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Sustainable long-term mitigation of floods and droughts in semiarid regions: Integrated optimal management strategies for a salt lake basin

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Abstract

We present a management project for the mitigation of extreme climatic events in the frame of cyclic wet and dry periods in the semiarid Pampean region of Argentina. The developed methodological approach allows quantitative planning of strategies to tackle the effect of recurrent floods and droughts in a salt lake basin through the formulation of an optimal control problem, which constitutes a novel approach to ecohydrological systems management. The control variables correspond to (i) diversion flows from a lake tributary to an artificial freshwater reservoir to damp lake flooding, (ii) freshwater flows from the reservoir to the salt lake to keep its salinity at desired values and (iii) freshwater flows to irrigate crops during drought periods. Further, we address the economic valuation of ecosystem services in the basin. Quantitative results provide useful insights on optimal management strategies and the effects of their implementation, as well as their impact on the valuated services in the watershed under study.

KEYWORDS
drought and flood mitigation, ecohydrology, inland basins, optimal control

1 | INTRODUCTION

Integrated water management at the watershed level is seldom applied in Argentina (Quirós & Drago, 2002), the second largest country in South America and to a large extent semiarid. The adaptive capacity of socio-ecological systems in Latin America is very low, whereas the vulnerability to extreme climate events is high (Mata et al., 2001). Climate change poses serious challenges for water management in arid and semiarid areas (Thompson & Flower, 2009). Therefore, sustainable water supply and food production are major issues in governance strategies capable to flexibly handle issues on water quality and availability problems in the frame of climate change (Sahoo & Schaldow, 2008).

In Argentina, floods cause economic losses that can represent 1.1% of the gross domestic product (World Bank, 2000). On the other hand, droughts have caused extensive damage in harvests, prairie and forest fires, as well as desertification, soil salinization, dust storms and rural population migration (Taboada et al., 2009). Globally, estimates of drought impacts from 1998 to 2017 show they have affected at least 1.5 billion people and led to losses of at least US$ 124 billion. Furthermore, numerous case studies suggest that impacts largely exceed these values (UNDRR, 2021).

Adaptive management of unstable water resources at proper time and spatial scales is critical in semiarid regions, particularly when long hydrological data series are scarce, as is frequently the case in South America (Bezerra da Silva et al., 2020; Ndehedehe & Ferreira, 2020). This paucity hampers the differentiation of superimposed local, regional and global trends, resulting in erroneous short-term policies based on a rationale derived from main shifting environmental baselines, such as the recurrent floods of the three decades between 1970 and 2000 in the Argentinean Pampa (Barral et al., 2019; Lara, 2006). In that period with rainfall above the historical average, management projects favoured the drainage of agricultural land in the Buenos Aires province (Latrubesse & Brea, 2009). However, since 2006 a rigorous

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drought began to affect this and neighbouring regions, severely damaging the agricultural structure of the semiarid grasslands, with high cattle mortality, loss of vegetation coverage, soil erosion, fish mortality and salinity increase in lagoons and lakes (Kopprio et al., 2010). The Pampean region underwent the worst drought of the last decades and historical records strongly suggest the current onset of a dry, warmer phase that could last 25–50 years (Viglizzo & Frank, 2006). This can raise a higher socio-ecological vulnerability through reduced freshwater availability and quality for direct human consumption, agriculture and industry, increased salinity and temperature of water bodies with shifts in their trophic structures (Estrada et al., 2009a, 2009b; Kopprio et al., 2010).

This risk scenario is embedded in the sensitive regional environmental setting of North Patagonia and Southern Buenos Aires region (Figure 1), close to the South American Arid Diagonal, whose boundaries can be highly variable according to oscillations in the rainfall regime (González Loyarte, 1995). The discharges of the North Patagonian Colorado and Negro Rivers show teleconnections to El Niño Southern Oscillation (Dettinger et al., 2000) and thus introduce a further variability source of global scale, superimposed on regional precipitation patterns, with consequences for agriculture and ecohydrological dynamics of water bodies.

Besides progressive shifts in the socio-ecological settings, the frequency and intensity of extreme events such as floods and droughts will also increase with climate change (IPCC, 2007). Coastal ecosystems and their basins are rapidly changing due to anthropogenic pressure and global warming; also inducing changes in patterns of resource use (Lara et al., 2002). Thus, river basins and riparian ecosystems are a natural unit for vulnerability assessment and coastal management (Szlafsztein & Lara, 2002). Typical Pampean lakes are relatively large (>100 ha) and shallow (Torremorell et al., 2007), vary from eutrophic to hypertrophic, present a highly variable hydrochemistry (Quirós et al., 2002), and frequently generate blooms of potentially toxic cyanobacteria (Estrada et al., 2009a; Quirós, 2000). Shallow lagoons and salt/brackish lakes are particularly sensitive indicators of environmental change, and a conceptual model has been developed for the management of the numerous Pampean salt lakes (Kopprio et al., 2014). Yet, methodological advances in research for the quantitative management of hydrological fluxes of these highly unstable South American water bodies is still incipient (Siniscalchi et al., 2019; Siniscalchi, García Prieto, et al., 2018; Siniscalchi, Kopprio, et al., 2018).

Overall, comprehensive, quantitative approaches to address salt lake dynamics are scarce. Dias and Lopes (2006) implemented and

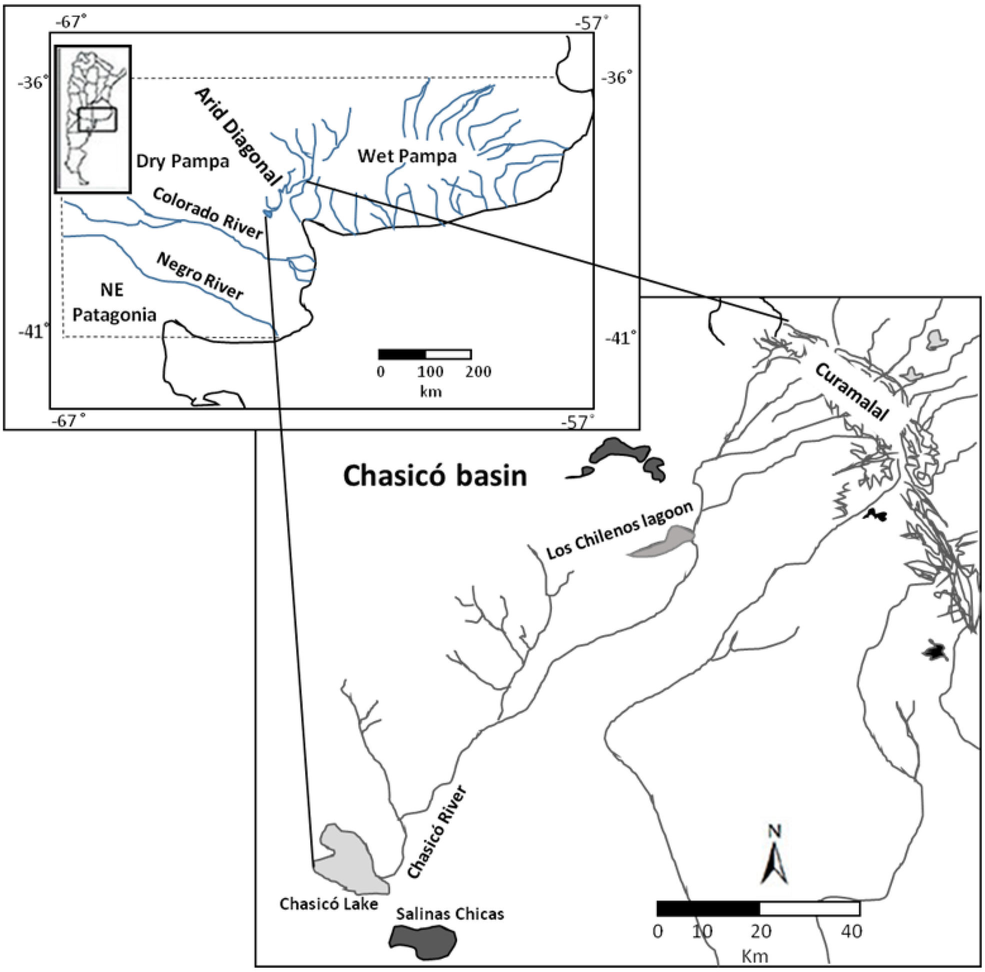

FIGURE 1 Hydrological and climatic setting of the study area. The arid diagonal divides the wet Pampa from the dry Pampa ecoregions

