Journal of Water Resource and Protection, 2020, 12, 261-274
https://www.scirp.org/journal/jwarp
ISSN Online: 1945-3108
ISSN Print: 1945-3094

Implications of the New Operational Rules for Cantareira Water System: Re-Reading the 2014-2016 Water Crisis

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How to cite this paper: Deusdará-Leal, K.R., Cuartas, L.A., Zhang, R., Mohor, G.S., de Castro Carvalho, L.V., Nobre, C.A., Mendiondo, E.M., Broedel, E., Seluchi, M.E. and dos Santos Alvalá, R.C. (2020) Implications of the New Operational Rules for Cantareira Water System: Re-Reading the 2014-2016 Water Crisis. *Journal of Water Resource and Protection*, **12**, 261-274.
https://doi.org/10.4236/jwarp.2020.124016

Received: February 28, 2020
Accepted: April 5, 2020
Published: April 8, 2020

Abstract

During the 2014-2016 water shortage crisis, the Metropolitan Area of São Paulo (MASP) water supply system extracted pumping volume from the Cantareira System. Before the crisis, between 1984 and 2013, the reservoir's average water extraction flow was 29.6 $m^3 \cdot s^{-1}$. During the period of pumping volume usage, the average extraction flow was 16.2 $m^3 \cdot s^{-1}$. Following the crisis, two new mitigation policies were implemented: a water extraction Resolution (in 2017) and a Resolution for water reallocation from another basin (in 2018). This study provides a novel investigation of the Cantareira System water crisis by assessing the mitigation policies impacts on storage level dynamics. The system storage level was evaluated using the reservoir simulation module of PDM-Cemaden hydrological model, assuming that the new policies had already been implemented prior to the crisis. A control simulation was run with observed in- and out-flow and operationally-practiced extraction flow. The storage level dynamics impacts were evaluated under 4 water mitigation policies scenarios varying the policies implementation starting date, the extraction flow range and including the water reallocation variable. Results showed that pumping volume would only need extraction during a short period (Scenarios I, III and IV), and considering the water reallocation, pumping volume extraction would not have been necessary (Scenario II). Although the pumping volume would still have been extracted during a short period, water shortage impact would have been lessened, had the policies been already implemented before the crisis. The water mitigation policies implementation supports the reservoirs storage management but does not guarantee that MASP water demand is fully met. Therefore, in order to effectively improve water security, further policies and practices to reduce water demand and enhance supply should be considered.

Keywords

Cantareira System, Drought, São Paulo, Brazil, Dead Storage, Water Crisis

1. Introduction

Drought is a complex natural hazard that impacts ecosystems and human activities in several ways, mainly associated with hydrological impacts. Hydrological droughts (HD) can be defined as the low streamflow, low inflow levels, and reduced available groundwater [1]. The often unnoticed onset and slow development of HD converges to devastating impacts on agriculture, hydroelectric power generation, water supply, public health, navigation, and recreation. In recent years, many HD events occurred around the world. For example, the metropolitan area of Barcelona faced a severe drought that affected various economic sectors between 2007 and 2008. Important communication campaigns were put into place which led to a significant water demand reduction and to the setup of mechanisms for public participation for future water management. Although HD has been gaining attention in the last decades, one further step is to integrate science, management, and policy. A strong interface between policymakers and scientists is necessary to ensure that research better addresses the drought impacts management.

Prolonged dry and hot weather, and consequently less than normal water availability, have historically challenged Northeast Brazil, but in the last decade, the Southeast has also been experiencing similar issues. Between 2014 and 2016, the Southeast and Central-West Regions of Brazil experienced an unprecedented HD [2] [3] [4]. The unfavorable climatological condition, combined with political management challenges, seriously impacted water supply [5] [6], mainly to the Metropolitan Area of São Paulo (MASP), hydropower generation, agriculture [7] [8] as well as the water quality [9]. For example, in the upper stream of the São Francisco river basin, an important basin that connects Northeast and Southeast Regions, the reservoir recorded a historical minimum storage level (2.6%) in November 2014, challenging the hydropower generation, water supply and irrigation [10]. In the United States, as well as in Brazil, the recurrent HD in California has challenged human activities along the history. The 2012-2016 drought in California was deep, prolonged and unusually warm. Interties, water stored in aquifers and reservoirs, water market agreements, and long-term water conservation avoided, with few exceptions, emergency conditions in the cities. In 1976-1977, the California drought event included the driest year on the record and deep urban water conservation was achieved as a result of significant water demand management programs [11].

