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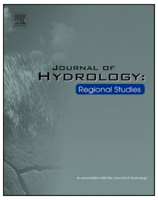

Human impact changes hydrological connectivity in a Patagonian fluvial basin

Facundo Scordo[a,b,*], Carina Seitz[c,d], Juan Esteban Fiorenza[e,f], M. Cintia Piccolo[a,b], Gerardo M.E. Perillo[a,c]

[a] *Instituto Argentino de Oceanografía, Universidad Nacional del Sur (UNS)-CONICET, Bahía Blanca, Buenos Aires, Argentina*
[b] *Departamento de Geografía y Turismo, Universidad Nacional del Sur, Bahía Blanca, Buenos Aires, Argentina*
[c] *Departamento de Geología, Universidad Nacional del Sur, Bahía Blanca, Buenos Aires, Argentina*
[d] *IPATEC, Centro Regional Universitario Bariloche (CRUB), (CONICET-UNCO), San Carlos de Bariloche, Argentina*
[e] *CONICET, Universidad de Buenos Aires (UBA), Instituto de Investigaciones Fisiológicas y Ecológicas Vinculadas a la Agricultura, (IFEVA), Buenos Aires, Argentina*
[f] *Universidad de Buenos Aires, Facultad de Agronomía. Departamento de Métodos Cuantitativos y Sistemas de Información, Buenos Aires, Argentina*

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ABSTRACT

Study region: The Cronómetro Lake basin situated east of the Andes in Argentina's Patagonian Andean pre-range environment.
Study focus: We analyzed the interannual fluctuation in the surface area of Cronómetro Lake (January 2000 to January 2021). We also studied the periods of humidity and drought and the anthropogenic activities in the lake basin to understand their impact on water availability within the basin.
New hydrological insights for the region: The area of Cronómetro Lake decreased by 34% in the last ten years. The lake's area reduction started in 2012, which coincides with the construction of fourteen channels perpendicular to one of its main tributaries (the SN1 Stream). The channelization of the SN1 Stream in its upper basin prevents its water from reaching the Cronómetro Lake. From 2012–2021, we have not observed a decrease in local rainfall or an increase in periods of drought. Therefore, we suggest the channelization of the SN1 Stream is the cause of the lake shrinkage. The reduction of the lake's surface generated the disconnection of the lake from its outflow, which dried. Currently, the Cronómetro Lake basin has become endorheic. The reduction in water availability in the Cronómetro Lake basin causes loss of aquatic and terrestrial ecosystem services, with negative implications for local economic activities.

1. Introduction

Lakes in arid and semi-arid regions are fundamental water resources and sentinels of climate variability and human impact in their basins (Adrian et al., 2009; Williamson et al., 2008, 2009). Lake levels naturally fluctuate due to stream inflows, precipitation, evaporation, human extraction, and outflows discharge (Wine et al., 2019). The natural fluctuation in the volume of the lakes is an essential hydrological process for maintaining the system's ecology (Wang et al., 2022). At present, climate warming and human

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* Corresponding author at: Instituto Argentino de Oceanografía, Universidad Nacional del Sur (UNS)-CONICET, Bahía Blanca, Buenos Aires, Argentina.

E-mail address: scordo@agro.uba.ar (F. Scordo).

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demand are postulated as the leading cause of water resources degradation and lake shrinkage in semi-arid areas (Liu et al., 2013; Fazel et al., 2017; Scordo et al., 2020a; Chen et al., 2020; Çolak et al., 2022). Nevertheless, human intervention, particularly water subtraction for agricultural irrigation, is the most influential factor in the reduction of lake volume worldwide (Beeton, 2002; Liu et al., 2013; Fazel et al., 2017; Wine et al., 2019; Wine and Laronne, 2020). Human pressure can lead to significant variations in the water balance, affecting factors such as lake size, and depth. Such morphological changes in lakes can modify their physical and chemical conditions, pushing the ecosystem into abrupt ecological changes (Scheffer et al., 1993; Beklioglu et al., 2001; Coops et al., 2003; Jeppesen et al., 2015).

The Argentinian Patagonia is an extended (800,000 km^2) semi-arid region with numerous rivers and lakes (Coronato et al., 2017). Some of these waterbodies are almost pristine, while others are significantly impacted by human activities, such hydroelectric and agricultural production, oil and gas extraction, and tourism (Alfonso et al., 2020; Scordo et al., 2020a, 2020b). The Argentinian Patagonia locates at the southern end of South America and east of the Andean Range. The rivers and lakes, especially in the Patagonian plains, are the only source of water for human consumption and the development of economic activities. Furthermore, the population in Patagonia is increasing with a higher demand and impact on water resources (INDEC, 2001, 2010). For example, increased water demand for human use has reduced the surface area and depth of the Musters Lake in central Patagonia (Scordo et al.,