assessed hydrodynamic, salt and heat transport models for a shallow coastal lagoon in Portugal. Dube et al. (2010) modelled the effects of variable salinities on plankton dynamics in shallow coastal lagoons. Yihdego and Webb (2012) developed a mathematical model to study seasonal and long-term trends in lake salinity. Gilboa et al. (2014) defined limits for acceptable levels of management policies to allow sustainable management of water quality in a lake ecosystem. Donia and Bahgat (2016) proposed the assessment of the current status of a salt lake with a hydrodynamic and water quality model. Simulations of different scenarios were compared. More recently, Mesman et al. (2020) used hydrodynamic simulations to study the effects of extreme weather events in North European lakes.

Only few authors have formulated lake management issues as optimal control problems. Estrada et al. (2009a, 2009b, 2011); Estrada and Diaz (2010) addressed the restoration of eutrophic reservoirs in Argentina as optimal control problems through the formulation of lake ecological models within a dynamic optimization framework. Di Maggio et al. (2015) and Siniscalchi et al. (2020) proposed integrated management of lakes and artificial wetlands through the application of dynamic optimization strategies. Sangiorgio and Guariso (2018) applied neural network-based stochastic use optimization of multi-reservoir systems in the Nile River basin, aiming minimization of irrigation water deficit and maximization of hydropower production. Siniscalchi, Kopprio, et al. (2018); Siniscalchi et al. (2019); and Siniscalchi, García Prieto, et al. (2018) developed a hydrological model within a dynamic optimization framework for flood management of a salt lake in a semiarid region in Argentina. Shalby et al. (2020) proposed models for climate change effects on a coastal lake in Egypt, yet they did not address the lake management problem within an optimization approach.

Further, sustainable management of sensitive ecosystems requires the identification and valuation of their services (Costanza et al., 2011, 2014; Millennium Ecosystem Assessment, 2005), and several valuation methodologies have been proposed (de Groot et al., 2010; Martín-Ortega et al., 2015). In particular, erosion prevention and land use change are associated to essential ecosystem services such as carbon dioxide sequestration by grasslands and natural woodlands, wood and fruit provision, and land for food production (Accatino et al., 2019). The compromise between conservation and exploitation of natural resources is still a controversial issue (de Groot et al., 2010; Grupta & Kumar, 2018). Girardin et al. (2021) insist on the fact that ecosystems that are protected and carefully managed are very likely to continue to store carbon for thousands of years. These are also more resilient to climate extremes and pathogens, such as in the case of Sierra Leone's tropical rainforest, cocoa agroforestry (where cocoa is planted with trees for shade, alongside pineapples, chillies and corn as an additional source of food and income) has been shown to produce cocoa sustainably while diminishing forest clearance. The authors underline the urgent need to increase investment in high-quality, nature-based solutions (NBS). Besides the important support for crop cultivation and forest plantation, cultural perception and habitat services, ecohydrology-NBS have the potential to significantly strengthen such efforts, as an essential component of Integrated Water Resources Management (IWRM) (Boelee et al., 2017). However, no systematic methods are proposed for quantitatively planning these strategies. Therefore, especially in vulnerable semiarid zones, the integrated management of land use and water bodies is a challenging and urgent issue. In this frame, Siniscalchi et al. (2019) carried out identification and valuation of the main ecosystem services offered by the endorheic basin of Chasicó Lake in relation to potential management approaches.

In this work, we systematically address strategies to dampen the effects of extreme climatic events on the ecohydrological dynamics of a Pampean salt lake and to irrigate drought-resistant crops in its grassland basin. This is implemented through methodologies that embrace key parameters from hydrology, climate, animal and plant physiology, providing optimal profiles for concrete lake and land management actions. The approach integrates dynamic mass balances, evaporation, kinetic equations, optimum salinity requirements for fish reproduction, as well as calculation of crop water requirements. Specific sustainability challenges are tackled as an optimal control problem, where time-dependent optimization variables are the water fluxes between a lake tributary, a constructed freshwater reservoir, the salt lake and a pilot cultivation area.

2 | MATERIALS AND METHODS

2.1 | Study context

Chasicó Lake is located in a depression, 20 m below mean sea level in the southwest of the Chaco-Pampean plain (38°38′S 63°03′W), Argentina, with maximum and average depths of 13.2 and 8 m, respectively. This endorheic salt lake (6500 ha) is part of a natural reserve (7900 ha) situated in a basin of 376,400 ha (Figure 2). Reserve regulations allow multiple uses, which include crop cultivation, woodland plantation and livestock.

The region is semiarid, with grasslands and xerophilic forest patches that mainly include *Prosopis*, *Geoffroea* and *Jodina* species (Cabrera, 1976). The basin's hydrologic regime is closely related to climatic conditions, with dry and wet cycles (D'ambrosio et al., 2013). During wet periods, average precipitations and evaporation in the lake are 700 and 1000 mm year^{-1}, respectively, while in dry periods, they are 256 and 1120 mm year^{-1}, respectively (Siniscalchi, Kopprio, et al., 2018). Large variations in the discharge of the Chasicó River are reflected in a wide range of lake areas and salinities, deeply impacting water quality and biota (Kopprio et al., 2014).

During the last century, there were flood events in 1918, 1923, 1924, 1976, 1978, 1983, 1993, 2001 and 2002—the latter during the wet period 1970–2002, with dry periods during 1930–1970 (Lara, 2006) and 2006–to date. Salinity values in the lake during the last sixty years ranged between 100 g L^{-1} (1963) and 16 g L^{-1} (1993).

Salinity and extension variations in the lake also affect the economy of the region through losses in cropland area and investment uncertainty in relation to tourism and sport fishing of silverside. The severe impact of droughts and floods on inland water resources and

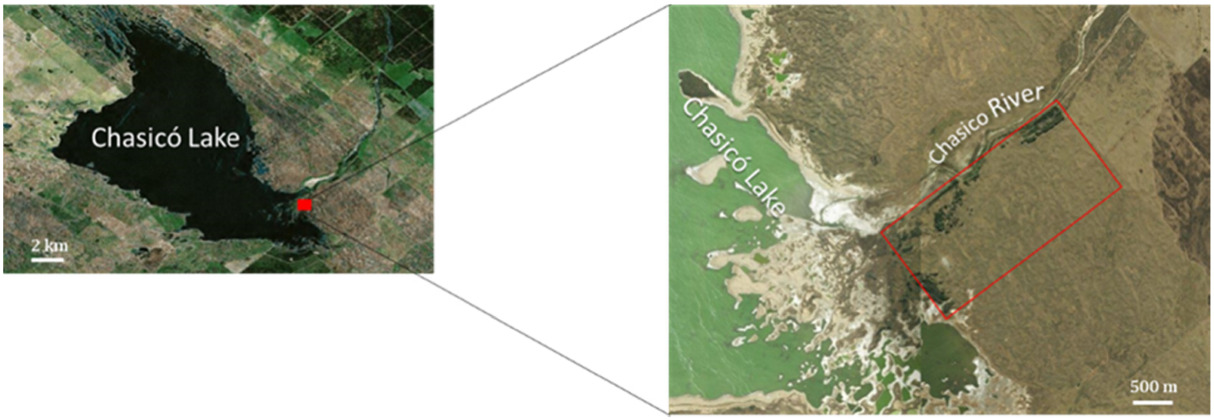

FIGURE 2 Chasicó Lake and natural reserve map. The red rectangle frames a pilot area of 300 ha

associated socio-economic activities in the Pampa calls for a close surveillance of this lake, which due to its responsive characteristics (Kopprio et al., 2014) should be considered a regional sentinel of hydrologic change.

