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Impact of hydroclimatic changes on the operation of water resources systems: a case study of the Cantareira Water Production System

Impacto das mudanças hidroclimáticas na operação de sistemas de recursos hídricos: um estudo de caso do Sistema de Produção de Água Cantareira

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ABSTRACT

This study explores the critical issue of climate change and its implications for the Cantareira Water Production System (CWPS), a vital water supply source for the Metropolitan Region of São Paulo (MRSP). Using data from the CMIP6 GFDL-CM4 model, the research assesses how climate change significantly affects the hydrological cycle, thereby influencing water availability and increasing the vulnerability of the CWPS to periods of water scarcity and instability. Water demand and the operation of the Santa Inês Pumping Station (SIPS) indicate that the transition from the observed scenario to the SSP2-4.5 and SSP5-8.5 scenarios results in a marked reduction in the percentage of the water supply considered normal, dropping significantly from 82.3% to 25.2% and 14.1%, respectively. The findings shed light on the challenges faced by CWPS in the context of climate change, offering valuable insights for the development of strategies and adaptive measures to ensure water security for MRSP. This study underscores the urgency of addressing climate change's potential consequences on water resources systems to safeguard the future of one of Brazil's most populous regions.

Keywords: Water allocation; Water scarcity; CMIP6; Hydroclimate impact.

RESUMO

Este estudo explora a questão crítica das mudanças climáticas e suas implicações para o Sistema Produtor de Água Cantareira (CWPS), uma fonte vital de abastecimento de água para a Região Metropolitana de São Paulo (MRSP). Usando dados do modelo CMIP6 GFDL-CM4, a pesquisa avalia como a mudança climática afeta significativamente o ciclo hidrológico, influenciando assim a disponibilidade de água e aumentando a vulnerabilidade da CWPS a períodos de escassez e instabilidade hídrica. A demanda de água e a operação do Elevatória Santa Inês (ESP)SIPS indicam que a transição do cenário observado para os cenários SSP2-4.5 e SSP5-8.5 resulta em uma redução acentuada na porcentagem do abastecimento de água considerado normal, caindo significativamente de 82.3% para 25.2% e 14.1%, respectivamente. As descobertas lançam luz sobre os desafios enfrentados pelo CWPS no contexto das mudanças climáticas, oferecendo alternativas valiosas para o desenvolvimento de estratégias e medidas adaptativas visando garantir a segurança hídrica da MRSP. Este estudo enfatiza a urgência de abordar as potenciais consequências das mudanças climáticas nos sistemas de recursos hídricos para proteger o futuro de uma das regiões mais populosas do Brasil.

Palavras-chave: Alocação de água; Escassez de água; CMIP6; Impacto hidroclimático.

INTRODUCTION

Ensuring freshwater availability is vital for societal well-being, particularly in the face of climate change challenges. The Cantareira Water Production System (CWPS), which serves Metropolitan Region of São Paulo (MRSP), is a crucial case for studying the effects of climate change on water security, as it supplies water to around nine million people. Climate change has led to increased climatic variability, with more frequent droughts and heavy rains, posing challenges for the CWPS (Braga & Kelman, 2020; Lopes et al., 2021).

Operating a complex reservoir system for water supply in a region faces complexity exacerbated by recent water scarcity issues. Effective management requires extensive hydrological data and modeling, with rainfall-runoff models vital for watershed management and risk assessment (Wang & Karimi, 2022) but is also linked to the requirements of water allocation. Operating reservoirs requires a thorough grasp of the local hydrological cycle. This knowledge helps estimate surface runoff to ensure an adequate water supply. Efficient reservoir management relies on computational models to support informed decisions (Fontes Santana & Celeste, 2022).

Climate change's effects on water resources and water-related infrastructure are becoming increasingly significant, with projections of reduced streamflow in several regions in Brazil, further emphasizing the need for adaptive and complex management measures (Silva et al., 2022). The water security of the region has been jeopardized as the CWPS grappled with substantial challenges arising from a nine-year drought, spanning from 2013 to 2021 (Domingues & Rocha, 2022; Santana et al., 2023). Tercini et al. (2021) underscore the urgency of recognizing and addressing climate change's potential implications on water resources to ensure the sustainable and secure provision of water in regions highly susceptible to its effects. Climate change impacts on South American flood trends reveal that nearly 70% of rivers in South America exhibit a negative trend for 2-year floods, emphasizing the pivotal role of reduced antecedent soil moisture in shaping future flood risks (Brêda et al., 2023).

The paper aims to assess these impacts through multidisciplinary approaches, including observed and projected form Coupled Model Intercomparison Project Phase 6, CMIP6 (Eyring et al., 2016), hydrological data analysis, water allocation, reservoir system operation, and the evaluation of current water resource management systems, recognizing the need for more complex management measures to ensure future water security.