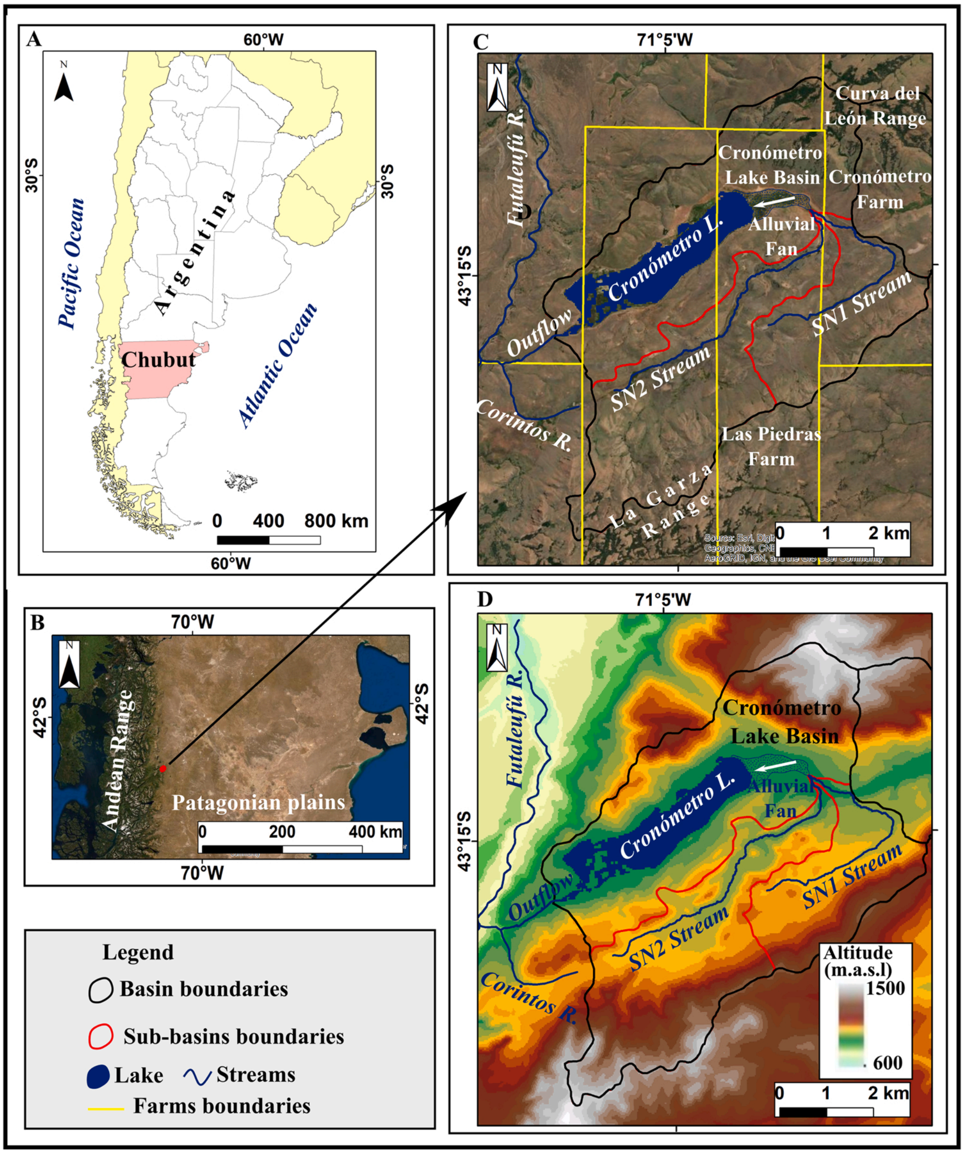

Fig. 1. Location of the study area in the province of Chubut (A) within the Argentinian Patagonia (B). Satellite (C) and topographic (D) map of the Cronómetro Lake basin before the channelization of the Sin Nombre 1 (SN1) stream in its headwaters in 2012. The map shows the sub-basins boundaries of the streams SN1 and Sin Nombre 2 (SN2), the confluence of SN1 and SN2 streams that produce the alluvial fan located on the eastern shore of the lake, and the boundaries of the farms Estancias Las Piedras and Estancia Cronómetro.

2017, 2018a, 2018b). Also, human pressure on water resources caused the disappearance of the Colhué Huapí Lake, a Patagonian waterbody that had an area of 800 km^2 in 2007 (Scordo et al., 2017, 2018a, 2018b, 2020a). Due to the reduction in the surface area of the Colhué Huapí , its outflow (the Chico River) dried, resulting in water scarcity problems in a region of 17,600 km^2 (Scordo et al., 2020a). Climate variability can also cause a reduction in lake surface area and depth. El Niño Southern Oscillation and the Antarctic Oscillation cause dry and wet periods in Patagonia (Pasquini et al., 2008; Scordo et al., 2018a). Lake surface area and depth decrease when the dry periods are long (more than a year). (Pasquini et al., 2008; Scordo et al., 2018a, 2020a). Studies that analyzed time series of lake level or surface area in combination with climatic trends and anthropogenic impacts are needed to identify if lakes are disappearing in Patagonia. If lakes are disappearing, it is necessary to know if the causes are climatic, anthropogenic, or a combination of both.

Despite the socio-economic importance and the need to preserve Argentinian Patagonia rivers and lakes, implementing *in-situ* monitoring programs of high temporal resolution of the water resources in this extended region is impossible due to its logistics and costs (Scordo, 2018). When implementing an *in-situ* monitoring program is not feasible, studies based on the analysis of remote sensing images can be an alternative for evaluating various aspects of hydrology and water resources over extended areas (Peng et al., 2005; Soti et al., 2009). Remote sensing techniques allow studying fluctuations in lake surface area (Bohn et al., 2016; Chen et al., 2020), water quality (Harma et al., 2001; Wu et al., 2009), and snow distribution (Lopez et al., 2008). In Patagonia, remote sensing-based studies showed that changes in lake area extension are indicators of climate variability and human impact (Scordo, 2018; Scordo et al., 2018a; Fuentealba et al., 2021). Therefore, remote sensing techniques could be used to improve lake and river monitoring in remote areas of Patagonia.

In this study, we determine the causes that reduced the water availability in the Cronómetro Lake basin, leading to a decrease in the surface area of the lake and a deterioration in the vegetation status on its shores. The surface area of Cronómetro Lake reached its minimum extent in 2021. The reduction in the Cronómetro Lake area has deteriorated its ecology and the surrounding vegetation, negatively impacting economic activities such as fish farming and sheep-cattle farming. The inhabitants of the region claim the lake shrinkage is due to the channelization of one of the main tributaries of the lake. However, the reduction in the surface area and depth of lakes in Patagonia can be due to climate variability (Pasquini et al., 2008), human intervention, or a combination of both climatic and human factors (Scordo et al., 2017, 2018a, 2020a). Therefore, we examined whether the reduction in the Cronómetro Lake area responds to climatic conditions trends or is related to anthropogenic impact. We analyzed the time series (from 2000 to 2021) of the lake area, vegetation status, precipitation, and a climatic index before and after the construction of channels in the headwater of the basin.

1.1. *Study area*

The Cronómetro Lake basin (43.249874°S; 71.086230°O) is located east of the Andes in the Patagonian Andean pre-range environment, in the Chubut Province, Argentina (Fig. 1A, and B). The Cronómetro Lake, with an elevation 850 m. a.s.l., has a surface area of 3.04 km^2 (by the year 2000), and a maximum depth of 4.4 m (Quirós, 1988). The lake has a fluvio-glacial origin and is surrounded by high elevation (1200 m a.s.l.) on its, northern, and southern coasts (Haller et al., 2010; Fig. 1C, and D). Several intermittent streams discharge into the Cronómetro Lake. The intermittent streams have their headwater in the mountain systems Cordón La Grasa on the southern coast of the lake and Cerro Curva del León on the northern coast (Fig. 1C, and D). The two main tributaries of the Conómetro Lake are the intermittent streams Sin Nombre 1 (SN1) and Sin Nombre 2 (SN2) (Fig. 1C). Both streams originate at the Cordón La Garsa, and meet 1.5 km to the east of the lake forming an alluvial fan that discharges into the Cronómetro Lake (Fig. 1C).

The lake is located within an area characterized by a cold, sub-humid climate (Coronato et al., 2017). Annual precipitation ranges between 400 and 500 mm. Precipitations, occurs predominantly during the winter, where 20–25 snowfalls occur on average. Mean maximum temperature is 30 °C, and mean minimum temperature is − 22 °C, with large thermal amplitudes (Coronato et al., 2017). The prevailing wind direction is from the west, with high speeds (29 km/h; Coronato et al., 2017).

The streams in the basins have two maximum flow discharges, a lower one in July-August from winter precipitation and a higher one in October and November from snowmelt in the basin (Bruniard, 1992). In dry years, the streams remain dry from March to May. Cronómetro Lake reaches its maximum level between December and January after all the snow in the basin melts. Until 2010, several authors (Valladares, 2004; Haller et al., 2010) considered the Cronómetro Lake basin exorheic since, through a permanent stream on its western coast, it discharges into the Corintos River, one of the main tributaries of the Futaleufú River that flows into the Pacific Ocean (Fig. 1C, and D).

