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RESEARCH ARTICLE

Droughts in São Paulo: challenges and lessons for a water-adaptive society

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ABSTRACT

Literature has suggested that droughts and societies are mutually shaped and, therefore, both require a better understanding of their coevolution on risk reduction and water adaptation. Although the São Paulo Metropolitan Region drew attention because of the 2013–2015 drought, this was not the first event. This paper revisits this event and the 1985–1986 drought to compare the evolution of drought risk management aspects. Documents and hydrological records are analyzed to evaluate the hazard intensity, preparedness, exposure, vulnerability, responses, and mitigation aspects of both events. Although the hazard intensity and exposure of the latter event were larger than the former one, the policy implementation delay and the dependency of service areas in a single reservoir exposed the region to higher vulnerability. In addition to the structural and non-structural tools implemented just after the events, this work raises the possibility of rainwater reuse for reducing the stress in reservoirs.

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droughts; urban water supply; water crisis; drought risk; paired event analysis; vulnerability

1. Introduction

Apart from other natural hazards, drought impacts are mostly non-structural, cover larger areas, and duration is difficult to pinpoint (Wilhite, Sivakumar, and Pulwarty 2014). Projections estimate that 1.8 million people are expected to face severe water conditions until 2030 (Zhang et al. 2019). 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 – United Nations International Strategy for Disaster Reduction 2015). Therefore, disaster risk management processes aim at improving preparedness, response, and recovery (IPCC 2012, 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, Konar, and Sivapalan 2017; Di Baldassarre et al. 2019). Although different drought events in the same region do not cause similar impacts (Wilhite, Sivakumar, and Pulwarty 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, F, and Gobbetti 1996; Hermann, Amaral, and Freitas 1987; Jacobi, Fracalanza, and Silva-Sanchez 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 manuscript 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 1: 1) Risk assessment: preparedness, exposure, hazard intensity, vulnerability and; 2) Risk reduction: response and mitigation.

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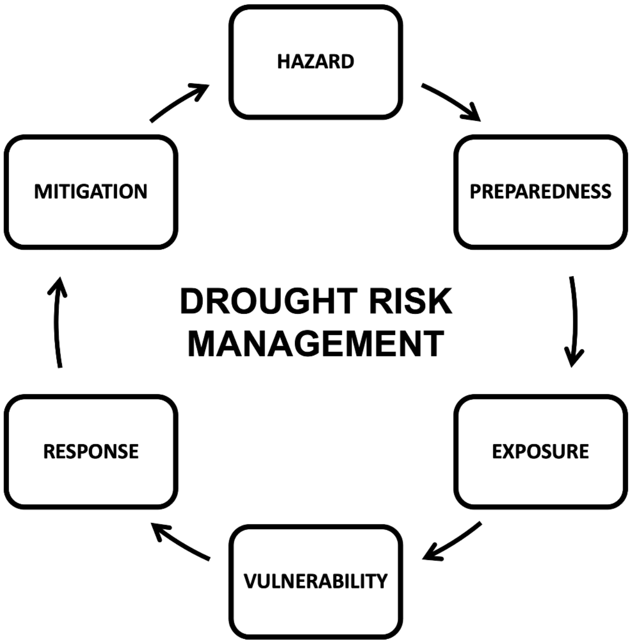

Figure 1. Presents the six phases of drought risk management and the chronological steps that require actions to better prepare and reduce damages.

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 n° 16,337/2016), 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. 2011) and water service valuation in this catchment area (Viani, Bracale, and Taffarello 2019; Taffarello et al. 2020; Guzmán, Mohor, and Mendiondo 2020).

The SPMR water supply system comprises several reservoirs presented in Figure 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, Jaguari-Jacareí (1.235 km^2 of draining area), Cachoeira (392 km^2 of draining area) and Atibainha (315 km^2 of draining area) and connected through tunnels to the Paiva Castro reservoir (338 km^2 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 and Kelman 2020). The other system addressed in this study is the Guarapiranga reservoir, whose drainage area, about 329 km2, is located within the Alto Tietê river basin (Brito, Miraglia, and Semensatto 2018; Whately and Cunha 2006).