CASE STUDY

The study area comprises a portion of the Paraíba do Sul River Basin, which flows into the Atlantic Ocean, and another portion of the Tietê River Basin, which is a tributary of the Paraná River, forming the River Plate Basin. The hydrographic basins were delineated using FABDEM (Hawker et al., 2022), a digital elevation model developed using machine learning techniques to remove buildings and forests from the Copernicus DEM (European Space Agency, 2022). The map of the study area is shown in Figure 1.

As described in Figure 1, the Jaguari/Jacareí basin (JAG), with its outlet being the reservoir of the same name, discharges into the downstream Buenópolis basin (BUE) with its outlet at the control point of the same name. The Cachoeira and Atibainha basins (CAC and ATA, respectively), with outlets at their respective reservoirs, discharges into the Atibaia sub-basin (ATI) and subsequently to the Valinhos sub-basin (VAL) with control points having the same names. The Paiva Castro basin (PAI) with its outlet being the reservoir of the same name and Jaguari of Paraíba do Sul basin (JPS) with its outlet being the reservoir of hydroelectric plant. The schematic model of the study area is shown in Figure 2. This system is known as the Cantareira Water Production System (CWPS).

As shown in Figure 1 and Figure 2, the reservoirs are interconnected by tunnels and conduits, the main water demands are the control points (BUE, ATI, VAL), the Santa Inês Pumping Station (SIPS), and the Hydroelectric Power Plant (HPP). In water allocation, a maximum capacity of 33 m^3s^{-1} was adopted for the interconnections to supply the SIPPS, apart from the transfer between JPS and ATA, which was 8.5 m^3s^{-1}. The minimum downstream flow rates from the reservoirs are 4 m^3s^{-1} in JPS, 0.25 m^3s^{-1} in JAG, 0.125 m^3s^{-1} in CAC and ATA, and 0.1 m^3s^{-1} in PAI. Table 1 presents the drainage area and storage of the case study elements.

The operational rule presented in the figure divides the reservoir into five stages, with the full operational volume up to 60% as the normal stage, supplying 33 m^3s^{-1} to the SIPS. The next stage is the attention stage, up to 40%, providing 31 m^3s^{-1} to the SIPS. In the first two stages, the control points VAL, ATI and BUE have limits (LCP) of 10, 3, and 2.5 m^3s^{-1}, respectively. The third stage is the alert stage with SIPS at 27 m^3s^{-1}, the fourth is the restriction stage with SIPS at 23 m^3s^{-1}, and the last is the emergency stage where SIPS withdraws 15.5 m^3s^{-1}. In the three lower stages, the control points have limits of 11, 2, and 2 m^3s^{-1}.

MATERIAL AND METHODS

The study initiated by gathering data on hydroclimate change scenarios, proceeded to simulate the behavior of the CWPS for each scenario through flow networks, and produced results in the form of water security indicators. Figure 4 illustrates the flowchart of methods.

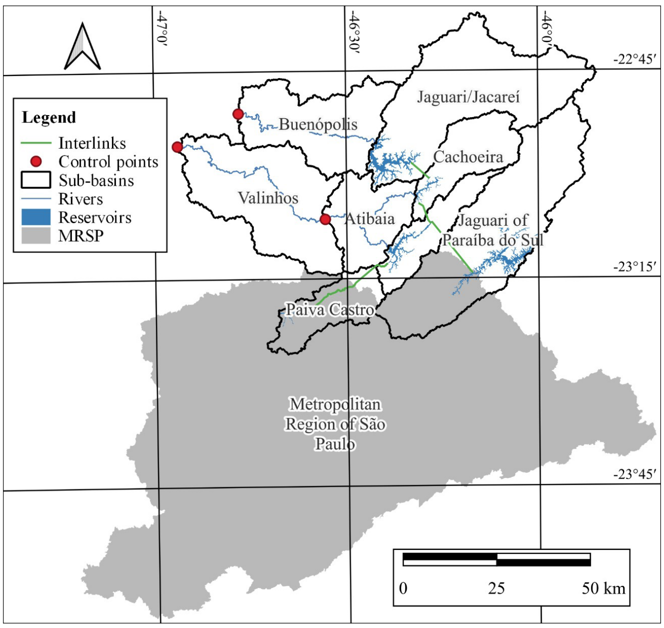

Figure 1. Map of the study area.

