Assessment of water resource management alternatives for the Paraiba do Sul river basin

Rebeca Doctors, Monique Melo*, Rafael Kelman*, Tarcísio Castro**

**PSR, Rio de Janeiro, Brazil, email: {rebeca, monique, rafael, tarcisio}@psr-inc.com*

***Abstract* - The Paraiba do Sul river basin (PSRB) plays a central role in Brazil. Over 180 municipalities in the states of São Paulo, Rio de Janeiro and Minas Gerais depend on its waters, through the operation of multipurpose reservoirs in the main stem and tributaries. The PSRB faced a severe drought in 2014. This event motivated discussions on reservoir operating rules, such as reservoir draft prioritization and reductions of minimum flow requirements that were ultimately established by the national water authority (ANA) in coordination with the national power system operator (ONS). New operative rules enacted by ANA Resolution 1382/2015 prioritize water supply over hydropower. It counteracted the concept that hydropower was responsible for reservoir overdraft, risking water supply of cities such as Rio de Janeiro. However, there is scarce technical justification to validate the new rules, much less to assess their impacts in multiple uses of water. The objective of this paper is to compare alternatives of PSRB operating schemes through a simulation approach. Three scenarios were investigated: (i) Reference Scenario, that considers the operation of the river basin prior to the 2014 water crisis, (ii) New Resolution Scenario, which evaluates the operation after the water crisis and considers the new rules set to prioritize water supply reliability; and finally (iii) an Alternative Scenario, based on guide-curve reservoir operation introduced in this article. A long period of inflow measurements - over 86 years - provides a consistent resource to perform this evaluation. The integrated, basin-wide simulations were made with the Water Evaluation and Planning (WEAP) model of the Stockholm Environment Institute (SEI), a friendly and opened framework for future research.**

Keywords: Integrated Water Resource Management, Reservoir operating rules, Paraiba do Sul River Basin, WEAP model.

1. Introduction

The natural variability of available water resources must be compensated by a combination of man-made infrastructure, such as reservoirs or water distribution schemes and a set of rules for water allocation and reservoir management for a reliable supply of demands. Natural variability and water availability may be impacted by climate change [1], increasing concerns for basic life-supporting consumption and economic-supporting water supply activities, especially in areas with large population and economy growth.

Even countries with relative abundant water availability may face problems if it is unevenly distributed. Brazil is such an example: the country holds 12% of worldwide fresh water availability due mainly to the Amazon basin. However, the relative water availability for densely populated area such supplied by smaller basins, such as São Paulo, is much smaller. The 2014 drought that stroke Brazil's most populous areas shed a light on water management [2] and weather related scarcity are a pressing concern, triggering discussions on effective water resources management [3].

Water resources administration in Brazil is decentralized and multi-leveled. The Water Law of 1997 [4] establishes that water resources are managed by river basin committees, composed of community members and representatives of the public sector. The National Water Authority (ANA) is the regulatory agency responsible for water resources management in Brazil. In more general terms, ANA is monitors water resources and plans for water allocation, coordination with river basin committees.

Although river basin committees should promote discussions on water management among stakeholders, conflicts of interest are usual among participants, leading to few or no agreements, as found in economic theory [5]. Thus, conflict resolution should be based on technical grounds [6] supported by a multi-disciplinary tool that relates bio-physical and socio-economic features of a river basin [7]. Successful planning depends upon an integrated assessment of multiple water uses whereas implementation relies on a technical framework that supports decisions made by the committees.

The main objective of this study is to evaluate an integrated assessment of the Paraiba do Sul River Basin (PSRB) with the Water Evaluation and Planning model (WEAP) developed by the Stockholm Environment Institute (SEI). WEAP was chosen for its user-friendly interface and flexibility to promote stakeholder technical discussions.

PRSB was chosen as a study case because of its complexity and central role in Brazil's most populous and economically developed region. As a final goal, this paper aims to contribute to a better assessment of water resources and to risk management through the formulation of an alternative operating rule. The remainder of the paper presents materials and method for this study, the scenarios modeled and the results found. The last section concludes and suggests future work.

