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Driving factors on wetland water area changes in the arid region of central-western Argentina (32° S) during the last two decades

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ABSTRACT. The wetlands along the Leyes-Tulumaya stream in central-western Argentina (32° S) are part of an old, inactive paleo-stream bed of the Mendoza River. These wetlands have been drastically impacted during the last 20 years, reducing their water areas or even completely drying out. The causes and driving factors of this major environmental impact have yet to be explored. Understanding the interaction of the different natural and/or anthropic factors influencing these wetland area changes in the recent past is imperative to apply proper management and conservation plans. In this contribution, the water areas of three lakes along the Leyes-Tulumaya stream are mapped using a GIS environment from satellite imagery to track variations in the last two decades. Assuming that natural variables have been forcing these environmental changes, annual precipitation, soil moisture, evaporation indexes, and the stream flow of the Mendoza River, are analyzed. Changes in the lake water areas along the Leyes-Tulumaya stream are, however, hardly explained due to these natural variables, so anthropogenic factors might have been key and thus need to be further explored.

Keywords: Wetlands, Environmental changes, Natural forcings, Anthropic forcings, Satellite imagery.

RESUMEN. Variaciones de las áreas de humedales en el centro-oeste de Argentina (32° S) durante las dos últimas décadas: factores dominantes. Los humedales a lo largo del arroyo Leyes-Tulumaya en el centro-oeste de Argentina (32° S) forman parte de un antiguo cauce inactivo del río Mendoza. Estos han sido drásticamente impactados durante los últimos 20 años, lo que reducido sus áreas e incluso algunos se han secado por completo. No obstante, los factores y las causas detrás de este severo impacto ambiental no han sido explorados aún. Esto es importante para comprender la interacción de los diferentes factores naturales y/o antrópicos que han influido en estos humedales durante el último tiempo. En función de lo anterior, en este trabajo se cartografían las áreas de tres lagunas del arroyo Leyes-Tulumaya utilizando un entorno SIG a partir de imágenes satelitales para así identificar cambios en las últimas dos décadas. Al asumir que las variables naturales han forzado estos cambios ambientales, se analizó su relación con la precipitación estival, la humedad del suelo, el índice de evaporación y el caudal del río Mendoza. Sin embargo, las variaciones de las áreas lacustres no muestran relación con estos factores naturales, por lo que forzantes de origen antropogénico podrían ser claves y se recomienda, por lo tanto, que sean explorados en detalle en futuros estudios.

Palabras clave: Humedales, Cambios ambientales, Forzantes naturales, Forzantes antrópicos, Imágenes satelitales.

1. Introduction

Wetlands are essential water reservoirs for our ecosystems, which have been affected by human activity in recent decades on a global scale, producing a devastating impact on numerous plant and animal species that use these spaces as refuges (*e.g.*, Scholz, 2015; Valdés-Pineda *et al.*, 2020; Yang *et al.*, 2020; Machuca-Sepúlveda *et al.*, 2021). The advance of agro-industrial activities has exerted increasing pressure on water resources in these systems, especially in recent decades, due to both the use of more efficient water extraction technologies and higher water consumption for agricultural, industrial, residential, and touristic activities (*e.g.*, Fernández, 2006; Valdés-Pineda *et al.*, 2020, 2022; Yang *et al.*, 2020; Machuca-Sepúlveda *et al.*, 2021). In addition, water bodies in wetland systems often present surface area variations due to climatic and/or environmental forcings, leading the system to stressful situations when combined with anthropic drivers (*e.g.*, Bianchi *et al.*, 2015; Fuentealba *et al.*, 2021).

In central-western Argentina (~32° S), the condition of the wetland systems is critical due to the prevailing arid-semiarid environmental conditions (Roig *et al.*,1991; Rubio *et al.*, 2014; Pereyra *et al.*, 2022). These wetland areas are highly fragile ecosystems given the scarcity of water availability throughout the year, combined with agricultural and urban development pressures. In the study area, one of the main factors influencing regional landscape change has been the growth of the cultivated area at a rate of 427 ha/yr in the middle-lower Mendoza River Basin, representing an increase of 10.4% for the period 1986-2018 when compared to previous estimates (Otta *et al.*, 2022). These changes have induced a greater exploitation of water resources for agricultural irrigation. In fact, four aquifer levels are currently being exploited around the Leyes-Tulumaya system: (1) a phreatic level between 10 and 40 m depth; (2) a first level from 60 to 120 m depth; (3) a second level between 150 and 200 m depth, and (4) a third level from 240 to 350 m depth (Pazos *et al.*, 1993). In the year 1993, a total of 16,000 wells had been registered around the city of Mendoza, with water extraction volume oscillations between dry and wet years of around 560-600 hm^3 and 100 hm^3, respectively, and an estimated average of water annual pumping at around 380 hm^3 (Pazos *et al.*, 1993). Based on historical analyses and satellite imagery, Mirábile *et al.* (2005) recognized a significant surface reduction of the shallow lakes in the study area between 1997 and 2002, which was then linked to the expansion of the agricultural frontier.

The Leyes-Tulumaya system was historically known as part of the Gran Ciénaga del Bermejo and experienced variations in its extension over the last 400 years (Prieto, 2000; Prieto *et al.*, 2008; Prieto and Rojas, 2012) (Fig. 1A, B). In the study area, there is great interest in understanding the causes behind the wetland changes since the ancient system is presently associated with a series of shallow (<10 m deep) lakes similar to oxbows, well preserved along the Leyes-Tulumaya stream (Vitali, 1940; Zambrano, 1978) (Fig. 1C). Action measures have been implemented since the second half of the 20th century, including public policies aimed at the conservation of natural resources and ecosystems under the Ramsar Convention. In consequence, current challenges relate to the changes the wetland system could be subjected to, particularly in the face of climate change scenarios (Fernández Cirelli and Abraham, 2002; Sampietro Vatuone and Peña Monné, 2019; Lauro *et al.*, 2022; Otta *et al.*, 2022).

Under the present climate change conditions, the global and regional impact of anthropic activities on natural ecosystems is exacerbated. Understanding the causality between natural and anthropogenic factors affecting wetlands can provide valuable tools for environmental protection. This study therefore analyses the changes in wetland water areas along the Leyes-Tulumaya system over the last two decades. Regional/local climatic and hydrological variables were analyzed together in order to determine their potential role behind the observed changes in lake surface areas, thus shedding light on how to direct wetland management and protection.