2. Material and methods

We analyzed the interannual fluctuation in the surface area of Cronómetro Lake, and the deterioration of vegetation status in the alluvial fan located on the eastern shore of the lake (January 2000 to January 2021). We also studied the periods of humidity and drought and the anthropic modifications made in the basin of the lake to understand their impact on the extension of the lake area and the vegetation status.

We delineated the boundaries of the Cronómetro Lake basin and the SN1 and SN2 streams sub-basins using the digital elevation model “Modelo Digital de Elevaciones para la República Argentina ($MED\text{-}Ar_{v2.0}$)” from the Instituto Geográfico Nacional (https://www.ign.gob.ar/category/tem%C3%A1tica/geodesia/mde-ar). The $MED\text{-}Ar_{v2.0}$ has a spatial resolution of 30 m on the horizontal plane and 1 m resolution on the vertical plane. We identified the headwater of the main streams. We also delineated and described the main landforms of the study area. For these objectives, we employed the $MED\text{-}Ar_{v2.0}$ digital elevation model, multitemporal Landsat (5 TM, 7 ETM+, and 8 OLI), and the national geological sheets 4372-IV Trevelin (Haller et al., 2010). The Landsat images have a spatial resolution of 30 m on the horizontal plane and are available for the entire study period. We downloaded the remote sensing images from https://earthexplorer.usgs.gov/ that corresponds to the United States Geological Survey. The national topographic map has a scale of 1:250,000, and we downloaded it from the Servicio Geológico Minero Argentino.

To identify and, delineate the human-made channels perpendicular to the SN1 stream, we used Maxar images with a more detailed spatial resolution (30 cm on the horizontal plane and 15 cm resolution on the vertical plane). We downloaded the Maxar images from Google Earth, which were available for 2010, 2011, 2013, and 2019. We also identified the boundaries of private land using a cadastral map of the Chubut Province (Fig. 1C).

We complemented this work with a fieldwork campaign in May 2022. We followed the procedures described by Knight et al. (2011) for geomorphological field mapping. We corrected the limits of the landforms, and the correlations among landforms, based on geographic positioning that we obtained from a GPS Garmin eTrex Vista (datum WGS84). Furthermore, in the field, we made a photographic record of the surveyed landforms and made field notes about their characteristics. We integrated all the information using the software ArcGIS 10.0.

We used Landsat (5 TM, 7 ETM+, and 8 OLI) images to analyze interannual fluctuations in lake surface area and the vegetation status in the alluvial fan. Although the Landsat images have a temporal resolution of 16 days, not all the available images were useful because of a high percentage of cloud cover. However, these images are freely available and have a high spatial resolution (30 × 30 m). One satellite image per year was processed to analyze the interannual lake area fluctuations. We analyzed one Landsat satellite image per year (22 in total) for 2000–2021, using mostly summer images from December and January. The highest river discharge occurred during spring (Oct and Nov), and its effects on lake area extension can be best observed during summer. Additionally, summer images contained less cloud cover. We used Landsat Collection 1 - Level 2 product (Path 229 and Row 92), downloaded from the website of the United States Geological Survey (http://earthexplorer.usgs.gov). This collection of Landsat images provides surface reflectance data ensuring consistent quality through time and across the different Landsat sensors. These images include calibration processes between the different sensors, and geographic, radiometric and atmospheric corrections (further information on the calibration and corrections processes can be found at https://www.usgs.gov/landresources/nli/landsat/landsat-collection-1-surface-reflectance.

To differentiate water from other types of land cover, we applied a red-green-blue (RGB) band combination (near-infrared, short wave infrared, red) to the Landsat images (Landsat 5 and 7: bands 4–5–3; Landsat 8: bands 5–6–4). This band combination has accurately distinguished water from other types of land cover (NASA, 1999; Horning, 2004; Chuvieco, 2010) and has been successfully used to study the surface area of other lakes in Patagonia (Scordo et al., 2017, 2018a). We obtained lake areas using a supervised classification (maximum likelihood), based on a defined region of interest (ROI) and vectorization made with the software QGIS 3.6. We used the raster calculator tool from ArcGIS 10.0 to calculate lake surface area. A comparison of the summer images showed the degree of lake surface change over time.

To analyze interannual fluctuations in the vegetation status along the alluvial fan we calculated the Normalized Difference Vegetation Index (NDVI; Kriegler et al., 1969; Tucker, 1979). The NDVI is computed as the difference between near-infrared (NIR) and red (RED) bands reflectance divided by their sum (Landsat 5 and 7: bands 4 (*B*4) − 3 (*B*3); Landsat 8: bands 5 (*B*5) − 4 *(B4)*; Eqs. 1 and 2).

$$NDVI_{L5yL7} = \frac{(B4 - B3)}{(B4 + B3)} \quad (1)$$

$$NDVI_{L8} = \frac{(B5 - B4)}{(B5 + B4)} \quad (2)$$

NDVI values range from − 1–1. The negative values of NDVI are associated to clouds, and water bodies, while values approaching zero represent rocks, bare soil, or concrete surfaces. Positive values correspond to vegetation, including trees, shrubs, crops, and grasses (Jones and Vaughan, 2010; Huang et al., 2021). Sparse or senescing vegetation may result in moderate NDVI values (0.2–0.66; Gamal et al., 2020). High NDVI values (0.66–0.9) correspond to dense and healthy vegetation.

We compared the fluctuations in the lake surface area and the vegetation status against the annual accumulated precipitation and the percentage of months with humid and dry conditions based on the Standardized Precipitation and Evaporation Index (SPEI; Vicente-Serrano and Beguería, 2016). We downloaded the time series of monthly precipitation data corresponding to the station 2234 located 20 km west from Cronómetro Lake (SSRH 2016; https://www.argentina.gob.ar/obras-publicas/hidricas/base-de-datos-hidrologica-integrada). The SPEI is a meteorological indicator that determines climatic conditions that have been abnormally dry or humid. The calculation of the SPEI uses modeled precipitation and evapotranspiration data (Vicente-Serrano and Beguería, 2016). The SPEI has been widely accepted and used in drought studies at various spatial and

Table 1
SPEI categories.

Categories	SPEI values
Extreme humid	< 1.5
Humid	0.5–1.5
Normal	-0.5–0.5
Drought	-0.5—1.5
Extreme Drought	> −1.5

