Regional Environmental Change (2021) 21: 19
https://doi.org/10.1007/s10113-021-01750-w

ORIGINAL ARTICLE

# Water management or megadrought: what caused the Chilean Aculeo Lake drying?

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Received: 6 June 2020 / Accepted: 7 January 2021 / Published online: 3 February 2021

## Abstract

The Aculeo Lake is an important natural reservoir of Central Chile, which provides valuable ecosystem services. This lake has suffered a rapid shrinkage of the water levels from year 2010 to 2018, and since October 2018, it is completely dry. This natural disaster is concurrent with a number of severe and uninterrupted drought years, along with sustained increases in water consumption associated to land use/land cover (LULC) changes. Severe water shortages and socio-environmental impacts were triggered by these changes, emphasizing the need to understand the causes of the lake desiccation to contribute in the design of future adaptation strategies. Thereby, the Water Evaluation and Planning (WEAP) hydrological model was used as a tool to quantify the water balance in the catchment. The model was run under a combination of three land use/land cover and two different climate scenarios that sample the cases with and without megadrought and with or without changes in land use. According to the results, the main triggering factor of the lake shrinkage is the severe megadrought, with annual rainfall deficits of about 38%, which resulted in amplified reductions in river flows (44%) and aquifer recharges (24%). The results indicate that the relative impact of the climate factor is more than 10 times larger than the impact of the observed LULC changes in the lake balance, highlighting the urgent need for adaptation strategies to deal with the projected drier futures.

**Keywords** Drought · Water budget · Anthropogenic · Attribution · Decision making · Land use/land cover

Communicated by Wolfgang Cramer

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## Introduction

Socio-economic changes and the continuous reductions of rainfall observed in Mediterranean-like climate regions (i.e., Hope et al. 2006; Polade. 2017) may lead to an unsustainable use of surface and subsurface water (Kundu et al. 2017). These areas are particularly prone to droughts, given that their annual water supply for agricultural production, industrial uses, and drinking water depends on few precipitation events mostly concentrated in winter (e.g., Polade et al. 2017; Rockström et al. 2010). As model-based climate simulations consistently project a dryer future in these regions of the world (Giorgi and Lionello 2008; Mariotti et al. 2015; Polade et al. 2014), negative socio-economic impacts and deteriorated livelihood conditions are thus expected (Del Pozo et al. 2019; Iglesias et al. 2011).

This is indeed the case of central Chile, the narrow strip of land between 30° S and 37° S bounded by the Pacific coast and the Andes cordillera. This region is the economic hub of the country, hosting more than 15 million people, and over 75% of the total Chilean irrigated agricultural activity (MOP 2016). Central Chile precipitation exhibits substantial interannual and interdecadal variability, modulated by planetary-scale climate modes (e.g., Garreaud et al. 2009), especially El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Superimposed on these fluctuations, a gradual decrease in precipitation, partly linked to contemporaneous climate change (Boisier et al. 2016, 2019; Vera and Díaz 2015), has emerged in the last 2–3 decades, as revealed in streamflow (Masiokas et al. 2019) and rainfall records (Boisier et al. 2019). The long-term drying has been exacerbated by the so-called central Chile megadrought (MD), an unprecedented dry spell with rainfall deficit of 20–35% since 2010 (Garreaud et al. 2017; Boisier et al. 2016; Garreaud et al. 2020).

Model-based projections of climate in central Chile indicate that the rainfall negative trends will continue during the twenty-first century, with reductions ranging between 5 and 30% under the Representative Concentration Pathways (RCP) 2.6 and 8.5, respectively. This will lead to runoff reductions of about 40% by the end of the century under RCP 8.5 (Barria et al. 2018; Bozkurt et al. 2018). Reductions in supply, along with increases in demand, generate water scarcity conditions and pose challenges to water managers. As the Chilean economy is based on agriculture and mining exports that are highly dependent on water, the economic growth has led to increases in water consumption of about 13% between 1990 and 2015 in the country (Anríquez and Melo 2018). This increase has contributed to the overexploitation of water resources in almost all Central Chilean catchments (Aitken et al. 2016). This water scarcity context has led to significant water stress, triggering socio-environmental conflicts (Bauer 2015; Rivera et al. 2016), particularly affecting the rural drinking water system provision. This challenge has been particularly acute since 2010, when the pressure of the increasing water demand on the water balance has intensified by the MD (MOP 2016; Donoso 2018), evidencing the limitations of the Chilean water management system to adapt and deal with non-stationary hydrology and increases in water demands (Barría et al. 2019b). Indeed, recent estimations indicate that, during the MD, around 200,000 Chilean people living in rural areas have received insufficient water supply, and around 6% of all the rural drinking water systems (APR) had to be supplied by tank trucks (Donoso 2018).

Within this context, the Aculeo Lake, an important touristic hotspot of the Metropolitan Region of Chile (Fig. 1) and sub-basin of the Maipo river catchment (Fig. 1b), has suffered a dramatic shrinkage of its water surface from 2012 to 2018. Since October 2018, this small (~ 12 km$^2$, ~ 58 × 10$^6$ m$^3$) and shallow (~ 10 m deep) water body has been completely dry (Fig. 2a, b, and c). This environmental calamity occurred in concomitance with the central Chile MD, which caused the mean annual runoff, water volumes stored in different reservoirs, and groundwater levels of the region to drop sharply. For example, the water volumes stored in the Peñuelas reservoir, the main source of drinkable water for the city of Valparaíso, and the groundwater level of Asentamiento Las Vertientes well, presented a marked decrease after year 2010 (Fig. 2d and e). Furthermore, the naturalized mean annual runoff for the Maipo basin (Fig. 1b), the major river of the Metropolitan region of Chile, suffered reductions of about 50% between the 2010–2015 and 1985–2009 periods.

Together with the MD, the Aculeo Lake desiccation coincided with an intensification of land use changes in the affluent catchment. This basin formerly characterized by an agricultural and rural tradition, transitioned to monoculture industrial agriculture (especially cherry trees), and deforestation due to urban expansion (Alaniz et al. 2016; Silva 2017). The reductions in surface water availability along with aquifer level depletion propitiated water shortages that triggered a number of social and environmental conflicts (Municipalidad de Paine 2019). Because of this, several public and private local stakeholders got engaged in a Voluntary Basin Management Agreement (VBMA) process, to collaborate toward improving water management, to reduce the vulnerability of the catchment to climate change (Ocampo-Melgar et al. 2021).

