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Participatory and Integrated Modelling under Contentious Water Use in Semiarid Basins

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Abstract: Addressing modern water management challenges requires the integration of physical, environmental and socio-economic aspects, including diverse stakeholders' values, interests and goals. Early stakeholder involvement increases the likelihood of acceptance and legitimacy of potential solutions to these challenges. Participatory modelling allows stakeholders to co-design solutions, thus facilitating knowledge co-construction/social learning. In this work, we combine integrated modelling and participatory modelling to develop and deploy a digital platform supporting decision-making for water management in a semiarid basin under contentious water use. The purpose of this tool is exploring "on-the-fly" alternative water management strategies and potential policy pathways with stakeholders. We first co-designed specific water management strategies/impact indicators and collected local knowledge about farmers' behaviour regarding groundwater regulation. Second, we coupled a node–link water balance model, a groundwater model and an agent-based model in a digital platform (SimCopiapo) for scenario exploration. This was done with constant input from key stakeholders through a participatory process. Our results suggest that reductions of groundwater demand (40%) alone are not sufficient to capture stakeholders' interests and steer the system towards sustainable water use, and thus a portfolio of management strategies including exchanges of water rights, improvements to hydraulic infrastructure and robust enforcement policies is required. The establishment of an efficient enforcement policy to monitor compliance on caps imposed on groundwater use and sanction those breaching this regulation is required to trigger the minimum momentum for policy acceptance. Finally, the participatory modelling process led to the definition of a diverse collection of strategies/impact indicators, which are reflections of the stakeholders' interests. This indicates that not only the final product—i.e., SimCopiapo—is of value but also the process leading to its creation.

Keywords: stakeholder participation; surface water-groundwater interaction; scenario modelling; integrated water management; agent-based modelling; SimCopiapo

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1. Introduction

Water resources are fundamental for supporting livelihoods, food production, energy generation and ecosystem services across the globe. Despite their relevance, water systems are under continuous threats, thus undermining water security [1] and promoting water stress [2]. Interdependencies between water, ecological and social systems across multiple scales and dimensions (e.g., water–energy–food–environment nexus [3,4]) continuously challenge the way water resources have been managed [5]. In this regard, Hoff [6] states that " . . . water management and governance have not yet adapted to these cross-scale and cross-sectoral interdependencies and their dynamics and associated uncertainties".

Water management challenges are no longer addressed solely as technical problems but rather have become part of complex policy and decision-making processes, where multiple stakeholders and institutions reflecting an array of diverse values and interests are involved [7–9]. "Integrated" approaches to account for the array of drivers that help to constrain/condition these water management challenges have therefore received a surge of attention in recent years [10–12].

Kelly et al. [13] discuss the term "integration" in the context of integrated assessment and define five levels with multiple loci in the modelling process: (a) integrated treatment of issues, (b) integration with stakeholders, (c) integration of disciplines, (d) integration of processes and models, and (e) integration of scales of consideration. Integration of biophysical and socioeconomic aspects [10,14] and integration across processes/models (e.g., surface water and groundwater interactions [15,16]), as well as integration with stakeholders [17], have all been documented in the water management-related literature. In the context of surface water–groundwater interactions, Barthel and Barnhaz [16] suggest that "integrated modelling" should explore aspects beyond the purely physical coupling process between surface water and groundwater systems and cover multiple scientific domains and disciplines, thus aligning with the level "integration of processes and models" proposed by Kelly et al. [13].

Jakeman et al. [18] suggest that the development and application of integrated modelling stands on several building blocks, with participatory modelling [19,20] and the development of modelling tools and software/hardware technologies considered as key pillars. In the context of policy analysis, more specifically, participatory processes are essential for linking science and policy [21] and to achieve the legitimacy of processes [22], with stakeholder participation and computer-based models regarded as key components of the participatory and collaborative modelling [17]. This society–science–policy interface [23] is usually moulded by different contextual pressures and communication protocols, thus rendering early stakeholder participation critical for successful outcomes in policy making [24].

There is no doubt that stakeholder participation in water resource management has received substantial attention in the last years [25–27]. The popularity of participatory modelling in particular has seen a substantial growth due to its compatibility with environmental paradigms such as Integrated Water Resources Management (IWRM) and Adaptive Management (AM) [28]. An advantage of participatory modelling resides in the potential to integrate meaningful input from decision makers and stakeholders into the modelling process [29]. Based on case studies from Africa, Asia, Europe and Oceania, Penny and Goddard [30] noted however that experimentation and learning beyond the "expert" group (to include non-expert participation) was mostly absent from discussions around model development.

To enable a participatory involvement, Basco-Carrera et al. [17] suggest that developed tools and models in the context of participatory modelling should be built using open source or freeware software where possible to facilitate distribution and use by stakeholders. Similarly, Carmona et al. [31] suggest that decision-making tools for successful stakeholder participation in natural resources management should be transparent, flexible and designed to elicit knowledge from different groups. Transparency and flexibility in the process of model development are also advocated by Bots et al. [21], with the aim of increasing stakeholders' trust by making the usually perceived "black box" model transparent.

Despite the clear need for stakeholder participation in the modelling development process, van Bruggen et al. [32] suggest that limited attention has been given to the model-based exploration and design of policy pathways with stakeholders. They argue that disciplinary fragmentation and the "not-invented-here" academic syndrome ("a negative attitude to knowledge that originates from a source outside the own domain" [33]) are factors hindering the development of modelling with stakeholders.

In arid and semiarid regions, collaborative processes and water governance are usually a major challenge [31,34–36] driven by contentious water use and competing stakeholder interests and values. This situation impacts the successful materialisation of the integration levels described by Kelly et al. [13] and poses challenges to the participatory modelling process as highlighted by Carmona et al. [31]. In particular, in these regions, the interaction between surface water and groundwater plays an important role [16,36,37]. This interaction is often complicated by agricultural and/or mining activities, as they will potentially alter the fragile flow regimes of the coupled water system [37]. As highlighted by Gorelick and Zheng [38], groundwater plays an important role, and its relevance will continue in the coming years, more importantly in arid and semi-arid regions.

This article describes the implementation of a participatory modelling process to develop and deploy an integrated modelling tool and digital platform (SimCopiapo) to support decision making in water management in a semiarid basin under contentious water use. The purpose of this digital platform is to explore alternative water management strategies to support scenario analysis and potential policy pathways with stakeholders, thus contributing to addressing the research need identified by van Bruggen et al. [32].

We build upon the work of Galvez et al. [34] to set up a participatory process in the Copiapó River Basin (CRB), northern Chile. We follow the integrated modelling levels suggested by Kelly et al. [13], and as such we include in the proposed integrated modelling tool surface water–groundwater interactions (*integration of processes and models*); local knowledge and expertise in water operational rules (*integration with stakeholders*); short-, mid- and long-term outputs, as well as sub-daily reservoir operations, daily water balance in irrigation districts and monthly time steps in groundwater assessment and different spatial scales for aquifer sectors and irrigation districts (*integration of scales of consideration*); and an agent-based model (ABM) to account for farmers' compliance against imposed caps on groundwater allocations (*integrated treatment of issues*). As suggested by the literature, we develop the integrated modelling tool and software platform in open source code with constant input from different stakeholder groups (water users, regulators, civil society, academy) [34] for transparency and flexibility [17,31] and to promote the legitimacy of the process [22] and ownership of results. The novelty of this work lies in advancing previous modelling efforts in the CRB [39–41] by improving on the operational rules of critical infrastructure in the CRB and co-designing water management strategies and impact indicators, all of which are designed with continuous input from key stakeholders by employing formal participatory and stakeholder engagement processes. A major feature of the proposed digital platform (SimCopiapo), compared to previous modelling efforts in the CRB, is the ability for users to run "on-the-fly" a loosely coupled [16] node–link water balance model and fully distributed groundwater model during interactive participatory sessions, thus facilitating social learning and knowledge co-creation. This was done in order to address research needs identified in the specialised literature [17,31,42]. Finally, the proposed digital platform (and integrated model) can be seen as a boundary object [43] bridging stakeholders and facilitating mutual understanding and cooperation—a practical exercise that has not been implemented before in the CRB [34].

The remainder of this article is arranged as follows. Section 2 describes the case study and the two-step methodological framework implemented in this work. Results of the integrated modelling process are analysed in Section 3 for a series of water management strategies and a base scenario. Section 4 presents a discussion of these results, and concluding remarks are offered in Section 5.

2. Materials and Methods

2.1. Case Study: Copiapó River Basin

The Copiapó River Basin (CRB) covers an area of 18,700 km^2 and is located in Northern Chile at the southern boundary of the Atacama Desert (Figure 1). The discharge contributions of the main tributaries Pulido, Jorquera and Manflas rivers in the headwater basins are regulated by the Lautaro Reservoir (26 Mm^3). The gauging station "Río Copiapó en La Puerta" shows an average discharge of 2.6 $m^3 s^{-1}$, whereas average annual precipitation in Copiapó city is 19 mm, reaching up to 500 mm y^{-1} for altitudes over 5000 m above sea level (asl) [44]. The CRB is a clear example of a semiarid basin under sustained water stress originating from both natural and anthropogenic causes, where water management can be regarded as inadequate [40,41,45,46].

