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REPORT

Surface-water/groundwater exchange in a sand dune lake in the Dry Pampean Plain, Argentina: stable isotopic evidence

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Abstract
Understanding the hydrological functioning of the scarce freshwater bodies of semiarid regions is crucial, especially in those areas affected by anthropic activities involving land-use changes. In the dry western edge of the Argentina Pampean plains, a system of more than 100 shallow lakes of remarkable stability occurs. These lakes exhibit low salinity compared to those located in the more humid belt. This system has constituted the main water resource for humans from prehispanic times to the present. Stable isotopes were used to establish the seasonal surface-water/groundwater interactions and the hydrological conditions in a lake of the Dry Pampean Plain (DPP), i.e., Lake Los Pocitos, to understand the mechanism that guarantees such a resource. Results indicate that evaporation mainly controls the isotopic composition of lake water, overwhelming the effect of higher rainfall inputs during the wet (but also most evaporative) season. The δ^{18}O mass balance model indicates greater groundwater inflow to the lake during the dry season (~0.4 m month^{-1}) compared to the wet season (~0.2 m month^{-1}). Lake level decreased in the wet season due to the lowest groundwater inflow and the greatest evaporation rate. Based on the proportion of water entering a lake that leaves through evaporation, Los Pocitos corresponds to a throughflow lake with a short water residence time (~0.47 years). These hydrologic conditions, along with freshwater inputs from a dune located at the western margin of the lake, determine the existence of this relatively stable and freshwater lake in the DPP where high evaporation rates are registered.

Keywords Groundwater/surface-water relations · Environmental tracers · Mass balance method · Water residence time · Argentina

Introduction

Lakes constitute one of the most sensitive ecosystems to anthropic impacts (Kidmose et al. 2013; Tao et al. 2013; Wetzel 2001). Often interactions with groundwater are central to lake hydrology, biogeochemistry, and ecological functioning, with natural and anthropic perturbations on aquifers relevant for lakes (Arnoux et al. 2017a; Shaw et al. 2013). This connection is crucial in dry sandy land regions where lakes are scarce and more reliant on groundwater supply and constitute important water resources for wildlife and humans (e.g., Bouchez et al. 2016; Harvey et al. 2007; Williams 1999). The estimation of groundwater inflow and outflow in lakes is often dismissed due to the difficulty of its quantification (e.g., Arnoux et al. 2017b). During the past decades, numerous studies have demonstrated that these interactions are of great importance not only for the water balance (e.g., Liao et al. 2018) but also for nutrient dynamics (Ala-aho et al. 2013; Brock et al. 1982; Lewandowski et al. 2015; Meinikmann et al. 2015; Oliveira Ommen et al. 2012). Thus, the understanding of groundwater-lake interactions is important for the effective management of water resources and aquatic ecosystems (e.g., Winter et al. 1998).

Different methods have been used to quantify groundwater/surface-water interactions. Among them, dissolved conservative constituents such as chloride and stable isotopes in

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the water molecule, have been widely used for this purpose (e.g., Bocanegra et al. 2013; Campodonico et al. 2019; Cao et al. 2018; Gibson et al. 2016; Gurrieri and Furniss 2004; Hofmann et al. 2008; Montalván et al. 2017; Petermann et al. 2018; Rosenberry et al. 2015; Shaw et al. 2017; Stets et al. 2010; Turner and Townley 2006). Stable isotopes are also valuable for estimating the water residence time (WRT) of lakes (Brock et al. 1982; Gat 2010; Gibson et al. 2016; Gibson et al. 2002; Gonfiantini 1986; Turner et al. 2010). Conceptually, based on the ratio of evaporation (E) to total water inputs (I), three hydrological conditions for lakes can be defined: desiccating ponds, terminal lakes, and throughflow lakes (e.g., Gibson et al. 2016). In the first hydrological setting, inflow occurs once or sporadically, while conversely, in terminal lakes, inflow is continuous and long-term evaporation balances inflow, thus no liquid outflow occurs. Finally, throughflow lakes are those with continuous inflow, which is balanced with the outflows represented by evaporation and lake water outflow. In this latter case, groundwater input is higher than lake surface evaporation (Gat 1995; Gibson et al. 2002).

