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The 2010–2020 'megadrought' drives reduction in lake surface area in the Andes of central Chile (32º - 36ºS)

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A R T I C L E I N F O

Keywords:
Megadrought
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Andes of central Chile
Freshwater availability
NDWI

A B S T R A C T

Study region: Andes central Chile (32ºS-36ºS) / Lakes
Study focus: Mountain lakes play a key role in the terrestrial freshwater reservoir, both for storage of snow melt and precipitation. Although lakes are sensitive to climate variability, the effect of global warming on water availability remains uncertain. Semiarid regions are especially sensitive to relatively small changes in temperature and precipitation as these have disproportionately large impacts on lake hydrologic budgets. Here, we mapped 12 lakes from the Andes of central Chile (32º-36ºS) using Landsat mission and Sentinel-2 satellites images from 1984 to 2020 and compared these results with the available climate data (precipitation, temperature, and evaporation).
New hydrological insights for the region: This approach provides a high-resolution temporal and spatial analysis for changes in lake surface over the last 36 years. Our results indicate that the number of lakes and respective surface area decrease latitudinally from south to north across central Chile, which is consistent the present-day rainfall gradient. Over the study period, lake surface areas decreased significantly between 7% and 25% during the so-called 'megadrought' (2010–2020). As lakes continue to dry up, the implications for freshwater availability are of considerable societal and environmental importance. Our results can assist with water management decisions and improve our understanding of future water availability across the region.

1. Introduction

Climate change has intensified the Earth's hydrologic cycle, which has negative consequences on freshwater availability (Frederick and Major, 1997; Abbaspour et al., 2012; Prein and Pendergrass, 2019). Effects include reduced water resource availability, intensified floods, and prolonged droughts (Garreaud et al., 2017; Prein and Pendergrass, 2019; Muñoz et al., 2020). Depending on duration and intensity, droughts can lead to substantial decreases in soil moisture (e.g., Zhao and Dai, 2015), lakes (e.g., Barría et al., 2021), rivers

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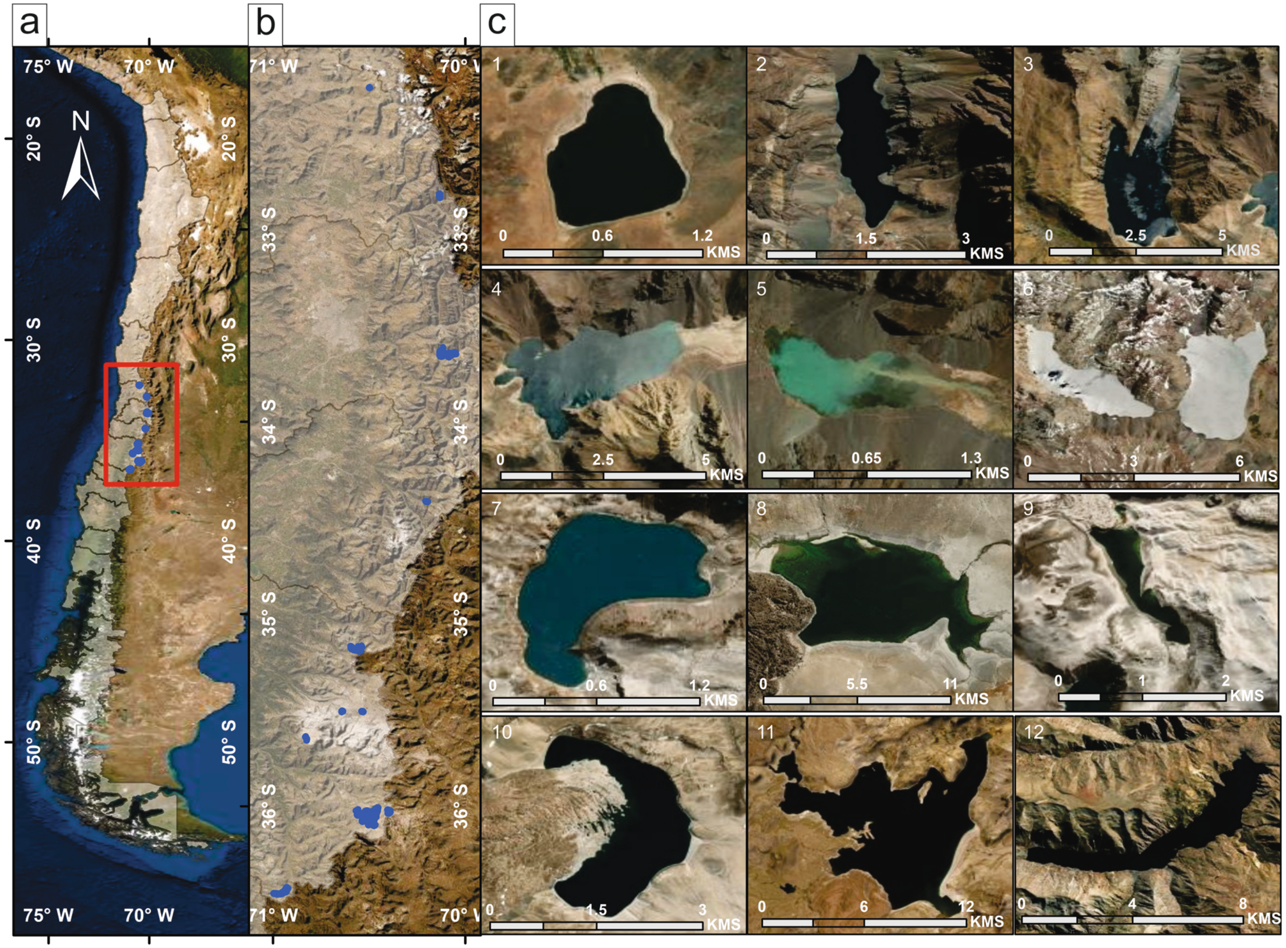

Fig. 1. a. Map showing overall location of lakes in the Andes of central Chile (32–36°S). b. The distribution of lakes with a surface area greater than 0.5 km^2. c. The lakes from left to right: 1. Chepical, 2. Laguna del Inca, 3. Laguna Negra, 4. Embalse El Yeso, 5. Yeso, 6. Teno, 7. Mollera, 8. Aguas Calientes, 9. Caracol, 10. Cari Launa, 11. Laguna del Maule, and 12. Dial.

(e.g., Udall and Overpeck, 2017), and groundwater (e.g., Van Dijk et al., 2013) with important social impacts (Garreaud et al., 2017; Barría et al., 2021). For example, in the Mediterranean region, water availability is expected to decrease between 9% and 17% if temperatures increase to 1.5 and 2ºC, respectively (Schleussner et al., 2016). Water is essential for life and the maintenance of ecosystems and improving our knowledge regarding how water reservoirs are impacted by ongoing climate change is crucial for water management decisions as well as mitigation.

Lakes are important reservoirs of global freshwater and can reduce the impact of droughts through water retention during wet periods (Wanders et al., 2015). However, lakes have experienced significant changes over the last few decades due to the synergic effects of climate change and human pressures (Gao, 2015; Venegas-Quiñones et al., 2020; Fuentealba et al., 2020). Many questions arise regarding water mass balance. For example, although many mountain lakes are currently increasing due to glacier mass loss owing to rising temperatures (Shugar et al., 2020; Fuso, 2021), their permanence is uncertain as glaciers will eventually disappear in the next decades. In addition, the lack of lake surveys and monitoring, particularly in remote areas (e.g., the Andes of central Chile), creates additional challenges for assessing how global change effects freshwater availability and forecasting (Gao, 2015). This lack of knowledge regarding these lakes is compounded not only by climate change but also by the lack of management and mitigation measures under current climate scenarios. Precisely, several lakes in low-lying basins of central Chile (Aculeo and Matanzas) dried up very recently in the last decade because of decreasing rainfall and inefficient water use (Fuentealba et al., 2020; Venegas-Quiñones et al., 2020; Barría et al., 2021).