The Cantareira water supply system, located in Southeast Brazil (**Figure 1**), is used to be responsible for supplying water for 8.8 million people [12], corresponding to 46% of MASP (or 65% of Sao Paulo city demand). This number was reduced to 5.5 million people during the 2014-2016 HD, when it received support from other water systems, and returned to attending 7.5 million people after the drought. Cantareira System pumping volume was extracted, between July 2014 and December 2015, after depletion of its 982 hm^3 active storage. Pumping volume refers to reservoir negative water levels which cannot be extracted by gravity, but only pumped out, demanding more energy for the water extraction [13]. In May 2014, the first pumping volume quota was set operational, adding 182.5 hm^3, and in October 2014 the second quota was activated, adding 105 hm^3, reaching a total storage capacity of 1284.5 hm^3. At the beginning of January 2016, both pumping volume quotas were recovered, because of the rainy season above the historical mean (SOND 2015 registered 28% above the Long-Term Mean—LTM) and the emergency practices implemented. At the end of the rainy season, in March 2016, the reservoir reached 36% of its active capacity.

The São Paulo State Sanitation Company—SABESP, a mixed-economy company responsible for water supply, sewage collection and treatment in the MASP, which holds the Cantareira System water permit, adopted a set of practices to reduce consumption and preserve the Cantareira reservoirs storage. Among the practices implemented, stand out: 1) tariff discount for reduced consumption; 2) additional use of other MASP water systems [14], namely: the Upper Tietê System (capacity of 520 hm^3), the Guarapiranga System (capacity of 171 hm^3), the Rio Grande System (capacity of 112 hm^3), the Upper Cotia System

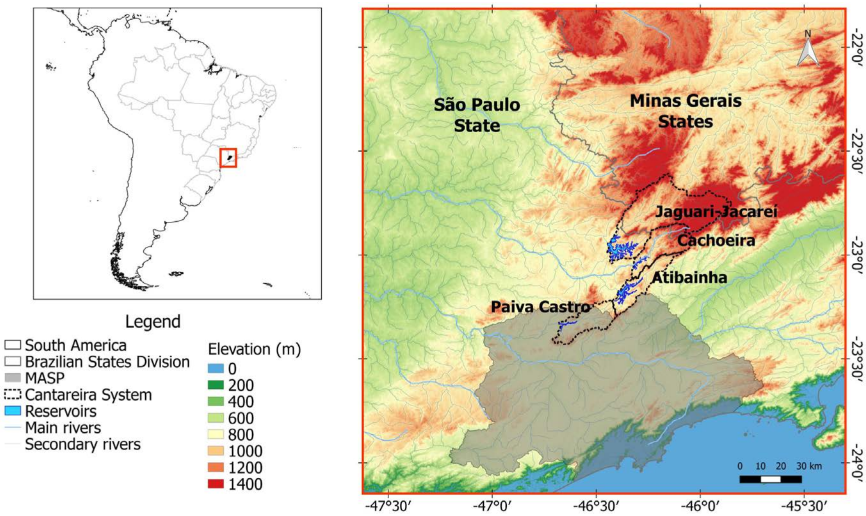

Figure 1. Location map of Cantareira System reservoirs and the Metropolitan area of São Paulo (MASP) in Southeastern Brazil.

(capacity of 16.5 hm^3), and the Rio Claro System (capacity of 16 hm^3); and 3) pressure decrease in the water distribution network to leakage reductions [15]. Notwithstanding the existence of other MAPS water supply systems, the Cantareira System is the main and largest source of water.