Understanding the nature and the causes of this environmental disaster is the key to work on preparedness efforts to confront the current and projected changes in climate. A hydroclimatic modeling process that includes local knowledge and concerns was implemented to accompany the VBMA. In this regard, one of the first and most recurring inquiries in the VBMA process was the cause of the Aculeo Lake drying: Water Consumption or the Megadrought? Although two recent studies (Alaniz et al. 2019; Valdés-Pineda et al. 2020) have pointed at the combination of the

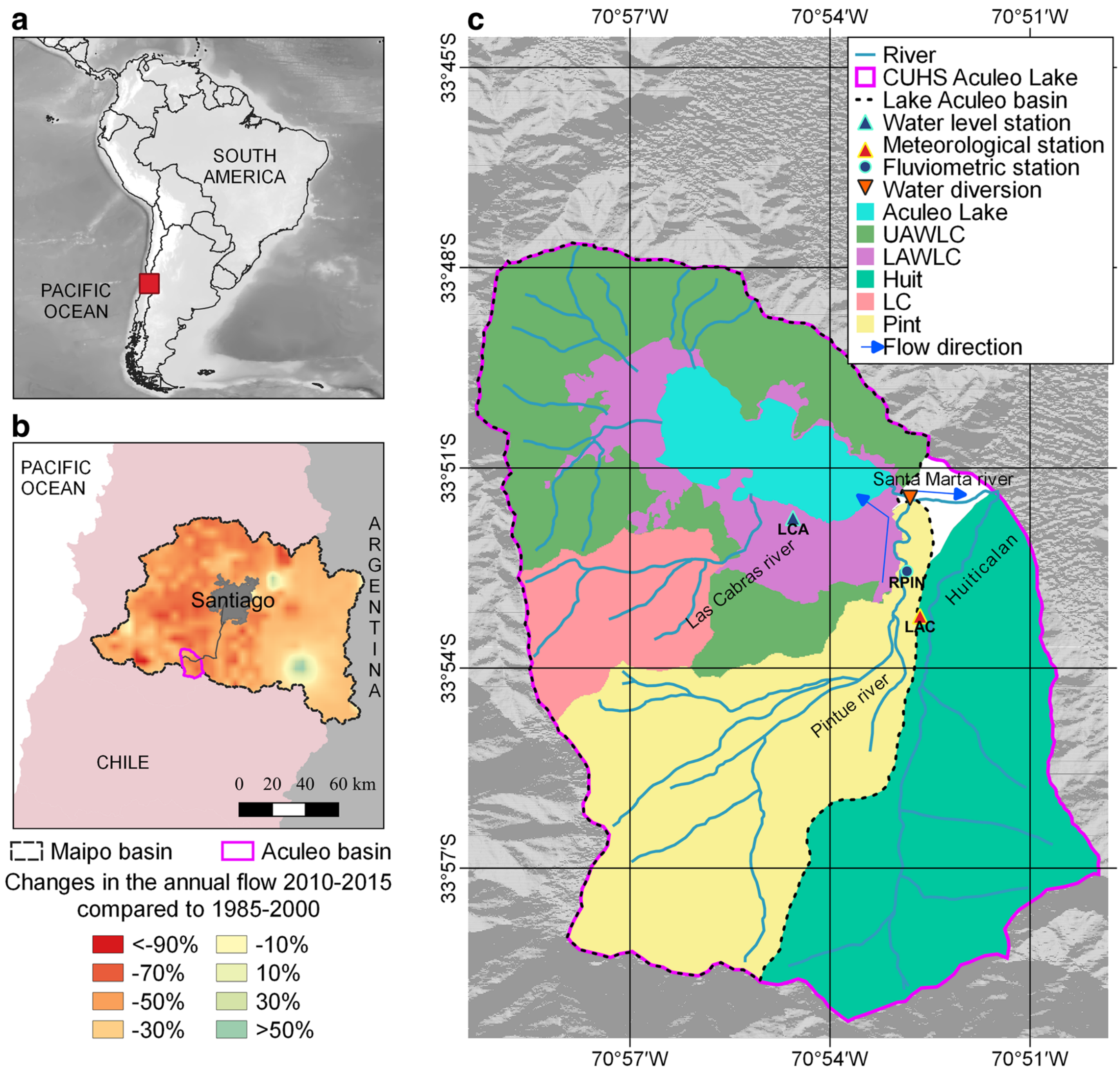

**Fig. 1** Location of the study area. **a** Location of the catchment in South America, **b** recent changes in naturalized annual flows based on the Chilean Water Balance (DGA, 2019), **c** subcatchments considered in the analysis, Upper Aculeo without Las Cabras (UAWLC), Lower Aculeo without Las Cabras (LAWLC), Pintue (Pint), Las Cabras (LC), and Huiticalan (Huit). The blue triangle represents the Los Castaños (LCA) lake water level station, the red triangle is the Aculeo Lake (LAC) meteorological station, and the blue circle is the Pintue river (RPin) fluviometric station

megadrought and increases in water consumption as the causes of the lake desiccation, they have not analyzed the water balance in the catchment, neither tested several scenarios that allows to properly attribute the disaggregated incidence of each of those factors today and toward the future. In particular, Valdés-Pineda et al. (2020), which applied the curve number method, did not consider climate scenarios and the current megadrought, greatly limiting their conclusion. This article aims to fill the gap by thoroughly exploring and understanding the causes of the Aculeo Lake desiccation, through implementing the Water Evaluation and Planning System (WEAP, Yates 2005, b) to estimate the relative impact of the MD versus land uses/land cover (as a proxy for water management) on the catchment water balance.

While the case of Aculeo Lake is important in its own, our analysis fits on a growing social awareness and request for unraveling the factors, natural or anthropogenic, which cause or exacerbate environmental disruptions worldwide. Examples of these events include Lake Urmia depletion, which has been related to either anthropogenic (AghaKouchak et al. 2015; Alizade Govarchin Ghale et al. 2018; Chaudhari et al. 2018; Hassanzadeh et al. 2012; Shadkam et al. 2016; Zeinoddini et al. 2015) or climatic causes (Arkian et al. 2018; Delju et al. 2013; Fathian et al. 2015), or the shallow Lake Mogan in Turkey, where the combination of climate and anthropic changes exacerbated detrimental water quantity and quality conditions (Coppens et al., 2020).