2. Study area

The Leyes-Tulumaya system, formed by a group of shallow lakes, wetlands, and the Leyes-Tulumaya stream, is the remnant of a huge historical wetland located in eastern Mendoza Province in west-central Argentina, at 610-680 m a.s.l. (Vitali, 1940; Zambrano, 1978) (Fig. 1B, C). The Leyes-Tulumaya stream corresponds to a ~N-S paleo-stream bed of the Mendoza River, emerging from an upwelling area near 32°59’ S/68°39’ W and extending for

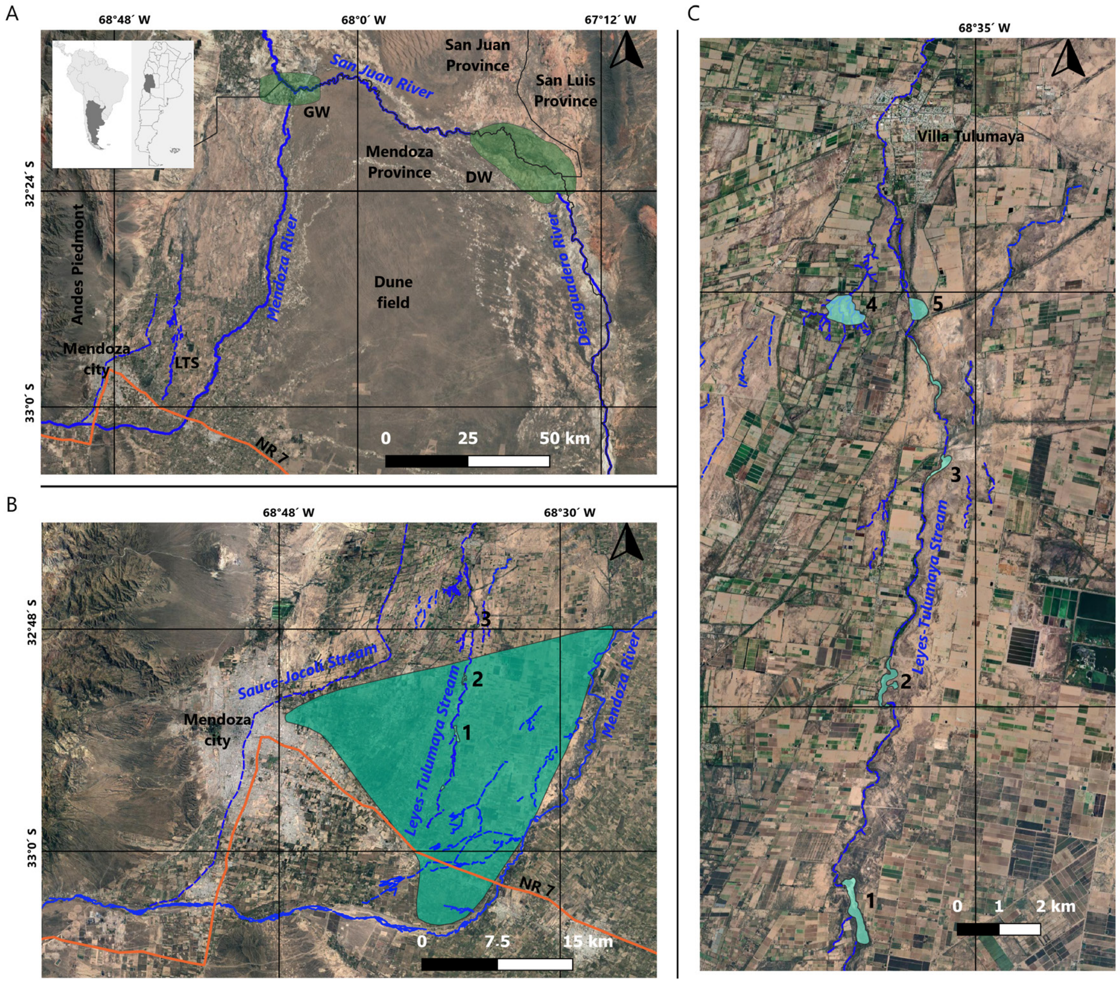

FIG. 1. Satellite image of the study area. **A**. Subregional figure with main rivers in blue. LTS: Leyes-Tulumaya system, GW: Lagunas de Guanacache wetland, DW: Desaguadero wetlands, and NR 7: National Route 7. **B.** Maximum surface of the Gran Ciénaga del Bermejo wetland at around year 1802 (light green area; modified from Prieto *et al*., 2008), with main streams and rivers in blue. **C.** Interconnected lakes along the Leyes-Tulumaya stream: (1) El Viborón, (2) La Paloma, (3) De Soria, (4) Lauriente, and (5) Montenegro. Historical lake locations taken from Mirábile *et al*. (2005).

about 35 km in a semi-straight line northwards from the town of Villa Tulumaya (Fig. 1C). A series of interconnected oxbows occur along this stream, called ponds and swamps in the literature (Prieto, 2000) and locally known as lakes (Fig. 1C). The El Viborón, La Paloma, and De Soria lakes are preserved at present while other historical lakes (*e.g.*, the Lauriente and Montenegro) disappeared as they were drained for agricultural practices as a consequence of the expansion of the agriculture frontier in the 1970s (Mirábile *et al*., 2005) (Fig. 1C).

2.1. Physiographic characteristics of the study area

The lakes of the Leyes-Tulumaya system are located in the fluvial-alluvial plain of the Mendoza River at the Andes piedmont (Fig. 1A). This extensive geomorphological unit is limited to the south by the current course of the Mendoza River, to the north by the Lagunas de Guanacache wetland, which is where the Mendoza and San Juan rivers merge, and to the east by the large sandy fluvial-aeolian plains of the Desaguadero River (Sepúlveda, 2001;

Devincenzi *et al*., 2015) (Fig. 1A). The sedimentary infill of this fluvial-alluvial plain is the result of the erosion of different lithologies that crop out in the mountain (western) areas of the upper Mendoza River Basin (González Díaz and Fauqué, 1993; Sepúlveda, 2001). In the Late Cenozoic, tectonic subsidence favored a large accumulation of sediments that reaches a current maximum thickness of up to 600 m (Rodríguez and Barton, 1993; Sepúlveda, 2001). This basin configuration was apparently structurally controlled by a submeridional fault system that would have conditioned the current disposition of the Mendoza riverbed (Zambrano, 1978).

A semi-arid climate characterizes the region with a mean annual precipitation of 210 mm (Mendoza Aero Meteorological station, https://www.smn.gob.ar/observaciones). Precipitation mainly occurs during the warmest months (December to March, 75%) through easterly surface winds and convective storms mainly forced by the South Atlantic Anticyclone (*e.g*., Viale and Garreaud, 2014; Viale *et al*., 2019). The Mendoza River is fed by snow melting in the Andes (Fig. 2). There, snowfall occurs between June and August, associated with frontal systems from the west along narrow latitudinal bands known as storm tracks (Garreaud *et al*., 2008). In the Leyes-Tulumaya area, the mean annual temperature is 17.1 °C, with a mean maximum during January of 32.3 °C and a mean minimum of 2.1 °C in July. Consequently, this region exhibits a water deficit, with an average evapotranspiration rate of 2.13 mm/day in summer (https://goo.su/54gdEq4).