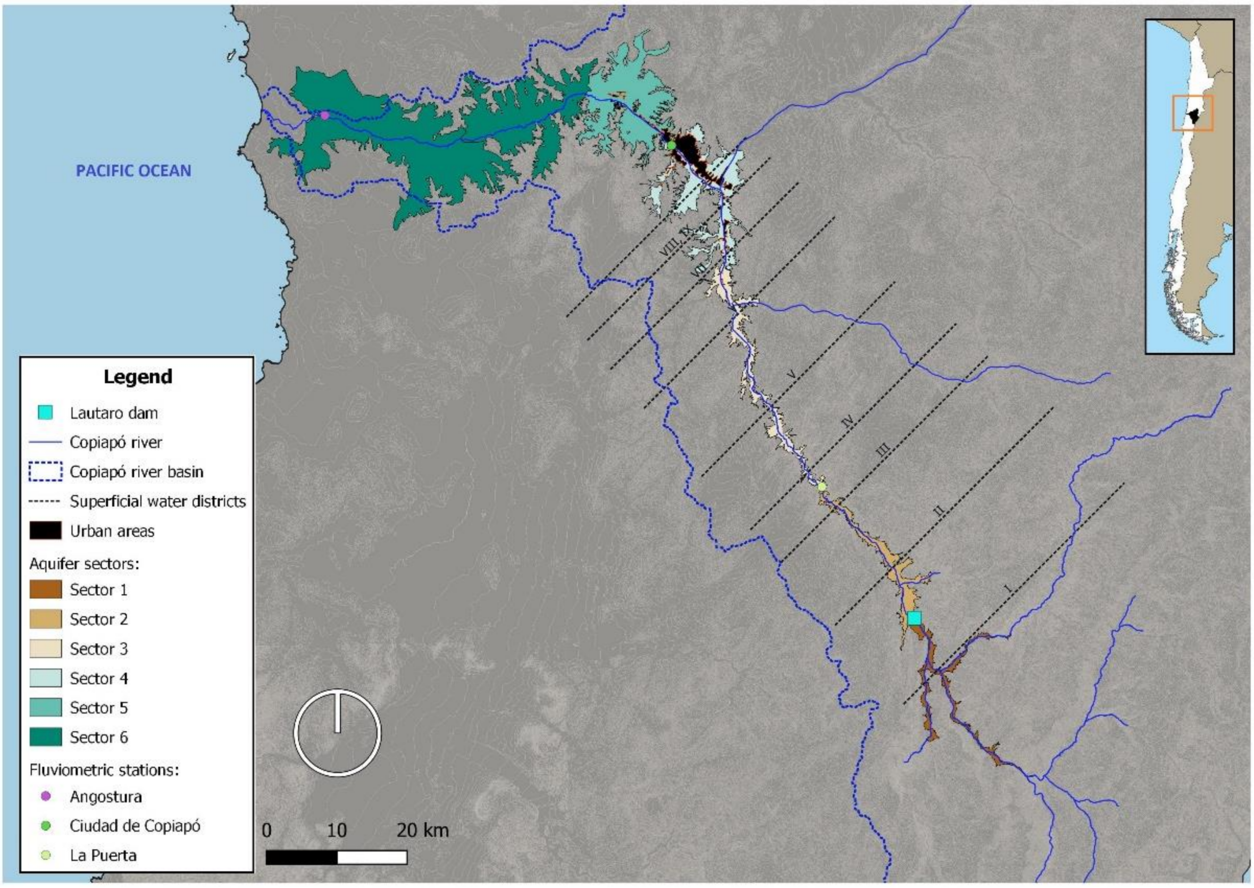

Figure 1. Location of the Copiapó River basin, main groundwater (aquifer) sectors, surface water irrigation districts (I: irrigation district D1, II: irrigation district D2, III: irrigation district D3, IV: irrigation district D4, V: irrigation district D5, VI: irrigation district D6, VII: irrigation district D7, VIII: irrigation district D8, IX: irrigation district D9. Most downstream districts (VIII and IX) are combined into irrigation district D89), and Lautaro Reservoir at the confluence of main tributaries (Jorquera, Manflas and Pulido rivers) to the Copiapó River. Urban areas in black color, coloured circles represent gauging stations (after [34]).

Currently, available surface water in nine irrigation districts (see Figure 1) is fully allocated for consumption, whereas the overexploitation of groundwater has been previously well documented in the literature [34,40,41] and is manifested by deteriorating groundwater quality and persistent deepening of groundwater levels. Administration of groundwater rights/licenses takes place in six groundwater/aquifer sectors (see Figure 1). Around 60% of groundwater demand is used for highly technified irrigation, whereas mining activities account for 30% and drinking water for 10% of the demand [47]. On an average water year, the Copiapó River dries up halfway to the outlet at the Pacific Ocean due to upstream water consumption and zero contributions from lateral intermediate sub-basins [48].

Groundwater rights for consumption total ca. 19 m^3 s^{-1} in the CRB, which contrasts with the estimated average recharge rates of 3 to 4.8 m^3 s^{-1} and effective groundwater demands of 6 to 14 m^3 s^{-1} [47,49]. Therefore, permanent conflicts between water users at different levels (upstream vs downstream users, surface water vs groundwater users) are detrimental factors for effective water resources management in the basin. These conflicts can be typified as Type 2, river basin conflicts, and Type 3, overexploited groundwater systems, by Bauer [50]. Rinaudo and Donoso [45] identified five factors leading to the current over-exploitation of Copiapo's groundwater resources: (i) limited knowledge of groundwater, (ii) legal complexity and political pressure, (iii) poorly-defined water permits, (iv) compliance and enforcement problems and (v) inconsistencies between management of surface water and groundwater.

Despite the peculiarities of the water resource management model in the Copiapó Basin [45,50], this management landscape is likely to reflect similar operational conditions as in other semiarid water-stressed basins around the world, thus providing generality to our findings.

2.2. Methodological Framework

We applied an intertwined two-step methodological framework in this work (Figure 2). First, we implemented a participatory process with existing key stakeholders to define and explore potential water management strategies and impact indicators of interest to stakeholders and to collect data on farmers' behaviours regarding groundwater regulation and operational rules for critical hydraulic infrastructure (c.f. Lautaro Reservoir). This step builds upon the work by Galvez et al. [34], who identified key stakeholders and barriers to collaborative water governance in the CRB and feeds into step 2. The second step consisted of designing and implementing a digital platform (termed SimCopiapo), which hosts a Graphical User Interface (GUI) (see Figure A1 in the Appendix A) with capabilities for stakeholders/modelers to run "on-the-fly" a node–link water balance model, a groundwater model and an agent-based model (ABM) [51,52]. This second step implemented the aspects identified through the participatory process in step 1. During participatory workshops, SimCopiapo was mainly run by stakeholders organised into groups with guidance provided by the research team. The purpose of this digital platform was to collaboratively explore different water management strategies as support for exploratory scenario analysis during participatory decision-making sessions with stakeholders. In the following sections, details for both steps are described.

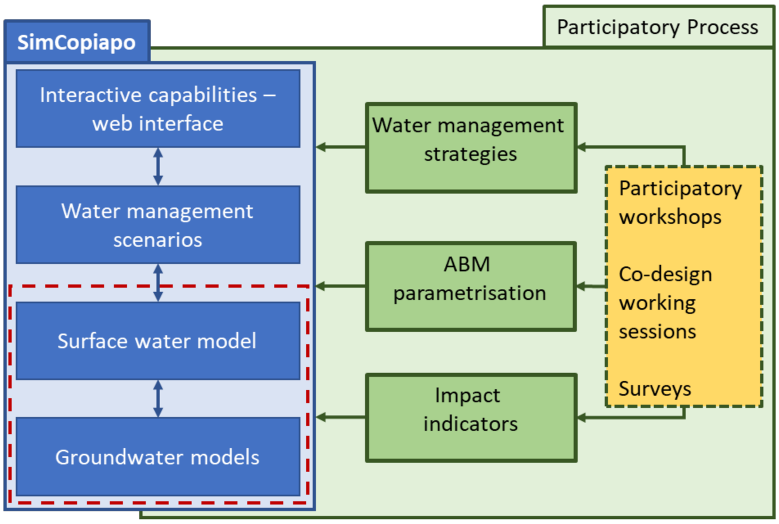

Figure 2. General methodological framework highlighting development of the digital platform SimCopiapo, participatory processes and the integration of the surface water and groundwater models (red dashed line).

2.2.1. Participatory Process

Galvez et al. [34] provide an overview of the stakeholders involved in the participatory process. We implemented 4 plenary workshops with 31 institutions and 5 working sessions with specific groups of stakeholders for data/local knowledge collection. In addition, we implemented two surveys with regional organisations in the study area: Water Resources Regional Advisory Committee (CARRH) (on-line) and Copiapó Exporters and Producers Association (APECO) (on-line). Surveys were used to collect information about farmers' behaviours regarding tolerance towards groundwater regulation (e.g., follow groundwater allocation rules) and the propensity to breach these rules following the social sub-model proposed by Castilla-Rho et al. [51,52]. This information was used to parameterise an agent-based model (ABM) to assess compliance against caps on groundwater use as explained in Section 2.2.3.

2.2.2. Water Management Strategies and Impact Indicators

From the participatory process, we co-designed with stakeholders 13 water management strategies grouped in 4 domains: (a) exchanges of water uses/rights among users, (b) improvement to current hydraulic infrastructure, (c) management of groundwater recharge and (d) management of water demand. These water management strategies are shown and described in detail in Table 1 and were implemented in the SimCopiapo platform.

The participatory process also allowed the definition of a series of key impact indicators of interest to stakeholders. To this end, we followed a similar approach as that proposed by Santos Coelho [53]. The main impact indicators identified were (a) river flows through the Copiapó city (termed as urban flows), (b) environmental flows at the Copiapó basin outlet, (c) storage at Lautaro Reservoir (headwater basin), (d) percentage change in aquifer storage in groundwater sectors 2 to 6 after implementing water management strategies and (e) compliance with the cap on groundwater use. A description of the main impact indicators is presented in Table 2. These and other impact indicators (e.g., water security for individual irrigation districts) are automatically generated and exported by the SimCopiapo platform.

Table 1. Water management strategies devised through the participatory process with main stakeholders in the Copiapó River basin.

Water Management Strategy		Description	Anticipated Impacts
Water use/rights exchanges	1.1	**Water use/right exchange between Candelaria—Aguas Chanar** This strategy consists of Aguas Chanar (water utility) decreasing groundwater abstraction in GW sectors 5 and 6 by 175 L/s, which instead is obtained from desalination water available from Candelaria mining company. As compensation, Aguas Chanar grants Candelaria mining company the same volume from the wastewater treatment plant downstream of Copiapó city.	• Groundwater heads recovery in GW Sector 5 • Perceived quality of potable water improves • Water security for urban population increases • Potential for improvements in environmental flows at the basin outlet
	1.2	**Water use/right exchange between Caserones—Ramadilla River** This strategy consists of Caserones mining company stopping groundwater abstraction (200 L/s) in GW sector 2. As compensation, Caserones mining company extracts the same volume as surface water in the headwater basin of Ramadilla River.	• Groundwater heads recovery in GW sector 2 • Decreases in tributary flows to Copiapó River in the headwater basin
	1.3-a	**Water use/right exchange between SW Irrigation districts D8 and D9 (D89)—SW irrigation districts D1-D7** This strategy consists of re-allocating unused surface water rights from irrigation districts D8 and D9 (downstream and combined into a single district, D89) to upstream irrigation districts D1 to D7. (It is worth noting that irrigation districts D8 and D9 are the most limited in areal extent compared to other districts and are located in the outskirts of Copiapó city, thus experimenting a fast land use change from rural to urban areas. See Figure 1 for location of combined district D89).	• Surface water security increases in irrigation districts 1 to 7 • Groundwater recharge increases in GW sectors 2, 3 and 4
	1.3-b	**Water use/right exchange between SW Irrigation districts D8 and D9 (D89)—Aguas Chanar** This strategy consists of re-allocating available surface water rights from irrigation districts D8 and D9 (downstream and combined into a single district, D89) to Aguas Chanar (water utility), which reduces groundwater abstraction in GW sectors 5 and 6 by Aguas Chanar.	• Groundwater heads recovery in GW sectors 5 and 6 • Perceived quality of potable water improves
	1.3-c	**Water use/right exchange between SW Irrigation districts D8 and D9 (D89)—Localised recharge Copiapó River** This strategy consists of using available surface water rights from irrigation districts D8 and D9 to recharge GW sectors 3 and 4 (upstream Copiapó City) through localised recharge in the Copiapó riverbed.	• Groundwater heads recovery in GW sectors 3, 4 and 5 • Improved quality of life in Copiapó city as more frequent surface flows observed through Copiapó city (urban flows)
	1.3-d	**Water use/right exchange between SW Irrigation districts 8 and 9—GW Sector 5/with excess localised recharge Copiapó River** This strategy consists of using available surface water rights from irrigation districts D8 and D9 conveyed by pipe system to farmers of GW sector 5 for irrigation purposes; water surplus as localised recharge through Copiapó riverbed.	• Groundwater heads recovery in GW sector 4 and 5 • Irrigation water security increases for farmers in GW sectors 5 and 6 • Improved quality of life in Copiapó city as more frequent surface flows observed through Copiapó city (urban flows)
	1.3-e	**Water use/right exchange between SW Irrigation districts 8 and 9—GW Sector 5/with excess Managed Aquifer Recharge in GW Sector 5** This strategy consists of using available surface water rights from irrigation districts D8 and D9 conveyed by pipe system to farmers of GW sector 5; water surplus as managed aquifer recharge in GW sector 5.	• Groundwater heads recovery in GW sector 4 and 5 • Irrigation water security increases for farmers in GW sectors 5 and 6