2.2 | Definition of management strategies and integrative methodological approach

In this work, we propose an optimal control problem to manage a salt lake basin within a semiarid region during wet and dry phases. The management strategies involve (i) to prevent flooding of the nearby fields, village and touristic areas within wet scenarios through upstream diversion from a lake tributary to a constructed freshwater reservoir (hereinafter called the reservoir), (ii) to optimize management of the reservoir by diverting freshwater to the salt lake, to keep salinity in the lake around a desired value for the reproduction of the commercially valuable fish species *Odontesthes bonariensis* (silverside) during drought periods and (iii) to include restoration strategies for native species of axerophilic woodland currently existing within the salt lake basin, combining new plantations of *Prosopis* sp. with drought resistant crops (quinoa), in a pilot area irrigated with freshwater taken from the reservoir.

These strategies are addressed as an optimal control problem, that is, a dynamic optimization problem, which is a constrained optimization problem subject to a differential algebraic equation (DAE) system. In this kind of problems, the control (time-dependent) variables constitute the degrees of freedom of the problem, whose optimal values are determined by the optimization algorithm. Dynamic optimization problems are formulated within a control vector parameterization framework in gPROMS (Siemens Process Systems Engineering, 2020). The quantitative output provides control variables profiles to plan management actions and predict their ecological and hydrologic effects, as well as irrigation requirements for drought resistant crops.

A case study of a 6-year wet period (700 mm/year average precipitations), followed by a 4-year dry period (256 mm/year), is analysed. The time-dependent optimization (control) variables are the diverted flows from the river to the reservoir and from it to the Chasicó Lake and the pilot area.

2.3 | Identification and valuation of ecosystem services

Ecosystem services for the Chasicó Lake basin were identified in previous work (Siniscalchi et al., 2019) and global valuation for each service was carried out following de Groot et al. (2012), in USD ha^{-1} year^{-1}.

2.4 | Integrated hydrological and vegetation dynamics

As a first step, we formulated dynamic water mass balances for a salt lake and the reservoir. Equation 1 shows water mass balance for the salt lake.

$$\frac{d\boldsymbol{m}}{dt} = \left[\boldsymbol{Q_{pp}}(t)\left(\frac{\boldsymbol{V}(t)}{\boldsymbol{h}(t)}\right) + \boldsymbol{Q_{river}}(t) + \boldsymbol{Q_{gw}}(t) - \text{Evap}\,(t)\left(\frac{\boldsymbol{V}(t)}{\boldsymbol{h}(t)}\right)\right]\boldsymbol{\delta_w}/1000 \tag{1}$$

where $\boldsymbol{m}$ is the total water mass in the lake (kg); $\boldsymbol{\delta_w}$ is water density ($\text{kg}\,\text{m}^{-3}$), which is assumed constant; $\boldsymbol{V}$ corresponds to salt lake volume (m^3) and $\boldsymbol{h}$ is average depth (m). $\boldsymbol{Q_{pp}}$ ($\text{L}\,\text{day}^{-1}$ m^{-2}) corresponds to precipitations, $\boldsymbol{Q_{gw}}$ ($\text{L}\,\text{day}^{-1}$) is groundwater flowrate. $\boldsymbol{Q_{river}}$ ($\text{L}\,\text{day}^{-1}$) is the tributary discharge to Chasicó Lake, which is calculated as follows:

$$Q_{river}(t) = Q_{cr}(t) - Q_{divert}(t) + Q_{res}(t) \tag{2}$$

where Q_{divert} ($\text{L}\,\text{day}^{-1}$) is the stream flowrate that could be diverted when necessary from Chasicó River (Q_{cr}) ($\text{L}\,\text{day}^{-1}$) to the reservoir during wet periods, to keep Chasicó Lake salinity within desired values (it is a control variable). Q_{res} ($\text{L}\,\text{day}^{-1}$) is the daily water amount that could be diverted from the reservoir to Chasicó River and, subsequently to the salt lake for salinity and volume control (this is also a control variable) in drought periods, if required.

Evaporation per unit area (***Evap***, L day^{-1} m^{-2}) is calculated taking into account energy and momentum balances (Penman, 1948), as follows (Siniscalchi, Kopprio, et al., 2018):

$$Evap(t) = \frac{10}{\lambda(t)}[W(t)\,Rn(t) + (1 - W(t))F_{wind}(t)(T_{vap0}(t) - T_{vap}(t))] \quad (3)$$

where W is a time-dependent weighting factor of the radiation effect on evaporation, which is calculated as function of the vapour pressure curve slope and of the psychrometric constant, at atmospheric temperature and pressure monthly averages (P_{atm}) (see Equations A3 and A4 in Appendix A), following Penman (1948). Rn is net radiation (Ly day^{-1}), F_{wind} expresses wind effect as available energy to evaporate water (km day^{-1}) and $(T_{vap0} - T_{vap})$ is a vapour saturation deficit; λ corresponds to water latent heat of vaporization. We formulated temporal regressions for the preceding forcing functions based on data from meteorological stations of the National Institute of Agricultural Technology (INTA) located in the localities of Bordenave (37°S 63°W), Médanos and Ascasubi (38°S 62°W) and (39°S 62°W), and from the Ministry of Agriculture (MMA) (Bonorino et al., 1989; Siniscalchi et al., 2017, Siniscalchi, García Prieto, et al., 2018, Siniscalchi, Kopprio, et al., 2018). Detailed equations are presented in Appendix A.

Additional algebraic equations include other forcing functions, represented by Fourier series, including tributary and groundwater flowrate, air temperature, relative humidity, solar radiation, mean wind rate and related meteorological variables.

As salt concentration in both groundwater and the tributary is negligible, we assume that salt mass is constant within the salt lake and salt concentration (Cs) is calculated as follows:

$$\frac{dCs}{dt} = -\frac{Cs(t)}{V(t)}\left[Q_{pp}(t)\left(\frac{V(t)}{h(t)}\right) + Q_{river}(t) + Q_{gw}(t) - \mathrm{Evap}(t)\left(\frac{V(t)}{h(t)}\right)\right]\delta_w \,/(\delta_w 1000) \quad (4)$$