To address these issues regarding remote lakes in the Andes of central Chile, satellite image analyses can provide useful tools. The advantage of this technique is the possibility of addressing wide spatial gradients (e.g., from global to local scales and across different geographies) spanning several decades at a low cost without instrumental records (Shugar et al., 2020). Satellite image analysis has been used to estimate changes in physical and biological properties on terrestrial and aquatic ecosystems (Crisman et al., 2014; Arsen et al., 2014; Yao et al., 2019). Numerous studies based on satellite images have established the changes in lake water dynamics, volume (e.g., Lu et al., 2013; Baup et al., 2014), morphometry (e.g., Ovakoglou et al., 2016), and surface area (e.g., Gao, 2015; Yao et al., 2019). In addition, Crisman et al. (2014) documented the expansion of exotic aquatic vegetation (i.e., *Phragmites australis*) in a shallow lake, Lake Koronia (Greece), which was under a progressive drop in water level from 1980 to 2001.

Long-term time series are required to detect significant trends in the water bodies. However, data availability of interannual and seasonal variations of lakes is very limited (Gao, 2015). Landsat satellite images allow mapping water surface bodies throughout the Normalized Difference Water Index (NDWI). This index was developed by McFeeters (1996) to delineate lake boundaries using reflective near-infrared radiation and visible green light (Özelkan, 2020). Although the spatial resolution can oscillate between 15 and 30 m, only since the 1990 s can the highest resolutions be achieved (Martínez Mena, 2017; Özelkan, 2020). Thus, a tradeoff exists between increased resolution versus temporal coverage, and it is often preferable to work with a lower resolution of 30 m across a longer time-series. Decreased resolution, however, means that only larger lakes can be properly analyzed regarding changes in the lake surface area. Here, we present an interannual reconstruction of lake surface areas using Landsat satellite images (Landsat 5, 7, 8) and Sentinel 2 to determine the effect of climate change on high Andean lakes freshwater availability from central Chile (32ºS - 36ºS) over the last 36 years. Our goals were to establish how these lake surfaces varied between 1984 and 2020 and to compare these changes with the available climate data (precipitation, temperature, and evaporation) to assess different causes for these variations. For this, we used the NDWI to map surface water of 12 lakes which were chosen for their size (surface > 0.5 km^2).

2. Study site

The Andes of central Chile (32ºS - 36ºS; Fig. 1) are characterized by a mediterranean climate, with cold-wet winters and hot-dry summers (Sarricolea et al., 2017; Shaw et al., 2021). Annual precipitation (in the 1984–2020 period 1984–2020) increases southwards from ~256 mm (32ºS) to ~790 mm (36ºS) (data accessed through TerraClimate– http://www.climatologylab.org/terraclimate.html-, last access 06/07/2021). Mean annual temperature estimated for the same period oscillates about ~3ºC (data accessed TerraClimate, last access 06/07/2021). During the last decade (2010–2020) the region between 32ºS and 37ºS has experienced a so-called

Table 1
Summary of the lakes chosen for this study with an area greater than 0.5 km^2.

Id	Lakes names	Location		Altitude (m a.s.l.)	Surface (km^2)	Depth (m)
1	Chepical[a]	32° 15.549' S	70° 29.921' W	3043	0.508	12.9
2	Laguna del Inca	32° 49.250' S	70° 8.015' W	2856	1.523	73.3
3	Laguna Negra[a]	33° 38.509' S	70° 7.466' W	2708	5.427	9.9
4	Embalse El Yeso[a]	33° 38.819' S	70° 4.416' W	2570	6.01	50
5	Yeso	34° 24.881' S	70° 11.873' W	2153	0.513	N/A
6	Teno	35° 10.858' S	70° 33.709' W	2550	7.985	60
7	Mollera	35° 30.283' S	70° 38.510' W	2687	0.501	N/A
8	Aguas Calientes	35° 30.376' S	70° 32.141' W	2565	0.696	N/A
9	Caracol	35° 38.787' S	70° 49.675' W	2027	0.939	N/A
10	Cari Launa	36° 1.722' S	70° 23.743' W	2707	2.214	N/A
11	Laguna del Maule[a]	36° 3.410' S	70° 29.901' W	2163	46.7	50
12	Dial	36° 26.742' S	70° 57.076' W	1607	6.997	N/A

N/A Not Available.
[a] Artificially dammed lakes.

'megadrought', observed by an increase of up to ~0.8 °C in mean annual air temperature and a reduction of up to 40% in annual precipitation (Garreaud et al., 2017; Serrano-Notivoli et al., 2021; Shaw et al., 2021). This episode seems to anticipate future conditions in this region, and meanwhile, projections do not show any significant recovery in the following decades (Muñoz et al., 2020). Moreover, a significant part of this so-called 'megadrought' shows anthropological attributions (Boisier et al., 2016).

Twelve lakes were chosen from the Andes of central Chile for this study (Table 1, Fig. 1). These have a surface greater than 0,5 km^2 and are located at elevations from 1600 m a.s.l. (Dial) to 3000 m a.s.l. (Chepical). Chepical Lake (3043 m.a.s.l.) is a high Andean, oligotrophic endorheic cold-monomictic freshwater lake dammed in 1885 (Martel-Cea et al., 2016). Its effluent is the Alicahue River that is in the upper basin of the La Ligua River (Valparaíso) and whose main supply is rain-snow. The main use of its water is for agriculture from Alicahue village. Laguna del Inca (2856 m.a.s.l.) is a natural lake and a tourist attraction located in the upper Aconcagua River basin (Valparaíso). Its regime is rain-snow, and its outlet is the Juncalillo River. Laguna Negra (2708 m.a.s.l.) is a glacial lake located in the upper basin of the Maipo River in San José de Maipo. Its regime is snow-river, and its main use is water storage (Dionizis Rojo, 2018). Near Laguna Negra is Embalse el Yeso (2570 m.a.s.l), an artificial reservoir that was built in 1964 to ensure the supply of drinking water to the Metropolitan Region of Chile. Its feeding regimes are snow-melting and input from the Yeso River (Dionizis Rojo, 2018). Laguna El Yeso (2153 m.a.s.l.) is in Machalí (O'Higgins) and its main tributary is the Río de las Leñas. Laguna el Teno (2359 m.a.s.l.) is a currently dammed, natural lake, located in the Mataquito River basin, in Romeral, Chile. Its regimen is snowy-rainy and its waters feed into the Malo River. Lagunas Aguas Calientes (2565 m.a.s.l.; San Clemente) and Lago de la Mollera (2686 m.a.s.l.; Molina) are in the upper part of the Maule River basin, in the Maule Region and their regime is snowy. Laguna Caracol (2027 m.a.s.l.) is in the Maule River basin (San Clemente) and its regimen is snowy. Laguna El Maule (2163 m.a.s.l.) is another natural lake dammed in 1947 and used as a water reservoir for irrigation and hydroelectric power generation (Carrevedo et al., 2015). Its regime is mixed, but the winter snow and rain contributions are the most important. Cari Launa Lake (2707 m.a.s.l.) is a slightly smaller lake (2.2 km^2) located 10 km from Laguna El Maule. Paleoclimatic reconstructions have been obtained from two of the twelve chosen lakes. Changes in moisture and ice cover for the last 3100 years at L. Chepical suggest drier conditions than today (and so, less lake level) around 1545 CE and 1670 CE (Martel-Cea et al., 2016). In a similar fashion, L. Maule shows lower lake levels during the Middle Holocene (~ 8.0–6.0 ka BP) coeval with a warm-dry phase described for much of southern South America (Frugone-Álvarez et al., 2020).