2. Materials and Method

1. Study Area: The PSRB and the 2014 water crisis

The PSRB encompasses three states of Brazil (Rio de Janeiro, São Paulo and Minas Gerais). It covers an area of 57 thousand km² [8] and hosts over 9 million people [9]. It also supports multiple uses of water, such as urban water supply, industries, hydropower and agriculture to 186 municipalities. A complex operation of reservoirs, pump stations and hydropower stations takes place in the PSRB. On average two thirds of the water flows are diverted from the main stem in the city of Barra do Piraí to the Guandu river. After going through a 45 m^3/s treatment plant, the water is distributed to the city of Rio de Janeiro.

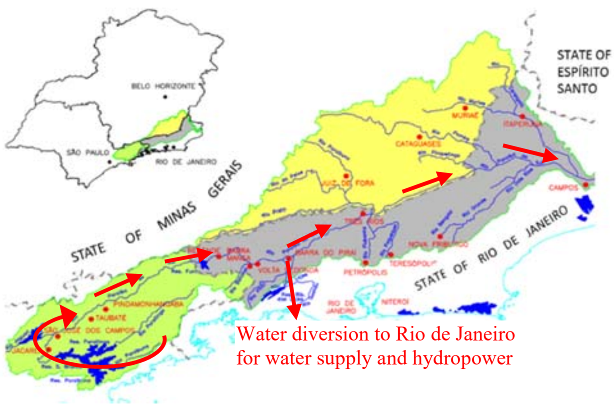


Figure 1. Illustration of the PSRB [10].

The 2014 water crisis had a great impact in the Cantareira system, responsible for the main water supply to the metropolitan region of São Paulo. During 2014-2015 the average streamflow in the Cantareira system was 50% lower than the worst record until then (1953), from 85 years of data, and it was only 25% of the mean yearly flow [11]. As a consequence, São Paulo took especial measures, such as reducing the pressure of the distribution network to reduce losses and promote efficiency on the demand side. On the supply side, the installation of pumps in the Cantareira system allowed the water to be withdrawn below the minimum elevation level [12]. The state also worked on advancing new supply alternatives, such as through the diversion of the waters from the Jaguari reservoir (within the PSRB) to the Atibainha reservoir, a part of the Cantareira water supply system (the most important water system for the city of São Paulo).

The PSRB was also affected by the drought. Its main reservoir, Paraibuna, nearly hit the minimum operation level at the end of 2014 (see Figure 2), after a cumulative depletion of nearly 2.6 billion m^3. Minimum flows were repeatedly reduced by multiple resolutions enacted by ANA in a pursue to store water.

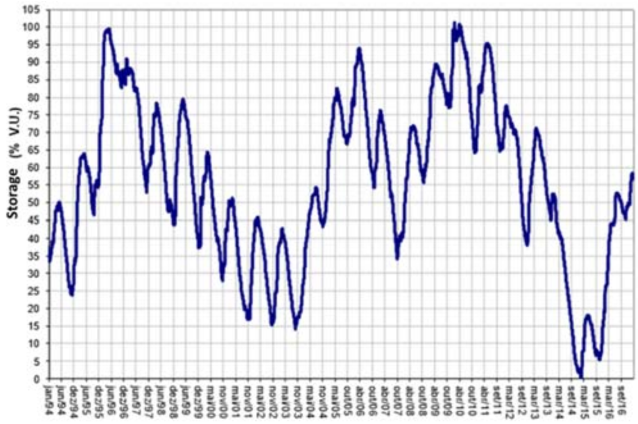


Figure 2. PSRB equivalent reservoir [10].

2. Reservoirs' operation rules

To mitigate impacts from the water shortage and prevent future crisis, ANA and other institutions have deliberated on several measures, in particular, the joint Resolution 1382/2015 established by ANA (federal level) and representatives from states of São Paulo (DAEE), Minas Gerais (IGAM) and Rio de Janeiro (INEA). It modified Resolution 211/2003 that established lower minimum flow requirements along the PSRB as shown in the next table. This was implemented to increase the amount of water stored in the reservoirs as a mitigation for new droughts.