Table 1. *Cont.*

Water Management Strategy		Description	Anticipated Impacts
Hydraulic infrastructure	2.1	**Impermeabilisation Lautaro Reservoir (100% in a 5-year period)** Lautaro Reservoir is the main regulation infrastructure in the basin, and it has a storage capacity of ca. 25 Hm^3. Infiltration losses however are close to 50% of the stored volume. This strategy consists of installing impermeabilisation geotextiles in the Lautaro Reservoir to reduce these infiltration losses.	• Volumes available at Lautaro Reservoir increase • Surface water available for irrigation districts 1 to 9 increases • Water security for farmers in irrigation districts 1 to 9 increases • Recharge rates and groundwater heads in GW sector 2 decrease
	2.2	**Surface water conveyance to irrigation sectors through pipes instead of open channels** Currently there is 42% conveyance losses in the irrigation system in the Copiapó basin. This strategy consists of replacing open-channel systems with pipe systems to reduce conveyance and evaporation losses. This assumes there is no expansion in the irrigated surface.	• Infiltration in irrigation districts 1 to 9 decreases • Surface water available for irrigation districts 1 to 9 increases • Water security for farmers in irrigation districts 1 to 9 increases • Groundwater recharge rates decrease in GW sectors 2, 3 and 4
	2.3	**Operation of desalination plant** This strategy consists of operating the desalination plant designed for the Atacama region. It considers a staged supply plan (90 L/s, 450 L/s, 930 L/s) until providing close to 930 L/s of drinking water after 25 years of operation. Aguas Chanar (water utility) progressively ceases groundwater exploitation in GW sectors 4, 5 and 6.	• Marine ecosystems potentially impacted • Water security for farmers in irrigation districts 1 to 9 increases • Surface water available for irrigation districts 1 to 9 increases • Water security for urban population increases • Perceived quality of potable water • Groundwater heads recovery in GW sectors 4, 5 and 6
Recharge management	3.1	**Managed aquifer recharge along the Copiapó River** This strategy consists of building infiltration ponds along the main river course at specific locations: (a) Nantoco (GW sector 2), (b) upstream Kaukari Park (GW sector 4), (c) downstream Kaukari park (GW sector 5), and (d) Piedra Colgada (GW sector 6). These ponds have been restricted to ca. 4 ha (surface area), 1.5 m depth and assuming a representative infiltration rate of 1 m/d based on [54].	• Groundwater heads recovery in GW sectors 2, 4, 5 • Protection against extreme events (floods) • Water security for urban population increases
Demand management	4.1	**Prorate of groundwater uses in GW sectors 3, 4 and 5** This strategy consists of decreasing groundwater demand in GW sectors 3, 4 and 5 by 40% and aligns with results by DGA-DICTUC [49], Suarez et al. [40] and Hunter et al. [41]. In this strategy we implemented an agent-based model (ABM) to assess the compliance achieved against this demand restriction. Based on cultural parameters surveyed among irrigators in the Copiapó basin, two sub-strategies were analysed: (4.1.a) high level of monitoring and fines by the regulator, and (4.1.b) low level of monitoring and fines by the regulator.	• Groundwater heads recovery across GW sectors 3, 4 and 5 • Compliance rate with demand restriction • Improved capabilities by the water regulator agency to devise monitoring/enforcement strategies based on prorate compliance levels
	5.1	**Greywater reuse/recirculation** This strategy consists of reusing greywater to reduce the demand of drinking water in 20% in urban areas of the Copiapó basin. Water utility decreases groundwater exploitation in GW sectors 5 and 6.	• Groundwater heads recovery across GW sectors 5 and 6

Table 2. Description of impact indicators and expected values co-designed with stakeholders through the participatory process.

Impact Indicator	Description	Expected Value by Stakeholders
Urban flows	Percentage of the simulated period where the simulated discharge at the Copiapó city gauging station is in the range [0; 5000] L/s. Based on the hydraulic design of the river cross section at that station, above 5000 L/s is considered to represent a high risk of flooding.	No. of months 0 < Urban flows < 5000 L/s/Total months simulated
Environmental flows at the outlet of the Copiapó Basin	Percentage of the simulated period where the simulated discharge at the "Copiapó en Desembocadura" gauging station is greater than 50 L/s. This value corresponds to the historical average outflow from the basin.	No. of months environmental flows > 50 L/s/Total months simulated
Storage of Lautaro Reservoir	Percentage of the simulated period where the simulated volume in the Lautaro Reservoir is greater than 50% of its total storage capacity.	No. of months storage Lautaro Reservoir > 50%/Total months simulated
Aquifer Volume GW sectors 2 to 6	Change ratio between final and initial aquifer volume, e.g., >1.0 indicates aquifer volume at end of simulation period is greater than initial volume.	Aquifer $\text{storage}_{\text{\_FINAL}}$/Aquifer $\text{storage}_{\text{\_INITIAL}} > 1.0$
Groundwater cap compliance	Compliance level expressed as the percentage of farmers adhering to the groundwater cap imposed by the regulator. This indicator is specific to water management strategy 4.1 only.	Compliance rate > 50%

2.2.3. SimCopiapo Platform

SimCopiapo is a digital platform built mostly in Python, including an API web and front-end HTML/JavaScript (Figure A1 in Appendix A). It includes capabilities to select pre-defined water management strategies devised by stakeholders, run "on-the-fly" a loosely coupled node-link water balance and groundwater models [16,55], display graphs/plots/maps for rapid assessment and export reports summarising the results of management strategies selected by the user. It also contains an ABM associated with water management strategy 4.1 (groundwater demand management) to assess farmers' compliance against caps in groundwater use imposed by the regulator.

Figure 3 shows the interaction between the components of the SimCopiapo platform, including node–link water balance, groundwater and agent-based models. SimCopiapo uses geospatial information (irrigation areas, aquifer sectors, channel network, production wells, etc.), historical hydrological timeseries at the headwater basins for the period 1991–2016 and a series of alternative water management strategies (see Table 1) selected by the user to set up a specific scenario run. SimCopiapo users also have the opportunity to select/input pre-defined alternative hydrological time series driving the simulation (historical 1991–2016, 50% historical, etc.) or to include new time series if required. SimCopiapo is built as an open-source tool to allow continuous, replicable, reproducible and transparent research and improvements by other users [56–58], thus improving on previous efforts developed under proprietary hydrological software [39–41,49].

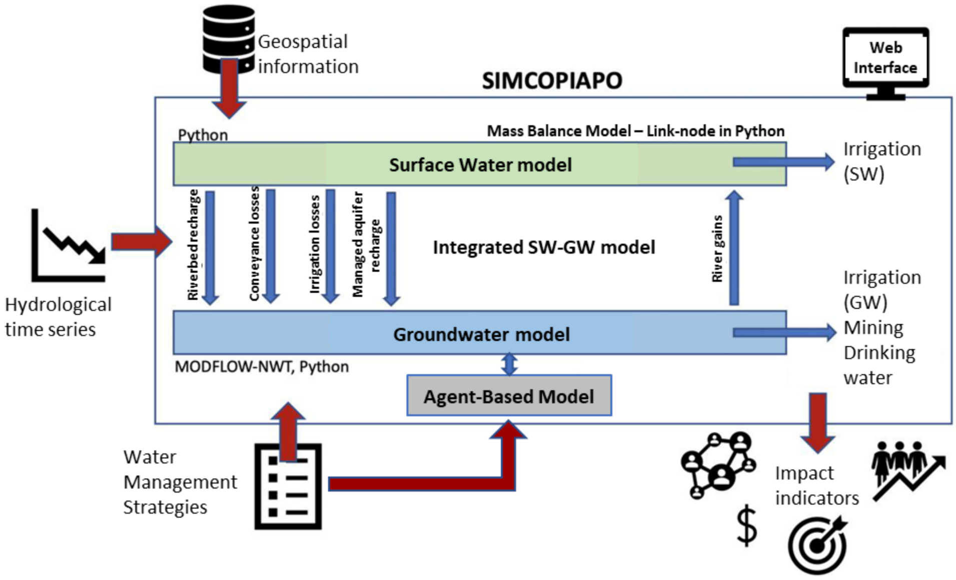

Figure 3. SimCopiapo digital platform and interactions of the integrated surface water and groundwater models and different modules and platform components.

It is worth noting that the objective of the digital platform is to facilitate the interaction among stakeholders in the contentious Copiapó river basin, where competing and conflicting water uses exist and the level of collaboration for water management is limited and generally perceived as inadequate [34]. Therefore, the focus is on providing a research tool able to run basin-scale assessments in order to support rapid appraisal of water management strategies enabling stakeholder discussion, collaboration and decision-making. Under these premises, SimCopiapo is aligned more closely to what Oxley et al. [24] define as a policy-oriented model, where *accurate* process representation is traded for *adequate* process representation and emphasis is focused on addressing practical policy issues. For this purpose, we illustrate how the digital platform can be populated with surface water and groundwater models previously documented and validated by stakeholders (e.g., [39–41,49]).

DGA-HIDROMAS [39] provides the latest surface water model available for the Copiapó basin implemented in the AQUATOOL software—a proprietary generic decision support system for water resources planning [59]. We translated the topology of the AQUATOOL model for the Copiapó basin into a node–link model coded in Python, accounting for the daily mass balance of the surface water system. The conceptual representation of this topology and the operation of the irrigation districts in the Copiapó River Basin is presented in Figure 4. This figure shows the upstream Lautaro reservoir as the main hydraulic infrastructure regulating surface flows to supply irrigation water to nine districts (D1–D9, irrigation districts D8 and D9 are combined into a single district, D89. See Figure 1 for locations of irrigation districts). Available surface water regulated from Lautaro reservoir is equally allocated between districts D1 to D7 (12% each), whereas districts D8 and D9 are allocated 8% each (i.e., 16% combined for D89). Figure 4 also shows the crop sectors (e.g., R2a-XX) belonging to each irrigation district, with some of the irrigation districts including more than one crop sector (e.g., R2a-13 and R2a-14 belong to irrigation district D6). It is worth emphasising that D8 and D9 are the most downstream irrigation districts located at the outskirts of Copiapó city, thus experiencing changes in land use patterns from rural to urban. Upstream of the gauging station "Copiapo @ Mal Paso", most of the available surface water is conveyed through a channel (1000 L/s maximum capacity), leaving just excess water flowing through the natural river course.