Native vegetation communities associated with the Leyes-Tulumaya system belong to the Monte Phytogeographic Province (Oyarzabal *et al*., 2018). The dominant xerophytic shrubland is characterized by plants with small leaves, reduced to thorns or absent, waxy or resinous leaves and thickened cuticles belonging to the Zygophyllaceae family and particularly represented by different species of the genus Larrea (*Larrea divaricata*, *Larrea cuneifolia*, *Larrea nitida* and *Larrea ameghinoi*). The arboreal stratum includes *Parkinsonia aculeata* and isolated specimens of *Neltuma flexuosa* and *Geoffroea decorticans*, accompanied by cactuses such as *Denmoza rhodacantha*, *Cereus* sp. and *Echinopsis sp*. Open azonal forests of *Neltuma* sp., *Salix humboldtiana* and *Acacia visco* develop associated with soils rich in silt and clay content (Oyarzabal *et al*., 2018). On the other hand, halophytic communities including *Atriplex argentina*, *Atriplex spegazzinii*, *Atriplex lampa*, *Suaeda divaricata*, and *Plectrocarpa tetracantha*, among others, along with abundant species of the Cactaceae family (*e.g*., *Denmoza rhodacantha*, *Opuntia* sp.) are present in well-drained sandy-clayey soils (Roig *et al*., 1996). The halophytic vegetation has an upper stratum composed of *Allenrolfea vaginata*, *Cyclolepis genistoides*, *Atriplex vulgatissima*, and *Neltuma alpataco*, and a lower stratum of *Neltuma strombulifera* in areas with clayey soils where swamps form periodically, but if the flooding period lasts significantly longer, species like *Baccharis spartioides*, *Distichlis spicata*, and *Tessaria absinthioides* dominate instead (Roig *et al*., 1996).

2.2. The Leyes-Tulumaya stream system

The Leyes-Tulumaya stream is not permanent at present since surface runoff (which depends on groundwater fluctuations and the frequency/magnitude of rainfall) is not enough to allow for surface water to circulate through the system. This system has been affected by human intervention, such as modification on the stream paths, partial damming, and stream bed invasion for growing crops or urban development. These anthropic changes, along with the passive (*i.e*., low speed) surface water circulation through the system, have led to water stagnation resulting in the El Viborón, La Paloma, and De Soria lakes (Fig. 1C).

As mentioned in the Introduction, the Leyes-Tulumaya system used to be part of a huge swamp known as the Gran Ciénaga del Bermejo, whose first historical records date back to the arrival of the Spaniards in 1561 AD. Based on historical maps, this wetland presented its maximum area in the mid-1800s, with an approximate surface of 45,000 ha (Fig. 1B). At its largest, the Gran Ciénaga del Bermejo was characterized as a network of 'green islands' with variable water extension and marshy sectors ideal for cattle breeding. Their surroundings were inhabited by the Huarpe people whose economy was based on fishing and goods exchange (Prieto, 2000; Prieto *et al*., 2008).

This extensive swamp decreased in area in the following decades in response to the seasonal discharges of the Mendoza River. Thus, any interannual episodic areal increase/decrease of the Gran Ciénaga del Bermejo was related to the increase/decrease of the Mendoza River seasonal streamflow (Prieto, 2000).

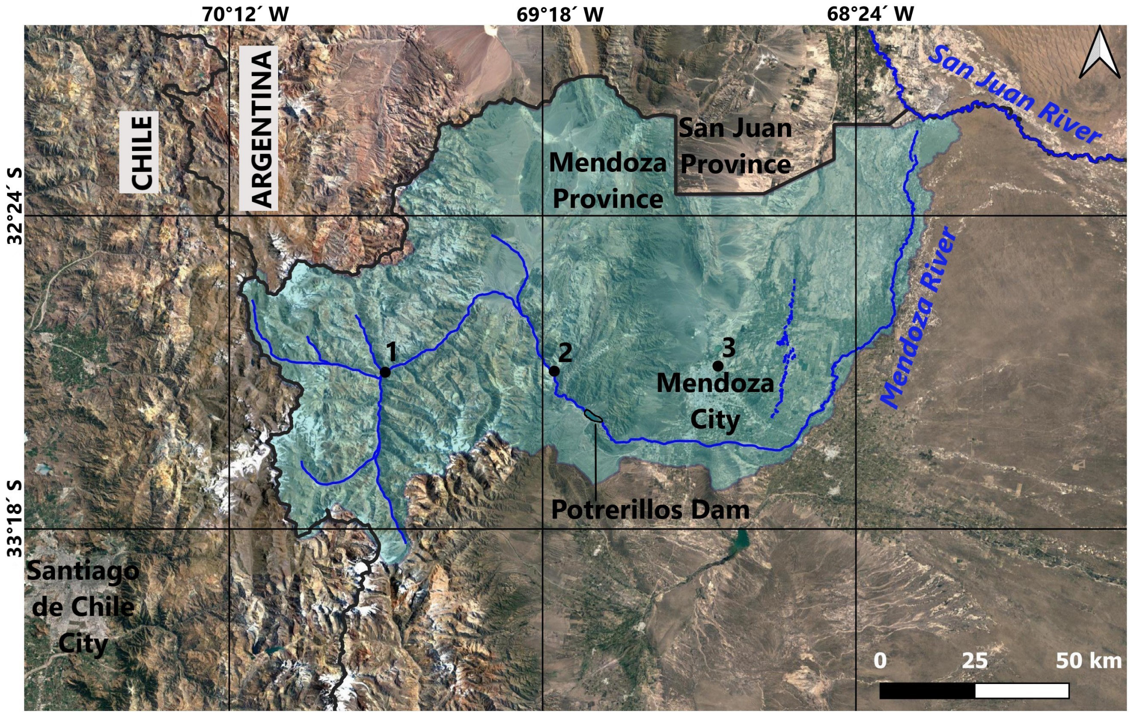

FIG. 2. Satellite image of the Mendoza River Basin. Basin boundaries are shown in aquamarine. Numbers refer to the gauge stations used to measure mean monthly streamflow along the Mendoza River: (1) Punta de Vacas, and (2) Guido. (3) refers to the Mendoza Aero Meteorological Station, used for mean monthly and annual precipitation records.

Based on early 18th century chronicles of ancient settlers (Prieto, 2000), the extension of the Gran Ciénaga del Bermejo showed a marked increase during the Little Ice Age (1520-1660 AD in the Southern Hemisphere; Villalba, 1994). Historical maps from the 18th century show how the surplus water from the first agricultural plots and the Mendoza River contributed to maintaining the wetland environment, even with a semi-permanent presence of water bodies. The first important modifications were observed at the beginning of the 20th century, associated with the drainage of wetland areas by local settlers for the development of activities such as agriculture and cattle raising. This process was dramatically accelerated with the intervention of public policies to improve irrigation systems and the allocation of more arable lands (Prieto, 2000).

