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The Chilean Laja Lake: multi-objective analysis of conflicting water demands and the added value of optimization strategies

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ABSTRACT

Water scarcity leads to conflicts over water allocation. Laja Lake in Chile is a natural lake, which was formed by a volcanic barrier. Outflow from the lake is created by seepage through the barrier and via a controllable artificial outlet, which adds reservoir characteristics to the lake. Hydroelectric power stations have been built at both outlets. Downstream, water is diverted into irrigation canals, and the Laja River forms the Laja Falls, a popular tourist attraction. The previous operating policy preferred the most upstream water user and was found to be inadequate because the lake level decreased over long term. The current reservoir operation policy was established through stakeholder negotiations. This study investigated whether optimization (using Non-Dominated Sorting Genetic Algorithm II) can further improve the operation of Laja Lake while maintaining a fair balance between stakeholder groups. The results were compared with the stakeholder agreement and the previous policy. The main difference is in the spring, when Laja Lake fills up before the irrigation season starts. The optimization strategy prioritizes hydropower generation during this period, resulting in reduced storage. Ultimately, optimization proves to be a valuable tool for identifying trade-offs and exploring different scenarios in water management.

Key words: hydropower, irrigation, NSGA-II, reservoir operation, stakeholder negotiation, water–energy–food nexus

HIGHLIGHTS

- The standard operational policy is not able to find long-term equitable solutions for the multi-purpose reservoir.
- Systems analytic methods can find balanced strategies for conflicting water demands.
- Trade-offs and alliances between stakeholders were identified using optimization and simulation followed by a ranking procedure.
- Different scenarios from the set of Pareto optimal solutions can be easily explored.

1. INTRODUCTION

Water management is increasingly a matter of managing conflicts over water allocation. This is due to overexploitation of the resource as a result of population growth, urbanization, and changes in the agricultural and industrial sectors (Zhang *et al.* 2018). Climate change with the intensification of hydrological extremes further exacerbates these problems (Ficklin *et al.* 2022). Conflicts over water distribution are emerging on both temporal and quantitative scales. According to Cai *et al.* (2004), there are distinctive characteristics of these conflicts. They are multidisciplinary complexity (interdependent impacts), domain-dependent knowledge (a global view is needed to find acceptable solutions), social value orientation (water management as a public issue), institutional constraints of rules and regulations, and cultural dimensions in which the stakeholders operate. The interaction of these characteristics makes it an extremely difficult task for water managers to find equitable solutions. When openly articulated disagreements arise between different stakeholder groups, they can lead either to negotiations between stakeholders, to top-down regulation by (local) authorities or to (armed) conflict. Broadly accepted solutions can be achieved through stakeholder participation and integrated water resources management. Both approaches have received considerable attention worldwide.

The management of water storage, particularly the operation of multi-purpose reservoirs, is a potential area of conflict. Two sectors that are often in conflict are agriculture and hydropower. Accordingly, trade-offs between hydropower generation and the agricultural sector have already been studied. The water–energy–food nexus is one approach that addresses this relationship (Zhang *et al.* 2018).

As shown by Chang & Chang (2009), Moeini & Nasiri (2021), and others, optimization can be used to generate equitable and sustainable solutions to multi-purpose reservoir operation problems. However, the technique has not been widely applied to real-time operations and management. According to Labadie (2004), the main reason for this is scepticism about the models, which may be due to the complexity of the optimization algorithms. In addition, the limitations of incorporating risk and uncertainty into the optimization, as well as the fact that many are only able to produce optimal results for the period of record, result in few applications. In most cases, it is also necessary to develop a customized programme for the given problem, which requires expert knowledge of optimization.

This study compares the system performance of a combined optimization and ranking approach with those of a previous stakeholder negotiation and the standard operational policy (SOP, Men *et al.* 2019) as an approximation of the operation before the negotiations. The objectives of the study are (i) to investigate the stakeholder agreement, (ii) to perform multi-objective optimization of the system, and (iii) to compare the results of the agreement with those obtained from the optimization study. Studies have already been carried out on Laja Lake using a multi-scale trade-off analysis to investigate the interdependencies between the hydropower and agricultural sectors by Gonzalez *et al.* (2020). This study aims to further investigate the region. Here, it is possible to compare the results of the optimization with an agreement between the stakeholders, which allows us to focus on investigating the added value of the optimization strategies.

2. CASE STUDY: LAJA LAKE

The Laja River Basin is located in south-central Chile (Figure 1). It is approximately 4,668 km^2 in size. It is bounded by the Andes to the east and the Nevados de Chillán stratovolcanoes to the west. The Laja River Basin has a snow-dominated hydrological regime (Muñoz *et al.* 2019).

The river flows from east to west. Its source is Laja Lake, which is formed by a natural volcanic barrier. Seepage through this barrier is possible and leads to the Hydroelectric Plant (HP) Abanico. An artificial tunnel also connects the lake to HP El Toro. The flow through the tunnel can be controlled, while the seepage depends on the level of the lake. One of the