Figure 2 highlights the drainage area of the two water supply systems addressed in this work, 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 33 m3/s, while the Guarapiranga system is the second largest and can produce up to 16 m3/s of drinking water (FABHAT – Fundação Agência de Bacia Hidrográfica do Alto Tietê 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, Miraglia, and Semensatto 2018; Freitas 2020; Goldenstein 1998; Whately and Cunha 2006, 2007; Wiel and Bintanja 2021).

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

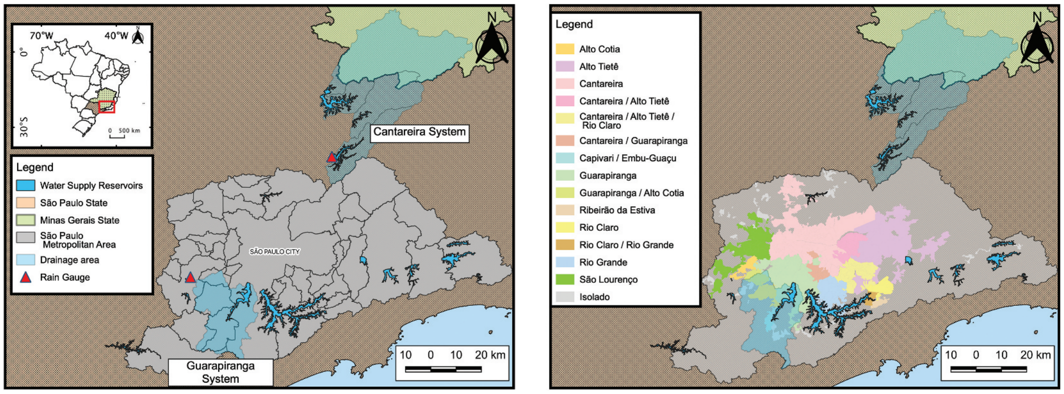

Figure 2. The left-hand map highlights the location of Cantareira and Guarapiranga systems within the São Paulo Metropolitan Region. The right-hand map presents the limits of service areas and respective supply systems that delivered water in 2018 (FABHAT – Fundação Agência de Bacia Hidrográfica do Alto Tietê 2019).

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 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,