After the 2014-2016 HD, in order to mitigate the vulnerability of the Cantareira System, a water extraction rule and water reallocation from another basin were implemented. In 2017, the Water and Energy Resources Department of São Paulo state (DAEE) and the National Water Agency (ANA) implemented a water extraction rule controlled by the hydrologically-conditioned reservoir storage level, via the ANA/DAEE resolution N˚925 [16]. Moreover, in 2018, water reallocation was implemented from the Jaguari reservoir, located in the Paraiba do Sul River Basin (Jaguari-PS), to Atibainha, a Cantareira System reservoir, guided by the resolution ANA N˚1931, issued in 2017 [17]. Notwithstanding the implementation of these mitigation policies, at the end of the 2018 dry season, the Cantareira System storage situation was worse than in 2017, reaching 33.5% of the active volume, which once again alarmed the authorities about the capacity to MASP water supply [18] [19] [20] [21].

Therefore, this study provides a novel investigation of the Cantareira System water crisis by assessing the mitigation policies impacts on storage level dynamics. The system storage level was evaluated using the Reservoir Simulation module of Probability Distributed Model (PDM-Cemaden) hydrological model, assuming that the new policies had already been implemented prior to the crisis. Therefore, this paper addresses three questions: 1) could the new water mitigation policies have avoided the pumping volume extraction, had they been implemented in the beginning of 2014 or 2) some years prior to the crisis? 3) are these rules effective to ensure the MASP water security?

2. Material and Methods

2.1. The Cantareira Water Supply System

The Cantareira System (**Figure 1**) comprises four water producing reservoirs: Jaguari-Jacareí, Cachoeira, Atibainha (these three constitute the “Equivalent System”), and Paiva Castro. The first three reservoirs capture and divert water through tunnels and channels, from some tributaries of the Piracicaba river basin to the Juqueri river basin, up to the Paiva Castro reservoir [12]. Finally, the water is pumped from Paiva Castro to the Águas Claras reservoir, in the lift station Santa Inês—ESI. This reservoir allows a continuous flow of 33 m^3·s^{-1} to be maintained for 3 hours if the ESI stops. The water is finally transferred by gravity to the Guaraú water treatment plant (ETA) before distribution in the network. The total drainage area is approximately 2300 km^2. The donating reservoirs upstream of the Piracicaba river basin also contribute with downstream reservoirs to supply cities within the Piracicaba, Capivari, and Jundiaí river basins (PCJ basins), which are managed together with Cantareira System.

In this study, the Cantareira System is considered as the equivalent system plus the Paiva Castro reservoir. The inflow is therefore the total of the reservoir's inflow, the outflow is the total of reservoir's outflow and the water extraction is the flow to the lift station Santa Inês, used for the MASP water supply. Figure 2 shows the time series of the observed in- and out-flow, the operationally-practiced extraction flow and also the storage level.

The climatological precipitation (1983-2013) over the Cantareira System is 1543 mm, with a markedly rainy season (between October and March), responsible for 74% of the total rainfall. The rainfall for the period from October 2013 to September 2014 was 39% below the climatological rainfall (Figure 3), which lead to inflow much lower than the LTM, and also below the minimum records [2]. The annual LTM inflow is 42.8 $m^3 \cdot s^{-1}$. The average inflow between October 2013 and March 2014 was 19 $m^3 \cdot s^{-1}$, 36% of the LTM for the period. More information about the meteorological conditions that lead to this precipitation deficit is presented in [2] and [4].