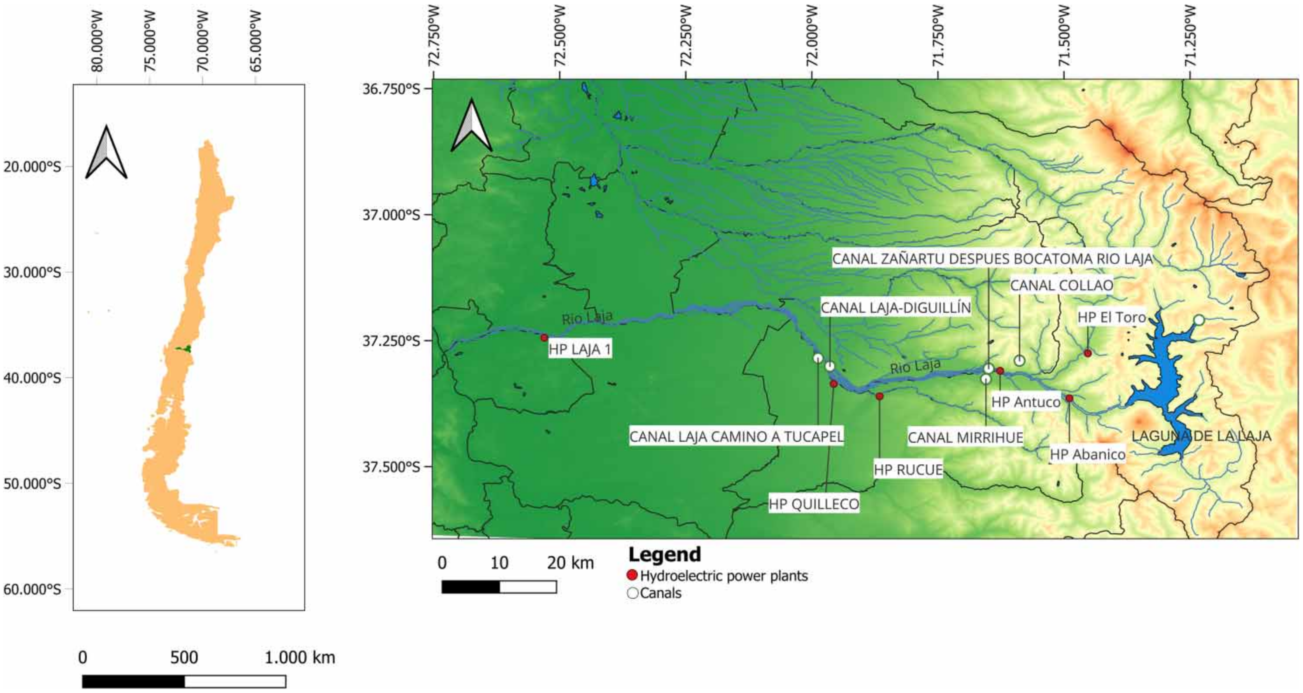

Figure 1 | Map of the study are in Chile (left) and the Laja River Basin (right).

peculiarities of the Lake Laja system is that the two HPs are interdependent, although there is no direct hydrological connection. The more water HP El Toro extracts from the lake, the less water seeps through the barrier and reaches HP Abanico, and vice versa. The water from the two HPs later forms the Laja River, which crosses the valley before reaching the BíoBío River. Downstream from Laja Lake, four other HPs operate and water is diverted for irrigation of agricultural land, as shown in Figure 1. At the confluence of the Laja and BíoBío Rivers are the Laja Falls, a major tourist attraction in Chile. An overview of the area is shown in Figure 1.

2.1. Climate and data

Rainfall in the area is mainly frontal, resulting in an average annual precipitation of between 1,100 mm at the basin outlet and 2,300 mm at the headwaters. During the winter months (June to August), snowfall is concentrated, accounting for about 47% of the annual precipitation (Muñoz *et al.* 2019). Filling of Laja Lake occurs in the spring (September to November) when the snow melts. The inflow data into the lake are taken from the government website (Coordinador Eléctrico Nacional 2022).

Water allocation in Chile is based on a private market for tradable water rights. Non-consumptive users must obtain water rights (e.g., HPs). The amount of water that can be used by a sector may not correspond to the actual water demand. However, since it is in the interest of the operators to make the best use of their acquired water rights, the measured flow data in the diversion canals are used as demand data in this study.

In the present work, the five main irrigation canals in the basin are considered. They are (from east to west): Collao, Zañatru, Mirrihue, Laja, and Laja-Diguillín, as shown in Figure 1. The streamflow data of the canals used in this study were retrieved from the governmental website of the General Directorate of Water (Dirección General de Aguas 2023). The canals are operated by an irrigation canal association that represents the farmers who have water rights on the canal. Since the agricultural sector is considered as a single water user in the study, the values for each canal are combined to calculate the demand.

The study extends over a period of 5 years from 2016 to 2020, where comparable data for all system elements are available and the new agreement had been implemented. The study period took place during a drought period in Chile (see Section 2.2).

2.2. The agreement on the operation of Laja Lake

The operation of the lake is crucial for various sectors in the area, as it mainly controls the water available in the basin. This, in turn, leads to conflicts between different stakeholders over the allocation of water and the operation of Laja Lake. Furthermore, starting in 2010, Chile experienced a series of water shortages, also known as the mega-drought (Garreaud *et al.* 2019). When the drought hit the region, the lake was already vulnerable due to overuse in previous years, leading to severe water shortages downstream. Eventually, the Laja Falls, a national tourist attraction, dried up. The sight of the dry Laja Falls raised public awareness of water management issues, and increasing public pressure forced a change in the lake's management. One point of conflict was that the lake management only considered stakeholders with water rights, creating a power imbalance between water users with and without water rights. In the negotiations that followed, an unprecedented step was taken: the tourism sector without water rights was included in the negotiations. Representatives of national and local governments also sat on the committee that negotiated the new operating rules. From touristic motivation, an 'environmental flow' was considered important.

