and increasing behaviors.

However, the causality of the water conservation behavior is not clear. The overlap of so many policies make it difficult to identify what was the key driver that made household use less water. For example, Figure 1.4 shows a parallel behavior of water availability and abstractions from the Cantareira System. When availability decreases, withdrawals reduce as well. So, what is causing the reduction, the pricing policies (Figure 1.2), the management of service areas (Figure 1.3) or any demonstration of awareness about the drought risk?

Therefore, the fundamentals of socio-hydrology presented by Sivapalan et al (2012) and Sivapalan and Blöschl (2015) are employed in this thesis to better understand those feedbacks between the human and the natural systems during the water crisis that occurred in the SPMR. While traditional statistical analysis considers stationarity, the socio-hydrological approach takes advantage of the system dynamics concepts, which evaluates the relationship between state variables over time. For instance, Figure 1.5 presents the key variables and the causal effects involved in the broad human-water supply system of the

São Paulo Metropolitan Region, where a feedback loop happens among the variables storage level, water stress, environmental awareness, consumption per capita, house demands and, again, storage level.

Beside this feedback loop, external variables also affect the entire system. This is what happens when we stress the inflow variable. If inflow reduces, storage level reduces as well, what leads to decreasing consumption per capita. Therefore, not only the feedback loop is explored in this thesis, but also the effect of external variables, such as the effect of tariffs on the consumption per capita and the role of water allocation from another basin, the Paraiba do Sul.

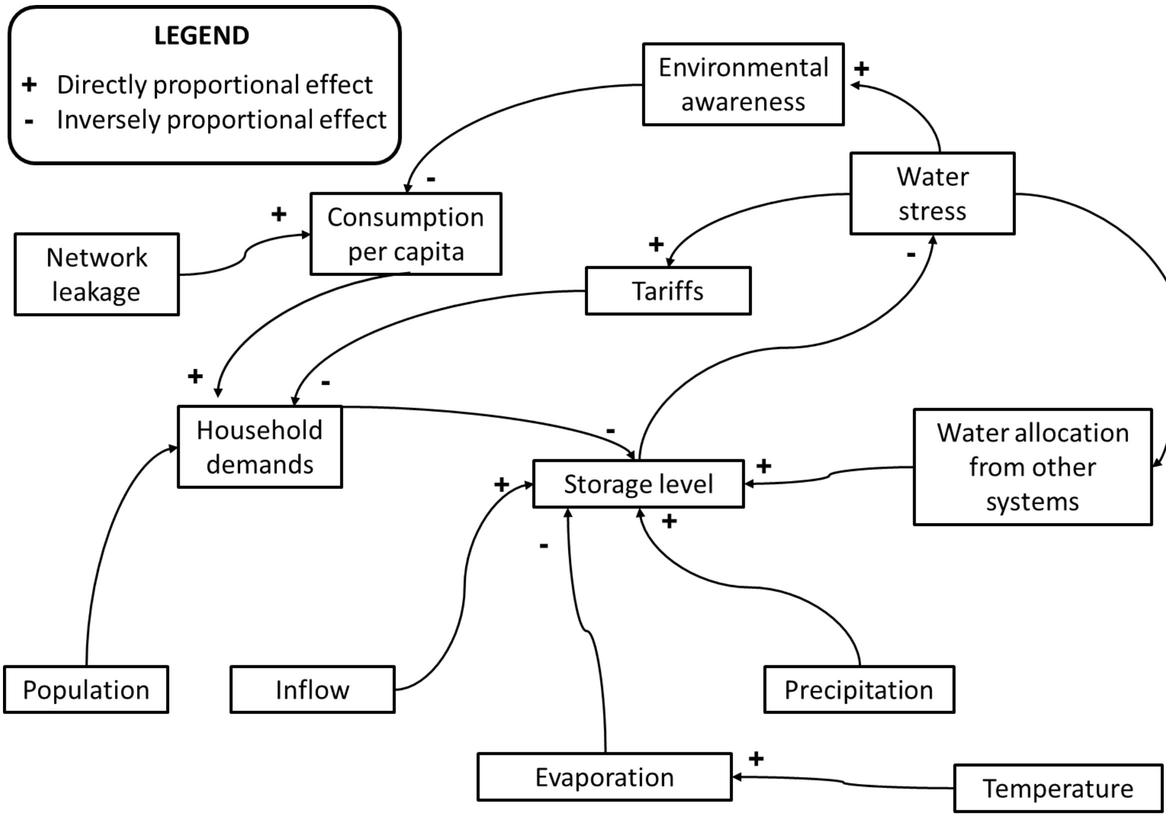

Figure 1.5: Perceptual model for the Cantareira Water Supply System

Therefore, the hypothesis behind this socio-hydrological system is that early implementation of drought policies could be effective on preventing the Cantareira reservoirs from reaching the dead storage level. Therefore, this thesis focuses on understanding the dynamics of the SPMR supply system because of i)the conflicts of interest due to the water allocation between the PCJ, Alto Tietê River Basin and Paraiba do Sul River Basin; ii) the large population served by the Cantareira System; iii) the different socio-economic characteristics of each municipality and; iv) the remarkable water crisis between 2014 and 2015.

1.1 RESEARCH HYPOTHESIS, OBJECTIVES AND GOALS

The guiding hypothesis of this thesis is that the 2013-2015 water crisis could be avoided as well as the water supply reservoirs' probability of emptiness could be reduced by stressing the interactions between the water availability and the community behavior. Therefore, the three main goals in Figure 1.6 are set to test such hypothesis.

Before conducting any experiment, the first goal is to precisely understand the study area: all the details around the water supply facilities, the institutions responsible to manage the water in the region and the identification of the consumers' profile. In addition, we review the existing literature on the conduction of water crisis in the region to evaluate how the coping strategies have evolved over time by comparing the drought risk management of two events.

The next goal addresses the water-demand policies. The first objective is to develop a socio-hydrological model within the context of water-conservation behavior, where the decision makers would be able to forecast whether the consumers will reduce their water use or not. Second objective is to build some scenarios to assess the efficiency of the early implementation of pricing policies and to test if this strategy alone would ensure the Cantareira storage level beyond the dead pool threshold.

The third goal addresses the consequences of a transboundary water-supply policy. The first objective is to simulate all the side effects of allocating water from other basins to the Cantareira reservoirs. Therefore, some scenarios reproduce the boundary conditions and the operation rules of the Paraiba do Sul River Basin reservoirs to address the second objective, which is building a pay-off matrix that considers the economic, environmental and demand impact of both players in a transboundary water allocation game.

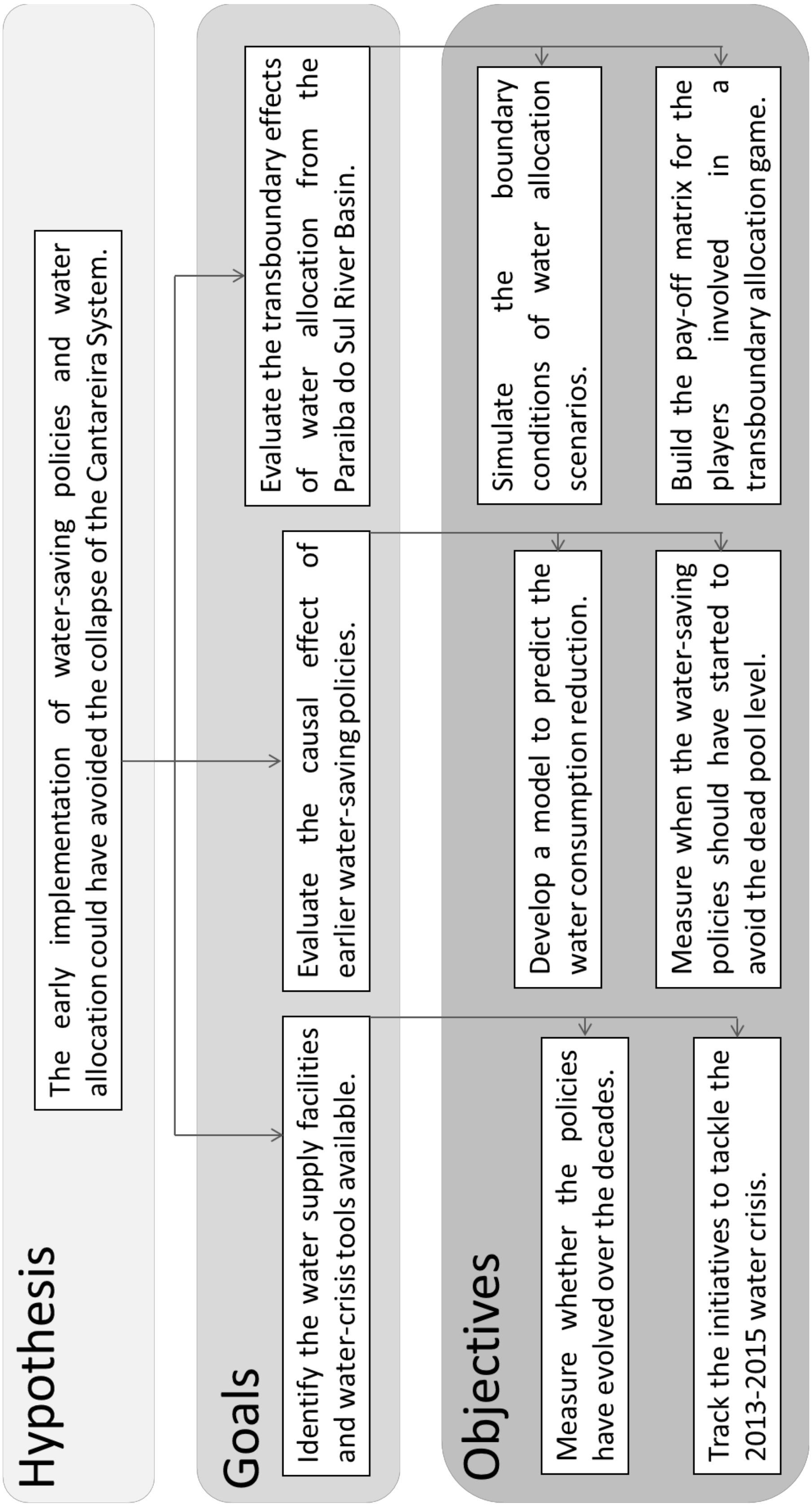

Figure 1.6: Interconnection between hypothesis, goals and objectives

1.1 TEXT ORGANIZATION

This thesis is organized in five chapters. The first one is this general introduction, which provides an overview regarding what is the background of the working hypothesis and how it is linked to the objectives and the methodology employed. The following three chapters address the key elements on the relationship between water and society at different time and spatial scales, presented in Figure 1.7, to evaluate whether it would be possible to avoid a deeper water crisis by preventing the Cantareira reservoirs from reaching the dead pool level. Finally, the last chapter present the conclusion and lessons learned from these experiments and point out recommendations for future works.

In **chapter two**, a literature review and data analysis regarding the key variables and indicators concerning the water availability and demand in São Paulo are put together to reframe a historical analysis on the coevolution of water availability and consumption to address how drought management has evolved over the last 40 years.

In **chapter three**, a machine learning model is employed to evaluate the consumers' responses to earlier water saving policies. The effectiveness of each policy and the social-economic aspects of every sub-region of Sao Paulo Metropolitan Region are evaluated. In addition, a scenario considering early implementation of water saving policies is built to answer whether it would be possible to prevent the Cantareira System from reaching the dead pool level by managing the demand-side component.

In **chapter four**, the water allocation alternative to prevent the water crisis and its consequences are explored in a game theory approach. São Paulo and Rio de Janeiro states are placed as upstream and downstream players, where every possible change on the operation rules of the Paraiba do Sul River Basin reservoirs are simulated and the respective payoffs are evaluated for each player.

Finally, **chapter five** summarizes the conclusions from each investigation. It is presented what limitations, lessons could be inferred, and what are the next steps towards the use of volunteer information to make predictions about possible trajectories.

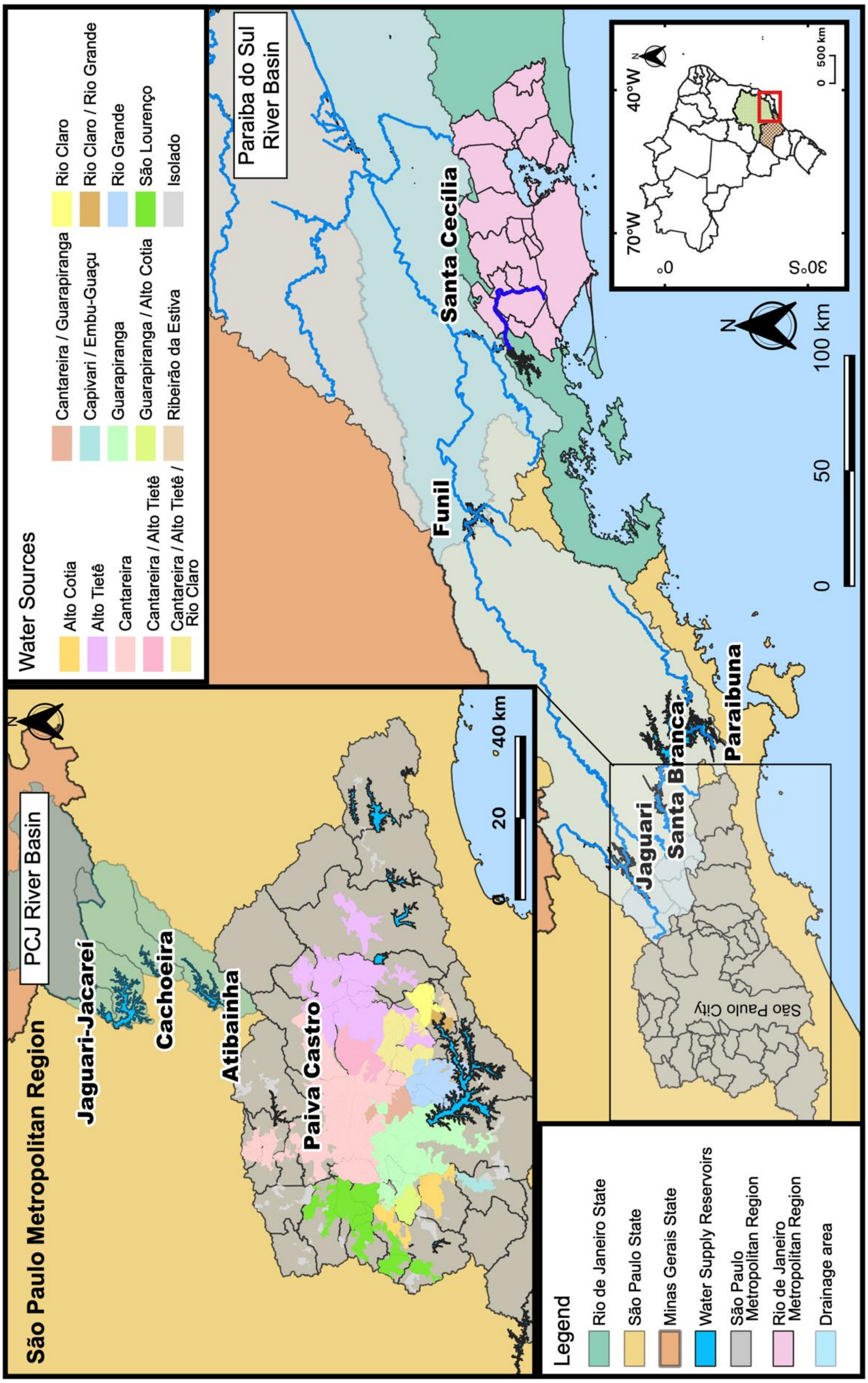

Figure 1.7: Presents the case study map. The map on the top is a zoom on the São Paulo Metropolitan Region, where the dynamics are explored in chapters two and three. The larger map focuses on boundary between the São Paulo and the Rio de Janeiro state, with special focus on the Paraiba do Sul River Basin, where the transboundary dynamics are investigated in chapter four.

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2 DROUGHTS IN SÃO PAULO: CHALLENGES AND LESSONS FOR A WATER-ADAPTIVE SOCIETY

A modified version of this chapter was published as Souza F. A. A., Mohor G. S., Guzmán-Arias D. A., Buarque A. C. S. , Taffarello D., Mendiondo E. M .(2022) Droughts in São Paulo: challenges and lessons for a water-adaptive society. Urban Water Journal.

2.1 INTRODUCTION

Apart from other natural hazards, drought impacts are mostly non-structural, cover larger areas, and duration is difficult to pinpoint (Wilhite et al, 2014). Projections estimate that 1.8 million people are expected to face severe water conditions until 2030 (Zhang et al, 2020). In the context of natural hazard risk reduction, such as droughts, the Sendai Framework assigned priorities that require actions from governments, decision makers and scientists (Aitsi-Selmi et al., 2015; UNISDR, 2015). Therefore, disaster risk management processes aim at improving preparedness, response, and recovery (IPCC, 2012; IPCC, 2014; Young, et al. 2019).

There is an increasing concern to understand societal adaptation resulting from interactions between human and water systems that might interfere with the water security component (Brelsford et al., 2020; Srinivasan et al., 2017, Di Baldassarre et al., 2019). Although different drought events in the same region do not cause similar impacts (Wilhite et al., 2014), it is recommended to analyze past local responses to provide an understanding of the evolution of adaptive capacity (de Nys, Engle and Magalhães, 2017; Dilling et al., 2019), which can be done by monitoring changes in risk trend components (Hagenlocher et al., 2019). Indeed, some studies have demonstrated significant insights into case study comparison, such as Kreibich et al. (2017), who compared paired events to evaluate the role of vulnerability on flood events, and Van Loon et al. (2019), who verified the effect of human activities on drought events by analyzing paired catchments.

In this context, the São Paulo Metropolitan Region (SPMR) and its millions of inhabitants have experienced remarkable extreme events alongside history, such as the droughts in 1910, 1924, 1985, 2004 and 2013 (Barbosa et al., 1997; Hermann et al., 1987; Jacobi et al., 2015; Lemos et al., 2020). The water supply system has constantly evolved, but much more emphasis is given during and after the occurrence of extreme events because of the damage they impose on human well-being, economic growth, and their impact on freshwater ecosystems (Anderson et al., 2018; Wiel and Bintanja ,2021). In spite of several studies that have characterized drought severity and identified key concerns in risk management, there is a need to look back and understand what has improved and what has been learnt between events to make society/communities more prepared for future droughts.

Therefore, the aim of this chapter is to compare two major droughts experienced by the São Paulo Metropolitan Region, to analyze how strategies to cope with risk have evolved and raise plausible alternatives to reduce water stress. The first case is the dry period between 1985 and 1986, which is the oldest event with records and information available to provide a comparison with the second case, the water crisis between 2013 and 2015. The analysis and discussion are guided by six phases of the two step water-adaptive risk management presented in Figure 2.1: 1)Risk assessment: preparedness, exposure, hazard intensity, vulnerability and; 2) Risk reduction: response and mitigation.

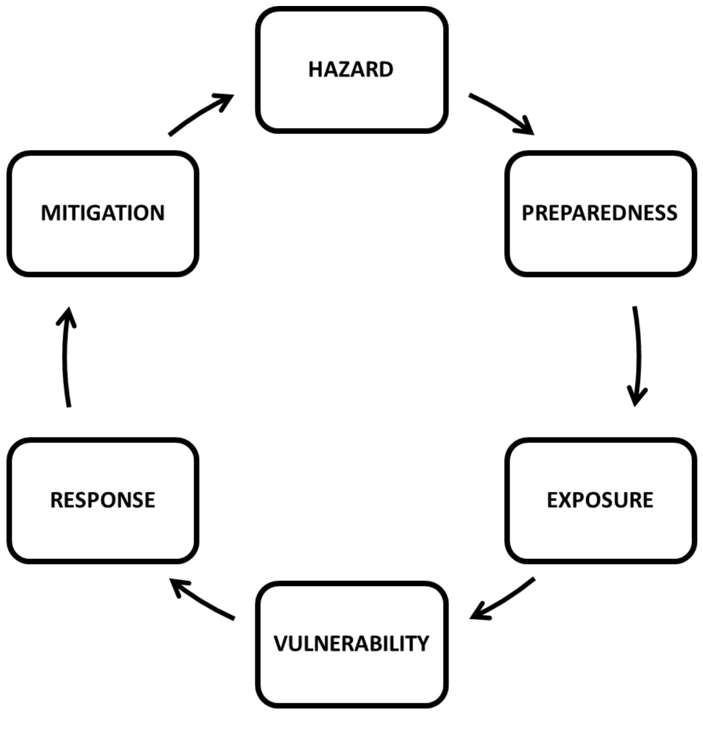


Figure 2.1: Presents the six phases of drought risk management and the chronological steps that require actions to better prepare and reduce damages.

2.2 BACKGROUND

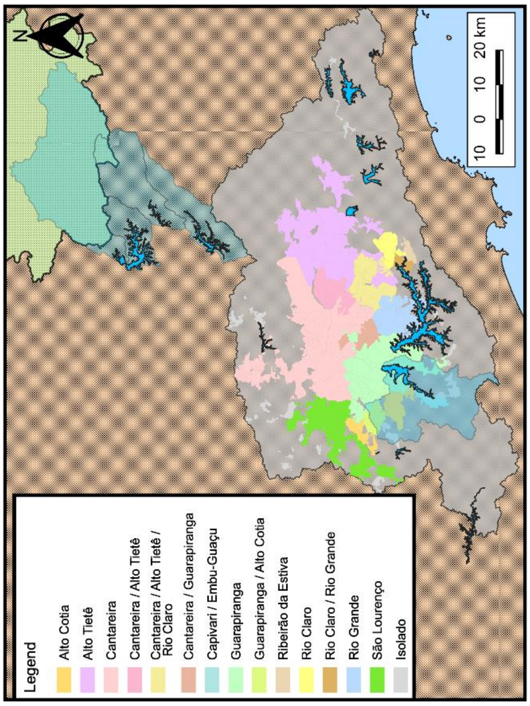
The São Paulo Metropolitan Region comprises several municipalities, where the largest one is São Paulo city, the capital of São Paulo state, and the most populated city in South America. São Paulo state is divided into 22 Hydrological Units for Water Resources Management (SP state law nº 16337/2016), which are the main river basins within the state boundaries. Although the SPMR is located in the Alto Tietê River Basin, the region currently receives water transfers from the Piracicaba-Capivari-Jundiaí River Basin (PCJ) because of high demands for household and economic activities (de Andrade et al., 2009) and water service valuation in this catchment area (Viani et al., 2019; Taffarello et al., 2020; Guzmán et al., 2020).

The SPMR water supply system comprises several reservoirs presented in Figure 2.2, which interconnects all service areas through an extensive pipeline network. In addition, pipelines and tunnels connect some of the water supply reservoirs within the region, facilitating water transfers whenever possible and needed. This infrastructure was implemented over time as the region faced the need to better manage the water resources. The water infrastructure, storage and distribution are maintained by the SABESP, the water utility company, which is a public-private partnership that has operated the water distribution in the São Paulo Metropolitan Region since 1973.

Streamflow is stored in one of the three reservoirs of the Cantareira System (1269 million cubic meters of storage capacity), Jaguari-Jacareí (1.235km² of draining area), Cachoeira (392 km² of draining area) and Atibainha (315km² of draining area) and connected through tunnels to the Paiva Castro reservoir (338 km² of draining area), where water is pumped to the Water Treatment Station in the Alto Tietê river basin (Souza et al., 2020). In addition, since 2018, the Cantareira system has been connected to the Paraíba do Sul river basin through a tunnel between the Atibainha reservoir (Cantareira) and the Jaguari reservoir (Paraíba do Sul river basin) (Braga & Kelman, 2020). The other system addressed in this chapter is the Guarapiranga reservoir, whose drainage area, about 329km2, is located within the Alto Tietê river basin (Brito et al., 2018; Whately and Cunha, 2006).

Figure 2.2 highlights the drainage area of the two water supply systems addressed in this chapter, the Guarapiranga and Cantareira, which were completed in 1908 and 1982, respectively (Milano et al., 2018; Whately and Cunha, 2006). The Cantareira system is the largest one in São Paulo, whose water production capacity is about 33m3/s, while the

Guarapiranga system is the second largest and can produce up to 16m3/s of drinking water (FABHAT, 2019). Emerging concerns in reservoirs of both systems that represent threats to local water security are wastewater discharges, polluting loads, increasing demands, climate variability and sedimentation (Brito et al., 2018; Freitas, 2020; Goldenstein, 1998; Whately and Cunha 2006; Whately and Cunha, 2007; Wiel and Bintanja 2021).



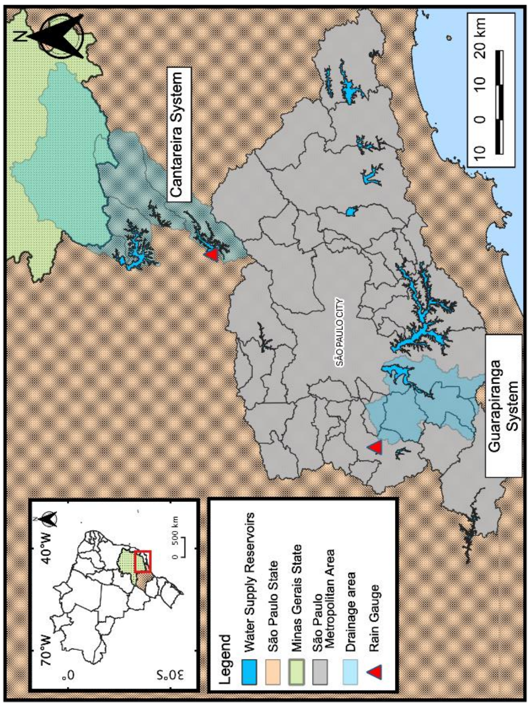


Figure 2.2: The left-hand map highlights the location of Cantareira and Guarapiranga systems within the São Paulo Metropolitan Region. The right-hand map presents the limits of service areas and respective supply systems that delivered water in 2018 (FABHAT 2019).

2.2.1 Review of Guarapiranga crisis

The São Paulo region witnessed a very dry period in the mid-1980s. The reduced rainfall implied in low flows that raised attention of authorities to avoid the water supply collapse. In 1985, five major systems were responsible for delivering water to most urban residents, the Cotia system (4%), Rio Claro system (9%), Rio Grande system (8%), Guarapiranga system (25 %) and the Cantareira system (54%) (Araújo, 1986). The latter system was fully completed by 1984, and therefore the Guarapiranga was the most important regionally at that time. Although the five systems had reduced inflow, the Guarapiranga storage was the most affected at that time because rainfall and inflows were dramatically reduced to 47.50% and 43,10%, respectively, compared to the long-term mean (Araújo 1986). Figure 2.3 presents the Guarapiranga storage on the first day of each month.

Strategies started to be implemented by the water utility, SABESP, in October 1985 to avoid the reservoir emptiness and the collapse of water supplied to about 14 million people (Araújo 1986). The efforts attempted to increase inflows, rearrange service areas to receive water from other reservoirs and reduce daily consumption. In December 1985, the sequence of scheduled water shortages forced citizens to reduce consumption until late February 1986. On the first day of March 1986, the Guarapiranga reservoir recorded 32% of its full capacity and, therefore, the rationing was over.

2.2.2 Review of Cantareira crisis

The south-eastern part of Brazil recorded rainfall below the historical average between 2013 and 2015 (Marengo et al. 2015). Many regions, such as the SPMR, recorded one of the driest seasons in history (Nobre et al. 2016). After the 1985 water crisis, another water supply system was added to those existing at that time, the Alto Tietê system (Marins et al., 2019). In addition, the Cantareira water supply system, the largest system in São Paulo since 1984 expanded the water production capacity from 22 m3/s in 1985 (Araújo, 1986) to 33m3/s (Marins et al., 2019; Deusdará-Leal et al., 2020). However, since 2004 the need to increase water production has been identified because the metropolitan supply system would not be enough to handle water demands from household and economic activities in the short term (Martirani and Peres, 2016; Ribeiro, 2011; Richter, 2017).

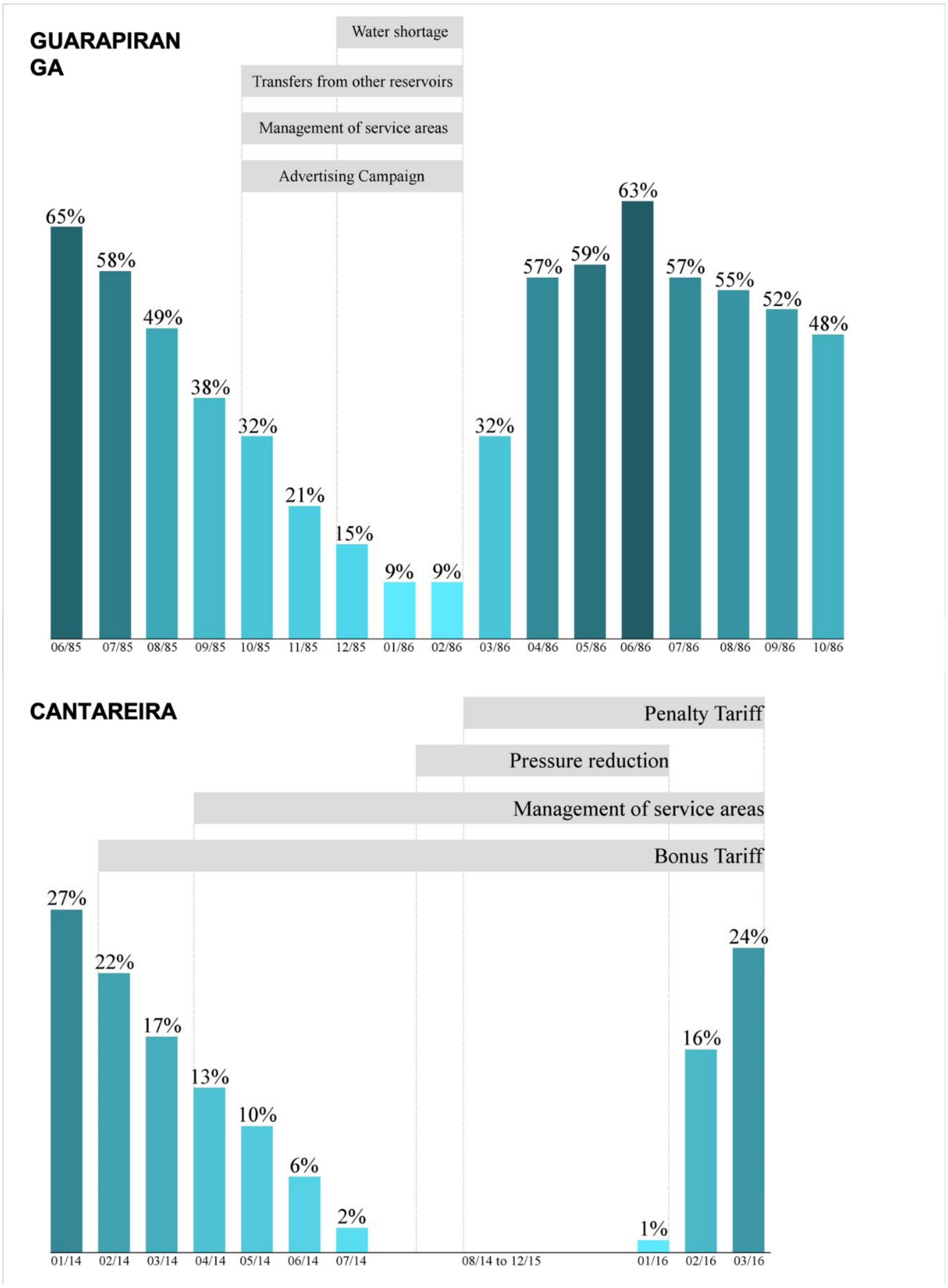


Figure 2.3: Timeline of Guarapiranga and Cantareira water crisis showing the water storage level in percentage and the main strategies adopted to cope with scarcity and demands.

Although the 2013/2014 rainfall anomaly affected the entire Brazilian Southeastern region, the Cantareira reservoir raised the attention of media coverage (Martirani and Peres, 2016) because it is one of the largest Brazilian water supply systems, from which 8.8 million people relied on to receive water (Braga and Kelman, 2020) and because it reached the dead pool level in 2014 (Deusdará-Leal et al., 2020). Figure 2.3 shows the measures implemented to increase inflows and reduce abstractions from the Cantareira reservoirs', which started in February 2014, and officially terminated in March 2016. In addition, Figure 2.3 also presents the percentage of useful storage levels on the first day of each month, where months equal to zero mean that the reservoir reached the dead storage.

2.3 DROUGHT RISK MANAGEMENT ASPECTS

Disaster Risk Management is the systematic process of using administrative directives, organizations, and operational skills and capacities to implement strategies, policies and improved coping capacities to reduce the adverse impacts of hazards and the possibility of disasters (ISDR, 2009). These measures should be implemented based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment (UNISDR, 2015). This process of understanding the risk is called risk assessment and it is the second step of a Disaster Risk Management Plan, following risk identification.

After the risk evaluation and analysis, the decision makers should plan and implement measures to reduce the risk. This step is referred to as Risk Reduction and is followed by Risk Monitoring. If in the monitoring step, the decision makers perceive that the measures are not performing as expected or need to be updated, the planning cycle starts again. In the following sections, we addressed the comparison of the two drought events in the RMSP with a focus on six aspects of two steps of a Drought Risk Management Plan: 1. Risk Assessment: a) preparedness, b) exposure, c) hazard intensity, d) vulnerability; 2. Risk Reduction: a) response, b) mitigation.

2.3.1 Hazard - Risk Assessment

The hazard intensities of both events are compared through the Standardized Precipitation Index – SPI (McKnee et al., 1993) and the Streamflow Drought Index – SDI, which is an adaptation of SPI for the reservoirs' inflow comparison (Nalbantis and Tsakiris,, 2008). Drought indices have been developed to assess drought severity using hydro-climatic variables (Mishra and Singh, 2010; Zargar et al., 2011; Rossato et al., 2017). While the SPI employs long-term precipitation records to classify time periods between extreme drought and extreme wet, indicating meteorological drought, SDI indicates the hydrological drought intensity because inflow records are used to compute the index following the same computation procedure of SPI (Melo et al., 2016). Both indices vary in the time period considered. The most usual are SPI-3, SPI-6, and SPI-12, numbers indicating the months aggregated to compute the index. The index interpretation suggested by Mcknee et al. (1993) and Angelidis et al. (2012) is moderate drought for SPI between -1.00 and -1.49, severe drought when SPI is between -1.50 and -1.99 and extreme drought, when SPI is below -2.00.