Based on historical records, climatic variations and anthropic activities on a regional scale may have been responsible for changes in the Leyes-Tulumaya system, modifying the geographic space drastically (Prieto *et al*., 2008). While the area is geologically conditioned from a morphotectonic point of view, since it is a depression collecting both surface and subsurface water, the activities directly aimed to drain the wetland were likely one of the main drivers of change during the 20th century.

Upstream the Leyes-Tulumaya system, in the Mendoza River, the construction of the Potrerillos Dam (1,270 m a.s.l.) was certainly one of the main modifications to the basin during the 21st century (Fig. 2). The dam was finished in 2003 and provides water yearlong for the population and the productive agricultural sector of northern Mendoza Province (Salomón *et al*., 2008). Although regulated, the Mendoza River flows downstream the dam with variable flow regimes related to the agricultural cycle, particularly in periods of water deficit.

3. Materials and methods

3.1. Antecedents and remote sensed imagery

Background knowledge on the Leyes-Tulumaya system, with a focus on the Gran Ciénaga del Bermejo, was built upon the compilation of previous studies (from the 1940s to the present), public information, geological information, and published reports (Vitali, 1940; Romanella, 1957; Zambrano, 1978; Prieto, 2000; Rodríguez and Barton, 1993; Sepúlveda, 2001; Mirábile *et al.*, 2005; Prieto *et al.*, 2008; Prieto and Rojas, 2012; Gómez *et al.*, 2014). These literature data were complemented with high-resolution satellite imagery for each lake (Landsat 8 and Maxar Technologies, freely available on Google Earth), spanning the years 2003-2021. The temporal image resolution varied from lake to lake, so direct comparisons were not always possible (Supplementary Table S1). Pre-2003 data were retrieved by using Landsat 7 imagery, which provides good temporal coverage since the 1980s although the spatial resolution was not as detailed (30 m per pixel). In consequence, the pre-2003 data were not used to determine the area of the lakes along the Leyes-Tulumaya stream.

3.2. Streamflow and meteorological data

The mean annual and monthly streamflows of the Mendoza River were obtained from the National Water Institute (INA by its acronym in Spanish). Only gauge stations upstream the Potrerillos Dam were chosen: Punta de Vacas (32°45’ S/69°50’ W, 2,380 m a.s.l.; series 1949-2021), and Guido (32°50’ S/69°16’ W, 1,540 m a.s.l.; series 1956-2021) (see gauge locations in Fig. 2). The selection of upstream gauge stations only was due to the limited data from gauge stations downstream the Potrerillos Dam since the discharges are immediately deviated for hydroelectric and irrigation purposes.

Cumulative annual and monthly precipitation data were obtained from the Mendoza Aero meteorological station (32°50’ S/68°48’ W, 700 m a.s.l.; series 1956-2021) due to its proximity to the study area (see location in Fig. 2). Snow precipitation data (taken from the Argentinian and Chilean Andes Snow Observatory platform, https://observatorioandino.com/nieve/) was not included within the analyzed climatic variables due to a strong correlation with the Mendoza River streamflow data for the period 2000-2022. This correlation is not new, being discussed in Masiokas *et al.* (2006), among others.

3.3. Topographic and lake surface data

Digital topographic data were retrieved from the ALOS Global Digital Surface Model, with a vertical accuracy of 10 m that can be corrected to 7 m, of the Japan Aerospace Exploration Agency (http://surl.li/zeaafs). A finer spatial resolution of 12.5 m was generated by applying a low-pass filter with a square kernel of 21x21 pixels using the r.neighbors function in a GRASS GIS environment. A morphometric analysis was then performed to highlight landscape features and determine the geomorphological configuration of the area drained by the Leyes-Tulumaya stream (Fig. 3).

The surface extent of the Leyes-Tulumaya system lakes El Viborón, La Paloma, and De Soria were calculated for the period 2003-2021 by loading the satellite images on QGIS (Supplementary Table S1). The temporal surface evolution of each individual lake was analyzed by using 65 images. For each lake, the measured areas were transformed into percentages based on the maximum area recorded during the timespan analyzed and compared across lakes only for data captured at the same time (Figs. 4 and 5). Yearly averages for the years 2003, 2011-15, and 2017-21 were obtained. By May 2022, the El Viborón lake was already fully desiccated and colonized by halophyte plants, as observed during field trip activities.

The analysis of lake areas to differentiate between natural and anthropogenic forcings through satellite monitoring is abundant in the literature (*e.g.*, Kuppel *et al.*, 2015; Houspanossian *et al.*, 2016; Ferrelli, 2020; Otta *et al.*, 2022; Whitworth-Hulse *et al.*, 2023). Recent studies have also integrated remote sensed imagery and statistical tools to elucidate the natural and/or artificial factors responsible for variations in different water bodies (*e.g.*, Sumiya *et al.*, 2020; Fuentealba *et al.*, 2021; Wang *et al.*, 2021; Soria and Apostolova, 2022).

3.4 Statistical correlations and ancillary information

The hydroclimatic variables considered in this study were (1) the streamflow of the Mendoza

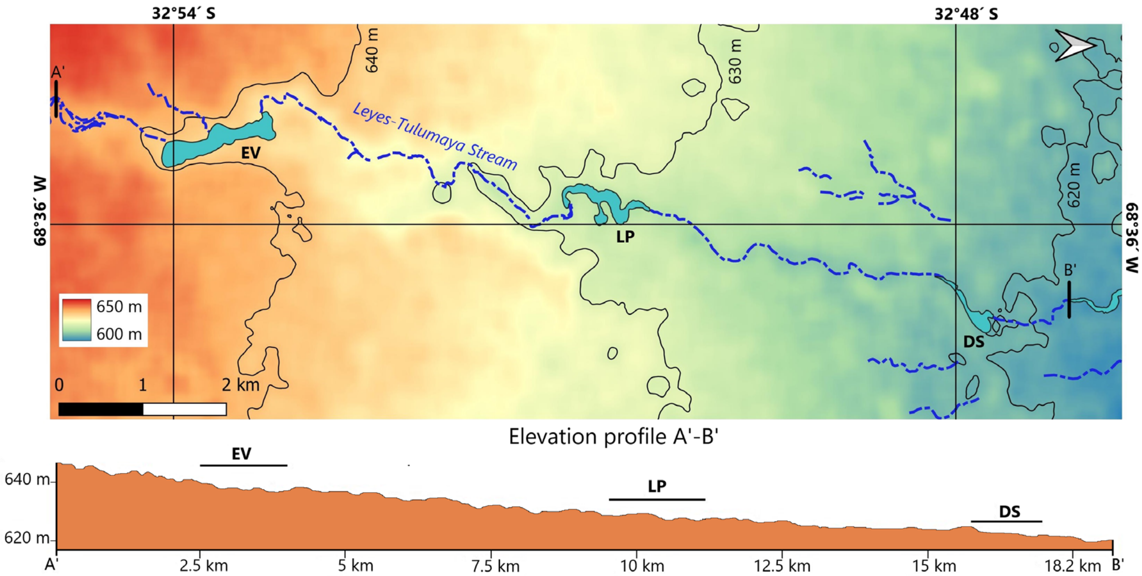

FIG. 3. Topographic map along the Leyes-Tulumaya stream system. North arrow points to the right. Bottom: Topographic profile along the main course of the stream, depicting the location of the El Viborón (EV), La Paloma (LP), and De Soria (DS) lakes.