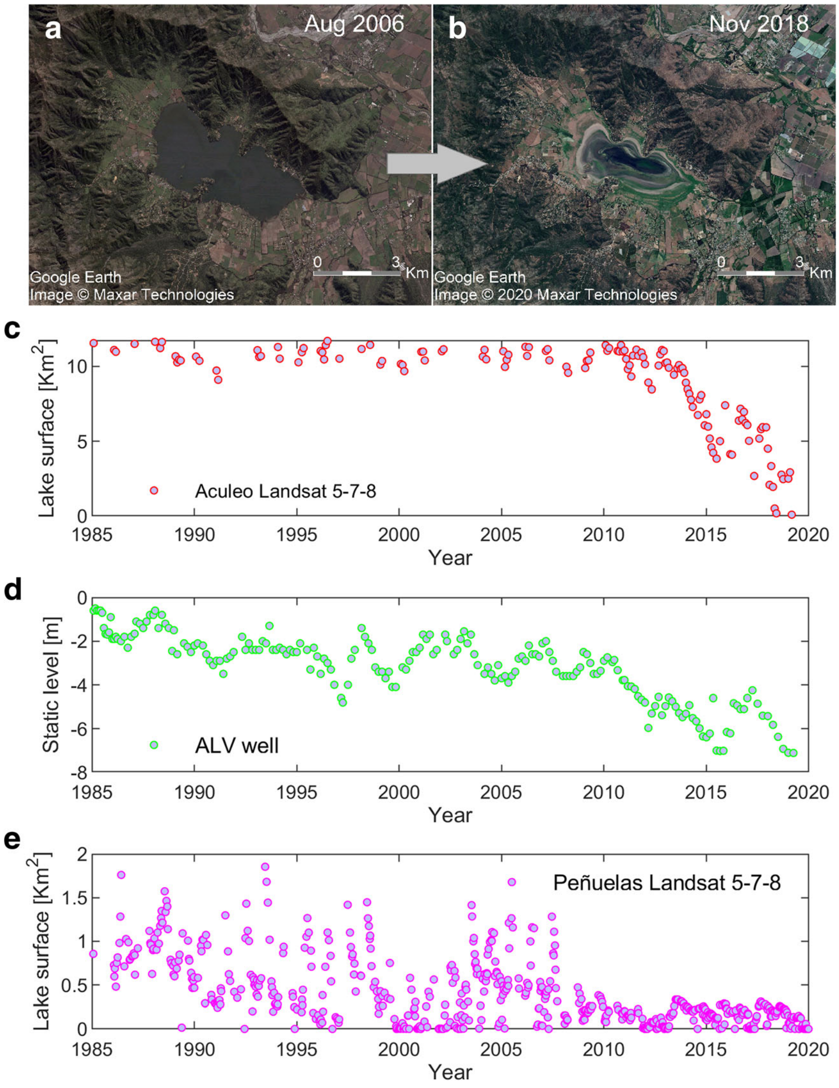

**Fig. 2** Aculeo Lake **a** before (year 2006) and **b** after (year 2018) the complete disappearance of the lake, **c** Surface of Aculeo Lake over the last 34 years estimated from the sensors Landsat 5, 7, and 8 in the Google Earth Engine platform; **d** monthly mean water depth in the Asentamiento Las Vertientes observation well (33° 08′ 49″ S and 71°33′ 18″ W); **e** monthly mean water volume in the Peñuelas reservoir (33° 48′ 33″ S and 70° 48′ 13″ W)

## Study area and datasets

The Aculeo Lake is a 58 × $10^6$ $m^3$ natural freshwater body located in the Metropolitan Region of Chile (Fig. 1b), about 50 Km south of Santiago. It is mainly fed by an endorheic catchment of 149 Km$^2$, highly dependent on the precipitation falling during the rainy season. Although the basin has a natural outlet in the eastern part of the lake (Aculeo river in Fig. 1c), a levee built for agricultural purposes at least 50 years ago prevents the outflow from the lake toward the Aculeo river.

The main tributaries to the Aculeo Lake catchment are the Pintue river and a number of ephemeral creeks that mostly activate during storm events. Due to interannual variability, the catchment annual rainfall ranges between 435 and 850 mm per year (1960–2018), with an orographic enhancement of about 1.5 between the lowest (350 m.a.s.l.) and highest (2.280 m.a.s.l.) parts of the basin (Barría et al. 2019a). The main tributaries and the delimitation of the studied area are based on the Aster Digital Elevation Model (DEM) (Tachikawa et al. 2011); they are presented in Fig. 1c. The study addresses two physical domains (Fig. 1c): the 200 Km$^2$ Common Use Hydrogeological Sector (CUHS) of the Aculeo Lake catchment, delimited by the Chilean Directorate of Water (DGA) for administrative purposes and to grant Water Usage Rights (WUR), and the 149 Km$^2$ Aculeo Lake catchment, which considers the main tributaries to the lake. Six subcatchments or hydrological units (HU) were considered for the water balance (Fig. 1c): Aculeo Lake, Upper Aculeo without Las Cabras (UAWLC), Lower Aculeo without Las Cabras (LAWLC), Pintue (Pint), Las Cabras (LC), and Huiticalan (Huit) subcatchment (not tributary to the lake). The Huiticalan basin was also included in the analysis because the administration of the water resources in the zone considers it to grant water use rights and because there are old agricultural manmade water detours from the Pintue to the Huiticalan rivers.

The hydrogeological characterization of the study area was conducted by a specialized consulting (Bluedot, 2020), which concluded the Lake Aculeo water balance is dominated by the surface fluxes. According to BlueDot (2020), there are two main aquifers in the study area (not shown): (1) the ~ 3.24 × $10^8$ $m^3$ Lake Aculeo Aquifer (connected to the Aculeo Lake) and the (2) 1.3 × $10^8$ $m^3$ Huiticalan Aquifer (connected to the Pintue and Huiticalan basins). Both aquifers present three main hydrogeological units: (a) a shallow colluvial and fluvial sediment units of low permeability, (b) a predominantly silt-sized aquitard of very low permeability, and (c) a confined aquifer compounded by coarse-medium sands characterized by a higher permeability. More information is presented in Table S1.

From a socio-ecological perspective, the local communities of Aculeo Lake basin are characterized by subsistence agriculture and rural tradition, greatly dependent on surface water for cropland irrigation (Valencia 2018). Moreover, this territory is one of the five "hotspots" of Mediterranean ecosystems with substantial biodiversity (CONAMA 2005; Myers et al. 2000). Like most of Central Chile, this region has encountered important land use changes, pressured by the high concentration of the economic activities and growing population (Miranda et al. 2017). Significant losses of the native forest toward shrubland, agriculture, and pasture lands have been reported in this area during the last 40 years (Schulz et al. 2010; Vergara et al. 2013), as these changes have the potential to increase pressure on water balance through increases in demand and reductions in groundwater recharge (Iroumé and Palacios 2013).

To characterize the water balance, the water consumption, and its changes in the Aculeo Lake basin, different hydrometeorological and land use/land cover (LULC) datasets were employed, which are described below.

## Hydrometeorological data

Precipitation and temperature records from the Laguna de Aculeo meteorological station (33.89° S and 71.45° W, 358 m.a.s.l.), administered by the DGA within the Aculeo Lake catchment, were used to characterize the local climate and as a primary input to run the WEAP model, described in sect. "WEAP model". The station (Fig. 3a and b) has monthly temperature and precipitation information since 1960 to date.

Monthly runoff records for the 2003–2009 period of the Pintue river station were used to verify the WEAP model, which indicate a pluvial regime with the maximum runoff of about 1463 l/s (with mean monthly runoff of 425 l/s). Pintue river station was administrated by the DGA and is currently suspended. Because of the short length of runoff records available in the catchment, the water levels recorded at the Laguna Aculeo en los Castaños station (33.88° S and 70.89° W, Fig. 4a) were used to obtain the volumes of accumulated water at the lake (January 2006 and May 2013), which were then used to calibrate the surface-groundwater balance model. The water levels were translated to water volumes using the lake bathymetry presented in Table S3, which shows that the maximum volume of the lake (58 × $10^6$ $m^3$) corresponds to a water level of ~ 6.4 m and a lake surface of ~ 12 $Km^2$. Considering that the largest tributary to the lake (Pintue river) provided around 425 l/s before the year 2012, the time of residence of the lake is lower than 4.5 years, indicating its high vulnerability to changes in the inflows.

## Land use–land cover data

Historical LULC was obtained from 3 years in which good quality Landsat and Google Earth images were available (i.e., 2006, 2012, and 2018). An unsupervised LULC classification of 2006, 2012, and 2018 Landsat mosaics was first conducted, which was suitable to classify categories of large extension such as native forest or shrublands, but not precise enough to classify agricultural and rural plots. Then, photo-interpretations of 2006, 2012, and 2018 Google Earth images were used to improve the classification of smaller agricultural and urban plots, which was afterward compared and corrected using pictures of *in situ* unmanned aerial vehicle (UAV) flights for the year 2018, and information of local interviews for the years 2006, 2012, and 2018.