Transparency was critical to building trust. To support this, the Ministry of Public Works now distributes monthly streamflow and lake-level data to all stakeholders. In addition, water rights and other hydrological data are made available online. This way, everyone can monitor whether the agreement is being honoured.

After 3 years of negotiations, a new agreement for the regulation of Laja Lake, called the *New Laja Lake Irrigation Agreement* (Ministerio de Obras Públicas 2018), was implemented in 2017 (Arumí *et al.* 2024). It grants the water use of the lake for the following year according to its level at the end of the filling season on December 1. In this agreement, the reservoir is divided into four volume segments. Each segment allows each party to release a certain amount of water, while leaving some in the lake as a reserve. Irrigation water can be used from December to April according to seasonal needs, while water for hydroelectric power generation can be released throughout the year. From now on, the reservoir operation policy used to manage Laja Lake will be referred to as the 'Real Policy' in this study.

3. METHODS

3.1. Scenarios of reservoir operation

The agreement was initially negotiated among stakeholders without the use of quantitative tools. In this study, the resulting operating policy is implemented as 'Real Policy' scenario. The SOP is used as a reference scenario to mimic the policy prior to the negotiations. The SOP is to always release as much water as possible to meet demand. Since the tunnel of HP El Toro is the only controllable outlet of the lake, the SOP only solves a single-objective problem. No water is stored for future shortages. The advantage is usually good demand coverage, here for HP El Toro, at the cost of high and long-term water shortages.

Based on these two scenarios, the improvement in system performance due to the negotiation of the new agreement can be shown.

Simulation and optimization are then used to investigate further improvements in reservoir control under multiple objectives with different weighting schemes, as might be expressed during stakeholder negotiations. The model combines complex mathematical multi-objective optimization with a transparent, easy-to-understand ranking method.

3.2. Hydrological simulation model

The simulation model is a lumped model, which is based on the mass balance of the available water in the river basin. It runs on monthly time steps during the study period. The mass balance is given in Equation (1).

$$S_{t+1} = S_t + I_t - Q_{\mathrm{Tunnel},t} - Q_{\mathrm{Seepage},t} - Q_{\mathrm{Spill},t} \tag{1}$$

where S_{t+1} is the storage at the next time step $t+1$ and S_t is the current storage. I_t is the net inflow to Laja Lake. There are no direct measurements of hydrological inflow, precipitation, and evaporation. I_t is calculated as the remaining element of the water balance, implicitly including all other hydrologic fluxes. The reservoir has two outflows: $Q_{\mathrm{Tunnel},t}$ is the release through the tunnel to be optimized and $Q_{\mathrm{Seepage},t}$ is the outflow from the lake via seepage. When the reservoir exceeds its maximum capacity, water is released as spill $Q_{\mathrm{Spill},t}$. The storage volume S of Laja Lake is constrained by its dead storage $S_{\min}$ and its maximum storage capacity $S_{\max}$ (in million cubic meters (MCM)) as shown in the following Equation (2). At the beginning, S_1 is set to the value of the 2015-12-31: $S_1 = 1{,}325.18\,\mathrm{MCM}$.

$$S_{\min} = 600 \leq S_t \leq S_{\max} = 5{,}850 \tag{2}$$

The seepage from Laja Lake is defined by Equation (3), also called the 'Laja Lake Seepage Law' (Ministerio de Obras Públicas 2007), where $H_{\mathrm{Laja},t}$ is the water level of Laja Lake in m.a.s.l. The calculation of $H_{\mathrm{Laja},t}$ in Equation (4) is defined according to the volume-elevation curve of Laja Lake.

$$Q_{\mathrm{Seepage},t} = \begin{cases} 9.26 \cdot 10^{-3} \cdot (H_{\mathrm{Laja},t} - 1{,}220)^{1.684} & \text{if } 1{,}220 < H_{\mathrm{Laja},t} \leq 1{,}340 \text{ m.a.s.l.} \\ 9.74 \cdot 10^{-2} \cdot (H_{\mathrm{Laja},t} - 1{,}275)^{1.370} & \text{if } 1{,}340 < H_{\mathrm{Laja},t} \leq 1{,}362 \text{ m.a.s.l.} \\ 8.44 \cdot 10^{-3} \cdot (H_{\mathrm{Laja},t} - 1{,}290)^{2.000} & \text{if } H_{\mathrm{Laja},t} > 1{,}362 \text{ m.a.s.l.} \end{cases} \tag{3}$$

$$H_{\mathrm{Laja,t}} = 1{,}300.6 + 1.89 \times 10^{-2} \cdot S_t - 2 \times 10^{-6} \cdot S_t^2 + 1 \times 10^{-10} \cdot S_t^3 \tag{4}$$

3.3. Optimization model

3.3.1. NSGA-II model

In the present study, a lumped simulation model is optimized using the Non-Dominated Sorting Genetic Algorithm II (NSGA-II). This algorithm was first developed by Deb *et al.* (2002). In each iteration, a population is composed of multiple chromosomes, which, in turn, are composed of genes. The method provides four basic operators: generating an initial gene pool, calculating the fitness of each chromosome, selecting chromosomes, and performing crossover and mutation (Tayfur 2017). The main features of NSGA-II are the elicitation principle, the diversity maintenance mechanisms, and the emphasis on non-dominated solutions. This algorithm was chosen because it is a well-tested optimization algorithm. For example, it was successfully used by Yang *et al.* (2016) to generate adaptive multi-objective reservoir rules under changing climate.