River, and (2) the precipitation in the Mendoza Aero meteorological station (Fig. 2), both on an annual and monthly basis. To correlate these two variables with the lake area data for the last two decades, the Pearson correlation coefficient was used.

The Global Lake Evaporation Volume (GLEV) dataset, which provides surface area and evaporation volumes for more than a million lakes and water reservoirs worldwide (Zhao *et al*., 2022), does not include information about the Leyes-Tulumaya lakes. To remedy this, in the present study an artificial water body associated with a sewage treatment plant (El Paramillo Wastewater Treatment Plant), close to the Leyes-Tulumaya system (32°50' S/68°33' W) was analyzed in Google Earth Engine. Data for this artificial reservoir were taken from the GLEV dataset as well, thus providing useful monthly information for the period 1985-2018. As for the vegetation and soil water contents, they were calculated by using the Normalized Differential Moisture Index (NDMI) by means of Sentinel-2 MSI Level-1C imagery (spatial resolution of 10 m in band B8 and 20 m in band B11) with Google Earth Engine for the 2016-2022 period (satellite data only available for this period). The NDMI was calculated by comparing bands 8 and 11 for each pixel during the analyzed period by keeping the coarser resolution (Strashok *et al*., 2022). NDMI values were also obtained for a specific area and plotted over time, highlighting the inter-annual variations of the index.

4. Results

4.1. Topographic controls on lake formation along the Leyes-Tulumaya system

The topographic profile of the Leyes-Tulumaya stream along ~18 km shows a progressive elevation decrease towards the north from a maximum of 644 m a.s.l. in the southern area to a minimum of 617 m a.s.l. in the northern area (stream slope of 0.086°) (Fig. 3). Therefore, groundwater flows from south to north, propelling that lakes located at lower altitudes have more stable areas (Gomez *et al*., 2024).

4.2. Lake area dynamics along the Leyes-Tulumaya system

The lake area changes along the Leyes-Tulumaya system reveal a similar evolution although at different rates (Fig. 4). The El Viborón lake, elongated in a north-south direction, reached a maximum extent

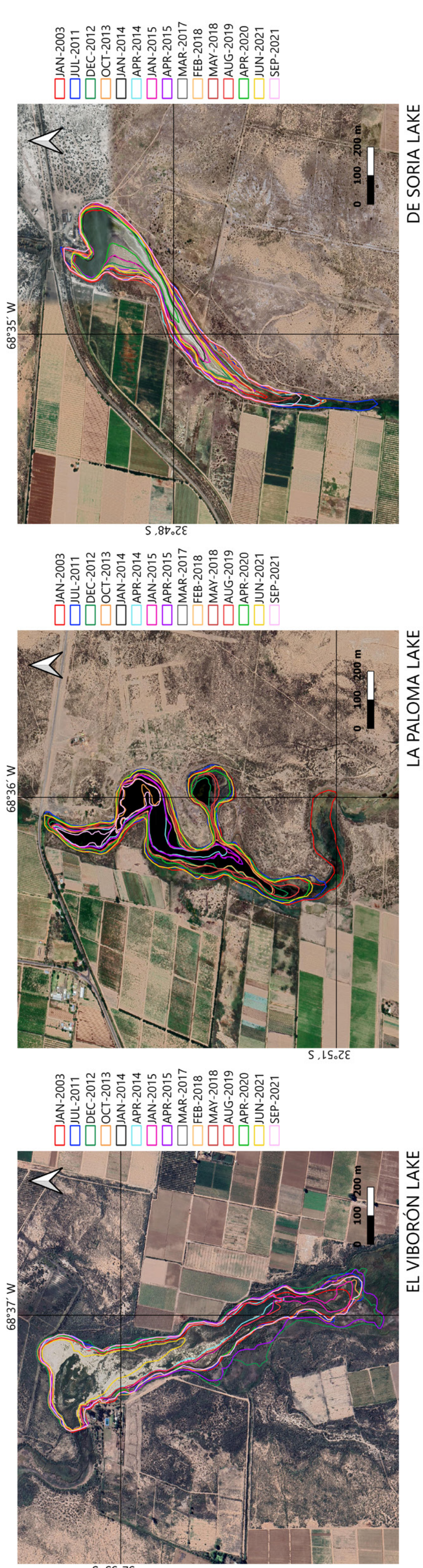

FIG. 4. Areal extension of the Leyes-Tulumaya system lakes from January 2003 to September 2021. Areas represented only for the months where data were obtained for all lakes (see Supplementary Table S1).

in July 2011 (~280,000 m^2) and a minimum in June 2021 (~70,000 m^2) (Figs. 4 and 5; Table 1). This lake showed area variations of 40% at the beginning of the record up to 75% at the end of the period analyzed. After a transient recovery in September 2021, this lake dried up in May 2022. The La Paloma lake, characterized by a meandering shape (Fig. 4), had its maximum area in January 2003 (~180,000 m^2) while its minimum was recorded in January 2014 (~12,000 m^2) (Figs. 4 and 5; Table 1). This lake showed area variations close to 90% (Fig. 5). The De Soria lake, the northernmost of the three, reached its largest surface area in July 2011 (~135,000 m^2) and its smallest in April 2020 (~40,000 m^2) (Figs. 4 and 5; Table 1). Water area variations of up to 70% were determined (Fig. 5).

Together, these three lakes reached large areas in July 2011, October 2013, April 2014, and August 2019, and small areas in January 2014 and April 2020. In addition, pronounced episodes of lake contraction-expansion were observed in the southernmost part of each lake (Fig. 4), thus reflecting the south-to-north gradient in topography.

The year 2003 marks in the region a sudden and significant increase in the areas used for agricultural activities and urban development, adding pressure on the stream bed system. It is worth noticing that lake water areas remained with no significant changes at least until the year 2011.

4.3. Hydroclimatic variables and their relationship with lake area data

The streamflow of the Mendoza River shows a clear negative trend since around the year 2006, with average values of ~43 m^{3}s^{-1} in the Guido gauge

TABLE 1. MAXIMUM AND MINIMUM LAKE AREAS FOR THE PERIOD 2003-2021.