2.2. Cantareira System Operational Rules

Before the crisis, between 1984 and 2013, the average extraction flow was 29.6 $m^3 \cdot s^{-1}$, ranging between 18.6 and 32.8 $m^3 \cdot s^{-1}$, and the average outflow was 10.6 $m^3 \cdot s^{-1}$, varying between 0.8 and 91.7 $m^3 \cdot s^{-1}$. This highest outflow value was

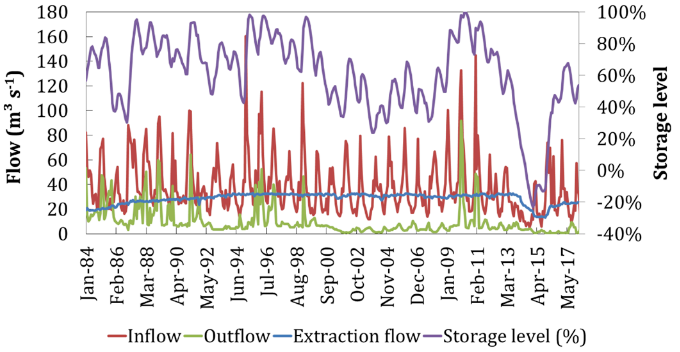

Figure 2. Times series of inflow, outflow, extraction flow and storage level in the Cantareira System. Data source: SABESP.

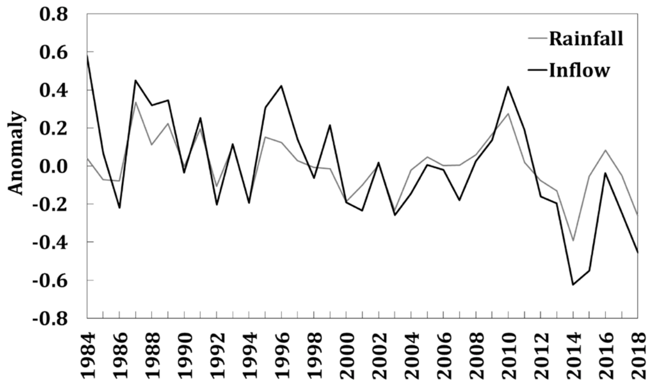

Figure 3. Times series of rainfall and inflow anomalies over the Cantareira System basins. Hydrological year: October to September. Data source: SABESP.

observed in 2010, during an extreme event when Cantareira System reservoirs were not able to support the large inflow. During the period of volume pumping utilization, from July 2014 to December 2015, the average extraction flow was 16.2 $m^3 \cdot s^{-1}$, varying between 13.4 $m^3 \cdot s^{-1}$ and 21.8 $m^3 \cdot s^{-1}$, and the average outflow was 2.2 $m^3 \cdot s^{-1}$, varying between 0.5 and 4.2 $m^3 \cdot s^{-1}$ (**Figure 2**).

Since May 2017, ANA and DAEE implement a new water extraction rule via the ANA/DAEE resolution N˚925 [16]. This resolution defines storage levels operational ranges and their respective maximum extraction flow, as shown in **Table 1**, ranging from a minimum of 15.5 $m^3 \cdot s^{-1}$ to a maximum of 33.0 $m^3 \cdot s^{-1}$, replacing a previous rule in which the maximum extraction had been set in 33 $m^3 \cdot s^{-1}$ for any storage condition. An evaluation on the water allocation rules in the Cantareira System, its drivers and how it has reflected in the regional sharing of the benefits can be found in [22].

In order to increase water supply, ANA implemented the water reallocation between the Cantareira System and the Jaguari reservoir from the Paraíba do Sul River Basin (PS) via resolution ANA N˚1931 [17], published in October 2017, and effectively started in April 2018. The water reallocation can operate both ways, although this process has just been favored Cantareira System. According to this resolution, the reallocation flow annual mean must be up to 5.13 $m^3 \cdot s^{-1}$, when the Cantareira storage level is lower than 60%, and the Jaguari-PS reservoir water level is ranging from 603 to 623 m [17].

2.3. Control Simulation of the Storage Level Dynamic

The System storage level was simulated by a Reservoir Simulation module coupled to Probability Distributed Model—PDM implemented at the Brazilian National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), PDM-CEMADEN [23]. The PDM is a conceptual hydrological model that transforms rainfall and potential evapotranspiration into streamflow and actual evapotranspiration. A detailed description of the PDM-Cemaden model can be found in [23] [24] [25]. Although this model is generally implemented to simulate the streamflow, in this study just the Storage Simulation

Table 1. Cantareira System (CS) reservoirs operational ranges and their respective maximum extraction flows for the MASP water supply (resolution ANA/DAEE N˚925) and the water reallocation mean flow from Paraíba do Sul river basin (PS) (resolution ANA N˚1931).