3. Methodology

We first surveyed all available lakes in the Andes of central Chile (32ºS-36ºS) using a public database available from the Dirección General de Aguas (DGA- Ministry of Public Works, Republic of Chile; data accessed through http://www.dga.cl/estudiospublicaciones/mapoteca/Inventarios/catastro_de_lagos.zip last modified on 5th September 2019). We then selected 12 lakes that had a surface area higher than 0.5 km^2. This minimum surface area is key to achieve a more precise representation of the lakes for each year, which needs to take into account that minimum pixel size from Landsat satellite images is 30 m (Table 2). The satellite image data used in this study were downloaded using Google Earth Engine (GEE), a public data catalog with a multi-petabyte curated collection of geospatial datasets (Gorelick et al., 2017). The bulk of the catalog is made up of Earth-observing remote sensing imagery, including the entire Landsat archive as well as the Sentinel-2 archive. A total of 36 Landsat images covered the 12 selected lakes for the period 1984–2020 (Table 2) were analyzed. All images were taken during the dry season (January to March) to improve image quality in the absence of cloud cover.

All Landsat and Sentinel images were processed using Google Earth Engine, which delivers geometrically, radiometrically and atmospherically corrected images. The Normalized-Difference Water Index (NDWI) proposed by McFeeters (1996) was used to obtain the surface from selected lakes. The index has the advantage of eliminating the presence of soil and terrestrial vegetation features present in the images (Yang et al., 2015). The index calculates the difference between two image bands and applies a threshold to segment the results into two categories (water and non-water features) to identify the lakes, and is expressed as follows:

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \tag{1}$$

The green band maximizes the reflectance of the water body while the NIR band, the near infrared, minimizes the rest of the vegetation and soil cover (Yang et al., 2017). The NDWI was calculated in Google Earth Engine (GEE) and reclassified in ArcMap 10.3 using an index of 0–1 (Water) and − 1–0 (other covers).

The climate dataset was obtained from the TerraClimate repository hosted by the University of Idaho's Northwest Knowledge Network (Abatzoglou et al., 2018; Supplementary Table 1) and include annual precipitation amount, mean annual temperature, and evapotranspiration (PET). This climate dataset is updated periodically as additional years become available, and we considered data

Table 2
Detail of satellite images used in this study.

Satellites	Sensor	Resolution	Band Combination
Landsat 5	TM (Thematic Mapper)	30 M	321
Landsat 7	ETM (Enhanced Thematic Mapper)	30 M	321
Landsat 8	OLI (Operational Land Imager)	30 M	432
Sentinel 2	MSI (MultiSpectral Instrument)	10 M	432

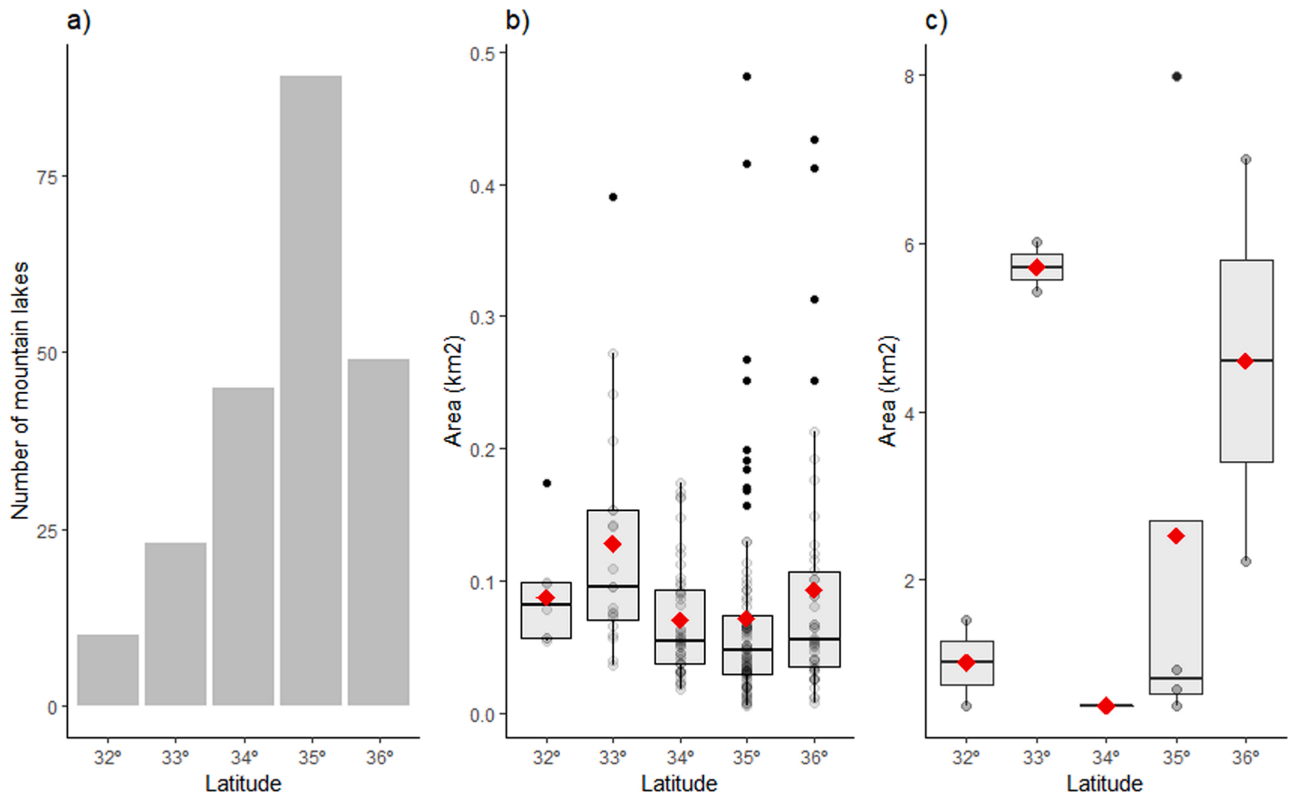

Fig. 2. Total number of lakes and surface distribution in the study area. The a) total number of the mountain lakes surveyed in our study by latitudinal band, b) the total area of all lakes and c) the total area of the lakes selected for the current study. Fig. 2.c does not include Laguna del Maule (46.7 km^2). Area and distribution for all lakes (N = 216) was obtained from Dirección General de Aguas. Red diamonds in boxplots b and c indicate the mean and black horizontal lines are medians.