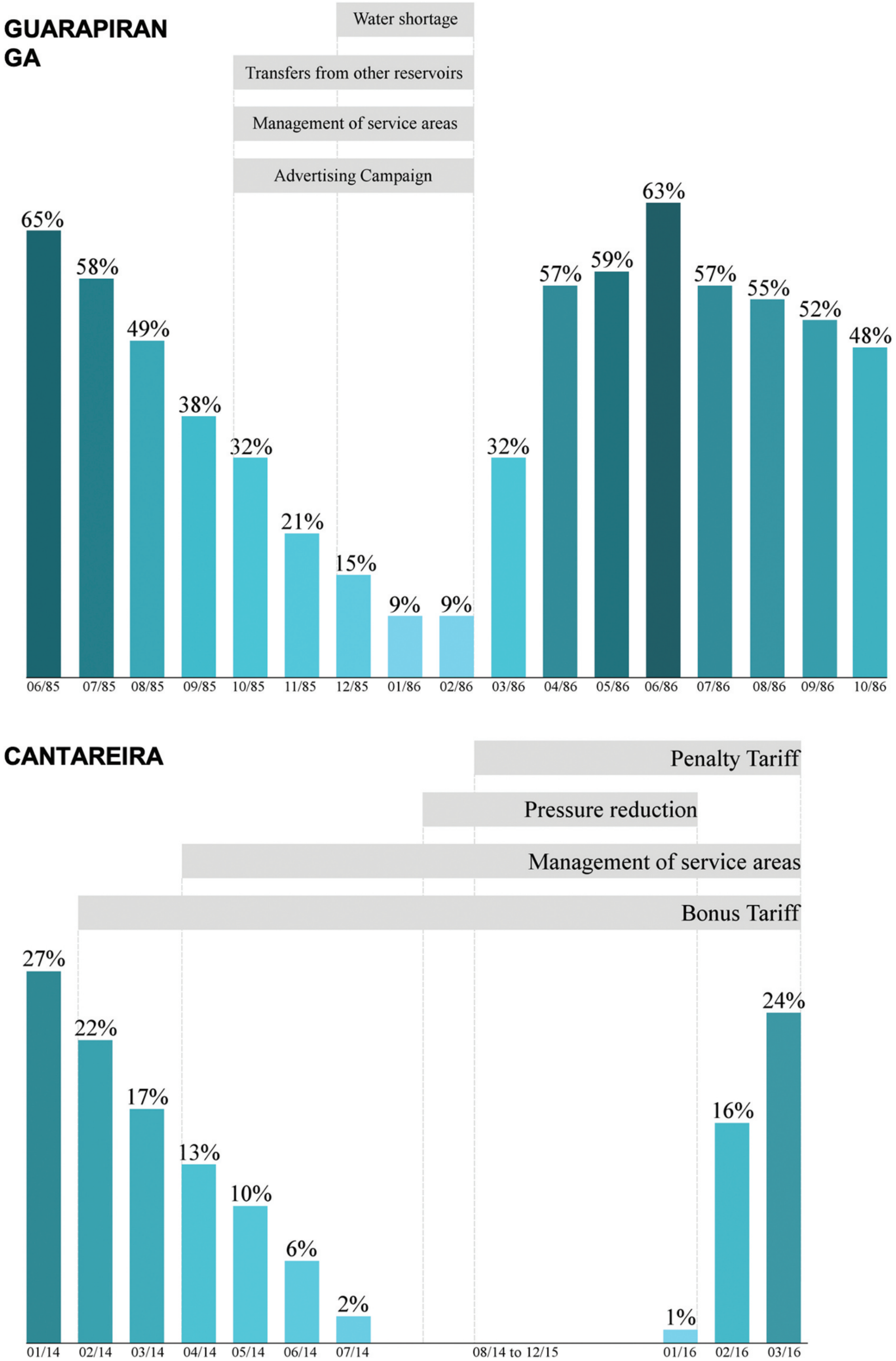

Figure 3. Timeline of Guarapiranga and Cantareira water crisis showing the water storage level in percentage and the main strategies adopted to cope with scarcity and demands.

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.

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 33 m3/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).

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 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 3 also presents the percentage of useful storage levels on the first day of each month, where numbers equal to zero mean that the reservoir reached the dead storage.

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 – United Nations International Strategy for Disaster Reduction 2009). 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.

Hazard – risk assessment

The hazard intensities of both events are compared through the Standardized Precipitation Index – SPI (McKee, Doesken, and Kleist 1993) and the Streamflow Drought Index – SDI, which is an adaptation of SPI for the reservoirs' inflow comparison (Nalbantis and Tsakiris 2009). 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 McKee, Doesken, and Kleist (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 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; McKee, Doesken, and Kleist 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.