Figure 2.4 presents the SPI and SDI indices calculated through the SPEI package in R (Beguería and Vicente-Serrano, 2017) for a comparison between both events regarding the data available at the time when scarcities hit SPMR. SPI for the Guarapiranga case employed cumulated monthly rainfall records from station 02346052 (HIDROWEB, 2020), between 1936 and 1986, and SPI for the Cantareira case used cumulated monthly rainfall records from station E3-099 (DAEE, 2020), from 1947 to 2015. The SDI for Guarapiranga and Cantareira cases considered monthly average inflow up to 1986 and 2015, respectively (SABESP, 2015). One rain gauge station was considered for each watershed because they are the ones with the longest time series and fewer missing records located within the basin boundaries.

Although SPI-6 and SDI-6 for Guarapiranga show that the drought of 1985-1986 was the most severe experienced since 1950, the intensities for 3 and 12 months were comparable to other events observed before. Conversely, the SDI for Cantareira between February 2014 and December 2015 were the most severe since 1930, as well as SPI-6 and SPI-12. When comparing both events, SDI for Cantareira were not only more severe than Guarapiranga ones, but also lasted longer. In terms of hazard intensity, SPI-12 and SDI-12 are between -1.5 and -2, which means both severe meteorological and hydrological droughts (Angelidis et al., 2012; Mcknee et al., 1993). In contrast, SPI-12 for Cantareira is slightly below -2.00 and SDI-12 is almost -4.00, what suggest an extreme meteorological drought and a very exceptional extreme hydrological drought.

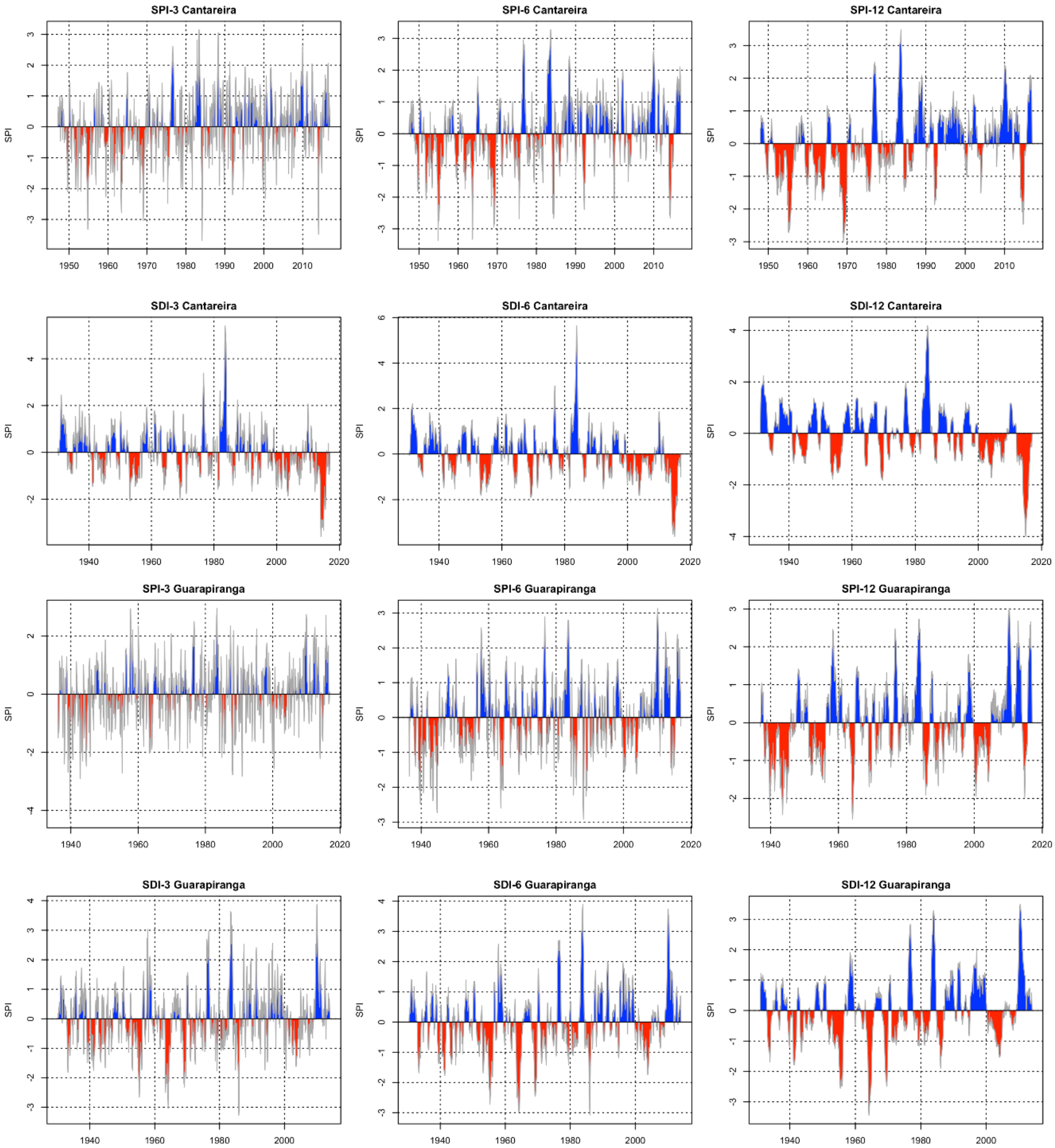


Figure 2.4: SPI and SDI indices for Guarapiranga and Cantareira systems. For the former system, SPI and SDI are calculated using records up to 1986, while the latter case employs historical data up to 2015.

Researchers attempted to find causes for anomalies in precipitation. Although the simulations conducted by Pattnayak et al. (2018) found strong evidence between warming sea surface temperature and the precipitation deficit over SPMR in 2000, 2004 and 2013, the association with the event in 1985 is not well correlated, which suggests other causes. In addition, the findings obtained by Zou et al. (2018) suggest that high pressures blocked the cold front passages from the Amazon to the Southeast region and reduced precipitation in São Paulo not only in 2014, but also in 2001. Zou et al. (2018) also found out great correlation between the dry seasons and the sea surface temperature of the Atlantic Ocean near the South-eastern coast.

2.3.2 Preparedness - Risk Assessment

Gillette (1950) and González Tánago et al. (2016) stated that droughts are a particular type of natural hazards because they have a slow and difficult to perceive onset, which provides time for authorities to implement structural and non-structural measures to cope with them (Solh and van Ginkel, 2014). Furthermore, Lemos et al. (2020) highlight the role of climate knowledge and stakeholder’s information in better preparing water supply systems for extreme events, by recognizing the system’s capacity and limitations. Thus, the preparedness aspect of risk management is discussed considering structural and non-structural measures to accommodate the severe impacts of drought hazard to reduce possible damage to people and assets that are exposed.

Some structural facilities take more time to be completed and rely on the immediate awareness of decision-makers to be effectively implemented. For instance, the capability to manage service areas is one of these drawbacks observed in the former event, but was better managed during the latter. Araújo (1986) mentions that the water utility, in that year, was capable of managing the boundaries of service areas supplied by the Guarapiranga reservoir to switch their water source to another system that supplied the nearby service areas. In contrast, Braga and Kelman (2020) highlights the distinguishable capacity of the water utility to manage the entire service during the Cantareira water crisis due to an extensive pipeline network and several pumping stations spread in the SPMR. According to the authors, 3.5 million consumers were covered by this structural policy.

In addition, a set of non-structural facilities was developed between both crises to better prepare the region against drought hazards. Taffarello et al. (2017) identified Payment for Ecosystem Services initiatives within the tributaries of Guarapiranga and Cantareira reservoirs. Such initiatives promote the risk reduction of inadequate land uses that might compromise water quantity and quality. Furthermore, Leão and Stefano (2019) and Empinotti et al. (2019) reviewed the evolution of the institutional agents in charge of the water supply system and identified that users and authorities have evolved, but the operation rules should be revised periodically and decentralized water governance by the local institutions is key in addressing the water crisis.

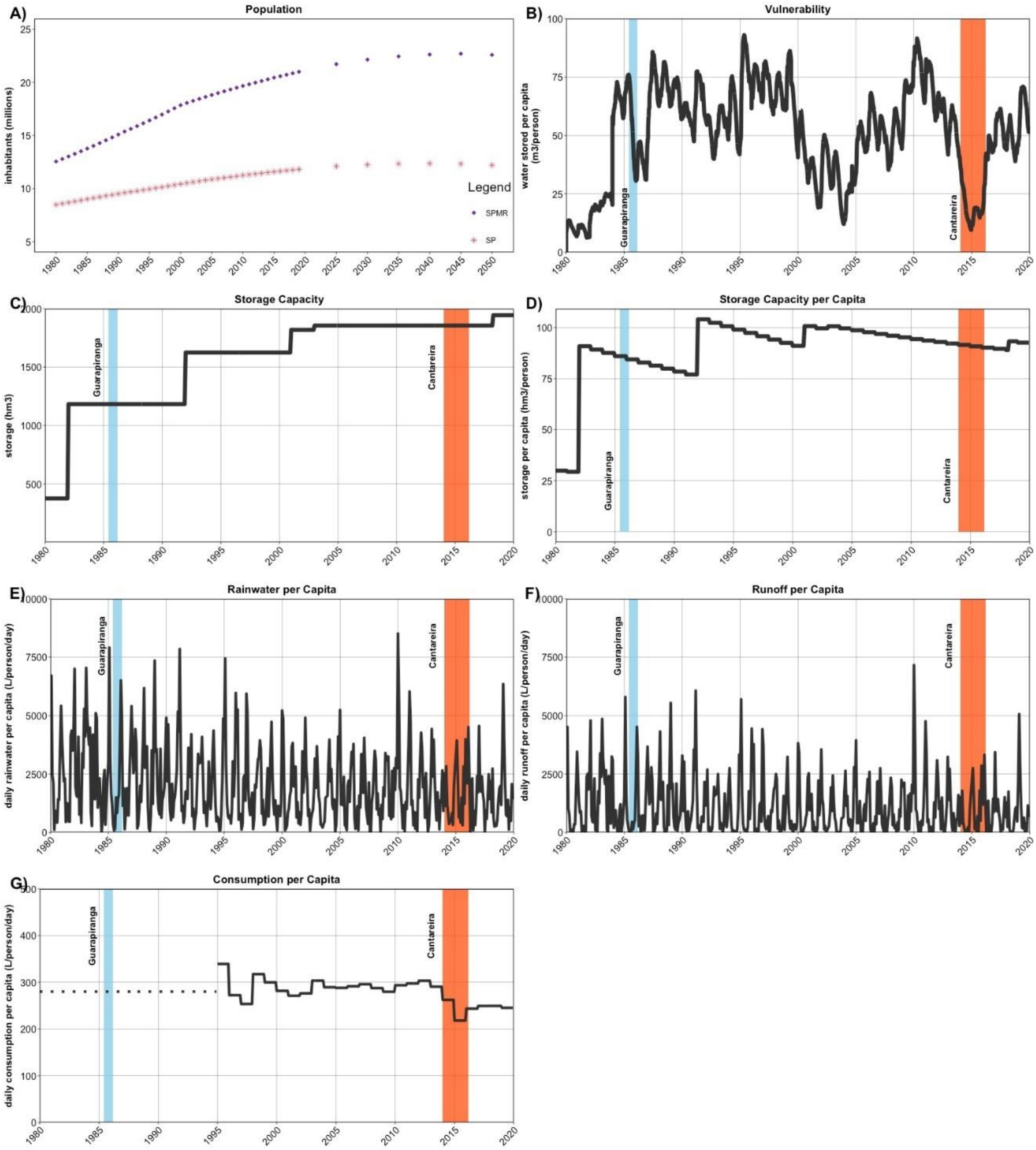


Figure 2.5: A) Presents the population growth observed between 1980 and 2020 and demography projections until 2050 (SEADE 2020), B) presents the water stored per capita at the local reservoirs for water supply in the São Paulo Metropolitan Region, C) presents the evolution of water storage capacity as new reservoirs were completed because of increased demand and, D) presents the potential water storage per capita given the reservoirs' capacity volume, E) presents the daily rainwater volume per capita, F) presents the runoff volume per capita (see supplemental material) and G) presents the actual consumption per capita between 1995 and 2019 and the assumed consumption per capita for the previous year,

considering the average consumption. The blue and orange shaded areas represent the Guarapiranga and Cantareira droughts, respectively.

2.3.3 Exposure - Risk Assessment

Since little can be done to change drought occurrence (Wilhite et al., 2014), exposure can be computed as the number of people, their livelihoods and assets in the area that could be affected by droughts (Carrão et al., 2016; IPCC, 2012; IPCC, 2014). Therefore, the spatial resolution determined to establish the exposure comparison between both events is the São Paulo Metropolitan Region, which comprises several municipalities and is home to millions of people.

Figure 2.5A shows the data regarding the number of inhabitants, retrieved from SEADE (2020). The graphic presents the population growth in São Paulo city, which had a smaller rate than the whole region. Although it brings evidence that smaller cities presented growth rates larger than São Paulo city, it does not change the fact that exposure increased equally for all municipalities because the supply system is integrated and responsible to deliver water to most of the region. It means that even if one service area was not supplied by the Cantareira reservoir in 2014, or by the Guarapiranga in 1985, they were subjected to the drought consequences because conservation policies, at some time, were implemented for all consumers and because the region is interconnected. Therefore,

Figure 2.5A reinforces the fact that exposure increased over time due to population growth.

Another increasing exposure element within the water supply system of SPMR is the financialization of the water market. Klink et al. (2019) raise important concerns about the institutional framework of water governance in SPMR. According to the authors, the water utility company joined the stock market by the early 2000s and therefore, water supply became a valuable business that was under threat during the Cantareira water crisis. Indeed, Guzmám et al. (2017) provide a better estimation of the non-stationary approach of droughts on the revenues of SPMR water utility.

2.3.4 Vulnerability

Definitions of vulnerability are differently assigned by different authors. Carrão et al. (2016) and IPCC (2014) define vulnerability as the propensity or predisposition of those elements exposed to drought to suffer the negative effects. Van Loon et al. (2015) go further and define that vulnerability differs according to the lack of capacity to cope with the drought risk, while Wilhite et al. (2014) and Prabnakorn et al. (2019) attribute the cause for different vulnerabilities to socio and economic factors, which varies from one region to another (Zarafshani et al., 2016). Since this chapter compares the same region at different points in time, we define vulnerability as the water available per capita in the reservoirs to supply all residents from SPMR, as a whole.

Figure 2.5B presents the historical records of water stored in supply reservoirs divided by the number of inhabitants, where blue and orange shaded areas represent the time period of Guarapiranga and the Cantareira water crisis, respectively. Unexpected jumps represent the date of reservoirs' completion (i.e., 1984, when the Cantareira system was completed). Therefore, the first impression from this timeline is that drought vulnerability threatens São Paulo more often than we expected. Some examples are the periods right after recovering from the 1985/1986 crisis, when the region was subjected to the same level of vulnerability, while the beginning of the 21st century (between 2000-2005) witnessed a vulnerability level comparable to the 2013-2015 water crisis.

The vulnerability assessment is complementary to the hazard intensity analysis to provide insights into the possible consequences of a given supply system under drought conditions. Even if drought indices indicate that the event is severe, the infrastructure available can be capable of coping with low inflows. For instance, although water stored per capita and drought indices were less dramatic in the former event in comparison to the latter, attention was attracted earlier and water saving policies were more intense in the former. The capability to manage service areas promoted an additional solution in the context of crisis management in the second event due to an extensive pipeline network. Next, we examine how the responses to the drought were implemented given the particularities at the time of each event.

Therefore, appropriate reservoir operations and transfers should be handled because several reservoirs are spread around the boundaries of the metropolitan region and deliver water to specific service areas, which are subjected to rainfall regimes and water availability of those reservoirs. This means that even though the equivalent water stored in all reservoirs is high, but one reservoir is empty, the service area that relies on that reservoir might suffer from rationing.

2.3.5 Response - Risk Reduction

This topic addresses the measures implemented by authorities to avoid the collapse of the SPMR water supply system and recover the reservoirs to the level before the crisis. The fact that more description is given to the Cantareira event does not mean that the event was more remarkable, but it means that little documentation was found concerning the earlier Guarapiranga event.

Araújo (1986) grouped the strategies adopted to fill the Guarapiranga reservoir and to reduce water consumption in three phases (Figure 2.3). The first phase was implemented between October and December 1985 and aimed at raising the Guarapiranga level. Therefore, local authorities and the water utility promoted maintenance of pipelines to increase the hydraulic capacity, transfers from the Capivari river, slight management on the service areas' boundaries supplied by the Guarapiranga, and advertising campaigns to promote water savings. However, the first phase did not meet the desired goal and, therefore, the second phase was implemented between December 1985 and February 1986. In this phase, local authorities implemented water rationings, which cut off water for 24h every three days in the beginning, then 9.3 million people had no water every two days by the end of this phase. In addition, water transfers were intensified. The Guarapiranga reservoir received water from the Cantareira, Alto Cotia and Rio Grande systems in this phase. Finally, the third phase was noticeable due to the end of the rationing. Owing to the wet season and precipitation comparable to the long-term mean, the local authorities decided to return the supply to the regular conditions. In terms of demands, consumption decreased during the crisis management because of awareness and rationing (Araujo, 1986). However, Ajzenberg and Piza (1989) verified a very remarkable water consumption increase in 1986/1987, the year after the water crisis.

Regarding the 2013-2015 water crisis, the first policy was implemented when the Cantareira system was at 22% of its storage capacity, in February 2014 (Braga and Kelman, 2016). Although it seems to be a late response, February is almost the end of the wet season, when authorities realized that rainfall was far below the long-term mean this year. A bonus tariff aimed at reducing consumption by giving discounts on water bills for consumers who reduced consumption. Meanwhile, authorities gathered together to compose a task force in February 2014 and reviewed the situation monthly to determine maximum withdrawals from the Cantareira reservoirs (Richter, 2017). In May 2014, the system reached the dead storage level, and therefore the water utility implemented a set of water pumps to maintain withdrawals from the Cantareira reservoirs (Millington, 2018). In addition, in May 2014, the Alto Tietê and the Guarapiranga systems became the sources of some service areas previously supplied by the Cantareira (Richter, 2017). In October 2014, the water utility launched the pipeline pressure reduction program, whose goal was to decrease leakages in pipelines (Braga and Kelman, 2016). In January 2015, the contingency tariff was created to reinforce water conservation (Braga and Kelman, 2016). This new policy increased fees of citizens who consume more water than the year before. In May 2015, the Rio Claro system started to help the Cantareira to supply service areas in SPMR (Braga and Kelman, 2016). Despite all these initiatives and current water available, the São Paulo State Government only declared the water crisis in August 2015 (Empinotti et al., 2019). The wet season that started at the end of 2015 could increase streamflow and refill the Cantareira reservoirs. Therefore, the reservoirs left the deadpool level in January 2016, and in March 2016 the bonus and contingency tariffs were over. Lastly, consumption records after 2016 reveal that consumers have not returned to the same level of consumption as of 2013, the year before the crisis (FABHAT, 2019). This is probably because of the remaining awareness created during the 2013/2016 water crisis and due to improvements in the infrastructure to reduce leakages.

2.3.6 Mitigation - Risk Reduction

Wilhite et al (2014) and Rossi (2000) enumerate possible solutions to mitigate future drought effects, which can be classified as structural and non-structural or supply-demand oriented. Therefore, the mitigation approach in this work considers the measures implemented after both events.

Figure 2.5C illustrates a solution broadly adopted worldwide, which are new reservoir constructions. Given the rising consumption, São Paulo authorities sought to meet the demands by building new reservoirs or shifting hydropower facilities to water supply purposes. Several years before the first event, authorities recognized the importance of implementing a new water source, when the Cantareira system was idealized. After that, the large Alto Tietê system was transformed into a new supply source and, in 2018, the São Lourenço system, which had hydropower purposes, became the new source for some service areas previously supplied by the Cantareira System (Marins et al., 2019; Mello et al., 2020).

Another mitigation strategy is the non-structural Early Warning Systems (EWS). Although seasonality indicates critical storage months, EWSs inform authorities and users about potential drought risks (Wilhite et al., 2014) after running simulations to verify whether water availability will meet current and future demands (Huang and Yuan, 2004). In this context, Araújo (1986) describes the risk of the emptiness of the Guarapiranga reservoir as a probability based on historical records. However, the national capability to forecast extreme events only saw a great increase after 2011, when the Brazilian Centre for Monitoring and Early Warning of Natural Disasters (CEMADEN) was created. In 2018, the CEMADEN started to regularly release forecast reports for strategic river basins, including the Cantareira inflows (Langenbrunner,, 2021). Therefore, the largest supply system in São Paulo became constantly monitored and received additional support to mitigate anticipated drought conditions and their consequences.

Some economic tools were evaluated, such as the implementation of insurances to mitigate economic losses observed during the latest event. Guzmán et al. (2020) and Mohor and Mendiondo (2017) observed possible scenarios considering the effects of climatic variables and possible demands on hypothetical insurance premiums. These simulations offer an alternative to mitigate economic losses caused to the economic sectors and to the water utility when the supply does not meet demand. Guzmán et al. (2020) and Mohor and Mendiondo (2017) highlight that this strategy is not only useful to cope with losses in the SPMR, but it can also be used to raise awareness of local consumers and policymakers.

Finally, master plans have been developed in São Paulo to cope with megacity challenges, such as urbanization, growing water demands, and climate change effects (Di Giulio et al. 2018, Santos et al. 2020). Although the region has developed master plans to address water supply concerns since the mid-1900s (Hermann et al., 1987), the implementation of river basin committees by the late 1990s improved the water resources monitoring and diagnosis by the River Basin Plans and the Water Resources State Plan, which report the current status of water demands, availability and challenges (Jacobi et al., 2015). At the regional level, other plans have been released since the last water crisis, the Municipal Plan of Basic Sanitation (PMSP, 2019A) and the revision of the Master Plan São Paulo Metropolitan Region Water Supply (SABESP, 2015), which aim at reporting possible scenarios of water demands, current capability of water production, limitations of existing water sources and alternatives to increase water availability. Finally, although Di Giulio et al. (2018) and Jacobi et al. (2015) recognize that much work remains to be accomplished, São Paulo authorities have addressed the concerns related to the effects of climate change in the 21st century. State authorities have been working on the State Policy of Climate since 2009, implementing enactments #13.798 (GESP, 2009; Sao Paulo State Act) and #12.187 (Brazil, 2009; Federal Climate Change Act). Moreover, the São Paulo Municipality created both a technical group to develop the Climate Action Plan and the water security #17.104 in 2019 (PMSP 2019B, Municipality Act).

2.4 RAINWATER AS AN ALTERNATIVE TO ALLEVIATE RESERVOIR PRESSURE

The previous section mostly focused on the drought and water supply management under the reservoir perspective. Alternatively, this section addresses the rainwater not only as an alternative to meet urban demands but also to evaluate the water stress within the SPMR. Therefore, Figure 2.5E and Figure 2.5F present the precipitation per capita (L/inhabitants/day) and the runoff per capita (L/inhabitants/day), where the former is the rainfall measured by a gauge located near the city center, while the latter was estimated based on SPMR pedology (Rossi 2017), impervious areas (Rossi 2017) and SCS coefficients (Sartori et al. 2005; USDA 1986). In addition, Figure 2.5G presents the estimated consumption per capita between 1980 and 1995, considered as the daily average of the actual consumption per capita between 1995 and 2019. Since the surface water is over exploited within the SPMR and its surroundings, the authorities are required to pursue alternative and accessible sources, such as rainwater.

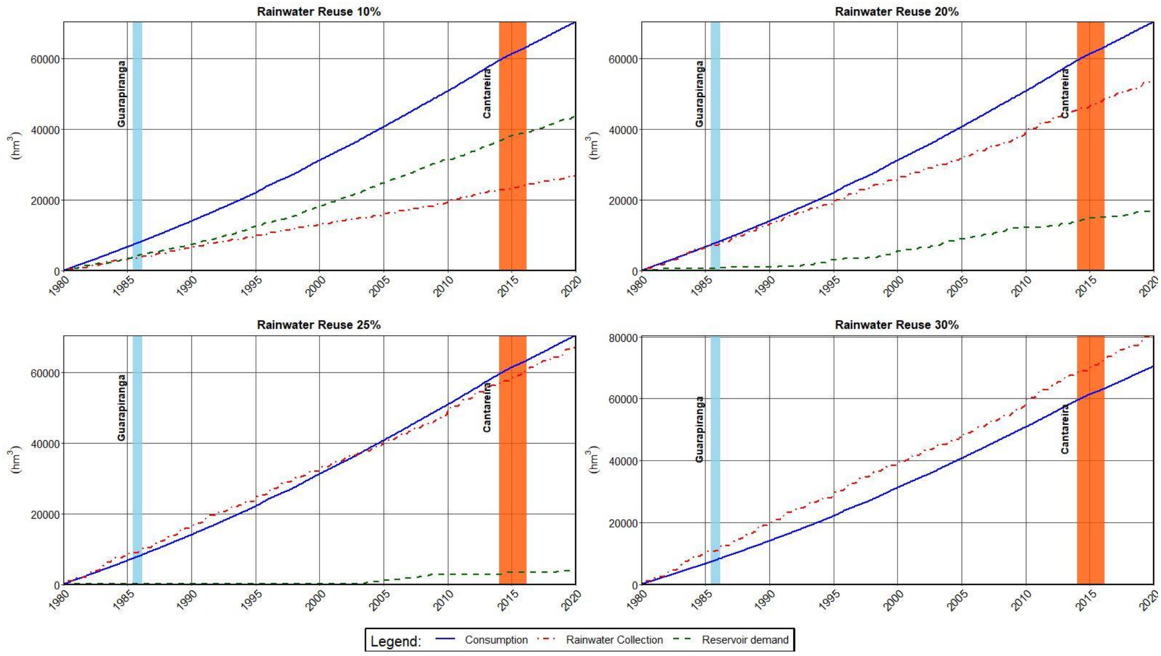


Figure 2.6: Presents four scenarios considering rainwater reuse at 10%, 20%, 25% and 30% of cumulated runoff since 1980, where the solid blue line is the cumulated water consumed by households, the red dot-dashed line is the hypothetical water collected from runoff and the green dashed line is the cumulated gap between consumption and rainwater reuse over time. The methodology description behind the runoff estimation is presented in appendix A.

Despite being hypothetical, the four scenarios are not far from ground, because their premise does not consider sophisticated rainwater collection systems in the whole region, but the reuse of the catchment runoff. Thus, the 10% and 20% rainwater reuse scenarios are not enough to replace the reservoirs' supply, but they could alleviate the pressure on them during the Guarapiranga and Cantareira droughts. Conversely, if runoff had been collected since 1980, the 25% rainwater reuse scenario would cover the demands during the Guarapiranga drought, while the 30% one would cover the demands for the entire period. Therefore, the aim of raising these possibilities is not to suggest replacing reservoirs by runoff collection systems, but to quantitatively present a plausible alternative to meet the growing demands of water-stressed region.

Although this alternative quantitatively meets the demands, it requires structural and technological challenges, such as reservoirs to accommodate the rainwater volume while it is not consumed, pipelines to deliver water across the extensive area and treatment technologies to reuse runoff water. Alternatively, the rainwater reuse can be practised at residential scale, where water tanks would store less water than a reservoir, but it would alleviate the surface water consumption.

2.5 CONCLUSIONS

This study has reviewed the literature available on the aspects concerning the water crises experienced in 1985-1986 and 2013-2015 by the São Paulo Metropolitan Region. Therefore, we present the six elements on drought risk management (Table 2.1) to provide a comparison on the aspects that were improved, require more action, and worsened between the two events, on the basis of existing documentation and data availability.

Table 2.1: Summarises the paired-events analysis concerning each phase of drought risk management, where ↑ indicates considerable enhancement and ↑↑ strong enhancement of the risk management aspect of the Cantareira event compared to the Guarapiranga event, while ↓ indicates considerable decrease and ↓↓ strong decrease on the capacity to cope with the drought between the later and former drought.

Phase of Drought Risk Management	**Comparison**	**Description**
HAZARD	↓↓	Standardized drought indices suggest that the later event was more severe and lasted longer than the former event
PREPAREDNESS	↑↑	At the time of the second event, the region advanced the structural and non-structural tools to prepare against water shortage.
EXPOSURE	↓↓	The 2014 event exposed more people and financial assets in comparison to the 1985 event.
VULNERABILITY	↓	The later event had less water available per capita than the previous one, as well as in early 2000s.
RESPONSE	↓	The responses were similar in both events, but late actions were observed in 2014.
MITIGATION	↑	Forecast technologies and economic tools were developed after the Cantareira drought.

It is undeniable that intensity and duration were more severe in the second event than in the first one. The SPI and SDI indices suggest that the latter event (2013-2015) was more severe and lasted one year longer than the former event. However, it could be expected that the decision-makers could cope with the Cantareira water crisis due to the structural and non-structural preparedness measures developed since the Guarapiranga crisis in 1985/1986. Yet, an analysis on the water availability per capita revealed that vulnerability metrics in the 2013/2015 drought were slightly worse than the 1985/1986 event. While some publications attribute the reason for the high exposure to population growth and high demands (Soriano et al., 2016), other studies point to the late warning and insufficient management of water demand (Jacobi et al. 2021). In fact, the per capita water storage graph shows that the vulnerability of the second was markedly deepened a few months before the first policy, the bonus tariff. Yet, while responses at the first event officially caused water shortages for millions of citizens, crisis managers did not declare the water cut-off as an official response during the second drought, but rationing was also reported to have occurred.

Additionally, even if other authors suggest that institutions did not properly conduct the Cantareira crisis management, there is plenty of evidence that SPMR has evolved the mitigation measures in almost three decades. We reinforce the purpose of this manuscript is not to evaluate the effectiveness of institutions and decision makers, but to review what has changed over time. Therefore, some mitigation strategies, such as the early warning system developed by the CEMADEN, master plans for water security, ecosystem-based adaptation strategies, and new reservoirs implementations are already underway. However, Di Baldassarre et al. (2018) points out that growing dependence on reservoirs can lead to increased vulnerability over the long term.

Despite the fact that hazard intensity is indeed a very strong indicator of potential drought damage, vulnerability analysis might be crucial to make a decision. Thus, in a complex and interconnected water supply system, such as the SPMR case, two possible effective responses are i) early water saving policies to medium vulnerability signs or ii) strict policies to manage water demands under high vulnerability. Alternatively, reusing rainwater could have reduced the dependencies on reservoirs, and therefore its implementation is strongly recommended to meet the growing demand.

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3 EFFECTIVENESS OF WATER CONSERVATION POLICIES ON MITIGATING THE EMPTINESS RISK OF THE CANTAREIRA RESERVOIRS

Coping with droughts rely on two main water management strategies, tackling the demand-side and providing resources on the supply-side. This chapter aims at exploring the aspects involved in the water conservation of households during the 2013-2015 water crisis in Sao Paulo. First, a brief literature review on water conservation policies is presented. Second, an investigation is made of the main drivers that led civilians to reduce water consumption at that time. Finally, scenarios showing intervention are presented to evaluate whether the early implementation of water-saving policies within the São Paulo Metropolitan Region could have prevented the Cantareira reservoirs from reaching the dead pool level.

3.1 LITERATURE REVIEW

Several urban centers around the world have faced times of water scarcity that forced utilities and authorities to manage the water resources available to meet both current and future demands. When predictions indicate that water availability is not enough to satisfy consumers' needs, the pathways lead decision-makers toward tackling the demand-side and providing resources on the supply-side. Despite the great potential of an increment of water availability that engineering solutions can provide, such as tunnels for water allocation, desalination plants and waste-water treatment plants for reuse, the time of implementation is the main constraint for such solutions. In this context, managing water demand, in other words, fitting the consumption to the water available, arises as an urgent and unique solution.

Cape Town, in South Africa, experienced an extreme condition in 2018, when a set of measures was implemented to avoid the "Day Zero", the day when no drinking water would be available to supply local consumers. Most of the strategies, which included increased water bills, water restrictions, water-saving devices and pipeline pressure reduction, aimed at reducing household consumption since no other source of water was available at that time to increase supply (Garcia et al. 2020, Matikinca et al 2020; Muller 2018, Savelli et al, 2021). Although researchers struggle to affirm which of the many policies implemented by the local authorities played the main role, Brühl and Visser (2021) and Matikinca et al. (2020) found more efficiency in communication campaigns on the risk of running out of water than any other policies.

In contrast, other parts of the world deal with more frequent water scarcity events, such as Australia, the United States and Brazil, where optimization of water usage is a constant goal of local utilities. While Fielding et al. (2012) observed in some places in Australia that previous drought experience is crucial in determining the water conservation culture of residents, as well as other demographic, psychosocial, behavioral, and infrastructure variables, Bolorinos et al. (2022) revealed that drought severity experience and income are not as determinant as consumers' age and political inclination on the persistence of conservation behavior after drought events in California. In Brazil, the Jaguaribe Basin experienced an intense drought between 2012 and 2017, when the system of reservoirs, built during the 20th century, was crucial to increase water security (Nunes and Medeiros, 2020). Although some measures were adopted by the state government to reduce water consumption at that time, the rural community adopted their own measures to avoid water shortage and changed their behavior after the drought (Silva, 2023).

Therefore, water policy literature splits water management policies between price and non-price measures. On the one hand, the price strategies comprehend financial incentives or penalties that aim at forcing consumers to reduce the water used. Increasing tariffs, where the price of water increases accordingly to larger consumption, allow users to decide if they are willing to pay more for their own use or if they fit their own consumption to pay lower prices to meet their very essential demands (Mansur and Olmstread, 2012, Ruijis, 2009, Stone and Johnson 2022). Another price-based strategy is the water-budget where consumers are allowed to use predefined targets on the basis of a prior consumption set by the utility and, in case their use exacerbates such a baseline, consumers are subjected to increasing prices. Stone and Johnson (2022) identified a positive welfare of Californian consumers who showcased their preference for water budget policy over the increasing marginal prices.

