Drought Contingency Plan for São Paulo Based on the 2014-2016 Water Crisis

Tomás Schmieder [a] & Maoz Bizan [a]
[a] *School of Civil and Environmental Engineering, Cornell University*
(tas274@cornell.edu & mb2389@cornell.edu)

Abstract: The São Paulo Metropolitan Region (SPMR) experienced a historic Water Crisis during a 2014-2016 drought, exposing the vulnerabilities of its primary water supply source, the Cantareira System. This report proposes a new drought contingency plan to enhance the system's ability to meet the growing water demands of SPMR while maintaining its resilience during prolonged droughts. Using a mass-balance model that integrates storage and inflow data from the system's key reservoirs, the study optimizes water release policies through a genetic algorithm. Two critical performance indicators—reliability and resilience—were used to evaluate the improved system functionality. The optimized plan maintains higher storage levels during drought conditions and balances trade-offs between water demand reliability and system resiliency. While the plan improves overall drought preparedness, further refinements are necessary to mitigate deficits during non-drought periods. Trade-offs in balancing system reliability and resilience are discussed, offering actionable insights for improving long-term water resource management for SPMR.

***Keywords**:* drought; optimization; water resources; resilience, reliability

1 INTRODUCTION

Providing water for SPMR has been a significant challenge throughout the city's history. The region has experienced intense population growth over the last two centuries, and accordingly, a massive increase in water demand. Zuffo et al note that development in the SPMR and across Brazil has reduced rainfall and polluted water sources, further straining the growing region's water needs [2023].

According to Zuffo et al, during the 1970s, the Cantareira System was built to solve the SPMR's water needs. The system sources water from tributaries in the Piracicaba (PCJ) River Basin and transfers it to the Alto Tiete Basin, where it can provide a water supply for the SPMR. The system comprises six reservoirs, including four in the PCJ basin [2023].

The Cantareira System has experienced numerous instances of extreme scenarios, both floods and droughts. Notably, the System faced a major flood in 1983, and a major drought in the early 2000s. In 2014, the SPMR faced a historically unprecedented drought which was beyond the limits considered when designing the Cantareira System and developing its management strategy. During the drought, rainfall levels in the SPMR were abnormally low. Its effect on the Cantareira System led to the 2014 Water Crisis, as detailed by Zuffo et al [2023].

During the water crisis, the Cantareira System was unable to meet the SPMR's demand, causing shortages of water for agricultural and potability purposes. Zuffo et al comment that due to the natural conditions, but also the System's management, water storage was nearly depleted by 2014 [2023]. Revising Cantareira's operating policy can boost the System's ability to withstand future droughts and extreme climate conditions.

A new contingency plan should meet these two objectives:

1. Reliability: increase outflow efficiency by adapting the system to meet the demands of a growing population while optimizing water distribution

2. Resiliency: prevent reservoir depletion by ensuring that reservoir levels remain above critical thresholds during prolonged droughts

This report defines a new reservoir model, optimizes adjustments to system outflows using a genetic algorithm, and establishes a new, dynamic control policy based on reservoir capacity percentages. This ensures sustainable water use without compromising long-term storage.

2 METHODOLOGY

2.1 Model Development

Of the six reservoirs making up the Cantareira System, only two account for 88% of the Cantareira System's total storage capacity. According to Zuffo et al, these reservoirs, Atibainha and Jaguari-Jacareí, both lie within the PCJ basin [2023]. Treating these as one unified reservoir with combined inflows and storage capacity maintains the core components of the Cantareira System and enables the development of a new control policy for the System.

The model employs a mass balance to simulate the storage and flow of the combined reservoir:

$$s_{t+1} = s_t + p_t + i_t - u_t^d \tag{1}$$

Precipitation for the combined reservoir is the sum of the precipitation over the surface area of the two constituent reservoirs, and inflow is the sum of river discharges into the two constituent reservoirs. Release for the combined reservoir is equivalent to outflow from the entire Cantareira System, not from one particular reservoir. The release is determined by the operating policy, and in 2014, was limited to a maximum of 33 m^3 s^{-1}. Evaporation is not explicitly balanced and is accounted for by a coefficient that precedes the inflow value.