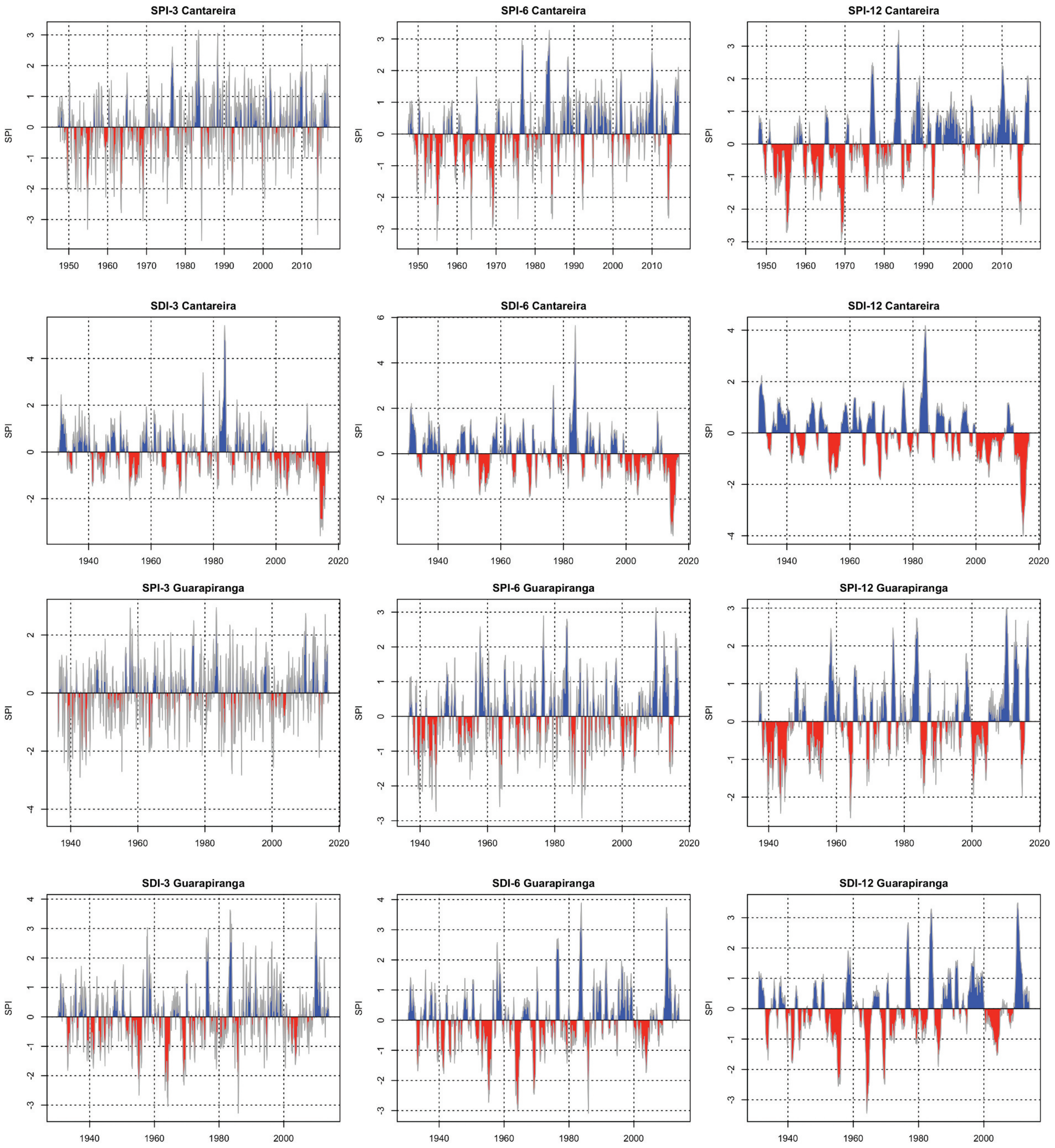

Figure 4. SPI and SDI indices for Guarapiranga and Cantareira systems. For the former system, SPI and SDI are calculated using records up to 1986, while the latter case employs historical data up to 2015.

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, Macau, and Sampaio 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, Macau, and Sampaio 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.

Preparedness – risk assessment

Gillette (1950) and González Tánago, Urquijo, and Blauhut 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, Budds, and Aversa (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.

Exposure – risk assessment

Since little can be done to change drought occurrence (Wilhite, Sivakumar, and Pulwarty 2014), exposure can be computed as the number of people, their livelihoods and assets in the area that could be affected by droughts (Carrão, Naumann, and Barbosa 2016; IPCC 2012, 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 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 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 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, Empinotti, and Aversa (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.

Vulnerability

Definitions of vulnerability are differently assigned by different authors. Carrão, Naumann, and Barbosa (2016) and IPCC (2014) define vulnerability as the propensity or predisposition of those elements exposed to drought to suffer the negative effects. Van Loon (2015) go further and define that vulnerability differs according to the lack of capacity to cope with the drought risk, while Wilhite, Sivakumar, and Pulwarty (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 study 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 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.