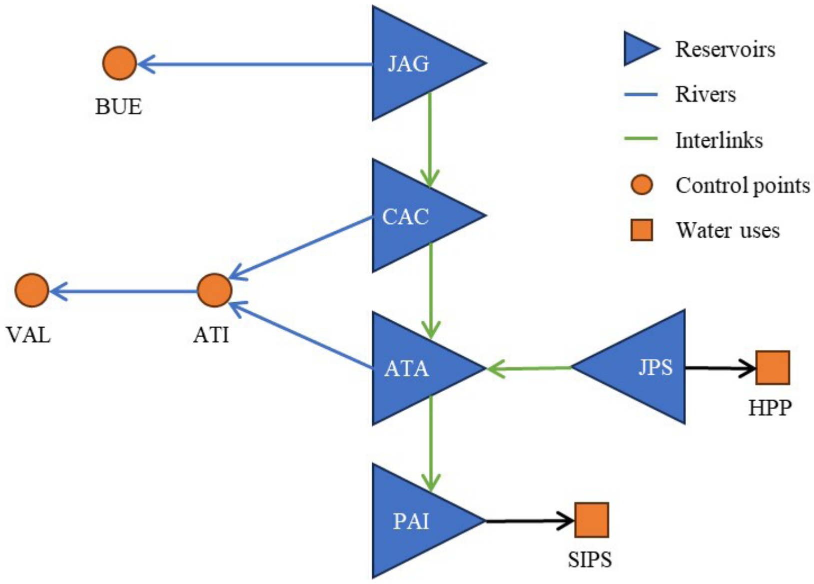

Figure 2. Schematic model of the study area. Adapted from Tercini & Mello Júnior (2023).

Table 1. Characteristics of the Cantareira Water Production System.

Basin	Abbreviation	Drainage area (km^2)	Storage (hm^3)
Jaguari of Paraíba do Sul	JPS	1309.2	792.5
Jaguari/Jacareí	JAG	1240.6	808.0
Valinhos	VAL	982.3	-
Buenópolis	BUE	713.9	-
Atibaia	ATI	437.0	-
Cachoeira	CAC	392.1	69.7
Paiva Castro	PAI	337.1	7.6
Atibainha	ATA	314.3	96.3
Total	-	5726.5	1774.1

Currently, the operational rule considers an equivalent system composed of JAG, CAC, ATA, and PAI operating in hydrological states according to the rule illustrated in Figure 3. The transfer from JPS to ATA is not carried out in normal stage for economic reasons, given the excessive cost of pumping.

This section describes the models and databases used for simulations.

Data

The runoff data from the river basins were taken from Tercini & Mello Júnior (2023) that was based on studies from Xavier et al. (2022) and (Ballarin et al., 2023) to select the most suitable climate model for the CWPS, calibrate and run hydrologic model to obtain the runoff. The database contains one observed scenario, from January 1961 to July 2020, and two projected scenarios, SSP2-4.5 and SSP5-8.5, from August 2020 to December 2100, based on the GFDL-CM4 model (Adcroft et al., 2019; Held et al., 2019). SSP2-4.5 means intermediate greenhouse gas (GHG) emissions, medium socio-economic development, and limits peak warming to 3°C during the 21st century with a probability of more than 50%. SP5-8.5 means very high GHG emissions, rapid growth, and excess warming of 4°C during the 21st century with a probability of more than or equal to 50% (Arias et al., 2021). The runoff used in this study was generated by the SMAP hydrological model (Lopes et al., 1982).

The research methodology from Tercini & Mello Júnior (2023) initiated with the collection of data on precipitation and temperature from climate models, along with field observations on precipitation, potential evapotranspiration, and discharge. Multi-criteria decision analysis was employed to evaluate climate models by comparing their precipitation with observed data in the study area. The applied criteria aimed to assess the overall ability of the models to replicate key statistics of the observed data relevant to hydrological studies. The indicators include time series at daily, monthly, annual, and hydrological year intervals (from October to September); average seasonality in terms of day and month of the year; extreme wetness based on day and month of the year; and extreme dryness based on day and month of the year. Subsequently, future potential evapotranspiration values were computed, and the hydrological model underwent calibration for the basins of the CWPS, and runoff data were generated for observed and future scenarios.

Downstream flow from the dams

The CWPS operating rule provides minimum flow values at the VAL, ATI, and BUE control points that are used to meet the needs of the Piracicaba Basin. To comply with the rule, it is necessary to discharge the flows from the reservoir and calculate the damping to the control points. These demands are represented by the monitoring of the flow at a control point (QCP, in m^{3}s^{-1}), which were estimated using the model described below. QCP must be greater than of the control point limit value (LCP, in m^{3}s^{-1}), as shown in Equations 1 and 2.

$$QCP_i = RO_i + RUD_i \tag{1}$$

$$QCP_i \geq LCP_i \quad (2)$$

Where RO is the runoff (m^3s^{-1}) is obtained by hydroclimate dataset and RUD is routed upstream discharge (m^3s^{-1}) calculated by the routing model (Collischonn & Dornelles, 2021) describes Equation 3.