Lakes	Area (m^2)		Date
El Viborón	Maximum	279,836	Jul-2011
	Minimum	71,150	Jun-2021
La Paloma	Maximum	182,588	Jan-2003
	Minimum	12,630	Jan-2014
De Soria	Maximum	135,236	Jul-2011
	minimum	40,425	Apr-2020

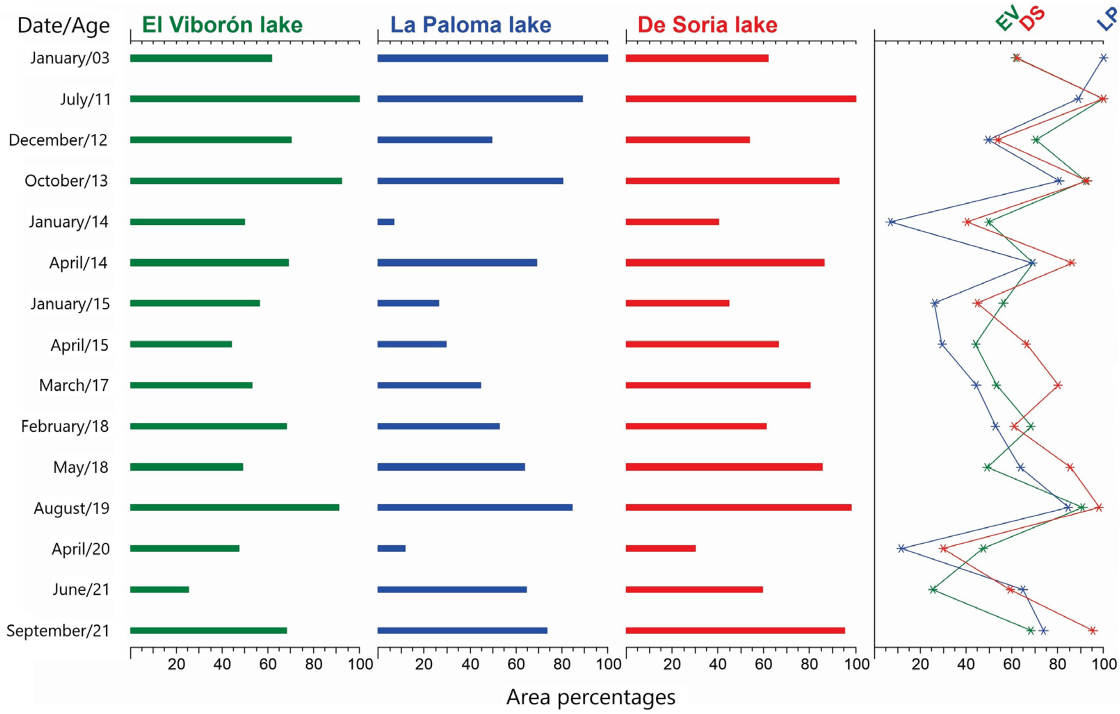

FIG. 5. Area percentages of the Leyes-Tulumaya system lakes El Viborón (EV), La Paloma (LP), and De Soria (DS), from January 2003 to September 2021. Right plot: Integrated temporal series of the three lakes.

and ~6 m^3s^{-1} in the Punta de Vacas gauge (Fig. 6). At Guido, maximum and minimum flow values of ~73 m^3s^{-1} and ~29 m^3s^{-1} were estimated; whereas at Punta de Vacas these were ~12 m^3s^{-1} and ~3 m^3s^{-1} (Fig. 6). The maximum values occurred in the same year (2006) for these two gauges.

The annual precipitation records show that most of it remained above 200 mm, peaking at between 400 and 500 mm in 2001 and 2016 (Fig. 6). The Pearson correlation coefficients of the hydroclimatic parameters (streamflow and precipitation) and the lake areas indicate weak correlations at both annual and monthly timescales (Table 2). This suggests that the lake area dynamics have been independent of precipitation and streamflow, at least for the last two decades.

4.4. Evaporation (GLEV) and soil moisture (NDMI) data

The artificial water body analyzed shows an overall steady increase in the evaporation volume for the 1985-2018 period, with a sudden increase in the early 1990s possibly due to the addition of a new water for sewage effluent treatment (Fig. 7A). The maximum area was 0.82 km^2 and the maximum evaporated volume was $0.16 \cdot 10^6$ m^3 $month^{-1}$, the first occurring in the winter of 2017 and the latter occurring in the summer of 1999.

The NDMI values, on the other hand, show an oscillatory pattern for the 2016-2022 period, with higher values (>0.03) during warmer, rainier months (December to March) and minimum values during colder, drier months (June to September) (Fig. 7B). The discrete peaks observed in the data series may be associated with flooding events after rainfall episodes and/or irrigation of agricultural lands in summertime. When the NDMI values are plotted on a map showing the combination of values for the period 2016-2022, the highest values are observed in cultivated areas, whereas the sector surrounding the Leyes-Tulumaya system lakes exhibits very low (negative) values (Fig. 7C).

During autumn (March to June), there are differences in the NDMI time series before and after 2020 (Fig. 7B). In the first case, NDMI values