Three **objective functions** are formulated as minimization problems for the study. The two HPs, El Toro and Abanico, have an independent objective function $f^{\mathrm{EL\ Toro}}$ and f^{Abanico} to emphasize their conflicting nature. The installed HP capacity (ppc) should be guaranteed at each time step t as can be seen in Equations (5) and (6), where p_t is the produced hydropower in MW at time step t for the considered hydropower plant.

$$f^{\mathrm{El\ Toro}} = \mathrm{Min.}\ \sum_{t=1}^{T} 1 - \left(\frac{p_t^{\mathrm{El\ Toro}}}{\mathrm{ppc}^{\mathrm{El\ Toro}}}\right) \tag{5}$$

$$f^{\mathrm{Abanico}} = \mathrm{Min.}\ \sum_{t=1}^{T} 1 - \left(\frac{p_t^{\mathrm{Abanico}}}{\mathrm{ppc}^{\mathrm{Abanico}}}\right) \tag{6}$$

The produced hydropower p_t mainly depends on the potential energy height h, the efficiency of the installed turbines η, and the water flowing through the turbines Q_t. The relationship can be seen in Equations (7) and (8). Here, ρ is the density of water ($g = 1{,}000\,\mathrm{kg/m^3}$) and g is the gravitational acceleration ($g =\ 9.81\,\mathrm{m/s^2}$). The two hydroelectric stations have fixed heads ($h^{\mathrm{El\ Toro}} =\ 545.0$ m for HP El Toro and $h^{\mathrm{Abanico}} = 145.7$m for HP Abanico).

$$p_t^{\mathrm{El\ Toro}} = \eta\ \cdot\ \rho \cdot g \cdot h^{\mathrm{El\ Toro}} \cdot Q_{\mathrm{Tunnel},t} \tag{7}$$

$$p_t^{\mathrm{Abanico}} = \eta \cdot \rho \cdot g \cdot h^{\mathrm{Abanico}} \cdot Q_{\mathrm{Seepage},t} \tag{8}$$

The water demand for all irrigation canals is aggregated and put into an objective function f^{Agri}, where the available water for irrigation is calculated over the demand of the agricultural sector, as shown in Equation (9).

$$f^{\mathrm{Agri}} = \mathrm{Min.}\ \sum_{t=1}^{T} \left(\frac{(R_t^{\mathrm{Agri}} - R_t^{\mathrm{Env}} - D_t^{\mathrm{Agri}})}{D^{\max}}\right)^2 \tag{9}$$

R_t^{Agri} considers the water available for the agricultural sector in the basin at time step t. Therefore, R_t^{Agri} consists of the outflow $Q_{\mathrm{Tunnel},t}$ and the seepage flow $Q_{\mathrm{Seepage},t}$ as well as water coming from other tributaries (Polcura and Rucue rivers). The environmental flow condition R_t^{Env} is substracted for each time step t because it has a single demand profile and should always be considered. It comes from the tourism sector, which requires a minimum flow of $R_t^{\mathrm{Env}} = 10\,\mathrm{m^3/s}$ to maintain the Laja Falls. D_t^{Agri} represents the agricultural demand and $D^{\max}$ is the maximum water demand of the agricultural sector during the study period ($D^{\max} \approx 295$ MCM).

When the environmental flow condition is not met, a penalty value is added to the objective function value f for each objective i for time step t. The penalty value depends on the amount of water overuse. In Equation (10), q_t is the discharge of the Laja River at the outlet of the study area.

$$f^i = f^i + \left(\left| Min.\left(\left(\frac{q_t - R_t^{\mathrm{Env}}}{q_t}\right),\ 0\right)\right|\right) \qquad \text{for } i = \text{El Toro},\ \text{Albanico},\ \text{Agri} \tag{10}$$

3.3.2. TOPSIS ranking

The result of the optimization is a set of Pareto optimal solutions. Further processing is required to find the preferred solution. In this study, this is done using the technique of preference order by similarity to ideal solution (Technique Of Preference order by Similarity to Ideal Solution (TOPSIS), Hwang & Yoon 1981). TOPSIS was chosen because it is a fast and easy-to-use decision-making tool for solving multi-criteria problems. To find the preferred solution, all solutions are ranked according to their closeness to the ideal solution and simultaneously their distance from the anti-ideal solution. In this study, the ideal solution is the minimum value of the objective function and the anti-ideal is the maximum value.

Different ranking schemes are used to explore the different scenarios. For this, the weight vector w is used. The components of the weight vector are: (1) the agricultural sector, (2) HP Abanico, and (3) HP El Toro. Two scenarios are chosen: in the first scenario, a weight of 50% is assigned to the two HPs together and 50% to the agricultural sector ($w = (0.5,\ 0.25,\ 0.25)$). In the second scenario, HP El Toro is given more influence, and HP Abanico and the agricultural sector are weighted the same ($w = (0.15,\ 0.15,\ 0.7)$).

3.3.3. Evaluation indices

For the qualitative analysis of the system performance, three indices are chosen according to Hashimoto *et al.* (1982). They focus on the reliability, resilience, and vulnerability of the system.

Reliability:

$$r_v = \frac{\sum_{t=1}^{T} R_t^i}{\sum_{t=1}^{T} D_t^i} \qquad \text{for } i = \text{El Toro, Albanico, Agri} \tag{11}$$

The reliability r_v refers to the volumetric reliability of the system in meeting the demand D_t^i with the available water R_t^i for user i at time step t in the study period T.