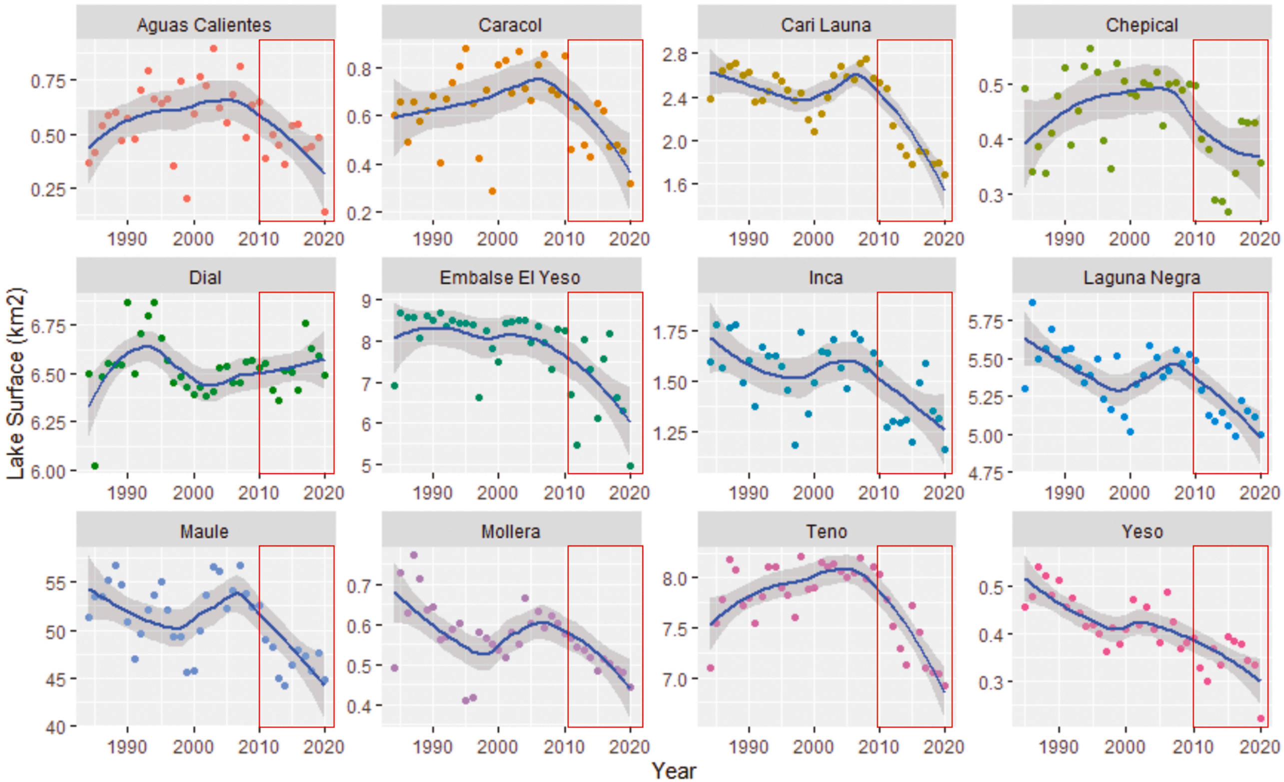

Fig. 3. Fluctuations of lake surface areas in the Andes of central Chile (32ºS-36ºS) from 1984 to 2020 (lakes with a surface above 0.5 km^2). Overall, lakes exhibit one of three major patterns, a 'humpbacked' (i.e., Chepical, Caracol, Teno, Aguas Calientes) with an initial increase up until the 2000 s followed by a major decrease, a 'linear' pattern characterized by a linear decrease, with a slight increase in the 2000 s, followed by a decrease (i.e., Cari Launa, Embalse El Yeso, Laguna del Inca, Laguna del Maule, Mollera, Yeso) or an overall increase (i.e., Dial Lake). The 'megadrought' is also shown for reference (red dashed rectangle).

from 1984 to 2020. The climatic data analyzed here were extracted based on the information available that was as close as possible to the studied lakes. Changes in lake surfaces were analyzed using descriptive statistics (mean, max, min, and standard deviation). We compare two periods, from years 1984–2009 and years 2010–2020 (the 'Megadrought') and applied the non-parametric Wilcoxon Mann Whitney test to see if the differences are statistically significant (Neuhäuser, 2011). We calculate the trends of the three considered climate variables (annual precipitation, annual mean temperature, and annual evaporation) from 1984 to 2020 using the Mann Kendall test (Mann, 1945; Kendall, 1962). We also estimate a 5-year moving average for the climatic variables, thus, for example, the hydrologic year of 1988 corresponds to the average of precipitation of 1987–1988. Finally, the climate variables were correlated with changes in lake surfaces between 1984 and 2020.

4. Results

4.1. Regional lake distribution between 32°S-36°S

A total of 215 lakes were surveyed in our study region and their size and number exhibit a conspicuous latitudinal gradient with an overall increase from north to south (Fig. 2). Thirty-two lakes occur in the northern sector (32–33ºS) and become more numerous further souths, with 89 lakes at c. 35ºS (Fig. 2.a). Lake surfaces span between 0.005 km^2 and 46.70 km^2, and the largest of these is Laguna del Maule (36ºS). Most lakes ($n = 203$) have a surface area lower than 0.5 km^2 (Fig. 2.b) and these add up to a total of 16.68 km^2 of water surface. Lakes located at 32ºS and 36ºS displayed a mean surface area of 0.09 km^2 (± 0.4 and ± 0.1 respectively). Between 34ºS and 35ºS lake areas exhibit an average of 0.07 km^2 (± 0.04 and ± 0.08 respectively), while those located at 33ºS show the largest spread of surface areas with a mean of 0.13 ± 0.09. Lake surface areas at our 35ºS band with areas greater than 0.5 km^2 ($n = 4$) add up to a total of 79.3 km^2 (Table 1).

4.2. Variations in lake surface area from 1984 to 2020

Lake surfaces show important variations across the temporal window analyzed (Fig. 3). Chepical lake (mean = 0.44 km^2 ± 0.08) oscillates from 0.57 km^2 in 1994–0.23 km^2 in 2015, Laguna del Inca (mean = 1.52 km^2 ± 0.18) fluctuates from 1.78 km^2 in 1985–1.16 km^2 in 2020, Laguna Negra (mean = 5.35 km^2 ± 0.21) ranges from 5.87 km^2 in 1985–5.0 km^2 in 2016 and, Embalse El Yeso (mean = 7.78 ± 0.95) varies from 8.69 km^2 in 1985–4.98 km^2 in 2020. Yeso lake (mean = 0.41 km^2 ± 0.07) fluctuates from 0.54 km^2 in 1987–0.22 km^2 in 2020, Teno lake (mean = 7.76 km^2 ± 0.39) oscillates from 8.22 km^2 in 1998–6.93 km^2 in 2020, Aguas Calientes lake (mean=0.55 km^2 ± 0.16) varies from 0.90 km^2 in 2003–0.14 km^2 in 2020 and Cari Launa (mean= 2.35 km^2 ± 0.32) fluctuates from to 2.75 km^2 in 2008–1.69 km^2 in 2020. Laguna del Maule (mean= 50.80 km^2 ± 3.83) ranges from 56.82 km^2 in 1988–44.14 km^2 in 2014. Overall, lower lake surfaces occurred during the 2010–2020 decade, whereas the highest surface areas occurred in the 1980 s, except for L. Mollera (mean = 0.57 km^2 ± 0.08) and L. Caracol (mean= 0.63 km^2 ± 0.16), with the lower surface areas recorded in 1995 (0.41 km^2) and 1999 (0.29 km^2) respectively. Dial exhibits the lowest variations during the entire

Table 3
Variation in lake surface area in the Andes of central Chile lakes comparing two periods: 1984–2009 and 2010–2020. Lakes displayed a significant loss of area when comparing the average surface lake area from the 2010–2020 periods with respect to the 1984–2009 period used here as a baseline.

Lake	Period	Average (km^2)	SD	Wilcoxon test (p-value)	Surface lost (km^2)	Surface loss (%)
Chepical	1984–2009	0.47	0.07	*	0.09*	19.92
	2010–2020	0.37	0.07			
Laguna del Inca	1984–2009	1.59	0.14	*	0.24*	14.84
	2010–2020	1.35	0.14			
Laguna Negra	1984–2009	5.45	0.14	*	0.30*	5.46
	2010–2020	5.15	0.14			
Embalse El Yeso	1984–2009	8.17	0.54	*	1.31*	15.99
	2010–2020	6.86	1.09			
Yeso	1984–2009	0.44	0.05	*	0.10*	21.89
	2010–2020	0.34	0.05			
Caracol	1984–2009	0.68	0.14	*	0.14*	21.17
	2010–2020	0.53	0.15			
Teno	1984–2009	7.92	0.26	*	0.55*	6.96
	2010–2020	7.37	0.36			
Mollera	1984–2009	0.61	0.06	*	0.09*	15.26
	2010–2020	0.51	0.04			
Aguas Calientes	1984–2009	0.62	0.12	*	0.18*	28.34
	2010–2020	0.45	0.13			
Cari Launa	1984–2009	2.50	0.17	*	0.58*	23.01
	2010–2020	1.93	0.23			
Laguna del Maule	1984–2009	52.34	3.24	*	5.21*	9.95
	2010–2020	47.14	2.39			
Dial Lake	1984–2009	6.54	0.14		0.019*	0.29
	2010–2020	6.52	0.11			

* $p\text{-value} < 0.05$.

period analyzed (mean of 6.53 km^2 ± 0.15), oscillating from 6.87 km^2 (± 0.17) in 1994–6.36 km^2 (± 0.11) in 2013.