Storage Level (%)	Condition	Maximum extraction flow ($m^3 \cdot s^{-1}$)	Water reallocation mean flow PS-CS ($m^3 \cdot s^{-1}$)
>60%	Normal	33.0	-
60%< and >40%	Attention	31.0	5.13
40%< and >30%	Alert	27.0	5.13
30%< and >20%	Restriction	23.0	5.13
<20%	Special	15.5	5.13

module for the superficial reservoir was used. Therefore, the observed in- and out-flow were used for the control simulation and also for all scenarios' simulations (Figure 4). The module was run starting in 2004 for the control simulation and used the operationally-practiced extraction flow data (Figure 4(a)). Flow data were obtained from SABESP website (http://mananciais.sabesp.com.br/Home).

2.4. Storage Level Dynamic Scenarios Simulation

In order to assess the Cantareira System storage level dynamics impacts, this paper addressed four scenarios based on water mitigation policies, varying the policies implementation starting date, the extraction flow range and including the water reallocation variable, as described in Table 2.

The scenario I considers water extraction following the Resolution ANA/DAEE N˚925. Scenario II considers, in addition to Scenario I, the water reallocation from Jaguari-PS, following the Resolution ANA N˚1931. Therefore, Scenario II

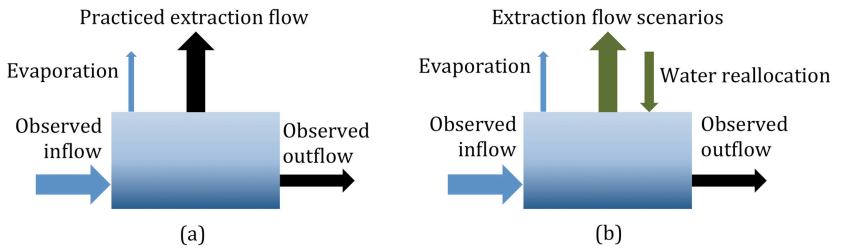

Figure 4. Hydrological representation of the Reservoir Simulation module of the PDM-Cemaden model for (a) control simulation and (b) scenarios simulations. The arrows thickness indicates the flow intensity. Blue and black arrows denote natural and human-controlled processes, respectively; green arrows highlight variables used for scenarios simulation.

Table 2. Description of the four simulation based on water mitigation policies scenarios adressed in this paper.

Scenario	Description	Time period of policies implementation
I	Maximum water extraction for storage level operational ranges from the resolution ANA/DAEE N˚925 (shown in Table 1)	2014-2018
II	Scenario (I) including the water reallocation flow, according to the resolution ANA N˚1931 (shown in Table 1)	2014-2018
III	Same extraction rule as Scenario I, but assuming an earlier policy implementation	2005-2018
IV	Intermediate water extraction flow for storagelevel operational ranges from the Resolution ANA/DAEE N˚925: Normal range: 32 $m^3 \cdot s^{-1}$; Attention range: 29 $m^3 \cdot s^{-1}$; Alert range: 25 $m^3 \cdot s^{-1}$; Restriction range: 19.5 $m^3 \cdot s^{-1}$; Special range: 15.5 $m^3 \cdot s^{-1}$.	2005-2018

is more optimistic than Scenario I. These scenario simulations start the policies implementation in March 2014, at the end of the rainy season in the Southeast Brazil and when concern with the critical reservoir storage was raised. In March 2014, the reservoir storage was only 17% of the active volume, and the rainfall, from Oct 2013 to Feb 2014, accumulated a climatological rainfall deficit of 61%. Both conditions could be enough to initiate a water use restriction. The water use restriction management in real-time during an HD is challenging, such that making decision to restrict reservoir water extraction in advance would be difficult.

