Cooperation under conflict: participatory hydrological modeling for science policy dialogues in the Aculeo Lake

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Abstract: Hydrological modeling tools can support collaborative decision processes by visually displaying hydrological systems connections, uncertainties, as well as conflicting preferences over water management strategies. Nevertheless, many challenges remain in the real application of these technical tools to successfully implement, capture, and communicate with non-experts the complexities of coupled human hydrological systems. A 5-steps process shows how a WEAP based hydrological study aiming to explore the disappearance of a 12 km^2 lake in the Aculeo basin in Chile was transformed into a multiple question driven socio hydrological modeling process to help answer the diversity of questions instigating conflict. Collaboration allowed constructing a surface-groundwater hydrological model that responded to local stakeholders' uncertainties, while testing a subset of socially accepted management strategies under two climate change scenarios, combining the strategies allows recovering up to half the Lake water volume. However, the 5-stepts participatory modeling process also shows how the increasing socio environmental conflicts over the causes and effects of the water scarcity are challenging barriers to overcome with modeling tools. As presented in this article, although flexible approaches and research agendas could better support the exploration of synergies towards collaboration and production of useful and socially acceptable hydrological models; there are still value-driven aspects of water management that need to be explored to better support science policy dialogues.

Keywords: water scarcity, modeling, participation, transdisciplinary, conflict, socio hydrology.

1 Introduction

Sound science is necessary to support decision making where population, economic and climate change have aggravated conflicts over water (Poff et al., 2016, 2003). However, on top of the scientific uncertainties impacting water stationarity (Galloway, 2011; Kiparsky et al., 2012; Milly et al., 2008), societal complexities make water related problems "wicked", given their competing and mutually exclusive deep human values and aspirations that are not resolved with technical and economic strategies (Nie, 2010). Addressing water problems from a technocratic and solely governance point of views, is to disregard the political and transformative power of water (Boelens et al., 2016; Melsen et al., 2018). In this challenge, the hydrological scientific community is aiming at finding ways to better incorporate the social-ecological interconnections (Mauser et al., 2013; McMillan et al., 2016; Salter et al., 2010), and the different types of knowledge that can contribute to a science policy dialogue (Nardi et al., 2021).

In this science policy challenge, there is an academic and practical need for a diversity of *approaches* and *tools* to better support transdisciplinary communication and understanding between scientists and non-scientists. These approaches should ideally facilitate transdisciplinary efforts, in at least two aspects of the decisions: i) *understand the context:* support communicating, structuring and displaying complex system information and connections (Arvai, 2003; Rowe and Frewer, 2000; Wilson and Arvai, 2006), and ii) *explore result*: support discussing on the role and impact of stakeholders within the decision context (Gorddard et al., 2016), such as understanding the environmental policy link of their choices (Brewer and Stern, 2005).

Despite their usually broad scale application, rigidity and engineering purposes, hydrological modeling tools could support in both the challenges of decision context and decision results mentioned earlier by: 1) visually displaying hydrological systems connections, as well as the uncertainties and knowledge gaps in the information; 2) clarifying and debating the impact of conflicting preferences in the evaluated water management strategies. Both the decision context and decision result are connected, as a legitimate scientific outcome, should result from a credible and salient science collaboration process (Cash and Clark, 2001).

However, science policy collaboration processes, are neither simple nor straightforward (Hegger et al., 2012; Scott et al., 2012). Non-scientists need to understand complex interactions between the natural, economic and social processes (Kahan, 2010; Nisbet, 2009; Somerville et al., 2011), and scientists need to incorporate diverse stakeholders adjusting the scientific process and results to different timeframes, and different needs (Rice et al., 2009). In the case of hydrological modeling, there are best practices recommendations regarding the level of involvement of participants in the design and testing of hydrological models (Voinov and Gaddis, 2008), that prove how process has a key role in the sense of co-authorship over the product and results of this collaboration (Basco-Carrera et al., 2017). Best practices for participatory hydrological modeling include: having a clear problem that all recognize and embrace; selecting an appropriate, simple, and flexible modeling tool for the question complexity, funding, and time; engaging different types of local knowledges from a diverse group of participants as early, as frequent, and as long (all stages of the process) as possible; in a neutral, transparent (in its uncertainties) and scientifically sound process that recognizes local historical disagreements; and incorporates facilitation and negotiation (Voinov and Gaddis, 2008; Voinov and Bousquet, 2010; Basco-Carrera et al., 2017).

These participatory hydrological modeling recommendations, however, are usually focused on situations in which there is time and disposition for a long engagement between academia and participants. As we experienced in the Aculeo Lake, the context in which these tools are applied can deeply vary, impacting the success of these best practices and frustrating complex science-society efforts. In this article we will explore these participatory modeling best practices recommendations in a case study that was 1) not originally intended as participatory, 2) in a community experiencing conflict over an environmental catastrophe and 3) while other governmentally-lead attempts at finding collaborative solutions were being implemented. The modeling process and results are described and explored to reflect on the achievements and pitfalls of science-society water modeling in difficult contexts. Insights from behind the scenes during the Aculeo Lake modeling process are used to develop guideline that contributes to participatory modeling and transdisciplinary efforts in contexts of high conflict and poor information on the hydrological system.

The Aculeo Lake desiccation in Chile is an example of where neither science by itself, nor public participation alone were enough to properly address the conflicting views of a water related wicked problem. The drying of the Aculeo Lake, a 12 km^2 water body, has been an internationally iconic prove of the water problems that Chile is facing (Barría et al., 2021). The photographs showing the before/after outcome, as well as of trucks distributing water, were used in diverse national and international media to discuss climate change and water governance in Chile[1]. To respond to the water scarcity, and specifically the Aculeo Lake desiccation causes and possible solutions questions, it was necessary to develop a basic surface-groundwater hydrological model. The hydrological modeling study coincided in time with a participatory process called the Voluntary Agreement for Watershed Management (AVGC in Spanish) - a dialogue process usually implemented by the Chilean Government in the context of Climate Change international agreements, but also implemented to find possible agreements between actors with very different interests. Consequently, the traditional hydrological modeling process had to be transformed into a collaborative modeling process in order to confront and include as most opposed views as possible. Exploring this case is important in Chile, as the combination of surface and groundwater hydrological WEAP modeling described in this article is being implemented in National watershed management to develop the first set of 101 Strategic Planning at the Watershed Level throughout Chile. Therefore, this study also contributes to show how a WEAP modeling process can also be used for collaboration and mutual learning in water resources management.