On the other hand, non-price mechanisms aim at changing consumers' behavior without charging their tariffs. Traditional non-price measures include water restrictions, leakage detection, awareness-raising campaigns and replacement of low-flow devices. Quesnel and Ajami (2017) evaluated the impact of media coverage and Google searches related to the San Francisco Bay, in California. The authors found a great correlation between drought-related news and reduction in water use as a translation of increasing awareness. Another example of a non-price measure is presented by Pratt (2023) that found an unintended effect of fines on non-targeted consumers, who are induced by their peers through social pressure that stigmatizes water conservation as a socially desirable value in California.

When comparing public preference between price and non-price policies, the conclusions change from case to case. While Olmstead & Stavis (2009) observed better cost-effectiveness in adjusting the water price to manage the demand, Totajada et al. (2019) showed that non-price measures had greater efficiency in reducing per capita consumption of Spanish consumers because water prices should be very high to impact high-income households. Alternatively, Reynaud (2013) saw potential in both methods across particularities of consumers. For instance, price policies are more likely to be implemented in low-income communities because they are more sensitive to changes in price than higher-income households. However, Reynaud (2013) observed greater potential in implementing non-price policies in highly educated municipalities.

Besides assessing water demand policies in times of water scarcity, other authors have investigated what variables play a significant role in reducing water consumption or promoting the conservation of awareness regardless of any water-saving policy implementation. An illustrative example that shows patterns of reduced consumption in times of no risk of rationing is presented by Fielding et al. (2012). The authors showed that the water conservation culture, observed by decision makers, persists over time. In addition, the authors also indicate poor evidence in the education level but significant importance of income in predicting less water use. Other socio-demographic variables were investigated in Ecuador by Espejo et al. (2021), where the authors found great importance in predictors such as the perception of environmental issues, gender, marital status and homeownership. Other researchers also found that climatic variables are relevant to determining water consumption at a household level. Singh et al (2017) concluded that among other variables, temperature and rainfall are as significant as family size, family income, number of bathrooms and the age of a house in forecasting short-term water demand in India. Additionally, Cabral et al. (2019) evaluated Portuguese water demand sectors and found that adding temperature variables increases the forecast capability of the multiple linear regression model that forecast water-demand, among other variables such as family age, pipe specificities, billing data and regional characteristics.

Some researchers delved into the causes that led households to change their behaviors to reduce their own consumption. Ehret et al (2021) analyzed more than twenty behavior intervention cases and fitted them into an information-motivation-behavioral skills model, which explains that successfully changing behavior interventions are led by at least two of the three components: information and knowledge about the water issue (problem awareness), personal concern to reduce consumption (social norms and identity or financial appeals) and the individual perception of their own ability to transform motivation and information into action. In England, Bryan et al. (2018) combined a psychological framework (the Protection Motivation Theory) with a machine learning method (K-means algorithm) to investigate why local consumers implement or not drought-related behaviors. Water users were classified into two categories, Contemplatives, who are uncertain about the need to save water, but not opposed to such actions, and Responsive Actors, who are already saving water or are planning to do so. Socio-demographic variables, for instance gender, age, education, residence time and income, were found to be less determinant on locals' intentions to reduce water consumption than the psychological variables, such as previous drought experience, and the willingness to undertake actions. Finally, Addo et al. (2019) assessed the effectiveness of water conservation communication and household water use reduction using principles of the Capability-Opportunity-Motivation model, a behavior change theory. The authors show that messages that appeal to attitudinal change are more persuasive than only stating the severity of water scarcity and therefore, communication campaigns with water conservation purposes should be tailored with such causal mechanisms.

In summary, the literature findings concerning water demand drivers are not in accordance with the researchers. While some authors see relevance in the climatic and infrastructure data to predict future demands, others find stronger evidence in socio-demographic and psychological variables. The same contrasting opinions are also observed regarding the best water conservation policies. On the one hand, some results observe great importance in the financial measures. On the other hand, some results show no causal effect on price tools, but on consumers' awareness instead.

Despite diverging opinions, the aforementioned literature contributes to the methodological evaluation of policy implementation and average estimation of water consumption. However, socio-hydrological literature contributes to the simulation of state variables in two-way feedback between hydrological and social systems, such as water availability and household demands. For example, Gonzales and Ajami (2017) developed a system-dynamic model to investigate the rebound effect. Such phenomena happen when communities change their behavior due to shocking events, such as droughts and floods, and, when the event has passed, the previous patterns emerge again. Therefore, the authors modeled such a system using memory, drought severity and water use variables to provide a comparative assessment in the San Francisco Region. Thus, the great advantage of the socio-hydrological approach is the capacity to explain community behavior and evaluate the water availability, which is not easily captured in methods that assume stationary approaches.

In the previous chapter, the policies implemented during 1985-1986 and the 2013-2015 water crisis in the São Paulo Metropolitan Region were discussed, including the literature concern with the effectiveness and timely implementation of counter-crisis policies. However, the practical effects of the early implementation are unknown. For example, how much advance would be required to prevent the withdrawals from emptying the Cantareira reservoirs? Would public awareness be raised if the bonus and contingency tariffs have been implemented earlier? Which neighborhoods saved more water at the height of the crisis?

Therefore, the aim of this chapter is to evaluate what would be a possible adherence to early implementation of water-saving policies by the consumers of the São Paulo Metropolitan Region and how this behavioral change would impact the water availability of the Cantareira System, as well as whether it would be possible to prevent it from reaching the dead pool lever or not.

3.2 METHODOLOGY

Five steps were performed to respond to the research question, i.e., whether the Cantareira reservoirs could be prevented from reaching the dead pool level by managing consumers' demand (see Figure 3.1). First, we requested some information from SABESP, the local water utility, and arranged some virtual meetings to better understand the water distribution dynamics. After those meetings, we defined how to downscale the spatial resolution of service areas throughout the São Paulo Metropolitan Region. Next, we collected socio-demographic data at the neighborhood level in São Paulo city and at a municipal level for the other cities. These data were converted into shapefiles using a GIS (Geographic Information System) tool to merge with the service areas and draw the consumers' profile. Next, a socio-hydrological model was developed to predict which service areas reduce their own consumption based on specific conditions. Next, this model is used to build scenarios considering early implementation of water conservation and predict which service areas would have reduced the water consumed. Finally, the water availability at the Cantareira System is determined.

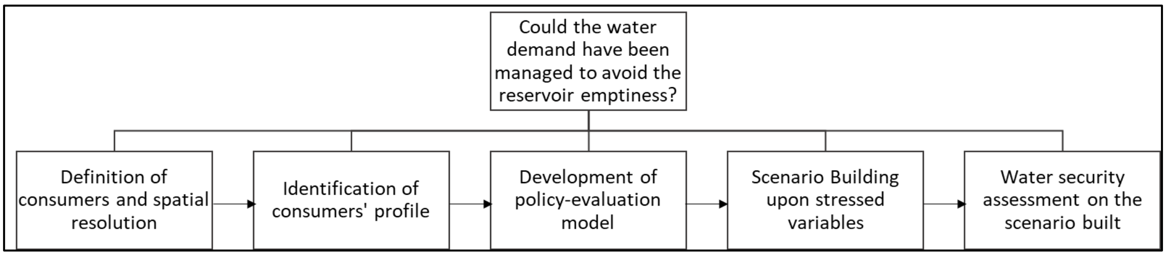

Figure 3.1: methodological flowchart

Before collecting the data to set up equations of a socio-hydrological model, Sivapalan and Blöschl (2015) recommended developing a perceptual model. This model is presented in Figure 3.2 and it represents the mechanisms of an urban water supply system in times of droughts. An important aspect of socio-hydrological models is the causal loop of main state variables, representing the two-way feedback between the human and water systems. In this case, the existing loop is the feedback between water availability, water-saving awareness and the actual abstractions from the Cantareira system. Additionally, external variables have causal effects on those state variables. For example, water availability is not only influenced by human abstractions, but also by the inflow, which is the key driver of the 2013-2015 drought.

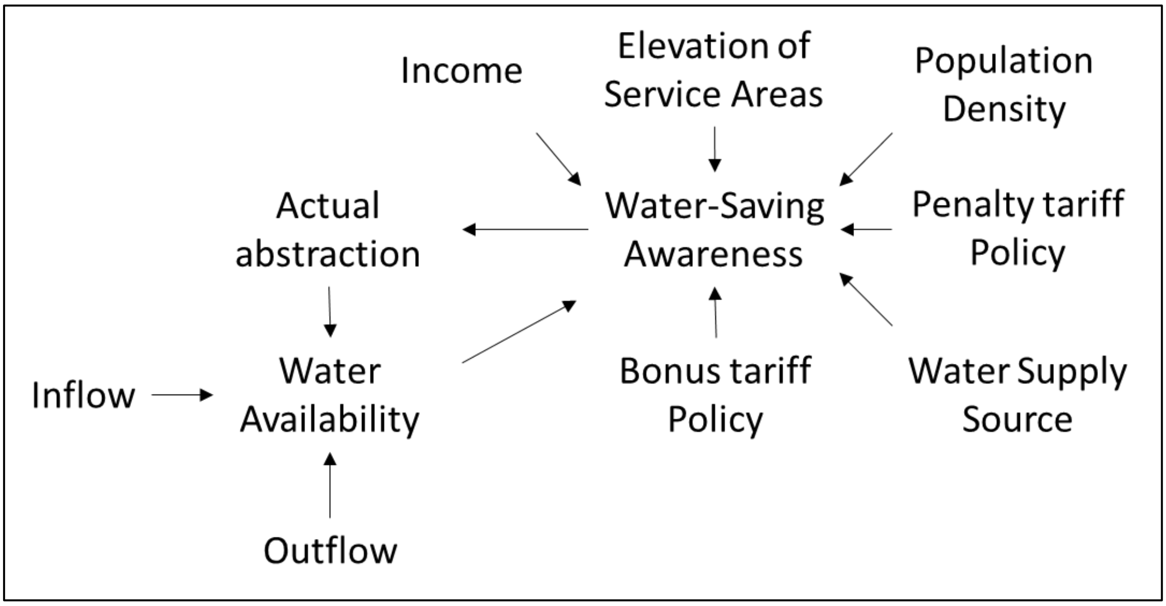

Figure 3.2: Causal Loop Diagram

Since the drivers that build water-saving awareness are difficult to be described through mathematical equations, a machine learning model was used to better forecast whether a given region in Sao Paulo would reduce the consumption or not. These types of models depend depends on the dataset available and are useful because it does not consider the underlying processes driving of water demand (Carvalho et al, 2020; Solomatine, 2009). Thus, historic records of seven variables, regarding the consumer characteristics, were tested as input on the model prediction: income, population density, water available in Cantareira reservoirs, elevation of residential address, whether bonus tariff policy was ongoing or not and whether penalty tariff policy was ongoing or not. The output of the model is binary, one if the service area would reduce the consumption, otherwise zero. Finally, a coefficient of reduction is multiplied by the actual consumption to estimate the simulated consumption, and therefore, recalculate the water storage in the reservoirs, and again recalculate the consumption in the following time step.

3.2.1 Data Acquisition and processing

3.2.1.1 Water Consumption Records

Although the total abstractions from the Cantareira System are known, as well as the average water consumed daily by an average Sao Paulo inhabitant, these two types of information are not capable to capture consumption patterns that different regions might have, and the changes that occurred from month to month in times of drought. Therefore, the local water utility (SABESP) shared, under request, the monthly average consumption, in liters per second, of more than 200 service areas from 2008 to 2019. Figure 3.4 shows that those service areas cover not only the Sao Paulo municipality, but the other cities which are part of the Sao Paulo Metropolitan Region. In this case, the consumption is measured by flow meters located directly at the distribution mains or in storage reservoirs that supply service areas.

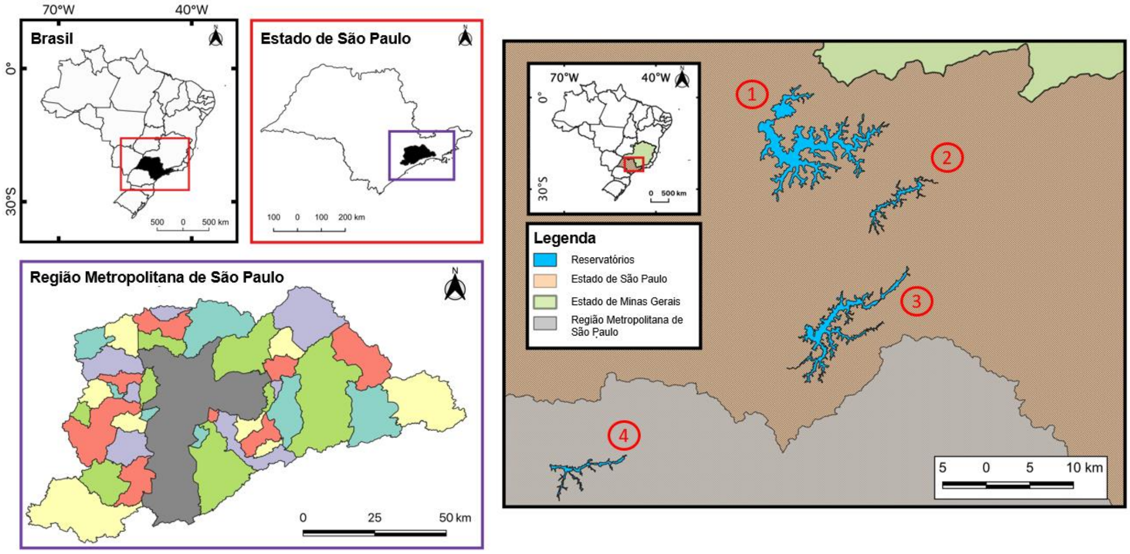

Figure 3.3: Part A presents the location of the São Paulo Metropolitan Region and the political divisions of municipalities. Part B presents the actual service areas and the intersection with municipalities and neighborhoods of São Paulo city.

For the spatial scale delimitation, the water consumption is as important as the infrastructure configuration. Thus, the map showing storage tanks, pipelines and actual service areas were requested to the water utility and presented in Figure 3.4. Because operations in pipelines and valves between surrounding regions might occur for maintenance purposes, for example, the next step was to merge the actual service areas to reduce the effect of connections between service areas, a mechanism that potentially masks the consumption measured in storage tanks. For example, in the case where part of a neighborhood is usually supplied by storage tank A, but because of problems in the pipeline, they are temporarily connected to storage tank B, the water meter located at A will record less consumption not because their consumers are reducing water use, but because part of the consumers have changed the supplier. Thus, the number of service areas was reduced to 51 (see Figure 3.5) after several meetings with SABESP consultants to better understand the coverage of service areas, the terminology used in the data shared, and general aspects of water distribution. Not only were the technical issues followed to merge such areas, but also the geographical, demographical and water reservoir supplier conditions were respected.

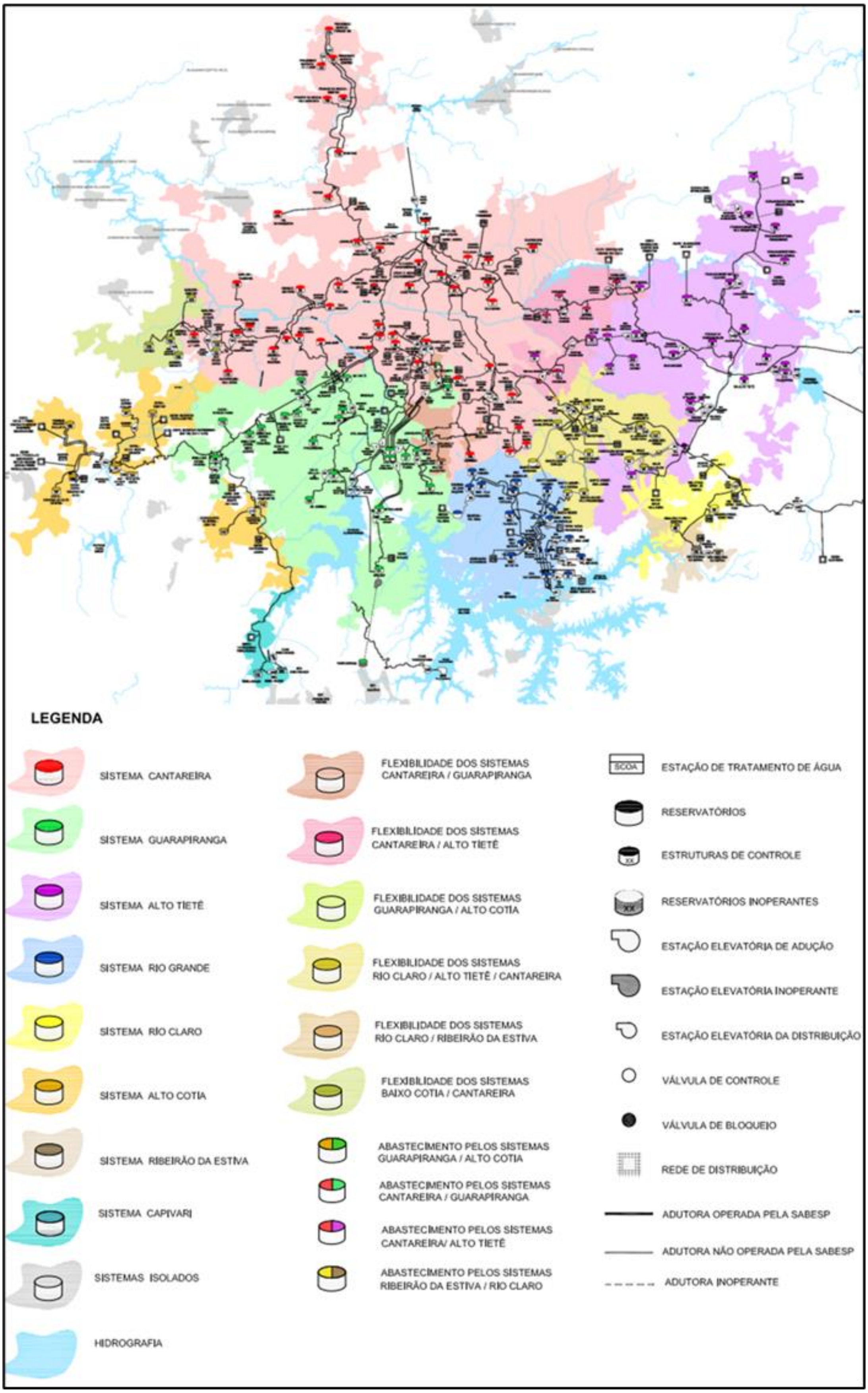

Figure 3.4: presents the Integrated Metropolitan System, the water supply configuration of the São Paulo Metropolitan Region

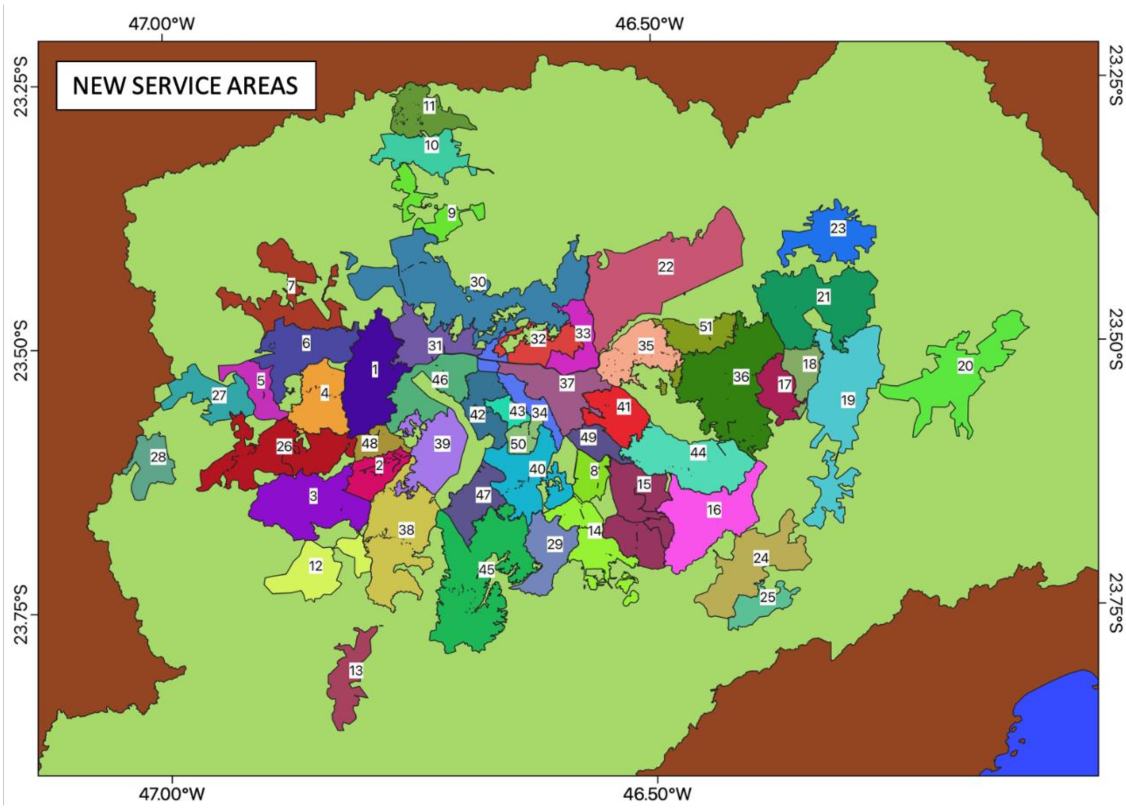

Figure 3.5: Present the new service area coverage that was developed to analyze water users' behavior.

3.2.1.2 Socio-demographic data and spatial information

Due to the fact that consumption is analyzed in a distributed way, at the service area level, aggregated demographic and geographic data do not fall within the scope of the model. Therefore, shapefiles containing the actual service areas, water basin and sub-municipalities of Sao Paulo Metropolitan Region were retrieved from the Alto Tiete River Basin Committee website (CBHAT, 2019) and the open data website of São Paulo Municipality (SPM-OD, 2020). Thus, the population, income and water consumption metrics were weighted accordingly to the surface area of service areas and sub-municipalities with the assistance of an open Geographic Information System open software Q-GIS as follows.

As the new service areas do not meet the same coverage of municipalities and sub-municipalities delimitation, the shapefiles of service areas and political divisions were overlayed with the assistance of QGIS to find the representative income and population. For instance, if a service area has 100km², where 50km² is part of a region with 10inhabitants/km² and the rest of the service area is part of a region with 20inhabitants/km², then the service area is assumed to have 15 inhabitants/km². Thus, population and income metrics were defined weighting accordingly to the representativeness area (km²) within a service area of water supply (presented in Figure 3.5).

The information regarding the income and population are calculated by the Brazilian Institute of Geography and Statistics (IBGE) and were retrieved from SEADE-IMP (2020). These two pieces of information refer to 2010, when the IBGE conducted the previous major survey before the 2013-2015 drought. The elevation data were retrieved from the Digital Elevation Model files (DEM), available at TOPODATA (2020). The DEMs were clipped using the new service areas' shapefiles and the mean elevation was calculated using a built-in algorithm available at QGIS. Lastly, information about the origin of the water consumed by the service areas was identified based on data available at (CBHAT, 2019) and based on the Integrated Metropolitan System, presented in Figure 3.4.

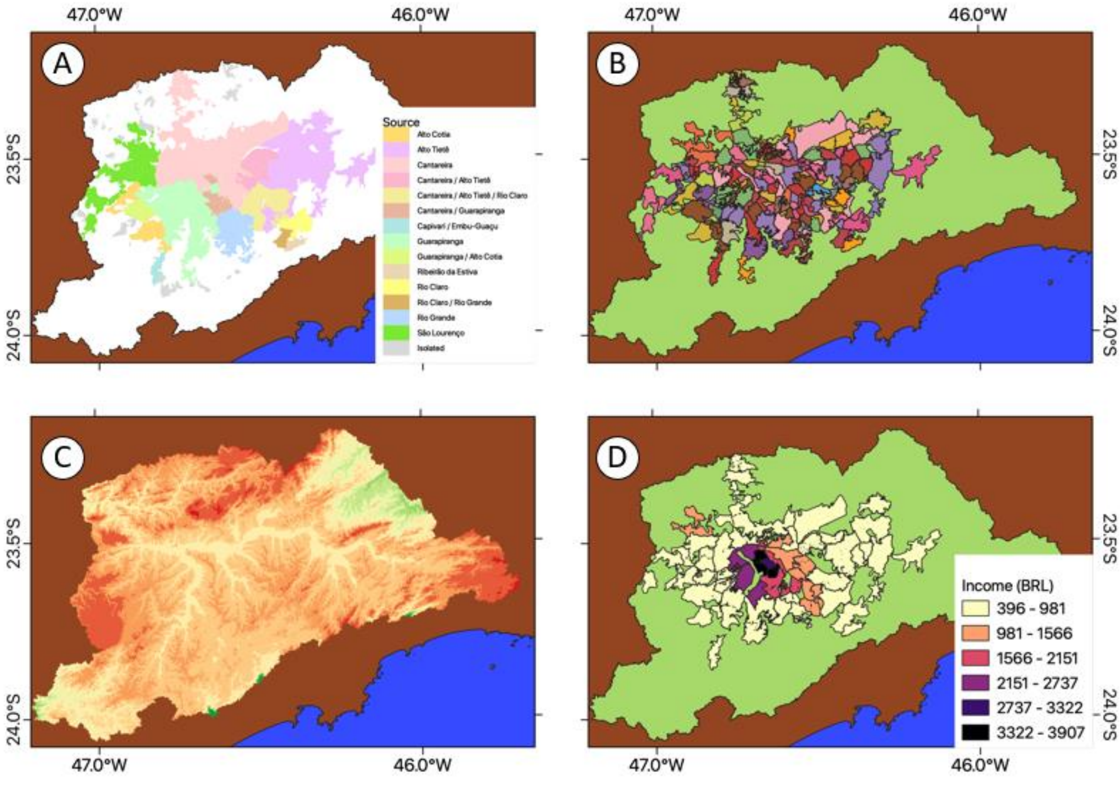

Figure 3.6: presents the spatial distribution of the data used, where the map in A) presents the water source that served the supply areas of the SPMR, B) presents the service areas, C) presents the Digital Elevation Model and D) presents the income per capita in BRL.

The summary of all service areas evaluated under the scope of the socio-hydrological model is presented in Table 3.1.

Table 3.1: Summary of socio-demographic indicators and origin of water supply of service areas modeled.

Service Area	Municipality	Elevation (m)	Surface (km2)	Population (in 2010)	Income (BRL)	Population Density (hab/km2)	Water Source (2019)
1	Osasco	761,0	65,0	666.621	758	10.263	Cantareira
2	Taboão da Serra	784,5	20,4	244.095	664	11.972	Guarapiranga
3	Embu das Artes	823,0	70,4	239.939	474	3.408	Guarapiranga and Alto Cotia
4	Carapicuíba	772,5	34,5	369.368	578	10.692	São Lourenço and Cantareira
5	Jandira	780,3	17,4	108.195	684	6.201	São Lourenço
6	Barueri	763,2	65,7	240.459	877	3.660	São Lourenço and Cantareira
7	Santana de Parnaíba	774,8	180,0	108.474	1.508	603	São Lourenço
8	São Caetano do Sul	763,5	15,3	149.185	1.579	9.731	Cantareira
9	Caieiras	794,9	97,6	86.389	683	885	Cantareira
10	Franco da Rocha	785,9	132,7	131.389	479	990	Cantareira
11	Francisco Morato	817,1	48,9	154.287	396	3.158	Cantareira
12	Itapecerica da Serra	820,2	150,7	152.407	487	1.011	Alto Cotia
13	Embu Guaçu	770,7	155,5	62.718	516	403	Capivari and Embu-Guaçu
14	São Bernardo do Campo	784,0	409,6	764.922	945	1.867	Rio Grande
15	Santo André	785,2	175,8	676.177	1.022	3.845	Rio Grande, Cantareira, Alto Tietê and Rio Claro
16	Mauá	811,8	61,9	416.585	584	6.729	Alto Tietê, Cantareira, Alto Tietê and Rio Claro
17	Ferraz de Vasconcelos	794,4	29,6	168.072	461	5.685	Alto Tietê
18	Poá	764,3	17,3	105.924	569	6.136	Alto Tietê
19	Suzano	768,9	206,2	262.179	552	1.271	Alto Tietê
20	Mogi das Cruzes	768,5	713,0	387.260	758	543	Alto Tietê
21	Itaquaquecetuba	761,9	82,7	321.329	413	3.887	Alto Tietê

Service Area	Municipality	Elevation (m)	Surface (km2)	Population (in 2010)	Income (BRL)	Population Density (hab/km2)	Water Source (2019)
22	Guarulhos	767,2	318,7	1.220.653	633	3.830	Cantareira
23	Arujá	789,5	96,1	74.758	745	778	Alto Tietê
24	Ribeirão Pires	798,4	99,1	112.994	726	1.140	Rio Claro
25	Rio Grande da Serra	777,5	36,3	43.912	487	1.208	Ribeirão da Estiva
26	Cotia	807,7	324,3	200.647	883	619	Guarapiranga, Alto Cotia and São Lourenço
27	Itapevi	798,4	82,7	200.415	475	2.424	São Lourenço
28	Vargem Grande Paulista	908,7	42,4	42.899	718	1.011	São Lourenço
29	Diadema	793,3	30,7	385.838	565	12.555	Rio Grande
30	São Paulo	797,1	115,8	798.433	709	6.893	Cantareira
31	São Paulo	755,6	31,5	292.265	948	9.282	Cantareira
32	São Paulo	752,5	21,5	215.608	1.429	10.035	Cantareira
33	São Paulo	737,2	21,5	243.974	830	11.358	Cantareira
34	São Paulo	742,7	20,7	265.392	1.701	12.825	Cantareira
35	São Paulo	761,7	35,2	383.145	813	10.893	Cantareira and Alto Tietê
36	São Paulo	787,0	92,2	1.276.825	506	13.842	Alto Tietê
37	São Paulo	746,9	39,7	380.667	1.494	9.581	Cantareira
38	São Paulo	780,5	72,2	857.770	570	11.882	Guarapiranga
39	São Paulo	766,3	40,9	360.077	2.381	8.798	Guarapiranga
40	São Paulo	783,1	45,6	573.309	1.962	12.563	Cantareira and Guarapiranga
41	São Paulo	776,6	27,8	356.768	1.130	12.849	Cantareira, Cantareira and Alto Tietê
42	São Paulo	767,2	24,6	297.786	3.907	12.094	Cantareira
43	São Paulo	801,9	8,9	168.636	3.249	18.853	Cantareira and Guarapiranga
44	São Paulo	817,2	58,6	691.495	510	11.796	Cantareira, Alto Tietê and Rio Claro
45	São Paulo	773,2	98,3	740.163	770	7.528	Guarapiranga
46	São Paulo	749,5	36,2	255.272	2.286	7.045	Cantareira
47	São Paulo	762,5	26,9	217.151	2.447	8.083	Guarapiranga
48	São Paulo	787,4	12,8	106.683	855	8.314	Guarapiranga
49	São Paulo	764,8	14,2	177.863	1.064	12.547	Cantareira
50	São Paulo	783,9	10,8	154.259	3.333	14.311	Guarapiranga and Cantareira
51	São Paulo	756,8	25,1	353.678	575	14.067	Alto Tietê

3.2.2 Water Saving Model

Following the premise of Figure 3.2, there are two components of the water saving model, the water conservation awareness, and the water availability. The former is calculated through a machine learning algorithm, while the latter is estimated based on a set of mathematical equations representing a system dynamic model.

3.2.2.1 Drought awareness component

A mathematical model is needed to build a hypothetical scenario of an early implementation policy on the consumers' behavior and the respective impact on water availability. In turn, the model should be capable of capturing the feedback of the updated water availability on the water-user behavior.

Therefore, the model developed evaluates whether a given service area would have reduced consumption or not based on the input variables. The target is to predict if the consumption of each month is less than the reference, which is the corresponding consumption within the same month of the year before the water crisis for the corresponding service area. If the consumption is less than the reference, we match it in one of the following ranges: more than 30% of water consumption reduction, more than 25%, more than 20%, more than 15%, more than 10% and more than 5%.

The sample comprises the monthly observations between 2013 and 2016 of the 51 service areas, which corresponds to a sample of 2,448 records. These samples were randomly split into training and testing sets at a split ratio of 25%. The train set was used to make the model learn the conditions when a given service area would reduce or not the consumption, while the test set was used to verify if the model actually learned from the train conditions and is able to reproduce at a different sample.