Further, the resolution 1382/2015 also restated the minimum flow requirement of 119 m^3/s from the pumping station of Santa Cecilia to the Santana reservoir and the minimum flow requirement of 71 m^3/s downstream of Santa Cecilia (which together add up to 190 m^3/s). This measure was reinforced to satisfy the water diversion to Rio de Janeiro and the other water supplies, which are downstream of Santa Cecilia and along the Paraiba do Sul river (see Figure 1 above).

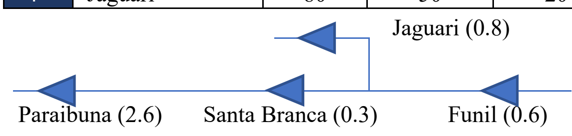
Table 1. Regulatory changes in the reservoirs' min. flow requirements

Reservoir Name	ANA Resolution 211/2013	ANA Resolution 1382/2015
Paraibuna	30 m^3/s	10 m^3/s
Santa Branca	40 m^3/s	30 m^3/s
Jaguari	10 m^3/s	4 m^3/s
Funil	80 m^3/s	70 m^3/s

Resolution 1382/2015 also established that reservoirs should deplete following a predefined sequence, as described in the following table.

Table 2. Depletion sequence for the reservoirs (Resolution 1382/2015)

Reservoir depletion sequence		Depletion stage (Useful Volume %)		
		1st	2nd	3rd
1st	Funil	30	30	30
2nd	Santa Branca	70	40	10
3rd	Paraibuna	80	40	5
4th	Jaguari	80	50	20



The diagram above illustrates the cascade. The number in parenthesis indicate the useful storage, in billion m^3. There are 12 total stages that can be implemented, which were established to save more water in the upstream part of the Paraiba do Sul river, located in the state of São Paulo. Reservoir volumes are implement one at a time, starting with the first reservoir (Funil) at the first stage (depletion stage of 30% of its useful volume). Once this first stage is observed, the depletion order follows to the second reservoir (Santa Branca) at the first stage, and it goes on until it reaches the depletion of the fourth reservoir (Jaguari) in the third depletion stage (20% of its useful volume). It is important to mention that the change in the depletion stage, from each reservoir to the next stage, can only occurs when all of them reach their minimum values for a given stage, allowing a variation of 5% of the reference value.

Although ANA claims this resolution is a response to the crisis and leads to a more preventive allocation of water resources, no information was given regarding how the figures of the table were defined. However, it was an important step to change the way the Paraiba do Sul system was previously managed. Prior to the 2014 water crisis, the water uses of the PSRB were mainly focused on hydropower production, controlled by ONS.

3. Model and data

The research of better operational rules for the allocation of water is a key concern for the river basin committees, who are mainly formed by local water users. In this case, it is fundamental that they are equipped with a model of simulation or optimization of water systems that undertakes a global planning vision, where the multiple uses of water are contemplated. Indeed, the mathematical simulation of the hydraulic systems operation allows to evaluate the performance of different policies to assist stakeholders, such as river basin committees, in the case of Brazil.

Although there are different models that evaluate in an integrated way the multiple uses of water, the WEAP model was chosen because of its friendly interface and easy operation. In addition to that, WEAP is widely used by hydrological planers throughout the world, which facilitates exchanges of knowledge.

WEAP is a model of water resources management that operates on the basic principle of water accounting. WEAP simulations are built on a set of scenarios, where simulation time steps can vary from daily to monthly [7]. For a given time step, it determines the optimal water allocation for each node defined according to a linear allocation problem, whose objective is to maximize satisfaction of demand, subject to a set of constraints, such as supply priorities and mass balances [7].

A schematic representation of the PSRB in WEAP is shown in the following figure. It was built with shape files from ANA's Hydroweb (for the rivers and geographic limitations of both the river basin and the municipalities) and with geographic data for the reservoirs location from SIGEL, a coordinate national system of the Brazilian National grid. Additional topology information was added with the help of Google Earth.

Figure 3. Schematic representation of the PSRB.

The representation of the power system operated by Rio Light[1] is circled in red in the figure. For this study, a vast amount of data was required. The data inputs were divided in water demands, historical series of affluent flows and reservoirs parameters. Both the affluent flows historical series and the reservoirs parameters (such as installed capacity, elevation x wet area x storage and tailwater x outflow tables) were collected from ONS.