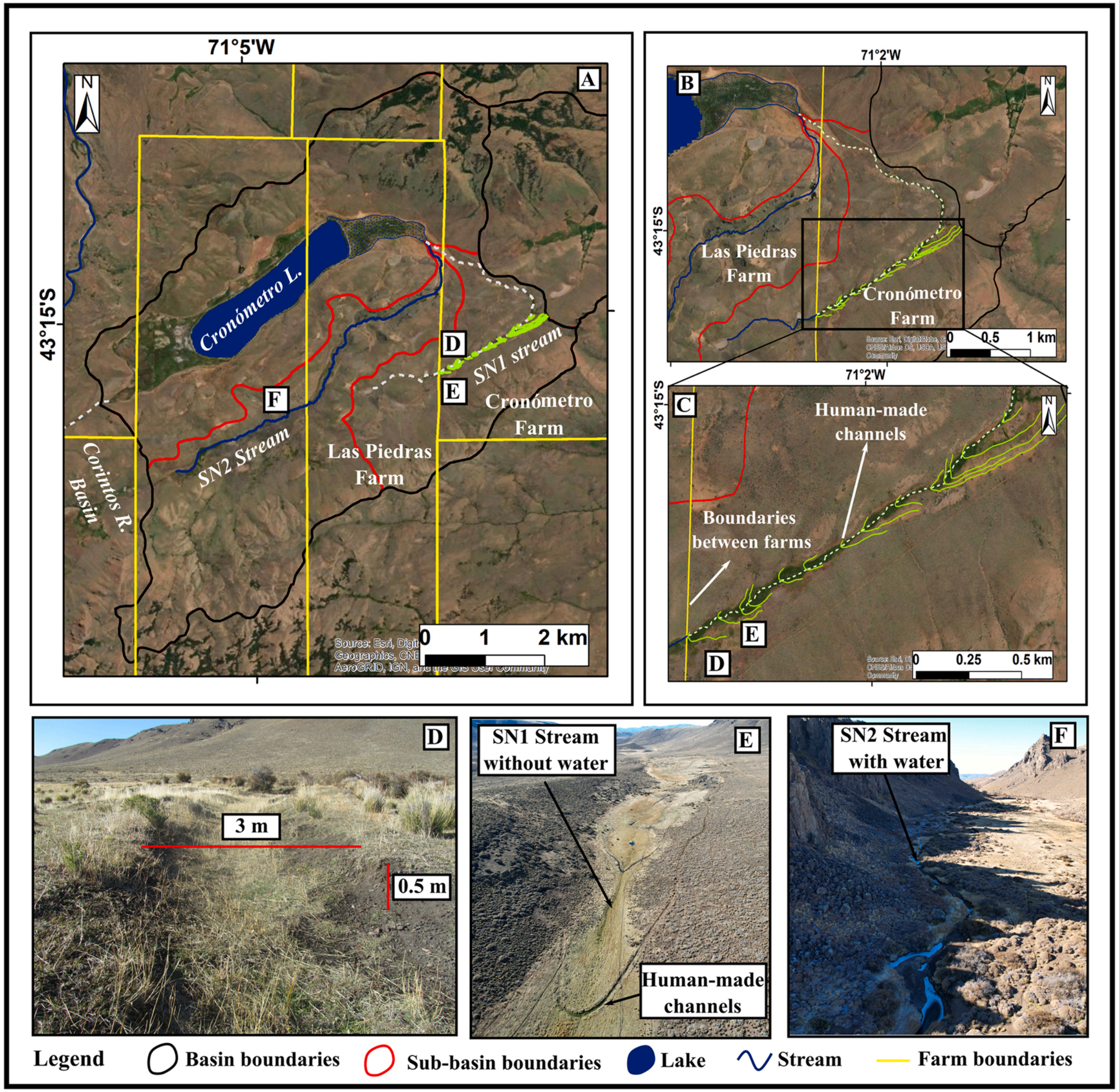

Fig. 2. Geomorphological changes in the Cronómetro Lake basin resulted from the construction of fourteen channels transversally to the Sin Nombre 1 (SN1) stream in its headwaters in 2012. (A) Satellite map of the basin. (B) Location of the channels in the headwaters of the SN1 Stream. (C) The channels were built by the owners of the Cronómetro Farm a few meters from the boundaries with Las Piedras Farm. (D and E) Geomorphology of the channels. (E) The SN1 Stream riverbed is currently interrupted by the channels. Therefore, it remains dry for most of the year. (F) On the contrary, water flows through the SN2 Stream, which has not been altered by human action. We took the photos in panels E and F on the same day in May 2022.