The categories obtained in the LULC classification, implemented to calculate the water consumption within the WEAP model (sect. "Climate scenarios"), were water bodies (i.e., lake), annual crops (cereals and horticultural plants), grassland, fruit trees (cherry trees, avocados, walnut trees), rural properties, native forest, shrubs, bare soil, and housing.

Because there are no high-resolution Google Earth images prior to 2006 to conduct the photo-interpretation, the LULC classification of that year (2006) was assumed as constant for the previous years. This is a plausible assumption considering that real state and export fruit industries had a notorious increase in the catchment only after the year 2010 (Barría et al. 2019b). As WEAP is a semi-distributed model, a linear interpolation of the LULC classification was calculated and included for each hydrological unit presented in Fig. 1c, for the years between 2006, 2012, and 2018.

## Observed trends and plausible drivers

The environmental implications of the recent collapse of Aculeo Lake are significant, as the water reductions are larger than any previously recorded fluctuation. Paleoclimate records of fossil pollen and sediments indicate that it is very likely that the lake only desiccated during the Holocene (7000–10,000 years ago), when dry and arid conditions prevailed in the region (Jenny et al., 2002). Therefore, it is highly possible that the aquatic biotic assemblage will be permanently disrupted after this event (Alaniz et al. 2019). As

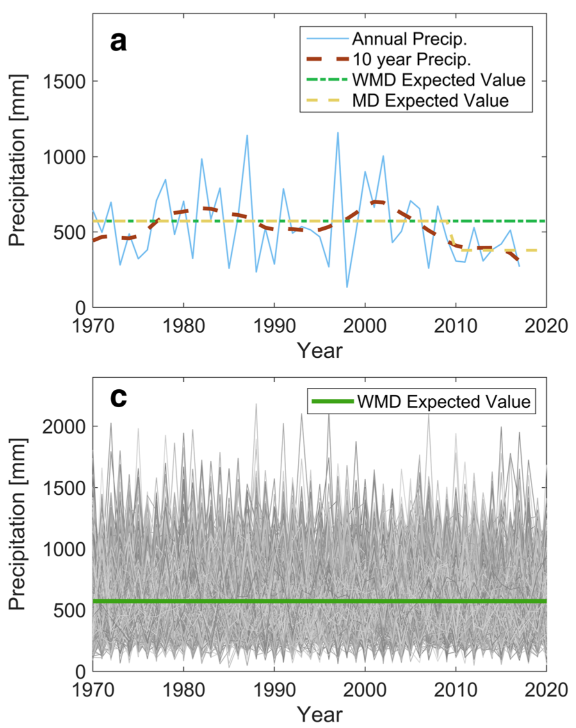

**Fig. 3** **a** Annual precipitation (solid blue line), and the expected values with (dashed yellow line) and without (dotted dashed green line) megadrought; **b** annual temperature (thin blue line) with the linear trend value built for this study (thick red line). The 1000 precipitation time series generated without megadrought (WMD) and with megadrought (MD) are in **c** and **d**, respectively

such dramatic shrinkage was concomitant with the central Chile MD (Garreaud et al. 2017) and substantial changes in land use and water management (Alaniz et al. 2016), these drivers are described below.

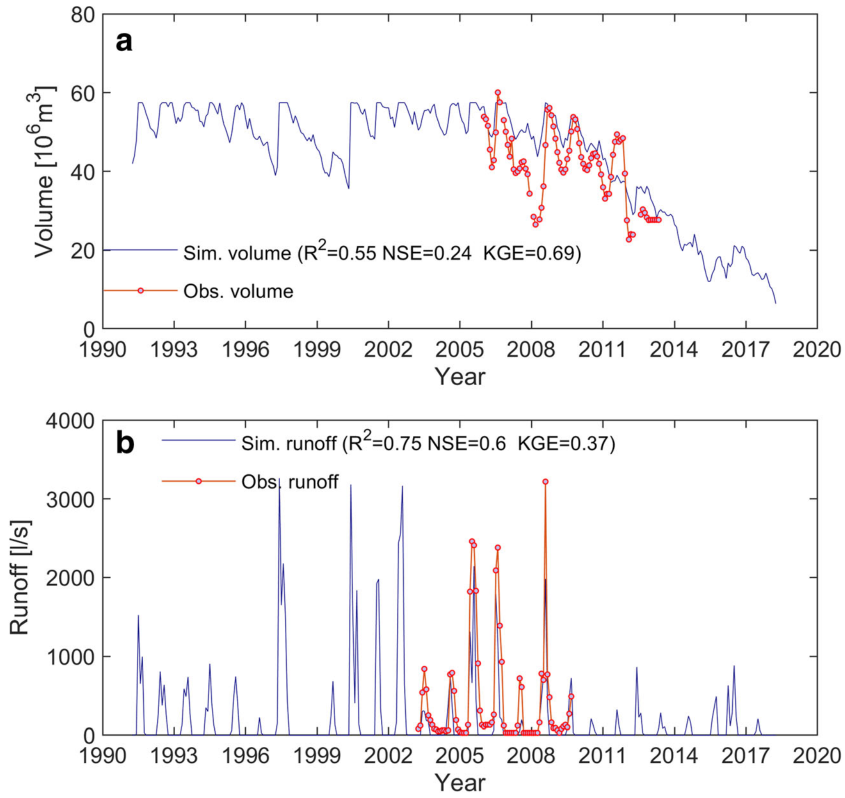

**Fig. 4** **a** Calibration of WEAP model, the blue line is the simulated water lake volumes, and red circles are the observed water volumes. **b** Verification of the WEAP model, blue lines are simulations of monthly runoff at Pintue stream, and red circles correspond to the recorded runoff values

## Climate variability and change

Figure 3a shows the annual precipitation (January–December) in the Laguna de Aculeo station, from where large year-to-year and low-frequency variability (i.e., 10-year spline) is evident. The local effects of the central Chile MD are also noticeable: the annual average rainfall between 1960 and 2009 is 544 mm (long-term mean), but it dropped in the 2010–2018 period to 355 mm, which translates into a precipitation deficit of approximately 38%. This reduction in the multi-year mean is due in part to the absence of very wet years that punctuated previous decades.

The annual temperature records (Fig. 3b) have a significant positive trend (5% level) since the late 70s with increases of about 0.75 °C during the last 48 years (see also Falvey and Garreaud 2009; Vuille et al. 2015), worsening the impacts of the precipitation decreases through evapotranspiration rate enhancement and consequent increases in water demand (Meza et al. 2014).