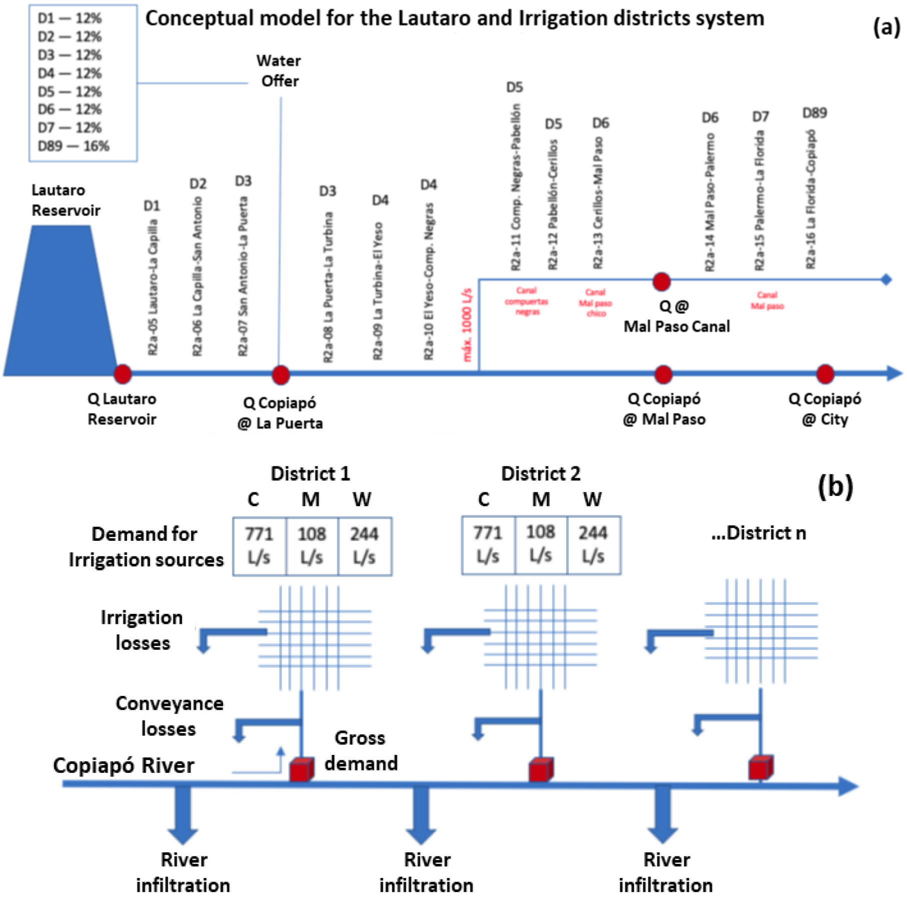

Figure 4. Conceptual model for the (**a**) operation of the Lautaro Reservoir and the (**b**) irrigation districts in the Copiapó River Basin. Values for parameters of the conceptual model are obtained from [39,40] and included in the node–link water balance model. Water sources for each irrigation district are distinguished between C: channel, W: wells and M: mixed source and are based on crop area supplied by that source.

For each irrigation district, information on crop types/surfaces, irrigation and water conveyance efficiencies, water sources, etc. is used to perform an internal supply–demand balance per irrigation area, considering alternative water sources (surface water, groundwater or combination). The water source indicates the water volume supplying crop areas for each irrigation district. The volumes demanded for each irrigation district are obtained from the crop surveys by DGA-DICTUC [49] and the water licenses. In this way, irrigation demands are supplied first by channel source, then mixed source and finally groundwater (wells). Results of the water balance for each irrigation district are spatially coupled to the aquifer sectors implemented in the groundwater model, which together with the infiltration through the riverbed define the main recharge rates for the aquifer sectors (see Figure 1).

This node–link mass balance model was fully coupled with the latest available groundwater model for the Copiapó aquifer developed in MODFLOW-2005 [60] by DGA-HIDROMAS [39]. Using the FloPy Python package [61], we translated this MODFLOW-2005 model for operation in Python and coupled it with the node–link model of the surface water system in the SimCopiapo platform. The daily node–link water balance model was aggregated to a monthly time-step for consistency with the MODFLOW model for the Copiapó aquifer. For full details on the coupling process we refer the reader to [62].

As shown in Figure 3, SimCopiapo also includes an agent-based model (ABM) to assess farmers' compliance against caps imposed on groundwater use in the Copiapó aquifer. This ABM is based on the social sub-model developed by Castilla-Rho et al. [51,52], which represents a social utility function, S, that follows a Cobb–Douglas functional form:

$$\mathrm{S} = \mathrm{grid}^{\mathrm{m}}\ (1 - \mathrm{group})^{\mathrm{n}} \tag{1}$$

where m = number of times a farmer reports a neighbour taking groundwater illegally, n = number of times a farmer is seen taken groundwater illegally, and grid-group are categories of the Cultural Theory proposed by Douglas [63]. S (social utility function) represents the loss of social reputation and the social costs to groundwater users when reporting non-compliant behaviour. Using survey data collected from farmers in the Copiapó basin [62] and the four grid-group categories (Egalitarian–Hierarchist–Individualist–Fatalist) proposed by Douglas [63] in Cultural Theory, we were able to parametrise equation 1 and thus farmers' decision-making processes. The user of SimCopiapo can adjust two parameters associated with the ABM model: (a) the percentage of groundwater users monitored by the regulator to check compliance and (b) the severity of the fines (as a percentage of the total farm revenue) if the farmer is caught taking groundwater illegally.

Equation (1) quantifies the loss of social reputation and the social costs to farmers when reporting non-compliant neighbours engaged in illegal extraction of groundwater in the Copiapó basin, and thus impact farmers' future decisions of engaging in non-complaint behaviour (i.e., taking groundwater illegally). Other factors impacting this decision relate to farmers' probability of being monitored by the regulator and the severity of fines if farmers are caught in non-compliant behaviour [48,49]. This social metric is combined with an economic (gross margins from crop enterprise) and institutional (monitoring/monetary fines) score into each farmers' objective function for decision making; i.e., whether to take groundwater illegally or not. For details on this implementation, the reader is referred to [51,52].

2.2.4. Improvements on Previous Integrated Modelling Tools

Suarez et al. [40] presented an integrated model for the CRB using the SIMGEN module of AQUATOOL software [59] (surface water only). More recently, Hunter et al. [41] presented an integrated model for the CRB based on [40] coupling the WEAP (Water Evaluation and Planning system) model [64] and the MODFLOW [60] groundwater model described by DGA-HIDROMAS [39]. Although these works claim the advantages of their corresponding integrated modelling frameworks, both tools rely on proprietary software and are therefore not amenable for rapid modifications by interested stakeholders, have been developed with limited input from key stakeholders in terms of potential water management strategies as well as impact indicators of interest to stakeholders, and concentrate only on demand management strategies. In this work, we improved on several aspects on the integrated modelling framework for the CRB: (1) the groundwater model developed by DGA-HIDROMAS [39] has been checked for spatial and temporal consistency of aquifer contributions to surface water at La Puerta and Angostura gauging stations; (2) evapotranspiration and groundwater demands were revised and activated; for the surface water model, (3) Lautaro Reservoir operational rule for water allocation was completely re-designed and implemented thanks to the advice of the Vigilance Board of the Copiapó River and its Tributaries; and (4) the operation of the irrigation districts was revised and deployed in Python considering (a) controlled discharge from the Lautaro Reservoir and (b) a supply–demand model for the irrigation districts considering allocation volumes, irrigation demands, irrigation losses, conveyance losses and gross water demand. For details on other improvements regarding updates on mining groundwater demands, downstream irrigation districts, drinking water demands and losses in the potable water network, the reader is referred to [62].

3. Results

3.1. Results Participatory Process

A total of 31 organisations representing the civil society (6), regional state agencies (16) and private/productive (9) sectors were engaged in the participatory process. On average and across all participatory workshops and working sessions, stakeholders from the civil society were the least involved (35% of organisations engaged), whereas stakeholders of the private sector were the most engaged, with 52% of the institutions of this sector taking part in the participatory sessions.

Regarding the on-line surveys for parameterising the ABM for groundwater regulation, the CARRH survey showed that civil society stakeholders were the most engaged, with 83% of the institutions of this sector providing responses, whereas only 31% of the institutions of the public sector were engaged in this process. Forty-four percent of private sector stakeholders participated in this survey. The APECO survey targeted 25 farmers of the CRB, with more than 83% concentrated in the upstream aquifer sectors 1 to 3 and the remaining 17% concentrated in downstream aquifer sectors 4 and 5. No responses were obtained from farmers in aquifer sector 6. Although not shown here, results of both surveys indicate a clear trend towards validating the importance of regulating groundwater resources for sustainable use and minimizing impacts to ecosystems and third parties, and enforcing this regulation in practice. Discrepancies among the CARRH stakeholders were observed on justifying the illegal extraction of groundwater on economic (profits) grounds and allocating importance to social costs (loss of reputation) if caught breaching caps on groundwater use imposed by the regulator. This discrepancies can be attributed to the heterogeneity of the stakeholders composing the CARRH [34]. On the contrary, the APECO survey indicated that farmers attributed a higher importance to the loss of social reputation (individual) if caught breaching the imposed cap on groundwater use and allocated a higher importance to collective enforcement policy such as effective monitoring of groundwater use. For details about the outcomes of the surveys and the implementation in the ABM model, the reader is referred to [50,51,60].

3.2. Validation of Node–Link Water Balance Approach to Surface Water Modelling in SimCopiapo

As the main driver controlling surface water flows and the recharge to aquifers is the operation of the Lautaro Reservoir, we focused on reproducing the observed discharges measured at the gauging station immediately downstream of the Lautaro Reservoir (Figure 5). For the simulated period implemented in SimCopiapo (1991–2016), we observe a much better correspondence between observed and simulated discharges compared to the original surface water models implemented by [40,41]. In general, peak releases are properly simulated with the exceptions of hydrological years 1997/1998 and 2001/2002, where both the original surface water model and the node–link model implemented in SimCopiapo show difficulties in capturing the peak behaviour.