The Pampean Plain (PP) in Argentina has gentle slopes and more than one hundred shallow lakes that developed on geomorphological depressions that originated mainly by wind deflation during the Quaternary (Tripaldi and Forman 2007) and shallow water tables. Besides, during the last few decades, a water-table rise has been registered in this area due to land-use change related to the replacement of native vegetation by crops (e.g., Jobbágy et al. 2021). The hydrology of these lakes depends on rainfall, groundwater discharge, potential evaporation, and the topographic position (e.g., Bocanegra et al. 2013; Drago and Quiros 1996; Romanelli et al. 2014). This region of Argentina has a marked rainfall gradient from east to west, whereby in the east, the Humid Pampean Plain (HPP) has an annual rainfall $>$1,000 mm, and the west region of the Dry Pampean Plain (DPP) presents an annual rainfall $<$700 mm (Iriondo et al. 2009). In semiarid zones like the DPP, lakes are natural groundwater outcropping areas. Lakes located in the study area, known as “Mercedinas” due to their proximity to the city of Villa Mercedes (San Luis Province), constitute the only surface-water bodies in this area, where water is scarce, and they provide an essential habitat for aquatic fauna and flocks of water birds. They also offer crucial water sources for livestock and have shaped human displacement, roads and settlements throughout the Holocene until recent times (Heider et al. 2019). Currently, these lakes are exposed to several anthropic impacts such as recreational activities, including fishing, and the modification of their surrounding landscape through cattle grazing of native grasslands and cultivation.

In closed-basin lakes such as those located in the DPP, a modification in the land use of the surrounding landscape can lead to an increase in groundwater recharge and water level rise, as documented when dryland agriculture replaces native vegetation, or water degradation due to below-ground nutrient inputs from fertilized plots (e.g., Blarasin et al. 2020; Nosetto et al. 2015; Santoni et al. 2010). Likewise, rise of the water table can generate salt leaching from soils into surface-water and groundwater systems (e.g., Jayawickreme et al. 2011). Furthermore, in the current environmental context, both climate and land-use change can lead to water-table fluctuations, which influence the dynamic of these kinds of lakes (Córdoba et al. 2014; Guerra et al. 2015; Liu et al. 2013; Nosetto et al. 2015; Tao et al. 2013).

Several studies have shown that groundwater constitutes an important water source in shallow lakes of the HPP (Drago and Quiros 1996; Fernández Cirelli and Miretzky 2004; Miretzky et al. 2001; Miretzky et al. 2000; Romanelli et al. 2014). However, this connectivity was not explored in the driest portion of the PP, and it may be particularly important in sand dune landscapes where an installed drainage network (permanent or ephemeral) does not exist. Moreover, in spite of the drier climate, lakes appear to be deeper and more stable than in the HPP, even during dry periods when most lakes across the plain desiccate (Vilanova et al. 2015). The main goal of this work is to establish surface-water/groundwater interactions, by means of stable isotopes, in one of the lakes of the sand dune system of the DPP known as Lake Los Pocitos. For this purpose, the δ^{18}O mass-balance model was applied to quantify the groundwater discharge flux into the lake and the E/I ratio was used to establish the hydrological conditions of Lake Los Pocitos. Thus, this study will contribute to the understanding of the role of groundwater in sustaining the Lake Los Pocitos ecosystem, and provide an insight on the persistence of lakes with low total dissolved salts, particularly in an area of high evaporation rates. Furthermore, the information generated in this contribution will help to elucidate the hydrological functioning of water bodies located in other semiarid and arid regions such as the Nebraska Sand Hills in the USA (e.g., Rossman et al. 2019) and the Badain Jaran Desert in China (e.g., Liu et al. 2016).