Scenarios III and IV were simulated for a longer policy implementation time period, starting one year after the permit renewal (2004). Scenario III used the same water extraction rule as Scenario I, although under different initial conditions. Since the Resolution ANA/DAEE N˚925 was implemented, in 2017, operationally-practiced water extraction has been below the maximum allowed, therefore, a new scenario (Scenario IV) was elaborated to assess this impact on storage level dynamics. Scenario IV used intermediate extraction flow for each storage level operational range from the Resolution, as described in Table 2.

In scenarios simulations, pumping volume utilization just would begin when Cantareira System storage level is below 0%, although it starts prior to this level in operationally-practice.

3. Results

3.1. Control Simulation

The control simulation performance indicators (Nash-Sutcliff = 0.98; Mean Absolute Error = 137.8; Root Mean Square Error = 7.49) showed the great ability of the PDM-CEMADEN model in simulating the storage level dynamics.

3.2. Scenarios Simulation

The Cantareira System 4-year simulations of storage level and extraction flow under Scenarios I and II are shown, respectively, in Figure 5 and in Figure 6. In Scenario I, the model estimated that, during the 2014-2016 water crisis, pumping volume would have been extracted during two shorter periods than operationally-practiced (observed), lasting 239 and 141 days, respectively, interspersed by 34 days of active volume utilization (around June, 2015), totalizing 380 days of pumping volume utilization (Table 3). Regarding pumping volume storage, the minimum estimated level would have been −11% (−110 hm^3), thus the pumping volume first quota would have been utilized, and the total pumped water volume would have reached 509 hm^3, equivalent to 52% of active volume (Table 3).

Cantareira System level storage under Scenario II showed that pumping volume utilization would not have been necessary during the 2014-2016 water crisis. The minimum estimated storage level would have been reached in January 2015, representing 3.9% (38 hm^3) of the active storage. This more optimistic storage dynamics is attributed to water reallocation, which would contribute to 243 hm^3, equivalent to 25% of the active volume, during the period between July 2014 to December 2015.

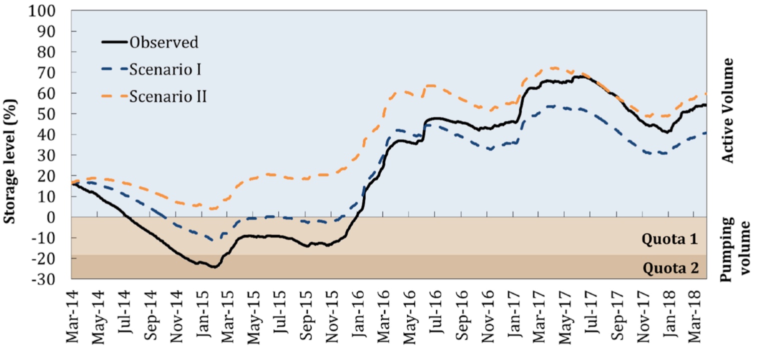

Figure 5. Cantareira System 4-years storage level simulations under two water mitigation policies scenarios: Scenario I (blue) and II (orange). Black line refers to observed data; pale blue, light brown and dark brown background areas depictions, respectively, active volume, pumping volume quota 1 and 2.

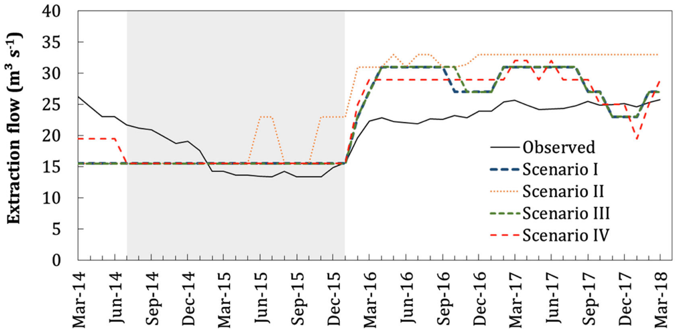

Figure 6. Cantareira System extraction flow for MASP water supply under four water mitigation policies scenarios (March 2014-March 2018): Scanario I (blue), II (orange), III (green) and IV (red). Black line refers to observed data. Gray area highlights the operationally-practiced (observed) time period of pumping volume utilization.

