LONG-TERM WATER SECURITY OF METROPOLITAN REGIONS: ASSESSMENT OF WATER SUPPLY SYSTEMS

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ABSTRACT

Over the 21st century, climate change will most likely impact hydrological drought trends around the world. The temporary reduction in water availability triggers public pressure for action, which in the short-term can then result in the expansion of reservoirs to increase water availability. However, the problem becomes more challenging if the long-term socioeconomic vulnerability and damage to ecosystems are taken into account. The systemic understanding of the complex interactions triggered by these components in the water supply system of these regions, especially in the long-term horizon, is essential to define more efficient operational strategies for these systems. Thus, this paper presents the development of a generic system dynamic model for the analyses of interactions between reservoir operational policies and water supply systems in metropolitan regions. The developed reservoir system dynamics approach is applied to the Cantareira system, which supplies approximately 9 million inhabitants in the metropolitan region of São Paulo, Brazil. For the period between the years 2009 and 2016, which comprises the worst water crisis experienced in the region (2013 to 2015), scenarios of reservoir operation policies was simulated. The results suggest that the developed model is capable to provide a practical means for identifying plausible long-term trends for water supply systems in metropolitan regions and under the effects of external drivers such as changing climatic and demand.

Keywords: water security; water supply; reservoir operation policies; climate change; water demand.

1 INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC, 2014), climate projections suggest scenarios of longer and more frequent droughts for South America. In Brazil, the Southeast region has been affected by prolonged droughts in recent years (Coelho et al. 2016; Nobre et al. 2016), making evident the need to evaluate integrated water resource management tools to develop climate change adaptation strategies.

Current systems analysis in water resources systems addresses the most challenging water issues of our times, including water scarcity and drought, climate change, water supply for food and energy production, decision making amidst conflicting objectives, and economic incentives for water use (Brown et al., 2015).

In water supply systems, traditional approaches to system planning and water resources management, do not consider the feedback relationships between the water and socio-economic dimensions in the water supply-demand cycle. According to Garcia et al. (2016), these approaches typically cannot provide insight into how different patterns of natural variability or human-induced changes can propagate through this coupled system, since there is no consensus on universally accepted laws of human behavior like the laws that exist for physical systems.

In the years 2013 to 2015, the southeastern region of Brazil suffered a severe water crisis (Marengo et al. 2020; Nobre et al. 2016). According to Coutinho et al. (2015), the volume of water in the Cantareira system, the principal water supply system of the São Paulo Metropolitan Area — SPMA, decreased significantly since mid-2013, the storage capacity of the reservoir was depleted in July 2014. Then, the Water and Sanitation Company of the State of São Paulo (SABESP) began to reduce withdrawals in January 2014.

Thus, this paper presents the development of a generic system dynamic model for the analysis of interactions between reservoir operational policies and water supply systems in metropolitan regions. For this purpose, some relationships that can influence the supply-demand cycle are structured. In a regional context, these improvements are applied to the Cantareira system, considering a socio-ecological framework in the analysis of hydroclimatic trends accomplished by choosing a trigger value of reduction demand, adopting the System Dynamics (SD) approach (Forrester, 1961; Sterman, 2000).

2 STUDY AREA

This study is delimited at the regional level, focusing on the water balance, hydroclimatic and socio-economic trends, associated with the vulnerability of the water supply system.

SPMA is located in the state of São Paulo in southeastern Brazil, approximately 600 km southwest of Rio de Janeiro and 80 km inland from the Atlantic Ocean (Figure 1). Almost 60% of the population lives in the city of São Paulo, resulting in one of the highest population densities in the country, about 7220 inhabitants per square kilometer. The city accounts for 12% of Brazil's national GDP ($1,648,870) and twice as much as Brazil's GDP per capita (Marengo et al. 2020).

Operated by SABESP, a series of channels and reservoirs form the Cantareira system (Figure 1). These structures capture and redirect water from some rivers in the Piracicaba, Capivari, and Jundiaí (PCJ) to the Alto Tietê (AT) basin, and can serve approximately 9 million inhabitants (ANA, 2016; Nobre et al. 2016).