Lake Los Pocitos region

Semiarid dune fields and sandy mantles of late Quaternary age cover most of the DPP, in west-central Argentina (Iriondo and Kröhling 1995; Zárate and Tripaldi 2012). The regional topographic slope is northwest-southeast. Ceci and Coronado (1981) established, based on a few drilled wells and several vertical electrical soundings, that the crystalline basement is located at 200 m depth in the S and W from the city of Villa Mercedes. The thicknesses of the saturated sedimentary aquifer formations and their hydrological parameters are mostly unknown. The groundwater regional flow follows the same direction of the regional topographic slope (NW-SE). The hydraulic gradient in the western part of the basin is 28% and in the southeastern is 30% (Ceci and Coronado 1981).

The only major permanent surface drainage is the Quinto River. However, the water table reaches the topographic surface in the region and floods the topographically lower areas, filling blowout depressions. In this sense, more than 200 seepage lakes are distributed over the sandy plain in deflation pans (Tripaldi et al. 2013; Vilanova et al. 2015). Lake Los Pocitos is one of these shallow inland water bodies (Fig. 1).

Lake Los Pocitos (33°58′12.77″ S - 65°34′16.07″ W) is a lake located south of the Quinto River, about 45 km away from the city of Villa Mercedes (Fig. 1c). It is located in the northwestern portion of the lake system. Its surface area is ~0.2 km^2, the maximum water depth is about 11 m, with an average water depth of about 2 m. Since it has no surface-water drainage networks, it gains water mainly via rainfall and groundwater discharge, and loses water primarily through evaporation and groundwater outflow. Groundwater outflow was observed by means of the environmental tracer ^{222}Rn (Echegoyen et al. 2021). Los Pocitos waters are alkaline (mean pH 9.1), with low salinity (mean TDS 651 mg L^{-1}), and of the HCO_3^--Na^+-K^+ type (Echegoyen et al. 2021).

The Lake Los Pocitos area is in the denominated Western Pampean dunefields (Zarate and Tripaldi 2012). This region is characterized by a low relief plain that includes well vegetated and diverse stabilized dunes surrounded by discontinuous aeolian sands mantles (Tripaldi and Forman 2007). The surrounding geology is dominated by aeolian sand deposits composed of lithic feldsarenites and feldspathic litharenites, where volcanic grains are by far the most common rock fragments (Tripaldi et al. 2010). Dunes show two main orientations in this area. Parabolic dunes (currently vegetated) suggest southeasterly paleowinds, whereas barchanoid ridges indicate a recent dune reactivation with winds coming from the northeast (Tripaldi et al. 2013). The compound parabolic dune at Lake Los Pocitos is a 3.5 m thick exposure of well-sorted fine sand, subdivided into two units according to the sedimentary structures (Tripaldi et al. 2013). The lower unit (~1 m thick) exhibits horizontal laminated sand deposited by wind ripple migration, and is covered by the upper unit (~2 m thick) which corresponds to a cross-laminated bedset originated by dune migration (Tripaldi et al. 2013). Barchanoid ridges at the western margin of the lake evidence an aeolian reactivation where the dunes migrate in a NE-SW direction. These sandy sediments have relatively weak pedogenesis (Colazo 2012).

Natural grasslands prevail in the area (Colazo 2012) with different degrees of alterations caused by cattle grazing (Viglizzo and Jobbágy 2010). Native chañar (*Geoffroea decorticans*) and caldén (*Prosopis caldenia*) trees have progressively encroached on the area and are particularly abundant on the eastern (downslope) margin of the lake. The lake shoreline and shallow margins are occupied by marshes dominated by *Cortaderia, Schoenoplectus*, and *Typha* species.