2.1 Operating Policy

The operating policy comprises of the water released to meet demand, u_t^d, at each timestep t. The management action vector is defined as:

$$u_t = [u_t^d] \tag{2}$$

2.2 Indicators

The gap between the water demand of the SPMR and water supplied by the Cantareira System is represented as the deficit, d_t^w, with respect to the water demand of SPMR, d^w, which is equal to 2.8512 hm^3 day^{-1}:

$$d_t^w = \begin{cases} d^w - u_t^d, & if\ u_t^d < d^w \\ 0, & otherwise \end{cases} \tag{3}$$

When the water released does not meet demand, the system is in a deficit and does not satisfy SPMR users. Using the operating policy, defining indicators for the model enables an understanding of how well the Cantareira System is meeting its designed requirements.

2.2.1 Reliability

Reliability describes whether the model meets the demand of the SPMR system. The indicator is a function of the deficit and the operating policy – the volume of water released to supply the SPMR:

$$I_{reliability,t} = f(u_t^d) = \frac{u_t^d}{d^w} \tag{4}$$

A higher reliability number means that the system is meeting the water demand, whereas a lower reliability number means that the system is failing to meet the water demand.

2.2.2 Resiliency

Resiliency describes how effective the system is at mitigating decreased inflows during droughts. The indicator is a function of the reservoir storage levels relative to $s_{critical}$, the critical threshold level:

$$I_{resilience,t} = f(s_t, s_{critical}) = \frac{s_t - s_{critical}}{s_{critical}} \tag{5}$$

The critical storage level, $s_{critical}$, is defined as 20% of the system's total capacity. We have defined the total capacity of our system to be the combined storage capacity of the Jaguari-Jacareí and Atibainha reservoirs, with a value of $s_{max} = 1685\ hm^3$. Therefore $s_{critical} = 337\ hm^3$. A higher resilience value indicates that the system is above the critical storage level and is doing well to mitigate the effects of a drought. A negative and lower number means that the storage levels are below or close to the critical storage level, and the system risks failure.

2.3 Current Contingency Plan

The outflow of the system, u_t^d, depends on the percent volume of the system. We can define this proportion as:

$$V_t = f(s_t, s_{max}) = \frac{s_t}{s_{max}} \tag{6}$$

The current contingency plan for water release is based on these decisions, as shown by Deusdará-Leal et al. [2020]:

$$u_t^d = \begin{cases} 2.8512, & if\ V_t \geq 0.6 \\ 2.6784, & if\ 0.6 \geq V_t \geq 0.4 \\ 2.3328, & if\ 0.4 \geq V_t \geq 0.3 \\ 1.9872, & if\ 0.3 \geq V_t \geq 0.2 \\ 1.3392, & if\ V_t \leq 0.2 \end{cases} \tag{7}$$

With the current contingency plan and historical data, average values for the indicators over the given data period can be found:

$$\frac{1}{N}\sum_{t=1}^{N} I_{reliability,t} = 0.847 \tag{8}$$

$$\frac{1}{N}\sum_{t=1}^{N} I_{resilience,t} = 1.165 \tag{9}$$

2.4 Objective Function

These indicators are combined into an objective function to represent the system's overall degree of functionality:

$$Objective = Maximize \begin{cases} \frac{1}{N}\sum_{t=1}^{N} I_{reliability,t} \\ \frac{1}{N}\sum_{t=1}^{N} I_{resilience,t} \end{cases} \tag{10}$$

Altering the outflows changes the values of the indicators, and can maximize the objective function, creating a new, improved contingency plan. To improve upon the current values of reliability and resilience, the contingency plan must be altered in a way that can adjust the average values of resilience and reliability to create the highest value possible for the objective function.