Resilience:

$$\gamma = \frac{P_S}{P} \tag{12}$$

The resilience index γ represents the number of failure periods which are followed by a non-failure period P_S over the number of failure periods P.

Vulnerability:

$$\sigma = \frac{\sum_{j=1}^{P_S} \max(\mathrm{Sh}_j)}{P_S} \tag{13}$$

The vulnerability of the system is assessed by the index σ, which calculates the maximum shortage Sh_j during the jth failure period over the number of failure series with a subsequent successful period P_S.

4. RESULTS AND DISCUSSION

The SOP releases the most water of all the strategies, starting with the filling of Laja Lake in the spring (September to November, Figure 2). This empties the reservoir and results in long periods where no releases are possible. The downstream users, here, in particular, HP Abanico and agriculture, only receive flow from the seepage and the downstream part of the catchment.

In general, Figure 2 shows that for all scenarios, most water is released during the summer months (December to February) to meet agricultural water demand and the minimum flow condition (Laja Falls). HPs can also use that released water for energy production, since their water use is not consumptive. However, the biggest difference between the optimized results and the Real Policy is in the spring. Since more water is available then, the optimization already releases water for the hydropower plants to meet their demand. This, in turn, means that less water is left for the summer months. If more weight is given to HP El Toro ($w = (0.15, 0.15, 0.7)$), even more water is released in the spring. For HP Abanico, it is better to store water in Laja Lake, which raises the level of the lake and eventually leads to more seepage. The Real Policy does not allow large amounts of water to be released in the spring, leaving more water in the reservoir.

Looking at the storage volume of Laja Lake in Figure 3, the SOP results in the lowest storage volume compared to the other scenarios. The optimized scenario where the agricultural sector is weighted with 50% ($w = (0.5, 0.25, 0.25)$) has the second highest storage and the scenario with the weighting $w = (0.15, 0.15, 0.7)$ has the second lowest storage of the four scenarios. This confirms the conclusions from the release curves that a higher weighting of HP Abanico leads to more storage in the long term. However, the restrictions of the Real Policy on the amount and timing of release maximize storage. Nevertheless, full storage comes at the cost of less reliability of HP El Toro. These results are consistent with other studies on the New Laja Lake Irrigation Agreement (Real Policy), such as Matus *et al.* (2019) and Muñoz *et al.* (2019). Since the inflow is very low in the year 2016, as shown in Figure 3, all four scenarios produce very low storage until the late 2017 filling season with high inflow rates.

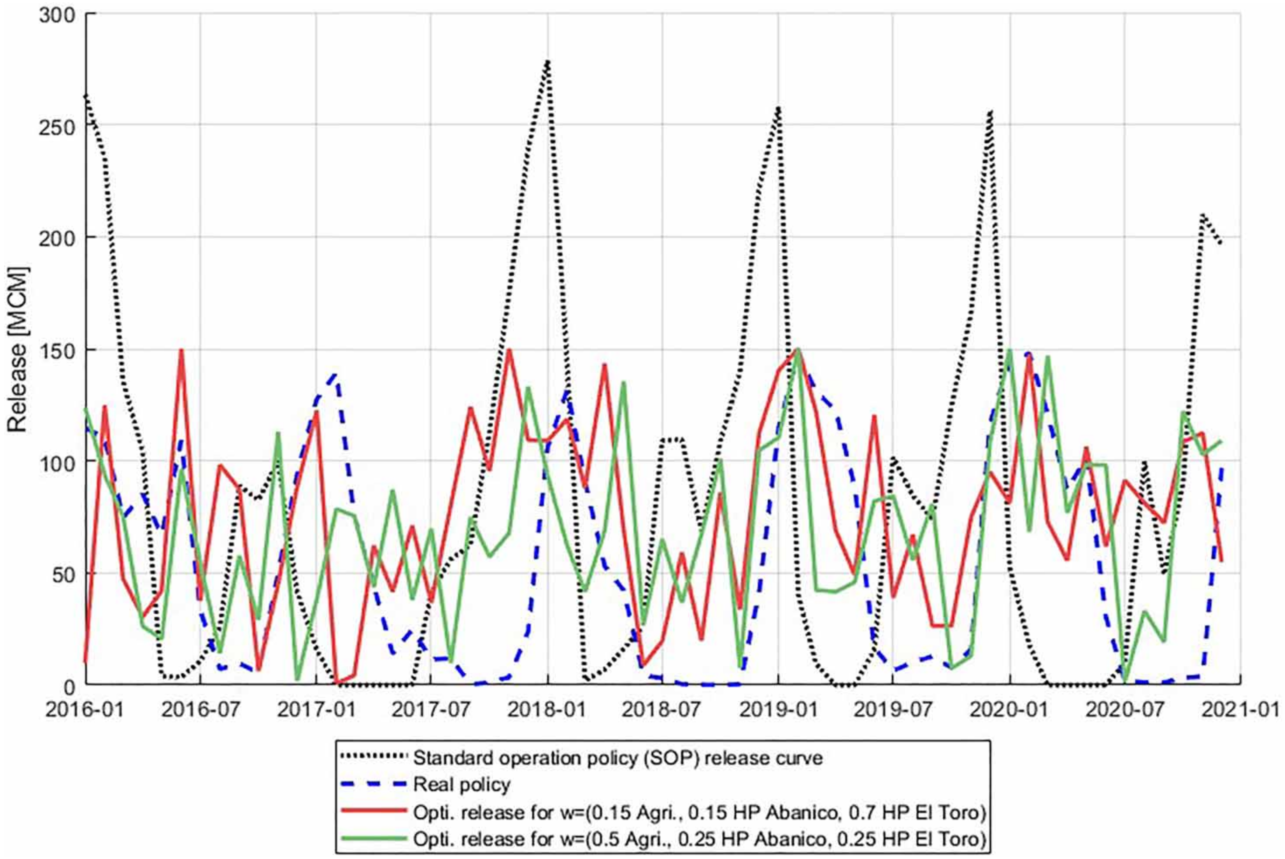

Figure 2 | Release curves of El Toro for different weighing scenarios compared to the SOP strategy and real policy.