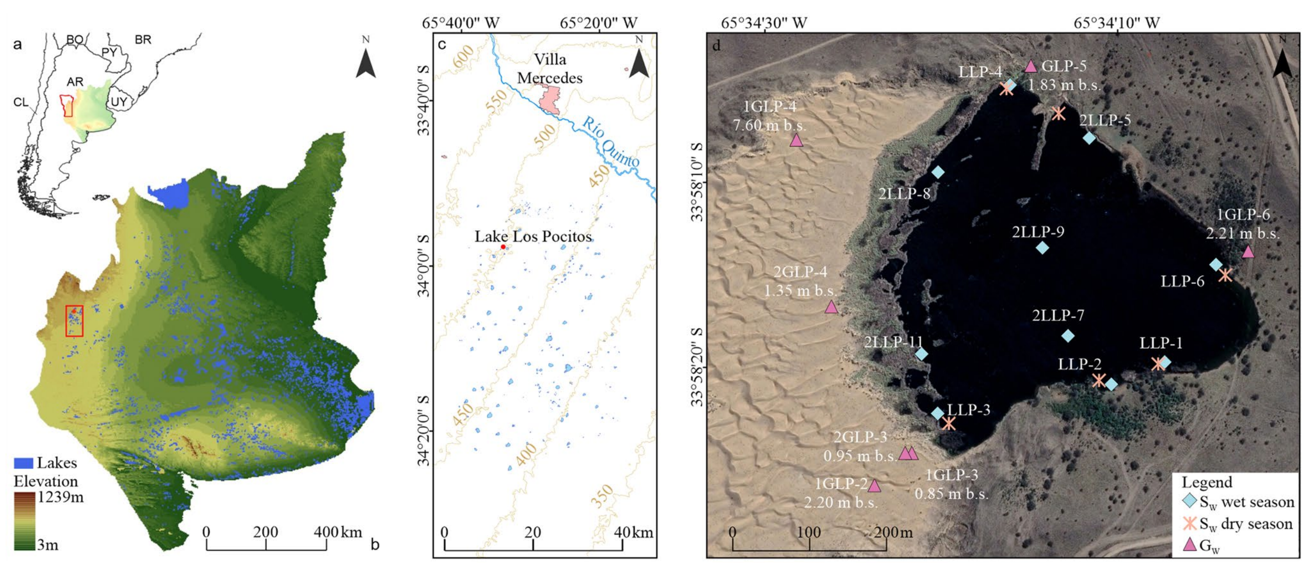

Fig. 1 **a** Location map of the San Luis Province and PP in Argentina. **b** Location of Mercedinas lakes and Lake Los Pocitos in the PP. **c** Mercedinas lakes, located south of the Quinto River and the city of Villa Mercedes (Lake Los Pocitos is located in the northwestern portion of the lake system). **d** Location of sampling points of surface water (S_W) and groundwater (G_W) during dry (September 2017) and wet (April 2019) seasons

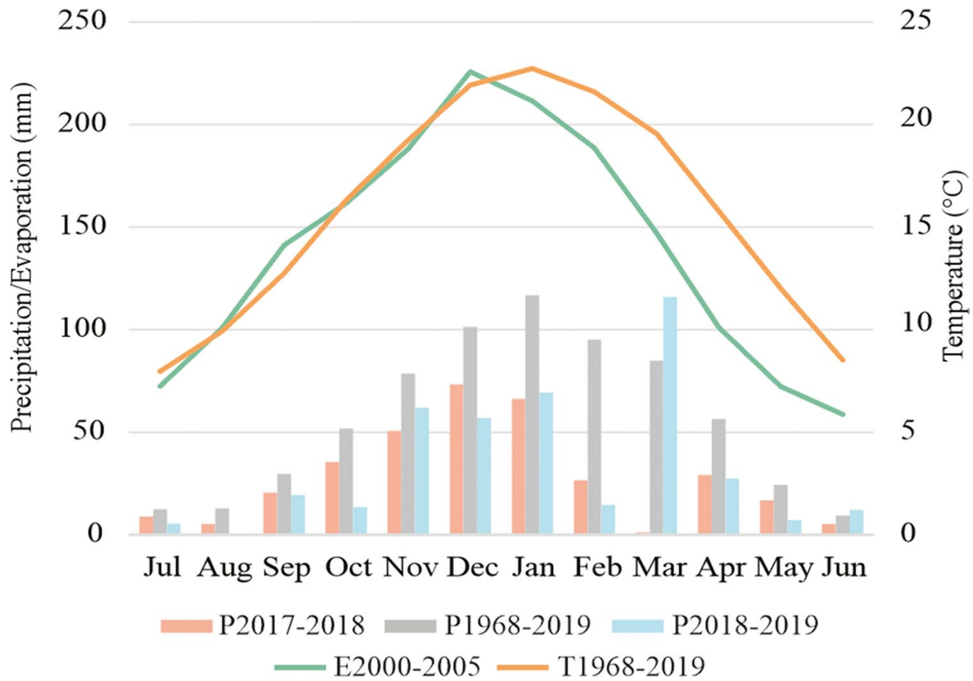

Fig. 2 Monthly mean rainfall (*P*) and temperature (*T*) series at the city of Villa Mercedes (1969-2019 record period). Evaporation (*E*) measured from evaporated ponds (2000-2005)