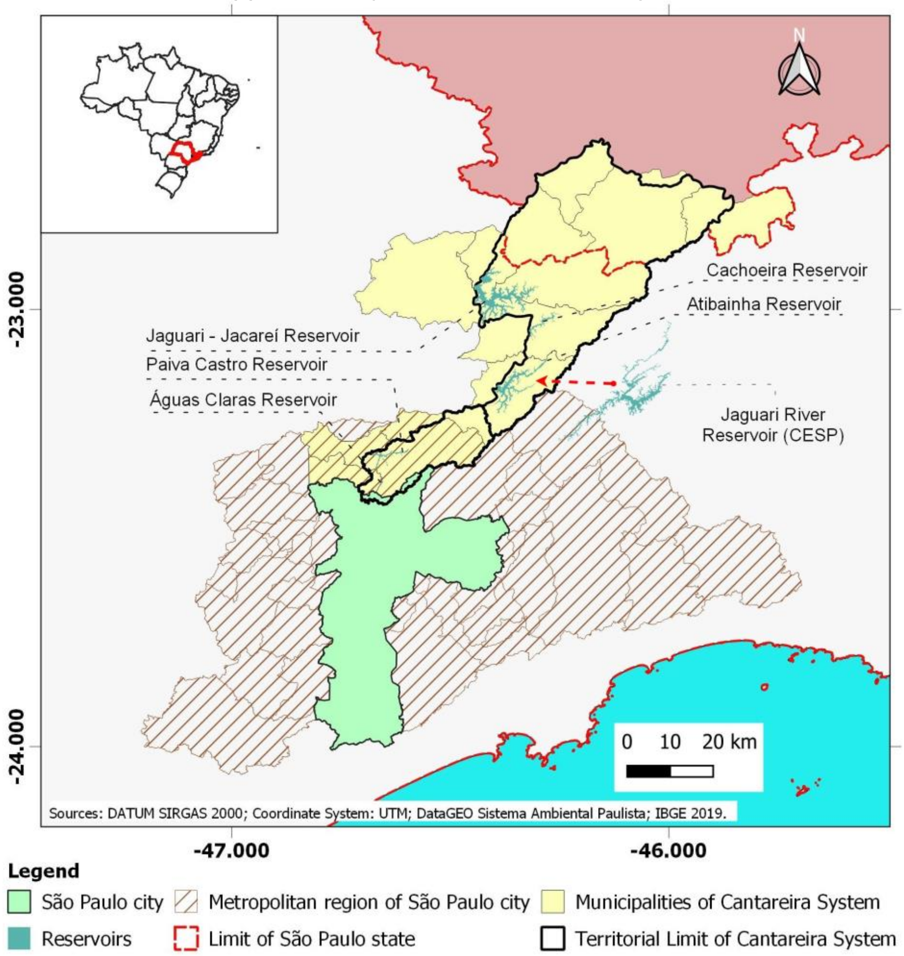

Figure 1. Regional context of the study area. (Highlighted in the red arrow is the connection between the Jaguari River and Atibainha reservoirs, in the Cantareira system).

The Jaguari river reservoir, on the other hand, belongs to the PS basin (Figure 1) and is managed by CESP, which includes power generation. According to SABESP (2015), the operational volume of Jaguari is 793 hm^3 (equivalent to 81% of the total useful volume of Cantareira) and its long-term average flow rate is 28 m^3/s (63% of the average natural inflow of Cantareira), besides having a high detention time (10.8 months).

3 METHODOLOGY

In this section, a generic reservoir model is developed for the systemic analysis of operational policies. The modeling strategy proposed by Jiang and Simonovic (2020) will allow assessing water supply systems. Involves a causal diagram of the long-term water security of metropolitan regions to map and analyze the main interactions between the components of the reservoir, and the development of the simulation model using a stock and flow diagram.

3.1 Causal loop diagram of a reservoir system: long-term water security

The continuous supply of abundant water in a region in a water shortage can generate a message to users about its water development potential (Mirchi et al. 2012). Considering a long-term analysis, while water resources are being depleted, the increase in development and demand for water may cause a more severe shortage.

These characteristics of the system obey the archetype of the type “Fixes that Backfire” (Figure 2). According to Gohari et al. (2013), the persistent water shortage is mainly due to the presence of an unresolved loop (R), which creates a vicious supply-development-demand cycle.