A comparison of lake surface areas during the two considered periods (1984–2009 and 2010–2020) are summarized in Table 3. The results reveal an important and significant (p-value <0.05) decrease during the last decade (2010–2020), especially in Aguas Calientes that vary from about 0.60 km^2 (± 0.16) during the 1984–2009 period to 0.45 km^2 (± 0.13) during the 2010–2020 period equivalent to 25.48% of surface loss. Cari Launa decreased from 2.50 km^2 (± 0.17) to 1.93 km^2 (± 0.23) with a surface loss of 23.01%. Yeso and Caracol oscillated from 0.44 km^2 ± 0.05 and 0.67 km^2 (± 0.15) respectively during the first period compared to 0.34 km^2 (± 0.05) and 0.53 km^2 (± 0.15) during the second period, with a total surface reduction of 21.89% and 20.97% respectively. Chepical, Embalse El Yeso, Laguna del Inca and Mollera lakes varied from 0.47 km^2 (± 0.07), 8.17 km^2 (± 0.05), 1.59 km^2 (± 0.14) and, 0.59 km^2 (± 0.08) to 0.37 km^2 (± 0.07), 6.86 km^2 (± 1.09), 1.35 km^2 (± 0.14) and, 0.51 km^2 (± 0.04) respectively. This shows a loss of total lacustrine surface area, in percentages, of 20.97%, 19.92%, 14.84%, 13.19% respectively (Table 3) for the study period. Lakes with smaller decreases were Laguna del Maule (9.95%), Teno (6,96%) and Laguna Negra (5.27%). In contrast, Dial was the only lake with no clear trend with a slight decrease of 0.019% (Table 2). The total loss of lake surface area for the Andes of central Chile was c. 8.73 km^2 during the last 36 years with most of this loss occurring in the last 10 years. Among these, Laguna del Maule was the lake that lost the most surface area (5.21 km^2), although percentage-wise this was not very high.

4.3. Climate variability from 1984 to 2020 in the Andes of central Chile (32°S-36°S)

Climate data for the Andes of central Chile exhibits important variations during the analyzed period. Annual precipitation from 1984 to 2020 are based on hydrological years (e.g., May 1983- April 1984) (Fig. 4.a.). The general trend of annual rainfall estimated by the Mann Kendall test indicated a significant decreasing trend (Table 4) oscillating from 5.8 mm/yr to 7.2 mm/yr for all lakes, except for Embalse El Yeso, Laguna del Inca, and Laguna Negra. Thus, increased interannual variability and the presence of very wet years are observed mainly during the period of 1984–2009, with the lakes Dial (mean=841 ± 210.9 mm), Laguna del Maule (643 ± 171.2 mm), and Caracol (716 ± 205.7 mm) recording the highest amounts of annual rainfall. Since 2010 annual rainfall has dropped noticeably at all lakes. For example, in the period 1984–2009, Chepical lake recorded an average annual rainfall of 280 mm (± 161.5), and Laguna del Inca showed 375.2 mm (± 182.1) and these averages dropped to 194 (± 83.0) and 259.0 mm (± 84.1) from 2010 to 2020, respectively. This represents a deficit of c. 31% for each lake. Likewise, from 1984 to 2009 Embalse El Yeso and Laguna Negra recorded an average annual rainfall of 444.7 mm (± 190.4) and 447.0 mm (± 199.0) respectively, which then dropped to 320.0 ± 107.1 mm and 324.1 ± 108.5, from 2010 to 2020, representing a deficit of 28% and 27%, respectively. In similar fashion, Mollera ($mean_{1984–2009}$ = 642.5 ± 184.3 mm; $mean_{2010–2020}$ = 490.4 ± 134.1 mm), Cari Launa ($mean_{1984–2009}$ =612.0 ± 163.0 mm; $mean_{2010–2020}$ = 466.9 ± 121.3 mm), Teno ($mean_{1984–2009}$ = 614.3 ± 186.2; $mean_{2010–2020}$ = 461.0 ± 147.2 mm), Caracol ($mean_{1984–2009}$ =

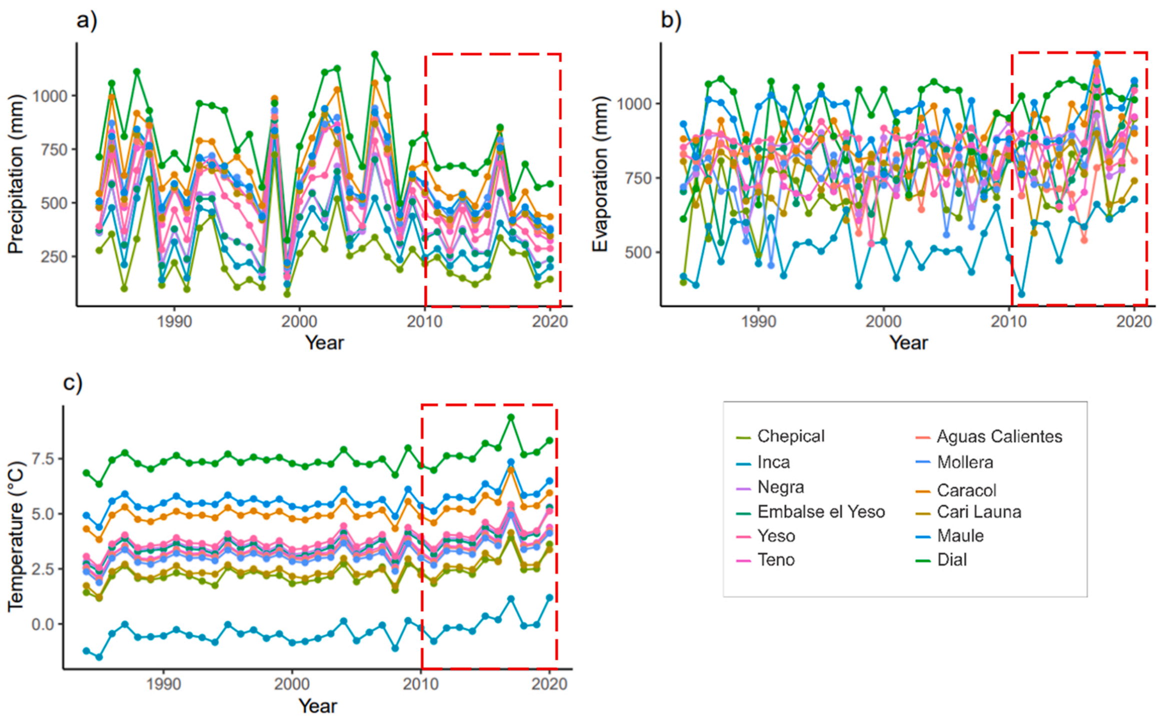

Fig. 4. Climate data from 1984 to 2020 for central Chile Andean lakes located between 32 − 36°S (Abatzoglou et al., 2018). a. Annual precipitation amount. b. Annual evaporation amount. c. Annual mean temperature. The 'megadrought' (Garreaud et al., 2020) is observed by the annual rainfall trend decrease as the average annual temperatures and annual evaporation increase in the last decade (red segmented lines).

Table 4
Mann Kendall test and Sen's slope estimate (Q) to climate data indicating a significative decreasing of annual precipitation, while significative and positive trend for temperature increase from 1984 to 2020. The increase of the evaporation in the most of lakes is not significative.