## Land use–land cover data changes

Following the remote-sensing analyses presented in sect. “Land use–land cover data,” the details of the 2006, 2012, and 2018 LULC classification are presented in Fig. 5a, b, and c, respectively. Although the LULC was disaggregated considering the HRU of Fig. 1c to run the WEAP model, the aggregated values at the catchment scale are presented in Table 1, summarizing the main changes in LULC between 1997–2006 and 2010–2018 periods. Both housing and rural properties have presented a marked increase between the earlier and later periods, disclosing the reported rising urbanization and population growth of this peri-urban sector (Alaniz et al. 2016). Rural properties expanded on ~ 70% within the studied period (when comparing the years 2017–2018 and 1997–1998 in Fig. S1a), mainly associated to decreases in annual crops and shrubland lands. Regarding agricultural land uses, the annual crop surfaces have gradually decreased over time in the catchment from approximately 794 ha in the 1997–2006 period to about 547 ha in the 2010–2018 period (31.1%). On the other hand, fruit trees have increased by approximately 37.9% (54.3 ha) related to the recent plantation of agricultural monocultures. The largest land cover in the catchment is native forest (representing ~ 53% of the total surface of the catchment), which has presented a reduction of about 3% over the analyzed period (difference between years 1997–1998 and 2017–2018). Finally, as the Aculeo Lake was depleted, the 1200 ha of the lake surface were naturally replaced by grassland and bare soil patches.

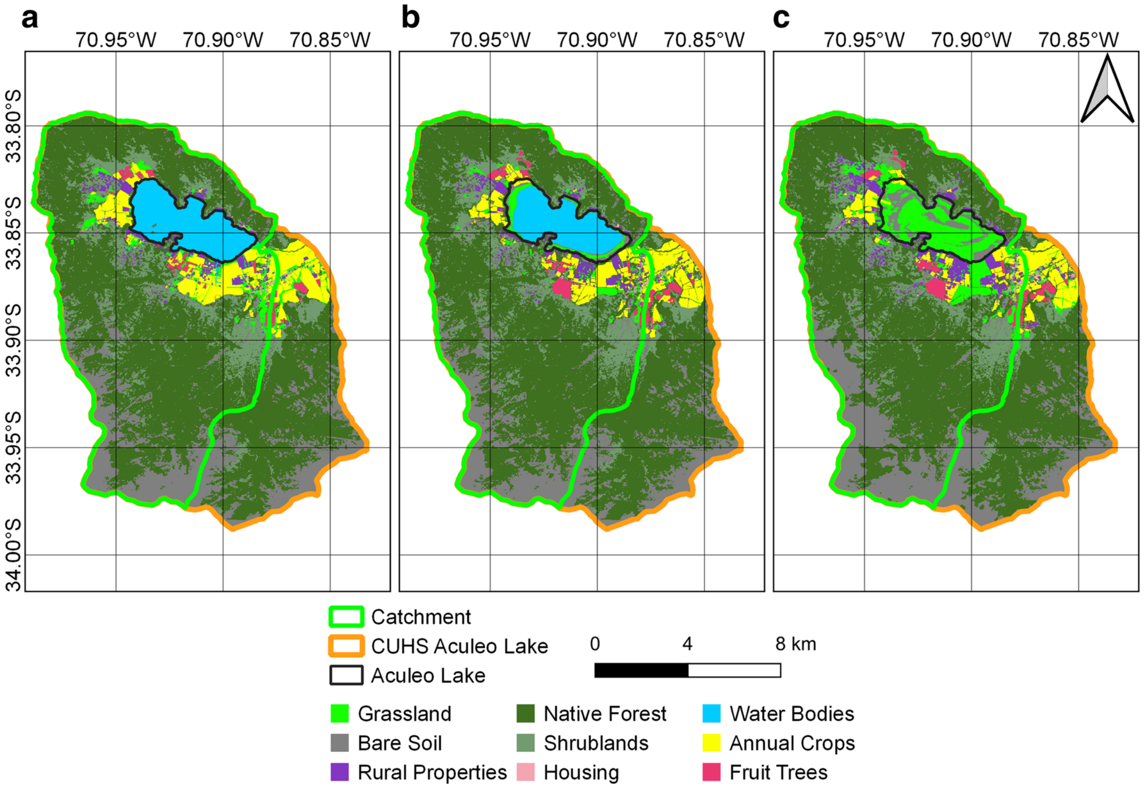

**Fig. 5** Land use/land cover classification of Aculeo Lake catchment in years **a** 2006, **b** 2012, and **c** 2018

**Table 1** Changes in land use and water consumption in the Aculeo basin between 1997–2006 and 2010–2018

| Land use category | Surface between 1997–2006 (ha) | Surface between 2010–2018 (ha) | Water consumption between 1997 and 2006 ($10^6$ $m^3$) | Water consumption between 2010 and 2018 ($10^6$ $m^3$) |
|---|---|---|---|---|
| Annual crops | 794.54 | 547.12 | 11.50 | 10.64 |
| Rural properties | 288.29 | 374.95 | 3.86 | 6.38 |
| Fruit trees | 143.06 | 197.36 | 1.72 | 2.90 |
| Housing | 72.80 | 83.99 | 0.36 | 0.36 |
| Total | 1298.69 | 1203.42 | 17.44 | 20.28 |

## Water balance and attribution methods

### Water evaluation and planning model

The semi-distributed WEAP model was implemented following the structure presented in Fig. S2, to estimate the water balance on a monthly time step at the subcatchment scale (detailed information regarding parameters and structure of the model is presented in Table S2, Text S1). As shown in Fig. S2, the model considers a simplified representation of the aquifer and its fluxes. Following BlueDot (2020) characterization, two aquifers (the Aculeo Lake and Pintue aquifers) were considered in the water balance. They were represented by buckets that collect the deep percolations of the basins. The model incorporates the occurrence of groundwater fluxes between the Aculeo Lake aquifer and the lake, based on their relative levels and hydrogeological characteristics (Table S1 and BlueDot, 2020).

The Aculeo Lake catchment model was forced by the climatic variables and according to the human and ecosystem uses of water in the catchment. The water levels for the period between January 2006 and May 2013 were used to obtain the storage volumes in the lake, which were then used to calibrate the hydrological model. A spin-up period of 21 years (1970–1971 to 1991–1992) was considered to set the initial simulation conditions. The water demanded by crops, fruit trees, and rural properties (one-half to four hectares) was also defined as separate hydrological units and simulated in nodes using historical LULC information (more details are presented in sect. “Estimation of water demand”). Also, household or drinkable water consumption was simulated through a demand node. A reservoir node was created to simulate the input/output fluxes (surface runoff, groundwater flow, evapotranspiration, irrigation extractions, and infiltration) of the Aculeo Lake according to its bathymetry (Table S3 of the “Supplementary Material”).

### Definition of combined land use/land cover and climate scenarios

As the hydrological model responded to a bottom-up raised concern about the water scarcity situation in the Aculeo Lake catchment, a continuous participation of the modeling team in the VBMA discussions, followed up by individual interviews with key actors and field visits allowed to define the scenarios to be evaluated with WEAP. From this, six scenarios were defined to be evaluated in the WEAP water balance model: scenario 1 considers a static LULC based on the classification of year 2006 (before the urban expansion and increases in fruit trees plantations in the catchment) under the observed climate conditions, including the megadrought (MD), while in scenario 2, the model was set up using stationary climate from 2010 onward without megadrought (WMD). Scenario 3 accounts for the current land use in the catchment (i.e., considers the occurrence of the observed urban expansion and increases in fruit tree plantations), under MD conditions, while scenario 4 considers the same LULC pattern but WMD. Two additional scenarios were implemented in order to further assess the importance of water consumption in the catchment. Scenario 5 which will be called “pristine land use” considers a hypothetic LULC in which human activities were eliminated and replaced by patches of native forest and shrubs (based on the same proportion at which these land cover categories exist in the less anthropogenized areas of the catchment) under MD conditions, while scenario 6 considers pristine land use but WMD.