2.5 Decision Variables

The new operating policy can be defined as following the format from the original operating policy:

$$u_t^d = \begin{cases} o_1, & if\ V_t \geq b_1 \\ o_2, & if\ b_1 \geq V_t \geq b_2 \\ o_3, & if\ b_2 \geq V_t \geq b_3 \\ o_4, & if\ b_3 \geq V_t \geq b_4 \\ o_5, & if\ V_t \leq b_4 \end{cases} \tag{11}$$

Using our objective function, we can define our decision variables as the thresholds and outflows that define the outflow policy:

$$\boldsymbol{\theta} = \{o_1, b_1, o_2, b_2, o_3, b_3, o_4, b_4, o_5\} \tag{12}$$

Where b_1, b_2, b_3, b_4 are the thresholds for the storage percentages, and o_1, o_2, o_3, o_4, o_5 are the corresponding outflows for each threshold.

2.6 Constraints & Penalties

Constraints are necessary to ensure the feasibility of the decision variables. Thresholds must progressively decrease, outflows must be non-negative, and the storage of the system is bounded between 0 and maximum storage capacity, s_{max}:

$$b_1 > b_2 > b_3 > b_4 \tag{13}$$
$$o_1, o_2, o_3, o_4, o_5 \geq 0 \tag{14}$$
$$0 \leq s_t \leq s_{max} \tag{15}$$

Penalties for unrealistic reliability and resiliency values, and excessively high outflow values, are also incorporated to ensure that the model remains feasible and realistic.

Using these constraints and data gathered on inflows, precipitation, and historical storage levels, the operating policy can be optimized to maximize the objective function. This represents a new contingency plan to reliably meet the water demand of SPMR and resist the effects of a drought.

2.7 Optimization

Using a Non-dominated Sorting Genetic Algorithm II (NSGA-II), the value of the objective function, determined by the two indicators, can be optimized. To maximize the objective function, the nine decision variables within $\boldsymbol{\theta}$ are changed, creating a multi-objective optimization problem. In changing the decision variables, the values of the indicators are changed, and a new value for the objective function is determined.

For the optimization, the indicators were normalized to have a maximum value of 1, and the utopia point was set to be (1,1), where:

$$\frac{1}{N}\sum_{t=1}^{N} I_{reliability,t} = 1 \tag{16}$$

$$\frac{1}{N}\sum_{t=1}^{N} I_{resilience,t} = 1 \tag{17}$$

The NSGA-II was run for the Cantareira System model using an initial population size of 1000 across 250 generations to find the Pareto front. The closest Pareto-efficient point to the utopia point was determined to be the optimal solution for a new contingency plan.

3 RESULTS & DISCUSSION

3.1 Optimized Contingency Plan

The Pareto front with all individual values found is shown below, demonstrating the trade-off between drought resilience and water demand reliability.

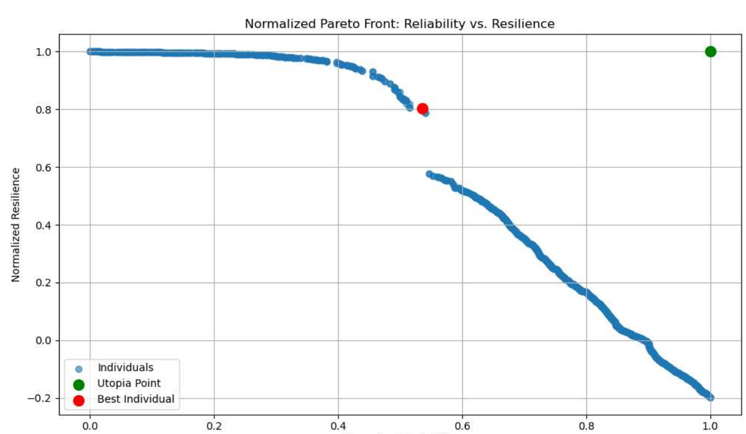

Figure 1. Pareto Front for Resilience and Reliability

The closest individual to the utopia point thus forms the new contingency plan, which is then used to calculate the balanced individual's reliability and resilience:

$$u_t^d = \begin{cases} 4.965, & if\ V_t \geq 0.821 \\ 0.053 & if\ 0.821 \geq V_t \geq 0.382 \\ 2.961, & if\ 0.382 \geq V_t \geq 0.316 \\ 2.678, & if\ 0.316 \geq V_t \geq 0.100 \\ 1.893, & if\ V_t \leq 0.100 \end{cases} \tag{18}$$

$$\frac{1}{N}\sum_{t=1}^{N} I_{reliability,t} = 0.938 \tag{19}$$

$$\frac{1}{N}\sum_{t=1}^{N} I_{resilience,t} = 3.127 \tag{20}$$

The optimized reservoir storage levels under the new operating policy can be depicted over time in comparison to the historical storage levels.