It may be beneficial in future work to include a storage-related objective function to optimize reservoir filling. This would align the storage results of the optimization with those of the actual policy.

Since seepage depends on the lake level, the curves shown in Figure 4 look very similar to the storage curves in Figure 3. The SOP strategy always releases water during the filling season of Laja Lake, which is too early for the agricultural sector, as shown in Figure 4. The scenario with more emphasis on the agricultural demand $w = (0.5, 0.25, 0.25)$ is better in satisfying the demand in terms of time and quantity, compared to the other weighting scenario and the SOP.

Figure 5 shows the hydroelectric power generated by the two HPs studied according to the different operating strategies. As indicated before, the Real Policy, leaving more water in the lake, can generate more power at HP Abanico and less at HP El Toro. Especially in the winter months, when there is no release through the tunnel, there is no power generation at HP El Toro with the stakeholder agreement in place. It is the other way around when looking at the SOP, and the optimization results are somewhere in between.

The Real Policy provides a clear benefit to the reliability of HP Abanico (Figure 6). In contrast to these results, the consequences of implementing the SOP strategy for HP Abanico are that reliability and resilience are the lowest of all the scenarios, and vulnerability is very high. Even though the SOP produces good results for HP El Toro, the other strategies tend to perform better for the agricultural sector. This is probably the result of the high release rates in the spring with the SOP, leaving less water for the summer months, when the agricultural sector actually needs it. This proves that the SOP strategy is not suitable for finding equitable operating rule curves for the reservoir studied.

Besides the good results for HP Abanico, the Real Policy produces good results for the reliability but not the vulnerability and resilience of the agricultural sector. For the other indices and stakeholders, the optimization results outperform the other policies. Nevertheless, HP El Toro is by far the most vulnerable in all the scenarios except SOP. This is due to the very high installed capacity of 400 MW, which is not met in most time steps. This applies especially to the Real Policy. It performs better in the optimization scenario where more weight is put on it ($w = (0.15, 0.15, 0.7)$).

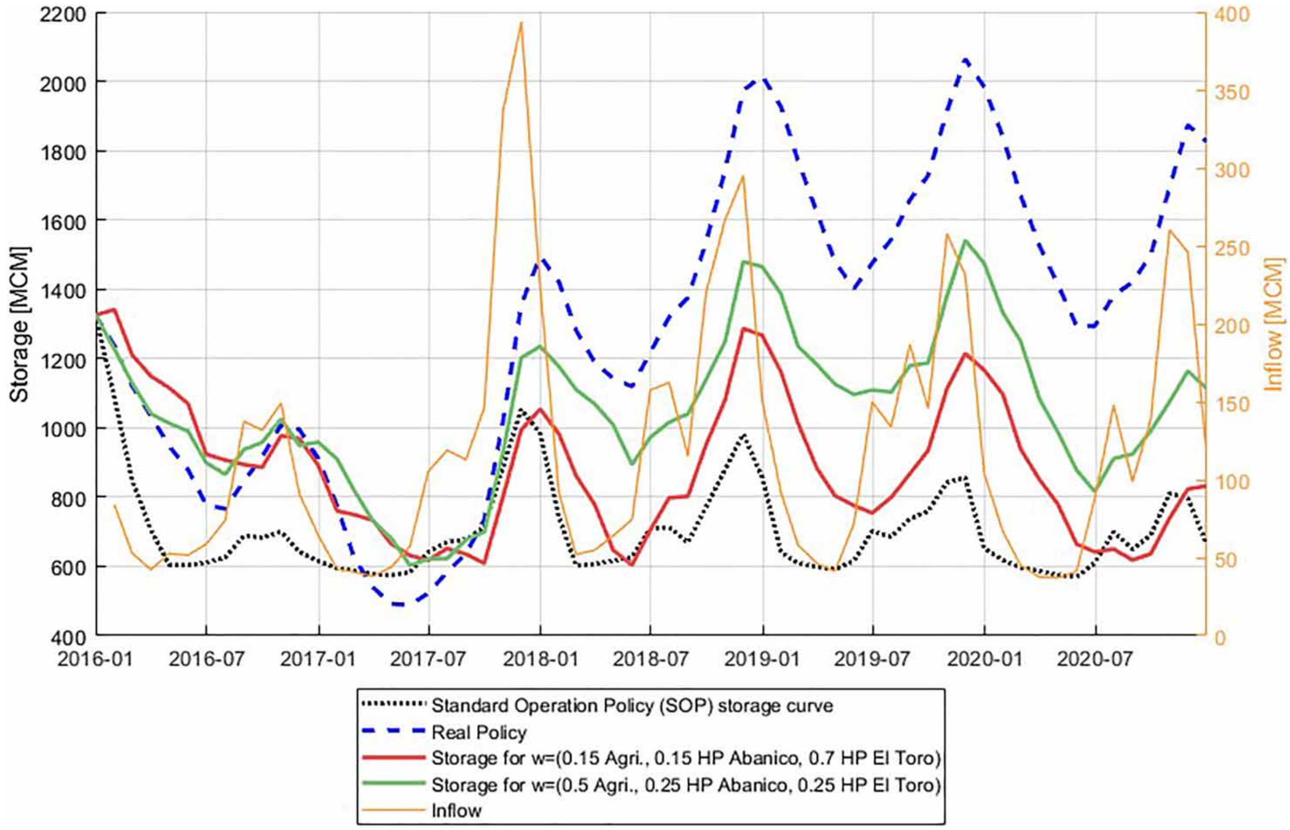

Figure 3 | Storage volume of Laja Lake according to different scenarios.