### Climate scenarios

To investigate the impact of the MD in the water balance, stochastic climate time series for the 1970–2020 period were obtained considering two cases: (1) climate under MD conditions (based on the observed climate data until year 2018), and (2) stationary climate (WMD), based in historical climate before the MD occurrence (before year 2010). To conduct a fair comparison of the climate scenarios, while approximating the uncertainty of rainfall and temperature data, 1000 time series were replicated for both cases. To evaluate the sensibility of the attribution analysis to the stochastic generation of data assumptions, two cases were analyzed: (a) stochastic generation data considering a stepwise change in precipitation for the MD period and (b) stochastic generation of data considering historical interdecadal climate variability in the catchment, which produces a smoother change in precipitation (Text S2 and Fig. S3). To assess the MD occurrence for the case (a), using hydrological years from 1970–1971 to 2017–2018, the precipitation time series were divided into two periods, before the MD (1970–1971 to 2009–2010) and during the MD period (2010–2011 to 2017–2018). Then, the mean ($\mu$) and standard deviation ($\sigma$) of each one of these periods were estimated and used to obtain the expected value of precipitation before and during the MD period (Fig. 4a). Finally, to simulate the scenarios with and without MD, 1000 precipitation time series were obtained based on the expected value of precipitation until 2020.

The expected value of temperature was calculated by fitting a linear regression to the observed times series in the period before MD (1970–1971 to 2009–2010) (Fig. 3b). The same expected value of temperature was considered for the two evaluated scenarios.

Climate data was generated around the expected values of precipitation and temperature for the MD (Fig. 3d) and WMD cases (Fig. 3c) considering the standard deviation of the observed data (Text S3). The Chadwick et al. (2018, 2019, 2021) annual climate generator was used to generate stochastic times series of precipitation and temperature, following the equations presented in Text S3 and in Chadwick et al. (2018), which were disaggregated to a monthly scale using the $k$-nearest neighbor ($k$-NN) method of Greene et al. (2012) (Text S3, for more detail about the $k$-NN method the reader is refered to Lall and Sharma 1996; Rajagopalan and Lall 1999). The WMD-generated precipitation time series are presented in Fig. 3c, whereas the MD-generated precipitation times series are in Fig. 3d.

The same procedure was used to obtain stochastic climate data for the MD and WMD scenarios, considering the interdecadal variability of precipitation in the catchment. The results are presented in Text S2 and Fig. S3 in the sect. “Supplementary Material.”

### Estimation of water demand

To calculate the rate of water demand, evapotranspiration was estimated for each LULC category, by multiplying the crop coefficient ($k_c$), to its potential evapotranspiration ($ET_0$). The $ET_0$ was estimated using WEAP model through a modified Penman-Monteith equation, under the rainfall-runoff (soil moisture method) method, using the following relation:

$$ET_c = k_c \cdot ET_0 \tag{1}$$

where $ET_c$ is the potential evapotranspiration of a determined land use category (e.g., cherry trees), estimated at a monthly time step. The $ET_0$ depends on the monthly climate (temperature and precipitation), allowing simulating different evapotranspiration needs of vegetation. Due to the limited literature on crop coefficients ($k_c$) for the native forest, shrubs, and grass of rural properties, the METRIC model (Mapping Evapotranspiration at high Resolution and with Internalized Calibration) was used. METRIC model (Allen et al. 2005) was chosen because of its high spatial resolution (30 m) and temporal range of available data; more information is provided in Text S4. This application uses an algorithm to estimate evapotranspiration ($ET_0$) globally, using an evaporative fraction ($ET_{\mathrm{rf}}$), which is comparable to the crop coefficient ($k_c$). A group of 235 monthly $kc$ scenes were analyzed between 2000 and 2018, which were used to obtain monthly values of $kc$ for each land cover category within the different elevation bands generated by WEAP, later averaged to fit the temporal resolution of the LULC maps presented in Fig. 5, i.e., 2006, 2012, and 2018 (more detail is presented in Text S4).

The calculations of water demanded for irrigation within the WEAP model were based on the monthly variations of soil moisture produced either by precipitation or irrigation losses. Based on an agricultural census conducted as part of the project, irrigation efficiencies of 50%, 85%, and 75% were assumed for the extractions to irrigate annual crops, fruit trees, and rural properties grassland, respectively (Eridanus 2019).

## Results

### Water balance

The WEAP model was calibrated against the observed water levels of the Aculeo Lake and verified against the Pintue river records, using the Nash-Sutcliffe efficiency coefficient NSE (Nash and Sutcliffe 1970), the Kling-Gupta efficiency coefficient KGE (Gupta et al. 2009), and the coefficient of determination ($R^2$) as a performance metric. As presented in Fig. 4a, the simulated lake levels have a good adjustment with the observed levels (correlation coefficient $R^2$ of 0.55, NSE of 0.24, and KGE of 0.69) and represent the decrease of the volumes observed between 2011–2012 and 2017–2018. The model also produces reliable simulations of the monthly runoff at Pintue river ($R^2$=0.75, NSE of 0.6, and KGE of 0.37). As presented in Fig. 4b, the model is better at simulating the low and mean flows while generating an underestimation of the peak flows.

The simulated mean annual runoff for the period between 1991–1992 and 2009–2010 is 255.8 l/s, which had a large decrease to about 64.9 l/s in the 2010–2011 to 2017–2018 period. This is consistent to the results presented by Garreaud et al. (2017), which showed sustained decreases of surface and groundwater flows in Central Chile during the decade, and the simulated reductions of about 43% in mean monthly naturalized runoff of the whole Maipo basin that is shown in Fig 1c. Detailed information of the simulated fluxes on the basin are described in Fig. S4 and Text S5. According to the results (Fig. S4), the mean monthly runoff inflow to the lake decreased from 831.4 to 466 l/s before and after year 2010, which means the time of residence of the lake before the desiccation (2010) was of about 2.2 years. Furthermore, the infiltration (Inf)/water extractions from the aquifer ($W_{ext\_ac}$) decreased/increased after the 2010–2011 year, which translated into a net recharge from about ~ − 9 l/s between 1991–1992 and 2009–2010 period, to an average of − 143 l/s after the year 2010–2011 (Fig. S4b). The negative net recharge is concordant with the hydrogeological characterization study (Bluedot 2020) showing aquifer level reductions. Finally, as indicated in Fig. S4, the net evapotranspiration from the lake (NetET) increased from 187.2 to about 227.8 l/s after year 2010–2011 following the observed increase in air temperature (Fig. 3b).

The verifications of the WEAP model allowed to identify that the main inflows to the Aculeo Lake are the surface fluxes (i.e., being 60 times larger than the groundwater fluxes), and that it is very likely the interaction between the aquifer and the lake occurred at low rates. These results are in accordance with BlueDot (2020), which indicates that the surface fluxes dominate the influxes to the lake water balance.