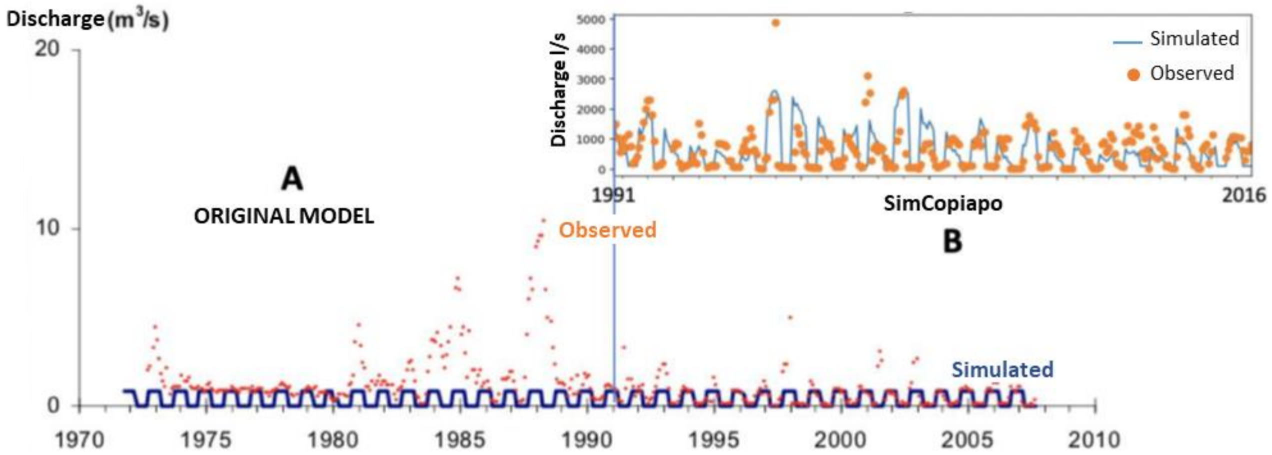

Figure 5. Release discharge from Lautaro Reservoir for the (**A**) original model developed by Hunter et al. [41] and Suarez et al. [40] and (**B**) adapted operational rule implemented in SimCopiapo.

Similarly, Figure 6 shows the simulated and observed discharges for the period 1991–2016 in La Puerta and Copiapó City gauging stations (see Figure 1 for locations). This figure shows that the operation of the Lautaro Reservoir and the improved supply–demand model for the irrigation districts implemented in the node–link water balance model in the SimCopiapo platform can reproduce the observed discharges in a reasonable manner, preserving the long-term trend and capturing relevant peaks in 1998/1999 and 2003/2004. It is worth noting that “Rio Copiapó en Ciudad” (Figure 6b) is a gauging station located downstream of all irrigation districts, and as such reflects excess volumes after irrigation use located upstream of Copiapó city.

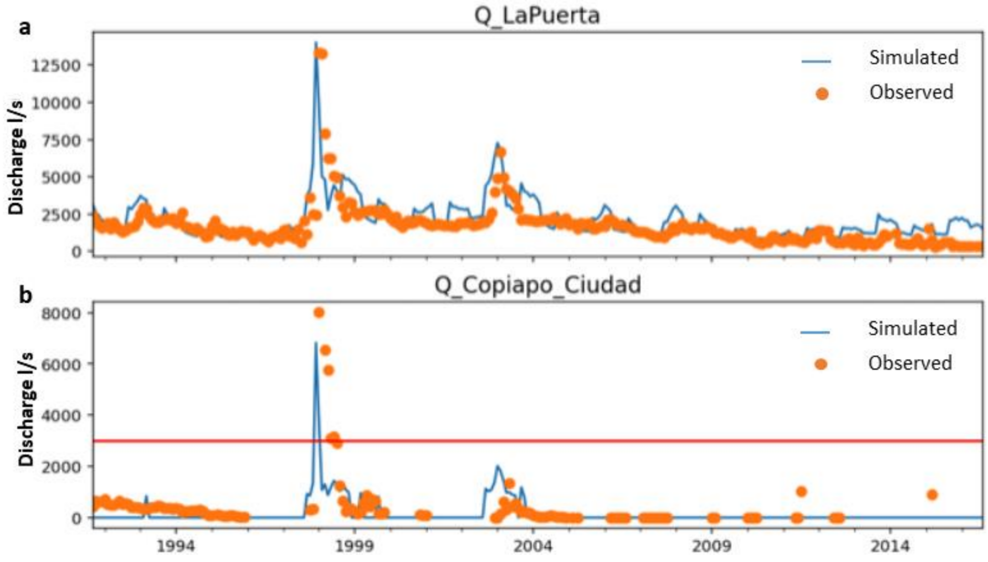

Figure 6. Simulated versus observed discharges in (**a**) “Rio Copiapó en La Puerta” and (**b**) “Rio Copiapó en Ciudad” gauging stations. Horizontal red line represents the average controlled discharge from Lautaro Reservoir (3020 L/s).

Closing the water balance obtained from loosely-coupled surface water and groundwater models has been identified as a drawback of the integration process [16,55]. La Puerta gauging station in the CRB is the main control point to verify that the coupling process of both the daily node–link mass balance model (implemented in Python) and the MODFLOW model (implemented in FloPy) is correct. In this sector, the Copiapó valley shows an important reduction in its cross section, and basement rocks are uplifted, thus substantially constraining the aquifer cross section, resulting in substantial contributions from the aquifer to the Copiapó River [39,49]. In general, discharges at La Puerta gauging station are influenced by the groundwater throughflows from groundwater sector 2 and the infiltration rates from the Lautaro Reservoir (see Figure 1). The infiltration losses in the Lautaro Reservoir were therefore adjusted between 500 L/s and 3500 L/s (as a function of the stored volume) until a reasonable match between the daily node–link mass balance model and groundwater model outputs at La Puerta was obtained. Figure 7 shows the match between both the node–link water balance and MODFLOW models at La Puerta gauging station. In general, we observe a good match between river gains from groundwater simulated through the drain package of MODFLOW and the node balance at La Puerta gauging station. We observe a good fit when simulating the temporality and magnitude of the time series, with a range between 1000 and 2500 L/s at "Rio Copiapó en La Puerta". Few discrepancies are observed at the start of the simulation period, most likely attributed to the stabilisation of parameters in the node–link model (warm-up period) and due to the aggregation of the monthly time steps into 6 month stress periods in MODFLOW.

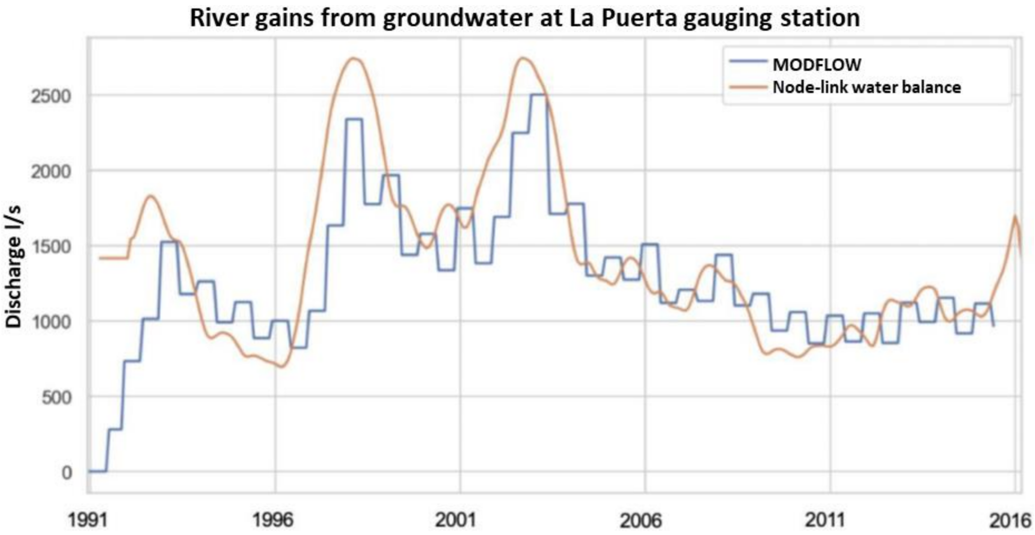

Figure 7. Validation of coupling process for daily surface water mass balance models and groundwater model at "Rio Copiapó en La Puerta" gauging station.

3.3. Results for Individual Water Management Strategies

To assess the results of individual (and combined) water management strategies we defined a base scenario reflecting hydraulic infrastructure, water demands, crop types and land uses corresponding to year 2018. This base scenario reflects a business-as-usual (BAU) approach. Both the base scenario and water management strategies are assessed for a 25-year period (2018–2042) in order to isolate the marginal impacts of implementing such strategies, using the observed hydrology for the period 1991–2016 as forcing data.

Table A1 in the Appendix A shows the individual results for each water management strategy described in Section 2.2.2. Individual water management strategies show spatially bounded impacts and marginal cumulative impacts at the end of the simulation period. Strategy 3.1, for example, shows an increase in infiltration flows in the Copiapó river of less than 3% the potential recharge volume due to constraints in the size of the recharge ponds and the available surface flows for infiltration. In the next sections, we analyse a selected group of results for individual strategies.

3.3.1. Water Uses/Rights Exchanges

For strategies promoting water uses/rights exchanges among users, the most attractive corresponds to strategy 1.3-c in Table 1, which promotes urban flows increases up to 263 L/s on average for the 25-year simulated period. Figure 8 shows the monthly frequency of the occurrence of urban flows for the base scenario and strategy 1.3-c. Stakeholders have defined the occurrence of urban flows through Copiapó city as an important indicator of quality of life, and results show a substantial increase in the occurrence of urban flows from 19% to 96% by implementing strategy 1.3-c.

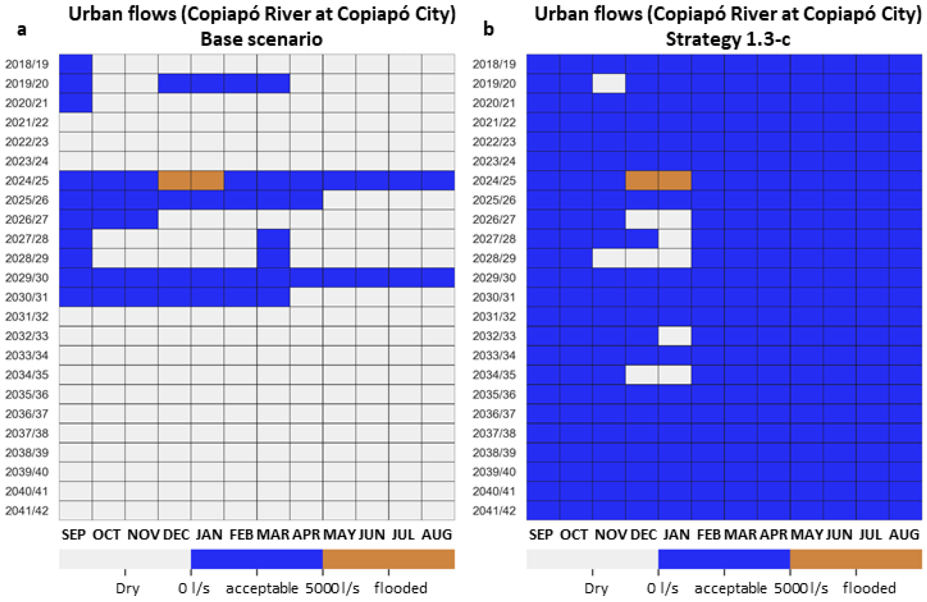

Figure 8. Monthly frequency of occurrence of urban flows at the Copiapó City gauging station for (**a**) base scenario and (**b**) strategy 1.3-c, for dry, acceptable, and flooded thresholds. Blue cells record the occurrence of average monthly discharges greater than 0 L/s and less than 5000 L/s at Copiapó city.