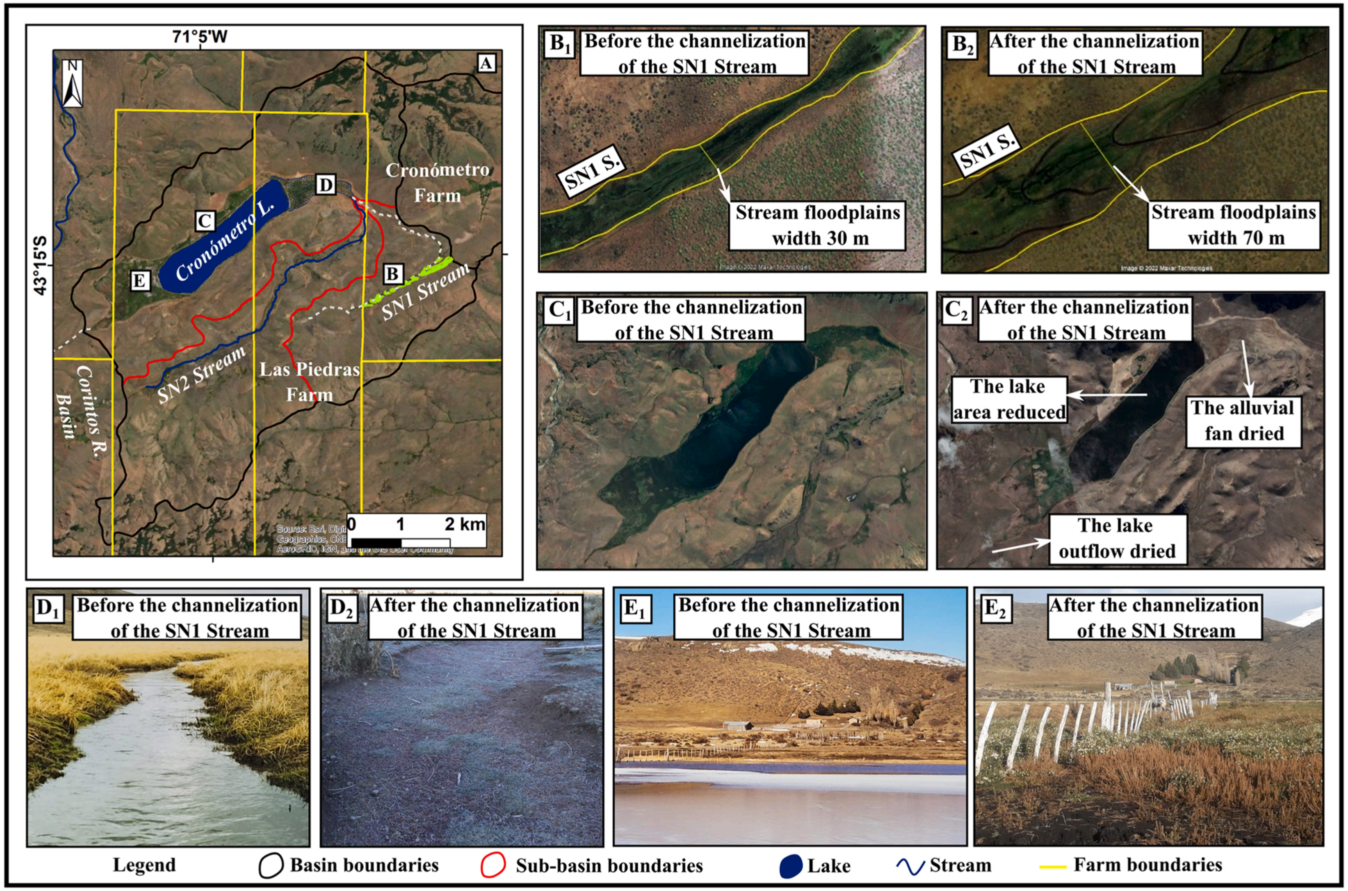

Fig. 3. Geomorphological changes in the Cronómetro Lake basin resulted from the construction of fourteen channels transversally to the SN1 stream in its headwaters in 2012. (A) Satellite map of the basin. (B_1, and B_2) After the channelization of the SN1 stream, its floodplain widens from 30 to 70 m. (C_1, and C_2) Image C_1 corresponds to January 2010, while image C_2 to January 2013. Panel C_2 shows the alluvial fan dry, the area of the lake reduced, and the outflow of the lake dry. (D_1, and D_2) Stream in the alluvial fan located east of the lake before (with water) and after (dry) the channelization of the SN1 stream. (E1, and E_2) The panels show the western coast of the lake before and after the channelization of the SN1 stream. The area of the lake decreased, so the lake outflow dried (E_2).

temporal scales (Vicente-Serrano et al., 2014; Wang et al., 2015; Peña-Gallardo et al., 2016; Yang et al., 2016). In Argentina, different studies found variations in the vegetation status, and waterbodies surface area correlated to humid and drought periods defined using the SPEI (Bohn et al., 2016; Brendel et al., 2017; Scordo et al., 2018b; Seitz et al., 2020). We downloaded the SPEI at a time scale of 6 months for the station located at 43.25° S and 71.25° W, with a spatial resolution of 0.5° from the SPEI Global Drought Monitor global model (https://sac.csic.es/s pei/home.html; Vicente-Serrano and Beguería, 2016). We used the 6-month time scale because time scales between 6 and 10 months are the most suitable to analyze droughts effects in water bodies supplied by temporary fluvial regimes and snow melt (Vicente-Serrano and López-Moreno, 2005). Table 1 summarizes the categories corresponding to each value range of the SPEI index (Wang et al., 2015).

2.1. Statistical analyses

We used linear models (LM) to compare the response variables (lake surface area, NDVI, and precipitation) among the time periods before (2000–2011) and after (2012–2021) the channelization of the SN1 stream. We used the previously mentioned time periods as a categorical explanatory variable in these models. Similarly, we used LM to test if there was a trend in the precipitation (response variable) for the entire study period, with years (2000–2021) as a numerical explanatory variable. We built all the models using the “lm” function in R’s basic package. We used the ANOVA test to evaluate if the effect of the explanatory variables over the response variables was significant in each model by applying the “Anova” function in the "car" package (Zuur et al., 2009; Fox and Weisberg, 2019). In the result section, the ANOVA test results for each model are expressed as *p-values*. In all the models the residuals met the assumptions of normality (Shapiro-Wilks’s Test $p > 0.05$) and homoscedasticity (Levene’s Test $p > 0.05$). All the analyses were performed in the statistical software R version 4.0.2 (R Core Team, 2020). Data and metadata are available in Scordo et al. (2022), and a figure to follow our methodological approach is available at Supplementary Material B.

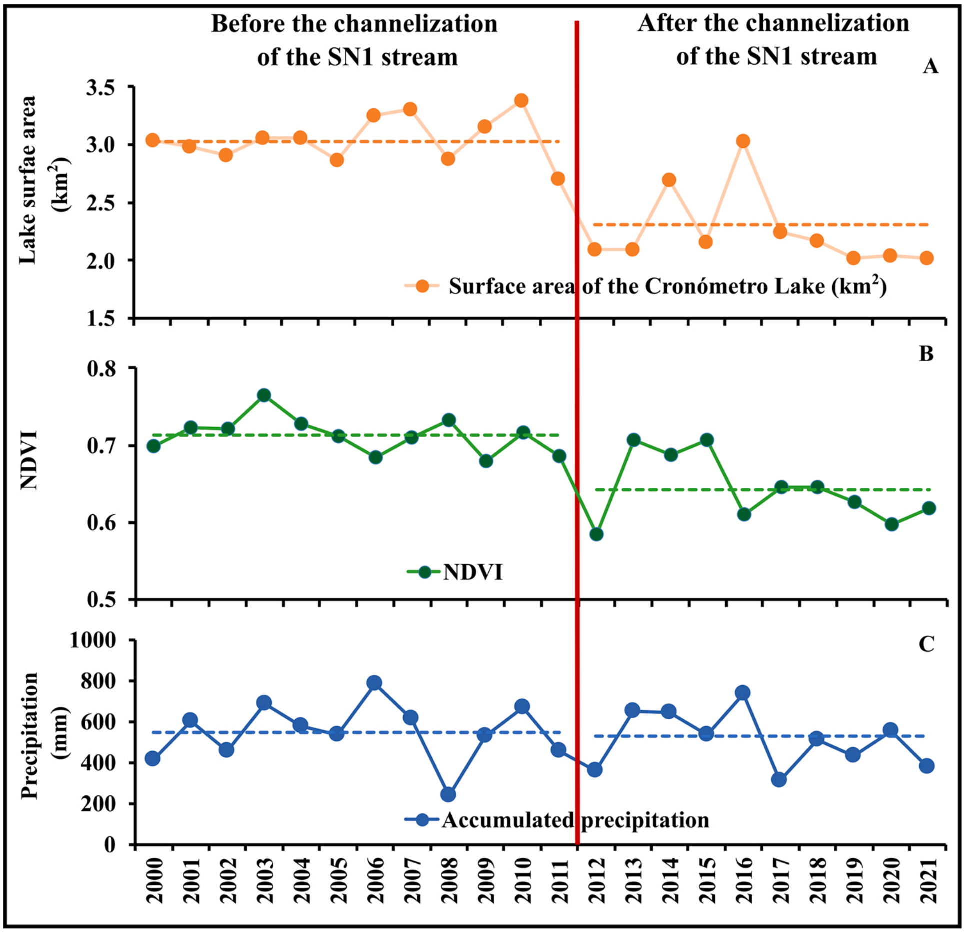

Fig. 4. Interannual fluctuations (dots) of the Cronómetro Lake surface area (A), the NDVI in the alluvial fan located on the eastern shore of the lake (B), and the accumulated precipitation (C) from 2000 to 2021. The red line separates the periods before (2000–2011) and after (2012–2021) the channelization of the SN1 stream in its headwaters. The mean values (dash lines) of the lake area, and the NDVI decreased after the channelization of the SN1 stream.