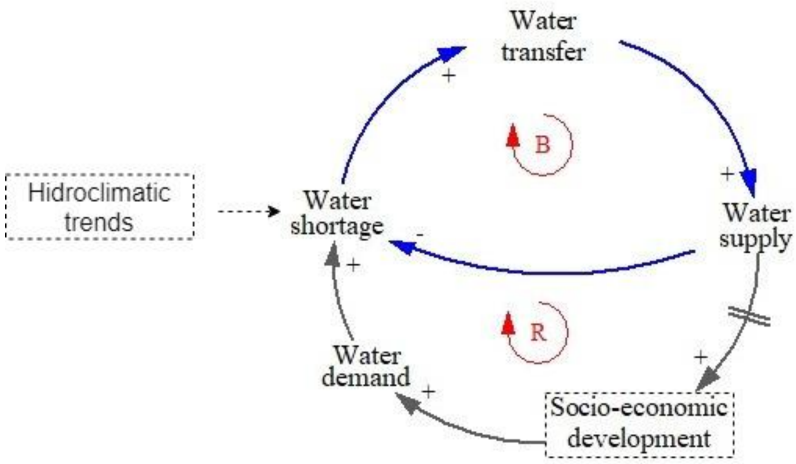

Figure 2. Under external drivers (hidroclimatic and socio-economic trends), the feedback loop with short-term water shortage reduction (B), and long-term water security (R), considering the time delay.

3.2 Stock and flow diagram of a reservoir system

The development of a generic reservoir model considers Jaguari-Jacarei reservoirs, Cachoeira, and Atibainha, as the single reservoir. The Cantareira operation considers the target demand (31 m³ / s) for the SPMA, the minimum required flow downstream of the system, in the PCJ basin for the period (2009 to 2016). To incorporate external drivers, the reservoir model considers the simplified water balance equation used in Cantareira ANA (2016), according to Eq. [1].

$$V(t) = V(t-1) + I(t) - RS(t) - RP(t) \qquad [1]$$

where $V_{(t-1)}$ = volume stored at the end of the month (t-1); $V_{(t)}$ = volume stored at the end of month (t); $I_{(t)}$ = turnout during month (t); $RS_{(t)}$ = water volume to supply the RMSP in the month (t); $DP_{(t)}$= volume that follows downstream of Cantareira (PCJ basin) in a month (t), according to (ANA, 2017).

3.3 Configuration of the simulation model and scenarios

Assessing the operating policies at the reservoir, the conceptual model in Figure 3 represents the characteristics adopted for development of a generic reservoir model.

Considering the water crisis period, a demand reduction scenario were considered. A target demand is admitted. The operational strategies are applied in the period (2009 to 2015). The reference scenario considered exclusively the inflow of the PCJ basin and the meeting of the target demand.

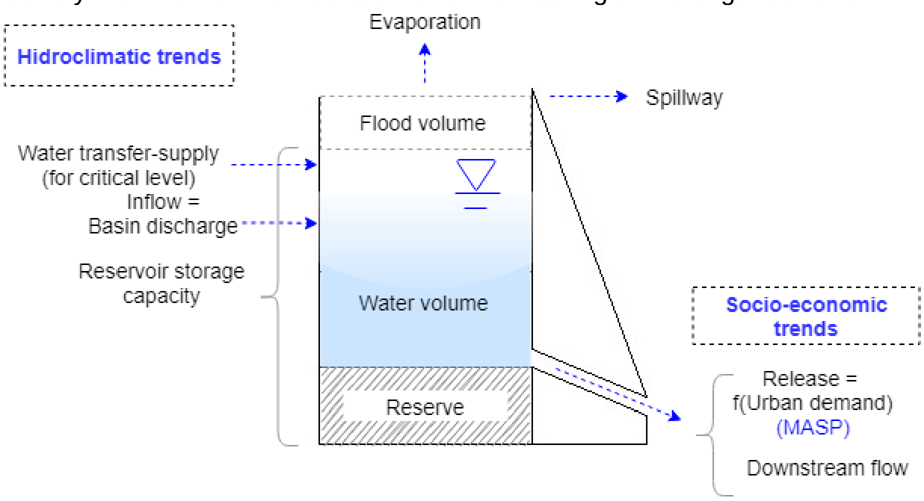

Figure 3. Conceptual model of a single reservoir.