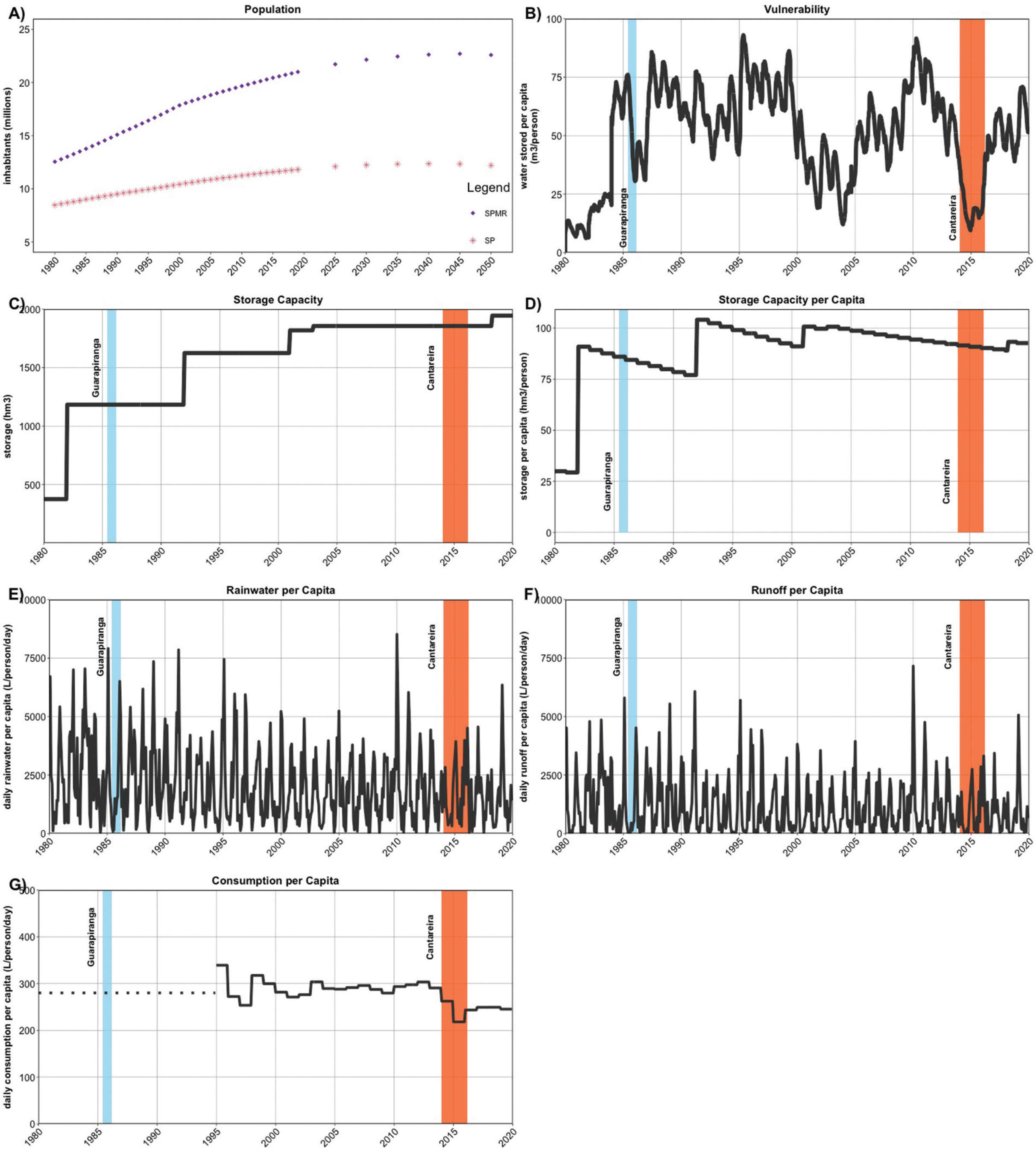

Figure 5. A) Presents the population growth observed between 1980 and 2020 and demography projections until 2050 (SEADE 2020), B) presents the water stored per capita at the local reservoirs for water supply in the São Paulo Metropolitan Region, C) presents the evolution of water storage capacity as 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.