Id	Lake	Precipitation		Evaporation		Temperature	
		Q (mm/year)		Q (mm/year)		Q (°C/year)	
1	Chepical	-2214		4391	*	0022	*
2	Inca	-3722		3647	*	0024	*
3	Negra	-4042		1811		0026	*
4	Embalse el Yeso	-3794		2660	*	0027	*
5	Yeso	-5397		-0430		0025	*
6	Mollera	-6118	*	3147	*	0023	*
7	Aguas Calientes	-5833	*	-1371		0023	*
8	Caracol	-6379	*	2460		0022	*
9	Teno	-5861	*	2724	*	0024	*
10	Cari Launa	-5915	*	0877		0018	*
11	Maule	-5842	*	0118		0019	*
12	Dial	-7195	*	1438		0018	*

* p-value < 0.05.

716.0 ± 206.0; $mean_{2010–2020}$ = 547.0 ± 137.0 mm), Laguna del Maule ($mean_{1984–2009}$ = 643.0 ± 172.0 mm; $mean_{2010–2020}$ =), Dial ($mean_{1984–2009}$ =842.0 ± 211.0 mm), Yeso ($mean_{1984–2009}$ =534.0 ± 197.0 mm) and Aguas Calientes ($mean_{1984–2009}$ =611.1 ± 174.0 mm) lakes experienced a precipitation deficit in the 2010–2020 period around 25% (Teno and Yeso), 24% (Mollera, Cari Launa, Caracol, Laguna del Maule and Aguas Calientes), and 23% (Dial).

Although a coincidence between precipitation and the surface areas of the studied lakes could be expected, this does not have statistical support. To explore the relationship between both variables, we compared a 5-year moving average of annual precipitation with the lake surfaces. As a result, Fig. 5 shows a positive and significant correlation, with a clear lag in lake response to rainfall input. This lag is of at least two or three years from the start of dry year to the eventual decline in surface lake area (Figs. 3 and 4.a). For example, since 2017 Laguna del Inca, Embalse El Yeso, Yeso, Teno, Aguas Calientes, and Cari Launa lakes displayed a lower amount of annual precipitation (Fig. 4.a), matching the lowest lake surface observed in 2020 (Supplementary Table 1).

The annual evaporation amount recorded during the study period (Fig. 4.b) exhibits a slight and non-significative positive trend (Table 3 Supplementary Figure 1). However, when comparing the 1984–2009 and 2010–2020 periods, there was an increasing trend of about 100 mm per year in the lakes Embalse El Yeso, Mollera, Chepical, Teno, and Laguna del Inca. Thus, in the 1984–2009 period, Embalse El Yeso oscillated around to 777.2 ± 96 mm/yr, Mollera about of 741.0 ± 104 mm/yr, and Chepical lakes in a mean of 685.61 ± 107 mm/yr. Those lakes increased the annual evaporation during the 2010–2020 period to a mean of 877.2 ± 139.1 mm/yr, 843.3 ± 65.9 mm/yr, and 777.5 ± 134.3 mm/yr respectively. Laguna del Inca and Teno also increase from a mean of 513.0 ± 77.0 mm/yr and 770.0 ± 69.0 mm/yr in 1984–2009 period to a mean of 607.2 ± 64 mm/yr and 854.0 ± 134.3 mm/yr, respectively during the 2010–2020 period. Although L. Dial (mean= 933 ± 144.0 mm/yr), and L. Negra (mean=809.0 ± 95 mm/yr) increase in the 2010–2020 period to a mean of 1040.1 ± 24.8 mm/yr and 886.2 ± 100.9 mm respectively, this trend is not significant (Table 3). In addition, the rest of the lakes increased in annual evaporation, this did not exceed 65 mm/yr. Thus, Caracol (mean=868.1 ± 68 mm/yr), Laguna del Maule (925.0 ± 94 mm/yr), Cari Launa (mean=752.1 ± 71.0 mm/yr), and Aguas Calientes (mean=787.1 ± 77.0 mm/yr) in 2010–2020 period increased to 933.0 ± 110.3 mm/yr, 984.0 ± 100.2 mm/yr, 778.6 ± 86.0 and 743.0 ± 103.0 mm/yr respectively, which is equivalent to an increase of 65.0 mm/yr, 59.0 mm/yr, 27.0, and 44.2 mm/yr, respectively. L. Yeso was the only lake where evaporation did not show important variations and fluctuated from about 853 ± 88 mm/yr in 1984–2009–854.4 ± 150.5 mm/yr in 2009–2020.

Annual mean temperature (Fig. 4.c) shows a sustained and significant increase since 2010 for all lakes (p-value <0.05; Table 4). This trend was estimated by the Mann Kendall test and the Sen's slope (Q) indicating increases between 0.18 and 0.27 °C/decade (Table 4). As with precipitation, we estimated a 5-year moving average of annual mean temperature and compared these to the surface areas of the lakes from the study site for 1984–2020. Significant negative correlations exist between both these variables for almost all the lakes studied (Fig. 6).

5. Discussion

5.1. Climate and regional lake distribution between 32 and 36°S

The distribution of the Andes lakes from central Chile, both in number and size, seemingly follows a latitudinal gradient (Fig. 2). In fact, as rainfall increases toward the south, the lakes increase in number and size. Hence, the reduction of water supply and increase of temperatures observed (Fig. 4.a) in the study site may have a strong impact on the surfaces of these lakes. However, this change was not analyzed here in detail and will eventually be necessary to know the state of these lakes. For this reason, NDWI applied to high-resolution images (15 m) needs to be assessed in terms of overall performance in achieving adequate results from small surfaces (Özelkan, 2020).

Globally, the combined effect of climate variability and human pressures are consistently drying up lakes in semiarid and arid