In previous work, a hydrological model for the Chasicó Lake was calibrated and validated with collected salinity data throughout 10 years and two bathymetries carried out during the same period (Siniscalchi et al., 2017; Siniscalchi, Kopprio, et al., 2018). In this work, we extend the model to include the design and dynamics of an artificial reservoir of fixed area (2800 ha). Its water mass balance, assuming constant water density, is as follows:

$$\frac{dVres}{dt} = Q_{divert}(t) + Q_{pp}(t)A(t)\,\delta_{H_2O} - Evap(t)A(t)\delta_{H_2O} - Q_{res}(t) - Q_q(t) - Q_p(t) \quad (5)$$

where Q_q is the daily water volume used for quinoa crop irrigation and Q_p corresponds to water requirement for *Prosopis* sp. once seedlings are transplanted to field. Water requirement for quinoa, Q_q, is calculated based on crop evapotranspiration $ETq(t)$ and precipitations as follows:

$$Qq(t) = \max[0, (ETq(t) - Q_{PP}(t))A_{cult1}] \quad (6)$$

where A_{cult1}(m^2) corresponds to total cultivated area with quinoa. $ETq(t)$ is actual evapotranspiration (L day^{-1} m^{-2}) for quinoa crop, calculated with Penman–Monteith equation (FAO, 2006), considering the potential evapotranspiration of the crop ($ET0(t)$) and a cultivation coefficient for quinoa ($Kq(t)$) (García Villanueva et al., 2017) as follows:

$$ET0(t) = \frac{k * \Delta(t) * Rn(t) + \gamma * \frac{900}{T_{air}(t)+273}\, F_{wind}(t)(T_{vap0}(t) - T_{vap}(t))}{\Delta(t) + \gamma(t) * (1 + 0.34F_{wind}(t))} \quad (7)$$

where k is an energy parameter that depends on air temperature (T_{air}), calculated as follows:

$$k = \frac{10}{(595 - 0.5\,T_{air}(t))} \quad (8)$$

Δ is vapour pressure derivative with respect to temperature (hPa °C^{-1}), calculated as follows:

$$\Delta = 33.8693 * \left(0.05904 * (0.00738 * T_{air}(t) + 0.8072)^7 - 0.0000342\right) \quad (9)$$

Rn is net radiation, γ is a psychrometric constant (mb °C^{-1}) calculated taking into account ambient temperature and atmospheric pressure monthly averages (P_{atm}). Finally, $(T_{vap0} - T_{vap})$ is vapour saturation deficit (for detailed calculation, see Appendix A).

Actual evapotranspiration for quinoa, $ETq(t)$ is calculated as follows:

$$ETq(t) = Kq(t) * ET0(t) \quad (10)$$

The cultivation coefficient for quinoa, $Kq(t)$, is represented with Fourier series during the periods with quinoa crops (between mid-October and mid-February) and zero, otherwise. These functions were developed considering crop water requirement through the different growth stages in a semiarid region, based on data from García Villanueva et al. (2017), as follows:

$$Kq(t) = 1.08375 + 0.39824\cos(z) + 0.37787\sin(z) + 0.26977\cos(2z) + 0.51847\sin(2z) \quad (11)$$

where z is the time function.

Irrigation for *Prosopis* sp. seedlings once transplanted in field (Q_p) is taken from reservoir and diverted flows for irrigation are calculated as follows:

$$Q_P(t) = \max\left[0, \left(ETp(t) - Q_{pp}(t)\right) * A_{cult2}\right] \tag{12}$$

where A_{cult2} corresponds to cultivated area with *Prosopis* sp. and ETp is actual evapotranspiration for this plant, calculated as follows:

$$\mathrm{ETp(t)} = \mathrm{K_p} * \mathrm{ET0(t)} \tag{13}$$

The *Prosopis* sp. cultivation coefficient (K_p) is correlated based on collected data from an arid region by Dzikiti et al. (2013), as follows:

$$K_P(t) = 0.18593 + 0.12395\,cos(z) + 0.02161\,sin(z) + 0.18794\,cos(2z) \tag{14}$$

where z is the time function.

2.5 | Dynamic optimization problem

The primary goal is to keep Chasicó Lake salinity (*Cs*) around a desired value of 23 kg m^{-3}, considered as optimal for silverside reproduction (Tsuzuki et al., 2000), while fulfilling the DAE system presented in the preceding section. In this way, the lake volume—and hence its extension—is also kept within acceptable bounds as well, since it is an endorheic basin. The upper bound is determined based on collected data from the study area to avoid flooding of a nearby village and fields. The lower bound is also based on collected data and to avoid high salinity values that may affect fish reproduction and survival. The resulting optimization problem is as follows:

$$\min Z = \int_0^{tf} (\mathrm{Cs(t)} - 23)^2\, \mathrm{dt} \tag{15}$$

$$\mathrm{Q_{res}, Q_{divert}}$$

Subjet to
DAE system 1–14; A1–(A10)

$$\mathrm{Cs(0)} = \mathrm{Cs^0}$$

$$\mathrm{V(0)} = \mathrm{V^0}$$

$$\mathrm{V_{res}(0)} = \mathrm{V^0_{res}}$$

$$\mathrm{Z(0)} = 0$$

$$0 \le \mathrm{Q_{divert}} \le \mathrm{Q^U_{divert}}$$

$$0 \le \mathrm{Q_{res}} \le \mathrm{Q^U_{res}}$$

$$\mathrm{Cs^L} \le \mathrm{Cs} \le \mathrm{Cs^U}$$

$$\mathrm{V^L} \le \mathrm{V} \le \mathrm{V^U}$$

$$0 \le \mathrm{V_{res}} \le \mathrm{V^U_{res}}$$

where Cs^0 corresponds to initial salinity value; V^0 is initial salt lake volume; Cs^L and Cs^U are lower and upper bounds on salinity; V^L and V^U are bounds on lake volume; $Q_{divert}(t)$, is the diverted stream flow to a nearby constructed reservoir to avoid flooding while keeping salinity at 23 kg m^{-3} in a wet scenario and is a control variable (degree of freedom of the optimization problem). Finally, $Q_{Res}(t)$ is the second control variable and corresponds to the stream flow that is fed to Chasicó Lake from the constructed reservoir to keep lake salinity at the desired value in dry periods. When solving the dynamic optimization problem, the definition of a 'wet' or 'dry' period is not required, since this is determined by the input profiles provided for precipitations, temperature, wind and current conditions at daily time intervals. The integral objective function is written as a scalar objective Z and an additional differential equation:

$$\frac{dZ}{dt} = \left[(\mathrm{Cs(t)} - 23)^2\right] \tag{16}$$

The resulting system has 11 differential equations, three of which correspond to mass balances (Equations 1, 4 and 5), one is the integral objective function and the remaining ones correspond to accumulated precipitations, evaporation and so forth. There are 28 algebraic equations, most of them accounting for evaporation (see Appendix A) and evapotranspiration calculations. Additional constraints have been included to take into account path constraints on stream flowrates and reservoir volume to avoid negative values. This approach has been implemented within a control vector parameterization framework within gPROMS (Siemens Process Systems Engineering, 2020), an equation-oriented environment, which uses information on gradients of the objective function and differential algebraic constraints with respect to control variables. In our case, the latter are the diverted flows from the tributary (Q_{divert}) and from the reservoir (Q_{res}). These variable profile parameters are calculated in the outer problem of the algorithm by solving a nonlinear programming (NLP) problem and are used in the inner problem parameters along the entire time horizon in each integration of the DAE system using a multishooting strategy. In this way, the optimization algorithm proceeds with the search for directions that minimize the objective function. Piecewise constant functions are selected for the control variables. The NLP problem formulated at the optimization outer level is solved with a successive quadratic programming method, which provides additional efficiency to the entire procedure.

2.6 | Cultivation scenarios and design

We formulate two cultivation scenarios for a pilot area (red rectangle in Figure 1) of 300 ha, which corresponds to 23% of the entire size of the natural reserve. In this sector, the Alexander von Humboldt tree nursery bred mainly European and North American species in the second half of the 20th century using spring water from a 700-m deep well for irrigation. Following a large fire that destroyed most trees, the nursery was abandoned. After Accatino et al. (2019), a percentage of around 20% is optimal to enhance synergies between productive activities and other ecosystem services. In Scenario (A), we consider the cultivation of 300 ha with quinoa at a density of 500,000 plants per ha (FAO, 2006; Gomez Pando & Aguilar Castellanos, 2016). In (B), we analyse the combined cultivation of quinoa and *Prosopis* sp. within 300 ha. Cultivation arrays are shown in Figure 3. In both cases, freshwater for irrigation is taken from the reservoir (Siniscalchi, García Prieto, et al., 2018).