Climate in this region is semiarid, with marked seasons (Fig. 2). The mean annual rainfall is 679 mm (record period 1968-2018, INTA Villa Mercedes gaging station), and the mean annual temperature is 15.7 °C. Rainfall occurs mainly during the austral spring and summer, between October and March (>50 mm/month for the same record period), whereas the austral winter has the lowest (<50 mm/month) rainfall inputs. Because of the highest temperatures, evaporation rates peak simultaneously with rainfall, and are maximum during the austral summer (Marchesini et al. 2020). Figure 2 shows that evaporation exceeds rainfall all the year, with an annual evaporation rate measured from evaporated ponds of 1,541 mm year^{-1} (for the record period 2000-2005 at the city of Villa Mercedes). The average relative humidity is 66%.

Materials and methods

Lake evaporation estimation (*E*)

Evaporation was estimated for each season (September 2017 and April 2019) by the Penman combination method (Rosenberry et al. 2007). Daily average air temperature, relative humidity, wind speed, and solar radiation data were obtained from the INTA Villa Mercedes gaging station. Water-surface temperature was measured directly in the field.

Sampling and analysis

Surface-water samples were collected from Lake Los Pocitos at a depth of about 0.3 m in both dry ($n=6$, September 2017) and wet ($n=10$, April 2019) seasons. During the two sampling campaigns, groundwater samples ($n=5$ and $n=2$, for dry and wet seasons, respectively) from the phreatic aquifer were obtained through hand-dug wells. The depth at which the water level was reached varied between 0.8 and 7.6 m below surface (bs; water samples were retrieved when the water table was reached), covering the entire perimeter of the lake (Fig. 1d).

Field measurements were performed following standardized methods (e.g., Rice et al. 2012); these determinations included temperature (*T*), electrical conductivity (EC), and total dissolved solids (TDS). Unfiltered samples for stable isotope determinations were stored in 50 ml polyethylene bottles filled to the top with water, and capped without leaving any headspace. Stable isotope measurements were performed using cavity ring-down spectroscopy (Picarro L2120-i) at the GEA-IMASL-CONICET Institute. Results are expressed as δ% according to Eq. (1).

$$\delta\% = 1000\,\frac{\left(R_{\mathrm{S}} - R_{\mathrm{V-SMOW}}\right)}{R_{\mathrm{V-SMOW}}} \tag{1}$$

where δ is the isotopic deviation in %, R is the isotopic ratio (^{2}H/^{1}H or ^{18}O/^{16}O), S is the sample, and V-SMOW is the reference material (Vienna Standard Mean Ocean Water; Gonfiantini 1978). Analytical uncertainties were ± 0.1% for δ^{18}O and ± 0.5% for δ^{2}H.

The lake perimeter was determined with a Garmin global positioning system (GPS) equipment and lake depths were measured using a Speedtech Depthmate portable sounder (readings are accurate from 0.6 to 79 m). The lake area and volume were calculated using geographical information systems (ArcGIS).

Isotopic mass balance

Groundwater inflow to Lake Los Pocitos was determined by employing a mass balance method based on $\delta^{18}O$ concentrations (Gibson et al. 2016; Gonfiantini 1986). Several studies have employed a similar approach to determine groundwater inflow into lakes. For instance, some recent works are those of Shaw et al. (2017) who used this model to determine groundwater inflow in a temperate seepage lake in Georgetown Lake in Montana (Canada), and Arnoux et al. (2017a), who applied this method in kettle lakes in Quebec (Canada). Recently, Campodonico et al. (2019) used the environmental tracer $\delta^{18}O$ to quantify groundwater inflow into Laguna del Plata (Mar Chiquita system, Argentina). Steady-state mass balance equations assume that lakes are well mixed and maintain a long-term constant volume (Gat 2010; Gibson and Edwards 2002). Lake levels were reconstructed for Lake Los Pocitos using the available Sentinel-2 imagery from June 2016 to September 2020 (Fig. 3). For this period, a lake area of $0.196 \pm 0.002\ km^2$ was calculated. The relatively constant lake area during this period, along with the depth of Lake Los Pocitos allows one to consider it a steady-state system for modeling purposes.