Water demands were aggregated by municipalities and by water uses (industries, irrigation and livestock needs as well as water supply to municipalities). Data was calculated in a previously prepared study to the pro-water management association of the Paraíba do Sul river basin (AGEVAP), as a function of population growth and forecasts made by the National Institute of Geography and Statistics (IBGE) and ONS [13].

The demand used as input in WEAP's simulation refers to 2010. Although it wasn't evaluated the impact of the population growth or the different water uses, this may be interesting for a further study.

Further, hydropower generation was modeled to simulate ONS. It was used ONS's historic data from 2000 to 2016 for hydropower output, reservoirs storage and streamflow for the following hydropower plants: Paraibuna, Santa Branca, Funil and Jaguari. We used Eureqa, an Artificial Intelligence powered modeling engine developed by Nutonian [14] to find equations that would better explain hydropower generation as a function of streamflow and reservoir storage. The latter were used as energy demand, which was modeled in WEAP in before months' calculations though a VBS Script. A minimum flow requirement curve was built after [15]. A quadratic approximation was used between outflow and storage yield, with a fixed relative standard deviation of 30% for the streamflow in the Paraiba do Sul main stem. The curve used for the four main hydropower plants of the PSRB is the following:

$$Q_{min,t}^{i} = Q_{nat,t}^{i} * \left[-0.21 * \left(\frac{EV_t^i}{EMV_t^i} \right)^2 + 0.59 * \left(\frac{EV_t^i}{EMV_t^i} \right) + 0.62 \right]$$

Where $Q_{min,t}^{i}$ is the minimum flow requirement in period t and for reservoir i, $Q_{nat,t}^{i}$ is the natural inflow and $\frac{EV_t^i}{EMV_t^i}$ is the relation between reservoir storage and its effective maximum storage.

1 A power system held by Light company, consisting of many hydropower plants.

4. Scenarios simulations

The study used monthly time steps with inflows data from 1931 to 2016. Three simulations were evaluated in WEAP for varying operating rules in the PSRB.

1. Reference Scenario, rules before the 2014 water crisis

Resolution 211/2003 is applied in this case (which is equivalent to the operation before the 2014 water crisis). The later establishes minimum flow requirements for the four main reservoirs in the PSRB, for Santa Cecilia (pumping station that diverts water from the main stem to the city of Rio de Janeiro) and Pereira Passos, small hydroelectric plant that is upstream of the Guandu river.

Beyond the establishments of minimum flow requirements, the Rio light operation follows ONS rules [16]. These rules are kept for the two other scenarios applications, since they suffer no modification in the period after the 2014 water crisis. Further to this, all scenarios have the same equations for energy demand and minimum flow requirement. This scenario is used as a baseline for comparison with the two other simulations.

2. Current rules, after the 2014 water crisis

Resolution 1382/2015 is applied in this case (operation after 2015). Simulations regarding depletion priorities were inserted in WEAP through a script that runs in the beginning of each month, just before the evaluation of water demands by WEAP.

3. Alternative Scenario

The third simulation proposes an alternative that uses guide curves for the reservoirs' operations. The objective is to assure that a minimum storage amount (5% of useful storage) is achieved at the end of the dry season (November), considering the worst hydrological condition. This idea is simpler than the proposed in Resolution 1382/2015 since it is less dependent on the operation of the other reservoirs. It is also quite close to a concept used by ONS when stipulating "risk aversion curves" for electricity systems.

The minimum flow requirements defined prior the water shortage crisis of 2014-2015 were kept in this scenario.

3. Results and discussions

As main results were evaluated three variables: the reservoir's storage volume and their hydropower production, which allow the analysis of the existing trade-off between water supply reliability and hydropower production, and the permanence curve above the pumping station of Santa Cecilia, which is a critical part of the Paraiba do Sul river for the city of Rio de Janeiro (as explained in Section 2).

The following figure compares the storage volume for the three scenarios during the simulated period.