The model used was the Extra Gradient Boost (XG Boost), a machine-learning algorithm presented by Chen and Guestrin (2016) as an evolution of decision-tree models. The decision-tree models are represented by equations (1) and (2), where $\hat{y}_i$ is the model output, K are the additive functions to predict the model outputs, m are the variables used, q represents the structure of each tree that covers the corresponding leaf index, is T the number of maximum leaves in the tree, every f_k corresponds to an independent structure q and weight w of the leaves.

$$\hat{y}_i = \phi(x_i) = \sum_{k=1}^{K} f_k(x_i)\,, f_k \in \mathrm{F} \tag{1}$$

$$\mathrm{F} = \{f(x) = w_q\}(q: \mathbb{R}^m \to \mathrm{T}, w \in \mathbb{R}^{\mathrm{T}}) \tag{2}$$

The objective function of the XG Boost is to minimize Equation (3), where l is a differentiable convex loss function that measures the difference between the predicted $\hat{y}_i$ and observed y_i. The second term Ω is presented in Equation (4), which is a penalty to the model's complexity to reduce the over-fitting effect of the model.

$$\mathcal{L}(\phi) = \sum_i l(\hat{y}_i, y_i) + \sum_i \Omega(f_k) \tag{3}$$

$$\Omega(f) = \gamma T + \frac{1}{2}\lambda \|w\|^2 \tag{4}$$

Equation (3) is optimized in an additive manner through Equation 5, where ${\hat{y}_i}^t$ is the prediction of the i-th instance at the t-th iteration. The f_t is added to minimize the objective function $\mathcal{L}^t$.

$$\mathcal{L}^t = \sum_i l\left(y_i, {\hat{y}_i}^{(t-1)} + f_t(x_i)\right) + \Omega(f_t) \tag{5}$$

Using second order approximation, replacing first order g_i and second order h_i, we arrive at Equation (8).

$$g_i = \partial_{\hat{y}^{(t-1)}} l(y_i, \hat{y}^{(t-1)}) \tag{6}$$

$$h_i = \partial^2{}_{\hat{y}^{(t-1)}} l(y_i, \hat{y}^{(t-1)}) \tag{7}$$

$$\mathcal{L}^t = \sum_i l(y_i, {\hat{y}_i}^{(t-1)}) + g_i f_t(x_i) + \frac{1}{2} h_i {f_t}^2(x_t) + \Omega(f_t) \tag{8}$$

For the instance set of leaf j defined as $I_j = \{i|q(x_i) = j\}$, Equation (8) can expand the term Ω by Equation (9).

$$\mathcal{L}^t = \sum_i \left[l(y_i, {\hat{y}_i}^{(t-1)}) + g_i f_t(x_i) + \frac{1}{2} h_i {f_t}^2(x_t)\right] + \gamma T + \frac{1}{2}\lambda {w_j}^2 \tag{9}$$

Finally, w_j is the optimal weight of leaf j and the corresponding optimal value of the objective function is Equation (11).

$$w_j = -\frac{\sum_{i \in I_j} g_i}{\sum_{i \in I_j} h_i + \lambda} \tag{10}$$

$$\mathcal{L}^t(q) = -\frac{1}{2}\sum_i \frac{\left(\sum_{i \in I_j} g_i\right)^2}{\sum_{i \in I_j} h_i + \lambda} + \gamma T \tag{11}$$

Assuming that I_L and I_R are the instance sets of left and right nodes after a split, then the loss function used to evaluate split candidates is represented by Equation (12).

$$\mathcal{L}^t(q) = -\frac{1}{2}\left[\frac{\left(\sum_{i \in I_L} g_i\right)^2}{\sum_{i \in I_L} h_i + \lambda} + \frac{\left(\sum_{i \in I_R} g_i\right)^2}{\sum_{i \in I_R} h_i + \lambda} - \frac{\left(\sum_{i \in I} g_i\right)^2}{\sum_{i \in I} h_i + \lambda}\right] - \gamma \tag{12}$$

Because it is computationally demanding to enumerate all the possible splits in a large dataset, which is a process called the exact greedy algorithm, the XGBoost uses both Equation 12 and the approximate algorithm for split finding, presented in Table 3.2. According to Chen and Guestrin (2016), this algorithm ranks the features and the first proposes splitting candidates based on percentiles of each feature's distribution. Thus, the algorithm maps the candidate points and calculates the statistics to find the best solution among candidates based on Equation 12. More details on the Extra Gradient Boost can be found in the original publication by Chen and Guestrin (2016).

Table 3.2: Split Finding Algorithm developed by Chen and Guestrin (2016)

Extra Gradient Boost Algorithm for Split Finding
For $k = 1$ **to** m **do**
Propose $S_k = \{S_{k1}, S_{k1}, \ldots, S_{kl}\}$ by percentiles on feature k
Proposal can be done per tree (global) or per split (local)
end
For $k = 1$ **to** m **do**
$G_{kv} \longleftarrow= \sum_{j \in \{j \mid s_{k,v} \geq x_{jk} > s_{k,v-1}\}} g_j$
$H_{kv} \longleftarrow= \sum_{j \in \{j \mid s_{k,v} \geq x_{jk} > s_{k,v-1}\}} h_j$
end
Follow same step as in previous section to find max score only among proposed splits

Before selecting the Extra Gradient Boost, three classification models were candidates, but the XG Boost model was selected because of the better performance. The other two classification models tested, a logistic regression model and a random forest model, were not selected based on the four metrics presented by Equations 1 to 4.

$$Error = \frac{FP+FN}{TP+TN+FP+FN} \tag{13}$$

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \tag{14}$$

$$Recall = \frac{TP}{TP+FN} \tag{15}$$

$$Precision = \frac{TP}{TP+FP} \tag{16}$$

Figure 3.7 provides a description of the interpretation of the four metrics in Equations 1 to 4, where FP are the summation False Positives, FN are the False Negatives, TP are the True Positives and TN are the True Negatives. Thus, the Errors is the most intuitive metric, which evaluates the frequency of wrong outcomes from the model. The complimentary metric of Errors is the Accuracy, which measures how often the model was correct. Another perspective of the model measures how good it is to predict the occurrence of the event. For example, in case Non-events outweigh Events and the model mostly sets Non-Events, the Errors might be close to zero while the measure of actual events might be close to zero; this is the illustration of Recall. Lastly, Precision measures how many times the model is correct when predicting that a given service area will reduce its consumption. This metric is very relevant to evaluate policy-implementation because it provides a more realistic view of the policy adherence.

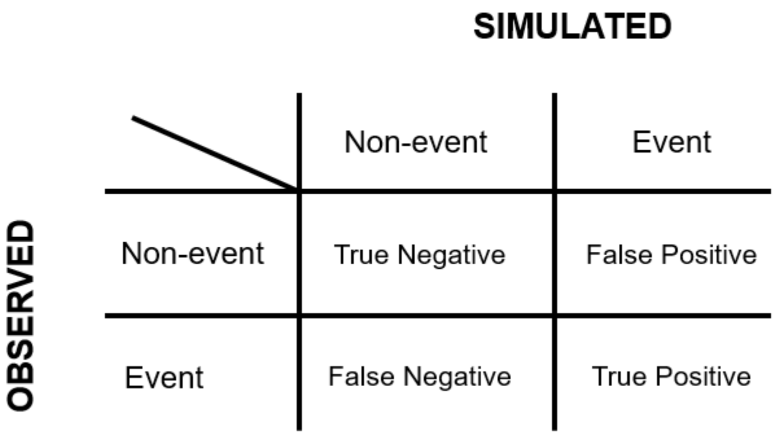

Figure 3.7: Representation of the confusion matrix of classification models.

The input variables have different levels of importance for each range of reduction on water consumption. The information gain is a metric used to measure the variable importance, or feature importance, which does not necessarily mean how the actual values of such variables will influence the prediction of a given class, but how this attribute contributes to the model on the classification task (Duan & Lu, 2010).

$$Gain(D,S) = H(D) - \sum_{i=1}^{s} P(D_i)H(D_i) \quad (17)$$

$$H(p_i) = \sum_{i=1}^{s} p_i \, log(1/p_i) \quad (18)$$

Since the basic strategy behind the decision tree models is to choose the variables with the highest information gain first, this gain can be measured by Equation 17. In information theory, entropy measures the randomness of a dataset, and it is represented by $H(D)$ in Equation 17, where D is the database state. This randomness is calculated by Equation 18, where p_i is the probability $log(1/p_i)$ of a given event happening. In a hypothetical example presented in Table 3.3, in which we evaluate the categorical variable that indicates if one place is served by the Cantareira System (1) or not (0), in a given month 20 service areas out of 51 meet the water consumption reduction desired by the current water-saving policy, and the entropy is $\frac{20}{51} log\left(\frac{51}{20}\right) + \frac{31}{51} log\left(\frac{51}{31}\right) = 0.290$. Therefore, the information gain using the variable Cantareira Source in a decision tree is the difference between how much information is needed to make a correct classification before a split and how much information is still lacking after the split. This is the concept of Equation 17, where the entropy is reduced by the weighted sum of the entropies from each of the subdivided datasets. Referring to the same hypothetical example of Table 3.3, the entropy of the subset of service areas supplied by the Cantareira System is the sum of the twenty tuples $\frac{5}{20} log\left(\frac{20}{5}\right) + \frac{15}{20} log\left(\frac{20}{15}\right) = 0.244$, while the entropy of the thirty-three tuples that are not supplied by the Cantareira System is $\frac{15}{31} log\left(\frac{31}{15}\right) + \frac{16}{31} log\left(\frac{16}{4}\right) = 0.300$. Finally, the information gain when using the variable that indicates whether the service area is supplied or not by the Cantareira System is equal to $0.290 - \left(\frac{20}{51} * 0.244 + \frac{31}{51} * 0.3\right) = 0.047$.

Table 3.3: Hypothetical dataset to exemplify the information gain calculation.

Service Areas	**Supplied by Cantareira**	**Reduced Consumption**
5	1	1
15	1	0
15	0	1
16	0	0

3.2.2.2 Water availability component

Besides determining whether a given service area is reducing or not its consumption, the impact of a possible conservation behavior on the reservoir storage needs to be determined to assess the effectiveness of the water policy and because the water availability is an input into the drought awareness component. Calculating the state variables for every month requires the nine steps presented in Figure 3.8. Every single step depends on the conclusion of the previous one and they are recursive for all the months simulated at the desired scenarios.

First, the probabilities of meeting one of the six water-saving ranges are calculated by the XGBoost model considering the implementation of both bonus and penalty tariffs. Next, each one of these probabilities is compared to the output of the same model considering no policy implementation. The goal of this step is to exclude an unintended prediction of the reduction happening when nothing has changed in the baseline conditions. Next, in case more than one range of water use reduction is predicted to happen, the model selects the greatest range to replace the actual consumption of the given month by the updated consumption. All these steps are calculated for every service area supplied by the Cantareira System and a weight factor is multiplied for each service area, based on the total consumption within the month. This is because the consumption measured at the pipe and storage tank meters refer to the consumption, which is less than the abstractions from the reservoirs. Thus, the updated consumption of all service areas is upscaled to find the corresponding updated withdrawals from the reservoirs and, finally, the updated water storage is calculated using the water balance equation. Once this step is finished, all the state variables for month t are calculated and the state variables for the month t+1 are calculated repeating all the previous steps, but including the new water availability that is expected to differ from the baseline.

$$P(reduction) = f\begin{pmatrix} water\ availability & water\ soure & bonus\ tariff \\ population\ density & income & penalty\ tariff \end{pmatrix} \quad (19)$$

$$\psi_{r,t} = \begin{cases} 1, & P(reduction) \geq 0.50 \\ 0, & P(reduction) < 0.50 \end{cases} \quad (20)$$

$$\Psi_{r,t} = \begin{cases} 1, & \psi_{r,t,baseline} = 0\ \ and\ \ \psi_{r,t_{scenario}} = 1 \\ 0, & otherwise \end{cases} \quad (21)$$

$$\theta_t = max(\Psi_{r,t}), where\ \ r\ \epsilon\ \{0.05, 0.10, 0.15, 0.20, 0.25, 0.30\} \quad (22)$$

$$\delta_{SA,t} = \ Q_{consump_{SA,t}} \cdot [1 - (r_{max} \cdot \theta_t)] \quad (23)$$

$$\mathrm{Q}_{\mathrm{abstrac}_{sim}} = \frac{\sum_{SA=1}^{51} Q_{consump_{SA,t}}}{\mathrm{Q}_{\mathrm{abstrac}}} \cdot \sum_{SA=1}^{51} \delta_{SA,t} \quad (24)$$

$$\frac{\mathrm{dS}}{\mathrm{dt}} = \mathrm{Q}_{\mathrm{in}} - \mathrm{Q}_{\mathrm{out}} - \mathrm{Q}_{\mathrm{abstrac}} \quad (25)$$

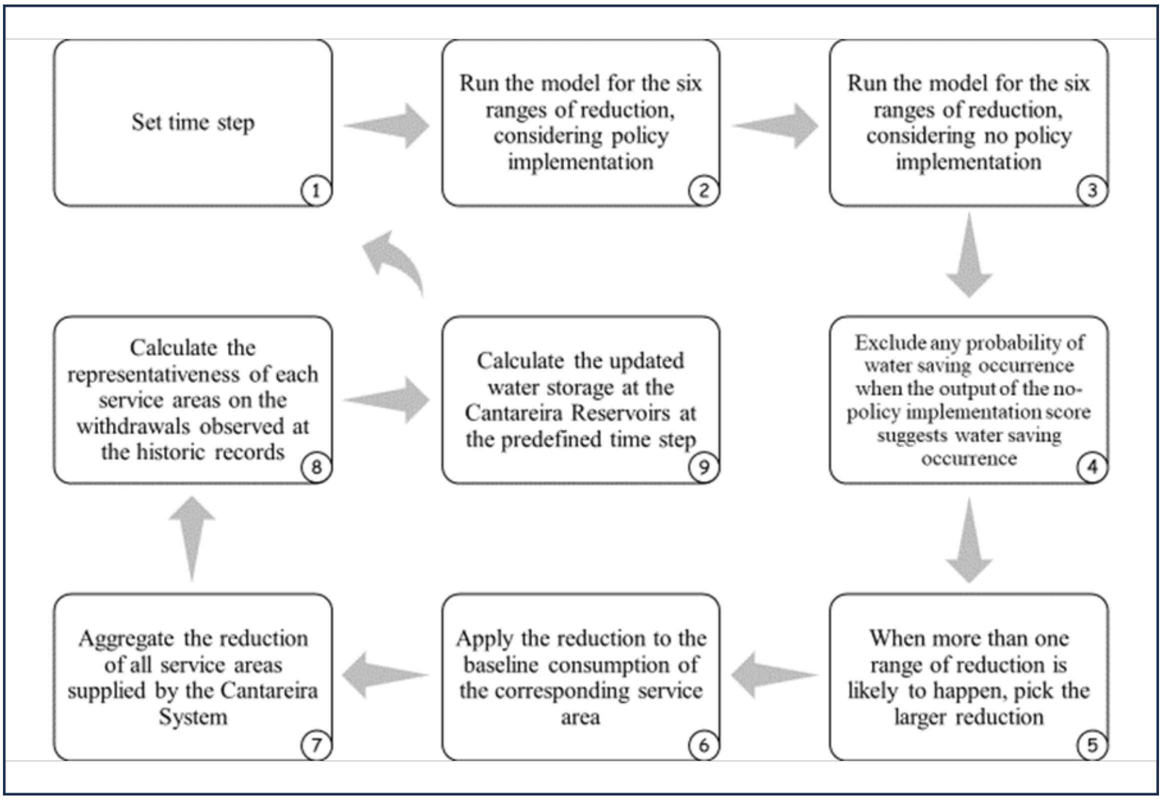

Figure 3.8: Flowchart of socio-hydrological model simulation for every time step

3.3 RESULTS

3.3.1 Significance of predictors

Before building scenarios, the significance of predictors was tested to find what would be the stronger predictor of conservation behavior in each region of SPMR. Thus, Table 3.4 presents the statistics of adjusted logistic regression for each range of reduction. The contingency tariff condition proved to be statistically significant for every range of reduction. Controversially, the bonus tariff presented the p-value larger than 5% and therefore with insufficient evidence of causal effect on the water use reduction.

This inferential approach has been used in previous studies (Singh et al. (2017); Parandvash and Chang (2016); Cabral et al. (2019) ; Hannibal et al. (2018); Grafton et al. (2011)), where conclusions around the key drivers of water use forecasting were tested, but conclusions change accordingly to the case studies. The approach herewith proposed not only evaluates the predictions of a changing behavior, but also assesses what the drivers are that led to a stronger reduction. For instance, while most of the variables seem to be correlated with the 5% reduction range, only the elevation of service areas and the ongoing contingency tariffs demonstrates some relationship with the 30% reduction.

Based on the evidence presented in Table 3.4, the scenario built considered a hypothetical storyline where the contingency tariff would have been implemented earlier to prevent the Cantareira reservoirs from reaching the dead storage level.

Table 3.4: Significance of features on predicting whether a given service area would reduce other water use.

		Estimate	Std. Error	z value	p-value
30% reduction	Elevation of service area	-0.02	0.01	-4.05	0.01%
	Population density	0.00	0.00	1.05	29.29%
	Income	0.00	0.00	-2.12	3.37%
	Storage at Cantareira reservoirs	-0.06	0.04	-1.68	9.32%
	Service area supplied by Cantareira	0.30	0.21	1.42	15.52%
	Ongoing bonus tariff	14.62	654.71	0.02	98.22%
	Ongoing contingency tariff	1.70	0.29	5.90	0.00%
25% reduction	Elevation of service area	-0.02	0.00	-5.07	0.00%
	Population density	0.00	0.00	-0.05	95.96%
	Income	0.00	0.00	-1.98	4.80%
	Storage at Cantareira reservoirs	-0.08	0.03	-2.71	0.67%
	Service area supplied by Cantareira	0.51	0.18	2.83	0.46%

	Ongoing bonus tariff	0.68	1.46	0.47	64.19%
	Ongoing contingency tariff	1.64	0.22	7.36	0.00%
20% reduction	Elevation of service area	-0.03	0.00	-6.86	0.00%
	Population density	0.00	0.00	1.52	12.81%
	Income	0.00	0.00	-3.82	0,.01%
	Storage at Cantareira reservoirs	-0.09	0.02	-3.74	0.02%
	Service area supplied by Cantareira	0.72	0.17	4.32	0.00%
	Ongoing bonus tariff	0.96	1.31	0.74	46.20%
	Ongoing contingency tariff	2.06	0.19	10.71	0.00%
15% reduction	Elevation of service area	-0.03	0.00	-7.62	0.00%
	Population density	0.00	0.00	3.19	0.14%
	Income	0.00	0.00	-5.27	0.00%
	Storage at Cantareira reservoirs	-0.15	0.02	-7.23	0.00%
	Service area supplied by Cantareira	0.87	0.17	5.26	0.00%
	Ongoing bonus tariff	-0.40	0.95	-0.42	67.43%
	Ongoing contingency tariff	1.58	0.17	9.55	0.00%
10% reduction	Elevation of service area	-0.03	0.00	-7.67	0.00%
	Population density	0.00	0.00	1.94	5.23%
	Income	0.00	0.00	-4.73	0.00%
	Storage at Cantareira reservoirs	-0.18	0.02	-10.28	0.00%
	Service area supplied by Cantareira	1.25	0.18	6.97	0.00%
	Ongoing bonus tariff	-1.05	0.64	-1.66	9.68%
	Ongoing contingency tariff	0.99	0.17	5.93	0.00%
5% reduction	Elevation of service area	-0.03	0.00	-7.21	0.00%
	Population density	0.00	0.00	2.95	0.32%
	Income	0.00	0.00	-5.59	0.00%
	Storage at Cantareira reservoirs	-0.18	0.02	-11.38	0.00%
	Service area supplied by Cantareira	1.48	0.21	6.87	0.00%
	Ongoing bonus tariff	0.05	0.55	0.08	93.30%
	Ongoing contingency tariff	0.57	0.20	2.90	0.38%

3.3.2 Model Performance

Table 3.5 shows that the models for each reduction range have different performances and lead to different interpretations. When comparing the 5% reduction to the 30% reduction, the lower range has more errors than the greater range but, in contrast, it has better recall. This happens because the 30% model has a tendency to predict that this reduction range will not occur, while the 5% model predicts that this reduction range will occur more often. In fact, both facts are true, as the 30% event decrease happened rarely, therefore the model is more inclined to predict that this event will not occur. When this happens, the Errors decrease but the Recall decreases as well because the actual event is set as a non-event by the model. The opposite happens to the lower range. Since lower reductions are more likely to happen, the model learned that more cases might occur, and therefore more errors occurs as well. However, the recall increases because less false negatives are set.

Table 3.5: Performance of the six models from 5% to 30% water consumption reduction.

Reduction	Errors	Accuracy	Precision	Recall
0.05	14%	86%	92%	89%
0.10	14%	86%	89%	86%
0.15	12%	88%	81%	92%
0.20	12%	88%	74%	81%
0.25	10%	90%	69%	75%
0.30	6%	94%	70%	80%

Additionally, it is also important to observe the precision metric behavior when talking about the policy evaluation. As the model evaluates the consumption of a service area, which is a region of several households, the predicted consumption must consider the reduction range weighted by the precision. This is because the precision metric shed light on the frequency of true positives that the model classifies as event occurrence. For example, for every 1000 samples classified as an event by the 30%-model, 700 are actual events. Thus, weighting the reductions reflects a more realistic view of the policy adherence that will support the policy maker.

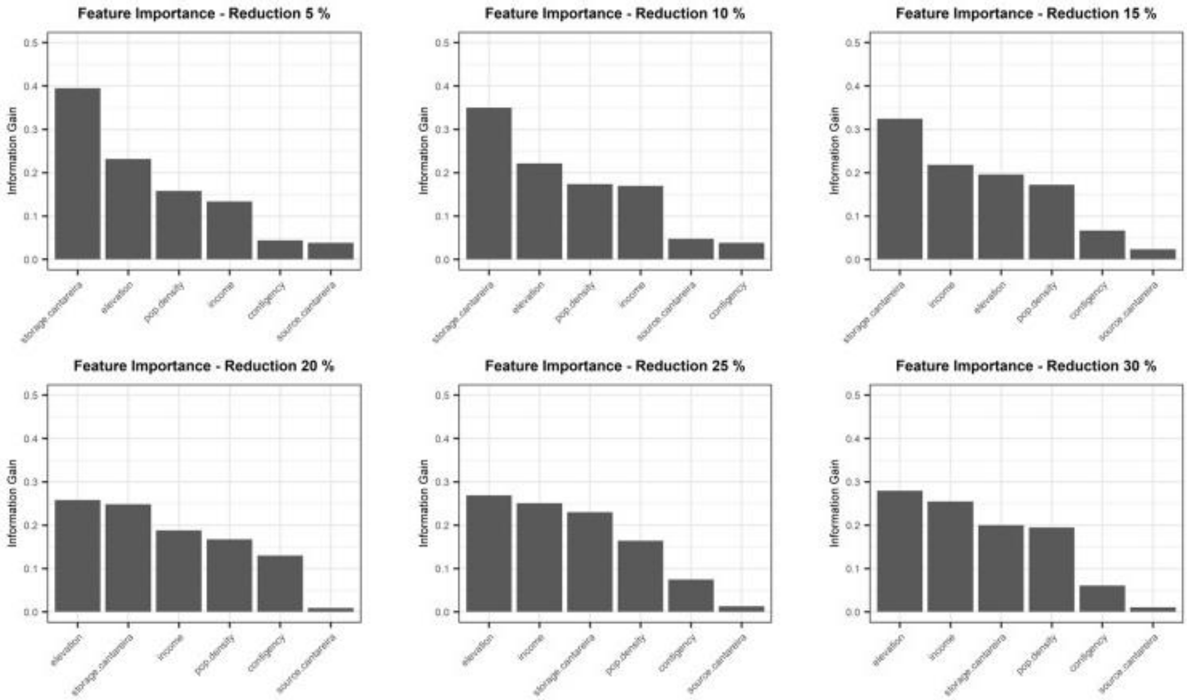

Figure 3.9: Importance of variables for each range of reduction on water consumption

The importance of variables oscillates when predicting whether the service areas would or not reduce their consumptions at different ranges of reduction, as presented in Figure 3.9. Although the storage level at the Cantareira is one of the variables that has the greatest information, the origin of the water does not seem to be as important when predicting the reduction. This conclusion is inferred when comparing the information gain of both variables, storage at Cantareira and Cantareira source, to the six models of water savings. The possible explanation might be that the individual awareness of not having water is associated to the fear of one reservoir in the town being at risk of emptiness rather than knowing that the water source that supplies the consumer's home is the one at risk, because they are more likely to not be unaware of the water origin (Souza et al., 2019). Additionally, the elevation of service areas is more relevant to predict larger reductions. This insight might be associated to the fact that water pressure in pipelines was reduced at the height of the crisis, when the larger reductions were observed, and as a result, the higher lands could be more affected.

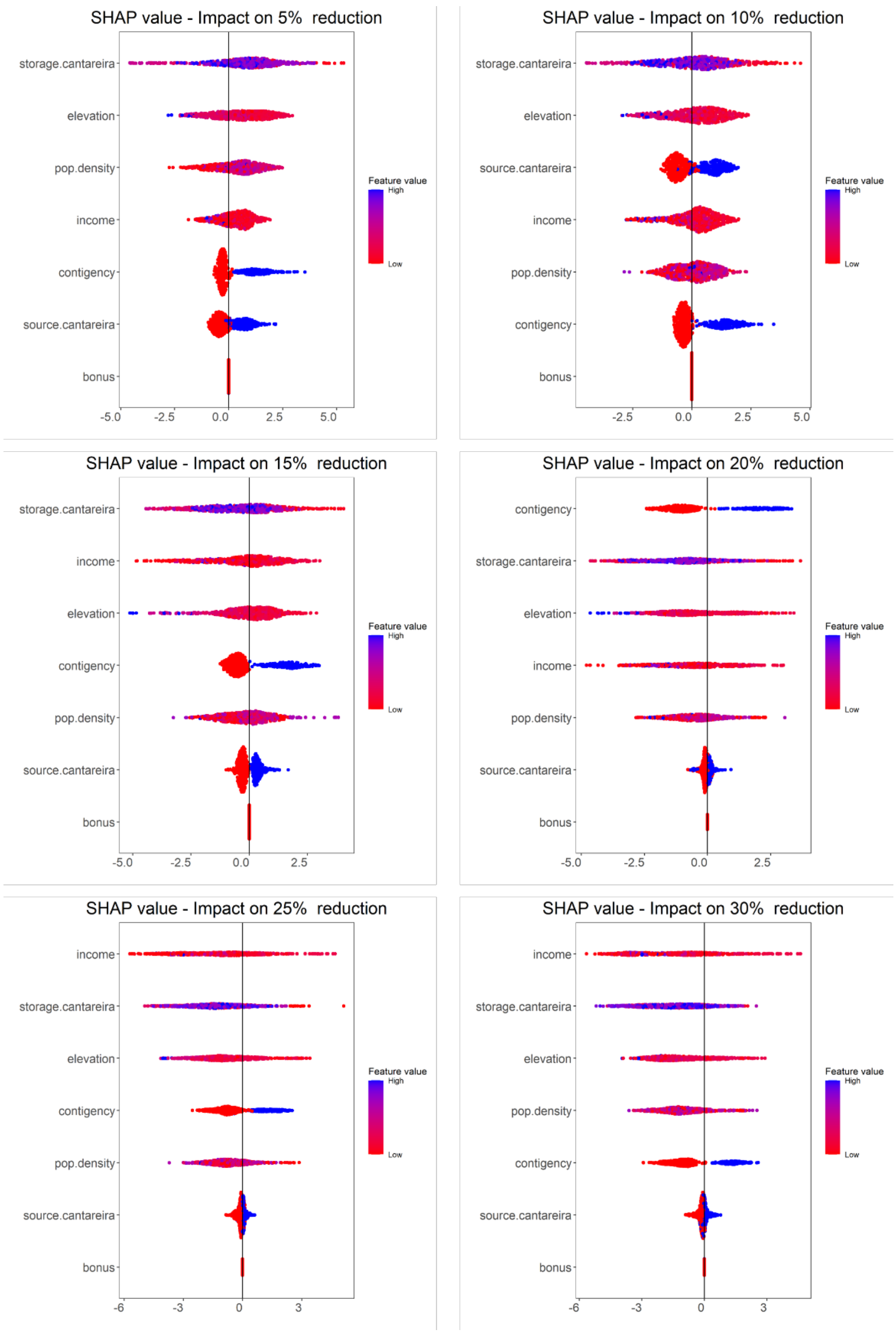

Figure 3.10: Presents the SHAP value of features employed to predict if service areas are expected to reduce water use. While blue dots indicate high values and red dots lower values of the corresponding variables, the x-axis indicate how much the value change the odds of prediction, which corresponds the likelihood of saving water.

Another form to interpretate black box and neural network models is the SHAP value (SHapley Additive explanation) approach (Lundberg and Lee, 2017; Herrera et al, 2023). The SHAP values have been employed in machine learning research to explain the importance of each feature on the model prediction. For example, the variables presented in Figure 3.10 demonstrates the effect of their values on the model prediction whether a given service will reduce or the consumption at the desired range of reduction. The blue colors indicate high value of the corresponding variable, while the red color represents lower values of the corresponding variable. Illustratively, there is clear evidence of the contingency policy role on the model output. The greater the contingency value, more likely the service area is to reduce the water use consumption. Because the contingency variable can only assume zero and one values, it shows a correlated causality between the policy implementation and the changing behavior, likewise the logistic regression suggested in Table 3.4. Another insight relies on the effect of population density variable. Highly populated service areas are less inclined to reduce consumption. Still, the role of income is not as clear as the other variables, but the SHAP values reveals more blue dots on the left side of the chart, which means the wealthier the service area is, less reduction is expected to be observed. Lastly, SHAP value approach suggests no clear causal effect of bonus tariff and the lowest relevance among the seven variables tested.

3.3.3 Scenario building

An alternative storyline was built to assess the impact of early implementation of water saving policies. Because the penalty tariffs demonstrated greater importance in predicting whether a region of São Paulo would reduce water use or not, the socio-hydrological model simulated the stock and flow variables changing this feature. The dashed line in Figure 3.11 presents the results of the simulated withdrawals, while the solid line represents the baseline of water abstracted from the Cantareira reservoirs and the bars are the corresponding rate of water use reduction. The results show that in 2013, when the storage level was between 60% and 20% of its maximum capacity, the water use reduction rate could be between 5% and 12%. However, in 2014, when the storage level was below 20% and reached the dead pool level, the reduction rates reached up to 20%. Since all the variables remain the same value for each service area, except the storage level, the reason behind the increasing reduction rates between these two years is the reduced water storage.

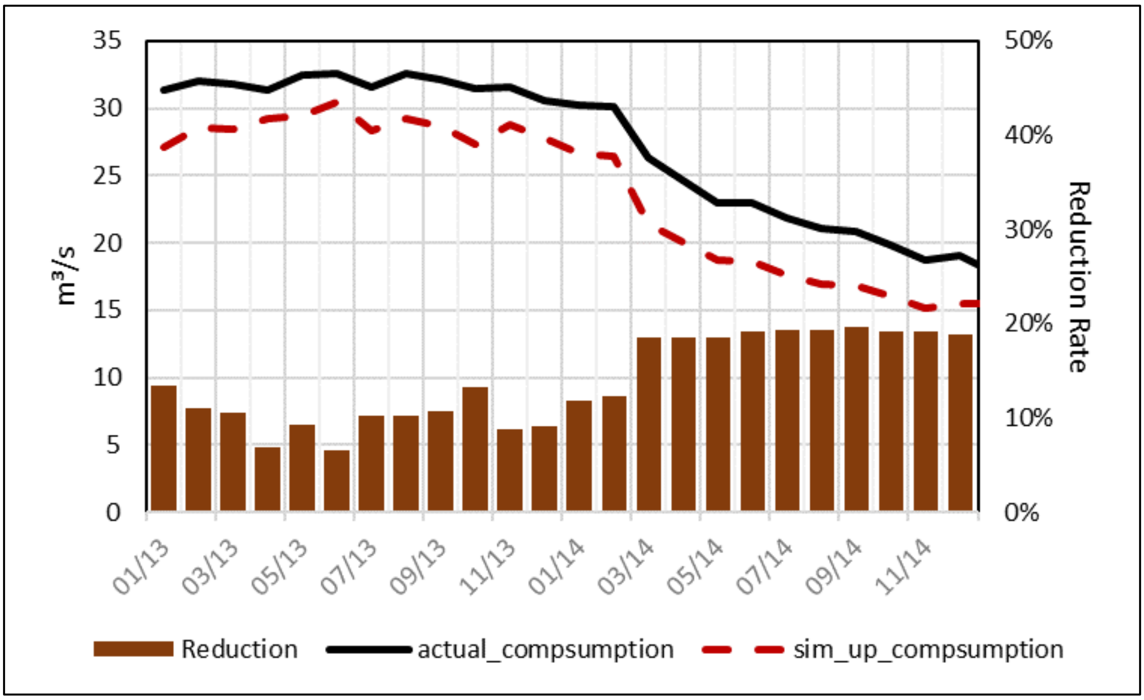

Figure 3.11: Comparison of the outputs of the model to the baseline, where the solid black line is the observed consumption, the dashed line is the modeled consumption and the bars at the bottom are the corresponding percentage of water use reduction.

The cumulative impact of such a reduction represents more than 280hm³ in two years, which is about 28% of useful storage. When compared to the minimum level observed at the time of the water crisis, in January 2015, the water deficit was about negative 228hm³. Therefore, the outputs of the socio-hydrological model suggests that implementing 2 years in advance would keep the water level around 50hm³ above the dead storage level. However, there is a political and an economic cost in implementing penalty tariffs. On the one hand, the political cost relies on the overpriced tariffs to be paid for basic services, which can be questioned because water level at the reservoir is not yet critical. On the other hand, the economic cost considers that the water saving in advance to a meteorological drought might impose restrictions to production of goods and services, thus limiting economic development. In this way, society would have missed the opportunity to grow economically if the drought does not happen.

Alternatively, a more conservative scenario was built considering that some residences within the service areas would not follow the expected reduction. This scenario decreased the predicted water use reduction of a given service area SA at month t, presented in Equation (21), by the precision metric presented in Table 3.5. For example, if one region consumed 100m³/s in a given month, and a 10% reduction is predicted by the model, the reduction is multiplied by the corresponding precision of the 10% model, which is equal to 76.4%. Thus, the conservative expected reduction is equal to 7.64%, which represents 92.36m³/s. The simulation of this scenario is presented in Figure 3.12, where the dotted line is the simulated conservative scenario. On average, reduction rates are 5 percentual points below the previous scenario.

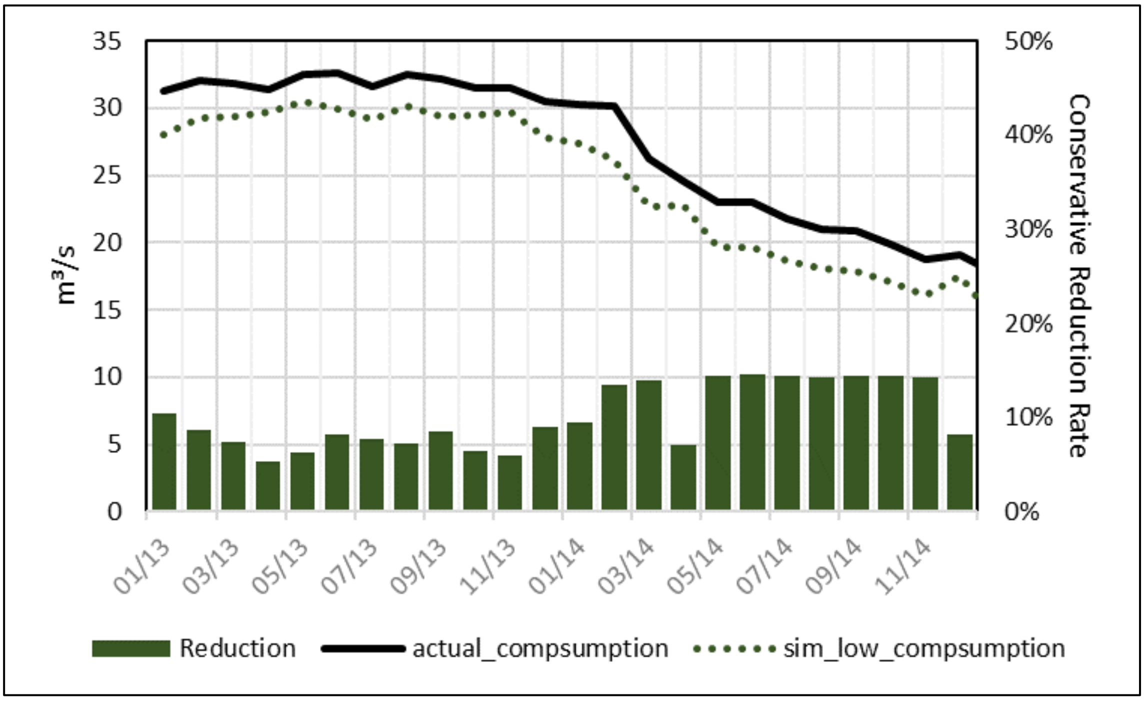

Figure 3.12: Compares a conservative scenario of policy intervention to the baseline, where the solid black line is the observed consumption, the dotted line is the modeled consumption and the bars at the bottom are the corresponding percentage of water use reduction.