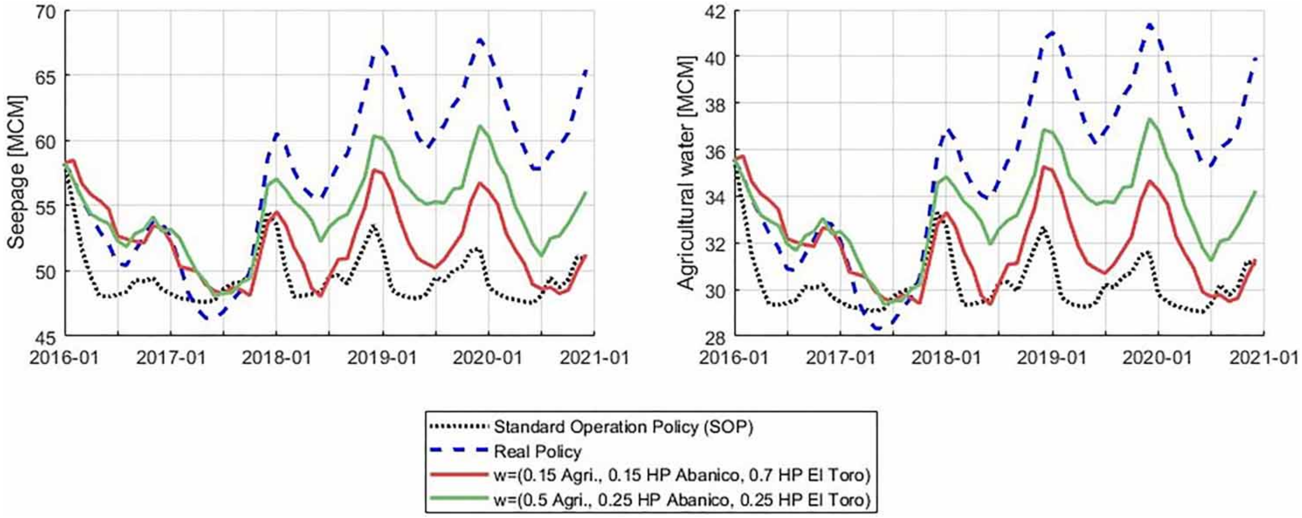

Figure 4 | Seepage (left) and available water for the agricultural sector (right) according to different scenarios.

The local characteristics of Laja Lake and its stakeholders, the national water law in Chile, and the stakeholder negotiation that took place are very specific and site-related frameworks for this case study. Nevertheless, the results show a clear added value when comparing the results of optimization with those of stakeholder negotiation. Optimization can clearly identify conflicts within a stakeholder group and reveal new alliances between stakeholders. Finding points of common interest can help in negotiations to understand each other better and to foster good and trusting relationships in the long term.

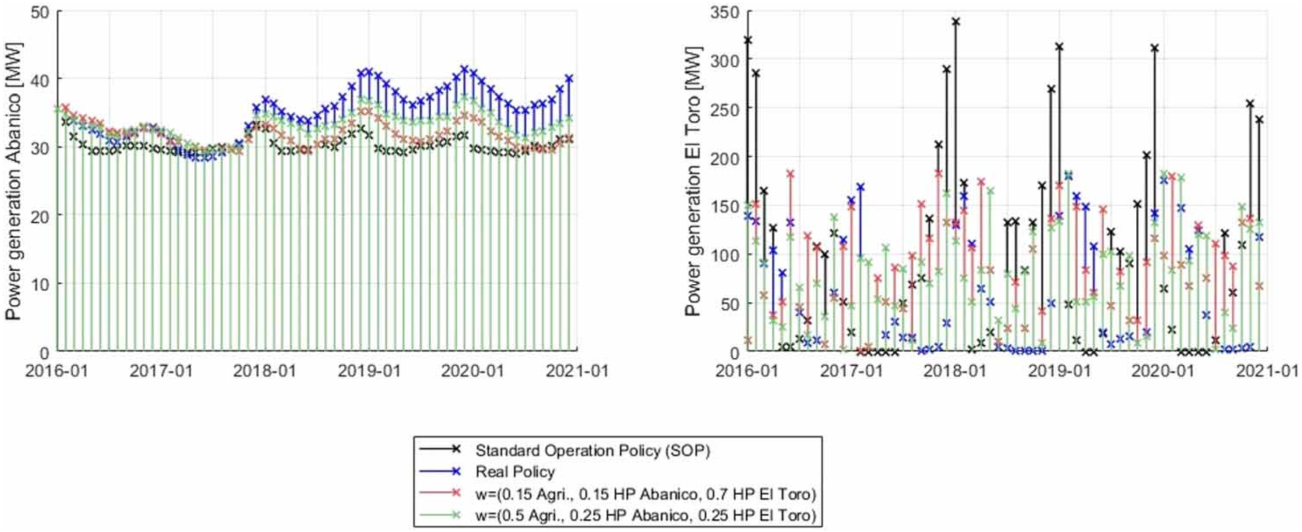

Figure 5 | Generated power for the hydroelectric stations Abanico (left) and El Toro (right) according to different scenarios. Installed capacity at the HP Abanico 136 MW and at the HP El Toro 450 MW.