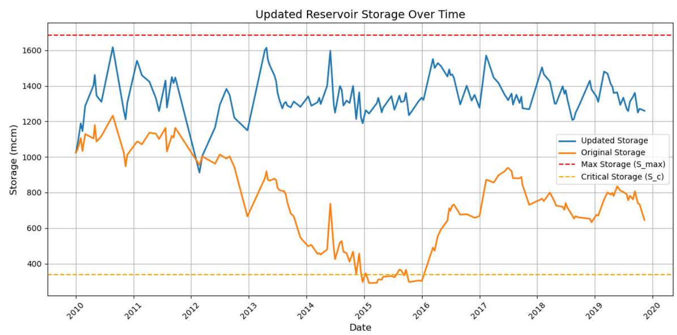

Figure 2. Historical vs. New Storage Levels

The System's outflow and deficit can also be depicted over time in comparison to the historical outflow and deficit over time.

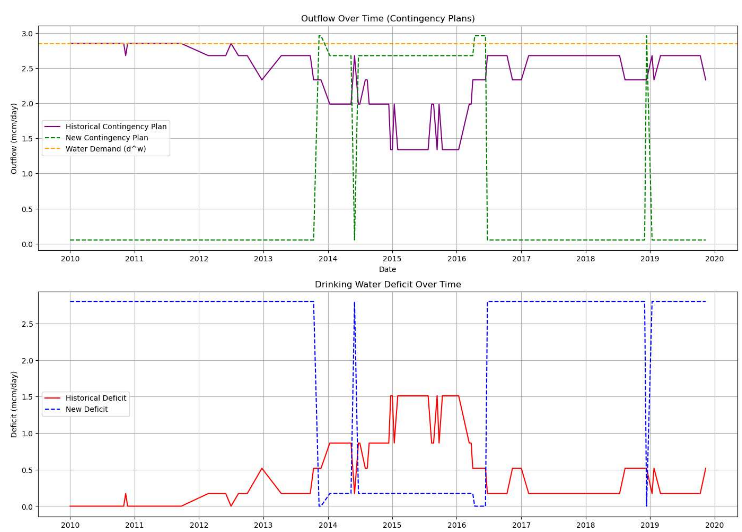

Figure 3. Outflow and Deficit vs. Time

3.2 Discussion

Figure 2 shows the historical storage levels in comparison to the storage levels calculated using the new contingency plan and thresholds. The new contingency plan does an improved job of keeping the storage levels higher and drought-resilient.

Figure 3 illustrates the difference between the historical and new outflow and deficit over time. Under the revised contingency plan, the outflows are much lower compared to that of the historical levels, and there are much higher deficits except during the drought. Although the new contingency plan significantly improves resiliency, it struggles to reliably supply water to SPMR due to the outflow being relatively low.

However, the value of the objective function is still higher than under the original contingency plan. This can be considered an improvement to the Cantareira System's operating policy and would be effective in reducing some of the consequences posed by a scenario such as the 2014-16 Water Crisis.

3.3 Discrepancies

Despite this model's overall effective representation of the Cantareira System, discrepancies in this characterization may cause some errors in the final optimization and are important to note.

The Atibainha and Jaguari-Jacareí reservoirs comprise the overwhelming majority of the storage volume of the Cantareira System, but these are only two of the system's six constituent reservoirs. Therefore, including the other four reservoirs in this model would likely maintain similar results, but could yield slightly different optimal solutions. Similarly, modeling the system as one large reservoir rather than six individual constituents neglects any impact on the system that may result from water transfer between different reservoirs or across different basins, rather than just within the PCJ basin.