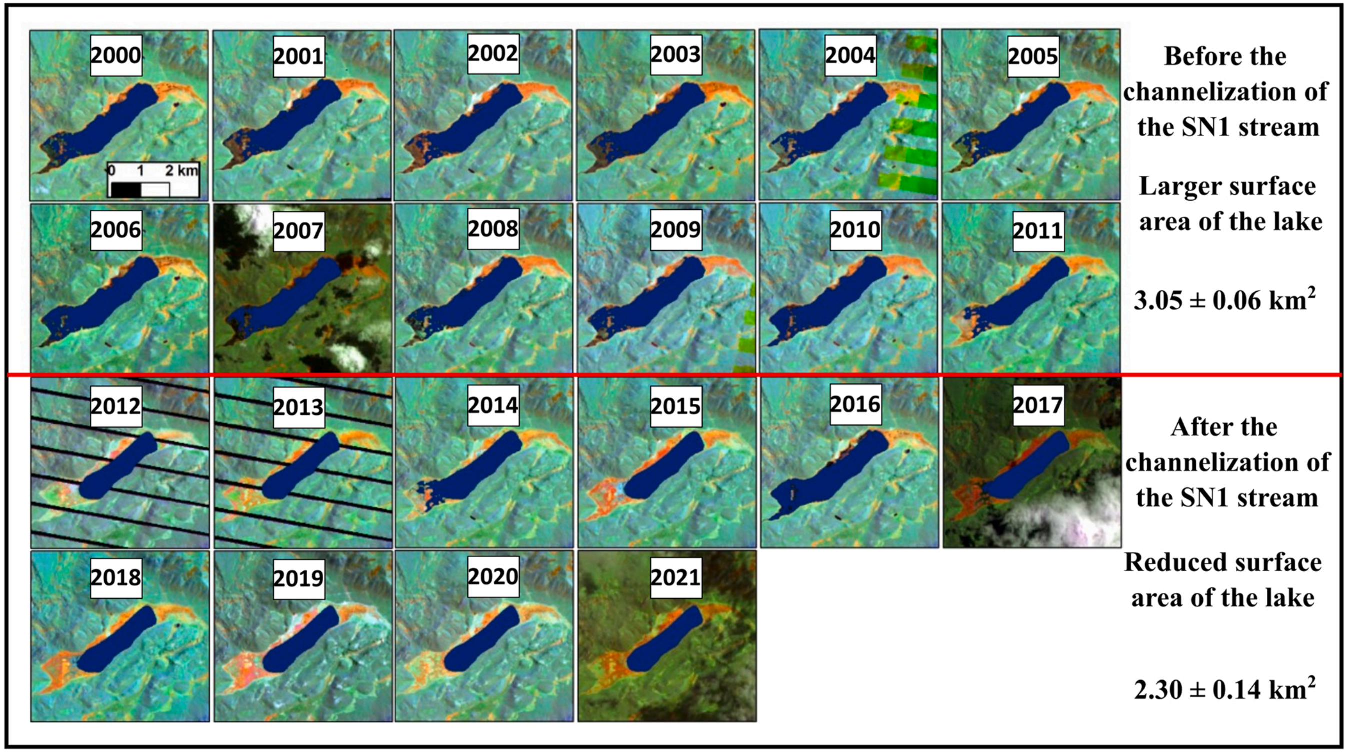

Fig. 5. Interannual fluctuations of the Cronómetro lake surface area obtained with Landsat images from 2000 to 2021. The red line separates the periods before (2000–2011) and after (2012–2021) the channelization of the SN1 stream in its headwaters.

3. Results

3.1. Anthropogenic modification of the SN1 stream geomorphology

During our fieldwork, we observed fourteen (14) human-made horseshoe-shaped channels crossing the SN1 stream transversally in its upper basin within Estancia Cronómetro boundaries (Fig. 2A, B, and C). These channels were built between 2011 and 2012 and modified the floodplains and the hydrology of the SN1 stream (Fig. 2D and E, Fig. 3B_1 and B_2). The human-made channels are 1–3 m wide, 250–850 m long, and 0.5 m deep, and the space between them ranges from 25 to 50 m (Fig. 2D). These channels spread the water of the SN1 stream towards the margins generating a broader floodplain and impeding the SN1 stream from continuing its natural flow (Fig. 3 B_1, and B_2). Cattle use these floodplains for feeding. While flooding land to generate pastures is a common practice in Patagonia, constructing channels that prevent a stream from continuing its natural riverbed is not a usual or accepted practice.

The fourteen channels that cross the riverbed of the SN1 stream were built between February 2011 and September 2012. The high-resolution Maxar images show that in February 2011, no channels crossed the riverbed of the SN1 stream. However, Estancias Las Piedras inhabitants reported these channels' presence in September 2012. The Maxar image from 2013 shows the channels crossing the riverbed of the SN1 stream (Fig. 3B_2) confirming what the inhabitants of Estancia Las Piedras reported in 2012.

The SN1 stream flowed naturally in its riverbed, and the width of the stream floodplain was 30 m on average before the construction of the channels (before 2012; Fig. 3B_1). While after the channels were built, the riverbed of the SN1 stream was no longer continuous, and its floodplain width increased to 70 m (After 2012; Fig. 3B_2). On the contrary, in all the analyzed images, we observed water flowing on the SN2 stream, and its floodplain width (50 m on average) remained unchanged. The photos we took during our fieldwork (Fig. 2E and F) corroborated what we observed in the remote sensing images; the SN1 stream flow is interrupted by the human-made channels, while water flows through the SN2 stream, which has no anthropogenic intervention.

The SN1 stream sub-basin has an area of 7.8 km^2, representing 20% (39.3 km^2) of the total Cronómetro Lake drainage basin. Therefore, if the SN1 stream dries because its channelization, it may deprive Cronómetro Lake of 20% of the surface contributions it received before the construction of the channels. Furthermore, due to the channelization of the SN1 stream headwaters, its flow does not reach the alluvial fan before the lake. Therefore, the streams of the alluvial fan that before 2012 remained with water for most of the year today are primarily dry (Fig. 3 C_1, C_2, D_1, and D_2).

3.2. Lake surface area

The mean surface area of Cronómetro Lake decreased by 25% after the channelization of the SN1 stream in 2012. From 2000–2011, the mean (± SE) surface area (3.05 ± 0.08 km^2) of Cronómetro Lake was significantly ($p < 0.01$) higher than in the period 2012–2021 (2.27 ± 0.09 km^2) (Figs. 4A and 5; Supplementary Material A1). The surface area of the lake reached its minimum values (2.00 km^2) during the last three years (2019, 2020, and 2021) of the study period. The lake surface area in 2019, 2020 and 2021, decreased by 34% compared to its mean surface area during 2000–2011 (Figs. 4A, and 5). Currently, due to the reduction in the surface area of the Cronómetro Lake, this waterbody has no outflow toward the Corintos River (Fig. 3 C_1, C_2, E_1, and E_2).

3.3. Vegetation status in the alluvial fan located on the eastern shore of the lake

The vegetation status (based on NDVI values) in the alluvial fan located on the eastern shore of the Cronómetro Lake decreased by 9% after the channelization of the SN1 stream in 2012 (Fig. 4B and Supplementary material C). From 2000–2011, the mean (± SE) NDVI value (0.71 ± 0.01) in the alluvial fan was significantly ($p < 0.01$) higher than in the period 2012–2021 (0.64 ± 0.01) (Fig. 4B; Supplementary material A2; Supplementary Material C). The vegetation status in the alluvial fan reached its minimum values ($\leq$0.60) in 2012, 2020, and 2021 after the channelization of the SN1 stream. NDVI values lower than 0.6 is the result of sparse or senescing vegetation.