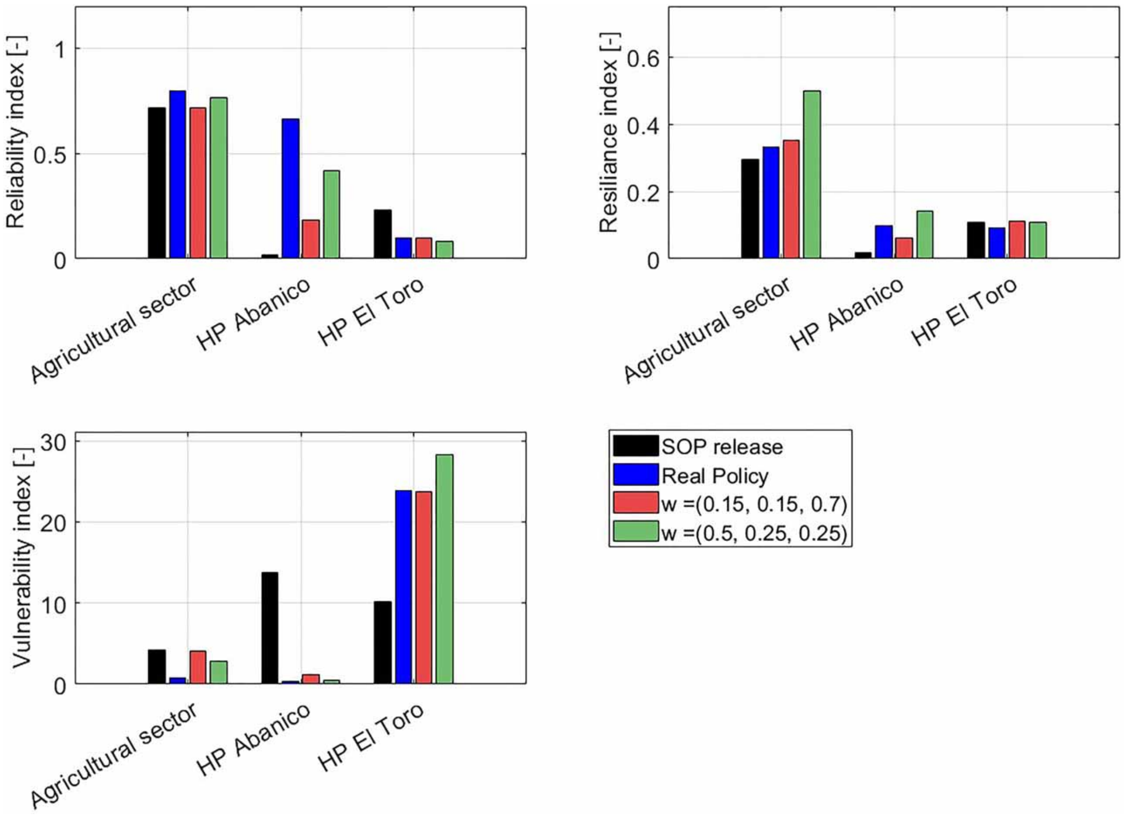

Figure 6 | Performance evaluation for different stakeholders and operating scenarios.

However, the results show that the exploration of the set of Pareto optimal solutions can lead to very different results. Deciding on one best solution is therefore a rather difficult task. Accordingly, the optimization and its results should be used to inform or guide, not to replace, negotiations.

5. CONCLUSION

This study was conducted to investigate whether optimization strategies can help to find fair and feasible solutions for reservoir operation under conflicting water demands. A combined approach was used to generate operational rules for Laja Lake in Chile. The results showed that finding equitable operating rule curves for multi-purpose reservoirs remains a challenging task for water managers. The SOP cannot fulfil it. On the other hand, the stakeholder negotiations have led to a good agreement. It helps to fill the Laja Lake reservoir and at the same time provides sufficient water for the agricultural sector. The high level of the lake, in turn, leads to good results for HP Abanico. Optimization has produced even better results in terms of system resilience and the reliability of HP El Toro. At the same time, the performance evaluation indices for the other objectives studied are close to those of the Real Policy. A higher reliability of HP El Toro comes at the cost of a lower lake level. Finally, the release policy resulting from the optimization is not yet a general solution, since only 5 years of data were available for the study.

In addition to water allocation, another important factor in the negotiations was transparency through data sharing. Ultimately, this also led to increased trust between the stakeholders. The optimization strategy presented here can support transparency already during the negotiation process. It can be used to show and explore different scenarios, highlighting the advantages and disadvantages for one group or the other. The process can be improved by adding new users and objectives, such as lake replenishment. Given the changing climate, it appears that adaptive management rules for Laja Lake seem inevitable. The last negotiation process took 3 years. To speed up future negotiations, it is recommended to use an optimization-simulation model, as presented in this study. A more complex hydrological model is required for applying the tool for future periods with simulated hydro-meteorological inputs. Examining different scenarios from the Pareto optimal front also increases transparency, as it allows the immediate exploration of the advantages and disadvantages of different strategies for all parties involved.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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