"Basin discharge" considers observed data (GET XLS DATA()). The downstream control conditions parameters are: "Minimum required flow downstream" (= 10 m³/s); spillway conditions; target demand (= 31 m³/s); and "Average flow" considered is (= 20 m³/s).

The reservoir behavior for the proposed operation scenarios was analyzed from simulation using the Software Vensim PLE Plus 6.4, the numerical approximation method adopted was the Runge-Kutta of fourth-order (details of the model are presented in Table 2).

A socio-ecological system (SES) framework (McGinnis, and Ostrom, 2014) is applied to establish the model identify the relevant processes and then the variables and their relationships in water supply systems (Figure 4).

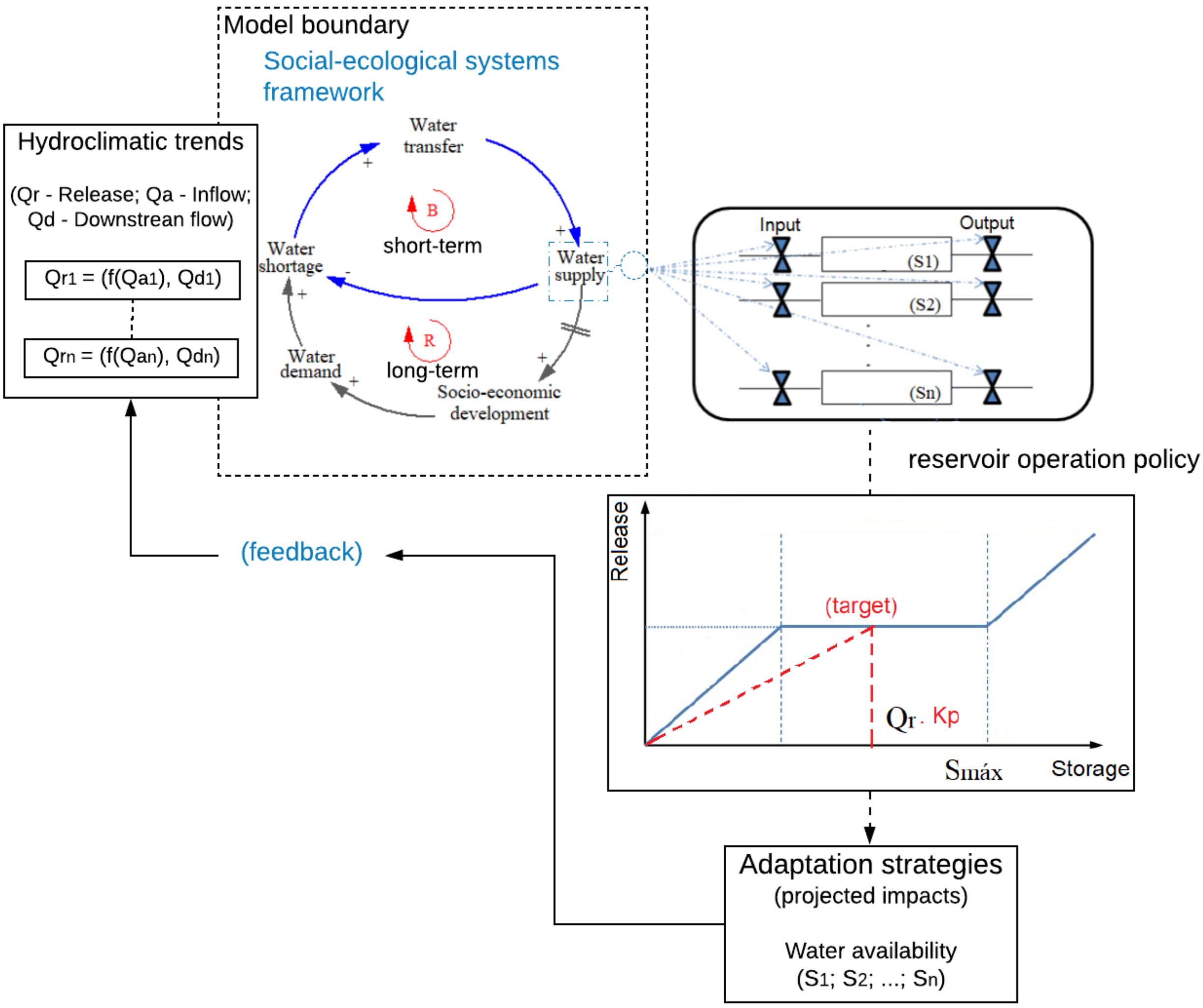

Figure 4. The modeling process.