## Water demand based on land use/land cover

The irrigation withdrawals (extractions of water) in the catchment were obtained through calculation of the evapotranspiration requirements of vegetation using the WEAP model and the observed LULC (sect. "LULC changes"). Results show that water extractions in the catchment during the 1997–1998 and 2017–2018 periods have been on an average $18.8 \times 10^6$ $m^3$/year, equivalent to a flux of approximately 600 l/s. An increase of about 16.3% has been observed in the basin-wide extractions between 1997–2006 and 2010–2018, but changes in extractions from different LULC vary widely (Table 1). The water extractions associated to annual crop irrigation have continuously decreased ($-0.86 \times 10^6$ $m^3$ between 1997–2006 and 2010–2018 periods), while extractions associated to fruit trees have increased ($1.18 \times 10^6$ $m^3$ between 1997–2006 and 2010–2018 periods). The largest increase corresponds to rural properties, which has gone from representing 22.2 to the 31.5% of the total extractions from the 1997–2006 to the 2010–2018 periods. As shown in Fig. S1a and S1b and in Table 1, despite the reductions in the productive land uses in the Aculeo basin, the water extractions have increased in time, related to the combined effect of higher temperatures, reduced precipitation, and highly consumptive land uses (fruit trees and rural properties).

## Evaluation of climate and land-water management scenarios

The simulations of the volume in the Aculeo Lake for scenarios 1 to 6 (sect. "Definition of combined LULC and climate scenarios") are presented in Fig. 6. As the climate scenarios considered in this analysis used 1000 stochastic climate time series, the results are presented considering different "exceedance probabilities" (10%, 50%, and 90% percentiles). The solid line corresponds to the 10th percentile (90% exceedance probability volume); the 50th percentile (50% exceedance probability) volume is presented in dashed line and the 90th percentile (10% exceedance probability) volume in dotted line. All the scenarios that considered the occurrence of the MD (1-3-5) produce continuous reductions of the Aculeo Lake levels (Fig. 6b, e, and h). In particular, the series of simulated volumes P50% indicate that, even considering no changes in the land use since 2006, it is very likely that the lake would still have dried up (volume less than $5 \times 10^6$ $m^3$ by 2018). The continuity and intensity of the MD also result in a significant reduction of the lake volume even when considering a pristine land use (scenario 5), although in that case, the P50% simulated volumes only reduced to $25 \times 10^6$ $m^3$ by 2018.

By the contrary, none of the simulations without the MD (scenarios 2-4-6: Fig. 6c, f, and i) produces a desiccation of the lake, prescribing the LULC of 2006 (scenario 2, before the urban expansion and increases in fruit trees plantations) or the historical LULC (scenario 4) results in a very similar lake response with a slight decrease in volume under all the exceedance probabilities evaluated. As expected, the simulations under pristine LULC and no MD produce a stable lake volume. The inescapable inference is that LULC changes are not a determinant factor in the Aculeo Lake shrinkage. On the other hand, the analyses of the pristine land use scenarios (scenarios 5 and 6: Fig. 6h and i) showed that, even without human extractions, it is very likely that the Aculeo Lake would have had an important lowering of the water levels (descent of 60% by year 2019) under MD conditions, but without a complete disappearance of the lake, as has happened in current condition. However, the 90% exceedance probability (10th percentile) volume of scenario 5 simulates the complete shrinkage of the lake.

The water lake simulations under the six scenarios defined before, but considering the stochastic generation of climate based on the interdecadal variability of rainfall (i.e., smoother change in precipitation, instead of the stepwise change) in the catchment (Text S6, Table S4, and Fig. S5 of the "Supplementary Material"), confirm the results presented in Fig. 6, regarding the key role of the MD in the shrinkage of Aculeo Lake during the last decade. The LULC changes have merely exacerbated the impact of the rainfall decrease, but—by themselves—they fail to produce a substantial change in the lake volume. Also, it is interesting to note that the historical LULC configuration (scenarios 3 and 4) produces a higher percentage of simulations with storage volumes above the lake's 50% of its capacity than the scenarios without changes in LULC since 2006 (scenarios 1 and 2) (Table S5). This might be related to the observed crop reductions in the basin, represented in scenarios 3 and 4, which were