3.3.2. Improvement to Current Hydraulic Infrastructure

In terms of water management strategies promoting improvements to current hydraulic infrastructure, strategy 2.1 (impermeabilisation of Lautaro Reservoir) shows substantial impacts (positive and negative). Figure 9 shows the water balance for the Lautaro Reservoir for both the base scenario and strategy 2.1. For this figure, we observe that releases from the Lautaro Reservoir become regular and over 2000 L/s, with 18 out of 20 water years using the spillway to regulate the reservoir's capacity. After fully implementing the impermeabilisation of the inundated surface by year 5, infiltration losses become 0, and the reservoir volume is above 50% its capacity for 14 out of the 20 remaining years. Although not shown here, this results in increases in water security for irrigation districts no. 6, 7, 8 and 9, which are most closely located downstream of the reservoir. In addition, by implementing strategy 2.1, an increase in the frequency of occurrence of urban flows through Copiapó city from 18% to 30% of the months in the simulation period 2018–2042 is observed.

Despite the positive impacts from the surface water perspective, a negative impact is observed for the groundwater sector 2, located immediately downstream of the Lautaro Reservoir. Groundwater sector 2 is a narrow tube-like aquifer recharged mainly through upstream groundwater throughflows originating from upstream aquifers and, most importantly, infiltration losses from the Lautaro Reservoir. Figure 10 shows the groundwater levels of representative observation wells located in groundwater sector 2. After implementing the impermeabilisation of the Lautaro Reservoir, a sustained decreasing trend is observed in the mid- (MT) and long-term (LT), reaching average values of -0.8 m/y. It is worth noting that these decreasing trends concentrate in the upstream half of groundwater sector 2, whereas groundwater levels around La Puerta remain stable or increase given the constriction of the aquifer section explained in sections above.

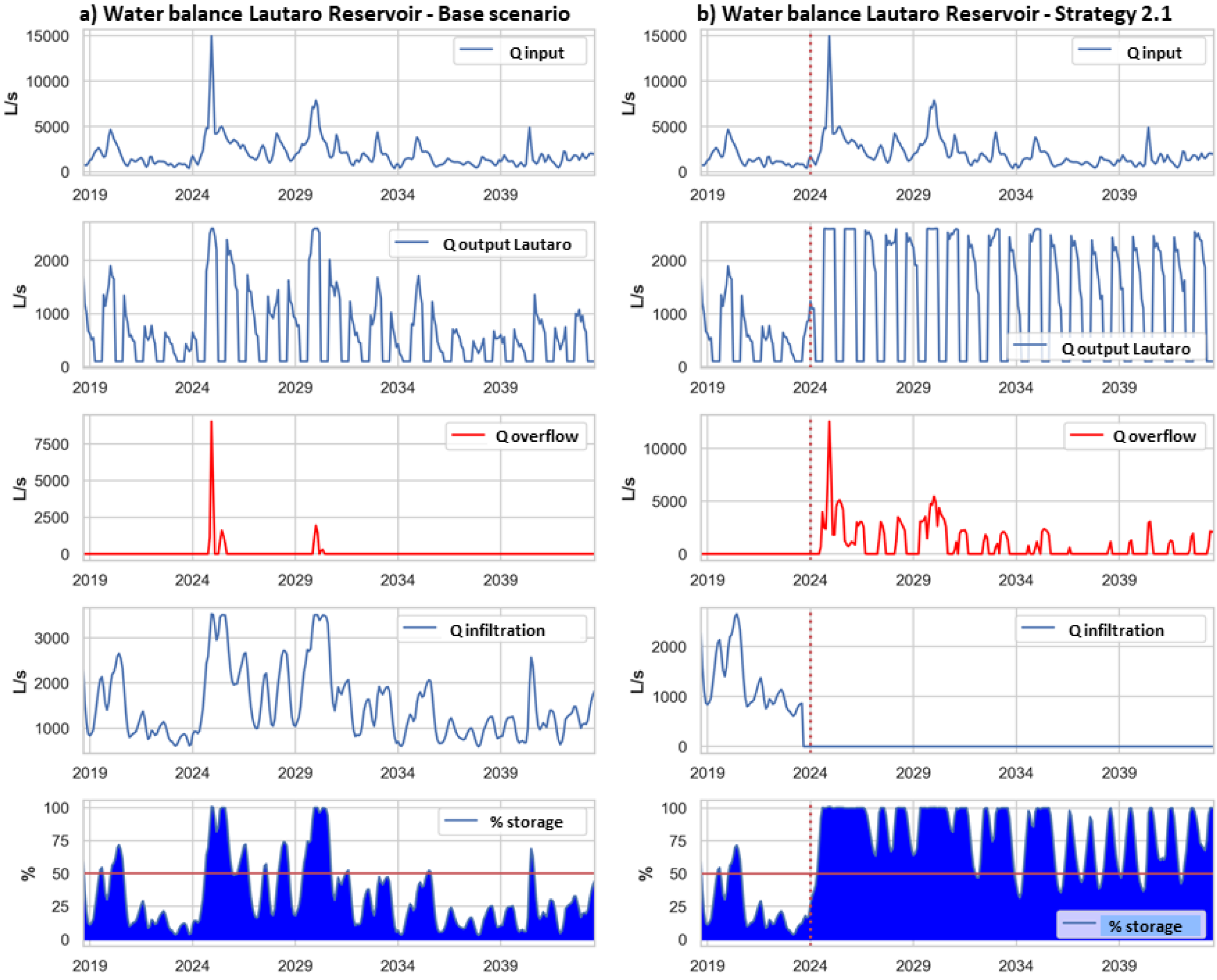

Figure 9. Water balance for the Lautaro Reservoir for (**a**) base scenario and (**b**) strategy 2.1, reflecting the impermeabilisation of 100% inundated surface after a 5 year period (vertical red dotted line).

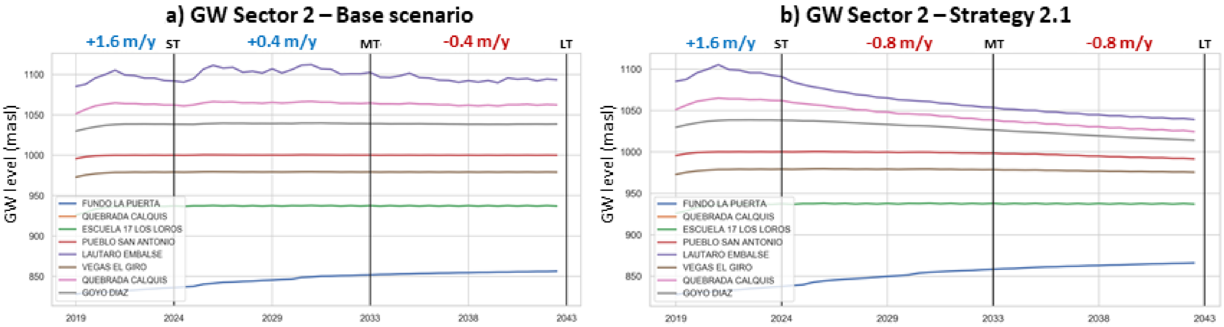

Figure 10. Time series of groundwater levels in representative observation wells located in the groundwater sector 2 for (**a**) base scenario, and (**b**) Strategy 2.1. ST: short-term, MT: mid-term, LT: long-term. Increasing average trend for each period for all observation wells in blue. Decreasing average trend for each period for all observation wells in red.

3.3.3. Demand Management

For the strategies promoting management of the groundwater demand, strategy 4.1 (a proportional reduction of 40% of groundwater use across groundwater sectors 3, 4 and 5) shows substantial impacts. This strategy was implemented through the ABM and assessed the level of compliance of the imposed cap on groundwater use and the impact on groundwater level/balance. Based on our previous experience, both monitoring of groundwater users and fine levels are strong deterrents when dealing with non-compliant behaviour in groundwater management [48,49]. Figure 11 shows two levels of enforcement tested in this strategy: (a) monitoring of 90% of users in groundwater sectors 3, 4 and 5 and substantial fine levels (90% gross profit from farm enterprise) if farmers are caught breaching the cap, thus defining a strong enforcement policy; and (b) lax monitoring (20% of users in groundwater sectors 3, 4 and 5) and fine levels (20% gross profit from farm enterprise), thus defining a weak enforcement policy. Figure 11a shows that for groundwater sectors 3, 4, 5 and 6, implementing the cap on groundwater use together with a strong enforcement policy brings storage volumes in these aquifer sectors back to values that are better than the initial state of the base scenario. On the contrary, when the enforcement policy is weak (Figure 11b), the impacts are limited to aquifer sector 5 and to a lesser extent in aquifer sector 6 given the proportional volume of groundwater for irrigation in these sectors. This indicates that at least 20% of the groundwater users of aquifers sectors 3, 4 and 5 need to be monitored if a cap on groundwater extraction is imposed by the regulator. For other impact indicators, implementing strategy 4.1 has a limited impact.

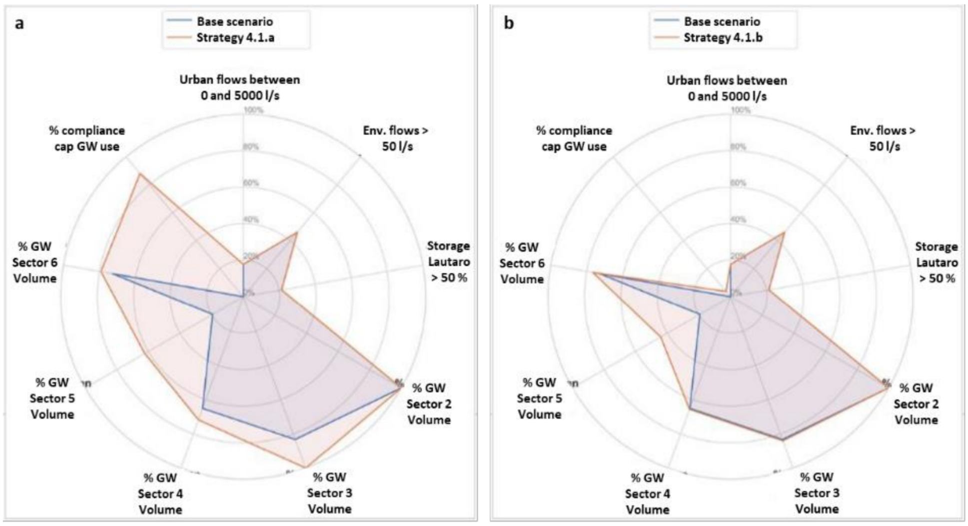

Figure 11. Impact indicators for strategy 4.1 (cap on groundwater use implemented through ABM) for two enforcement strategies: (**a**) high level of monitoring (90% of groundwater users) and fines (90% of revenue if farmer caught breaching the cap) and (**b**) low level of monitoring (20% of groundwater users) and fines (20% revenue if farmer caught breaching the cap).