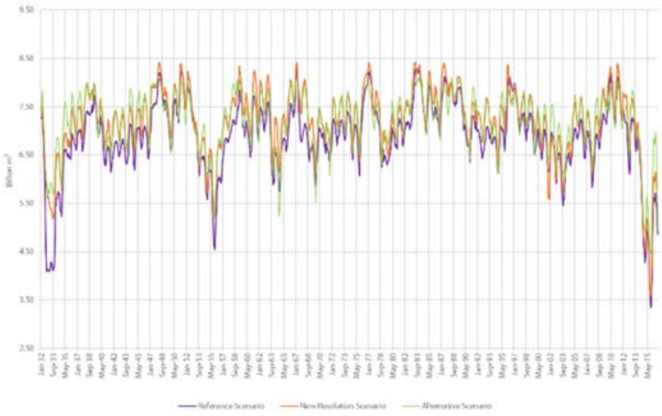


Figure 4. Storage volume for the three scenarios.

It is possible to see that the Reference Scenario has a consistently lower storage volume. The New Resolution Scenario and the Alternative Scenario, on the other hand, vary among having higher storage volumes. However, in the end of the period observed, when the water shortage crisis was most accentuated, the Alternative Scenario stays in a higher level, as shown in the figure below.

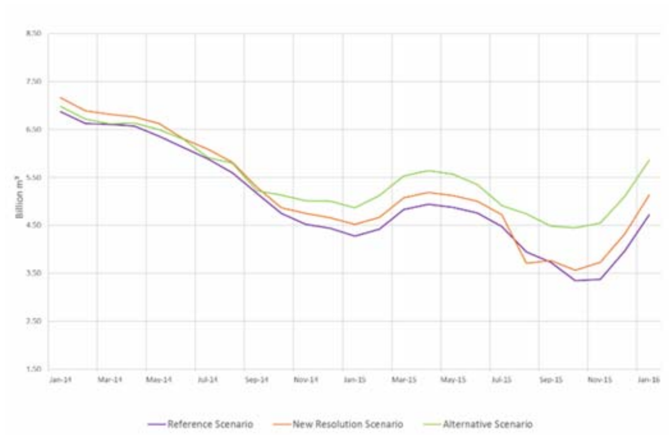


Figure 5. Storage volume for the three scenarios during water crisis.

Results for hydropower profile are similar throughout the scenarios, as observed for storage volume profile. However, the New Resolution Scenario has a consistently lower generation.

Figure 6. Yearly hydropower generation for the three scenarios.

This result can also be seen from the following graph, which shows the average, maximum and minimum points of hydropower generation for the three scenarios. Both the Reference Scenario and the Alternative Scenario have a close average hydropower generation (with the Reference Scenario being only marginally greater than the Alternative Scenario), even though the later has a greater maximum and lower minimum values observed. Moreover, the New Resolution Scenario has lower values for hydropower generation for all values observed (maximum, average and minimum).

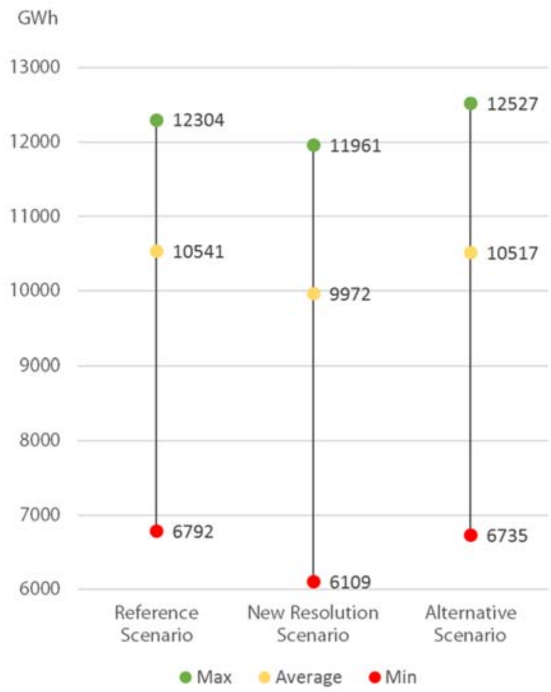


Figure 7. Hydropower generation comparison among the 3 scenarios.