2 The Aculeo water crisis

The Aculeo Lake basin is a 200 Km^2 sub basin of the Maipo River in the Metropolitan Region,

[1] AFP. Drought wipes popular Chilean lake from the map. In: https://www.youtube.com/watch?v=ylnrj_cSB5Y; Aljazeera. Chile suffers the worst drought in 60 years. In: https://www.youtube.com/watch?v=qO_YMvUfW-g

Central Chile (Figure 1), a mainly agricultural zone 50 km south from Santiago, the capital of Chile, but also, was one of the most iconic touristic hotspots of the Metropolitan region of the country. Runoff from several creeks from the upper basin (2000 m.a.s.l.) flow into the Aculeo Lake located in the middle of the valley. Around 526 mm of rainfall is the annual average (data from 1960-2016), 94% of which is received in autumn-winter (April to September) and 6% is spring-summer rain (October to March). This is a heavily intervened basin, as many agricultural basins in Central Chile (more on this below). The lake should naturally drain to the Aculeo creek (also called Santa Marta or Santa María) towards the Huiticalan creek, but a small detour infrastructure keeps water from naturally flowing.

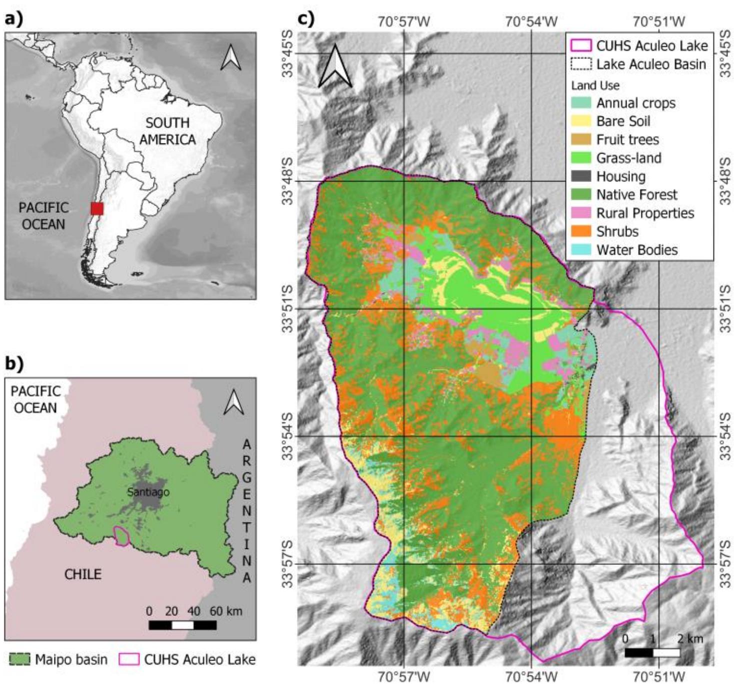

Figure 1. The Aculeo Basin located in central Chile near the capital Santiago (left panel), and main land uses (right panel).

Agriculture and livestock have been the main productive activities in the Aculeo valley, since 1660 when this was a private large state (hacienda). During this time, the Aculeo Lake basin also went through a physical transformation from a natural basin to an anthropogenic watershed with a series of channelization for different productive activities. The first Agrarian Reform in 1962 Law No. 15,020, redistributed land among peasants until the military coup of 1973 (Bellisario, 2007; Órdenes and Díaz-Diego, 2018). During the military government, the 1981 Water code distributed water use shares (WUS) to be transacted in a free market (Bauer, 2004; Madaleno and Gurovich, 2007), given by the General Water Directorate (DGA) to anyone who asks as long as there is availability. The 1981 Water Code had slight adjustments in 2005 with the establishment of water ecological flow restriction for new water rights, a fee in the case of non-use of water rights and the obligation to report transactions on water rights, but its essence is still primarily market based.

The Aculeo Lake drying process started in 2010, until it went completely dry in 2018. The phenomenon coincided with the *megadrought* (Garreaud et al., 2017, 2019), a climate event manifested as a sequence of years with 25% to 45% precipitations deficit affecting Central Chile since 2010 in terms of reduction in streamflows and increasing evapotranspiration processes. Nevertheless, several uncertainties remained related with the human management factor in the water scarcity problem, as water wells were also suffering from a decline in their water levels. In this regard a hydrological modeling study was commissioned by the Regional Government to explore the potential causes of the lake desiccation (Barría et al., 2020). The hydrological study used a surface (WEAP software) and groundwater (MODFLOW software) hydrological model to explore possible solutions to restore the Aculeo Lake or alleviate the water scarcity.

As it should be expected, the lake desiccation exacerbated conflicts among users, including additional indirect conflicts, such as livestock wandering and later dying because of the lack of water, creating problems for ecosystems and later major sanitary issues. This ecological and social problem, led the Sustainability and Climate Change Agency (ASCC in Spanish) mandated by the Environmental Ministry to work on an AVGC. The AVGC is a process in which different private and public organizations (including academia) voluntarily work to identify different actions and strategies in which to collaborate to address a basin challenge (e.g. a private company may support a civil organization to find funds for water conservation). Water scarcity was one of those problems in discussion, which also further pushed interaction with the hydrological modeling study. Although the AVGC and the hydrological modeling were designed to be implemented in parallel, giving the level of conflict and large number of uncertainties, we saw an opportunity to actively participate in the AVGC process and advance towards a more collaborative hydrological modeling.

3 Data and methods

The methods section is organized in two main elements for the hydrological modeling: 1) the model structure construction (section 3.1); and 2) the process of discussion on problems and solutions that structured the model (section 3.2). Although we show both aspects in isolation, both are profoundly interlinked as the process of discussion helped define the model structure and outcomes. As it will be presented in Results section 4, the modeling outcome have its own technical merit, however the process has some lights and shadows that leads the discussion.

3.1 Model development

The surface-groundwater model used for the hydrological balance analysis was the semi distributed hydrological modeling software Water Evaluation and Planning System (WEAP) (Yates et al., 2005a, 2005b). WEAP has been successfully used in participatory processes to study climate change adaption options (Bhave et al., 2014), ecosystem services assessment (Yates et al., 2005a) or the economic impact of water agricultural policies (Varela-Ortega et al., 2011). The aquifer and its connection to the lake and other catchments, is represented by a node that gathers its hydrogeological characteristics, analyzed as part of the hydrological study project (Barría et al., 2021). The development of the WEAP model, water balance, and the attribution study that unraveled the 'causes' of the lake desiccation (i.e. between two possible causes, the *megadrought*, and increasing water demands, due in land use/land cover changes), concluding that the *megadrought* was the main cause, are described in detail in two technical reports (Barria et al. 2020, Bluedot, 2020), as well as in a peer-reviewed paper (Barría et al., 2021).