In absence of surface drainage networks, the water balance at Lake Los Pocitos is controlled by groundwater discharge into the lake, groundwater outflow from the lake, rainfall, and evaporation. Thus, its general water mass balance can be stated as follows:

$$\frac{dV}{dt} = G_i + P - G_o - E \tag{2}$$

where V is the water volume in the lake, t is time, G_i is groundwater inflow, P is precipitation, G_o is lake groundwater outflow and E is evaporation.

A lake isotopic balance can be performed by measuring or calculating the isotope compositions (δ) for all the components of the water balance equation. When combining each term of Eq. (2) with $\delta^{18}O$ values, the following equation is obtained:

$$\frac{dV\delta_L}{dt} = G_i\delta_{Gi} + P\delta_P - G_o\delta_{Go} - E\delta_E \tag{3}$$

Since water outflow from the lake does not cause isotopic fractionation, one can assume that isotopic compositions from groundwater outflow and the lake water are the same ($\delta_{Go} = \delta_L$; Sacks et al. 2014). Rearranging and combining Eqs. (2) and (3), one can calculate the groundwater inflow as follows:

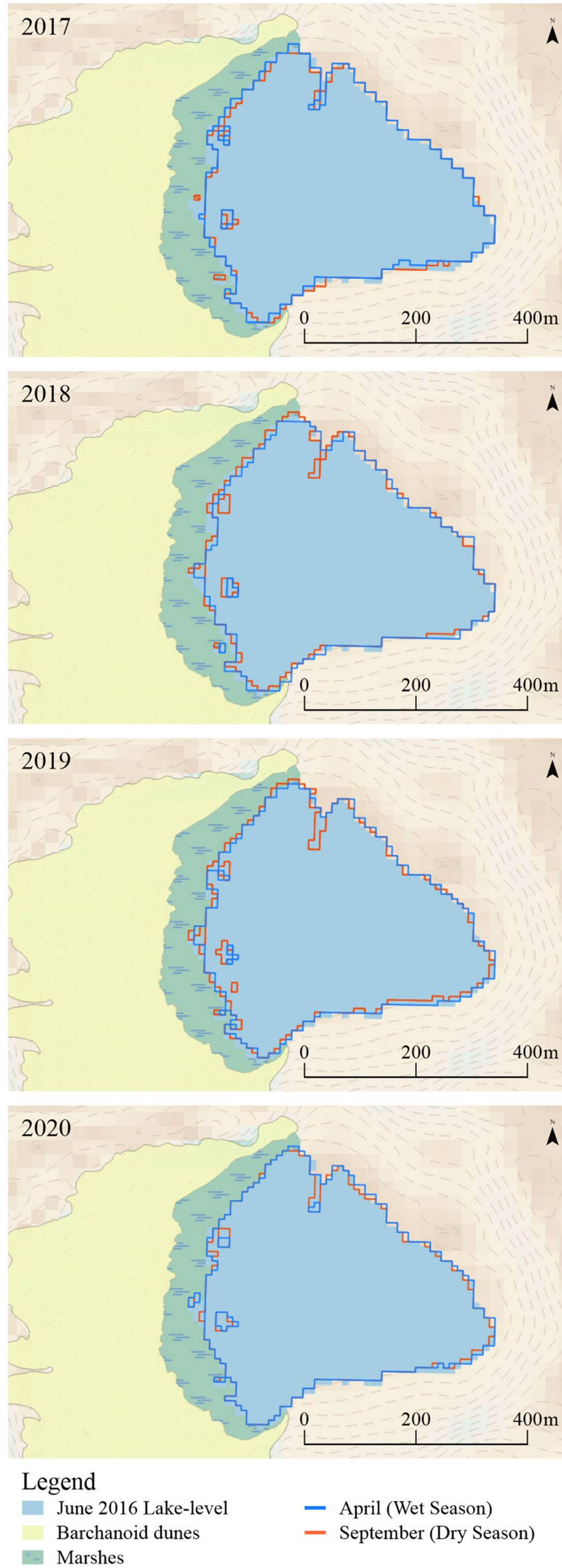

Fig. 3 Lake-level variation from June 2016 to September 2020

$$G_i = \frac{P(\delta_L - \delta_P) + E(\delta_E - \delta_L)}{\delta_{Gi} - \delta_L} \tag{4}$$