Table 3. Cantareira System pumping volume utilization data: operationally-practiced and based on 4 water mitigation policies scenarios.

Scenario	Pumping volume utilization			
	Period	Days	Extraction flow mean $(m^3 \cdot s^{-1})$	Total extracted volume hm^3 and (%)[a]
Practiced	Jul 12th, 2014 to Dec 30th, 2015	537	16.2	745 (76%)
I	Oct 06th, 2014-Jun 01st, 2015 and Jul 06th, 2015-Nov 23th, 2015	380	15.5	509 (52%)
II	Not used	0	-	0 (0%)
III	Oct 23th, 2014-Mar 01st, 2015	130	15.5	174 (18%)
IV	Jan 22th, 2015-Feb 07th, 2015	17	15.5	23 (2%)

[a] In relation to the active volume, *i.e.* 982 hm^3.

The Cantareira System 13-year simulations under Scenarios III and IV are shown in **Figure 7**. In Scenario III, the model estimated that pumping volume would have been extracted during 130 days, a number of days lower than the

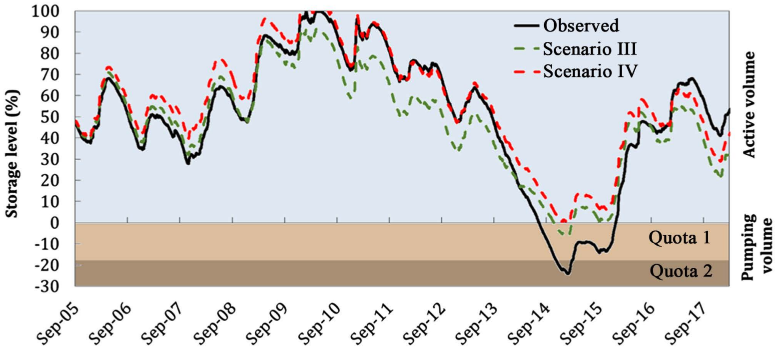

Figure 7. Cantareira System 13-years storage level simulations under two water mitigation policies scenarios: Scenario III (green) and IV (red). Black line refers to observed data; pale blue, light brown and dark brown background areas depictions, respectively, active volume, pumping volume quota 1 and 2.

operationally-practiced. The minimum estimated storage level would have been −6% (−61 hm^3), reached in February, 2015, therefore, just the pumping volume first quota would have been utilized. Total pumped water volume would have reached 174 hm^3, equivalent to 18% of the active volume. In Scenario IV, the storage level simulated showed that pumping volume would still have been extracted, although just during 17 days. Regarding pumping volume utilization, the estimated minimum storage level would have been −0.4% (−4 hm^3), reached in February, 2015 and the total pumped volume would reach 23 hm^3, equivalent to 2% of the active volume.

4. Discussion

The scenario simulations pointed out that extraction flow mean would be 15.5 m^3·s^{-1} (except for Scenario II) during the period July 2014 to December 2015, a lower value than real practiced (16.2 m^3·s^{-1}) (Table 3). Regarding this time period, the simulated storage level under Scenario II would have been higher than under other scenarios and also than observed storage level, which would have allowed a higher extraction flow mean (17.2 m^3·s^{-1}). However, under all scenarios simulated, it would have not been possible extracting the total demand observed before the water crisis (29.6 m^3·s^{-1}).

After the 2014-2016 water crisis, all four simulations showed that storage level would have been lower than the observed (Figure 5 and Figure 7) which could be explained by higher extraction flow mean estimated. Successively, higher extraction from Cantareira System could have lessened impact the MASP water supply.

Scenarios I and III followed the same extraction rule as established on Resolution ANA/DAEE N˚925, however, their initial storage level was 17% in 2014 and 47% in 2005, respectively, leading to different storage levels dynamics during the 2014-2016 water crisis. Pumping volume would have been less utilized (250 days; 335 hm^3) had the Resolution been implemented years (Scenario III) earlier compared to months (Scenario I) prior to the crisis. The early implementation of this policy could have reduced the water system vulnerability.