In particular, we propose the sustainable use of *Prosopis* sp. because, besides being a native species, its fruits have high nutritional value (15% protein, 2200-kcal energy per kg of dry mass and 52% dry digestible mass (Marmillon, 1986; Privitello et al., 2001) that can be used as cattle fodder, and as flour for human consumption. In the long term, it can provide high-quality wood, which is used for doors, windows and furniture.

Prosopis sp. seedlings are obtained from native plants of xerophilic forests within Chasicó Lake basin. Seeds are germinated within a nursery garden irrigated with available spring water from the above mentioned well, which can provide 348 m^3/h and whose salinity is lower than 1 g/L (Romanazzi et al., 2012). Six-year old plants are transplanted to open field and are irrigated, if required, during the first 6 months with a minimal water requirement of 0.03 $L\,m^{-2}\,d^{-1}$ (Córdoba et al., 2013). After that period, no superficial irrigation is required as they use groundwater.

3 | RESULTS AND DISCUSSION

3.1 | Salinity, flood control and drought mitigation in Chasicó Lake

In the present work, we propose management strategies through the described ecohydrological integrated approach within a dynamic optimization framework for a 10-year span composed of six wet years, followed by a 4-year dry period. These are realistic scenarios based on the analysis of long data series that comprise rainfall data for the 1911–2019 period in the upper basin, taken from a meteorological station from the National Institute of Agricultural Technology (INTA). Historical data provide very good estimations of patterns for precipitations, temperature, and so forth, associated to extreme events. Parameters for Fourier series representing these time dependent inputs based on historical data have been estimated with the analysis tool Solver in Excel. A detailed description can be found in Siniscalchi, Kopprio, et al. (2018). And wet and dry periods are indeed strongly cyclic in the study region.

During the first 6 years we consider wet conditions with average precipitations of 700 mm $year^{-1}$ and average evaporation of 1000 mm $year^{-1}$. We include temporal profiles for precipitations, groundwater flows (considered as 30% of precipitations after Bonorino et al., 1989) and Chasicó River discharge, as well as wind, solar radiation and other meteorological parameters as forcing functions. The quantitative output provides concrete management strategies comprising (i) daily flowrates for a diversion stream sent from Chasicó River to the reservoir for water storage, (ii) reservoir filling rate, (iii) Chasicó Lake dynamics and (iv) evaporation and crop evapotranspiration profiles. In the dry scenario (last 4 years), freshwater from the reservoir is used to damp salinity oscillations in Chasicó Lake and to irrigate drought-resistant crops in its basin.

As a first step, we deal with the analysis of the 6-year wet period, starting from initial conditions corresponding to a lake volume of 480 $hm^3$and a salinity value of 23 kg m^{-3} (in January, high summer in the south hemisphere). The filling of a reservoir with a fixed area of 2800 ha begins during this period ($V_{res}^0 = 0$).

Figure 4 shows profiles for precipitations, groundwater flows and calculated evaporation within this period. Figure 5 shows Chasicó River discharge profile before diversion to the artificial reservoir (Q_{cr}). River flowrate reaches a maximum of 4.108 $L\,d^{-1}$ associated to upstream average precipitations of 1000 mm $year^{-1}$. This figure also shows flows corresponding to the river diversion stream flowrate profile (Q_{divert}) to the constructed reservoir. This is the optimal profile for the control variable (Q_{divert}), represented by piecewise-constant functions (30 day-step), which correspond to the opening and closure of floodgates to the diversion stream and constitutes the core of the management strategy. The diversion channel size can be also estimated from the calculated flowrates. In this way, the presented results provide concrete measures to avoid flooding of the nearby fields and touristic village and to keep salinity at optimal values for silverside reproduction during the wet period under study.

FIGURE 3 Proposed cultivation arrays. (a) Quinoa crop in 300 ha; (b) mixed cultivation of quinoa (200 ha) and *Prosopis* sp. (100 ha)

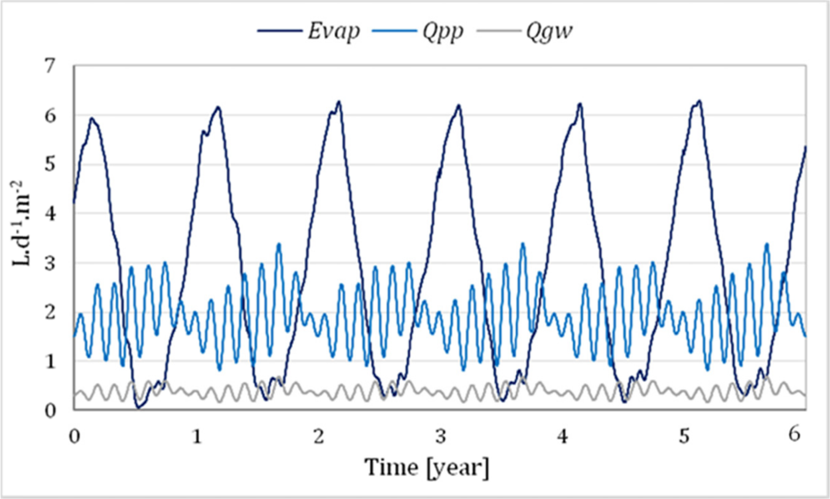

FIGURE 4 Precipitations (Q_{pp}) and groundwater (Q_{gw}) flowrate (forcing functions) and calculated evaporation (*Evap*) profiles for a six-year wet period

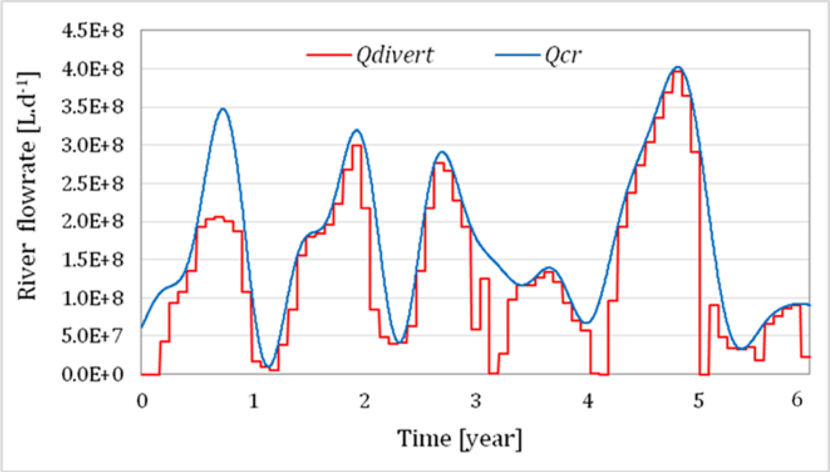

FIGURE 5 Chasicó River discharge (Q_{cr}), and diverted stream flowrate (Q_{divert}) to a constructed reservoir during a six-year wet period