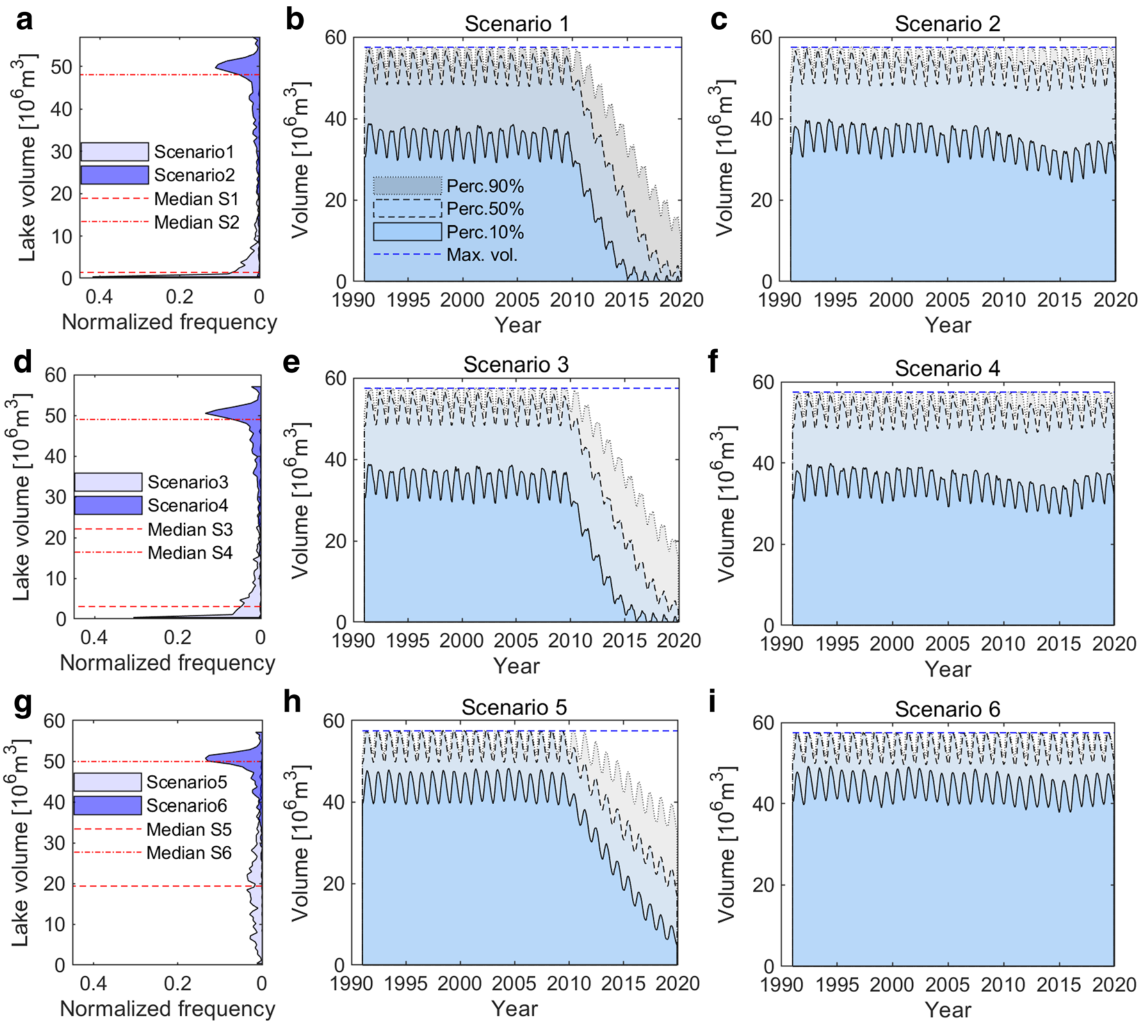

**Fig. 6** Distribution of Aculeo Lake volume simulations on December 2018: **a** land use/land cover (LULC) of year 2006, under megadrought (MD) (S1) and without megadrought (WMD) (S2) climates; **d** historical (changing) LULC, under MD (S3) and WMD (S4) climates; and **g** pristine LULC, under MD (S5) and WMD (S6) climates. The results of scenarios evaluated at WEAP balance model for: **b** scenario 1, MD and LULC of year 2006; **c** scenario 2, WMD and LULC of year 2006; **e** scenario 3, MD and historical (changing) LULC; **f** scenario 4, WMD and historical (changing) LULC; **h** scenario 5, MD and pristine LULC; **i** scenario 6, WMD and pristine LULC

mostly replaced by fruit trees that have greater irrigation efficiencies.

To further appreciate the impact of the climate and LULC, the distributions of the simulated lake water volumes under the six scenarios (1000 runs in each case) for December 2018 are presented in Fig. 6a, d, and g. The water lake levels presented in Fig. 6a and b show a clear difference between the distributions considering the different climate configurations, being the simulations under MD concentrated around a complete depletion of the lake (about $0 \times 10^6$ $m^3$ lake water volume). In the case of the pristine land use (Fig. 6g), despite the MD scenario that does not have a peak around $0 \times 10^6$ $m^3$, its median has a noticeable difference compared with the WMD scenario.

Finally, the proportion of simulations that show the Aculeo Lake that has more than 50% of its water capacity during the 2012–2019 period is presented in Table S5. According to these results, when comparing scenarios 1 and 3 (both with MD), there is only 4.5% of difference between the scenario that consider stationary and variable LULC. When comparing scenarios 2 and 4 (both WMD), there is a 0.9% difference just due to the possible LULC changes. However, the difference between scenarios 1–2 and scenarios 3–4 are 87.8% and 84.2%, respectively, thus clearly showing that the relative importance of the climate is larger than the LULC changes in the reductions of water levels of the lake. Overall, by comparing the changes between different scenarios (1, 2, 3, and 4), the climate WMD and MD have an impact that is more than 10 times greater than the different LULC configurations analyzed.

## Conclusions and discussion

The Aculeo Lake in central Chile started a rapid and dramatic shrinkage in 2012, and since 2018, it has been completely dry.

That dramatic desiccation caused substantial environmental and socio-economic damages (Alaniz et al. 2019; Barria et al. 2019a). This 58 × $10^6$ $m^3$ surface water body is fed by an endorheic basin of 149 $Km^2$ and is connected to a confined aquifer through an aquitard of low permeability. Therefore, the water balance is dominated by surface fluxes that are 60 times larger than groundwater flows. The low storage capacity of the lake and its short time of residence (2.2 years) shows the vulnerability of the Aculeo Lake to climate and land uses changes. Reductions of rainfall of about 38% were observed during the last decade (2010–2018) relative to the historical average, in connection with the central Chile megadrought (Garreaud et al. 2017). In addition, basin-wide water consumption has increased by approximately 16.5% since the 1990s, leading to a water imbalance. Agriculture is the main consumer of water in the catchment (71%), but despite the increase in fruit tree coverage (increase of approximately 62.4 ha between 1991–1992 and 2018–2019), the decreases in annual crop surfaces (decrease of approximately 368 ha between 1991–1992 and 2018–2019) have resulted in rather stable agricultural water demands over time. A raise of private rural properties of approximately 210 ha between 1997–1998 and 2017–2018 was detected, which might be partly responsible of increases in water consumption within the basin.

Using 1000 WEAP runs in each of the six prescribed climate-LULC scenarios allowed us to determine that, for the Aculeo Lake desiccation, the relative impact of the MD was more than 10 times larger than the LULC changes. According to the scenario analysis explored in the study, without the MD event, the lake would not have dried up. The results indicated that when considering the LULC of 2006, without changes in time (without urban expansion and export fruit growth), it is very likely that the impact of the megadrought would have dried up the lake. On the other hand, considering the results of the pristine LULC scenarios (without human consumption), the lake would have lost two-thirds of its total volume under the occurrence of the MD. Most likely, the Aculeo Lake without human intervention would not have completely dried up. This indicates that water resource management measures, such as control of extractions, the proration of extractions, and increases in supply, may have prevented or diminished the reduction of the Aculeo Lake levels.

At the regional scale, the impact of the recent MD on Central Chilean water resources has also been discussed by Garreaud et al. (2017) and Valdés-Pineda et al. (2020). As presented in Fig. 2, similar drying patterns have been observed during the last decade in other Central Chile surface and groundwater water bodies, where the storage volumes are low and thus very dependent on the recharge sources. This emphasizes the relevance of monitoring and attribution studies, especially on endorheic basins of low residence time, which are particularly vulnerable to changes in the inputs flows such as the Lake Chad in the Sahel belt (Bouchez et al. 2019; Bouchez et al. 2016; Pham-Duc et al. 2020).

These results, however, cannot be directly extended to other catchments in central Chile or elsewhere, as the LULC distribution of the Aculeo basin is quite particular (around a 53% of the total surface of the basin is covered by native forest, and around a 64% correspond to the sum of shrubland and native forest, which greatly influence the hydrology of the catchment and do not have irrigation requirements). For instance, analyses of the combined impacts of land use changes and climate in three pluvial catchments characterized by important forest and agricultural land use (Vez from Portugal, Poyang Lake from China and Mara River from Kenya) showed that further increases of agricultural land use had a larger impact on water scarcity compared with climate change in the Mara river catchment (Mango et al. 2010), whereas in the Vez catchment, land use and climate had a comparable impact on the annual runoff discharges (Carvalho-Santos et al. 2016), and climate impact is dominant in comparison with the land use changes in the Poyang Lake catchment (Guo et al. 2008). This highlights the importance of developing attribution studies applying quantification frameworks such as the one presented in this article. In particular, the quantification and analysis of the relative impacts of the anthropic (LULC) and climate factors on the water balance are fundamental for the design and implementation of water management plans at the watershed scale (Carvalho-Santos et al. 2016).

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10113-021-01750-w.

**Acknowledgments** We especially thank BlueDot Consulting for providing the hydrogeological information to feed the WEAP model. We are grateful to the stakeholders who attended the meetings and provided valuable feedback and to all the community and public services that engaged in the VBMA process. Data are publicly available from the Dirección General de Aguas, Chile (http://snia.dga.cl/BNAConsultas/reportes). We finally thank the referees for their constructive suggestions.

**Funding** This research was supported by the Regional Government of Santiago, project FIC-RM 2017 Code BIP 40002646-0. This work was also supported by the FONDECYT Initiation Grant 11200854.

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