3.2.Participatory process to hydrological modeling of the Aculeo basin

As it was explained earlier, a Voluntary Agreement for Watershed Management process initiated at the same time as the hydrological modeling study[2]. Authors of this paper were conducting the hydrological study, but at the same time, guest participants of the AVGC discussion acting as potential academia partners for the resulting agreement. As this study was conducted independently, but simultaneously with the AVGC process, there was a synergy that resulted in increased stakeholder participation in the hydrological modeling, and also led to consider the modeling results in the lake rehabilitation measures discussions.

In the line of the participatory modeling literature and the categories of participation (Basco-Carrera et al., 2017), the Aculeo Lake modeling followed a *consultation* during the modeling stage and a *discussion* during the scenario analysis, going back to a *co-design* to refine the model structure and input used in the modeling stage (Figure 2). Contrary to Bhave et al. (2014) where the objective was focused on the alternatives, in this project the original effort was to understand the hydrology and understand the causes of the water scarcity, reason why the model was built. Modeling water management alternatives was a necessary addition after constructing the model and realizing the existing level of conflict caused by scientific uncertainties that the AVGC was encountering when exploring collaboration towards facing water challenges.

As Figure 2 shows, the hydrological model structure was built with inputs from the stakeholders by discussing: i) causes of the water crisis, and ii) management strategies to solve the crisis. First, an initial hydrological modeling structure for the Aculeo basin was complete (i.e. which allowed having inflows and outflows). Then a list of eight water management strategies (e.g. water use by the agricultural sector), as well as four institutional support ideas management strategies were collected from the AVGC debates, including extreme positions presented by the different

[2] FIC-R 2017 BIP 40002646-0 “Caracterización del consumo hídrico y del sistema hidrogeológico en la cuenca de Aculeo, determinación de posibles soluciones y campaña de educación ambiental”.

stakeholders during those open discussions. A refined list of those 12 strategies mentioned and others that are being applied in other basins were presented to 25 individuals from nine stakeholders groups participating in the AVGC process (Table 1) to elicit their interest or concerns about the strategies. During these individual and confidential interviews, stakeholders were requested to comment and suggest changes, as well as to give a 1-3 value to each idea, where 1 was a very bad idea, 2 an acceptable idea, and 3 an excellent idea. Variations and considerations on each ranking were also gathered to make sure the wording of each strategy was understood.

Table 1. Stakeholder groups interviewed in the Aculeo Lake basin.

Stakeholder group	Description and water use source
Local Authorities	Mayor, environmental officers and other authorities of the Paine Municipality where the basin is located.
Neighborhood Groups	Organizations representing the citizens of the different lake side towns that were organized and participating of the discussions.
Development group	A group of neighbors that were participating of the discussions and had a displayed interest in the Lake along with other investment projects in the Region.
Rural Potable Water Association (APR in Spanish)	Group of water shares owners that extract, distribute and, in some cases, treat water in rural areas. These organizations, under the 20,998/2016 are non-profit. According to a new law from November 2020, they will have to become a Service with different norms and obligations (still in process). There are two APR near the lake, distributing surface and groundwater water to over 400 riverine families.
Medium size farm owners	Farmer owning land with more than 12 ha of basic irrigation requirements (National Irrigation Commission, CNR in Spanish). Medium size farmers in Aculeo are located in the mid and upper basin, mainly produce export goods (such as cherry, grapes, nuts, and other

	fruits), have drip irrigation, and may be organized in channel associations (a*sociación de canalistas*), legal entity in the Chilean Water Code for the management of water infrastructure in a basin.
Small size farm owners	Farms that have less than 12 ha of irrigation land (CNR and INDAP (Institute of Agricultural Development classification), located in different sectors of the basin, mainly producing cereals and horticulture for the local market under surface/gravity irrigation, and organized in irrigation groups or water communities (*Comunidad de agua*) around a common well or surface water share.
Tourism camp sites owners	Private areas around the lake rented for camping and recreation. Water for human consumption, as for gardening irrigation and pools came from private wells, as they are not usually associated with the APRs.
Livestock association members	*Arrieros* or transhumance livestock producers (an old tradition in mountain ranges following the seasonal change of pasture and water). In Aculeo, as in many parts in Chile, *arrieros* do not own water nor land, but pay an old "tribute" to landowner in the form of non-paid day of work per head of cattle passed through their land.
New building sector	Organizations of either real state groups or new built areas ("condominium" of second homeowners that populated areas around the lake). These organizations have their private anonymous societies for water distribution that own underground water shares. However, the lake was important for recreational activities and affected their real state value.

A subset of the best ranked "Action/Strategies" adjusted based on the interviews, were simulated in the Aculeo Basin WEAP Model:

- **Agricultural irrigation efficiency:** The improvements in agricultural water efficiency is commonly used in Chile to increase irrigation area. The strategy here is to increase water efficiency, but without increasing agricultural area. The interviews allowed to corroborate that industrial agriculture already has high irrigation efficiency, but there still are important amounts of annual crops with water efficiencies of 50%. Two scenarios were simulated in WEAP, Scenario 1 increased the water efficiency of annual crop to 70%, while Scenario 2 increases to 85%.

- **Rural house grass gardens reduction:** An increase of second homeowners during the last decade coincided with the water crisis, generating discomfort and suspicion among traditional inhabitants about their preference for grass gardens, being the cause of the lake disappearance. Eliminating rural house gardens was perceived by the hydrological modeling group (the authors), as a good strategy before the interviews. However, people that used to work in other agricultural activities are currently working as gardeners, hence eliminating gardens might have quite a big impact. After interviews, simulation used recommendations by Bown and Fuentes. (2019), which is 20% of the gardens with grass, 30% the shrubs of intermediate consumption and 50% of the surface with cacti species, stones, or xerox type garden, with no irrigation. This scenario incorporates both the need to reduce water consumption and the peoples need of not eliminating grass due to the impact it may have to their jobs.
- **Recovery of Water Use Shares:** This watershed has a long history of occupation, which has resulted in numerous manmade water structures, some are not even known by landowners due to their antiquity. Even though diversion was confirmed to be legal, and eliminating it means the expropriation of WUS, an extreme measure in Chile given that water shares are real state asset, the strategy was simulated to respond to stakeholders' concerns. This potential strategy considers the diversion of water not being used in some months of the year by other nearby basins (which would make it feasible without actually expropriating WUS) in two inflow scenarios, one with 700 l/s and the other with 1,000 l/s, from March to May. In fact, there is a project currently being under study called "Aguilino

Chanal" that may have a similar goal, so we used the name for familiarity with the concept.