$$\mathrm{RUD_i} = \frac{(1-2KX)\mathrm{UD_i} + (1+2KX)\mathrm{UD_{i-1}} + (2K(1-X)-1)\mathrm{RUD_{i-1}}}{2K(1-X)+1} \quad (3)$$

Where K is the parameter to represent the time release is delayed (d) and X is the parameter referring to the reduction of the re-lease peak in the stream. The UD is upstream discharge (m^3s^{-1}), for VAL is the discharge in ATI, but for BUE and ATI is the values of downstream flow from the dams (DFD, in m^3s^{-1}) required to meet the control point were optimized using the objective function (OF) of Equation 4. Index i is about the value on a daily time interval and $i-1$ is a previous interval value.

$$\mathrm{OF} = \min \sum_{i}^{m} DFD_i \quad (4)$$

The objective function (OF) of Equation 4 aims to prevent QCP from falling below the established limit while maximizing water savings and minimizing DFD. The optimization was performed using the minimize function from the *scipy.optimize* library (Virtanen et al., 2020). The objective function is subject to the constraints presented in Equations 1, 2, 3 and 5.

$$MDFD_i \leq DFD_i \leq LCP_i + 1 \quad (5)$$

The MDFD is the minimum downstream flow from the dam (m^3s^{-1}), and the upper limit DFD represents a margin to ensure that the optimization has a viable solution, allowing for the damping of the flow discharged by the equivalent reservoir. The Table 2 shows the MDFD for each reservoir.

Water allocation

Once the requirements were established at the control points, we employed a flow network model to compute the distribution of water in accordance with the predefined operational rules for the system. The tool used was LabSid AcquaNet 2013 to allocate

Table 2. Minimum downstream flow from the dam for each reservoir.

Reservoir	MDFD (m^3s^{-1})
JPS	4
JAG	0.25
CAC	0.125
ATA	0.125
PAI	0.1

MDFD: Minimum Downstream Flow from the Dam.

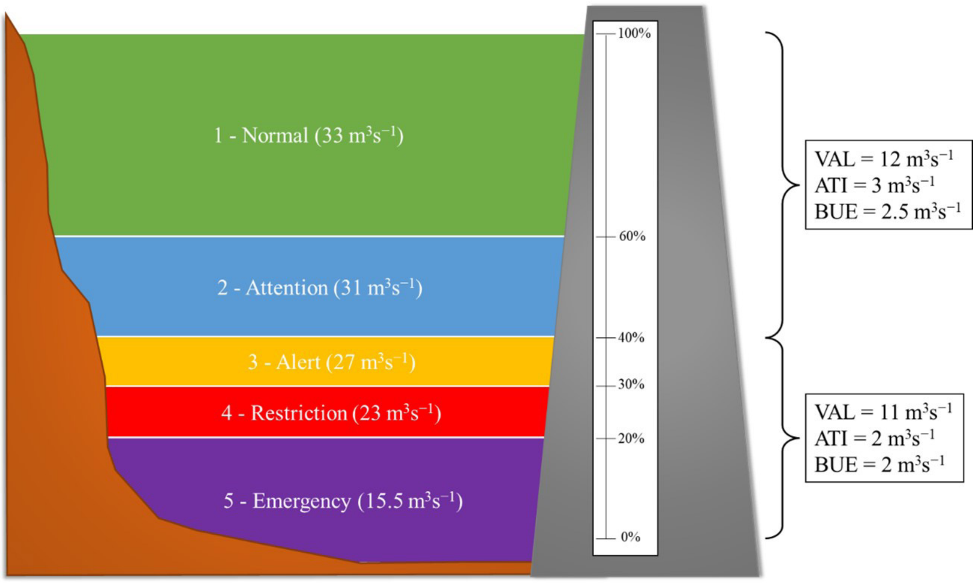

Figure 3. Operational rule of the Cantareira water production system.

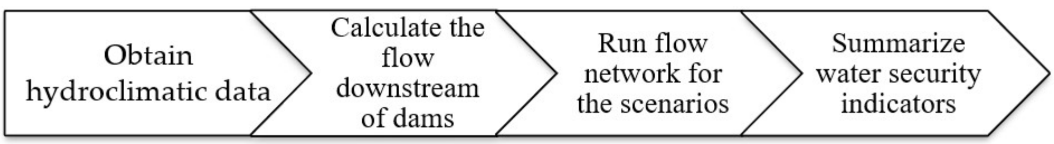

Figure 4. Flowchart of methods.

water to various points within the watershed to meet the demands of each point based on user-defined priorities. The key information required for the functioning of software are water system topology, runoff monthly average series at points of interest, physical information about system components (reservoirs, channels, water conveyance structures, pumping stations) and user-established priorities for demands and reservoir volumes (Porto et al., 2003).