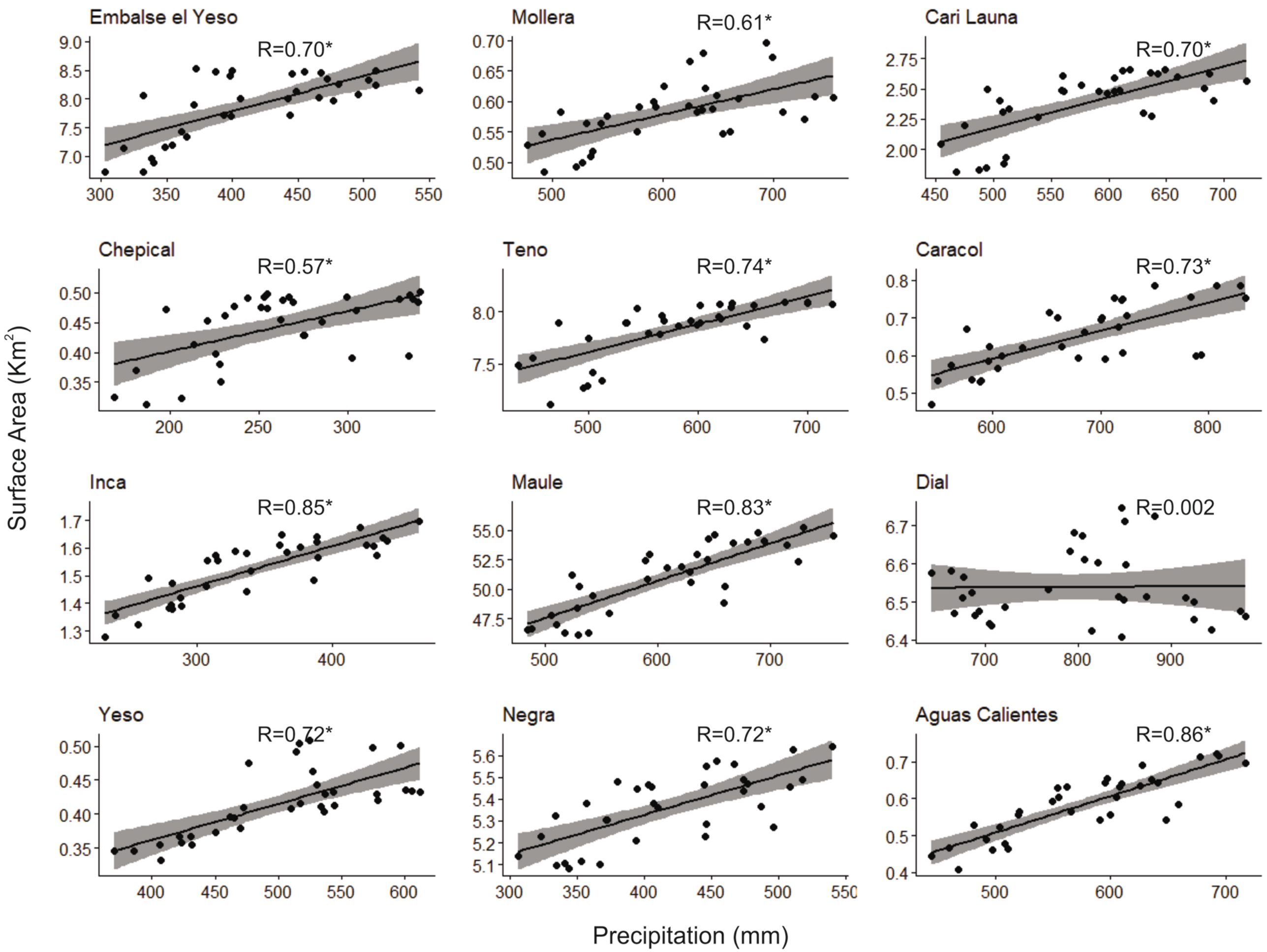

Fig. 5. Pearson correlation between a 5-year moving average of mean annual precipitation and annual surface of Andean lakes (32ºS-36ºS). *p-value < 0.05.

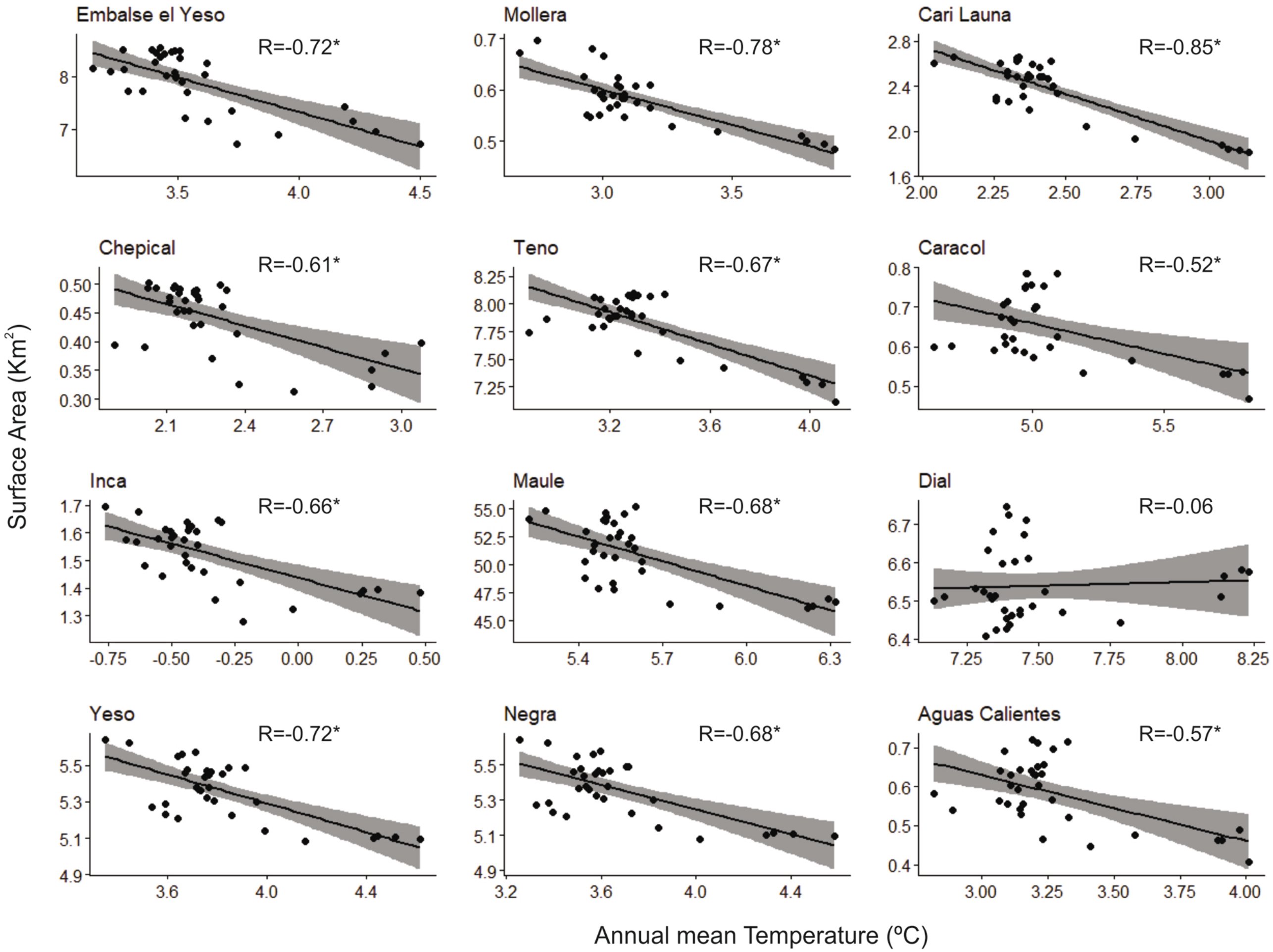

Fig. 6. Pearson correlation between a 5-year moving average of mean annual temperature and annual surface area of Andean lakes (32ºS-36ºS). *p-value < 0.05.

regions. For example, Lake Urmia in Iran (Alizade Govarchin Ghale et al., 2018) and Lake Baiyangdian in China (Lu et al., 2013). At lower elevations in central Chile, small lakes have been drying out over the last decade (e.g., Aculeo, Barría et al., 2021; and Matanzas Lakes, Fuentealba et al., 2020). Therefore, the lakes from the Andes of central Chile can be expected to at least decrease in lake level. These lakes add up to a total of 16.68 km^2 of water surface (Fig. 2.b) and their reduction can lead to serious social problems. In this sense, the maintenance of agricultural and livestock activities development in its watersheds or even water supply security to high-density populated areas, such as in the Santiago Metropolitan region can be at risk. This maintains lake levels although this increases pressure on groundwater resources. For example, a major reduction in groundwater (about 300%) during the so-called 'megadrought' has been reported for the Petorca basin, which no longer has any surface expressions of the watertable in the lower valleys (Muñoz et al., 2020). Therefore, the reduction of water supply, together with the development of human activities can generate a serious hydric scarcity (Barría et al., 2021). Moreover, the reduction of the number of lakes between 35ºS and 36ºS could be related to a large drop in average elevation of the Andes as latitude increases. Since snow and rainfall distribution depend on elevation, lower elevations imply lower water supply, hence, a lower number of lakes.