Finally, Figure 3.13 presents the effect of changing behavior due to early water policy intervention. The solid line represents the actual storage level in the Cantareira system at the last day of each month, while the shaded part is the expected storage based on the model simulation. The simulations show higher and lower intervals where the uncertainty of the model is addressed. Therefore, if the policies were implemented two years in advance, it would be expected lower emptiness risk. However, the implementation of such policies with large anticipation is questionable and will be discussed in the next section.

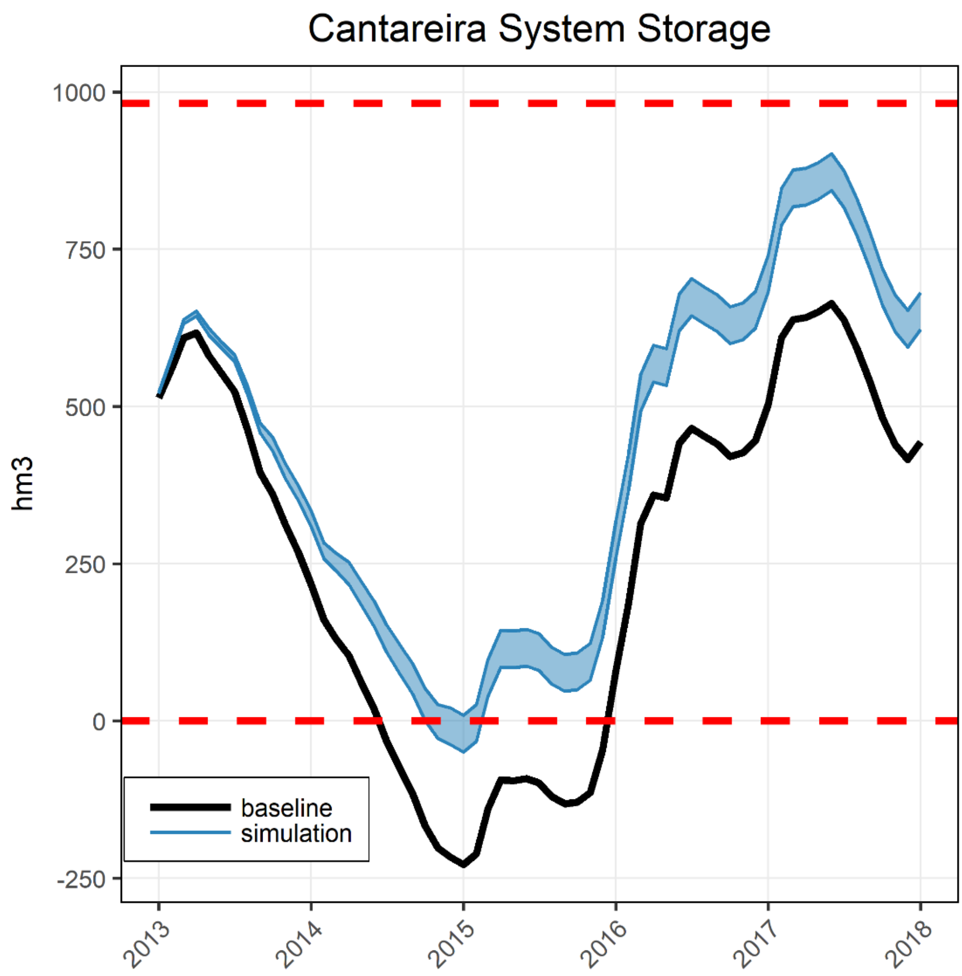

Figure 3.13: The impact on the storage of the Cantareira System in a scenario considering the implementation of the Fine Policy for users who do not reduce water consumption, where the shaded area represents the simulated scenario and the solid line represents the storage history during the crisis period water.

3.4 DISCUSSION

Although the assessment of the intervention scenario using the socio-hydrological model suggests an efficient management of the demand-side policies, the overall results must be carefully interpreted. Although the risk of emptiness is considerably reduced in case the measure was implemented two years in advance, Figure 3.13 shows that the water level at that time was more than 60% of the reservoirs' capacity. Convincing water users that they will be thirsty in two years' time might not be an easy task. However, one way to convince stakeholders to change their behavior is by providing scientific evidence that severe reduced rainfall is expected for the following two years and communicating that attitudinal change is required from now on, as observed by Addo et al (2019).

Because the methodology uses a distribution resolution of water users at service level, it enables policy designers to improve solutions in regions where the model suggests low water use reduction. Instead of penalizing the entire megacity with increased tariffs because a few regions have not reduced consumption, and therefore masking the overall reduction of all users, some customized interventions can be made at those places. As alternatives, massive campaigns, severe tariffs or even rationing are possible solutions to meet the desired reduction.

Some input features of the model have further embedded meanings. For instance, more water use reduction is expected when lower water is stored in the Cantareira reservoirs. However, the households' concerns on the water availability depends on an agent to let them know about the water level in reservoirs. Usually, this agent is the media coverage, who highlights the drought severity and the risk of rationing, or the water utility and authorities, who are concerned about not meeting the demands and the profitability of the company. Thus, the water storage feature is equivalent to the users' knowledge on the drought severity. If the drought was not informed, or lower attention was given, then the users could have reduced less water and therefore the water storage variable would not be as significant for the model. Thus, one possible interpretation of the scenario is that the water storage component is equivalent to the intensity of media coverage and conservation campaigns. Therefore, the early efforts of information spread could have boosted the water policy adherence. Additionally, there is room for future investigations to explore the nature of communication campaigns, if they had a behavior-change appeal, or if they were merely informative about the water storage, as example.

Similarly, the aim of population density variable is not only to predict the behavior of crowded regions, but also how the users who live in smaller places, such as apartments, respond to the conservation policies. Although Table 3.4 shows that only the 5% reduction range has statistical significance, the conclusion is that residents of smaller places are more likely to reduce water consumption. Complimentary, the income predictor shows more significance, where more policy adherence is expected in wealthier regions.

This combination of variables is an important feature of machine learning models, such as XG Boost, whose outstanding ability is to map the vast combination of different ranges of continuous variables, with the various classifications of categorical variables, in the prediction task. Illustratively, the logistic regression shows no overall significance of bonus policy on the conservation behavior. However, the XG Boost model might find a leaf in the tree where the bonus tariff does reduce the consumption of one specific range of income. However, the drawback of such a method is not being capable of clearly stating all the countless rules mapped. This is why the predictions of the model are evaluated under the lens of the four metrics presented in Table 3.5 to ensure the method can be reproduced in real world problems.

This methodology can be reproduced for other water crises in São Paulo or other megacities when all the data required is available. Unfortunately, this spatial resolution of water consumption and socio-demographic variables were not found for previous events in São Paulo, such as the Guarapiranga crisis in 1985-1986. For this reason, the predictivity capacity and the robustness of the model was tested when we randomly split all the observations into training and testing sets. However, the method can be reproduced whenever a new event occurs in São Paulo and the presented results can be compared to other case studies.

Some limitations of our approach are the lack of validation at individual level and the estimation of reservoirs' evaporation. One possible validation of our results could be to collect a substantial amount of data regarding individual end-users. Examples such as Bolorinos et al. (2022); Brühl and Visser (2021) statistically assessed the role of drivers of consumption in times of water scarcity. Additionally, the evaporation is embedded on the water balance variables of the reservoirs (inflow, outflow and storage). Therefore, the simulations did not update the reservoirs' surface area and respective evaporation as it could add more uncertainty to the model.

3.5 CONCLUSION

This chapter aimed at reproducing the water supply system of the São Paulo Metropolitan Region to evaluate the practical effects of early water saving policy implementation within the context of the 2013-2015 water crisis. This system was modeled using system dynamic concepts, focusing on the variables that guide the human-water interactions. An evaluation on the two water conservation policies, the bonus tariff and the contingency tariff, demonstrated more statistical significance on the latter one, which increases consumers' water bills if they do not reduce their consumption. Therefore, the alternative scenario showed that a significant reduced risk of reservoir emptiness would only be observed if this policy had been implemented two years earlier.

The main contribution of this chapter is on how to evaluate public adherence to water-demand management policy. The methodology differs from current literature because most of the existing studies uptake demand forecast methods in policy design. Such methods traditionally use regression models or time series models that have a continuous demand variable as output. Instead, the approach proposed in this study, first, forecasts if consumers are expected to reduce their consumption or not, and second, what range of reduction is expected. In addition, consumers were analyzed in a distributed manner to assess how sociodemographic specificities contribute to creating the availability of reduced water and to assess the weighted effect of different users on the lumped consumption.

The outputs have demonstrated that if policies had been implemented earlier, consumers could have saved water enough to avoid the Cantareira reservoirs from reaching the dead pool storage level. However, because of the drought severity and duration observed between 2013 and 2014, the water-demand management would only have succeeded if the policies had been implemented two years in advance. Because water availability is one the most significant drivers that lead consumers to conservation behavior, it would be difficult for decision makers to anticipate the real need to implement this strategy two years in advance as the volume stored at that time was more than half of the storage capacity. Moreover, long-lasting increased tariffs could have deteriorated the authorities' image in the face of public opinion due to the long duration of policies.

Therefore, despite the uncertainty of the severity and duration of the drought, which was to come, even before the onset of low flows, managing the water demand well in advance could have been an effective tool to combat the water crisis, according to the expected adherence of domestic users to policies to reduce water consumption, suggested by the socio-hydrological model. In order to reduce uncertainties regarding the water security of the São Metropolitan Region, the next chapter explores how to decrease consumers' exposure using supply-side management strategies.

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4 TRANSBOUNDARY ALLOCATION FROM THE PARAIBA DO SUL RIVER BASIN AND THE PAYOFFS INVOLVED

4.1 INTRODUCTION

Although the terminology “transboundary rivers” often refers to the watercourses that cross a range of boundaries, from the country level to small territories, more attention is given to international rivers that cross more than 300 basins worldwide (McCracken & Wolf, 2019; TFDD, 2018). Therefore, divergences are likely to emerge because two or more actors, linked to those courses, have particular preferences for water use or because they perceive the constraints of water as a zero-sum game (Baranyai, 2019), where the gains of one player are equivalent to the loss of the other player (Madani, 2010). In this game-theory framework applied to water resources management, Dinar and Hogarth (2015) and Yoosefdoost et al. (2021) define the appropriate elements.

- Game: this is the metaphor that describes the rationale behind the decision-making behavior of multiple actors. Whenever an agent seeks to maximize its benefits by anticipating the responses to his/her actions by other agents, this agent is playing a game.
- Players: these are the actors who interact with each other within the game context.
- Rules: these determine the possible actions in a game. Stylized models set strict rules to mathematically describe the game features.
- Actions: these are the set of moves that players can make in the game.
- Payoff (or utility): this is the value of benefits and/or costs resulting from the actions made by the player him/herself and the other players within the game.
- Outcome: this is the result of the game caused by the combination of actions made by all players.
- Equilibrium: this is when the players maximize their payoffs. Games can have more than one equilibrium.

Therefore, a transboundary river game cannot be interpreted as a dispute for water control, but as the maximization, by each player, of the benefits that players can gain from water use. Thus, seeking for the payoff maximization between two or more players of a transboundary basin might lead to conflict or cooperation scenarios. As an example, Wolf et al (2003) developed a “conflict-cooperation” scale called Basins At Risk, where a scale of 15 classifies events in worldwide river basins ranging from -7, “the most conflictive” to

+7, "the most cooperative" (voluntary merging of countries) (+7). In this study, the two international basins that cover the Brazilian territory have events classified by the authors: the La Plata Basin with score +4 ("non-military, economic, technological or industrial agreement") as a result of an agreement between Paraguay and Argentina to build a joint dam, and the Amazon Basin with score +6 ("major strategic alliance") due to the Amazonian Cooperation treaty, for economic development, among eight countries – including Brazil.

Besides the two international aforementioned basins, the Brazilian territory has several transboundary rivers from the intermunicipal level to the interregional level. A great example is the Sao Francisco river basin that begins in the South-East region, in Minas Gerais State, and crosses eight states. This large number of players result in several games played within this basin, where the latest one is the water transfers from the Sao Francisco river to the nearby arid region, which has triggered several debates about the payoffs involved (Lopes et al, 2021, da Silva et al., 2021, Roman, 2017).

Recent studies have also added an extra ingredient to the transboundary dynamics: the human element. Additionally, the socio-hydrological front of water sciences has proposed to investigate the two-way feedback between hydrological and societal systems (Sivapalan et al, 2012; Sivapalan and Bloschl, 2015). Within the transboundary rivers' context, Wei et al (2021) explored the underlying processes that drive upstream and downstream countries into conflict and cooperation because of water. One of the main elements is the benefit from water management, which is a very similar approach to the game theory, but others are identified as slow or fast processes that play an important role, such as power status, institutional capacity and social motive. Illustratively, Shrestha et al (2022) not only reproduce scenarios of the water cycle dynamics alone, but the influence of water management on water availability, the influence of water availability on social preferences, and finally, the impact of social preferences on water management. This socio-hydrological loop is stressed to assess the results arising from the willingness of Canada and the United States to cooperate. Similarly, Ghoreishi et al. (2022) linked the outputs of a willingness to cooperate model of the riparian counties of the Nile River to explain historical facts of socio-political interactions among the countries.

A Brazilian transboundary example is the Paraiba do Sul River Basin (PbSRB), which covers the Sao Paulo, Minas Gerais and Rio de Janeiro states' surface. This river crosses one of the wealthiest and most populated regions in South America. Thus, several consumers and water-uses are involved in a complex game, which added an extra ingredient: a tunnel connecting the PbSRB to the Cantareira System to boost the water availability upstream to supply the Sao Paulo Metropolitan Region.

Because the water-use preference of upstream players has changed, several state variables within this transboundary river system will also shift. Therefore, the aim of this chapter is to investigate the rules involved in this game, fulfill the payoff matrix for every possible action and respond to whether the transfers would solve the 2013-2015 water crisis experienced in Sao Paulo or not and the consequences involved.

4.2 METHODOLOGY

4.2.1 The Paraiba do Sul River Basin

The Köppen climate classification of Paraíba do Sul River Basin (PbSRB) varies among Cwa, Cwb, Aw (Capozzoli and Cardoso, 2021) and it covers about 61,307km² of three Brazilian states: Minas Gerais; Rio de Janeiro; and São Paulo (Kumler and Lemos, 2008). The region has great importance not only because of the 13% of Brazilian GDP production (OECD, 2017), but also because it is the home of more than 9.6 million inhabitants (CEIVAP, 2020). In addition, a water transfer infrastructure, at Santa Cecilia pumping station, is responsible for boosting the Guandu River streamflow from 25m³/s up to 185m³/s for industrial, hydropower and domestic purposes (ANA, 2017), including the water supply to about 75% of the total 13 million citizens from the Rio de Janeiro Metropolitan Region (CEIVAP, 2020; Paiva et al, 2020), which is not located within the PbSRB.

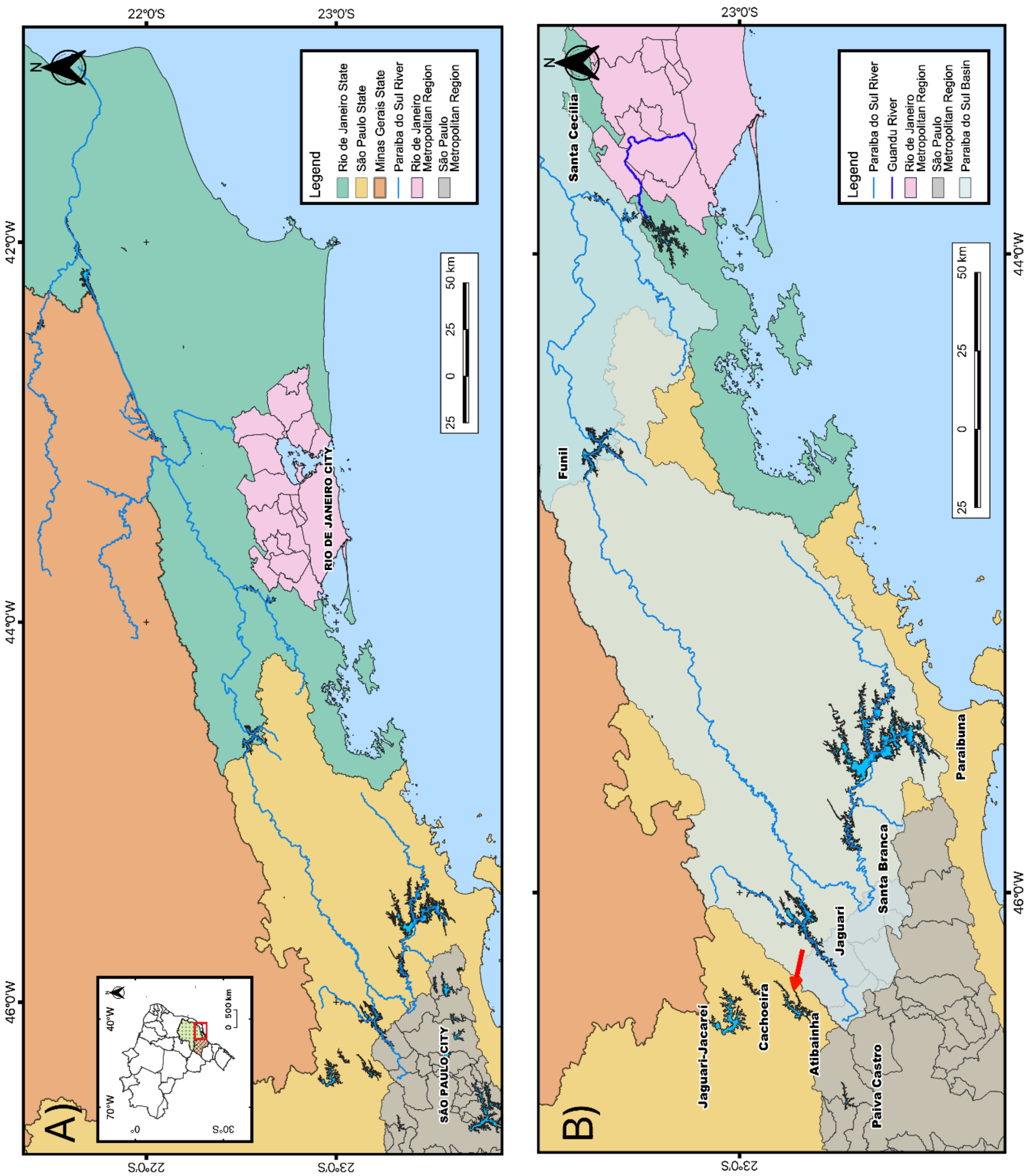

Figure 4.1: Map A show the three Brazilian states crossed by the Paraiba do Sul River Basin, with emphasis on the Sao Paulo and Rio de Janeiro Cities. Map B highlights the connection between the Cantareira System and the Paraiba do Sul reservoirs.

The drought experienced between 2013 and 2015 was the most severe since 1931 (ANA, 2015; Costa et al, 2015). Discussions to avoid the reservoirs' emptiness began in 2014, when a special group of stakeholders was formed to review the operation rules of the Equivalent System, which is formed by the Paraibuna, Funil, Santa Branca and Jaguari reservoirs (Vasconcelos, Formiga-Johnsson and Ribeiro, 2019). In December 2016, when the water crisis was officially declared over, the latest operation rules for each reservoir were released to avoid the reservoirs' emptiness and to ensure they would meet all demands in future droughts (Vasconcelos, Formiga-Johnsson and Ribeiro, 2019). Adding to these complex operations, a tunnel connecting the PbSRB (at Jaguari reservoir) to the Cantareira system (at Atibainha reservoir) was completed in 2018 to alleviate the water supply pressure at the São Paulo Metropolitan Region (Braga and Kelman, 2020), the most populated region in Brazil with more than 20 million inhabitants. The operation rules for this tunnel were released in October 2017.

Despite the recorded consequences and the efforts to respond to the drought at that time, the impacts of the latest operation rules and the tunnel between PbSRB and Cantareira remain unknown. On the one hand, the low flows dramatically affected the water quality (Pacheco et al, 2017) and the urban supply, and therefore, the restrictive rules aim at preserving the minimum storage level and reservoir releases. On the other hand, unintended consequences, such as a possible reduction of hydropower production (Cuartas et al, 2022; Hunt et al, 2018; Zanbon et al, 2017) and downstream water availability, could be observed as consequences of water conservation policies upstream.

4.2.2 Modelling

A mathematical model was developed to reproduce the water fluxes within the PbSRB and simulate possible scenarios resulting from new operation rules. This model not only considered the four main reservoirs of the PbSRB, but also the transfers to the Cantareira System (Figure 4.1). In addition, the model also accounted for the hydropower produced by the four dams. The water level, inflow, verted flow and turbined flow was retrieved from the National Water and Sanitation Agency (ANA, 2021), the monthly hydropower production of each reservoir was retrieved from the National Electric System Operator (ONS, 2021) and the water storage and transfers from the Cantareira System was retrieved from the water utility of São Paulo Metropolitan Region (SABESP, 2021).

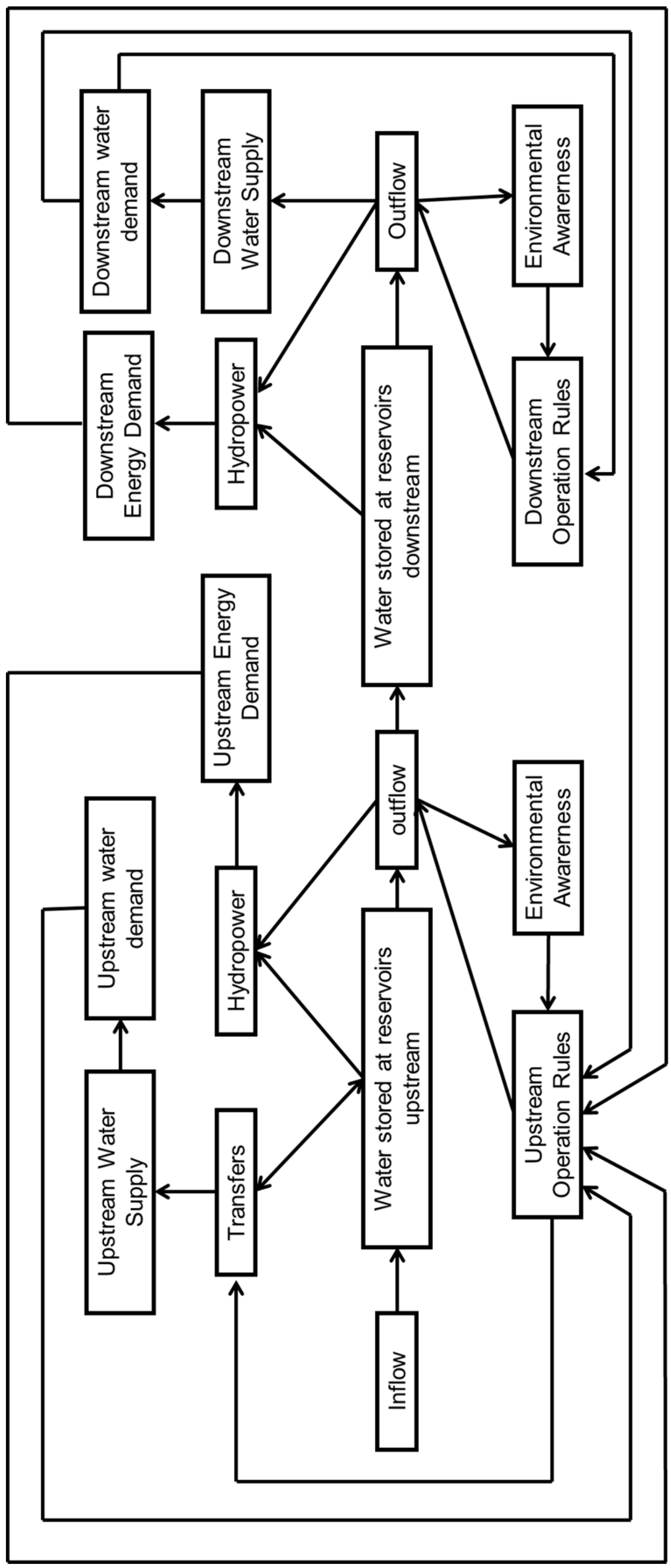

Figure 4.2: Causal loop diagram of the processes involved in the Paraiba do Sul River Basin processes between upstream and downstream states of Sao Paulo and Rio de Janeiro.

A set of equations was derived from the mass balance principle to measure the changes of water stored and released from reservoirs. The changes in water storage ($\frac{dS}{dt}$) were simulated by Equation (26), where Q_{in} is the inflow (m³/s), Q_{out} is the outflow (m³/s), and Q_{transf} is the water transfer (m³/s) between the Cantareira System and the Atibainha reservoir (PbSRB). Equation (27) estimated the tributaries' contribution (Q_{trib}) between two reservoirs in m³/s, where $Q_{out_{\text{up}}}$ is the outflow from the upstream reservoir (m³/s) and $Q_{in_{\text{down}}}$ is the inflow of the downstream reservoir (m³/s). Finally, Equation (28) estimates the amount of water that leaves the reservoirs, where Q_{turb} is the turbined flow (m³/s), Q_{vert} is the verted flow (m³/s), $\text{Q}_{\text{seepage}}$ is the seepage flow (m³/s) and Q_{evap} is the evaporation (m³/s).

$$\frac{dS}{dt} = \text{Q}_{\text{in}} - \text{Q}_{\text{out}} \pm Q_{transf} \quad (26)$$

$$\text{Q}_{\text{trib}} = \text{Q}_{\text{out}_{\text{out}}} - \text{Q}_{\text{in}_{\text{down}}} \quad (27)$$

$$\text{Q}_{\text{out}} = \text{Q}_{\text{turb}} + \text{Q}_{\text{vert}} + \text{Q}_{\text{seepage}} + \text{Q}_{\text{evap}} \quad (28)$$

Besides the water availability in reservoirs, the local community also reaps benefits from the energy generated by hydropower plants. Since energy is not only affected by the forebay level, but also by the turbined flow, which is the water released through the turbines to produce energy, the changes in water releases and transfers might also affect the electricity produced upstream and downstream. Therefore, the power produced can be calculated through Equation 29, where HE is the hydroelectricity produced in a month (kWh), η is the turbine efficiency (dimensionless), ρ is the water density (kg/m³), Q_{turb} is the turbined flow (m³/s), g is the gravity acceleration (m/s²), Δh is the difference between inlet and outlet (m) and Δt is the number of hours in a month (h). For the simplification purpose, Shrestha et al. (2022) suggest a simplified approach using the time series of hydroelectricity produced HE (kWh), Q_{turb} turbined flow (m³/s) and forebay level records $\text{h}_{\text{forebay}}$ (m) combined with a linear regression to fit parameter α from Equation 30. Thus, Figure 4.3 presents the parameter α fitted for the PbSRB reservoirs, as well as the r-squared, which shows to be a good approach to simulate hydropower production.

$$HE = \eta \cdot \rho \cdot \text{Q}_{\text{turb}} \cdot g \cdot \Delta h \cdot \Delta t \quad (29)$$

$$HE = \alpha \cdot Q_{turb} \cdot h_{forebay} \tag{30}$$

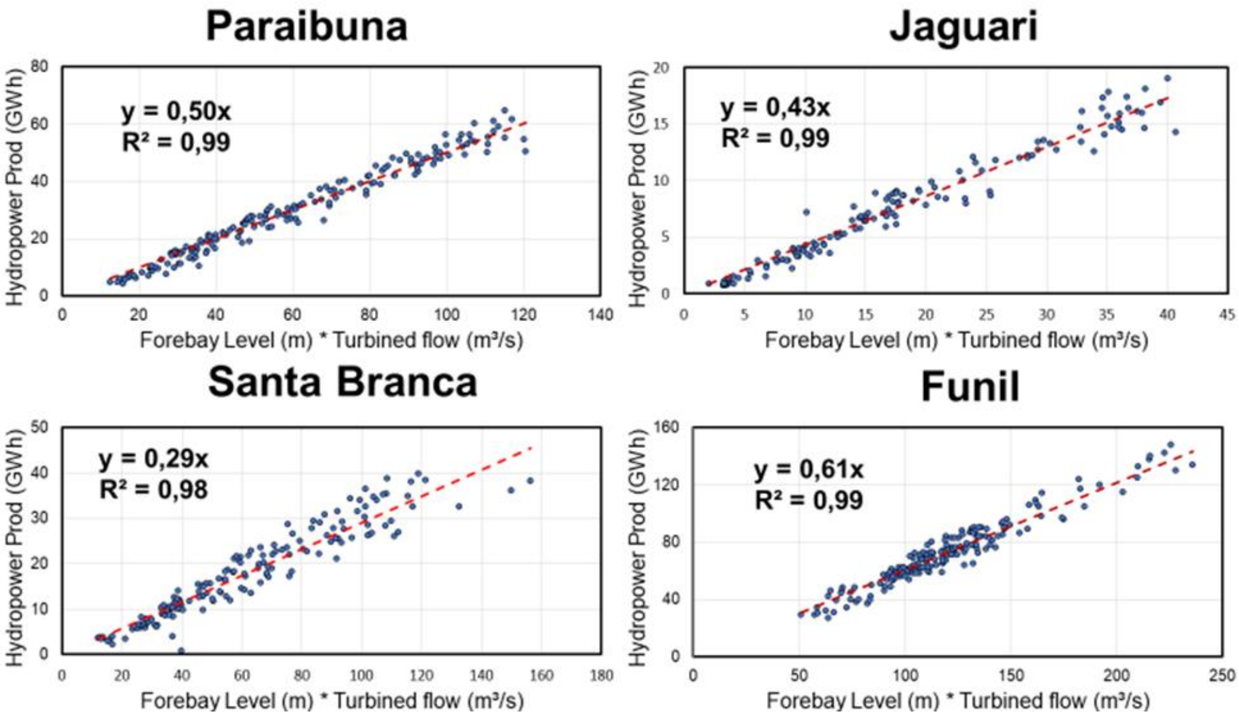

Figure 4.3: Correlation between produced hydropower and the product of forebay level and turbined flow.

4.2.3 Scenario Building

Table 4.1: Presents the three scenarios simulated to outline possible impacts on the change of water allocation and reservoir operation within the Cantareira and Paraiba do Sul Systems.

Scenario	Description
1	Simulates water transferred from the Paraiba do Sul River Basin to the Cantareira Reservoirs
2	Simulates the operation rules for the Paraiba do Sul Reservoirs updated after the drought
3	Combines the simulation of scenarios 1 and 2

Because the authorities have developed new strategies to tackle future droughts, the tree scenarios presented in Table 4.1 are built to evaluate what consequences such strategies would have caused to both upstream and downstream states. Equations (26) to (30) support the simulation of possible scenarios to consider water management changes made to the PbSRB after the 2013-2015 drought. Firstly, the decision-makers from São Paulo State, Rio de Janeiro State, Minas Gerais State and the Federal Regulatory agencies revised the operation rules for the PbSRB's equivalent system in the joint resolution ANA/DAEE/INEA/IGAM N1.382/2015 as a response to the drought consequences. This document currently guides the minimum reservoir storage and outflow releases as presented in Table 4.2. Additionally, the simulations also address the impact of the tunnel that connects the PbSRB to the Cantareira System, which is responsible for supplying the São Paulo Metropolitan Region. The scenarios were created considering the monthly average transfer from Jaguari reservoir (PbSRB) to the Atibainha reservoir (Cantareira System) between 2018 and 2020, which corresponds to 5.1m³/s. Thus, Equations (26) to (30) support the simulation of possible scenarios to indicate whether the actual operations reach the thresholds, but do not provide alternative water releases whenever this happens. Therefore, Equation (31) address the turbined and verted flows to follow the operation rules indicated by Table 4.2, where S_{jag} is the simulated storage at the Jaguari reservoir (m³), $S_{\mathrm{min_{jag}}}$ is the minimum storage for the Jaguari reservoir (hm³), S_{cant} is the simulated storage for the Cantareira System (hm³), and $S_{\mathrm{thers_{cant}}}$ is the maximum limit to transfer water from PbSRB to the Cantareira System (hm³).

Table 4.2: A summary of the updated operation rules for the PbSRB reservoirs, which were revised after the 2013-2015 drought.