These results show a clear evidence of the trade-off between system reliability and hydropower generation, especially in the Reference Scenario case. However, since the Alternative Scenario kept minimum flow requirements as established prior to the water crisis, having thus a constraint that 'tells' reservoirs to release more water (compared to the current operation that was enforced after the water shortage crisis), it generates more hydropower even though its storage volume is greater than the Reference Scenario. In addition to this, it is important to note that the Alternative Scenario has a higher storage level for the water shortage crisis of 2014-2015 when compared to both scenarios, which is an important point to be considered as it kept more water stored during a critical period.

It is important to mention that for none of the simulated scenarios, there was an observed unmet water demand. Hence, there was still enough water in the PSRB to attend the local population water use. However, an additional water demand could stress the system.

Below is the permanence curve of Santa Cecilia, which is a critical point in the PSRB to Rio de Janeiro. As previously mentioned, 119 m³/s should be pumped from Santa Cecilia to Santana in order to supply Rio de Janeiro's water demand. The remaining 71 m³/s are released downstream of Santa Cecilia to the main stem. Thus, a total streamflow of 190 m³/s should be found above Santa Cecilia pumping station.

Despite both New Resolution and Alternative Scenarios meet the target of 190 m³/s in over 80% of times, which is greater than the observed for the Reference Scenario, the Alternative Scenario provides more water supply security for Rio de Janeiro and downstream cities than the New Resolution Scenario.

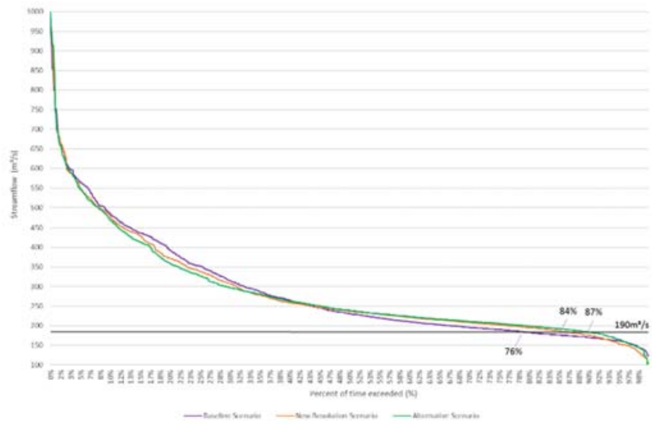


Figure 8. Permanence Curve in Santa Cecilia among the 3 scenarios.

From the results above, it could be said that the Alternative Scenario is a Pareto optimal operation, since water resources are better off allocated (hydropower generation, storage volume and percent of time exceeded for the streamflow upstream of Santa Cecilia are greater).

4. Conclusion

The PSRB plays a central role in the Southeastern region of Brazil, as it crosses three of the most economic important states of Brazil and is of strategic importance to the metropolises of São Paulo and Rio de Janeiro.

In 2014-2015, the PSRB suffered a severe water shortage crisis, which lead to increased discussions on its operation. In Brazil, water resources are managed by both the federal government (through the National Water Agency) and river basin committees, which promote discussions among stakeholders with a more local perspective. Conflicts of interest are usual among participants, leading to few or no agreements.

In order to support the river basin committees' decisions and optimize the multiple water uses, it is important that the stakeholders have a technical ground for their discussions. In this sense, this paper evaluated an integrated assessment of the PSRB using WEAP, a tool developed by SEI for the planning and management of water resources.

This paper presented three simulations based in different operations of the PSRB: (i) Reference Scenario, (ii) New Resolution Scenario and (iii) Alternative Scenario. The first scenario models the operation prior to the 2014-2015 water shortage crisis, the second models the current operation, as established by the resolution 1382/2015, and the alternative scenario proposes an alternative that uses guide curves for the reservoir's operations.

As found in the main results evaluated, all three scenarios have similar reservoirs' storage and hydropower generation profiles. However, the Reference Scenario has a consistently lower storage volume, as it prioritizes hydropower generation. The remaining scenarios vary among having greater storage volumes, but the Alternative Scenario holds more water stored during the crisis period (2014-2015). The Alternative Scenario had more hydropower, since it maintained greater values of minimum flow requirements.