The flow network is depicted using nodes and arcs, with nodes representing network points where flows converge or diverge, and arcs denoting the connections between nodes responsible for transmitting these flows. Flows, representing the amounts of water over time, serve as decision variables within the model. The model incorporates certain key assumptions, including constraints on the minimum and maximum transport capacities of arcs, a requirement that the sum of incoming flow quantities at a node equals the sum of outgoing flow quantities, and an assignment of costs to each arc associated with flow transportation (Carvalho et al., 2009).

The formulation of the optimization model is presented in the Equations 6 to 9.

$$\min \sum c_{ij} \cdot X_{ij,t} \quad (6)$$

$$L_{ij,t} \leq X_{ij,t} \leq U_{ij,t} \quad (7)$$

$$\sum X_{ij,t} = \sum X_{jk,t} \quad (8)$$

$$S_{w,t} = S_{w,t-1} + I_{w,t} - z_{w,t} - X_{ij,t} \quad (9)$$

Here, c_{ij} signifies the cost of transporting a single unit of flow through the arc *ij*, X_{ij} represents the flow quantity passing through this arc in the time t, L_{ij} denotes the minimum capacity of arc *ij*, and U_{ij} designates the maximum capacity of arc *ij*. Equation 6 represents the objective function, aimed at minimizing the overall cost of flow transportation across the network. Equation 7 is a constraint ensuring network capacity. Equation 8 represents the constraint imposed to ensure mass conservation when the flow where the flow that arrives at the node through the arc *ij* leaves it through the arc *jk*, and Equation 9 the balance of the reservoir *w*, on which *S* is the volume, *I* the inflow, *z* the overflow of the reservoir.

Due to its high efficiency, the Out-of-Kilter algorithm was employed. This algorithm, a primal-dual linear programming approach, has been specifically developed for the efficient resolution of cost minimization challenges within flow networks. A salient feature of the water allocation model is its automatic inclusion of several functions commonly used in watershed simulation, relieving users from manual programming, and its capability to handle a considerable number of variables.

Demands within the model can be categorized as either consumptive or non-consumptive. Fulfilling these demands depends on user-assigned priority values, which range from 1 to 99, with 1 indicating the highest priority. Notably, priorities (*P*) and costs (*C*) exhibit a one-to-one relationship ($C = 10 \cdot P - 1000$), ensuring that cost values are consistently negative. Hence, the model, when addressing a given priority, effectively reduces the network's cost by a factor of *C* per unit of supplied flow.

Reservoir operations are determined based on the concept of target volume or target level, to which a specific priority is assigned. Consequently, whenever the stored volume falls below this predetermined target, the reservoir initiates water storage, provided that no other network priorities supersede it.

Volumes stored above the target level incur zero cost, making them available to fulfill any demand, regardless of priority. Conveyance losses in channels and evaporation from reservoirs are factored into the model through an iterative process.

The optimization of the flow network model occurs at monthly intervals, with a sequential approach. However, it is important to highlight that in most flow network models, the optimization process is not dynamic, meaning it does not guarantee a global optimum for a future period spanning multiple time intervals.

RESULTS AND DISCUSSIONS

The average monthly flows observed and projected with the hydrological model for the SSP2-4.5 and SSP5-8.5 climate scenarios in the CWPS basins were grouped into the hydrological year (September to August) and shown in Figure 5. It is observed that the minimum runoff for the hydrological year for the group of basins with regulations in SSP2-4.5 scenario is 23.2 m^3s^{-1} and for SSP5-8.5 scenario 19.1 m^3s^{-1}. In summary, 25% and 38% lower than the worst hydrological year observed, respectively. The comparison of average flow between the time series is presented in the Figure 6. It is shown that the trend for any hydroclimatic change scenario is a decrease in the inflow discharge to the CPWS reservoirs. The SSP2-4.5 scenario has 25.7% less water availability, and the SSP5-8.5 scenario has 35.1% less compared to the observed values.

Tercini & Mello Júnior (2023) observed a decrease in the average annual precipitation projected in the GFDL-CM4 climate model compared to the observed precipitation. The SSP2-4.5 scenario showed a reduction of 45.4% and the SSP5-8.5 scenario 56.1%, consistent with Domingues et al. (2022), who reported a 50% reduction for the Jaguari River. They checked the tendency of the increase in drought frequency both in intensity and the number of months classified as dry (months of April to September), as well as in the magnitude of the drought. The reduction in projected precipitation resulted in a decrease in flows. In this study, the greatest