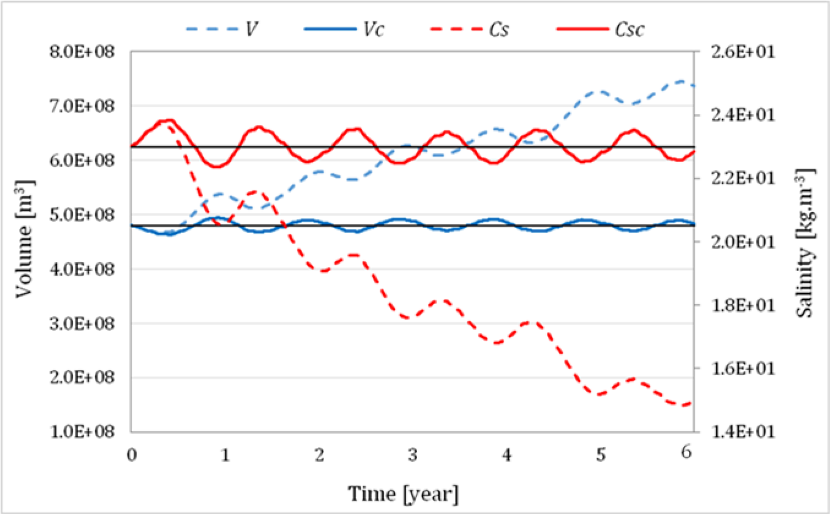

FIGURE 6 Chasicó Lake volume (*V*) and salinity (*Cs*) profiles during a 6-year wet period, considering no control (dashed lines) and control through Chasicó River partial diversion to a constructed reservoir

Figure 6 shows Chasicó Lake volume and salinity profiles during the 6-year wet period. Lake volume and salinity profiles are shown in dashed lines for a 'no control' scenario, simulating lake dynamics under the considered forcing functions, with no control actions. It can be seen that Chasicó Lake volume reaches 750 hm^3, almost twice its initial volume. These conditions correspond to a wet period that took place during the 80s (Bonorino et al., 1989), causing a severe flooding of the nearby village with significant losses for locals, piers, touristic infrastructure and surrounding farms. In turn, salinity values decrease from 23 to 15 kg m^{-3}, which are not optimal for silverside reproduction. Figure 6 also shows both lake volume and salinity profiles for the optimal management strategies determined by the proposed eco-hydrological model within an optimization framework (continuous lines). It is worth noting that these variables oscillate (due to meteorological and environmental conditions) around the desired value for salinity (horizontal line at 23 kg m^{-3}; see objective function in Equation 15) and the corresponding lake volume, through control actions taken by diverting a stream from Chasicó River (Q_{divert}) to the reservoir.

As a second step, we study a 4-year dry period. This case represents similar conditions to the period 2014–2018 in the region. In this scenario, average accumulated precipitations and evaporation are 256 mm $yearr^{-1}$ and 1120 mm $year^{-1}$, respectively. Their temporal profiles are shown in Figure 7. It can be seen that evaporation varies between 0.15 and 6.8 L d^{-1} m^{-2}, resulting in an accumulated 1120 mm yr^{-1}; which is approximately 4.4 times annual accumulated precipitations. This scenario requires control actions to prevent salinity increase. Therefore, the reservoir is used as freshwater source to damp salinity oscillations in the lake and to irrigate drought-resistant crops in its basin.

Figure 8 shows profiles corresponding to Chasicó River flowrate before diversion (Q_{cr}), groundwater (Q_{gw}) and a stream taken from the reservoir (Q_{res}) to increment river discharge into the lake, being Q_{res} the control variable. It can be noted that Q_{res} peaks correspond to minimum values of river flowrate (Q_{cr}) and maximum evaporation (see Figure 7). Further, the optimal amount of freshwater stream taken from the reservoir to keep lake salinity within desired values is an order of magnitude larger than the current river flowrate at any time during this dry period.

Lake volume and salinity profiles with and without optimal management through water input from the reservoir (Q_{res}) are shown in Figure 9. Profiles in dashed lines correspond to a no-control scenario. In this case, it must be noted that salinity value increases to 33 kg m^{-3} in 4 years, starting from an initial value of 23 kg m^{-3}, with an associated lake volume decrease to 340 hm^3. Continuous lines correspond to optimal profiles if control actions are taken, i.e., freshwater is fed to Chasicó River from the reservoir, thus keeping salinity within small oscillations around the desired value (23 kg m^{-3}).

Finally, Figure 10 shows the volume profile for the reservoir throughout the entire 10-year period under study. It can be seen that starting its filling at the beginning of the wet period, its volume reaches a maximum of 252 hm^3 after 6 years. This volume would correspond to a water body with a fixed area of 2800 ha and approximately 9 m depth. This extension represents 43% of the current lake area, and could be constructed, for example, by deepening nearby natural depressions or paleochannel beds cut by dunes. The reservoir can provide freshwater not only to damp lake salinity oscillations, but to irrigate drought resistant crops during the 4-year dry period, as it is discussed in the next section. Freshwater outflows for irrigation are also taken into account in the reservoir volume dynamics shown in Figure 10. As reported by Curtis et al. (2001), the cost of constructing a 123,348-m^3 reservoir is US$ 47,000. By applying the six tenths rule (Towler & Sinnot, 2013), an approximate value of US$ 4,500,000 is obtained. This cost is well in the range of the yearly benefits or avoided losses that could be achieved by the implementation of the proposed management strategy, as it will be shown in the following sections.

3.2 | Crop cultivation and forest plantation in Chasicó Basin

Based on model results for quinoa and *Prosopis* sp. seedlings evapotranspiration and current precipitations, we determined that during wet periods, no irrigation from the reservoir is required. Water requirement profiles are presented for the 4-year dry period. As stated in a previous section, we analyse two scenarios: (A) the

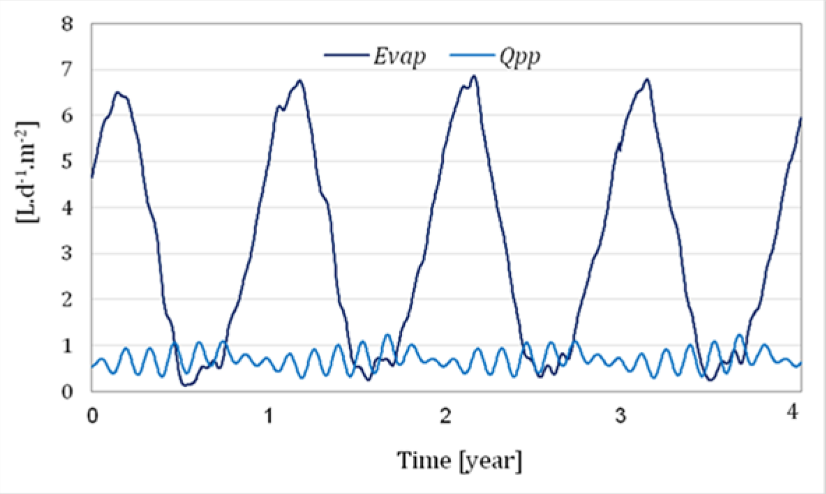

FIGURE 7 Precipitations and evaporation during a 4-year dry period in Chasicó Lake

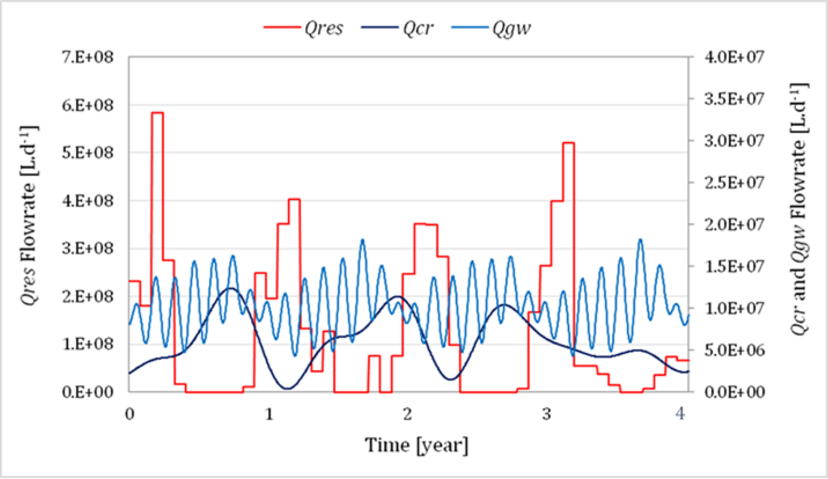

FIGURE 8 Profiles for Chasicó River (Q_{cr}), groundwater (Q_{gw}) and a control freshwater stream taken from a constructed reservoir (Q_{res}) during a 4-year dry period