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.

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 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 24 h 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 (Araújo 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, Budds, and Aversa 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 – Fundação Agência de Bacia Hidrográfica do Alto Tietê 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.

Mitigation – risk reduction

Wilhite, Sivakumar, and Pulwarty (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 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, Sivakumar, and Pulwarty 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, Mohor, and Mendiondo (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, Mohor, and Mendiondo (2020) and Mohor and Mendiondo (2017) highlight that this strategy

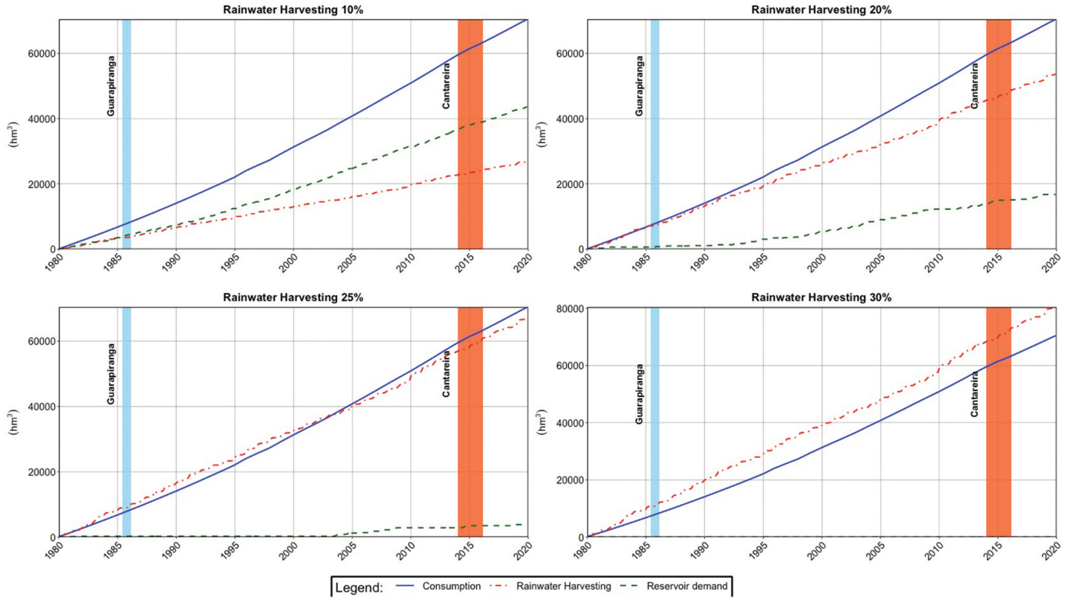

Figure 6. Presents four scenarios of rainwater reuse considering the cumulative collection of runoff since 1980, at 10%, 20%, 25% and 30% rate, where the blue solid line is the cumulated consumption, the red dot-dashed line is cumulated runoff collection given the rainwater harvesting rate and the green dashed line is the gap between cumulated water consumption and cumulated rainwater harvesting.

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, Amaral, and Freitas 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, Fracalanza, and Silva-Sanchez 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, Fracalanza, and Silva-Sanchez (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 – Governo do Estado de São Paulo 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).

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, Figures 5E,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, Lombardi Neto, and Genovez 2005; USDA 1986). In addition, Figure 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 6 presents four scenarios considering rainwater harvesting at 10%, 20%, 25% and 30% of cumulated runoff since 1980, where the solid blue line is the cumulated water consumed by households, the green dashed line is the hypothetical water collected from runoff and the red dot-dashed line is the cumulated gap between consumption and rainwater harvested over time. The methodology description behind the runoff estimation is presented in the supplemental material.

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 harvesting 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 harvesting 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 harvesting can be practised at residential scale, where water tanks would store less water than a reservoir, but it would alleviate the surface water consumption.

Table 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.

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 the six elements on drought risk management (Table 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.

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, Buckeridge, and Ribeiro 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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