The analysis of hydroclimatic trends was accomplished by choosing a trigger value of reduction demand, Kp. This trigger value (Kp times the period's demand) in which the target demand gradually declining, with the projected reservoir contents under changing climatic effects (release; inflow; downstream flow).

4 RESULTS

Based on these configurations, the proposed reservoir model is presented in Figure 5. The loop B4 is highlighted. It was incorporated to analyze long-term water crisis scenarios. These adaptation strategies can be activated as result of both climate variability and changes in demand patterns. (Configurations are presented in Table 2).

Table 2. Main model variables and their corresponding values and units

Variable	Type	Calculation	Unit
Downstream flow	Auxiliary	IF THEN ELSE(Reservoir>=(0.15*Storage capacity), IF THEN ELSE((Reservoir+Inflow)>=(Storage capacity - Flood volume),Average flow rate, MAX((0.15*Inflow), Minimun flow rate)),0)	m^3/Month
Release	Auxiliary	Target demand	m^3/Month
Reservoir	Level	Inflow-Downstrean flow-Losses-Release MASP	m^3
Evaporation	Auxiliary	Evaporation rate*Area	m^3/Month
Spillway	Auxiliary	IF THEN ELSE((Reservoir+Inflow-Downstream flow-Release MASP)>Storage capacity ,(Reservoir+Inflow-Downstream flow-Release MASP-Storage capacity),0)	m^3/Month
Total inflow	Auxiliary	Basin discharge data	m^3/Month
Target demand	Auxiliary	IF THEN ELSE(Reservoir>=(0.15*Storage capacity), IF THEN ELSE((Reservoir+ Inflow)<Demand*Kp,(Reservoir+Inflow)/Kp, Demand), 0)	m^3/Month
Demand	Auxiliary	8.5536e+007	m^3/Month

The loops represent the main interactions considered to analyze the reservoir. Loop B1 represents the control conditions for the “Spillway”. Loop B2 represents the conditions allowed for evaporation losses. And the B3 loop establishes the relations to control the "Downstream flow", as a function of the "Minimum required flow", "Average flow" (when the storage does not present critical conditions), and "Flood volume" (= 33,96 hm³). In this case, it was adopted as a spill scenario all situations where the volume exceeds the "Reservoir storage capacity"(= 1492,45 hm³).

The "Basin discharge" variable can also be influenced by climate variability, triggering changes in the storage pattern of the reservoirs.
The "water transfer-supply" represents a short-term scenario, adopted in critical storage levels. Considering the long-term analyses, the researched strategies evaluate the trigger point in isolation, applying the demand reduction factor. Therefore, water transfers remained deactivated in the simulated period.