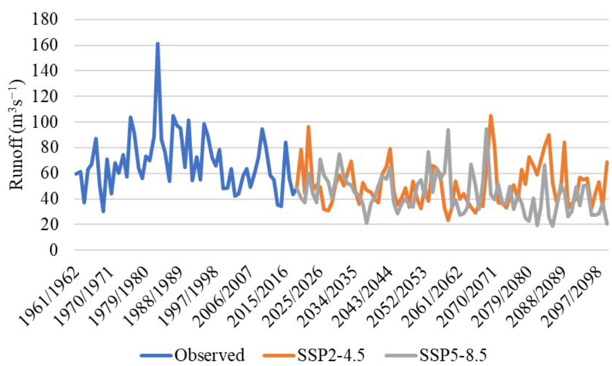

Figure 5. Time series observed and projected annual average flows with climate model GFDL-CM4 scenarios SSP2-4.5 and SSP5-8.5 in CWPS basins.

impact on projected flow occurred for the SSP5-8.5 scenario, which provided the greatest reduction in projected precipitation.

According to the Intergovernmental Panel on Climate Change (2023), the 50% percentage of annual average precipitation, evapotranspiration and runoff projected for warming levels above 2°C for the SSP5-8.5 scenario tends to decrease by 10%, 12% and 1% in the Paraná River basin, where CWPS is located. The differences in projection results are due to the uncertainty of the data sets, the spatial and temporal scales adopted and non-climatic factors.

The calculation of downstream flow from the dams to meet the control points considered the hydrological states predicted by the operating rule. The Figure 7 shows the time series of the sum of the discharges from JAG, CAC, and ATA basins.

The analysis of the time series in the Figure 7 shows a trend of increasing discharge volume from the dams to meet the control points. It is observed that the highest regulated discharge in the SSP2-4.5 scenario will be in 2057/2058 with 7.4 m^3s^{-1}, and in the SSP5-8.5 scenario, it will be in 2085/2086 with 9.4 m^3s^{-1}. In other words, it is 15% and 46% higher than the highest average discharge in the observed hydrological year in the SSP2-4.5 and SSP5-8.5 scenarios, respectively. The comparison between the average discharge of the time series and the operating rule is shown in Figure 8.

In Figure 8 is evident that the trend for any hydroclimatic change scenario is an increase in the discharge volume from the JAG, CAC, and ATA reservoirs of the CPWS. The SSP2-4.5 scenario has 47.9% more water demand, and the SSP5-8.5 scenario has 90.4% more compared to the values observed in the simulation for normal and alert operational rule conditions. For stages below alert, the downstream water demand from the dams is 48.5% and 94.0% higher compared to the observed scenario for SSP2-4.5 and SSP5-8.5, respectively.

The result of the AcquaNet flow network for the storage of CPWS reservoirs is presented in the Figure 9 and Figure 10.

The time series of stored water (Figure 9) shows that there would be no reservoir drying in the observed scenario, with the lowest simulated volume being 176.1 hm^3 in November 2015. The simulation for the SSP2-4.5 projection indicates three events where the reservoirs would dry up, but they remain dry for a maximum of two consecutive months. The SSP5-8.5 scenario indicates a higher tendency for the reservoirs to dry up, with the simulation accounting for eleven events, and in the most critical event, the reservoirs remain dry for nineteen consecutive months.

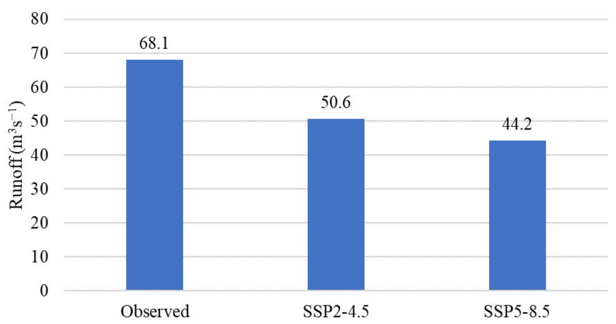

Figure 6. Comparison between observed and projected average flows with climate model GFDL-CM4 scenarios SSP2-4.5 and SSP5-8.5 in the CWPS.

The exceedance curve of the different scenarios highlights the trend of storage reduction. At the 50% exceedance level, the volumes would decrease from 1572.7 hm^3 (88.6%) to 564.3 hm^3 (31.8%) and 351.4 hm^3 (19.8%) in the SSP2-4.5 and SSP5-8.5 scenarios, respectively. At the 90% exceedance level, the values would drop from 856.4 hm^3 (48.3%) to 154.5 hm^3 (8.7%) in the SSP2-4.5 scenario and to 4.1 hm^3 (0.2%) in the SSP5-8.5 scenario. The outcome of the water allocation for the water supply and downstream conditions is shown in the Table 3.