5.2. Climate variability as a possible cause of decreasing in lakes surfaces

The lakes with a surface greater than 0.5 km^2 analyzed here displayed a general trend to reducing its area during the 1984–2020 period (Fig. 3). The changes in the lake surfaces area exhibit one of three major patterns, a 'humpbacked' (i.e., Chepical, Caracol, Teno, Aguas Calientes) with an initial increase up until the 2000s followed by a major decrease, a linear decrease, with a slight increase in the 2000s, followed by a decrease (i.e., Cari Launa, Embalse El Yeso, Laguna del Inca, Laguna del Maule, Mollera, Yeso) and an overall increase (i.e., Dial Lake). Nine of the twelve lakes included Laguna del Inca (32ºS), Laguna Negra (33ºS), Embalse El Yeso (33ºS), Yeso (34ºS), Teno (35ºS), Aguas Calientes (35ºS), Cari Launa (36ºS), and Laguna del Maule (36ºS), showed a smaller surface area in the 2010s decade (Fig. 3). When comparing the changes that occurred during the two periods (1984–2009 and 2010–2020), the surface area reduction from the second period was at least 6% (Table 3). This means a total loss of 8.73 km^2 of water surface. The lakes located from 34ºS to 35ºS and from 2100 m. a.s.l. to 2700 m a.s.l. were those that experienced the greatest drop (Tables 1 and 3).

Although this trend does not appear to have a latitudinal gradient, the loss of surfaces is in agreement with recent climate trends. The correlation of the changes in lake surface with a 5-year moving average of annual precipitation (Fig. 5) is positive and significant, which seems to show a lag in the lake response to precipitation input. Furthermore, we detected a lag of at least two or three years with a low amount of precipitation before the surface lake decreases (Figs. 3 and 4.a). Thus, the decreasing amount of precipitation (Fig. 4.a) affects the water supply to the lake, but its response is not immediate and follows a 3-year lag approximately. This lag is consistent with the report for Lake Aculeo (33º 50′ S, 70º 54′ W, 350 m a.s.l) which indicates the time of residence of water from precipitation in the lake was of about 2.2 years (Barría et al., 2021). The lakes located north of 34ºS recorded the highest surface values between 1985 and 1987 (except for Chepical, which was in 1994) while the lakes located at the southward of 34ºS registered their highest surfaces in different years between 1987 and 2008. In contrast, years with a high amount of annual precipitation were 1998 and 2006 for practically the entire study region (Fig. 4.a). Lake Dial is unique in that shows only a slight decrease (0.02%) in surface area during the 2010–2020 period. The most likely explanation may be related to feeding regimes that do not respond on interannual timescales to either increasing temperature and decreasing precipitation such as those that are maintained by large groundwater reservoirs. Fully understanding the reasons for why L. Dial fails responds to recent climate variability will require a water budget analysis to unravel this unique behavior, which is beyond the scope of this present study.

The variability of annual evaporation amount recorded (Fig. 4.b) in the study site during the temporal window seems to not influence the lakes surface changes (Table 2 and Fig. 3). The low increase in evaporation amount does not exceed 100 mm/yr when the two periods 1984–2009 and 2010–2020 are compared. Regarding annual mean temperature (Fig. 4.c), an important increase occurred for the period 2010–2020 of about 0.7 °C with respect to the 1984–2009 period. This increase is consistent with the results reported by Shaw et al., (2021) indicating that temperature has experienced a warming trend of up to ~0.8 °C per year during the period 2010–2020 for central Andes (32ºS to 35ºS). Probably because of temperature dynamics, the lakes suffer an important drop in their surface areas. We used a 5-year moving average of annual mean temperature which correlated negatively and significantly with the areas from the lakes during the temporal window analyzed here (Fig. 6).

5.3. Influence of the recent 'megadrought' on decreasing trends in lake surface area

The lakes show a clear drop in surface area during the period of 2010–2020 compared to the 1984–2009 period, used here as baseline (Fig. 3 and Table 2). This drop occurs across the entire study site and is largely associated with a reduction in precipitation and an increase in temperatures. These results are consistent with decreased snow-covered areas that feed Andean lakes during the summer (Shaw et al., 2021). Together with an increase of mass glacier loss observed in recent decades (e.g., Shaw et al., 2021; Fariás-Barahona et al., 2020) these could be all part of the effect of the so-called 'megadrought' of central Chile observed since 2010 (Garreaud et al., 2017, 2020). This can be further accentuated as temperatures increase and coupled with less precipitation (rainfall and snowfall) and the earlier onset of spring melting of winter snow (Kim et al., 2009). Garreaud et al. (2020) suggested that only a partial recovery of the region's precipitation is expected during the coming decades, which implies that the lakes from Andes central Chile will continue to decline. This period is well known for being one of the most intense regional droughts in the last centuries (Serrano-Notivoli et al., 2021). Furthermore, even with some wet years, the lag detected here (i.e., 3 years of lag) in the response of lakes to increase its areas could make any eventual recovery difficult.

Our results point to many other areas of inquiry that need to be further assessed. For example, we have not included the different sources of water inputs to the lakes such as fluxes from tributaries, changes in snow vs. liquid precipitation, and groundwater inputs. These factors could exercise important controls on any changes in the level of the lakes. Although very little public information exists regarding groundwater availability for each of our study lakes. The scientific literature available for northern and central Chile suggests an important reduction in aquifers possibly due to the impact of reduced lake surface areas because of rainfall deficits and groundwater compensation (Taucare, 2020). In addition, increasing withdrawals from lakes due to anthropogenic activities (for agriculture, mining, and drinking water) combines with hydroclimate stress, leading to overexploitation of groundwater resources (Muñoz et al., 2020; Garreaud et al., 2017). This poses challenges to water managers that must be considered (Barría et al., 2021). Moreover, the recent 'megadrought' could be only one of the drivers leading to lakes surface area reduction. Changes in the water demand have not been considered in this study and could explain a significant part of the water extraction from these Andean catchments.

Despite the clear effect of this warm and dry period, human intervention on each of these lakes need to be analyzed separately. Land use and land cover changes were identified as one of the main drivers of the hydrological response of lacustrine ecosystems (Song et al., 2018, Fuentealba et al., 2020). Considering that the above-mentioned changes vary depending on elevation and social requirements, these affect lakes differently (Martínez-Retureta et al., 2020). A more detailed approach needs to be undertaken to analyze the different effects of human interventions on each lake to establish the full extent of impact from the so-called megadrought in this area, and how these can change in the future (Benavidez-Silva et al., 2021, Galleguillos et al., 2021).

6. Conclusion

The use of satellite imagery and the NDWI index are useful tools to evaluate interannual changes in lake surface areas and afford a reliable and quick way to compare these changes to available climate data. Almost all the lakes located in the Andes of central Chile analyzed here displayed a general trend towards diminishing surface areas during the 2010–2020 period. These declines coincide with major regional climate trends including decreasing precipitation and increasing temperatures. Temperature shows a significant increasing trend at all the lakes of the Andes in central Chile during 2010–2020. Unlike temperature, evaporation and precipitation trends were not significant for most lakes. Decreasing precipitation, however, occurs coevally with increasing evaporation. Therefore, these variables show behaviors consistent with regional climatic variability over the last decades.

The changes reported here pose serious challenges for water managers and local to regional stakeholders, since good management of this resource is necessary to face climate change and the severe and ongoing water crisis in central Chile. These results can assist with management of this resource and improve our understanding of future water availability in the region.

This research addresses the changes in the water input to the lakes through to the changes in the annual precipitation amount in each study site. However, to improve our knowledge of the dynamics of these lakes other variables should be incorporated. For example, surface and groundwater fluxes. Future research should also consider incorporating lake bathymetries to further estimate how much water volume has been lost during the recent (and ongoing) 'megadrought'.

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CRediT authorship contribution statement

Magdalena Fuentealba: Conceptualization, Formal analysis, Investigation, Writing – original draft, Project administration. **Camila Bahamóndez:** Conceptualization, Investigation, Data curation, Writing – review & editing. **Pablo Sarricolea:** Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing. **Oliver Messeguer-Ruiz:** Conceptualization, Investigation, Funding acquisition, Writing – review & editing. **Claudio Latorre:** Conceptualization, Investigation, Funding acquisition, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2021.100952.

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