The Alternative Scenario also showed higher reliability for maintaining streamflow requirement upstream of Santa Cecilia, which is crucial to the water supply of Rio de Janeiro. Thus, the alternative operation rule, established after guide curves for the main reservoirs, shows overall gains for the PSRB (higher water supply reliability with no sacrifice for hydropower).

Finally, further research should include in the simulations a water withdrawal from Jaguari reservoir to Cantareira - the most important water supply system of São Paulo. A 5 m^3/s diversion scheme is being built. It may reach 8.5 m^3/s in the future.

5. Acknowledgements

We would like to thank WEAP for the student licences granted to Rebeca Doctors (Pontifical Catholic University of Rio de Janeiro) and Monique Melo (Federal University of Rio de Janeiro).

6. Reference

[1] R. Sethi, B. K. Pandey, R. Krishan, D. Khare, and P. C. Nayak, “Performance evaluation and hydrological trend detection of a reservoir under climate change condition,” *Model. Earth Syst. Environ.*, vol. 1, no. 4, p. 33, Dec. 2015.

[2] F. L. Otto, C. S. Coelho, A. King, E. CoughLan de Perez, Y. Wada, G. Jan van OLdenbOrgh, R. Haarsma, K. Haustein, P. Uhe, M. Van Aalst, J. A. Aravequia, W. Almeida, and H. Cullen, “Factors other than climate change, main drivers of 2014/2015 water shortage in southeast Brazil,” *Am. Meteorol. Soc.*, vol. 96, no. 12, 2015.

[3] OECD, “Resources Governance in Brazil,” OECD Publishing, Paris, 2015.

[4] Presidência da República, *9433*. Brasília: Casa Civil, 1997.

[5] R. Axelrod, “Conflict of Interest: An Axiomatic Approach,” *J. Conflict Resolut.*, vol. 11, no. 1, pp. 87–99, 1967.

[6] ANA, “O COMITÊ DE BACIA HIDROGRÁFICA O QUE É E O QUE FAZ? VOLUME 1.” ANA, Brasília, 2011.

[7] D. Yates, J. Sieber, D. Purkey, and A. Huber-Lee, “WEAP21 – A Demand-, Priority-, and Preference-Driven Water Planning Model Part 1: Model Characteristics,” *Water Int.*, vol. 30, no. 4, pp. 487–500, 2005.

[8] L. M. Kumler and M. C. Lemos, “Managing Waters of the Paraiba do Sul River Basin, Brazil: a Case Study in Institutional Change and Social Learning,” *Ecol. Soc.*, vol. 13, no. 2, p. , 2008.

[9] CEIVAP, “Sistema de Informações Geográficas e Geoambientais da Bacia Hidrográfica do Rio Paraíba do Sul,” 2017. [Online]. Available: http://sigaceivap.org.br/siga-ceivap/observatorioBacia. [Accessed: 25-Jan-2017].

[10] ANA, “Boletim de monitoramentos dos reservatórios do sistema hidráulico do Rio Paraíba do Sul,” *Boletins Monit.*, vol. 12, no. 3, pp. 1–20, 2017.

[11] ANA, “FAQ Cantareira,” 2016. [Online]. Available: http://www2.ana.gov.br/Paginas/servicos/saladesituacao/v2/faqcantareira.aspx. [Accessed: 25-Jan-2017].

[12] Agência das bacias PCJ, “Boletim de monitoramento dos reservatórios do sistema Cantareira.” Fundação agência das bacias hidrográficas dos rios Piracicaba, Capivari e Jundiaí, São Paulo, 2016.

[13] PSR, “Avaliação dos impactos de novas transposições de vazão no rio Paraíba do Sul.” Rio de Janeiro, 2013.

[14] M. Schmidt and H. Lipson, “Distilling Free-Form Natural Laws from Experimental Data,” *Science (80-.).*, vol. 324, no. 5923, pp. 81–85, 2009.

[15] L. S. F. Gomide, “Range and Deficit Analysis Using Markov Chains,” *Hydrol. Pap. 79*, no. 79, p. 83, 1975.

[16] ONS, “Atualizações de séries históricas de vazões - período 1931 a 2007,” Rio de Janeiro, 2007.