Finally, to evaluate the sustainability of the strategies, a *business as usual* climate change scenario (Representative Concentration Pathway RCP 8.5, Van Vuuren et al., 2011) and a moderate scenario (RCP 4.5) were also considered in the water balance simulations. To assess the effectiveness of these strategies, a reference scenario, without management strategies under climate change was also implemented. We used approximately 100 general climate models (GCMs) simulations from ~30 models, under the RCP 4.5 and RCP8.5 scenarios (Van Vuuren et al., 2011), which were bias corrected using the Quantile Delta Mapping method (QDM, Cannon et al., 2015). Model final outcomes were presented in different meetings with local stakeholders and governmental officials to receive and give feedbacks on future steps that were being considered. The final use of the model, however, encountered other challenges that will be discussed in section 4.5.

4 Results

The main results from this research are presented in a 5-steps guideline that indirectly resulted as the main outcome of this modeling engagement. Figure 2 describes the 5-step guideline that addresses both modeling phases, but also science-policy challenges that could guide future research.

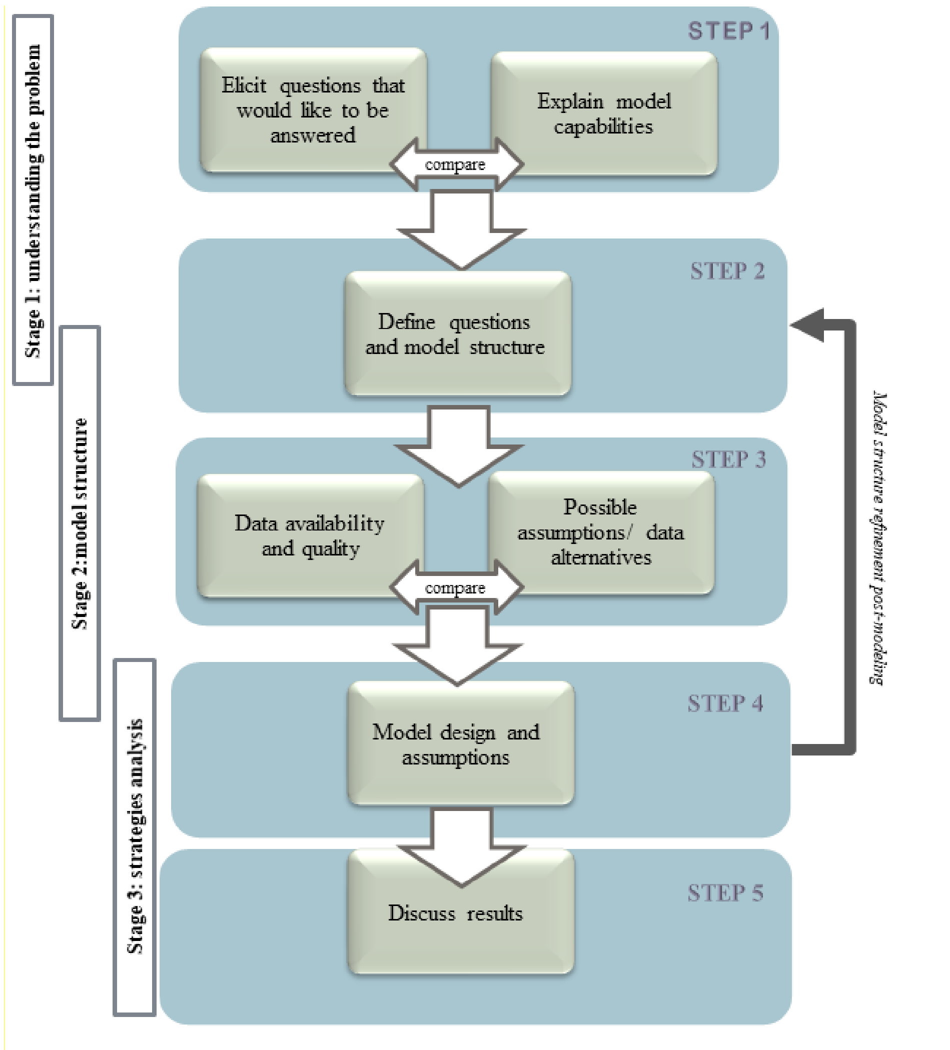

Figure 2. Main steps that guided the participatory modeling process. In the left there is a comparison with the questions/comment's interaction stages presented in figure 3.

4.1 Step 1. Collecting the questions

Understanding the problem helps framing the model; but is also an opportunity to evaluate the context and the possibility of reducing non-modeling uncertainties with other sources and tools.

Therefore, in an initial step, it was important to collect all pressing questions that stakeholders would like to have an answer (Figure 3), while carefully explaining the limitations and capabilities of the hydrological model in terms of representing biophysical processes around a specific problem. In this step, contrasting opinions verted during the meetings on both the causes of the water scarcity and the need to rehabilitate the Lake hinted at the level of underlying tension in this community (Ocampo-Melgar et al., 2021), but also pointed at the uncertainties that were essential to be addressed. From all questions and lines of explanation, we identified plausible from impossible questions to answer with the model, and then define which impossible questions were key to address for the stakeholders to be confident about the hydrological modeling representation of their basin, e.g. discerning which inflows and outflows were legal, despite of not being physically necessarily for a basin representation (see step 4.3).