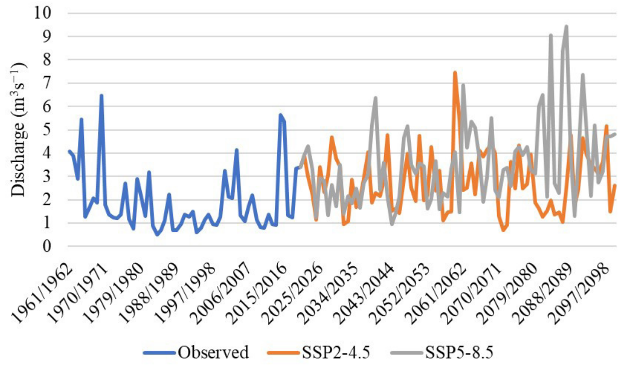

Figure 7. Time series of observed and projected annual flow scenarios downstream of the JAG, CAC, and ATA reservoirs for the normal and attention stages.

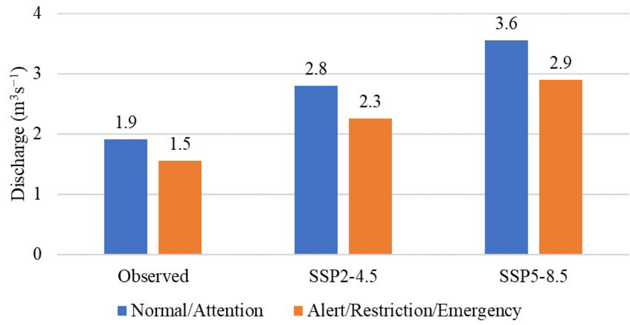

Figure 8. Comparison between observed and projected average downstream flows of the JAG, CAC, and ATA reservoirs.

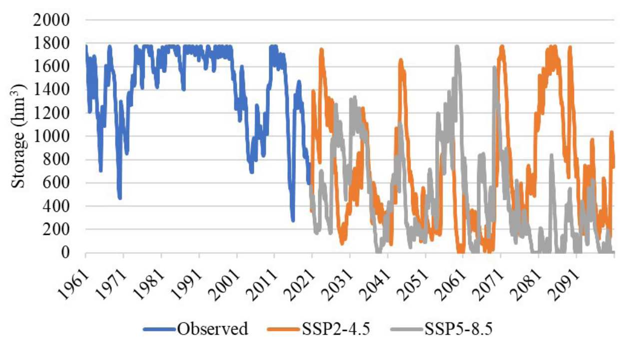

Figure 9. Observed and projected, SSP2-4.5 and SSP5-8.5 scenarios, storage time series in CWPS reservoirs.

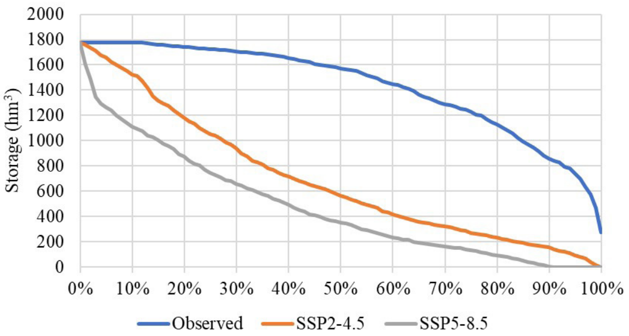

Figure 10. Storage duration curve for CWPS reservoirs for projected and observed scenarios.

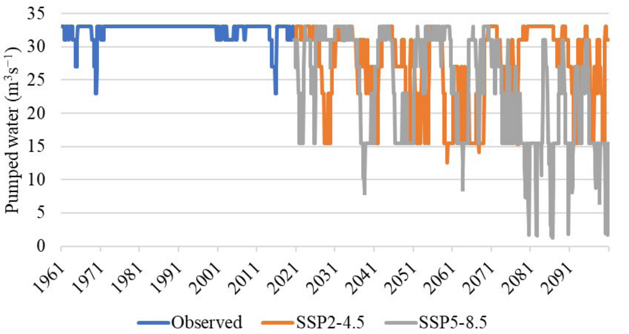

Figure 11. Pumped water in SIPS.

Regarding water demands, the SIPS shows no deficits in the observed scenario, in the SSP2-4.5 scenario, it not only reduces the required demand but also experiences one month of deficits, and in the SSP5-8.5 scenario, the situation worsens with 10 months of deficits. The pumped flows in SIPS are presented in the Figure 11. Energy generation in HPP is also affected, going from 3 months of deficits to 11 and 31 months in the SSP2-4.5 and SSP5-8.5 scenarios, respectively. In the most critical scenario, the minimum flow reaches zero, meaning no energy generation. Downstream flows from the dams, despite having top priority, also face an impact in the SSP5-8.5 scenario, where 6 months of meeting these requirements will be affected.