3.4. Precipitation

From 2000–2021, the precipitation does not present a trend ($p = 0.43$; Slope ± SE = −3.82 ± 4.75 mm/yr; Supplementary Material A4) that would explain the reduction in the surface area of the Cronómetro Lake or the vegetation status (Fig. 4C). From 2000–2011 the average (± SE) accumulated precipitation (547 ± 41 mm) was not significantly different ($p < 0.56$) than in the period 2012–2021 (511 ± 45 mm; Supplementary Material A3). The year 2008 presented the minimum accumulated precipitation value (236 mm) and occurred before the channelization of the SN1 stream. The precipitation in 2008 was 45% lower than the average precipitation after the channelization of the SN1 stream (from 2012 to 2021). However, the surface area of the lake during the year 2008 (2.88 km^2) was 6% higher than during 2012–2021 (Fig. 4A). This indicates that even under extremely low rainfall conditions, the area of the Cronómetro Lake should not have decreased to its present values.

3.5. Standardized Precipitation and Evaporation Index (SPEI)

The SPEI data reveal no extreme drought conditions from 2014 to 2021 in the region of the Cronómetro Lake (Fig. 6). From 2001–2011, 28% of the months presented dry conditions, 48% presented humid conditions, and 24% presented normal conditions. From 2012–2021, only 5% of the months were dry, 55% were humid, and 40% presented normal conditions. This analysis shows that drought conditions did not prevail after 2012. Therefore, drought conditions were not the cause of the reduction in the lake area and vegetation status.

4. Discussion

Our study shows anthropogenic impact is the leading cause of the reduction in the Cronómetro Lake area. The area of Cronómetro Lake decreased by 34% in the last ten years. The reduction in the Lake area started in 2012, which coincides with the construction of fourteen channels perpendicular to the riverbed of the SN1 stream. The SN1 stream is one of the main tributaries of Cronómetro Lake. The channelization of the SN1 stream in its upper basin prevents its water from reaching the Cronómetro Lake. From 2012–2021, we have not observed a decrease in local rainfall or an increase in the severity or duration of drought periods. Therefore, we suggest that the channelization of the SN1 stream is the cause of the lake's morphometric and hydrological changes. The Cronómetro Lake used to have an outflow draining westerly toward the Corintos River basin (Fig. 1C, 3E$_1$, and Fig. 5). However, the reduction of the lake's surface generated the disconnection from its outflow and, consequently, the disconnection from the Corintos River basin (Fig. 3A and E$_2$, and Fig. 5). Currently, the Cronómetro Lake basin is endorheic. Also, reduced water availability has deteriorated vegetation on the eastern shore of the lake.

The water captured for irrigation in the headwaters of the Cronómetro Lake basin caused hydrological and morphological modifications in the basin. There are several examples of anthropogenic actions to favor agricultural activity that resulted in lake surface reduction and river desiccation in other basins in Argentinian Patagonia (Scordo et al., 2017, 2018a, 2020a) and worldwide (Micklin, 2007; Liu et al., 2013; Fazel et al., 2017; Wurtsbaugh et al., 2017). The Aral Sea desiccation is the most iconic case of environmental degradation due to water extraction for economic development (Boroffka et al., 2006; Micklin, 2007; Gaybullaev et al., 2012). Among other cases of lakes that tend to desiccation due to human actions (denominated as lakes with Aral Sea Syndrome) are Lake Urmia (Irak) (AghaKouchak et al., 2015), Lake Chad (Africa) (Coe and Foley, 2001), Great Salt Lake (USA) (Wurtsbaugh et al., 2017), Lake Poopó (Bolivia, South America) (Satgé et al., 2017), Acuelo lagoon (Chile) (Valdés-Pineda et al., 2022) and Colhué Huapí(Argentina) (Scordo et al., 2017, 2018a, 2020a).

The Cronometro Lake reduction due to anthropogenic activity occurred in the context where human activities, such as hydroelectric and agricultural production, oil and gas extraction, introduction of non-native species, and tourism, are degrading other Patagonian Lakes (Ortubay et al., 2006; Alfonso et al., 2020; Scordo et al., 2020a; b). The rivers and lakes, especially in the Patagonian plains, are the only water source for human consumption and the development of economic activities. Furthermore, the population in Patagonia is increasing with higher demand and impact on water resources (INDEC, 2001, 2010). For example, human pressure on water resources and infrastructure built without a previous environmental impact study caused the disappearance of the Colhué Huapí Lake, the largest lake in the Patagonian plains (Scordo et al., 2020a). The drought of the Colhué Huapí resulted in water scarcity problems for agricultural activities and fisher families' relocation (Tejedo, 2003). In Argentine Patagonia, there are almost no water management committees to work toward defining water uses at a basin level. The extensive Patagonian territories, added to the lack of controls on water use, favor excessive water extraction without penalties (Scordo, 2018). In particular, the Cronómetro Lake basin does not have a water management committee that controls water use. Implementing a committee working at the basin level could generate consensus on the use of water that would prevent Cronometro Lake from disappearing.

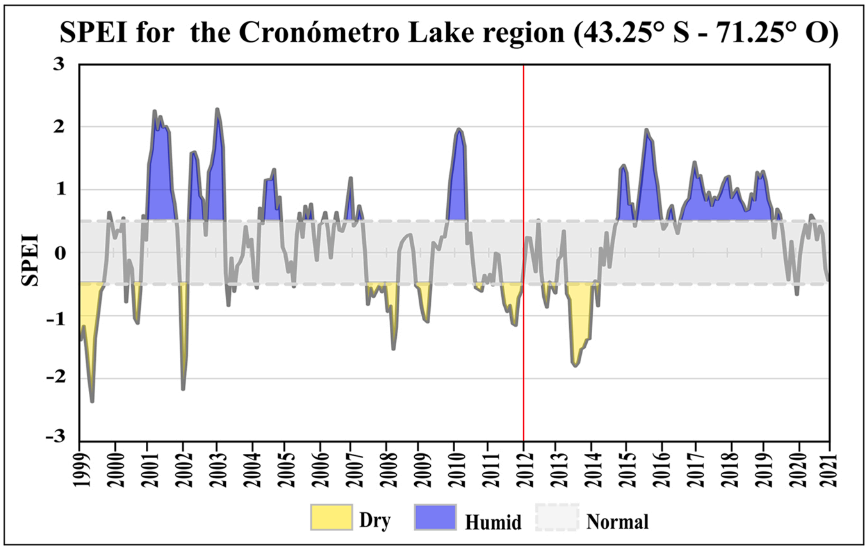

Fig. 6. Monthly fluctuations (grey line) of the Standardized Precipitation and Evaporation Index (SPEI) from 2000 to 2021 in the Cronómetro Lake region. The red line separates the periods before (2000–2011) and after (2012–2021) the channelization of the SN1 stream in its headwaters. Drought conditions have not prevailed since 2014.