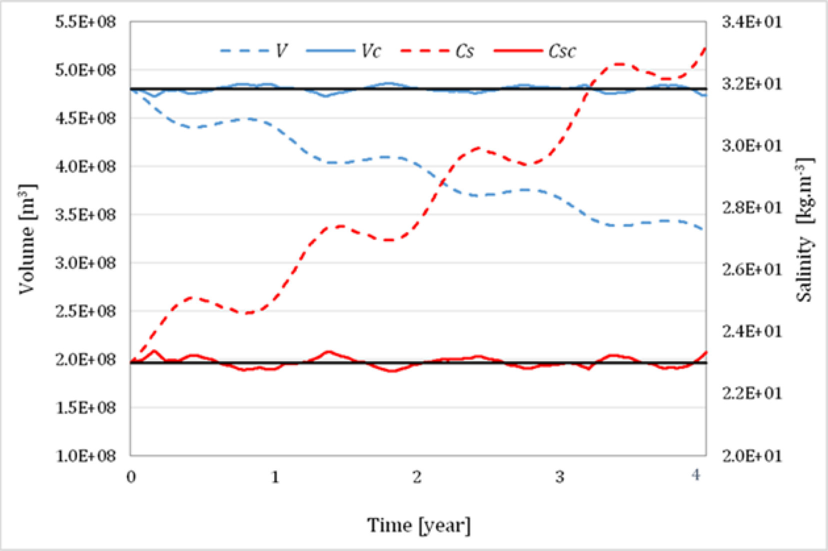

FIGURE 9 Volume and salinity profiles with (continuous line) and without (dashed line) optimal management

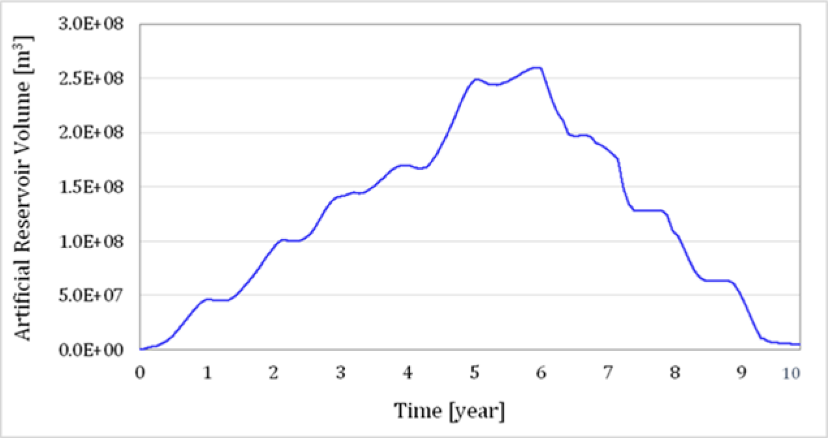

FIGURE 10 Constructed reservoir volume profile during the entire period under study (10 years)

cultivation of 300 ha with quinoa and (B) the combination of 200 ha of quinoa with 100 ha of *Prosopis* sp.

Figure 11 show profiles for precipitations (*Qpp*), water requirement for quinoa crop (*Qq*) and water requirement (*Qp*) and evapotranspiration (*ETp*) for *Prosopis* sp. in Chasicó Basin, during the cultivation period for quinoa (15 October–15 February). For the sake of clarity, water requirement for crop and seedlings is presented in L day^{-1} m^{-2}. It can be seen that no irrigation is required for *Prosopis*

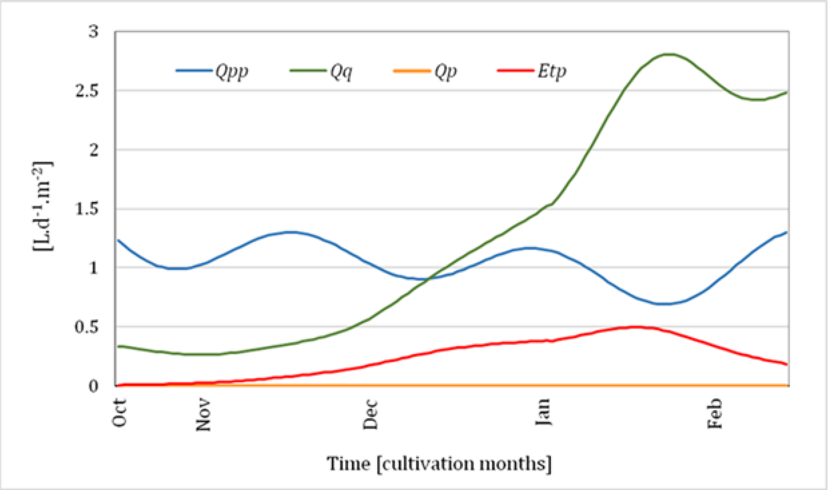

FIGURE 11 Profiles for precipitations (*Qpp*), water requirement for quinoa crop (*Qq*) (15 October–15 February), water requirement (*Qp*) and evapotranspiration (*ETp*) for *Prosopis* sp. in Chasicó basin

TABLE 1 Ecosystem services provided by Chasicó Natural Reserve and monetary values for each service

	Ecosystem service	Description	Value (US$/ha/year)		Total value (US$/year)
Regulating services	Climate regulation	Regulation of global temperature. Mediated processes on climate	Grasslands	40	40,000
			Woodlands	7	2800
	Erosion prevention	Runoff regulation	Grasslands	44	44,000
			Woodlands	13	5200
	Pollination	Flowers diversity for insects, birds and bats	Woodlands	31	12,400
Habitat services	Nursery and genetic diversity	Birds and other animals habitat	Grasslands	1214	1,214,000
			Woodlands	1277	510,800
Provisioning services	Raw material	Wood, and other raw material	Grasslands	53	53,000
			Woodlands	170	68,000
	Water supply	Filtering, retention and storage of water	Grasslands	60	60,000
	Food	Cattle pasture	Grasslands	1192	1,192,000
		Cattle fodder	Woodlands	52	20,800
		Meat fish (silverside)	Chasicó Lake	38.2	248,400
Cultural services	Tourism and recreation	Sport fishing, tracking, birds-watching, windsurf, kayaking, rowing	Grassland	26	26,000
			Woodlands	7	2800
			Chasicó Lake	2166	14,079,000

Note: Values estimated according to de Groot et al., 2012.

sp.; even within a dry period, precipitations are enough for its growth, as they exceed its evapotranspiration. This result is in agreement with literature data on this genus, which show that it can grow with annual accumulated precipitations between 50 and 200 mm year^{-1} (Dzikiti et al., 2013).

Regarding quinoa crop, Figure 11 shows that it requires irrigation throughout its entire life cycle, with a peak corresponding to the onset of grain maturation. Its accumulated irrigation requirement amounts to 1254.2 m^3 ha^{-1}, which means that only 0.376 hm^3 of freshwater are required from the artificial reservoir each year to irrigate 300 cultivated hectares.