Most terms in Eq. (4) can be measured directly, with the exception of the isotopic composition of evaporated lake water (δ_E), which is difficult to measure. Thus, δ_E can be estimated using the linear resistance model provided by Craig and Gordon (1965), which describes δ_E (Eq. 5) as a function of the lake isotopic composition (δ_L), the relative humidity (h), the isotopic composition of local atmospheric water vapor (δ_A), and fractionation factors.

$$\delta_E = \frac{\alpha^* \delta_L - h\delta_A - \varepsilon}{1 - h + 10^{-3}\Delta\varepsilon} \tag{5}$$

All fractionation factors were calculated using the experimental equations defined by Horita and Wesolowski (1994). The equilibrium isotope fractionation factor at the temperature of the air-water interface for ^{18}O (i.e., α*) is given by:

$$\alpha^* = \frac{1}{\alpha_{L/V}} \tag{6}$$

where $\alpha_{L/V}$ is defined by Gonfiantini (1986) as the ratio in liquid versus vapor, and can be estimated with Eq. (7):

$$\alpha_{L/V}\left(^{18}O\right) = \exp\left(\frac{-7.685}{10^3} + \frac{6.7123}{T} - \frac{1666.4}{T^2} + \frac{350410}{T^3}\right) \tag{7}$$

where T is the temperature in degrees K.

The kinetic fractionation factor ($\Delta\varepsilon$) depends on humidity, and can be calculated using Eq. (8).

$$\Delta\varepsilon = K(1 - h) \tag{8}$$

where $K(^{18}O) = 14.2\%$, which is a value determined from wind tunnel experiments (Gonfiantini 1986).

The total fractionation factor (ε) is expressed in % and is estimated with Eq. (9):

$$\varepsilon = \varepsilon^* + \Delta\varepsilon \tag{9}$$

where ε* is the equilibrium fractionation factor which depends on temperature and it is estimated with Eq. (10):

$$\varepsilon^* = (1 - a^*) + \Delta\varepsilon \tag{10}$$

Finally, the isotopic composition of ambient atmospheric water vapor (δ_A) was calculated by means of Eq. (11) assuming equilibrium with precipitation (Gibson et al. 2008):

$$\delta_A = \frac{\delta_P - \varepsilon^*}{1 + 10^{-3}\varepsilon^*} \tag{11}$$

Hydrologic conditions and lake water residence time

Stable isotopes can also be used to classify the hydrologic conditions of lakes such as desiccating water bodies, terminal lakes, or throughflow lakes (Gibson et al. 2002; Gonfiantini 1986). In well-mixed and steady-state conditions, the general water mass balance and the isotopic mass balance equations can be rearranged from Eqs. (1) and (2), and the fraction of total water inputs lost by evaporation (*E/I*) can be calculated as follows:

$$\frac{E}{I} = \frac{\delta_L - \delta_I}{\delta^* - \delta_L} m \tag{12}$$

where δ_L represents water discharged from the lake, δ_I represents inflowing water, δ* is the limiting isotope enrichment factor, and m is the enrichment slope. Values of *E/I* between 0 and 1 reflect varying degrees of throughflow lakes, $E/I = 1$ correspond to terminal lakes, and $E/I > 1$ represent desiccating water bodies (Gat 1995; Gibson et al. 2016). These last types of lakes are transient systems ($dV/dt < 0$) and therefore cannot be considered to be in a hydrological steady state (Gibson et al. 2002).