The diversion of water from the SN1 stream caused a loss of hydrological connectivity preventing the transport of water, nutrients, and sediment toward the Cronómetro Lake and rivers downstream, which reduced wildlife habitat. The design of the water diversion channels did not consider a return of the exceeding water to the SN1 stream. Therefore, water entering the irrigation channel decreases its flow and remains available for evaporation, infiltration, and groundwater recharge. Flow reduction by water diversion increases the water residence times and the ratio between channel surface area and volume, resulting in a larger surface area that favors evaporation (Wine et al., 2019; Alger et al., 2021). Also, when the stream flow decrease affects the exchange between the surface and groundwater, potentially depressing the base flows and accelerating the summer discharge recession (Alger et al., 2021). The design of the diversion channels over the riverbed of the SN1 is inefficient for semi-arid regions due to the high evaporation rate, low rainfall, and high-water demand for vegetation (Coes and Pool, 2005). This is evident in our study case, where after the construction of the channels, the SN1 stream lost hydrological connectivity and is prone to desiccation. In contrast, water flows for extended periods on the SN2 stream, which has not been impacted by human construction.

Water diversion from intermittent streams, particularly in the headwater area of an arid or semi-arid region like the SN1 stream, should consider its cumulative impacts on the hydrology, biogeochemistry, and ecology of the entire watershed (Miller, 2005; Wipfli, 2005; Levick et al., 2008). Small-scale reservoirs and low-volume water diversions with an incorrect design and without control can reduce watershed connectivity like a large-scale dam (Deitch et al., 2008; Bauer et al., 2015). Ephemeral and intermittent streams provide the same ecological and hydrological functions as perennial streams by moving water, nutrients, and sediment throughout the watershed (Levick et al., 2008). When the hydrological connectivity of the streams is altered, they cannot function properly and lose their ecological functions to maintain vegetation and wildlife habitat abundance and diversity, and water quality and quantity (Levick et al., 2008; Alger et al., 2021).

The reduction in water availability in the Cronómetro Lake basin caused loss of aquatic and terrestrial ecosystem services, with negative implications for local economic activities. For example, in Cronómetro Lake, rainbow trout's artisanal fish farming industry ended when the lake lost its connection with its outflow and some of its tributaries. Also, before 2012, the Institute for Continental Fishing of the Chubut province used the Cronómetro Lake to raise trout, which then were used to stock lakes across the region. This activity also ended when the lake lost its connection with its outflow and tributaries. Rainbow trout spawn almost exclusively in rivers (Raleigh, 1984). Local fishers claim the number of fish and the quality of the meat decreased after the Cronómetro Lake area decreased, and trout could no longer use the streams for spawning. Furthermore, since 2012, the sheep-cattle economy of the three farms that surround the lake in the lower basin has declined (according to their owners) due to the deterioration of the vegetation. Our remote sensing analysis lined up with the farm owners' claims, as we observed vegetation status has worsened on the east coast of the lake since 2012. Furthermore, lake area retreats cause loss of bird habitats and more frequent dust storms that threaten human health (Wurtsbaugh et al., 2017). Therefore, it is essential to identify the tradeoffs between the direct benefits of consumptive water use in the upper basin and ecosystem services provided by lakes in the lower basin (Wurtsbaugh et al., 2017).

Our study shows that human water subtraction for agronomic activities is the predominant factor in reducing the area of the Cronómetro Lake. Water scarcity is a growing problem worldwide, with agronomic activities concentrating 70% of the water demand (FAO, 2017; Scott et al., 2020). Moreover, future projections expect irrigation expansion will be more significant in low-income countries like Argentina (FAO, 2017). In this scenario, we highlight the importance of calculating a basin water balance before permitting human water diversions to develop economic activities. A water balance allows identifying whether the causes of lake area reduction are water diversions or climate variability (Wurtsbaugh et al., 2017). Also, with a water balance, is it possible to define the water inflow needed to maintain lake ecology (Wurtsbaugh et al., 2017). Without a water balance, natural variability can be an excuse for overlooking a human-driven natural disaster (Wurtsbaugh et al., 2017).

5. Conclusion

We found that water capture for irrigation in the headwaters of the Cronómetro Lake basin caused the reduction in water availability, leading to a decrease in the surface area of the lake and the drought of its outflow. Therefore, the Cronómetro Lake basin lost its connection with the Corintos River basin and became endorheic. These hydrological changes in the basin negatively impacted the ecosystem of the lake and the economic activities in the lower basin.

While this study presents evidence that anthropogenic impact is the leading cause of the reduction in the Cronómetro Lake area, we acknowledge the limitations of our work. There are no data of stream discharge, precipitation, and snow deposition within the basin. The precipitation data we used correspond to a weather station located 20 km west of Cronómetro Lake. Patagonia has a strong precipitation gradient from west to east. Fifty kilometers east of the Andes, precipitation is 1000 mm lower than in the range. The lack of measurement of stream discharge did not allow us to calculate a water balance for the basin or account for the changes in the stream discharge before and after the construction of the channels. We also found no official records regarding the number of trout in the lake or the number of sheep in the farms. Lacking such crucial data did not allow a more specific analysis as regards the economic impact that the hydrological modifications in the upper basin caused in the lower basin. Furthermore, our calculations of lake surface area have uncertainty associated with the pixel size of the Landsat images. The variation in the surface area of lakes is sometimes slight and can be challenging to detect with a 30 × 30 m pixel size. In addition, we did not study how lake areas varied intra-annually. Using images, such as Sentinel, with higher time resolution and smaller pixel size may allow another level of detail for further research. Therefore, if society wishes to restore or preserve Cronómetro Lake, additional resources are desperately needed to install a weather station, promote a stream monitoring program within the basin, and produce new remote sensing studies.

Water subtraction for agricultural irrigation caused the disappearance of other rivers and lakes in Argentinian Patagonian and other regions with arid and semi-arid climates. In such environments, lakes and rivers can be the only water source life depends on. Our study shows that remote sensing techniques are a feasible monitoring tool for extended and remote areas when *in-situ* measurements are impossible due to logistics and costs. We suggest using remote sensing techniques to analyze if lakes are at risk of disappearing worldwide in arid and semi-arid regions with increasing agricultural activities.

CRediT authorship contribution statement

Facundo Scordo: Conceptualization, Data Curation, Methodology, Formal Analysis, Writing- Original draft preparation, Writing- Reviewing and Editing, Project Administration, Resources. **Carina Seitz:** Conceptualization, Methodology, Writing- Original draft preparation, Writing- Reviewing and Editing, Project Administration, Resources. **Juan E. Fiorenza:** Data Curation, Methodology, Formal Analysis, Writing- Reviewing and Editing. **M. Cintia Piccolo:** Conceptualization, Writing- Reviewing and Editing, Project Administration, Resources, Supervision. **Gerardo M. E. Perillo:** Conceptualization, Writing- Reviewing and Editing, Project Administration, Resources, Supervision.

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.

Data availability

Data and metadata are available at Scordo, Facundo; Seitz, Carina; Fiorenza, Juan Esteban; Piccolo, Maria Cintia; Perillo, Gerardo M.E. (2023), “Human impact changes hydrological connectivity in a Patagonian fluvial basin”, Mendeley Data, V1, doi: 10.17632/tnn3f826fh.1

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101315.

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