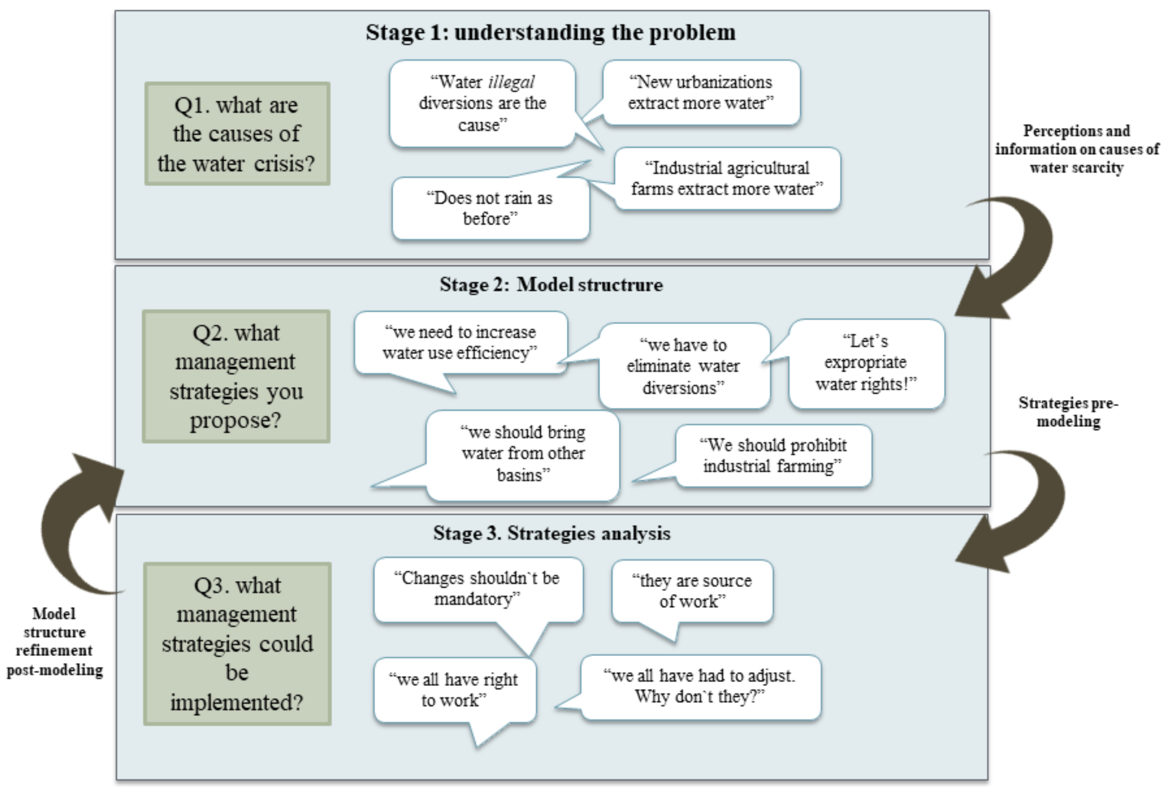

Figure 3. Main questions that emanated from the voluntary agreement conversations that fed the modeling process in terms of framing the problem, design the basing structure and identify potential strategies.

4.2. Step 2. Dividing questions for the conceptual modeling development and for the simulation of strategies

In a second step it was necessary to organize questions in variables for the model, in terms of structure (i.e. where do inflows, and outflows come from and go?) and questions that were more related with possible strategies. In the case of questions that were related with the model structure, it was necessary to consider their connections with enough flexibility to be able to modify the conceptual model later, as other inquiries or questions can arise in the process that may change the conceptual view of the basin. This was the case of land uses water demands, as there were many uncertainties with the official information (see Step 3). The final land uses classification required several iterations in how the variable were being conceived, along with stakeholder involvement and legal information analysis, such as the analysis of records at the Real State Conservator to confirm the official land use of each plot (see Barria et al., 2021; Barria et al., 2020, chapter 4).

Similarly happened on the set of questions/comments that were more related with what stakeholders considered were possible solutions. To better turn these comments into strategies, individual interviews and group discussions with stakeholders were used to assess the social acceptability of the strategies, even though some of these "solutions" did not have legal, nor technical possibility of being implemented, e.g., transfers from a neighbor basin that is already over allocated. Results of the interviews allowed to select a subset of strategies that could be tested with the hydrological model, and a group of strategies for which technical, financial, and legal information was gathered to contribute to their analysis (Barria et al., 2020, chapter 5).

The interviews showed that the most "extreme" solutions may not necessarily have the majority support. In Table 2, a summary of individual rates or evaluations of each strategy show a positive view on some strategies, although they are recognized as not solutions to the water scarcity problem. Other strategies were reworded and changed in the model after the interviews. This was the case of "elimination of grass", which after the round of interviews it was clear nobody agreed as it was described. The strategy was implemented in the model as an alternative garden for semi-arid central Chile, which according to Bown and Fuentes (2019), water consumption can be reduced up to an 80% in the summer months, through changes in plant species and their distribution.

Table 2. Assessment and general comments on the strategies or lines of actions provided by the interviewees

Action/strategy	**General comments**	**General acceptance (rate 2 or 3)**	**General difficulty on implementation**
1) Swap: water shares exchange systems between users	"It is a solidarity solution"	100%	Has been applied before in other basins. Although it requires a legal and mandatory water users' agreements.
2) Support for the Rural Drinking Water Organizations that provide drinking water	"It is necessary to avoid another water crisis."	100%	There are institutional and financial changes that have been assessed for the State agency to better support rural organizations
3) Implementation of underground Water Communities (*Comunidad de Aguas Subterráneas* CASUB in Spanish)	"It is necessary but does not solve the illegal water extractions problem."	89%	Is the formal organization to manage aquifer water resource. There are experiences in other basins. While this project was being conducted, the General Water Directorate (DGA) was starting conversations on this line.
4) General Water Directorate (DGA) strengthening	"It is necessary to define new and different roles than only inspection and fining."	89%	There are institutional and financial changes that have been assessed in different reports for the DGA to better conduct their supervision role in Chile.

5) Agricultural water use efficiency	"It is necessary, although it does not solve the problem of those small agricultures who quit, due to the drought."	100%	It requires investment on infrastructure and human capabilities.
6) Urban water use efficiency (rural house grass gardens elimination)	"It is necessary but should not be mandatory nor extreme. Better to support voluntarily reductions as it will affect jobs for local people."	77%	It has been applied voluntarily by individuals, but never as a Municipal regulation.
7) Industrial farming prohibition	"This is a terrible idea that will affect agricultural jobs."	44%	No precedents for this type of measures. Except in cases where the market forces a crop change for economic reasons.
8) Proration of water shares between legal users	"It is fair and necessary. Although it does not consider illegal water extractions."	100%	It is a strategy being used in several basins in Chile to, which leads to water reduction according to availability, and possibly exchanges between users when one of them does not need it.
9) Intra basin transfer by connecting water diversions for human consumption in critical season	"It is not a solution for human consumption as it does not have enough quality. Could be a solution to have some water in the lake."	100%	There is a project and different ideas, but none has been applied before.
10) Recovery of Water Use Shares (buying water shares)	"It can be unconstitutional to expropriate water shares. Should only be bought and for human consumption only."	100%	This type of strategy has been carried out in severe cases of water scarcity and overexploitation of water bodies, where the State has had to buy water shares to meet conservation or drinking water needs, as in the case of the Ligua-Petorca basins.
11) Water transfer from other basins	"It is the only solution for the lake, but it can be very conflictive as there are no other basins nearby with extra water."	89%	There are some small projects in the same basin, but no transfers from other basins have been done before. It will require large agreements and if done it will have social and environmental impacts.
12) Water reuse	"It is a survival strategy that has been already implemented voluntarily; but does not solve the problem."	89%	It requires financial support for infrastructure and human training.