3.4. Results for Combined Water Management Strategies

Any single water management strategy cannot address the basin-scale water management challenges identified in the CRB by different authors (see e.g., [34,40,41,45]). Impacts of individual strategies are sectoral and, in some cases, spatially and temporally constrained. It then seems appropriate to combine alternative water management strategies to assess multiple stakeholders' interests/perspectives. Based on the participatory process, a prioritised combination of water management strategies attractive to stakeholders of the CRB was defined by simultaneously implementing strategies 1.3-c, 2.1, 2.3, and 4.1a (see Table 1). Strategy 2.3, which corresponds to operating a desalination plant to supply 90 L/s (first

5 years), 450 L/s (next 5 years) and 930 L/s (last 15 years), has been included as this strategy is already in early operation in the CRB.

Figure 12 shows the results for impact indicators when combining these strategies. We found a substantial increase in the occurrence of urban flows from 20% to ca. 100% of the simulated period (25 years), thus enhancing the quality of life perceived by stakeholders of the CRB; marginal increases in the environmental flows at the basin outlet, thus promoting a healthy habitat for the wetland at the Copiapó River mouth; substantial increases in the storage volume of the Lautaro Reservoir from 20% to 72% of the simulated time with volumes greater than 50% its maximum storage capacity, thus impacting water security for irrigation districts; recoveries in heads and stored volumes in groundwater sectors 3, 4, 5 and 6, thus decreasing pumping costs to users and contributing to groundwater sustainability in the long-term; high levels of compliance (>80% groundwater users) to caps on groundwater use supported by a robust enforcement policy formulated around high monitoring rates and substantial fines.

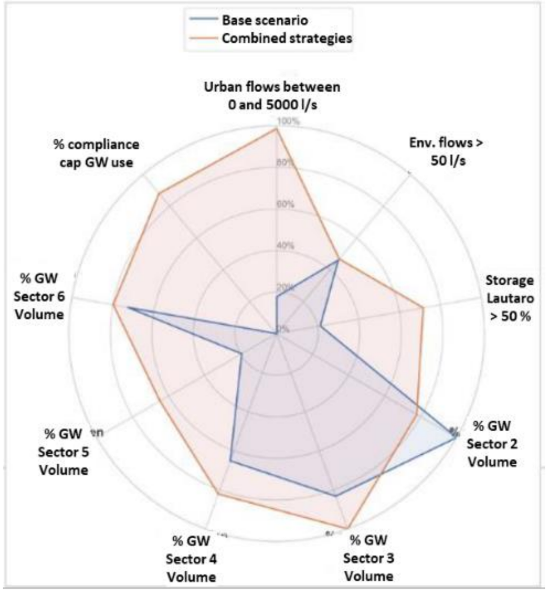

Figure 12. Impact indicators for the combinatory of water management strategies prioritised through the participatory process.

All these positive impacts also carry a negative impact, which is the detrimental impact on groundwater heads and stored volumes in the upper section of the aquifer sector 2, immediately downstream of the Lautaro Reservoir. Figure 13 shows that after implementing the combination of water management strategies, decreases in groundwater heads in the upper section of aquifer sector 2 can reach up to 40 m compared to the base scenario. Long-term increases in groundwater heads in sectors 3 and 4 can reach between 30 m and 40 m in aquifers immediately downstream of La Puerta gauging station and around 10 m in aquifer sector 5 downstream of Copiapó City gauging station.

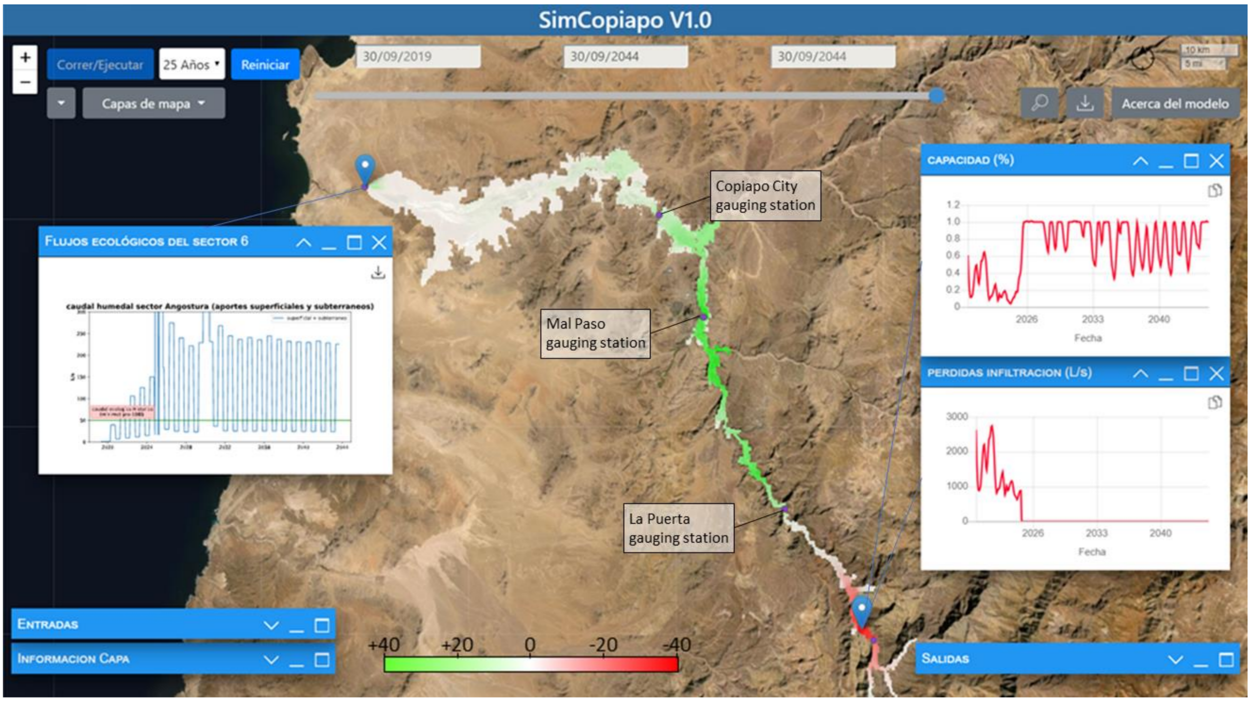

Figure 13. Groundwater head difference (m) between base scenario and combined water strategies. Inside panels show results of Lautaro Reservoir water balance (storage (% maximum volume) and infiltration losses (L/s)) and river flows (L/s) at the outlet of the CRB.

4. Discussion

The situation in the CRB indicates human and environmental vulnerabilities [38] stemming from the sustained exploitation of groundwater resources. Several authors have tried to explain the factors driving the water crisis in the CRB from economic, regulatory and management perspectives [34,45,46,48], whereas others have suggested technical solutions such as basin-scale or sectorial groundwater use restrictions [40,41,49]. Evidence by Wurl et al. [65] in a similar context (arid overexploited aquifer in Mexico) suggests that water management problems can no longer be addressed purely as technical problems and should consider a wide range of stakeholders' perspectives to strengthen the resilience of water resources. In this work, we have contributed towards this by devising potential water management strategies (i.e., technical solutions) and relevant impact indicators through a bottom-up participatory process driven by key stakeholders in the CRB.

Our approach directly addresses one of the tasks Rinaudo and Donoso [45] suggest the regulator should implement as part of a groundwater management model; i.e., implement an efficient enforcement strategy, e.g., by proposing minimum monitoring coverage and fine levels to achieve compliance on cap reductions based on ABM results. Although not explicitly addressed by our integrated modelling approach, the remaining tasks defined by Donoso and Rinuado (i.e., calculate sustainable groundwater abstraction limits, defining sharing rules, reallocation of water use rights and rules to adjust volume of water use rights) can be assessed implementing minor modifications to the SimCopiapo tool (e.g., test rules to adjust volumes of groundwater rights in different aquifer sectors).

SimCopiapo can be classified as a policy-oriented model [24] where adequate process representation, addressing practical policy issues and supporting decision-making with stakeholder participation are regarded as key features [42]. One of the purposes of the participatory modelling was social learning and acceptance of model improvements through direct participation in designing the conceptual model, water management strategies and impact indicators for discussion. Following the classification of Hare [42] the participatory modelling exercise implemented in SimCopiapo aligns with a Front and Back-End (FABE) category, where stakeholder involvement concentrates on early (conceptual model design, definition of operational rules, impact indicators and water management strategies) and later stages (assessment of water management strategies, discussion of potential policy pathways) of the modelling process. The effectiveness of the methods used in this participatory process is yet to be asserted through a follow-up process with decision and policy-makers of the CRB. A promising research direction is a post-hoc assessment using boundary objects attributes (credibility, salience, legitimacy) as suggested by Falconi and Palmer [43] to assess the success of SimCopiapo as a participatory model.

Our integrated approach and proposed digital platform (SimCopiapo) contribute to addressing the challenges identified in the use of models to operationalise IWRM by Badham et al. [66]. First, the bottom-up participatory process contributed to addressing a difficult problem in water policy by streamlining multiple pressures, conflicting values, competing goals and limited resources in a transparent way; and second, it helped in handling the human element in IWRM by reconciling potential conflictive agendas by stakeholders. The latter has been recognised as an important research avenue in water management [46,67,68].

Results show that no single strategy is able to provide definite long-term solutions to the water management challenges observed in the CRB nor to capture the multiplicity of stakeholders' interests expressed through the impact indicators identified. DGA-DICTUC [49], Suarez et al. [40] and Hunter et al. [41] proposed basin-wide or sectoral reductions in groundwater use (demand management) by values between 20% and 50% on the basis of cost analysis or a multi-dimensional measure of sustainability. While useful, assuming monetary motivations are central to water management and a key driver of behavioural change in groundwater users ignores the role that social, ecological and cultural values might have in this regard, thus constraining the assessment of water management strategies [69,70]. SimCopiapo contributes to equilibrating the assessment by transparently assessing physical, ecological and social aspects of the water management strategies devised, thus counter-balancing the bias towards exclusively cost-based assessments observed in the literature (e.g., [71–73]).

Our results indicate that management of groundwater use is one of the most critical water strategies to recover the aquifer sectors in the CRB. However, there needs to be a clear enforcement policy to trigger the minimum momentum required to achieve social acceptance of this policy. This is fully aligned to one of the drivers suggested by Rinaudo and Donoso [45] triggering the water crisis in the CRB. Results indicate that there seems to be a middle point between lax and strong enforcement policies to achieve this reduction in demand in a sustainable way. The definition of where this middle point lies is beyond the scope of this article, but our results bring a first approximation to this; i.e., between 20% and 90% monitoring coverage and between lax (fines accounting for 20% revenue) and strong (fines accounting for up to 90% revenue) fine levels for breaching the imposed cap on groundwater use. These results are fully aligned with findings by Castilla-Rho et al. [51,52] for other aquifers around the globe.