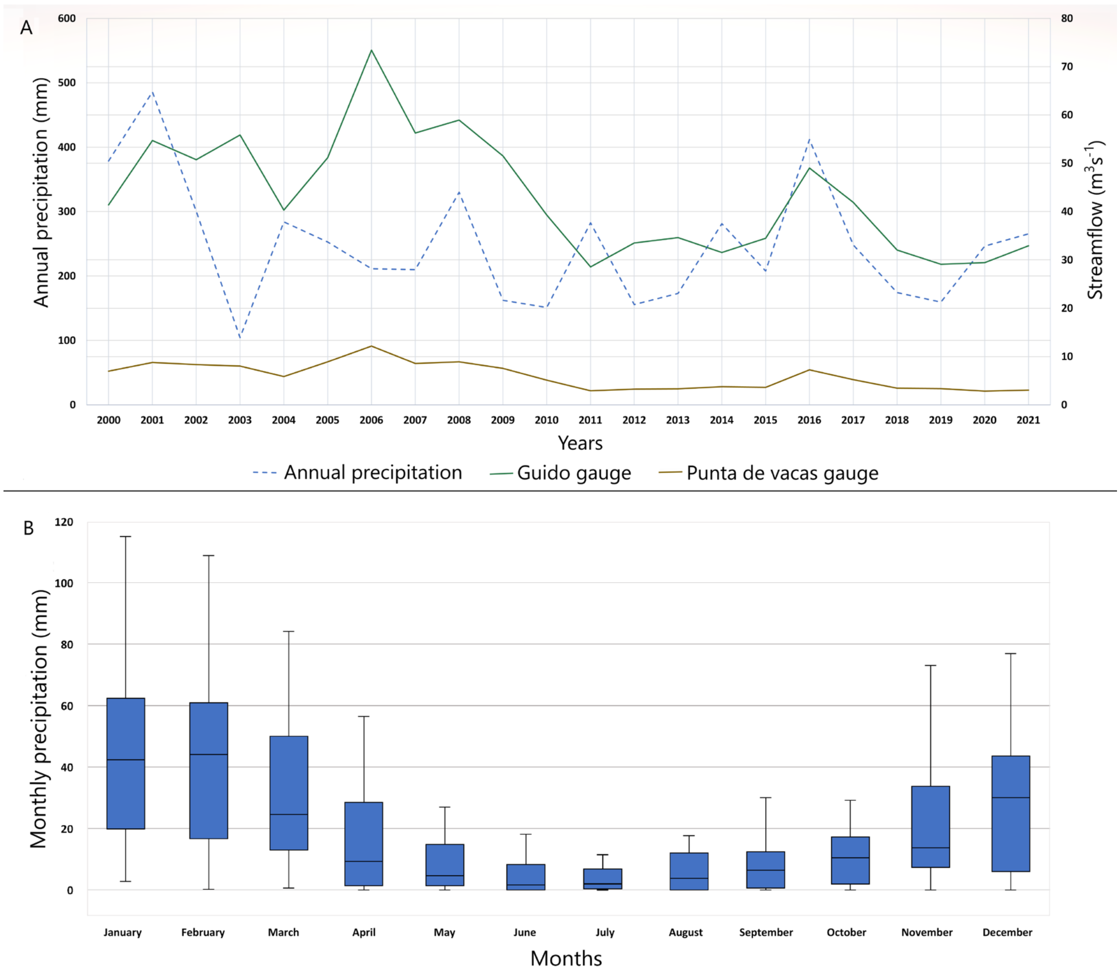

FIG. 6. **A.** Annual precipitation record from the Mendoza Aero Meteorological Station (mm) and streamflow record of the Mendoza River (m^3s^{-1}) at the Guido and Punta de Vacas gauges. **B.** Box and whisker plot showing the monthly precipitation record from the Mendoza Aero Meteorological Station (mm) for the period 2000-2021.

TABLE 2. PEARSON CORRELATION COEFFICIENTS BETWEEN STREAMFLOW AND PRECIPITATION RECORDS VERSUS LAKE AREAS, BOTH ON A MONTHLY AND ANNUAL BASIS, FOR THE PERIOD 2003-2021. NUMBERS ROUNDED TO THE THIRD DECIMAL PLACE.

Annual Records	El Viborón	La Paloma	De Soria
Precipitation at Mendoza Aero	-0.095	-0.474	-0.041
Streamflow at Guido	-0.235	0.331	-0.097
Streamflow at Punta de Vacas	-0.245	0.310	-0.108
Monthly Records	**El Viborón**	**La Paloma**	**De Soria**
Precipitation Mendoza Aero	-0.017	0.044	-0.076
Streamflow at Guido	-0.152	-0.002	-0.412
Streamflow at Punta de Vacas	-0.127	0.251	-0.320

Note: 66/99 data were included for the annual/monthly records correlation with a significance of 0.23/0.19.

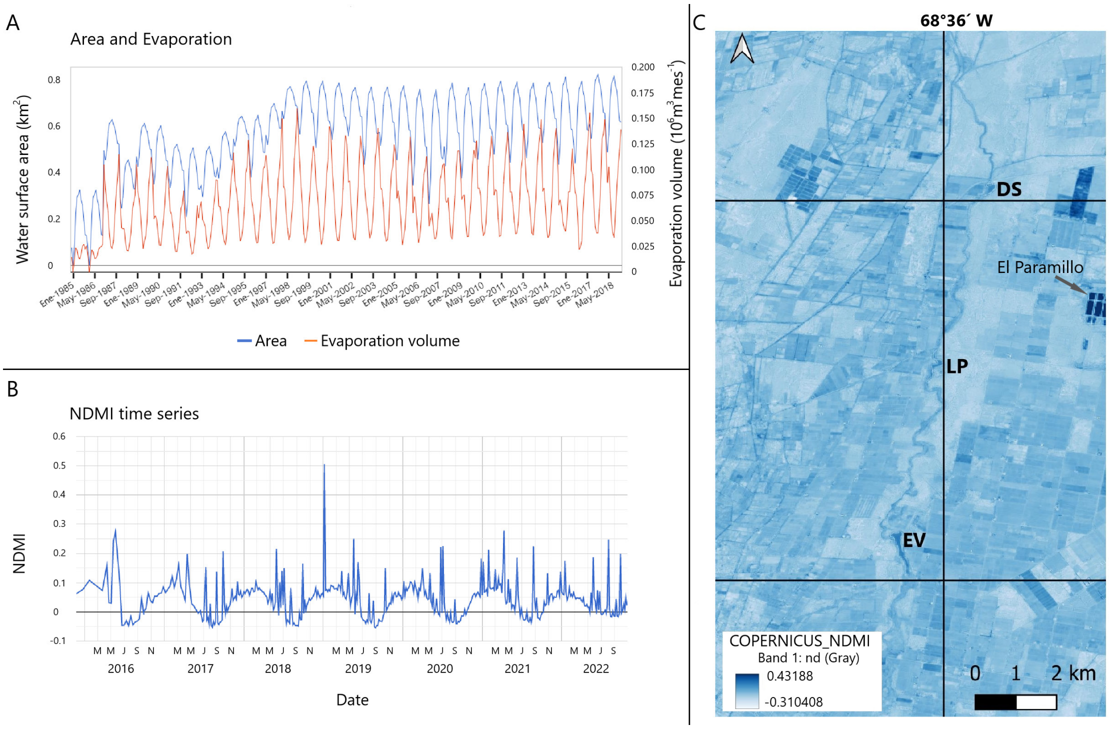

FIG. 7. **A.** Area (in km²) and evaporation volume (in 10^6 m³ per month) for an artificial water body near to the study area based on the Global Lake Evaporation Volume (GLEV) dataset for the 1985-2018 period. **B.** Normalized Difference Moisture Index (NDMI) time series for the 2016-2022 period. Months reported in the chain M(March)-M(May)-J(July)-S(September)-N(November). **C**. Single-band, pseudo color image in the blue range showing the NDMI variations for the 2016-2022 period. Note that the El Paramillo wastewater treatment plant remains with water during the whole time, so this is why it shows a dark blue color. EV: El Viborón, LP: La Paloma, and DS: De Soria.

are typically -0.05, possibly associated with water releases for irrigation, while in the second case they are bit higher, between -0.03 and -0.01, and possibly indicate a higher availability of water resources for crops. In 2022, minimum values oscillate around 0, reflecting less intense dry autumnal periods.