Additionally, to the percentage of low bad rating of some of the cases (e.g. water reuse), it is important to notice in this step, the representativeness of the stakeholder group that gave the low rating (e.g. may be an important economic sector), as well as the justifications given for their evaluation, as this information points out to aspects that could facilitate their implementation and avoid future conflict. This was the case of strategies that are implemented at a household scale, and therefore could require government support to alleviate the economic burden mentioned by citizens. At the same time, results showed that sometimes the most mentioned or publicized strategy in the heat of conflict, may be recognize as a not very good option while discussed in private (e.g. industrial farming prohibition).

4.3. Step 3. Evaluating information availability and quality

Once questions have been sorted in those for the model structure and those for the simulation of strategies, next step is to evaluate the availability of official and scientific information. In this case, main challenges, among many, were the short fluviometric records in the basin (i.e., less than seven years for only one station), the non-existence of previous detailed groundwater studies, and uncertainties on the number of WUS granted in the basin. The first two of these unknowns had to be addressed for the hydrological modeling to represent the historical hydrology. Given the level of conflict and distrust, to avoid eliminating questions or concerns due to an initial presumed lack of data, it was important to include stakeholders in this step by letting them know the information gaps, as well as the alternative methods and assumptions that had to be adopted to be able to proceed. This step was key for the participants to understand the scientific process behind the model, but also for the modelers to find alternative sources of information, e.g., private aquifer information and non-public local governmental records on water use efficiency.

On the third data gap (uncertainty on WUS), although from a water balance perspective water uses legal or not need to be considered in the hydrology, this variable was also an important source of conflict (identified in Step 1), as there was a perception that a drastic increase in new agricultural uses and homes had caused the water desiccation (Ocampo-Melgar et al., 2021). Therefore, more information was necessary to reduce WUS uncertainties, although not necessarily hydrological uncertainties. Two side analysis had to be conducted to have more clarity on both the legal and the actual water uses. Historical aerial photography and WUS information were analyzed on a specific manmade stream diversion channel up in the basin, that according to some stakeholders, through those diversions people had been stealing water from the watershed. The diversion channel was visited, followed by interviews with the Agriculture and Livestock Service and review of 1956 property documents borrowed from the Real State Conservative, confirming the legality of those water shares. Second, a water share study in the Real State Conservative was conducted to provide more clarity about how many shares have been granted in the basin (see chapter 4, Barria et al., 2020). Results showed that WUS collated by the DGA official data base represent only a 30% of the total WUSs granted in the basin, where the remaining 70% (granted during the Agrarian Reform) are not considered in current water balance estimations. This means that if all granted WUSs were actually used, the lake would have dried up long before the beginning of the *megadrought* (most likely during mid 80s), and adaptation strategies oriented to restore the lake would be useless.

In this step, although we agree with previous research that stakeholders' involvement improves hydrological model acceptance within the community (Voinov and Gaddis, 2008; Voinov and Bousquet, 2010; Basco-Carrera et al., 2017), as well as helps opening doors to alternative information that the community may have, we also found that this does not necessarily reduce conflicts, as the information found in this case was not what some stakeholders were expecting. This was for example the case of the connection between the lagoon and the aquifer that was found dominated by surface flows, due to the confining layer of clay that separates them; theory that was not accepted by those that were convinced that the increase of water extractions was the cause of the lake disappearance. Similar reaction was received by those that were convinced that diversions and agricultural uses were illegal because they were not in the official data base, but as explained earlier, this is because water distributed during the agrarian reform has not been registered in the official records (Barria et al., 2020).

4.4. Step 4. Share model intermediate outcomes and assumptions

Once data has been evaluated, and the model is tested, there are intermediate outcomes to share and hypothesis to discuss before the model is considered finished. The AVGC meetings were used to present intermediate results, while an opportunity for stakeholders to question and challenge the accuracy and validity of the hydrological model being constructed, which in turn forced the modeling team to challenge official information and search for alternatives sources and approaches to find answers, such as the official versus the real number of water wells.

In terms of the intermediate outcomes, results of the three strategies that could be modeled by the WEAP tool proved to be an efficient combination of high and moderate social accepted strategies: 1) the diversion of water not being used for some months of the year by the agriculture users of the Aguilino Channel (Aguilino), 2) Agricultural irrigation efficiency, increasing the efficiency of annual crops from 50% to 85%, and 3) Rural house grass gardens reduction, implemented as follow: 20% of the gardens with grass, 30% the shrubs of intermediate consumption and 50% of the surface with cacti species, stones, or xerox type garden, with no irrigation.

Figure 4 shows the lake water volume simulated under the historical, and climate change scenario as a result of the water balance of the basin. According to the simulations, by implementing the three adaptation measures under the historical climate ("Hist. adapt.", panels a, b, e and f of Figure 4), the volume of the lake would have been around 34 Mm^3 (56% of the lake volume) during the *megadrought*. Note that as presented by Barria et al. (2021), the Aculeo Lake is completely desiccated since year 2018. The simulations under climate change projections reveal that there are significant differences on the simulated water volumes when comparing the "no adaptation" (solid lines panels a and b of Figure 4) against the "adaptation" scenarios (dotted lines panels a and b of

Figure 4). Under both climate change scenarios, the effectiveness of the strategies is evident for the dry 15th percentile, which generate an increase in 28.2 and 20.8 Mm^3 of the lake volume compared to the scenarios without the strategies, under the RCP4.5 and the RCP8.5 scenarios respectively. Moreover, the average of the different GCMs simulations (50th percentile) also shows large differences in the lake volume by including or not the strategies, with differences that fluctuates between 10.2 and 39.8 Mm^3 under the RCP4.5 and the RCP8.5 scenarios respectively, for the 2050-2100 period. Finally, the simulations for the last 30-years of the century under the severe climate change scenario, indicate that by implementing the three adaptation measures, half of the time, the lake would have ~50 Mm^3.