Reservoirs	Minimum Storage (%)	Minimum outflow (m3/s)
Funil	30	70
Santa Branca	10	30
Paraibuna	5	10
Jaguari	20	4

$$\begin{cases} for\ S_{jag} \leq S_{\mathrm{min_{jag}}}\ or\ S_{cant} \geq S_{\mathrm{thers_{cant}}} \{Q_{transf} = 0 \\ for\ S_{jag} > S_{\mathrm{min_{jag}}}\ and\ S_{cant} < S_{\mathrm{thers_{cant}}} \{Q_{transf} = 5{,}1 \end{cases} \tag{31}$$

Additionally, the model must also simulate the outflow components given the scenarios of water transfer and/or minimum storage and outflow. Therefore, Equations (32) to (35) present the Operation Rules developed to simulate the state variables of the three scenarios. In all these formulas, the premise is to primarily respect the minimum storage and outflow. Then, whenever it is possible to switch outflow between the turbines or spillways, it will always prioritize the outflow through the hydropower turbines to stimulate the hydropower production.

$$\begin{cases} \text{for } Q_{transf} = 0 \begin{cases} \text{for } Q_{vert_{jag}} \geq Q_{min_{jag}} \begin{cases} Q_{turb_{jag_{sim}}} = Q_{turb_{jag_{obs}}} \\ Q_{vert_{jag_{sim}}} = Q_{vert_{jag_{obs}}} \end{cases} & \text{(a)} \\ \text{for } Q_{vert_{jag_{obs}}} \leq Q_{min_{jag}} \text{ and } \left(Q_{vert_{jag_{obs}}} + Q_{turb_{jag_{obs}}}\right) \geq Q_{min_{jag}} \begin{cases} Q_{turb_{jag_{sim}}} = Q_{turb_{jag_{obs}}} \\ Q_{vert_{jag_{sim}}} = Q_{vert_{jag_{obs}}} \end{cases} & \text{(b)} \\ \text{for } \left(Q_{turb_{jag_{obs}}} + Q_{vert_{jag_{obs}}}\right) < Q_{min_{jag}} \begin{cases} Q_{turb_{jag_{sim}}} = Q_{min_{jag}} \\ Q_{vert_{jag_{sim}}} = 0 \end{cases} & \text{(c)} \end{cases} \\ \text{for } Q_{transf} > 0 \begin{cases} \text{for } Q_{vert_{jag_{obs}}} \geq \left(Q_{transf} + Q_{min_{jag}}\right) \begin{cases} Q_{turb_{jag_{sim}}} = Q_{turb_{jag_{obs}}} \\ Q_{vert_{jag_{sim}}} = Q_{vert_{jag_{obs}}} - Q_{transf} \end{cases} & \text{(d)} \\ \text{for } 0 < Q_{vert_{jag_{obs}}} \leq \left(Q_{transf} + Q_{min_{jag}}\right) \ and \ \left(Q_{turb_{jag_{obs}}} + Q_{vert_{jag_{obs}}}\right) \geq \left(Q_{transf} + Q_{min_{jag}}\right) \begin{cases} Q_{turb_{jag_{sim}}} = Q_{turb_{jag_{obs}}} + Q_{vert_{jag_{obs}}} - Q_{transf} \\ Q_{vert_{jag_{sim}}} = 0 \end{cases} & \text{(e)} \\ \text{for } 0 < Q_{vert_{jag_{obs}}} \leq \left(Q_{transf} + Q_{min_{jag}}\right) \ and \ \left(Q_{turb_{jag_{obs}}} + Q_{vert_{jag_{obs}}}\right) < \left(Q_{transf} + Q_{min_{jag}}\right) \begin{cases} Q_{turb_{jag_{sim}}} = Q_{min_{jag}} \\ Q_{vert_{jag_{sim}}} = 0 \end{cases} & \text{(f)} \\ \text{for } Q_{vert_{jag_{obs}}} = 0 \ and \ Q_{turb_{jag_{obs}}} \geq \left(Q_{transf} + Q_{min_{jag}}\right) \begin{cases} Q_{turb_{jag_{sim}}} = Q_{turb_{jag_{obs}}} - Q_{transf} \\ Q_{vert_{jag_{sim}}} = 0 \end{cases} & \text{(g)} \\ \text{for } Q_{vert_{jag_{obs}}} = 0 \ and \ Q_{turb_{jag_{obs}}} < \left(Q_{transf} + Q_{min_{jag}}\right) \begin{cases} Q_{turb_{jag_{sim}}} = Q_{min_{jag}} \\ Q_{vert_{jag_{sim}}} = 0 \end{cases} & \text{(h)} \end{cases} \end{cases}$$

(32)

Equations 32a to 32h have the following rationale:

a) Since water is not transferred but the actual verted flow is greater than or equal to the minimum outflow, then the simulated turbined flow and simulated verted flow are set to be equal to the records.

b) Since water is not transferred and the actual verted flow is less than the minimum outflow, but the total outflow is assured to be greater than or equal to the minimum outflow, then the simulated turbined flow and the simulated verted flow are set to be equal to the records.

c) Since water is not transferred and the actual outflow is less than the minimum outflow, then the simulated turbined flow is set to be the minimum outflow while the simulated verted flow is set to zero.

d) Since water is transferred and the actual verted flow is greater than or equal to the sum of the minimum outflow and the volume transferred, then the simulated turbined flow is set to be equal to the records while the simulated verted flow is the record reduced by the transfers.

e) Since water is transferred and the actual verted flow is not as large as the sum of the minimum outflow and the volume transferred, but the actual outflow is larger than the sum of transfers and the minimum outflow, then the simulated verted flow is set to zero while the simulated turbined flow is the surplus of actual outflow minus the transfers.

f) Since water is transferred and the actual outflow is not as large as the sum of transfers and the minimum outflow, then the simulated turbined flow is set to the minimum outflow while the simulated verted flow is set to zero.

g) Since water is transferred and the actual verted flow is zero, but the actual outflow is larger than the sum of transfers and the minimum outflow, then the simulated verted flow is set to zero while the simulated turbined flow is the surplus of actual outflow minus the transfers.

h) Since water is transferred, the actual verted flow is zero and the actual outflow is not as large as the sum of transfers and the minimum outflow, then the simulated turbined flow is set to the minimum outflow while the simulated verted flow is set to zero.

$$
\begin{cases}
\text{for } S_{par} > S_{\min_{par}} \begin{cases}
\text{for } Q_{vert_{par_{obs}}} \geq Q_{\min_{par}} \begin{cases} Q_{turb_{par_{sim}}} = Q_{turb_{par_{obs}}} \\ Q_{vert_{par_{sim}}} = Q_{vert_{par_{obs}}} \end{cases} & (a) \\
\text{for } Q_{vert_{par_{obs}}} \leq Q_{\min_{par}} \text{ and } \left(Q_{vert_{par_{obs}}} + Q_{turb_{par_{obs}}}\right) \geq Q_{\min_{par}} \begin{cases} Q_{turb_{par_{sim}}} = Q_{turb_{par_{obs}}} \\ Q_{vert_{par_{sim}}} = Q_{vert_{par_{obs}}} \end{cases} & (b) \\
\text{for } \left(Q_{vert_{par_{obs}}} + Q_{turb_{par_{obs}}}\right) < Q_{\min_{par}} \begin{cases} Q_{turb_{par_{sim}}} = Q_{\min_{par}} \\ Q_{vert_{par_{sim}}} = 0 \end{cases} & (c)
\end{cases} \\
\text{for } S_{par} \leq S_{\min_{par}} \begin{cases}
\text{for } Q_{vert_{par_{obs}}} \geq Q_{\min_{par}} \begin{cases} Q_{turb_{par_{sim}}} = Q_{\min_{par}} \\ Q_{vert_{par_{sim}}} = 0 \end{cases} & (d) \\
\text{for } 0 \leq Q_{vert_{par_{obs}}} < Q_{\min_{par}} \begin{cases} Q_{turb_{par_{sim}}} = Q_{\min_{par}} \\ Q_{vert_{par_{sim}}} = 0 \end{cases} & (e)
\end{cases}
\end{cases}
$$

(33)

Equations 33a to 33e have the following rationale:

a) Since the reservoir did not reach the minimum level and the actual verted flow is larger than or equal to the minimum outflow, then the simulated turbined flow and the simulated verted flow are set to be equal to the records.

b) Since the reservoir did not reach the minimum level and the actual verted flow is less than the minimum outflow, but the total outflow is assured to be greater than or equal to the minimum outflow, then the simulated turbined flow and the simulated verted flow are set to be equal to the records.

c) Since the reservoir did not reach the minimum level, but the actual outflow is less than the minimum outflow, then the simulated turbined flow is set to be the minimum outflow while the simulated verted flow is set to zero.

d) Since the reservoir reached the minimum level, but the actual verted flow is larger than the minimum outflow, then the simulated turbined flow is set to be the minimum outflow while the simulated verted flow is set to zero.

e) Since the reservoir reached the minimum level and the actual verted flow is less than the minimum outflow, then the simulated turbined flow is set to be the minimum outflow while the simulated verted flow is set to zero.

$$\begin{cases} \text{for } S_{stb} > S_{\mathrm{min_{stb}}} \begin{cases} \text{for } \mathrm{Q_{vert_{stb_{obs}}}} \geq \mathrm{Q_{min_{stb}}} \begin{cases} \mathrm{Q_{turb_{stb_{sim}}}} = \mathrm{Q_{turb_{stb_{obs}}}} \\ \mathrm{Q_{vert_{stb_{\mathit{sim}}}}} = \mathrm{Q_{vert_{stb_{obs}}}} \end{cases} & \text{(a)} \\ \text{for } \mathrm{Q_{vert_{stb_{obs}}}} \leq \mathrm{Q_{min_{stb}}} \text{ and } \left(\mathrm{Q_{vert_{stb_{obs}}}} + \mathrm{Q_{turb_{stb_{obs}}}}\right) \geq \mathrm{Q_{min_{stb}}} \begin{cases} \mathrm{Q_{turb_{stb_{sim}}}} = \mathrm{Q_{turb_{stb_{obs}}}} \\ \mathrm{Q_{vert_{stb_{\mathit{sim}}}}} = \mathrm{Q_{vert_{stb_{obs}}}} \end{cases} & \text{(b)} \\ \text{for } \left(\mathrm{Q_{vert_{stb_{obs}}}} + \mathrm{Q_{turb_{stb_{obs}}}}\right) < \mathrm{Q_{min_{stb}}} \begin{cases} \mathrm{Q_{turb_{stb_{sim}}}} = \mathrm{Q_{min_{stb}}} \\ \mathrm{Q_{vert_{stb_{\mathit{sim}}}}} = 0 \end{cases} & \text{(c)} \end{cases} \\ \text{for } S_{stb} \leq S_{\mathrm{min_{stb}}} \begin{cases} \text{for } \mathrm{Q_{vert_{stb_{obs}}}} \geq \mathrm{Q_{min_{stb}}} \begin{cases} \mathrm{Q_{turb_{stb_{sim}}}} = \mathrm{Q_{min_{stb}}} \\ \mathrm{Q_{vert_{stb_{\mathit{sim}}}}} = 0 \end{cases} & \text{(d)} \\ \text{for } 0 \leq \mathrm{Q_{vert_{stb_{obs}}}} < \mathrm{Q_{min_{stb}}} \begin{cases} \mathrm{Q_{turb_{stb_{sim}}}} = \mathrm{Q_{min_{stb}}} \\ \mathrm{Q_{vert_{stb_{\mathit{sim}}}}} = 0 \end{cases} & \text{(e)} \end{cases} \end{cases} \tag{34}$$

Equations 34a to 34e have the following rationale:

a) Since the reservoir did not reach the minimum level and the actual verted flow is larger than or equal to the minimum outflow, then the simulated turbined flow and the simulated verted flow are set to be equal to the records.

b) Since the reservoir did not reach the minimum level and the actual verted flow is less than the minimum outflow, but the total outflow is assured to be greater than or equal to the minimum outflow, then the simulated turbined flow and the simulated verted flow are set to be equal to the records.

c) Since the reservoir did not reach the minimum level, but the actual outflow is less than the minimum outflow, then the simulated turbined flow is set to be the minimum outflow while the simulated verted flow is set to zero.

d) Since the reservoir reached the minimum level, but the actual verted flow is larger than the minimum outflow, then the simulated turbined flow is set to be the minimum outflow while the simulated verted flow is set to zero.

e) Since the reservoir reached the minimum level and the actual verted flow is less than the minimum outflow, then the simulated turbined flow is set to be the minimum outflow while the simulated verted flow is set to zero.

$$
\begin{cases}
\text{for } \mathrm{Q_{transf}} = 0 \text{ and } \mathrm{S_{fun}} > \mathrm{S_{min_{fun}}} \begin{cases}
\text{for } \mathrm{Q_{vert_{fun_{obs}}}} \geq \mathrm{Q_{min_{fun}}} \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{turb_{fun_{obs}}}} \\ \mathrm{Q_{vert_{fun}}} = \mathrm{Q_{vert_{fun_{obs}}}} \end{cases} & \text{(a)} \\
\text{for } \mathrm{Q_{vert_{fun_{obs}}}} < \mathrm{Q_{min_{fun}}} \text{ and } \left(\mathrm{Q_{vert_{fun_{obs}}}} + \mathrm{Q_{turb_{fun_{obs}}}}\right) \geq \mathrm{Q_{min_{fun}}} \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{turb_{fun_{obs}}}} \\ \mathrm{Q_{vert_{fun}}} = \mathrm{Q_{vert_{fun_{obs}}}} \end{cases} & \text{(b)} \\
\text{for } \left(\mathrm{Q_{vert_{fun_{obs}}}} + \mathrm{Q_{turb_{fun_{obs}}}}\right) < \mathrm{Q_{min_{fun}}} \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{min_{fun}}} \\ \mathrm{Q_{vert_{fun}}} = 0 \end{cases} & \text{(c)}
\end{cases} \\
\text{for } \mathrm{Q_{transf}} = 0 \text{ and } \mathrm{S_{fun}} \leq \mathrm{S_{min_{fun}}} \begin{cases}
\text{for } \mathrm{Q_{vert_{fun_{obs}}}} \geq \left(\mathrm{Q_{min_{fun}}}\right) \begin{cases} \mathrm{Q_{turb_{fun}}} = 0 \\ \mathrm{Q_{vert_{fun}}} = \mathrm{Q_{min_{fun}}} \end{cases} & \text{(d)} \\
\text{for } 0 \leq \mathrm{Q_{vert_{fun_{obs}}}} \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{min_{fun}}} \\ \mathrm{Q_{vert_{fun}}} = 0 \end{cases} & \text{(e)}
\end{cases} \\
\text{for } \mathrm{Q_{transf}} > 0 \text{ and } \mathrm{S_{fun}} > \mathrm{S_{min_{fun}}} \begin{cases}
\text{for } \mathrm{Q_{vert_{jag_{obs}}}} \geq \left(\mathrm{Q_{transf}}\right) \text{ and } \left(\mathrm{Q_{vert_{fun_{obs}}}} + \mathrm{Q_{turb_{fun_{obs}}}}\right) \geq \left(\mathrm{Q_{min_{fun}}} + \mathrm{Q_{transf}}\right) \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{turb_{fun_{obs}}}} \\ \mathrm{Q}_{\mathrm{vert}_{fun}} = \mathrm{Q_{vert_{fun_{obs}}}} - \mathrm{Q_{transf}} \end{cases} & \text{(f)} \\
\text{for } 0 < \mathrm{Q_{vert_{fun_{obs}}}} < \left(\mathrm{Q_{transf}}\right) \text{ and } \left(\mathrm{Q_{vert_{fun_{obs}}}} + \mathrm{Q_{turb_{fun_{obs}}}}\right) \geq \left(\mathrm{Q_{min_{fun}}} + \mathrm{Q_{transf}}\right) \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{turb_{fun_{obs}}}} + \mathrm{Q_{vert_{fun_{obs}}}} - \mathrm{Q_{transf}} \\ \mathrm{Q_{vert_{fun}}} = 0 \end{cases} & \text{(g)} \\
\text{for } \mathrm{Q_{vert_{fun_{obs}}}} = 0 \text{ and } \left(\mathrm{Q_{vert_{fun_{obs}}}} + \mathrm{Q_{turb_{fun_{obs}}}}\right) \geq \left(\mathrm{Q_{min_{fun}}} + \mathrm{Q_{transf}}\right) \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{turb_{fun_{obs}}}} - \mathrm{Q_{transf}} \\ \mathrm{Q}_{\mathrm{vert}_{fun}} = 0 \end{cases} & \text{(h)} \\
\text{for } \left(\mathrm{Q_{vert_{fun_{obs}}}} + \mathrm{Q_{turb_{fun_{obs}}}}\right) < \left(\mathrm{Q_{min_{fun}}} + \mathrm{Q_{transf}}\right) \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{min_{fun}}} \\ \mathrm{Q_{vert_{fun}}} = 0 \end{cases} & \text{(i)}
\end{cases} \\
\text{for } \mathrm{Q_{transf}} > 0 \text{ and } \mathrm{S_{fun}} \leq \mathrm{S_{min_{fun}}} \begin{cases}
\text{for } \mathrm{Q_{vert_{fun_{obs}}}} \geq \left(\mathrm{Q_{transf}} + \mathrm{Q_{min_{fun}}}\right) \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{min_{fun}}} \\ \mathrm{Q_{vert_{fun}}} = 0 \end{cases} & \text{(j)} \\
\text{for } 0 \leq \mathrm{Q_{vert_{fun_{obs}}}} \begin{cases} \mathrm{Q_{turb_{fun}}} = \mathrm{Q_{min_{fun}}} \\ \mathrm{Q_{vert_{fun}}} = 0 \end{cases} & \text{(k)}
\end{cases}
\end{cases} \quad (35)
$$

4.3 RESULTS

The goodness-of-fit (GoF) metrics presented in Table 4.3 are close to 1, which means that the model has a good representation of water transfers and hydroelectricity production for the simulated period between 2008 and 2018. Since drinking water and electricity are the two most relevant stock variables related to the benefits that stakeholders and local community can obtain from the rivers, the GoF metrics evaluated how good the model represents the actual monthly volume of water stored in reservoirs and the monthly hydropower generated in their facilities. The Nash-Sutcliffe efficiency criterion was used for the comparison purpose as several studies have used this method over the last decades (Nash and Sutcliffe, 1970; Liu, 2020), while the Kling-Gupta Efficiency (KGE) is a more recent GoF metric, which has gained importance lately because this is an empowered version of previous NSE (Gupta, et al, 2009). Equations (36) and (37) present NSE and KGE equations, where x_{sim} is the value simulated by the model, x_{obs} is the actual value, σ_{sim} is the standard deviation simulated, σ_{obs} is the standard deviation observed, μ_{obs} is the mean observed, μ_{sim} is the mean simulated and r is the linear correlation coefficient between x_{sim} and x_{obs}.

$$NSE = 1 - \frac{\sum(x_{sim} - x_{obs})^2}{\sum(x_{obs} - \mu_{obs})^2} \qquad (36)$$

$$KGE = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{sim}}{\sigma_{obs}} - 1\right)^2 + \left(\frac{\mu_{sim}}{\mu_{obs}} - 1\right)^2} \qquad (37)$$

The plots from Figure 4.4 and Figure 4.5 present the comparison between observed and modelled data, which were used to calculate the GoF metrics in Table 4.3. This comparison is relevant because the modelled data will be further used as the baseline to be compared with the scenarios simulated. Both KGE and NSE signalized a good fit of storage simulated because the model used the mass balance equations, which does not require any calibration in case the data available is accurate. On the other hand, the hydropower simulation required calibrating the parameter α from Equation 30, which was presented in Figure 4.3. Thus, the simulations did not fit as well as they did for water storage, but the performance is still good since the GoF metrics are greater than 0.80. Lastly, Figure 4.5 also presents the comparison between observed versus modelled outflow from Funil because this is the basis to estimate the difference of water released to the downstream state (Rio de Janeiro) for each scenario.

Table 4.3: The table shows the two goodness of fit metrics: Nash–Sutcliffe model Efficiency criterion (NSE) and Kling-Gupta Efficiency (KGE) for water storage and hydropower production for the five reservoirs modelled, except the Cantareira System because it does not produce hydropower.

Reservoirs	Storage		Hydropower	
	NSE	KGE	NSE	KGE
Jaguari	0.99	0.98	0.96	0.94
Paraibuna	0.99	0.99	0.96	0.88
Santa Branca	0.98	0.96	0.91	0.87
Funil	0.89	0.92	0.93	0.93
Cantareira	0.99	0.99	-	-

Firstly, Scenario 1 met the main goal from the upstream state (Sao Paulo) because it would be possible to prevent the Cantareira System from reaching the dead pool level due to the transfers from the Jaguari reservoir. Figure 4.6 shows that the minimum level of the Cantareira System would be about 14%, while no substantial differences are observed in the other PbSRB reservoirs. This is because of the operation rules, which work to offset the reduced inflow to also reduce the outflows. The effect of the outflows' reduction is presented in Figure 4.7. While the Paraibuna and Santa Branca reservoirs would not be affected because they are not interconnected to the Jaguari reservoir, the Jaguari and Funil reservoirs would have reduced outflow, then less hydropower would be produced, and less water would be available to the downstream state (Rio de Janeiro).

On the contrary, given Scenario 2, the plots in Figure 4.8 and Figure 4.9 show that the upstream demand for more water would not be fully met and the downstream consumers would observe some reduction on the water released by the Funil reservoir. In this scenario, no transfer is observed, therefore the changes happen because of minimum rules for storage and releases to meet environmental demands of water quality and quantity. Therefore, the Cantareira System would still operate below the dead pool level, while the Santa Branca and Funil reservoirs would operate at a greater level than the observed storage between 2014 and 2016. Additionally, keeping the Santa Branca reservoir filled would have a positive effect for hydroelectricity after 2014, while the Funil reservoir observed 4 major drops in hydropower production because the minimum level was reached, therefore the outflow dropped to the minimum releases.

Finally, given the hypothetical Scenario 3, where transfers from the PbSRB to the Cantareira System would happen simultaneously with the updated operation rules, which would ensure minimum storage and minimum outflows: i) the Cantareira System would not reach the dead pool level, ii) the Funil and Santa Branca storage would be greater during the drought, but iii) both hydropower and water availability downstream would be significantly reduced. The largest outflow reductions observed downstream would be in 2008 (-13,80m^3/s) and 2014 (-13,67m^3/s). In parallel, the largest hydropower reduction would be -6.5% and -28.9% in 2008 for Funil and Jaguari, respectively, and -7.2% and -17.7% in 2014 for Funil and Jaguari, respectively.

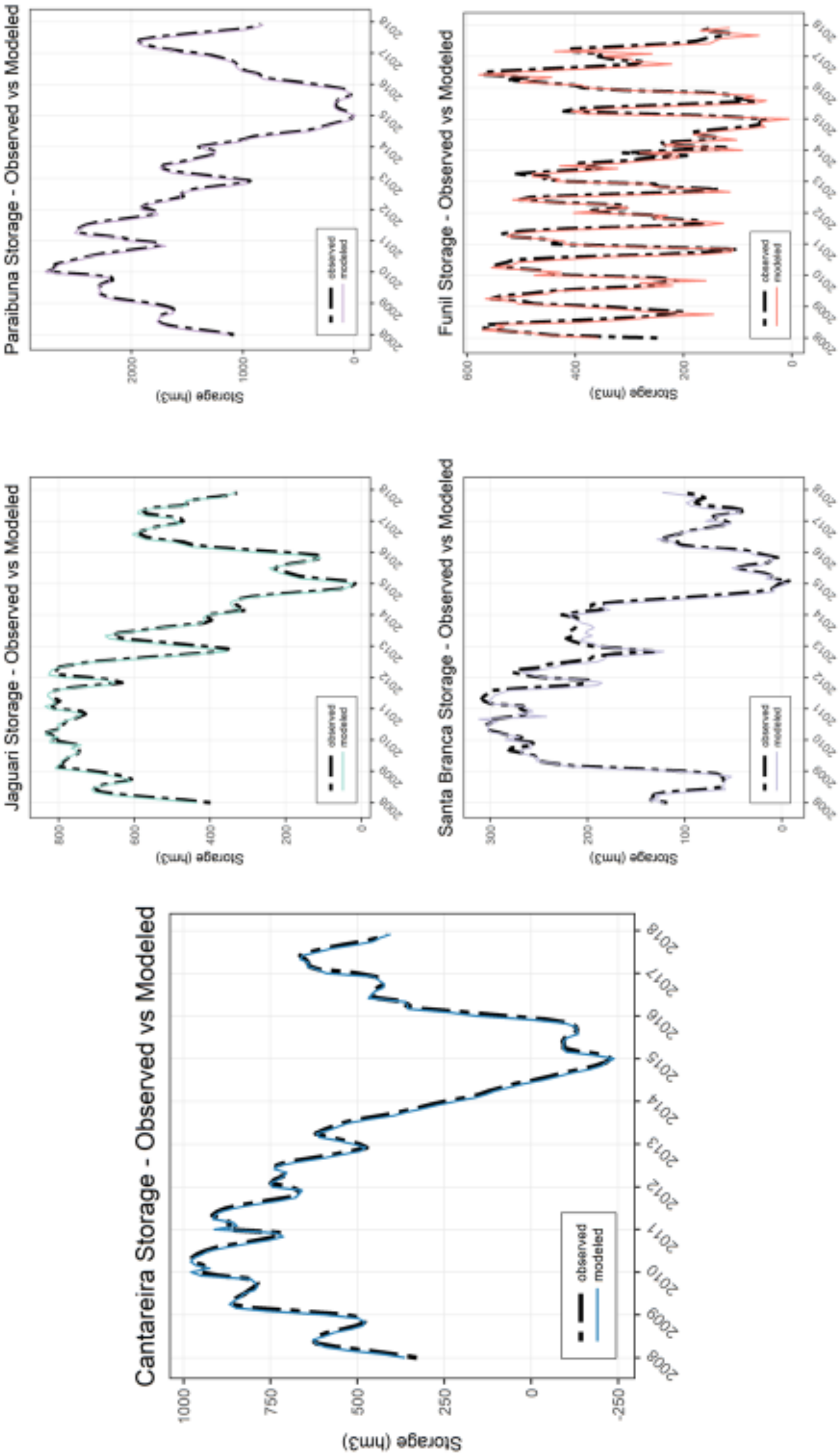

Figure 4.4: The figure compares the historical records and the model output of water storage within the Paraiba do Sul reservoirs and the Cantareira System, where the dashed lines are the actual storages and the solid lines are the modelled storage.

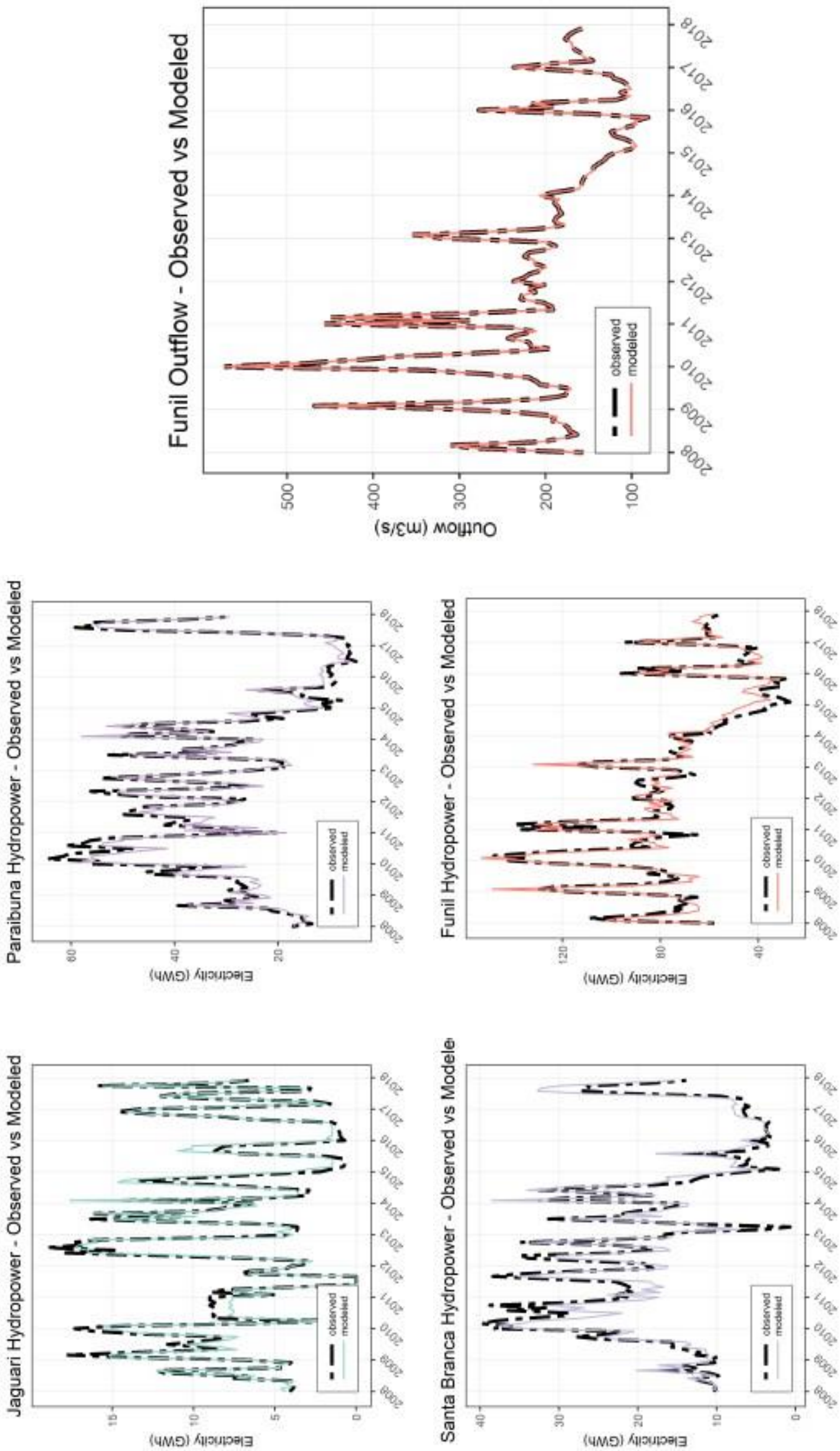

Figure 4.5: The figure compares the historical records and the model output of hydropower generated within the Paraiba do Sul dams and the outflow released by the Funil reservoir, where the dashed lines are the observed data and the solid lines are the modelled data.

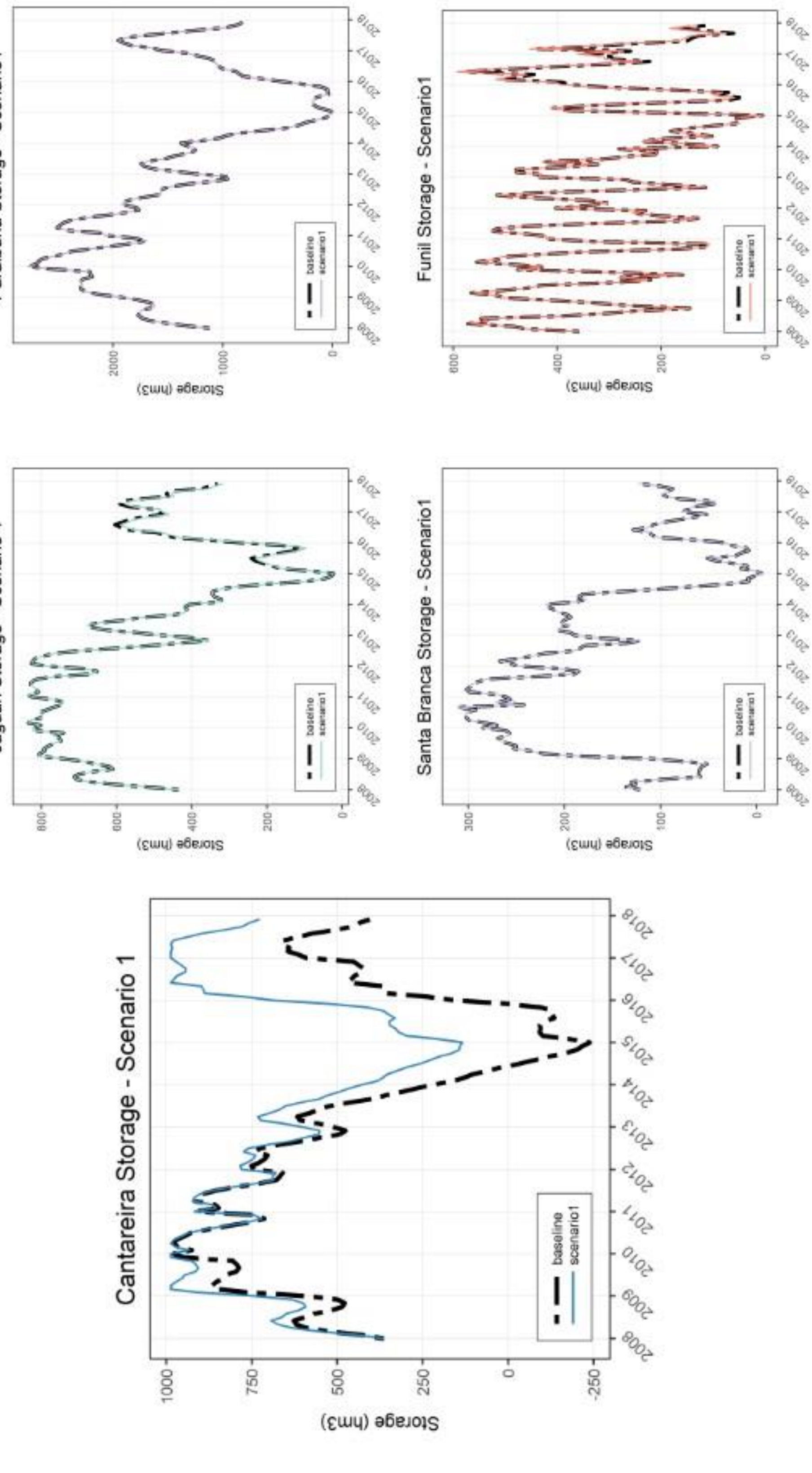

Figure 4.6: The figure compares the baseline and the Scenario 1 output of water storage within the Paraiba do Sul reservoirs and the Cantareira System, where the dashed lines are the baseline that was previous modelled and the solid lines are the scenario outcomes.