Simulations results showed that Cantareira System total storage (active and pumping volume) would not be enough to meet the total MASP water demand observed prior to the crisis, even considering the water reallocation from another basin. Therefore, other water systems located in the MASP should have been utilized in order to supply 29.6 $m^3 \cdot s^{-1}$. The Alto Tietê System utilization increased during the 2014-2016 water crisis, which also led this system into a crisis. Wherefore, requiring more inflow from this system could not be possible.

The water reallocation over longer distances probably increases the financial resources utilization and energy's needs. For that reason, the sustainability of the water supply project for crisis management should be carefully analyzed. In addition, prolonged and severe droughts usually affect large territorial areas, which challenges the regional water management, as occurred in the HD addressed in this paper. Several reservoirs in the Southeastern Brazil faced an unfavored condition during 2014-2016 [8] [13] [26]. The Jaguari-PS reservoir recorded the historical minimum value of 3% of active volume in December 2014 [27], and the water reallocation to Cantareira System was questionable. Therefore, the assumption that water problems there will finally be resolved with the construction of more infrastructure could fail due to growing human needs and climate change [28].

Water systems management can be influenced by various resources: financial, natural and adaptative capacity. Appropriate operational practices can substantially reduce these resources impacts on water systems under water scarcity and drought [29]. Each hypothetical scenario in this study presents alternatives for the Cantareira System operation in order to support the management of possible future water scarcity.

5. Conclusions

In 2014-2016 Cantareira System faced an unprecedented HD that overwhelmed the MASP water supply. This study assessed Cantareira System mitigation policies (implemented after the crisis) impacts on the system storage level dynamics. Impacts were evaluated under four water mitigation policies scenarios by varying policies implementation starting date, extraction flow magnitude range and including the water reallocation variable.

Answering the three addressed questions in this paper, 1) the storage level simulation under Scenario I pointed out that Cantareira System pumping volume would have been utilized to supply the MASP water system, which had the extraction rule (Resolution ANA/DAEE N°925) been implemented in March 2014. Moreover, Scenario II results showed that the Cantareira System active volume would have been able to supply the MASP water system, provided that surplus input from another basin (Resolution ANA N°1931) had been used since March 2014. 2) Scenario III and IV results showed that pumping volume would still have been utilized during a period of time shorter than operationally practiced, had the policies already been implemented some years prior to the crisis. 3) The water mitigation policies implementation supports the water supply via reservoirs storage management. Further, despite water reallocation from Scenario II suffices to pumping volume saving, the MASP water demand prior to the crisis is not fully met. Considering the observed negative impacts of precipitation and inflow in recent years and São Paulo's economic contribution to the country's Gross Domestic Product (GDP), a strategic planning approach to water security is necessary, via the mismatches evaluation between water supply and demand. The proposed flow magnitude reduction addressed in Scenario IV could support policy makers to improve the Resolution ANA/DAEE N˚925 aiming to further decrease the Cantareira System vulnerability.

Lastly, policies and practices could shift from water-supply to demand-management approaches contributing to water security improvement. An implemented practice example was the temporarily incentive to reduce consumption applied during the crisis. Actions should also address reducing leakages from water supply distribution network and enhance sewage collection and treatment and also the public participation for future water management.

Acknowledgements

The authors are very grateful to Diogo Amore, hydrological scientist, for text and English revising. The authors are grateful for the finantial support from CEMADEN Institutional Capacity Building Program, (CNPq Process N˚454809/2015-8); from CAPES Pro Alertas CEPED/USP (88887.091743/2014-01), from the Consolidation of research and technological development work, Process N˚401897/2014-1, and from the National Institute of Science and Technology for Climate Change Phase 2 under: CNPq Grant 465501/2014-1, FAPESP Grant 2014/50848-9. The authors gratefully acknowledge the São Paulo State Basic Sanitation Company (Sabesp) and the National Water Agency (ANA) for providing the data required in this study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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