Future research avenues might consider including crop choices in the supply–demand and ABM models, implementation of other water management strategies and impact indicators, optimising the level of monitoring and fines to achieve a target compliance in different aquifer sectors or groundwater user groups (e.g., mining, industry) and testing multi-level ABM parametrisations for time-varying water management policies as in Du et al. [74].

5. Conclusions

In this work, we demonstrated the value of combining participatory modelling and integrated modelling to develop a digital platform tool (SimCopiapo) supporting social learning and knowledge co-construction for water management in a semiarid basin under contentious water use. We have contributed to transparently positioning a policy-based model as a boundary object to bridge a diverse group of stakeholders with individual and competing interests and perspectives.

Current water management in the Copiapó River Basin (CRB) is not providing the required solutions for resource sustainability, with previous research to date proposing (optimised) cost-based technical solutions focusing solely on groundwater demand reductions. This narrow perspective however does not seem to hold for complex water management problems with no single/simple solutions that act and depend on values and priorities by multiple stakeholders. Early stakeholder engagement and participation for social learning and knowledge co-construction are therefore essential steps in this process.

Our results suggest that management of groundwater demand in the CRB together with a portfolio of strategies including water rights exchanges, improvements to hydraulic infrastructure and robust enforcement policies are best suited to capture the diversity of stakeholders' interests and perspectives when addressing the water management challenges observed in the CRB. This diversity is expressed through a series of impact indicators, which, directly or indirectly, are a reflection of not only available groundwater resources for use but also ecological (e.g., basin outlets) and social (e.g., urban flows) aspects of relevance to stakeholders. An important aspect to manage groundwater demand is the establishment of an efficient enforcement policy to monitor caps imposed on groundwater use. In the absence of a clear policy and an institutional/legal framework to achieve this, water users' behaviours will continue to be non-cooperative, therefore leading to unsustainable groundwater use in the long-term.

Finally, we can conclude that including stakeholders in the participatory modelling process has led to the definition of a rich and diverse collection of water management strategies and ways to assess these strategies, which are a good reflection of stakeholders' interests and visions. This indicates that not only the final product—i.e., the SimCopiapo digital platform—is of value but also the process leading to its creation.

Author Contributions: Conceptualisation, R.R., J.C.-R. and G.B.; methodology, R.R. and J.C.-R.; software, R.B. and J.C.-R.; validation, R.R., J.C.-R., G.B. and C.P.; formal analysis, R.R. and J.C.-R.; investigation, R.R., J.C.-R., G.B. and C.P.; resources, E.C.; data curation, R.R., J.C.-R., G.B., R.B. and C.P.; writing—original draft preparation, R.R.; writing—review and editing, R.R., J.C.-R., G.B., R.B., E.C. and C.P.; visualisation, R.R. and J.C.-R.; supervision, R.R. and E.C.; project administration, E.C. and G.B.; funding acquisition, R.R., G.B., J.C.-R. and E.C. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study, and clearance from the CSIRO Ethics Committee was obtained for this research (097/18).

Data Availability Statement: All data collected and necessary to reproduce this research are available from CSIRO Research Data Planner (rdp.csiro.au) and the corresponding project website https://research.csiro.au/gestion-copiapo/en/projects-simcopiapo-participative-modelling-for-water-management/, accessed on 14 March 2022.

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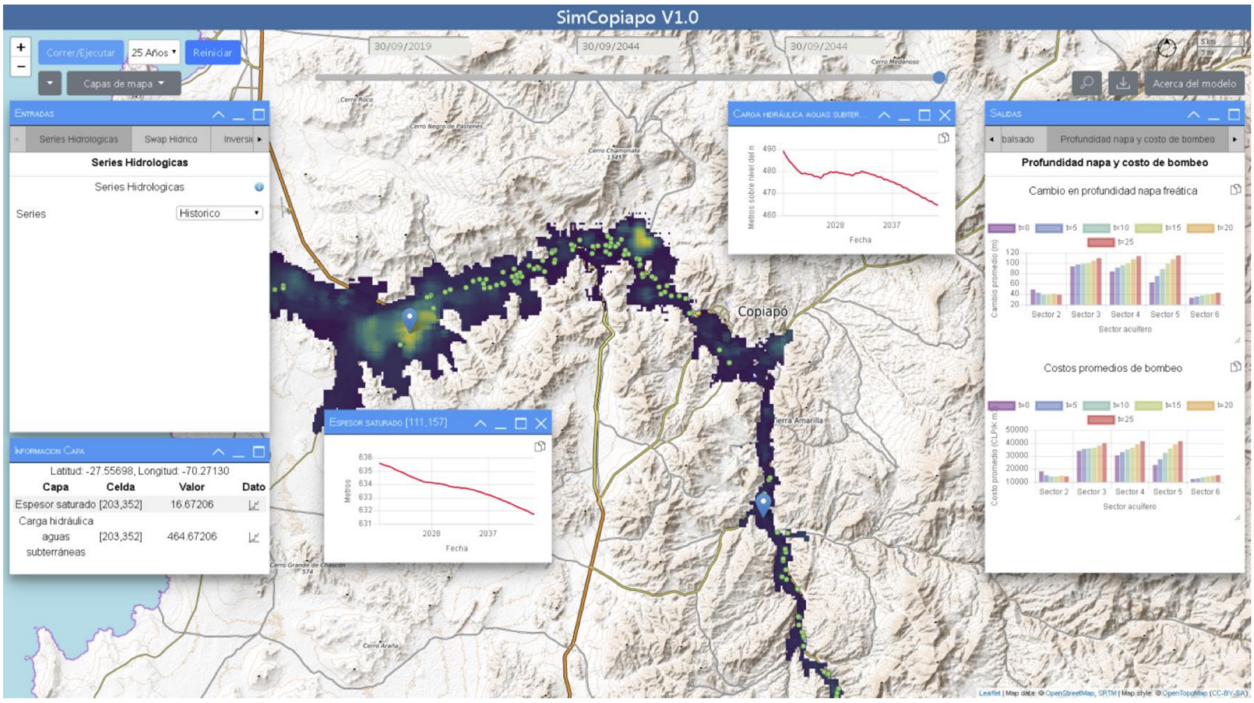
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A



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Capa	Celda	Valor	Dato
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Carga hidráulica aguas subterráneas	[203,352]	464.67206	

Figure A1. Graphical user interface for SimCopiapo platform v1.0 (in Spanish).

Table A1. Summary of impacts for water management strategies implemented in SimCopiapo.

Water Management Strategy		Description	Simulated Impact
Water use/rights exchanges	1.1	Water use/right exchange between Candelaria–Aguas Chanar	(o+) Groundwater heads/volumes increase in GW sectors 5 and 6
	1.2	Water use/right exchange between Caserones–Ramadilla River	(o−) Stored volumes in Lautaro Reservoir decrease (o−) Groundwater heads/volumes decrease in GW sectors 3 and 4 (o−) Urban flows through Copiapó city decrease (o−) Irrigation security decreases in districts 1, 7, 8 and 9
	1.3-a	Water use/right exchange between SW Irrigation districts 8 and 9–SW irrigation districts 1–7	(++) Urban flows through Copiapó city increase (o+) Groundwater heads/volumes increase in GW sectors 3, 4 and 5 (o+) Irrigation security increases in district 6 (o−) Irrigation security decreases in district 7
	1.3-b	Water use/right exchange between SW Irrigation districts 8 and 9–Aguas Chanar	(o+) Groundwater heads/volumes increase in GW sectors 4 (o+) Groundwater heads/volumes increase in GW sectors 3 and 5 (oo) No substantial impact detected in irrigation districts
	1.3-c	Water use/right exchange between SW Irrigation districts 8 and 9–localised recharge Copiapó River	(++) Urban flows through Copiapó city increase (o+) Groundwater heads/volumes increase in GW sectors 3, 4, 5 and 6 (oo) No substantial impact detected in irrigation districts
	1.3-d	Water use/right exchange between SW Irrigation districts 8 and 9–GW Sector 5/with excess localised recharge Copiapó River	(o+) Groundwater heads/volumes increase in GW sectors 3, 4, 5 and 6 (o+) Environmental flows at the outlet of the basin increase (oo) No substantial impact detected in irrigation districts
	1.3-e	Water use/right exchange between SW Irrigation districts 8 and 9–GW Sector 5/with excess Managed Aquifer Recharge in GW Sector 5	(o+) Groundwater heads/volumes increase in GW sectors 3, 4 and 5 (oo) No substantial impact detected in irrigation districts

Table A1. *Cont.*

Water Management Strategy		Description	Simulated Impact
Hydraulic infrastructure	2.1	Impermeabilisation Lautaro Reservoir (100% in a 5 year period)	(++) Stored volumes in Lautaro Reservoir increase (o+) Urban flows through Copiapó city increase (o+) Groundwater heads/volumes increase in GW sectors 3, 4, 5 and 6 (o+) Irrigation security increases in districts 6, 7, 8 and 9 (– –) Groundwater heads/volumes decrease in GW sector 2
	2.2	Surface water conveyance to irrigation sectors through pipes instead of open channels	(++) Irrigation security increases in all irrigation districts (o+) Groundwater heads/volumes increase in GW sectors 3 and 4
	2.3	Operation of desalination plant	(o+) Groundwater heads/volumes increase in GW sectors 5 and 6 (oo) No substantial impact detected in irrigation districts
Management of recharge	3.1	Managed aquifer recharge along the Copiapó River	(o+) Groundwater heads/volumes increase in GW sector 4 (oo) No substantial impact detected in irrigation districts
Demand management	4.1-a	Prorate of groundwater uses in GW sectors 3, 4 and 5 (high enforcement level: monitoring and fines at 90%)	(++) Groundwater heads/volumes increase in GW sectors 3 and 5 (++) Compliance with caps in groundwater use (o+) Groundwater heads/volumes increase in GW sectors 4 and 6 (oo) No substantial impact detected in irrigation districts
	4.1-b	Prorate of groundwater uses in GW sectors 3, 4 and 5 (low enforcement level: monitoring and fines at 20%)	(++) Groundwater heads/volumes increase in GW sector 5 (o+) Compliance with caps in groundwater use (o+) Groundwater heads/volumes increase in GW sector 6 (oo) No substantial impact detected in irrigation districts
	5.1	Greywater reuse/recirculation	(oo) No substantial impact detected

(oo): no decreases/increases over the simulation period with respect to base scenario; (– –): decreases over the simulation period more than 20% with respect to base scenario; (o−): decreases over the simulation period less than 20% with respect to base scenario; (o+): increases over the simulation period less than 20% with respect to base scenario; (++): increases over the simulation period more than 20% with respect to base scenario.

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