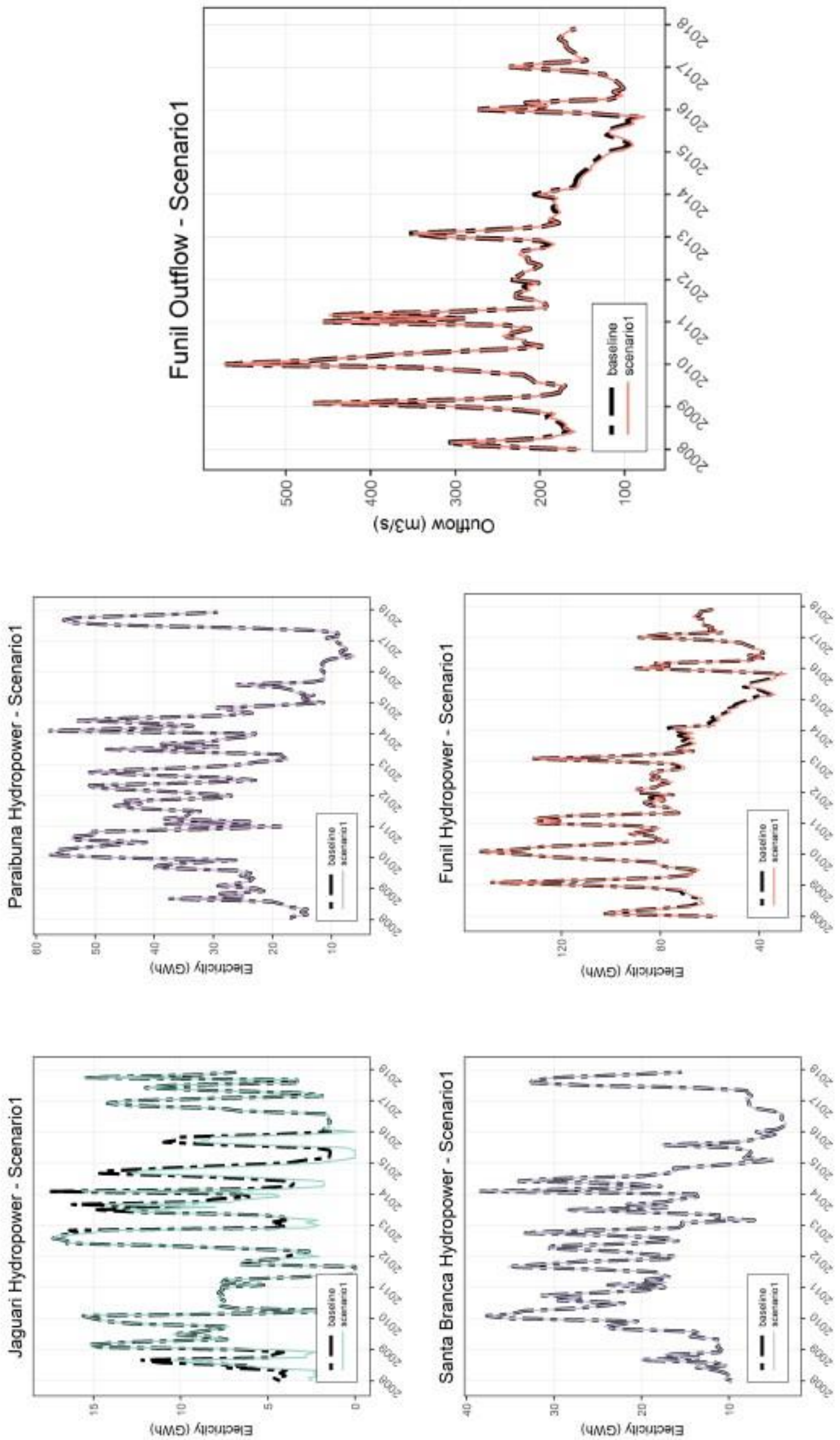

Figure 4.7: The figure compares the baseline and Scenario 1 output of hydropower generated within the Paraiba do Sul dams and the outflow released by the Funil reservoir, where the dashed lines are the baseline that was previous modelled and the solid lines are scenario outcomes.

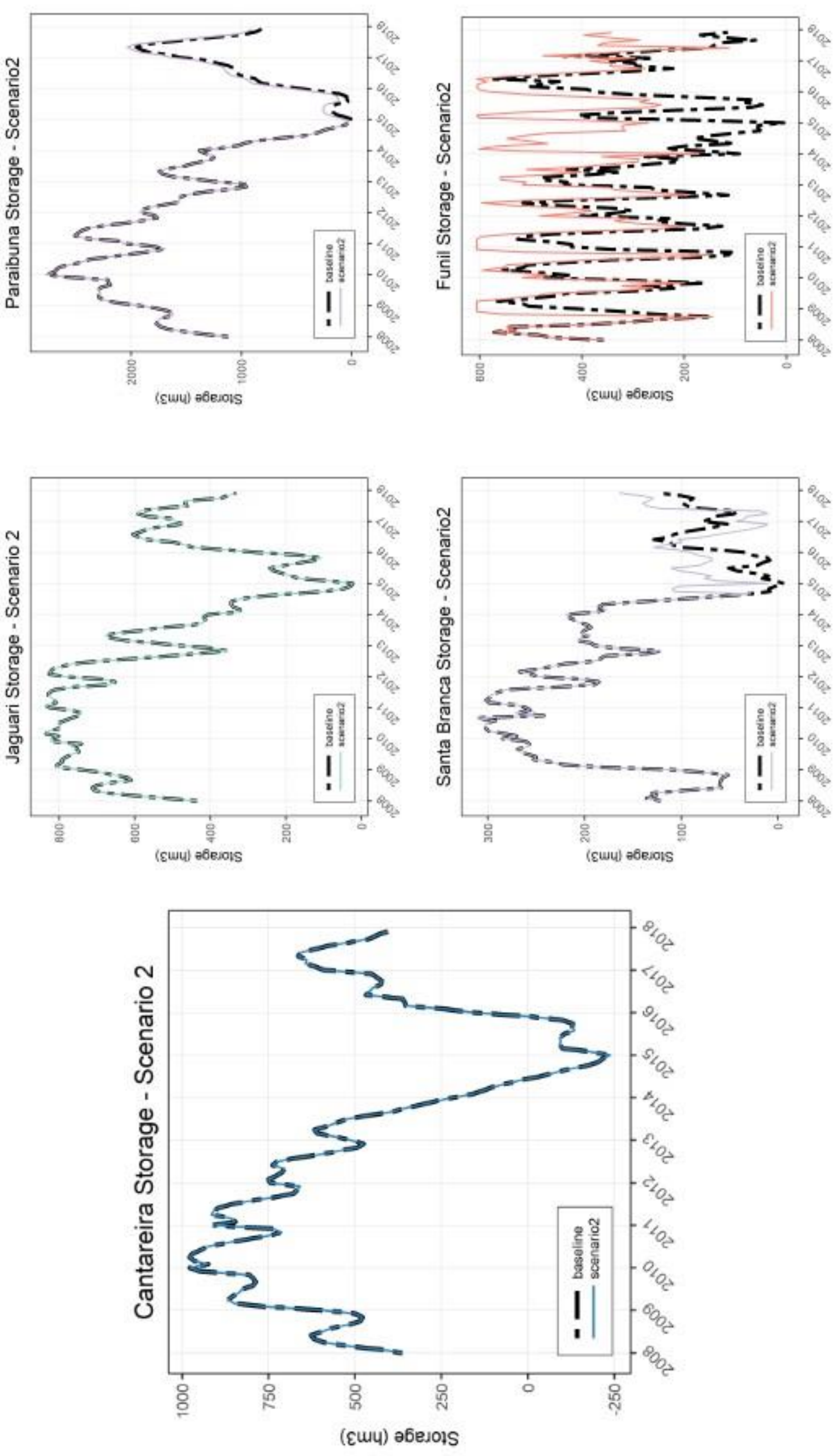

Figure 4.8: The figure compares the baseline and Scenario 2 output of water storage within the Paraiba do Sul reservoirs and the Cantareira System, where the dashed lines are the baseline that was previous modelled while the solid lines are the scenario outcomes.

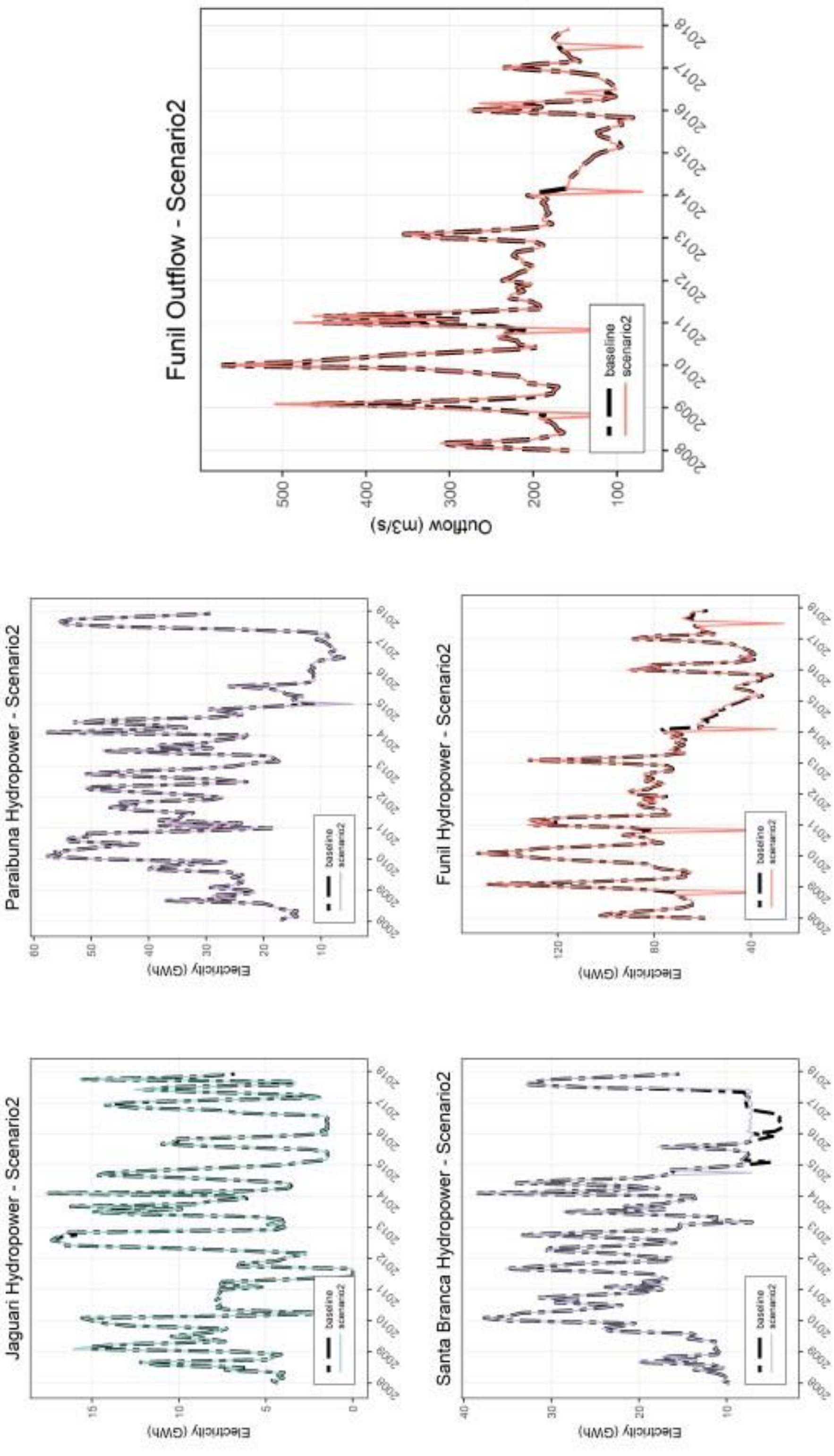

Figure 4.9: The figure compares the baseline and Scenario 2 output of hydropower generated within the Paraiba do Sul dams and the outflow released by the Funil reservoir, where the dashed lines are the baseline that was previous modelled and the solid lines are scenario outcomes.

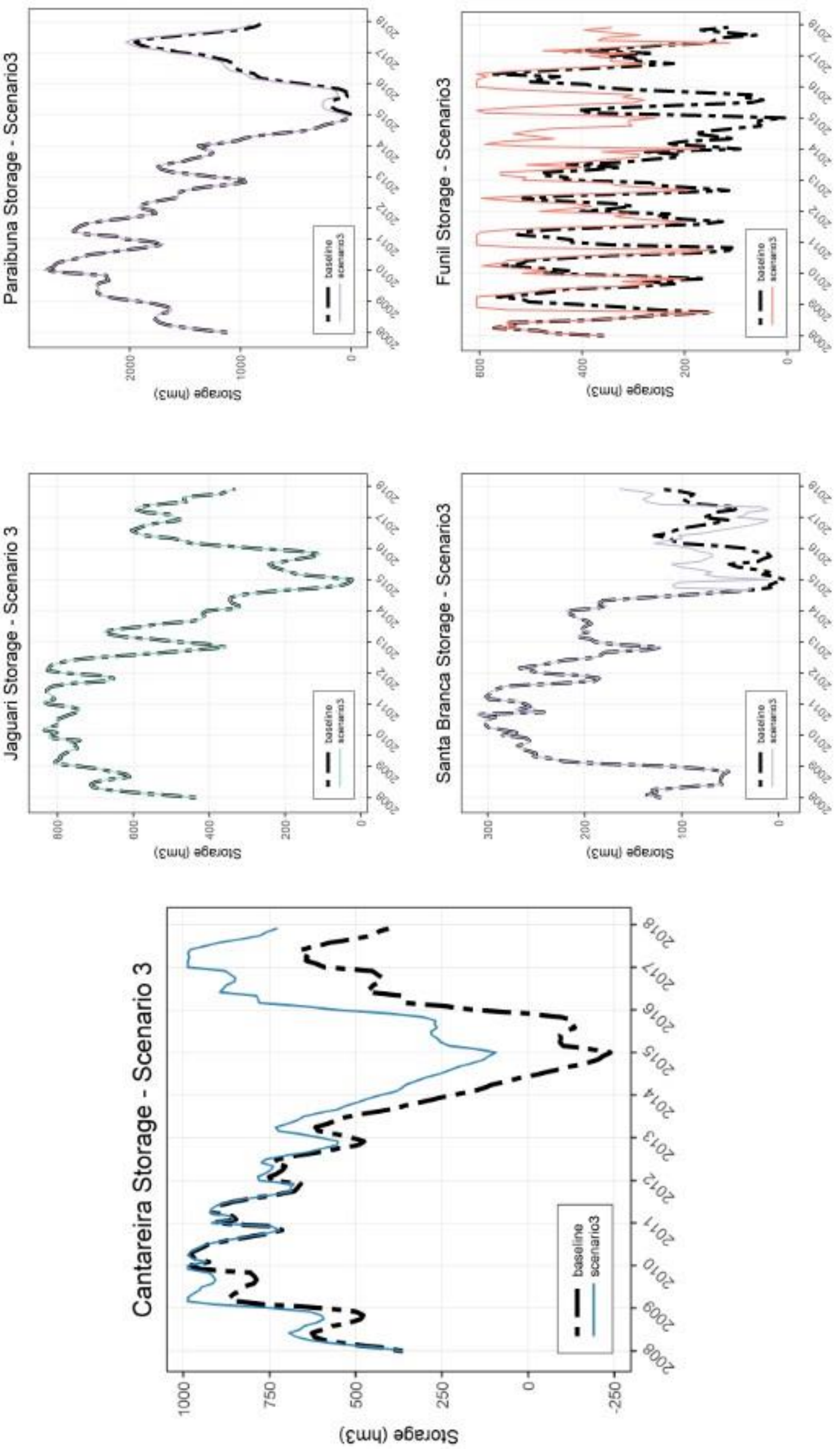

Figure 4.10: The figure compares the baseline and Scenario 3 output of water storage within the Paraiba do Sul reservoirs and the Cantareira System, where the dashed lines are the baseline that was previous modelled and the solid lines are the scenario outcomes.

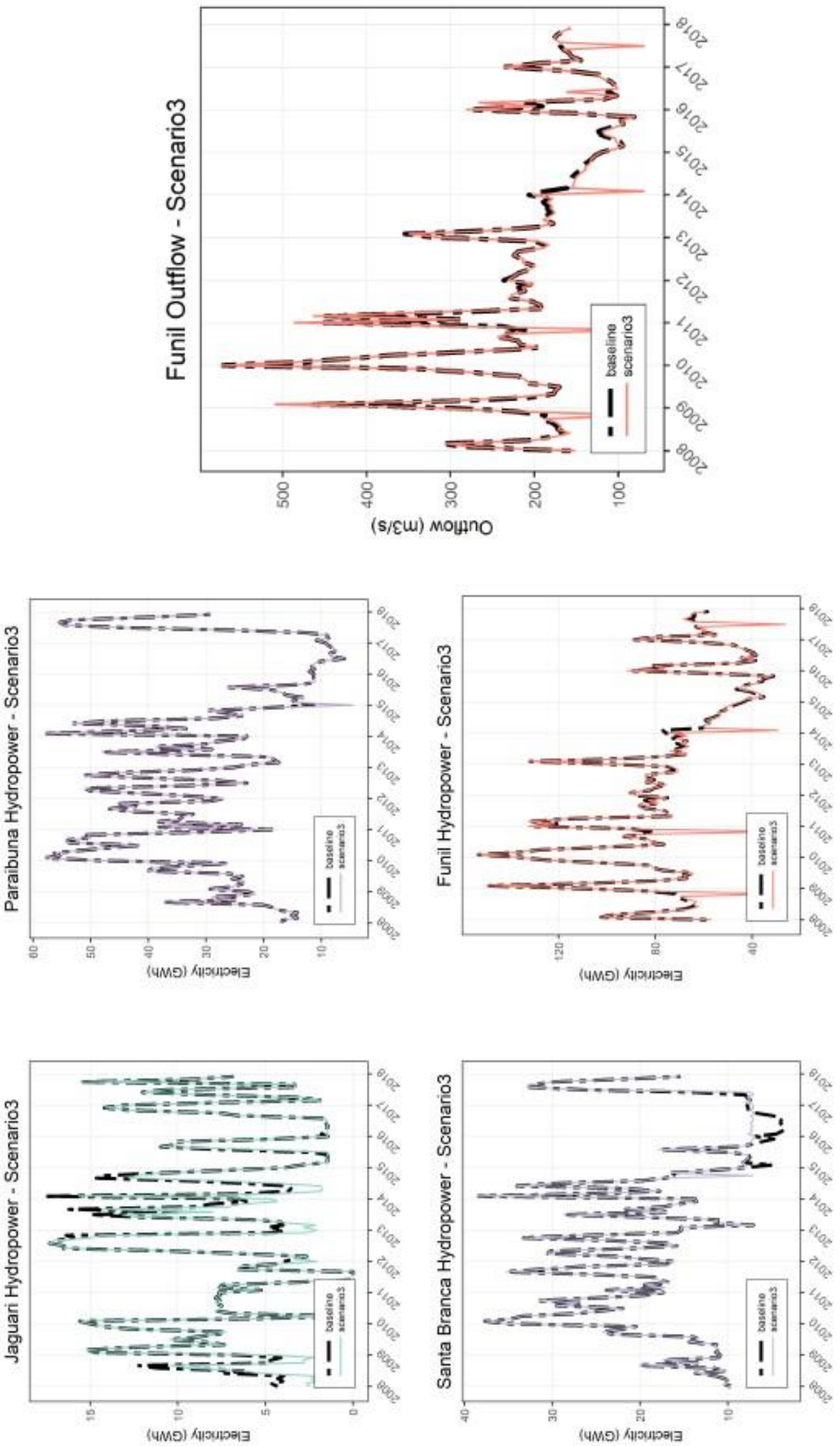

Figure 4.11: The figure compares the baseline and Scenario 3 output of hydropower generated within the Paraiba do Sul dams and the outflow released by the Funil reservoir, where the dashed lines are the baseline that was previous modelled and the solid lines are scenario outcomes.

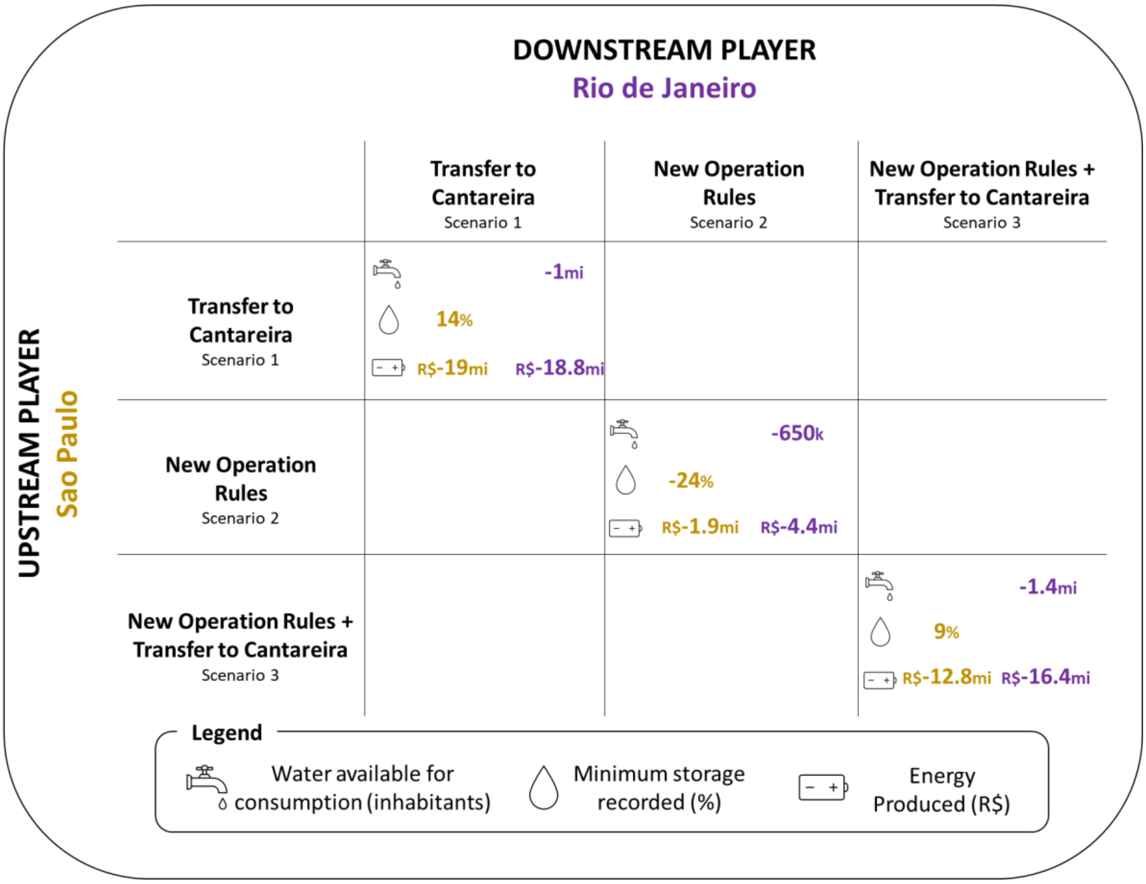

Figure 4.12: Presents the payoff matrix, which compares the corresponding impacts for each player as a result of each scenario simulated, on the basis of the baseline resulted from the model.

4.4 DISCUSSION

All the simulations above aimed at fulfilling the payoff matrix of this game played between the upstream and the downstream Brazilian States. The payoff matrices aggregate the outcomes for all players involved. Therefore, Figure 4.12 summarizes the outcomes for both players regarding the minimum water stored within the Cantareira System available for the upstream consumers, the variation of water released to the downstream consumers and the changes on hydroelectricity produced by the PbSRB reservoirs located in Sao Paulo (Paraibuna, Santa Branca and Jaguari) and in Rio de Janeiro (Funil).

The dimensions of some variables were changed to assist the decision-making process. The water released by the PbSRB was converted to the number of inhabitants that could be supplied, while the energy produced was measured in Brazilian currency (BRL). The first was calculated by assuming the amount of people that could be supplied, considering 200 liters per day as the average consumption of a person and a leakage loss of 50% (Souza et al, 2019). The second unit was estimated by multiplying the difference of hydropower production by the average energy tariff between 2013 and 2015 (EPE, 2016).

Although there are drawbacks for both players in every scenario, the upstream player would meet its main goal in scenarios 1 and 3. However, in terms of household supply, the downstream player would be less penalized in scenario 1, while in terms of electricity Rio de Janeiro would be less penalized in scenario 2. These insights might be used for the next negotiation among the stakeholders. For example, with the information that withdrawals from the Jaguari reservoir (PbSRB) might endanger the supply of 1 million people, the downstream state could request a financial compensation from the upstream player to build the necessary infrastructure to provide the equivalent resource.

Similarly, the reduced hydropower indirectly affects the finances of local state governments through the taxes paid by the private companies in charge of each hydropower plant. For instance, when the energy utilities do not produce the assured hydroelectricity, the contracts might require them to provide the energy from other sources that are usually more expensive than the energy produced by hydropower plants. Therefore, the payoff matrix also supports the private companies either located upstream or downstream to request the losses resulted from the allocations and/or updates operation rules.

It is important to remember that the matrix in Figure 4.12 considers the payoffs for the similar conditions observed during the 2013-2015 drought. Although historical time series suggest that the recurrence of such an event would be hard to happen again, the rapid changes in climatic variables, such as rainfall and temperature, has shifted to non-stationary condition. Therefore, extreme events such as droughts and floods are more likely to happen. Therefore, the payoff matrix would not represent an unusual game, but a forthcoming game instead.

International examples have demonstrated a higher influence of upstream players because their geographical position. However, such benefit should not be used for their own concerns when cooperation between neighbors is desired (Lu et al, 2021; Wei et al, 2022). Not only because São Paulo and Rio de Janeiro States are subjected to the federal governance, but because they host a large amount of inhabitants, both players should seek solutions that bring benefits for both sides, even if a given strategy does not bring the best payoff for the individual player.

Since the model, developed for the purpose of this study, used simple equations to reproduce the water balance in reservoirs, the generation of hydropower and the alternative scenarios of operation rules, there are a few limitations implied. The first consideration regards the lack of evaporation data. The historic hydrological records of the Paraiba do Sul River Basin reservoirs embedded the evaporation of inflow, outflow, and storage variables. A more in-depth study could better investigate the evaporation rate of each reservoir to disaggregate the result of this process from the other hydrological variables. Because several reservoirs are involved in the model and the period simulated comprises very low water storage with reduced surface area in reservoirs, the accuracy gained on the evaporation modeled would not overcome the uncertainty associated to multiple reservoirs' evaporation and the conclusions presented in the payoff matrix would not change.

The other limitation concerns scenarios 1 and 3, when the Cantareira reservoir could have more water available and prevent it from reaching the dead pool level. If this actually happened, the drought management in the Sao Paulo Metropolitan Region could be different and more water could have been withdrawn from the Cantareira if it was available at that time. Given that the abstractions were reduced after 2013, other alternative scenarios 1 and 3 are plotted in Figure 4.13. Those two scenarios assume that water consumption had not been affected by the water saving policies after 2013, and therefore the alternative withdrawals would be the average between 2013 and 2014. Thus, Figure 4.13 illustrates the respective withdrawals and the comparison between the baseline and the simulated scenarios 1 and 3 considering the actual and alternative abstractions. The conclusion is that allocating water from the Paraiba do Sul River Basin would alleviate the pressure for Cantareira's water, but it would still require water saving policies in the Sao Paulo Metropolitan Region.

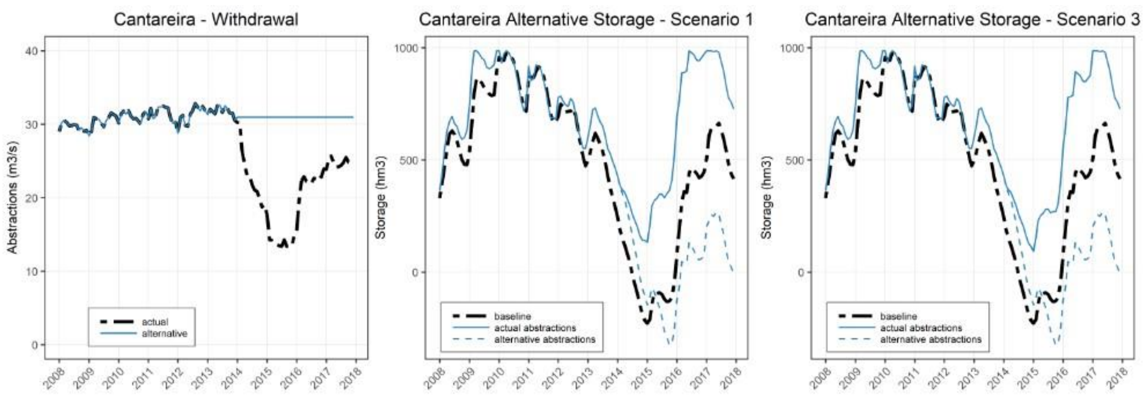

Figure 4.13: Alternative abstractions from the Cantareira System.

Despite the fact that the model and conclusions drawn from this study regards the extreme scenario similar to that observed between 2013 and 2015, the model can also be used for prediction purposes. For instance, the climate change literature provides a variety of models and scenarios from short to very long scenarios. Thus, it would be possible to estimate the recurrence of such extreme drought scenario over the next decades to draw the corresponding payoff matrix. This would not only support downstream and upstream states to guide their public policies, but it would also support the private sector of hydropower generation to improve their strategic planning.

4.5 CONCLUSION

Two players were clearly defined in this chapter; upstream it is São Paulo state, whose major goal was to allocate more water from the Paraiba do Sul River Basin, and downstream it is Rio Janeiro, whose consequences from the upstream goal, combined with the operation rules updated after the last drought, would represent drawbacks during the 2013-2015 water crisis. In fact, human water consumption is not the only benefit that communities gain from rivers, but also other economic and environmental benefits, as presented in the model. Thus, the model reproduces the consequences of a paradigm shift on the water use preferences. The three scenarios combine two new preferences resulted by the shock caused by the drought: supply the urban demand upstream and the maintenance of minimum storage and river flow downstream of the reservoirs.

The simulations showed that it would be possible to meet both preferences, but the costs associated would negatively affect the hydropower generation in reservoirs located upstream and downstream the basin. Additionally, the water availability downstream would compromise more than 1 million urban consumers during 2013-2015. These two drawbacks can be appropriate managed by the stakeholders guided by the payoff matrix developed in this study. Given the decision made, the matrix presents the consequences for both sides of the basin, so they can better plan the allocation of economic resources and develop the necessary infrastructure to cover the losses expected.

Finally, the allocation of water from the Paraiba do Sul River Basin to the Cantareira System would prevent the reservoirs from reaching the dead pool level only if the abstractions, after 2013, had remained reduced. Therefore, the transfers would partially solve the water availability problem in Sao Paulo Metropolitan Region because water savings would still be necessary.

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5 GENERAL CONCLUSION

Every chapter of this thesis followed different methodologies to answer the hypothesis that early interventions could have prevented the water crisis observed in the São Paulo Metropolitan Region between 2013 and 2015.

The first objective was to better understand how the urban water supply facilities work, evaluate the conduction of the water crisis and assess how the drought risk management has evolved over time in São Paulo. Therefore, **chapter two** shed light on the spatial dependency of several reservoirs in São Paulo. While the entire region was concerned on the storage level of the Cantareira in 2015, a few service areas were indeed at risk of rationing because they relied in this single water source. A similar analysis provided in this chapter showed that between 1985 and 1986, one reservoir was at risk of emptiness, what led to rationing of the service areas supplied by this reservoir. Therefore, because of the large water demand, several reservoirs are responsible for delivering water to the SPMR and, in case one of them might be at risk of emptiness, it does not mean the water utility will fail to supply water to all citizens, but those consumers who are exclusively dependent on that single reservoir might be at risk. In addition, chapter two also concluded that much has evolved in terms of infrastructure and forecasting between 1985 and 2015. However, the severity and duration of the later event was crucial to deepen the drought crisis. Lastly, chapter two raised the concerns of other authors that early action could have prevented the crisis, this point was further explored in the next chapter.

Given the hypothesis that early action could be effective to tackle the Cantareira drought, the demand-side policies were investigated in **chapter three**. Besides the assessment of what policy was the most effective, the methodology proposed in this chapter provided an evaluation of water conservation awareness at the service area level. This means that the observed water use reduction was not evaluated at its average, but at a distributed resolution. Such method not only evaluated what would be the impact on the water security context, but also assessed the key drivers that led consumers to change their patterns of consumption through machine learning methods. The XGBoost model and the logistic regression revealed that the contingency tariffs were more correlated than the bonus tariff on promoting the conservation awareness. Additionally, the water level at the Cantareira system presented strong relevance in predicting whether a region would reduce its own water use. Because citizens are only informed about the concerns regarding the water availability through communication campaigns and media coverage, these two agents are expected to play an important role in raising drought awareness. However, the outputs of the socio-hydrological model showed that the early implementation of such policies would only be effective if they had been implemented two years advance. Given the fact that the Cantareira level at that time was about half of its capacity, decision makers would not be willing to implement unpopular tariffs with large anticipation. Thus, another possibility could be managing the supply-side.

The results presented in **chapter four** show what would be the implications of water transferred from the Paraiba do Sul River Basin to the Cantareira System. First, if the tunnel, which connects the Jaguari reservoir (at the Pb do Sul River Basin) to the Atibainha reservoir (at the Cantareira System) was completed at that time, the Cantareira System could not have reached de dead pool storage as well as minimum environmental flows and storages at the PB do Sul River Basin could be met at the same time. However, the hydropower production would have reduced, representing about 20million BRLs of losses for São Paulo and Rio de Janeiro states. Additionally, the water transferred to the Cantareira System would be equivalent to the amount of water used to supply about one million citizens from the Rio de Janeiro state. Since the tunnel is already completed at the time of this publication, we understand that both upstream and downstream states are aware about those implications. One possible explanation is that preferences have shifted, and therefore, ensuring the demand attendance of upstream households and respecting environmental concerns is the main priority of authorities.

Finally, the previous three chapters show that the early implementation of drought measures could have prevented the Cantareira System from reaching the dead storage level. Of course, there would be collateral effects, for example less acceptance of public opinion regarding the long duration of pricing policies, or even economic losses for allocating water from transboundary basins. In addition, this important to note that the São Paulo Metropolitan Region is a megacity that requires mega solutions as well. Decision makers could also explore the possibility of interconnecting all water sources to prevent, in future droughts, that a service area relies in a single reservoir.