Comparatively, although the three strategies contribute to the water balance, as presented in panels c) and d) of Figure 4, the linkage to agricultural channel adaptation measure, has the largest contribution to the lake water volumes under the climatic scenario. Among the three strategies, the contribution of the Aguilino for the 2050-2100 period under the RCP8.5 scenario, represents about 83% of the increase in the water volume, which is around ten times more than the contribution of the agricultural water use efficiency and the garden water use efficiency. Although the two strategies oriented to improve the irrigation efficiency in the basin have a comparatively lower impact on the water balance at the basin scale, they can be part of a combination of strategies socially accepted by the stakeholders proved by the high ranking obtained, which could contribute to increase awareness of the complex water scarcity problem and to develop preparedness under climate change and its impacts.

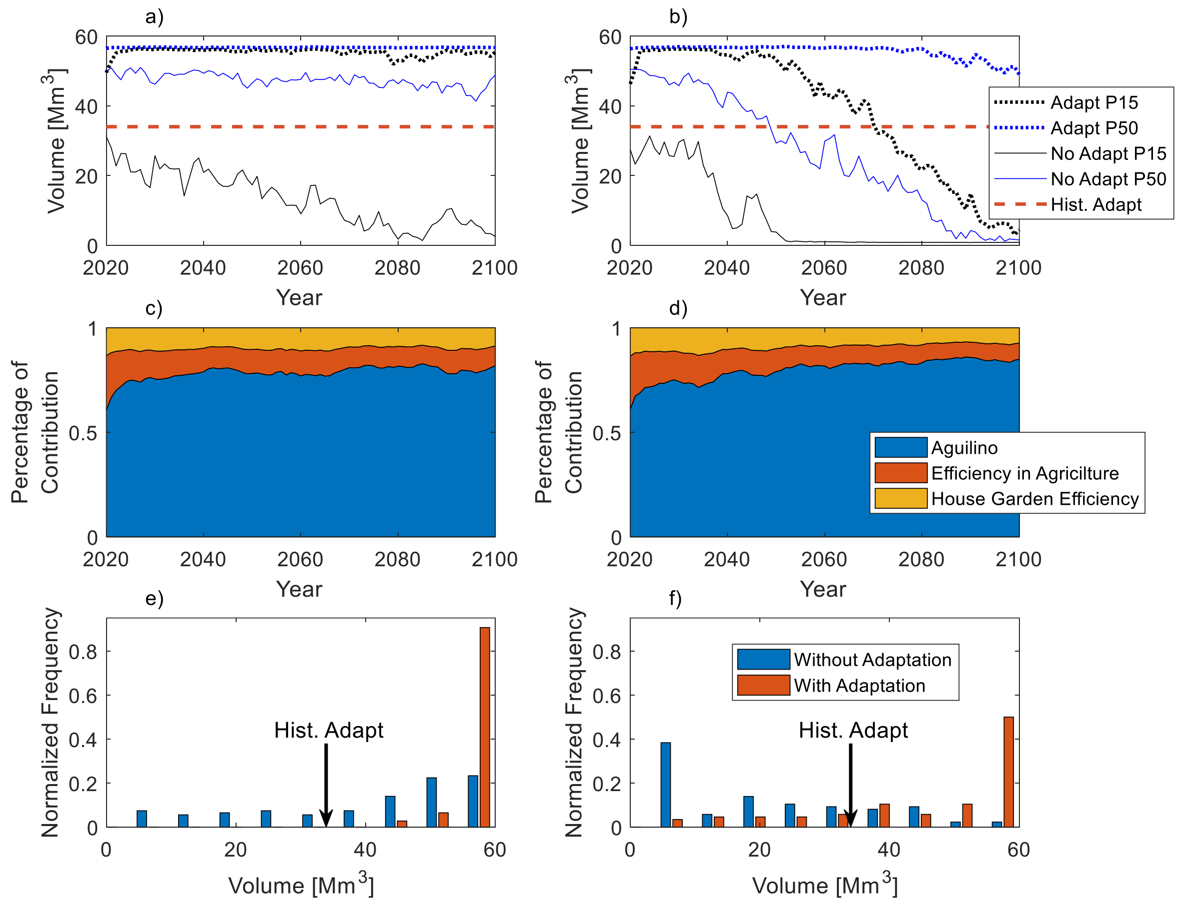

Figure 4. WEAP model water balance results under the combination of strategies; a) annual lake water volume simulated under the RCP4.5 scenario, b) same as "a)" but under RCP8.5 scenario, c) projected percentage of contribution of each strategy under the RCP 4.5 scenario, d) same as "c)" but under RCP8.5 scenario, e) normalized water volume frequency using different GCMs simulations on the period 2071-2100 under the RCP4.5 scenario, f) same as "e)" but under RCP8.5 scenario.

Regardless of the stakeholders' feedback that helped improve the model and the interesting combination of strategies and novel information that was gathered during the process, as we learned from the Aculeo case, the scientific process of progressively adjust model and results may be perceived as lack of certainty by some participants, especially by those that support certain theories that are discarded in the process. On top of this, in step 4 we thought it was important to be unbiased and avoid rising expectations on the identification of "culprits" early in the process, as this does not contribute to the necessary dialogue, nor represents the complexity of socio hydrological systems. However, not being vocally strong about placing guilt may be perceived as taking sides; a misguided perception that can impact trust in the process.

4.5. Step 5. Communicating and discussing results

Once the model and strategies evaluation were finished, to increase readability results were published in a book in Spanish (Barria et al., 2020) and presented in different public workshops and portrayed by the media. Presenting final results to the public however, was one of the most failed aspects of the science-society collaboration. As it was experienced in the Aculeo case, modeling results did not leave everybody pleased, as there are conflicts underneath that a scientific answer won't diffuse. As Goleman (1989) has discovered once an idea is conceived, of how the world works, one tends to incorporate information that validates that idea and discard contradictory information, hence people whose original ideas does not match the results will tend to discard your study. Therefore, disseminating scientific information in the media, when these results involve conflictive issues, required careful skills that usually are not part of researchers, nor academic institutional communication. Understanding the context, conflicts, perceptions and values involved were important to design the model, but also must guide the most sensitive way to inform results (Abels, 2007).