3.3 | Valuation of ecosystem services

In this work, we intend to complement ecosystem services by enhancing the economic value of the reserve, not only by proposing management strategies to control floods and mitigate droughts, while keeping lake salinity within suitable values for silverside reproduction, but by cultivating drought-resistant crops and native tree species within allowed sectors.

Since we focus our study on Chasicó Natural Reserve (7900 ha), to estimate the natural capital of its subsystems, global values are multiplied by their respective areas. The lake covers 6500 ha, while native grass and woodlands extend over 1000 and 400 ha, respectively. Ecosystem services are valuated in US$/year and are listed in Table 1. They include regulating services (climate regulation, erosion prevention and pollination), provision services (raw material, water supply, land and food supply), habitat services (nursery and genetic diversity) and cultural services (tourism and recreation). As it can be seen in Table 1, ecosystem services with highest economic value correspond to tourism and recreation in the salt lake area (14.1 MM US$/year), where sport fishing of the high commercial value silverside constitutes an important attraction. This resource is threatened due to the large variability of salinity in Chasicó Lake (Kopprio et al., 2010) and control strategies for dampening lake salinity and extension oscillations are main goals of this work. Habitat services, including nursery and genetic diversity for birds and other animals, are valuated in 1.7 MM US$/year for the Natural Reserve. Food provisioning services such as cattle pasture, cattle fodder and fish meat (silverside) are in third place of economic importance with 1.5 MM US$/year. For silverside, we consider average CPUE (catch per unit effort) values of 233 kg/day, during a sports fishing period of 90 days/year (Berasain, 2016). Silverside meat is exported and there are silverside hatcheries in, for example, Japan (Berasain, 2016; Colautti et al., 2006).

We show that water requirement of a combined quinoa and *Prosopis* sp. cultivation array during dry periods can be provided by the designed reservoir. Quinoa sales from the 200 cultivated ha could provide 3.6 MM US$/year income considering a 2 t/ha yield at 9000 US$/t. The cultivation of *Prosopis* sp. within 100 ha, as a way to restore native xerophilic forests and services such as water infiltration, gradual release of water, soil retention, food provision, fibre, wood, tourism and recreation. In particular, *Prosopis* sp. fruits can be used to make flour of high nutritional value, as supplements for human consumption and cattle fodder (Pérez et al., 2020; Risio et al., 2016). In 2016, Argentina had a production of 7000 t of wood from *Prosopis caldenia*, *Prosopis alpataco* and *Prosopis flexuosa* (MAyDS, 2016), which shows that in the long-term the proposed woodland could also enhance incomes in the area under study.

4 | CONCLUSIONS

The integrated, transdisciplinary (Hiwasaki & Arico, 2007) ecohydrological and dynamic optimization methodological instruments developed and presented in this work were applied for management planning in a semiarid Pampean basin during dry and wet periods. In particular, for Chasicó Lake these tools dealt with a 6-year phase of water collection from the river into a constructed reservoir during a wet period, and one of water release lasting four years in a dry stage. Realistic approaches and conservative assumptions based on long-term field data, together with the optimization of fluxes management indicate that, within a decadal time frame, flood prevention and drought mitigation would be highly effective. Strong fluctuations of lake size, its hydrochemical properties and living resources would be significantly dampened, increasing system resilience and promoting sustainable socio-economic activities.

The proposed control actions could reduce the economic losses related to floods and droughts in about 95% and 60%, respectively, following estimations of the World Bank (2000) and Taboada et al. (2009). Additionally, the revenues from silverside fishing, quinoa cultivation and forestry would keep stable in the pilot area under study. In both cases, the impact on tourism facilities, village and neighbouring fields would be significantly mitigated, contributing to a substantial reduction of investment uncertainty.

The development of decision-making tools like the proposed ecohydrological model within a dynamic optimization framework can allow the development of realistic, low-cost mitigation policies to address extreme climatic events. This is relevant for a territorial planning enabling a more sustainable social and economic development of highly vulnerable semiarid regions, in determining concrete strategies and their effects in the short, middle and long term.

The present work was envisioned as pilot strategy for a sector of a salt lake basin within a natural reserve during a time span of 10 years. Further research based on the developed model would allow the up-scaling of the proposed measures to the whole Chasicó basin and several similar watersheds. Considering recurrent wet and dry periods of about 25–50 years, a multi-reservoir approach complemented with wetland creation could represent the basis for an enduring policy for mitigation of regional strong climatic oscillations superimposed on global climate change for the Pampean region.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A

Evaporation calculation

Evaporation is calculated using the equation proposed by Penman (1948), as follows:

$$Evap(t) = \frac{10}{\lambda(t)}\left[W(t)\,Rn(t) + (1 - W(t))F_{wind}(t)\,(T_{vap0}(t) - T_{vap}(t))\right] \tag{A1}$$

where W is a weighting factor of the radiation effects on evaporation; Rn is net radiation (Ly day^{-1}), F_{wind} wind effects as available energy to evaporate water (km day^{-1}) and ($T_{vap0} - T_{vap}$) is a vapour saturation deficit; λ corresponds to water latent heat of vaporization.

Each factor calculation is as follows:

$$\lambda(t) = 595 - 0.51\,T_{air}(t) \tag{A2}$$

where λ is latent heat of vaporization (cal g^{-1}) and $T_{air}(t)$ is daily average air temperature (°C)

$$W(t) = \frac{\Delta}{\Delta + \gamma} \tag{A3}$$

Δ is the vapour pressure curve slope and γ is a psychrometric constant (mb °C^{-1}) calculated taking into account temperature and atmospheric pressure monthly averages (P_{atm}), as follows:

$$\gamma = \frac{(Cp\,Patm)}{(0.62198\,\lambda)} \tag{A4}$$

where Cp is dry air specific heat at constant pressure (0.240 kcal kg^{-1} °C^{-1}).

Net radiation, $Rn(t)$(Ly.day^{-1}) is calculated as follows:

$$\mathrm{Rn(t)} = (1 - \alpha)\,\mathrm{R(t)} - \mathrm{Rb(t)} \tag{A5}$$

where α is albedo for salt water (0.06) (Almorox, 2003); $R(t)$ is solar radiation data (global radiation) and $Rb(t)$ is thermal radiation loss, estimated as follows:

$$Rb(t) = Rb_0(t)\left[1.2\left(\frac{R}{R_{S0}}\right)(t) - 0.2\right] \tag{A6}$$

R_{S0} is solar radiation in cloudless days; $Rb_0(t)$ is thermal radiation loss in cloudless days.

$$\mathrm{Rb0}\,(t) = \varepsilon\sigma \mathrm{Tair}^4 \tag{A7}$$

where ε is emissivity value and σ is Stefan–Boltzmann constant (11.71 * 10–8 Ly day^{-1} k^{-4}). ε is estimated as follows:

$$\varepsilon = \left(0.39 - 0.05\sqrt[2]{\mathrm{T_{vap}}}\right) \tag{A8}$$

$$F_{wind}\,(t) = 15.36\,(1 - 0.0062\,\mu_2) \tag{A9}$$

where μ_2 is average monthly wind speed (km day^{-1}) at 2-m elevation.

[T_{vap0}(t) − T_{vap}(t)] is vapour saturation deficit. T_{vap}, vapour tension, is calculated based on relative humidity $Hr(t)$, which is correlated based on daily data (Equation 11). $Tvap0(t)$ is the vapour saturation pressure calculated as (Almorox, 2003)

$$T_{vap0}(t) = 6.107\,\mathrm{Exp}^{(17.27\,T_{air}/237.3 + T_{air})} \tag{A10}$$