5. Discussion

Regional topography plays an active key role in controlling the water flow pattern of the Leyes-Tulumaya stream, forcing the arrangement of the wetlands along this stream and the presence of shallow lakes like oxbows and/or ponds (Fig. 3). Indeed, Gómez *et al*. (2014) reported that the flow lines of the aquifer follow the northward orientation of the Leyes-Tulumaya stream. The latter implies that those shallow lakes located in upper topographic positions, even only a few meters above other water bodies, will drain to the north. Particularly, it is more feasible to preserve those water bodies located at lower topographic elevations, such as the De Soria lake, than those located higher up, such as the El Viborón lake (Figs. 1 and 3). Therefore, when it comes to surface water areas, the De Soria lake has varied relatively less in magnitude when compared to the El Viborón lake (Figs. 4 and 5). The El Viborón lake dried up in May 2022 due to important environmental transformations, observing the development of a 20-30 cm-thick layer of salt crystals and the colonization of the surface by *Oxybasis macrosperma* halophytic plants (field observations). The La Paloma lake, on the other hand, located in an intermediate topographical position, showed a water surface reduction of up to 90% in 2014 and 2020 (Fig. 5), while the El Viborón and La Paloma lakes showed decreases between 60 and 70% for the same years. The latter suggests that the topographic position of the lakes is not the unique factor behind the surface variabilities observed.

The joint analysis of lake water area variations and hydroclimatic variables (streamflow and precipitation) show no evident relationships among them over at least the last couple of decades (Table 2). This finding may be related to the fact that the Leyes-Tulumaya system has long been immersed in a productive matrix experiencing multivariable, smaller-scale natural and anthropogenic forcings that hinder the proper role of climatic variables. Alterations in this impacted system include (1) the construction of the Potrerillos Dam in the Mendoza River in 2003, (2) minor blockages of the Leyes-Tulumaya stream due to increasing urbanization and agricultural activities, and (3) the management of water resources for agro-industrial activities and/or the use of the aquifers for agriculture activities.

The evaporation (GLEV) and soil moisture (NMDI) data are not clearly related to the lake areas either (Fig. 7), but the times series of these two variables do contribute to understanding their behavior during the analyzed periods. The evaporation volume responds well to the interannual cycle dynamics of the Leyes-Tulumaya system, showing greater water availability in summer and lesser in winter (Fig. 7A). On the other hand, the soil moisture data evidence hydrological stress periods associated with low lake levels (high radiance; Fig. 7B) with direct negative effects on the studied wetlands.

Contrary to the findings presented here for the Leyes-Tulumaya system, basin-scale studies developed at the Lagunas de Guanacache, a wetland of higher hierarchy located in northeastern Mendoza Province, noticed a direct relation between climatic variables and lake water areas during the 1960s and 1970s (Contreras *et al*., 2011; Arancibia Abrahan, 2019; Álvarez *et al*., 2024). This relationship prevailed until the anthropic intervention of the system in the 1980s with the construction of small dams associated with the creation of agricultural oases. Since then, the lacustrine water areas of the Lagunas de Guanacache began to decrease (Contreras *et al*., 2011; Arancibia Abrahan, 2019; Álvarez *et al*., 2024).

Although the Leyes-Tulumaya system corresponds to a wetland of lower hierarchy when compared to the Lagunas de Guanacache, the sustained water area variability of the three lakes analyzed is probably having significant impacts on the long-term dynamics of the ecosystems along the middle-lower Mendoza River Basin. The existence of a large, ancient swamp of higher hierarchy during historical times (the Gran Ciénaga del Bermejo; Prieto, 2000; Prieto *et al*., 2008), followed by drained (or dry) lacustrine bodies along the Leyes-Tulumaya system in present times, implies a drastic environmental change at least during the last 400 years that continues at present, and is even being reinforced, given the development of anthropic activities (Otta *et al*., 2022).

The Leyes-Tulumaya system and the Lagunas de Guanacache are not anomalies, in fact, on a global scale, research on higher hierarchy wetlands also shows accelerated impacts on these ecosystems in recent decades (Zuquette *et al*., 2020; Assefa *et al*., 2022; Zhu *et al*., 2022). Major changes in wetlands worldwide are associated with the impacts of climate change, resulting in an increased vulnerability of these fragile environments that needs to be investigated further (Stewart *et al*., 2013; Wardrop *et al*., 2019).

6. Conclusions

This study reveals that the areas of three lakes along the Leyes-Tulumaya system, in central-western Argentina, have been highly variable over the last 20 years. These area variations occurred in phase, indicating their connectivity through the Leyes-Tulumaya stream, reason as to why it is considered here as a system. Topography is an important but not unique conditioning factor in the persistence of the lacustrine areas. In fact, the lakes located at lower topographic positions (the La Paloma and De Soria) showed smaller area fluctuations, while the El Viborón lake, located at higher altitude, experienced greater fluctuations until its complete drying in 2022.

No evident relationships were found between the hydroclimatic variables (precipitation and streamflow) and the lake area data for the last 20 years. This is because the Leyes-Tulumaya system has been severely altered by different anthropogenic activities since the beginning of the 21st century. Therefore, further studies are required to investigate and quantify the impacts of urban and agricultural activities on the Leyes-Tulumaya ecosystem, including surface water and groundwater management. Future studies will benefit from finer satellite temporal resolutions so as to track in more detail, and predict with greater accuracy, the changes that these threatened environments are subjected to.

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Supplementary Material

TABLE S1. TIME SERIES OF MEASURED AREAS (M^2) OF THE EL VIBORÓN, LA PALOMA, AND DE SORIA LAKES BETWEEN THE YEARS 2003 AND 2021.

El Viborón		La Paloma		De Soria	
Date	Area (M^2)	Date	Area (M^2)	Date	Area (M^2)
Jan-03	172,217	Jan-03	182,588	Jan-03	83,932
		Apr-05	158,171	Apr-05	89,405
Jul-11	279,836	Jul-11	162,464	Jul-11	135,236
Dec-12	197,083	Dec-12	90,556	Dec-12	72,378
				Jun-13	52,996
Oct-13	258,141	Oct-13	147,306	Oct-13	125,743
Jan-14	139,314	Jan-14	12,630	Jan-14	54,511
Apr-14	193,599	Apr-14	126,114	Apr-14	116,653
Jan-15	157,328	Jan-15	47,948	Jan-15	60,652
Apr-15	123,690	Apr-15	53,911	Apr-15	89,765
		May-15	57,128		
		Jun-15	66,760	Jun-15	96,557
Jul-15	142,204				
Sep-15	232,530	Sep-15	139,821		
		Mar-16	144,284		
				May-16	119,541
Jul-16	207,198	Jul-16	153,557		
Mar-17	149,052	Mar-17	81,184	Mar-17	108,368
Apr-17	135,321	Apr-17	94,463		
Feb-18	191,301	Feb-18	96,476	Feb-18	82,294
May-18	137,639	May-18	116,388	May-18	115,542
Sep-18	191,274				
		Oct-18	137,853	Oct-18	123,474
				Jul-19	109,332
Aug-19	254,358	Aug-19	154,474	Aug-19	132,672
Apr-20	132,859	Apr-20	21,268	Apr-20	40,425
		Jun-20	102,154		
Oct-20	188,079	Oct-20	135,674		
Jun-21	71,150	Jun-21	118,291	Jun-21	80,154
Sep-21	191,300	Sep-21	134,715	Sep-21	128,991

The date format consists of the abbreviation of the month and the last two digits of the corresponding year.