The Figure 11 highlights the trend of decreasing flow supplied for the MRSP water supply, as the operational rule is related to storage. Even though the rule aims to save water to prevent deficits, they occur more frequently in the SSP5-8.5 scenario. The average pumped flow decreases from 32.4 m^3s^{-1} in the observed scenario to 27.1 and 23.5 m^3s^{-1} m^3/s in the SSP2-4.5 and SSP5-8.5 scenarios, respectively. The Figure 12 displays the duration of the operational rule stages and failures for each scenario.

The current water supply, which is typically considered normal, drops significantly from 82.3% in the observed scenario to 25.2% in the SSP2-4.5 scenario and 14.1% in the SSP5-8.5 scenario. Emergency situations, which do not occur in the observed scenario, become frequent, occurring 16.0% of the time in the SSP2-4.5 scenario and 30.7% of the time in the SSP5-8.5 scenario. Furthermore, the SSP5-8.5 scenario experiences a 6.6% failure rate in meeting emergency flow requirements, potentially leading to a collapse of the current MRSP water supply planning.

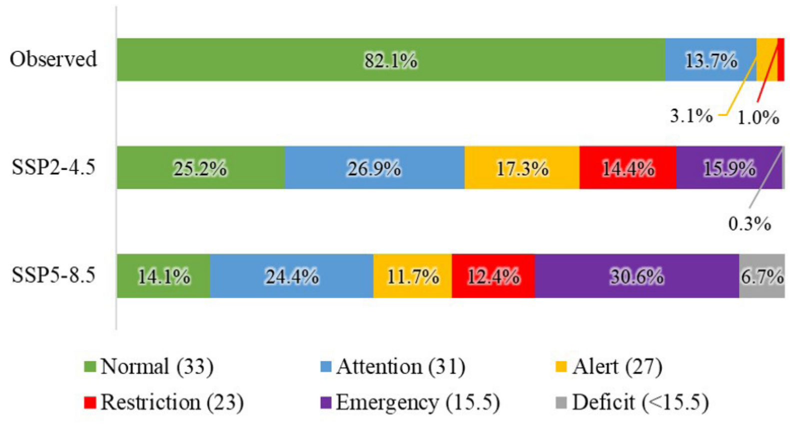

Figure 12. Duration of the operational rule stages, pumped water, and failures for observed scenario (1961 to 2020) and projected scenarios (2020 to 2100) scenario in SIPS to supply MRSP.

Table 3. Demand indicator of the water allocation.

Demand indicator	SIPS			HPP			Downstream flows		
	a	b	c	a	b	c	a	b	c
Maximum time below required demand (month)	0	1	10	3	11	31	0	0	6
Frequency below required demand (%)	0.0	0.2	6.6	0.4	21.9	35.5	0.0	0.0	1.5
Required average demand (m^3s^{-1})	32.4	27.2	24.1	20.0	20.0	20.0	6.0	6.6	7.3
Average flow rate supplied (m^3s^{-1})	32.4	27.2	23.6	20.0	18.6	16.9	6.0	6.6	7.2
% of average required demand	100	100	97.9	99.9	93.2	84.7	100	100	99.2
Minimum flow rate supplied (m^3s^{-1})	23.0	12.5	1.3	10.1	4.0	0.0	4.6	4.6	0.6

a: Observed, b: SSP2-4.5, c: SSP5-8.5, SIPS: Santa Inês Pump Station and HPP: Hydroelectric Power Plant.

CONCLUSIONS

This study investigates the pressing issue of hydro-climatic change and its ramifications for the CWPS, the primary water source for 14 million people in Brazil. Utilizing the Database for Policy Decision-Making for Future Climate Change, the research, employing flow network model to evaluate the current water resource management systems, highlighting the increased vulnerability of the CWPS to water scarcity. The results unveil significant challenges and potential impacts on water resources in the MRSP, with observed and projected flows indicating a concerning decrease in water availability, particularly under the SSP5-8.5 scenario.

The downstream flow from the dams, as regulated by the operating rule, is also affected. The projected scenarios predict a substantial increase in regulated discharge volumes. The water allocation simulations underscore the potential risks of reservoir drying. Water demand and the operation of the SIPS indicates that the transition from the observed scenario to the SSP2-4.5 and SSP5-8.5 scenarios results in a marked reduction in the percentage of the water supply considered normal, dropping significantly from 82.3% to 25.2% and 14.1%, respectively. These simulations emphasize the importance of initiative-taking strategies to maintain water security.

The findings underscore the critical importance of addressing the impacts of hydroclimate change on water resources and the necessity for adaptive measures to ensure the continued provision of water supply for the MRSP and conflict with energy generation. These results can serve as a foundation for informed decision-making and the development of policies to address these challenges effectively. It is imperative that such initiatives consider the uncertainties inherent in climate data and non-climatic factors, thus emphasizing the need for comprehensive, resilient water resource management strategies.

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