5.1 RECOMMENDATIONS FOR FUTURE WORKS

To the best of the authors' knowledge, this work is the one of the first researches that have addressed the water supply system of the São Paulo Metropolitan Region using a socio-hydrological approach. Thus, the following aspects could be further explored in future works that aim at exploring the same case study or other urban water supply systems.

a) Further analysis could investigate unintended consequences of the measures proposes in this work, for instance, the supply-demand cycle and the safe development paradox phenomenon , which state that keeping the Cantareira reservoirs full would have increased water consumption and might have increased communities vulnerability.

b) Future studies can reproduce the same methodologies presented in this work to consolidate a theoretical background on how to cope with drought risk in mega cities. A similar effort was presented by Kreibich et al (2022), where some researchers have grouped paired events of droughts and floods at different locations around the world.

c) The hydrological models presented in chapter three and four considered the evaporation is the reservoirs constant because the surface area was very reduced since the reservoirs were almost dry. Thus, future research should better address this component to improve uncertainties around the water availability within the Cantareira System.

d) The model presented in chapter three reproduced the same conditions of the pricing policies at the time of the water crisis to evaluate how the water users would change their own behavior. However, it was not explored if different tariffs could have resulted in other behaviors. Therefore, next studies can address the role of price elasticity of water conservation tariffs in times of extreme drought.

e) The withdrawals presented in Figure 1.4 show that it decreased during the water crisis, but it increased again when the effects of the crise were over. Therefore, it is expected that some service areas have maintained the conservation behavior even after the drought, while others have note. Future works can explore what are those areas, what are the variables that drive to this behavior and how this affects future conservation policies.

f) The scenarios built in this chapter reproduced alternative storylines considering the same conditions of the 2013-2015 drought because it was the most severe observed so far. However, there are plenty of evidence that climate is rapidly changing all over the world, including São Paulo. Therefore, future studies can address how the water conservation policies and the operation rules of the Paraiba do Sul River Basin will affect the consumers' demand.

APPENDIX A

This document presents the description about equations and assumptions regarding the data presented in the manuscript Droughts in São Paulo: Challenges and Lessons for A Water-Adaptive Society (Souza et al, 2022).

5.2 Water Availability per capita

This variable is the total water stored per capita in the reservoirs, available in time t, to supply the São Paulo Metropolitan Region.

$$WA_{TWS(t)} = \frac{WA_{(t)} \cdot 10^6 \cdot 10^3}{Pop_{(t)} \cdot 10^6}$$

Where:

$WA_{TWS(t)}$: Water availability, according to TWS framework, at month t (L·person^{-1}·day^{-1})

$WA_{(t)}$: Daily Average of water stored in reservoirs at month t (hm^3)

$Pop_{(t)}$: Population in SPMR at month t (Million person)

5.3 RUNOFF

5.3.1 SCS Method

$$R_{(t)} = \frac{\left(P_{(t)} - I\right)^2}{P_{(t)} - I - S}$$

$$S = \frac{25400}{CN} - 100$$

$$I = 0.20 \cdot S$$

Where:

$R_{(t)}$: runoff at month t (mm·month^{-1})

$P_{(t)}$: rainfall at month t (mm·month^{-1})

S: potential maximum retention after runoff begins

I: initial abstractions

5.3.2 Parameters

P_t: Precipitation series from IAG station

CN: was calculated according to Pedology of São Paulo State (Rossi, 2017), Brazilian soils classification (Sartori, 2004) and CN tables (USDA, 1986). The CN numbers were determined according to the soil type for Woods-grass cover type (table 2-2). The final CN, equal to 71, was determined by the weighted average from the table below.

PEDOLOGY	ÁREA (km^2)	SOIL CLASSIFICATION	CN
Área Urbana	2168,68	-	98
Afloramento rochoso	0,12	D	79
Argissolos	1476,82	B	58
Cambissolos	2273,73	C	72
Gleissolos	126,33	D	79
Latossolos	1379,05	A	32
Neossolos	46,18	D	79
Organossolos	256,19	D	79
Plintossolos	0,18	D	79
Rios, represas e lagoas	218,79	-	100

5.4 WATER CONSUMPTION

5.4.1 Individual water consumption

Annual series of total water produced were retrieved from SNIS for all 39 municipalities from São Paulo Metropolitan Region. Although the records available corresponds to annual water production between 1995 and 2019, there are many missing records for most municipalities prior to 2000.

Individual water consumption was determined following the equation:

$$WC_{ind} = \frac{WP \cdot 10^3 \cdot 10^3}{365 \cdot Pop}$$

Where:

WC_{ind}: Individual water consumption (L·person^{-1}·day^{-1})

WP: Annual water produced, according to SNIS (1000 m^3·year^{-1})

Pop: Official number of inhabitants within São Paulo Metropolitan Region

5.4.2 Imputation before 1995

Since SNIS provides time series after 1995, it is required to replace missing data in order to perform the water balance. Individual water consumption was assumed as the mean of historical series recorded between 1995 and 2019. In addition, the confidence interval was determined as follows.

$$WC_{ind_{CI}} = \overline{WC_{ind}} \pm Z \frac{S_{WC_{ind}}}{\sqrt{n}}$$

$$WC_{ind_{CI}} = 280.07 \pm 2.95$$

Where:

$WC_{ind_{CI}}$: Confidence interval of individual water consumption (L·person^{-1}·day^{-1})

$\overline{WC_{ind}}$: Mean of individual water consumption (L·person^{-1}·day^{-1})

$S_{WC_{ind}}$: Standard deviation of individual water consumption (L·person^{-1}·day^{-1})

n: Time series length

Z: coefficient of normal statistics at 95% confidence rate

5.5 WASTEWATER PRODUCTION

5.5.1 Return rate of wastewater

Annual series of total wastewater produced were retrieved from SNIS for all 39 municipalities from São Paulo Metropolitan Region. Although the records available corresponds to annual wastewater production between 1997 and 2019, there are many missing records for most municipalities prior to 1998.

Return rate of wastewater was determined as follows.

$$WWP_{ind} = \frac{WWP \cdot 10^3 \cdot 10^3}{365 * Pop}$$

$$RR = \frac{WWC_{ind}}{WC_{ind}}$$

Where:

WC_{ind}: Individual water consumption (L·person^{-1}·day^{-1})

WP: Annual water produced, according to SNIS (1000 m^3·year^{-1})

Pop: Official number of inhabitants within São Paulo Metropolitan Region

WWC_{ind}: Individual wastewater collected (L·person^{-1}·day^{-1})

WWP: Annual wastewater collected, according to SNIS (1000 m^3·year^{-1})

RR: Return rate of water consumed

5.5.2 Imputation before 1998

Since SNIS provides complete time series after 1998, it is required to replace missing data in order to perform the water balance. Return rate was assumed as the mean of historical series recorded between 1998 and 2019. In addition, the confidence interval was determined as follows.

$$RR_{CI} = \overline{RR} \pm Z \frac{S_{RR}}{\sqrt{n}}$$

$$WC_{ind_{CI}} = 0.463 \pm 0.001$$

Where:

RR_{CI}: Confidence interval of return rate

RR: Mean of return rate

S_{RR}: Standard deviation of return rate

n: Time series length

Z: coefficient of normal statistics at 95% confidence rate

5.6 REFERENCES

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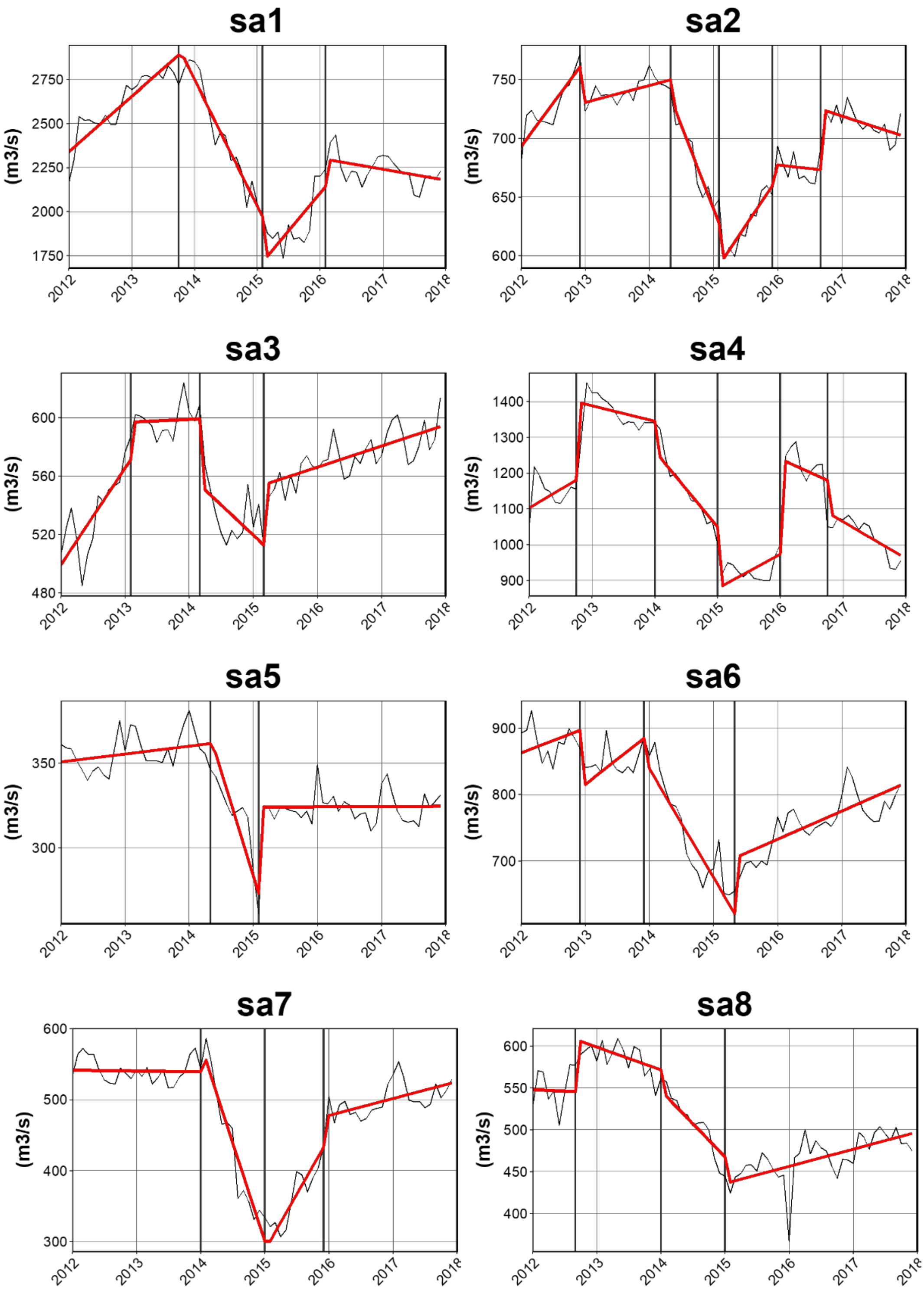
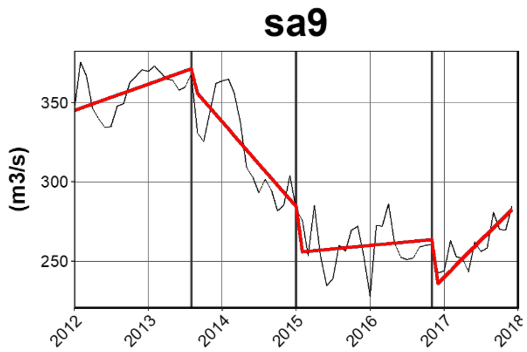
APPENDIX B

The following graphics represent the equivalent water consumption of the service areas created within the scope of chapter three.

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300
250
(m3/s)
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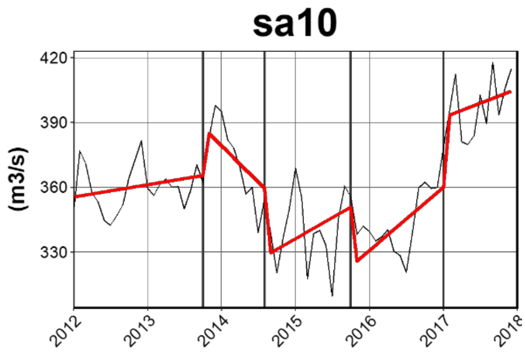
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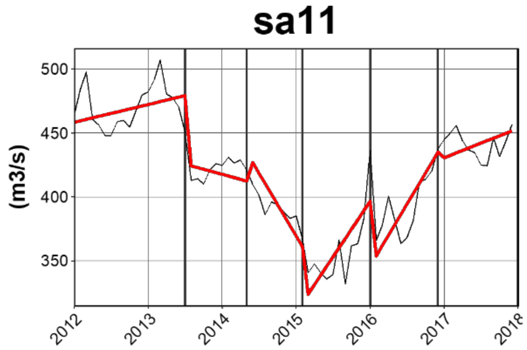
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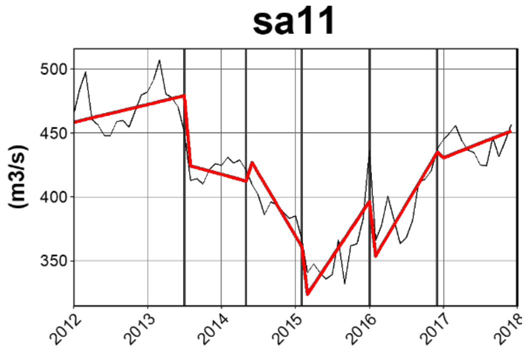
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(m3/s)
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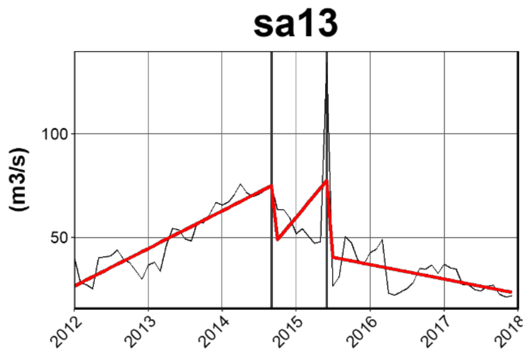
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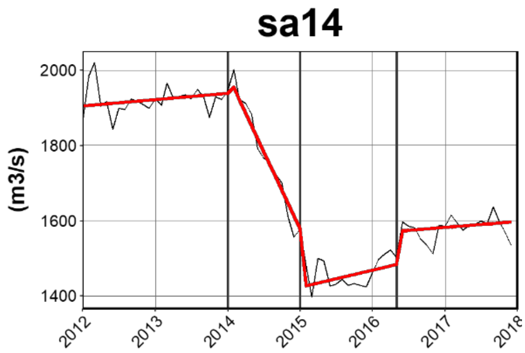
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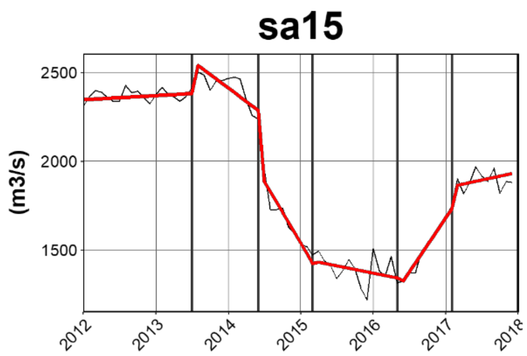
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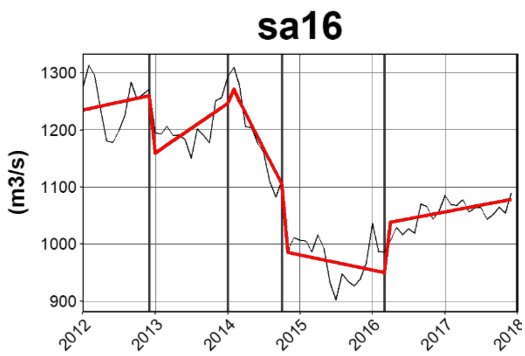
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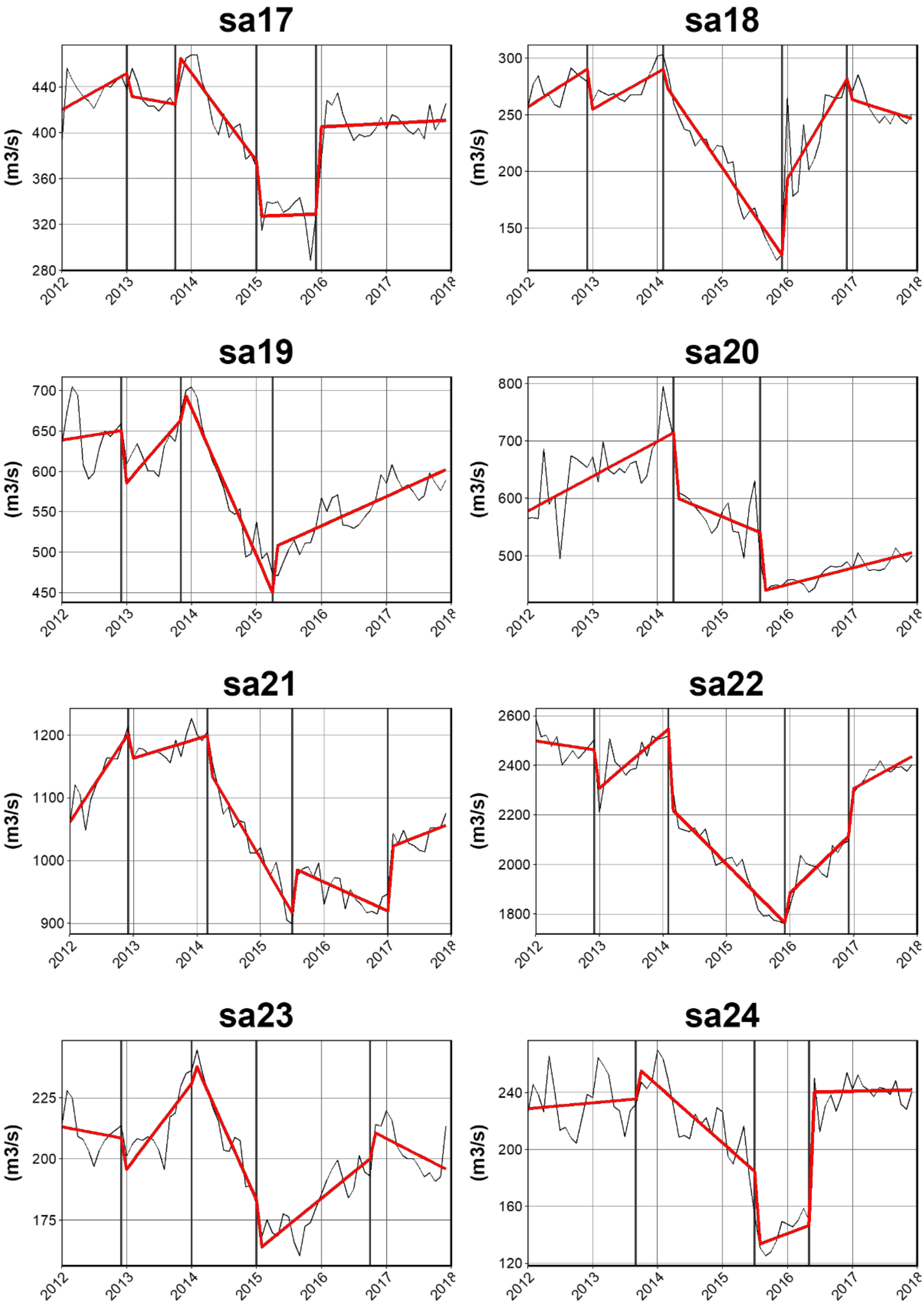
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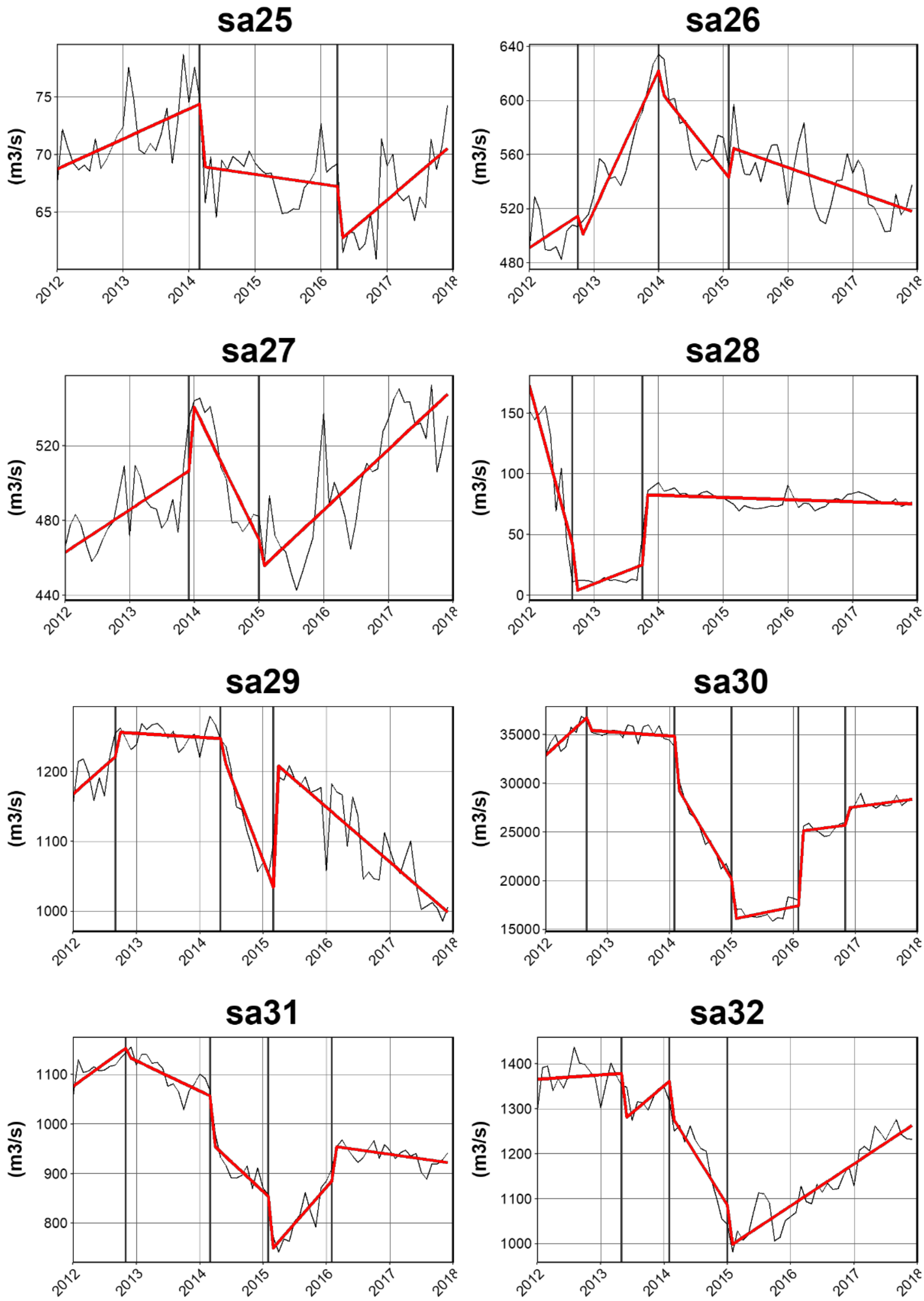
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(m3/s)
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2016
2017
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480
(m3/s)
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520
480
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(m3/s)
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50
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1000
(m3/s)
sa30
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20000
15000
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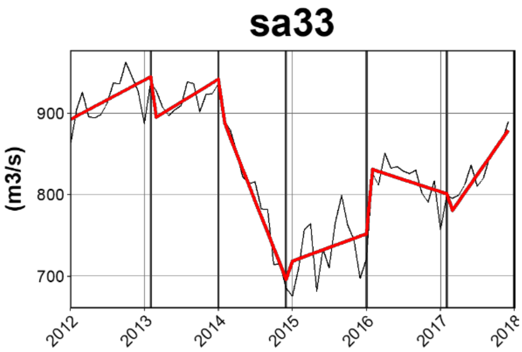
(m3/s)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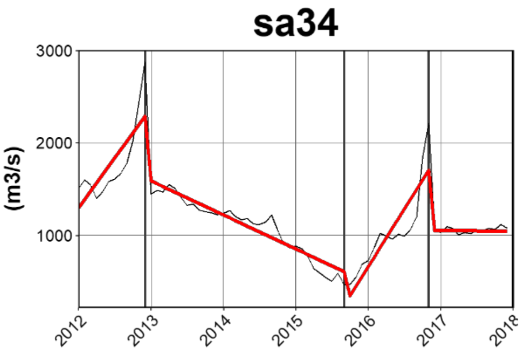
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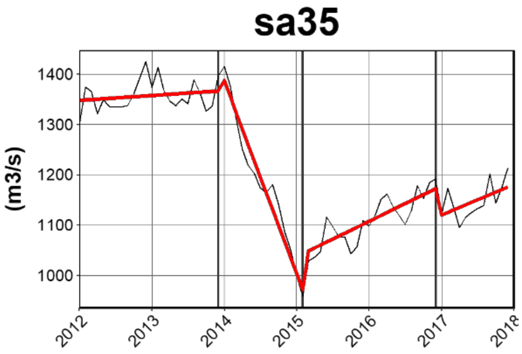
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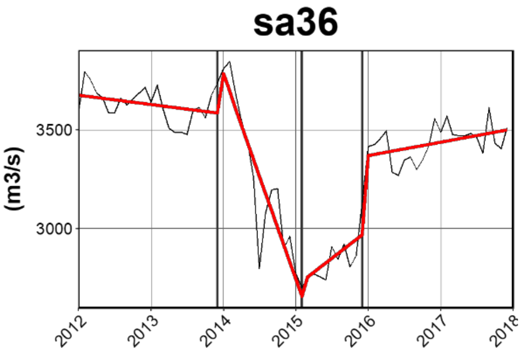
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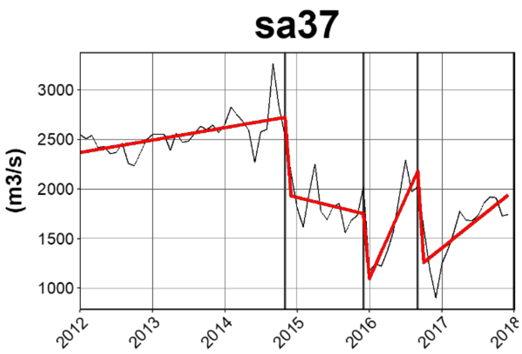
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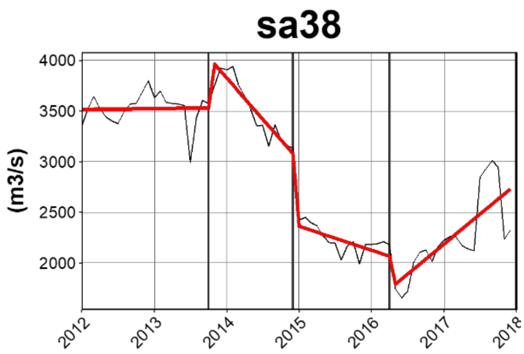
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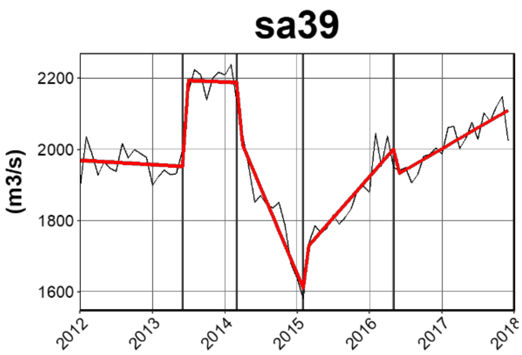
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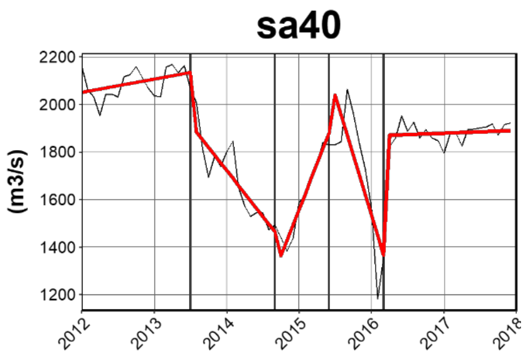
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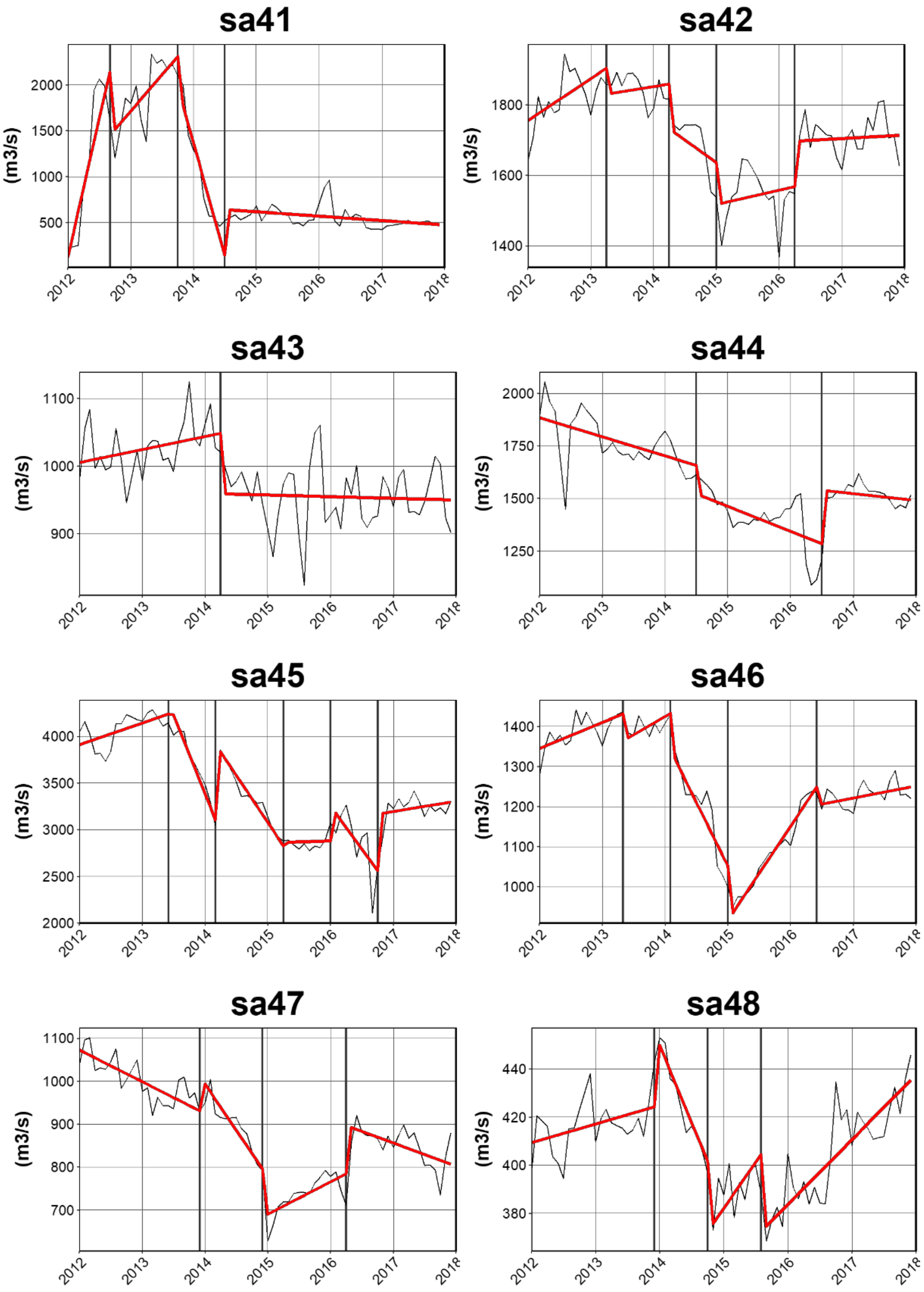
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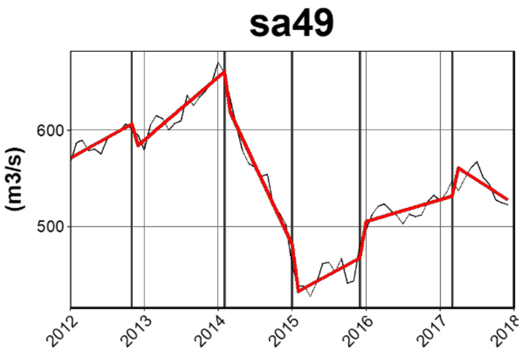
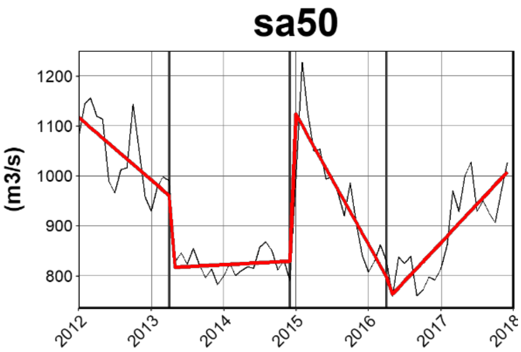
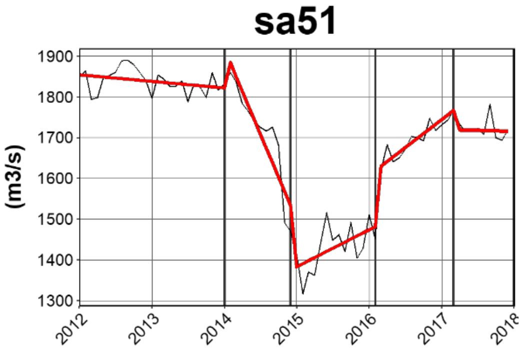
sa43
(m3/s)
1100
1000
900
2012 2013 2014 2015 2016 2017 201
sa44
(m3/s)
2000
1750
1500
1250
2012 2013 2014 2015 2016 2017 201
sa45
(m3/s)
4000
3500
3000
2500
2000
2012 2013 2014 2015 2016 2017 201
sa46
(m3/s)
1400
1300
1200
1100
1000
2012 2013 2014 2015 2016 2017 201
sa47
(m3/s)
1100
1000
900
800
700
2012 2013 2014 2015 2016 2017 201
sa48
(m3/s)
440
420
400
380
2012 2013 2014 2015 2016 2017 201


sa49
(m3/s)
600
500
2012
2013
2014
2015
2016
2017
2018


sa50
(m3/s)
1200
1100
1000
900
800
2012
2013
2014
2015
2016
2017
2018


sa51
(m3/s)
1900
1800
1700
1600
1500
1400
1300
2012
2013
2014
2015
2016
2017
2018

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