Genetic algorithms are largely an effective tool for multi-objective optimization. However, each trial of running a genetic algorithm yields slightly different results due to the nature of these algorithms. The results in this paper can largely be replicated but may contain some very slight differences. This effect can be reduced by choosing a suitably large number of individuals and generations but cannot be eliminated entirely. Therefore, the contingency plan presented in this paper may not be the absolute optimal solution, but still represents a significant improvement.

4 CONCLUSIONS

This paper presents an optimized contingency plan for droughts affecting the Cantareira System serving the SPMR, addressing major challenges caused by the System's operating policy leading to the 2014-16 Water Crisis. The policy increases the Cantareira System's resiliency during extended drought periods while maintaining a similar, albeit slightly decreased, level of reliability for its consumers.

While this new contingency plan improves the balance of these objectives, it includes some trade-offs, particularly with the slight decrease in reliability. More refinement and reconnaissance on the nuances of stakeholder needs can enable further optimization of this solution. However, the reliability of the Cantareira System was already not sufficient to meet the SPMR's demands during the 2014-2016 Crisis, and the new plan improved the System's performance during similar crises.

Further study can inform a more holistic contingency plan for the SPMR's water security during periods of drought. Including other methods into a contingency plan, such as insurance policies or new infrastructure projects such as a water storage bank, is beyond the scope of this paper, but can drastically improve the region's water security and certainly warrant further exploration.

NOTATIONS AND UNITS

u_t	management action
u_t^d	outflow released at time t
d^w	demand of the SPMR system, constant
d_t^w	deficit at time t
p_t	precipitation at time t
i_t	inflow at time t
s_t	storage at time t
$s_{critical}$	critical storage, constant
V_t	percent of storage at time t
$I_{reliability,t}$	reliability indicator at time t
$I_{resilience,t}$	resilience indicator at time t
θ	outflow policy
b_1, b_2, b_3, b_4	threshold percentages
o_1, o_2, o_3, o_4, o_5	outflows for plan

REFERENCES

De Freitas, G.N., São Paulo drought: trends in streamflow and their relationship to climate and human-induced change in Cantareira watershed, Southeast Brazil, *Hydrology Research*, 51(4), 750–767, 2020.

De Souza Leão, R. and De Stefano, L., Making concrete flexible: Adapting the operating rules of the Cantareira water system (São Paulo, Brazil), *Water Security*, 7, 100032, 2019.

Deusdará-Leal, K.R. *et al.*, Implications of the New Operational Rules for Cantareira Water System: Re-Reading the 2014-2016 Water Crisis, *Journal of Water Resource and Protection*, 12(04), 261–274, 2020.

Domingues, L.M. and Da Rocha, H.R., Serial droughts and loss of hydrologic resilience in a subtropical basin: The case of water inflow into the Cantareira reservoir system in Brazil during 2013–2021, *Journal of Hydrology: Regional Studies*, 44, 101235, 2022.

Food and Agriculture Organization of the United Nations (FAO), "AQUASTAT Dams Database." [Online].

Funk, C.C. *et al.*, *A quasi-global precipitation time series for drought monitoring*. Report 832. Reston, VA, 12, 2014.

G. S *et al.*, "GloFAS v4.0 hydrological reanalysis," 2022.

Kelman, J. *et al.*, *Crise Hídrica, Estratégia e Soluções da Sabesp*. Sabesp, 2015.

Lehner, B. and Grill, G., Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems, *Hydrological Processes*, 27(15), 2171–2186, 2013.

Lehner, B. *et al.*, High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management, *Frontiers in Ecology and the Environment*, 9(9), 494–502, 2011.

S. Galelli and S. S. Mahto, *InfeRes*. (Jun. 06, 2024). Python. Critical Infrastructure Systems Lab. [Online].

Sabesp, Sistema Cantareira: Plano de Contingência II - Ações Contingenciais e Resultados, 2014.

Zuffo, A.C. *et al.*, The Cantareira System, the Largest South American Water Supply System: Management History, Water Crisis, and Learning', *Hydrology*, 10(6), 132, 2023.