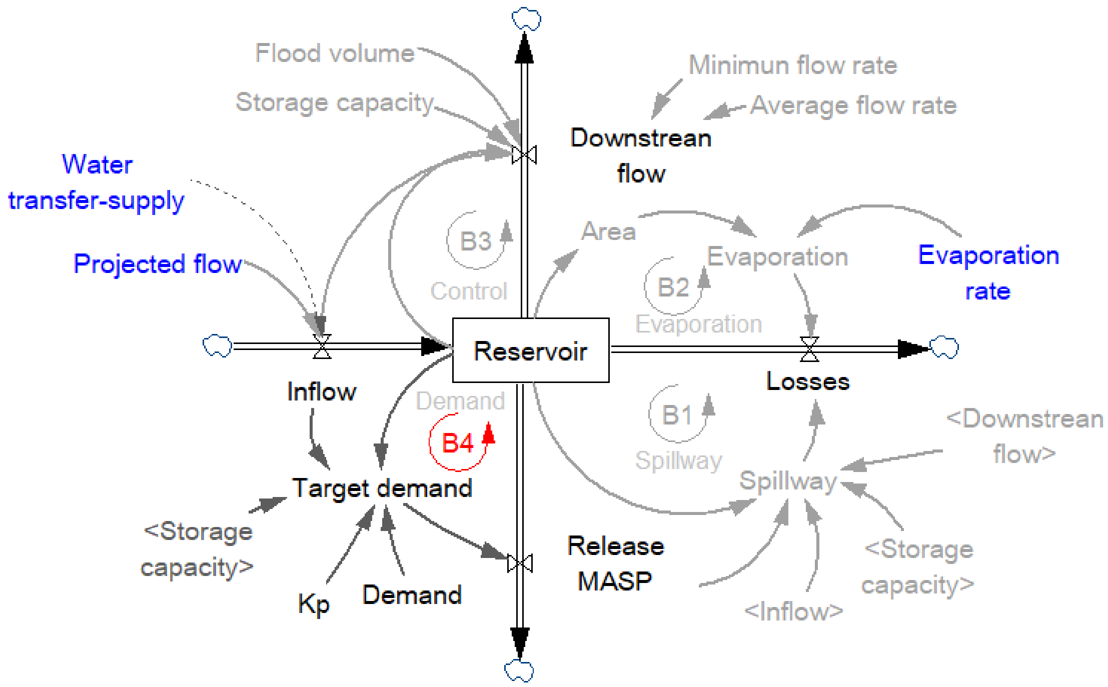

Figure 5. Reservoir model. Incorporated mechanisms for systemic analysis (hydroclimatic and socioeconomic trends).

Figure 6 illustrates simulations to analysis about a trigger value (Kp times the period's demand), 12 and 18 months. It is observed that the earlier the demand reduction period starts, projecting future deficits, the system can respond more efficiently to critical events.

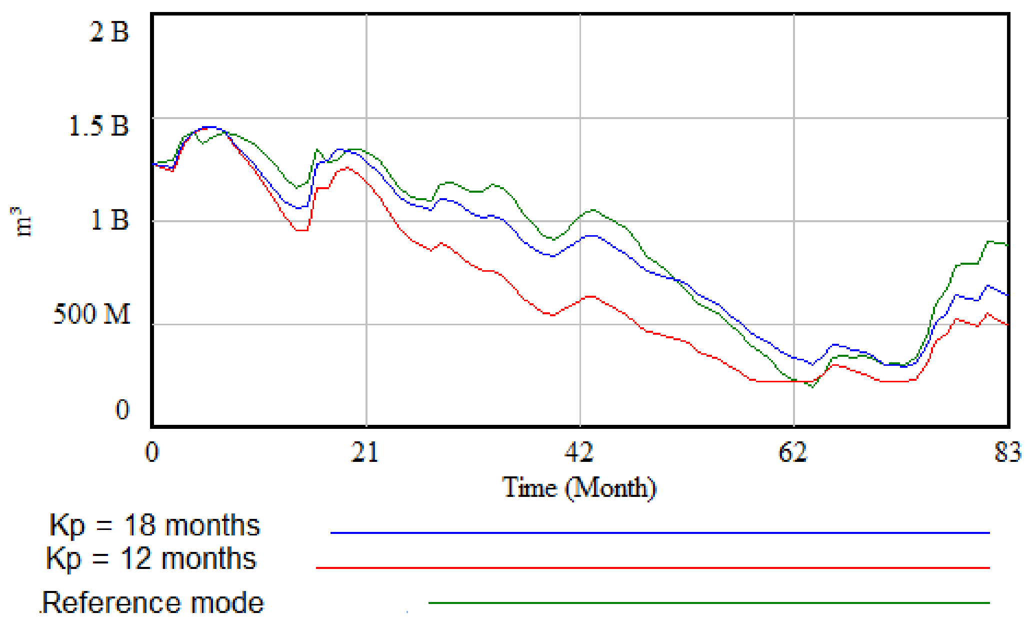

Figure 6. Duration curve for simulated scenarios. Both scenarios were started in January 2013, four months before the system presented deficits in the supply-demand balance (considering the demand, 31m³/s).

5 CONCLUSIONS

In the recent scenario of prolonged droughts experienced in several regions around the world, there is an important gap of systematization in the interface between integrated management of water resources and vulnerability to external drivers (hydroclimatic and socio-economic trends).

The development of integrated models for reservoir management, adopting the SD simulation can provide a systemic analysis in metropolitan regions and subsidize the future steps. This structuring allows robust numerical simulations, based on water balance components for complex and dynamic systems.

These water restrictions may be required to develop a model tariff adjustment at the whole system level, besides improving the ability to deal with uncertainties associated with external drivers.

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