The process and model results were key to support conversations and strategies evaluation during the first year of the Collaborative meetings (2018-2021). However, other political changes and economic interests affected the internal dynamics of this collaborative group that had a short span of funding (2 years). At the same time, as the model results not necessarily validated all opinions and expectations, it was no longer useful for some stakeholders at the AVGC. The hydrological modeling is however an important result still being presented and used in decisionmakers settings. Currently, the Aculeo WEAP model is part of a new project set to estimate the ecosystem services of native forest and to analyze the exacerbated impact of climate change in the water balance due to both: changes in native forest dynamics and the basin hydrological response; a project that will engage with other stakeholders in the Aculeo basin.

5 Discussion

The modeling approach implemented in the Aculeo highlighted the importance of the participation in the modeling process, as they allowed for the identification of a combination of strategies that are of moderate impact, but of higher local acceptability than the large structural options. On the contrary, a solely top-down hydrological modeling would not have considered less efficient solutions, due to their relative more moderate impact in terms of the lake inflows. However, stakeholder involvement in the modeling process not necessarily smoothed the discussion, as we explored in the 5-step guideline that guided the interaction with participants. From this experience, we have insights for science society initiatives involving hydrological modeling under limited information, and when underlying conflicts may demand a more cautious, but still, participatory process, to help uncover crucial elements for the modeling process success:

- **Conflictive situations require facilitated participation:** Although the 5-steps guideline shows a process of communication during modeling, this was possible due to the facilitated setting of the AVGC. Future modeling processes should consider proper neutral facilitation and different instances for one on one dialogue and group deliberation. For example, the Aculeo process showed that information (in this cases strategies preferences) obtained by individual interviews result very different than group conversations when discussion were used to show power over other stakeholders. Including this instances in a more structured way could have reduced the extreme opinions during the group meetings.
- **Accepting manageable uncertainties:** In our experience, it is better to discuss

uncertainties as early as possible, as assumptions and information gaps will show eventually. Including local decisionmakers in the process of finding alternative solutions to those gaps may help empower them and make them participant of the modeling. As proposed by many authors before, complex problems where there is a high uncertainty in knowledge, distribution of power and ambivalent goals, are better approached through participatory and deliberative methods to discuss different possible narratives, than a single participatory modeling or top down policy approaches (Pellizzoni, 2012; Stirling, 2006; Wise et al., 2014). However, there is also a large chance of finding very different and contradicting information that is impossible to contrast, such as when there is a fine legal interpretation in between, or where there are no possibilities to confront the reality due to lack of data or time and funds constraints.

- **Approaching positions have a limit:** The use of hydrological models for supporting decision making in the Aculeo participatory process, showed the acceptance and legitimacy of model increased once stakeholders noticed their knowledge and opinions were incorporated, which may or may not increase model complexity. When opinions are later confronted with the modeling results, an increased understanding may help bring closer originally opposite opinions, as it has been previously showed in deliberative processes that focus in understanding the problem and learning about different facts and values, while avoiding never ending discussion on the scientific uncertainty (Hermans et al., 2007). However, as we found, in some cases, when conflicts have surpassed a dialogue limit, and when many economic and political interests are involved, not even the best available science will make their positions closer. As Weible et al. (2010) discusses, how science is integrated in a discussion, will depend on if this is a "collaborative" vs an "adversarial" policy situation, as either of those contexts will define if scientist are allies of all, or adversaries of one of the "coalitions". Therefore, when conflicts are high, if scientific findings do not support a group of belief systems that explain a position (Goleman 1989), this automatically sets science in the adversary side (Weible et al., 2019).

- **No neutral role for the hydrological model:** The model development and application should aim at supporting the conversation by showing different scenarios, while avoiding choosing a side. Nevertheless, as we found in this experience, maintaining neutrality is extremely difficult in situations of high conflict, especially in these times, as expressed by Pellizoni (2012), when *science and technology are charged with growing social expectations, but are greeted with equally growing skepticism or hostility*. Especially when the decision is over a politically contentious topic with uncertain science, there is the high probability that lack of credibility ("we don't believe this"), legitimacy ("the process has been corrupted"), and/or salience ("science answered the wrong question") of the results complicate the use of science for policy making (Cash et al., 2006). As Vogel et al. (2007) stated, "When scientists neglect—even if unintentionally—the political and strategic nature of scientific knowledge, and the political context in which it is produced, they can be faced with uncomfortable and challenging situations for whose navigation many are ill-equipped". Recognizing the political role of the hydrological model is part of making the process and us, as researchers, better at identifying better ways to address science society communication. Understanding the impact of our results in the community we are researching is just as important as being scientifically unbiased (Babidge, 2016; Budds, 2008).

6 Conclusions

The participatory modeling implemented in the Aculeo basin was key to navigate throughout the complex situation, understand and recognize local actors' opinions, and concerns in the model structure, and in the identification of strategies. The participation of this team as members in the discussions of the Voluntary Agreement group, resulted in a diversification of questions and possibilities for the modeling process. Specifically, the participatory identification and evaluation of strategies allowed to better adjust the hydrological model to answer questions that were causing suspicions and further conflicts among stakeholders. The same process was also important for the identification of a combination of strategies that were of moderate impact, but of higher local acceptability than the large structural options. The surface-groundwater hydrological model tested a subset of socially accepted management strategies under two climate change scenarios, showing that combining more low impact, but socially acceptable adaptation measures such as using the out of season irrigation surplus (March to May), improving irrigation efficiency for agriculture industry, and decreasing the grass surface in new urbanizations, would allow to recover up to half the Lake water volume even under a pessimistic climate change scenario. Possibly, a solely top-down hydrological modeling would not have considered less efficient solutions, due to their moderate impact in recovering the Lake.

However, as the experience was not completely successful in terms of engagement, this article also shows that hydrological modeling requires now, more than ever, funding transdisciplinary approaches both in its construction, but also in its application as it is key to achieve credible, salient, and legitimate processes for decision making. As exposed in the Aculeo basin, especially when contentious water related conflicts are high and attribution of climate change impacts are uncertain, collaboration in the hydrological modeling process and appropriate attribution analysis are key in finding management options that could contribute to both answering the problem, as well as to understand the conflict. This, however, may not necessarily be enough to reduce conflicting positions, that are constantly stirred according to personal interests.

Author contribution

AOM, PB and CC, designed the study, contacted, and interviewed local stakeholders and participated in the voluntary agreement. AOM elaborated preliminary analysis of the interviews and the participatory experience. CR gathered information for an economic and legal analysis of the strategies. PB and CC developed the hydrological model and simulated the strategies. AOM, PB, CC and CR discussed the results, AOM, PB and CC prepared the manuscript.

Competing interest

The authors declare that they have no conflict of interest.

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