The limiting isotope enrichment factor (δ*) is estimated with Eq. (13).

$$\delta^* = \frac{h\delta_A + \varepsilon}{h - 10^{-3}\varepsilon} \tag{13}$$

The enrichment slope (m) can be calculated with Eq. (14).

$$m = \frac{h - 10^{-3}\varepsilon}{1 - h + 10^{-3}\Delta\varepsilon} \tag{14}$$

Water residence time (τ) is a determinant parameter of the ecological health of lakes, and it is defined as the average time that a water molecule spends in the system. For instance, WRT has also been related to the N removal efficiency by the ecosystem (e.g., Finlay et al. 2013).

The lake WRT can be calculated from the estimation of *E/I* and lake volume (V), according to the equation proposed by Gibson et al. (2002):

$$\tau = \left(\frac{E}{I}\right)\left(\frac{V}{E}\right) \tag{15}$$

Results and discussion

Lake evaporation estimation (*E*)

Evaporation (E) measured from evaporated ponds located at INTA Villa Mercedes gaging station was 1,541 mm year^{-1}, for the 2000-2005 period. These data are not available for the sampling period, therefore the Penman method was used to calculate E. The obtained results were 79 and 176 mm month^{-1} for the dry and wet seasons, respectively. The difference between the evaporation values estimated by means of the Penman method and those measured directly at INTA ponds is <10% for the 2000-2005 period.

Isotopic composition

Stable isotopic compositions can be visualized in the conventional δ^2H (%) vs. δ^{18}O (%) plot (Fig. 4), jointly with the local meteoric water line (LMWL) of the city of Río Cuarto (located 150 km NE of Lake Los Pocitos), i.e.: δ^2H (%) = 8.3 δ^{18}O (%) + 15.2 (Cabrera et al. 2019). The obtained results indicate that groundwaters were more depleted in heavy isotopes (δ^{18}O = −5.9 to −3.2%; δ^2H = −35 to −19%; Table 1) than surface waters (δ^{18}O = −1.6 to 1.4%; δ^2H = −10 to 3%; Table 1); besides, lake samples showed different isotopic compositions during both seasons. During the dry season, in September, the average stable isotopic composition of lake water was −1.3% for δ^{18}O and − 8% for δ^2H, while conversely, during the wet season, in April, lake waters were more enriched in heavy isotopes, and showed mean values of 0.9 and 0% for δ^{18}O and δ^2H, respectively.

All surface-water samples plot below the LMWL, evidencing evaporation processes and defining a local evaporation line (LEL), which can be explained by the equation: δ^2H (%) = 4.8 δ^{18}O (%) - 3.6 (R^2 = 0.98; Fig. 4).

As stated in the preceding, groundwater samples correspond to the shallowest portion of the phreatic aquifer. The groundwater samples were divided into shallow (<1.5 mbs) and deep (>1.5 mbs) waters according to their isotopic composition. Shallow groundwater presents δ^{18}O and δ^2H values of −4.3 to −3.2% and -27 to −19%, respectively. Except for the sample located at the east side of the lake (1GLP-6), δ^{18}O values in deep groundwater around Lake Los Pocitos varied from −5.9 to −5.1%, and δ^2H values varied between −35 and -27% (Table 1). The LEL origin coincides with the isotopic signatures of groundwater samples, suggesting that they constitute an important source of water from which surface water is evaporated. Three samples plot near the LMWL but over the LEL, and correspond to groundwater samples that were taken on the dune at shallow depths (<1.5 mbs). In arid environments with sandy soils where the water table is high, direct evaporation from a bare soil surface is an important factor to consider (Gat 1996). Groundwater sample 1GLP-6 on the eastern margin of the lake shows a similar isotopic composition to lake waters, reflecting the effects of capillary evaporation. The remaining groundwater samples showed a similar isotopic signature to rainfall, as they plot near the LMWL. These groundwater samples are deeper (>1.5 mbs) and indicate that groundwater around Lake Los Pocitos has a dominant meteoric origin, whereas shallow groundwater is affected by evaporation processes (Fig. 4). This effect of evaporative losses on shallow groundwater (less than 1 mbs) was also observed in other points of the PP (Poca et al. 2020). Particularly, a deep groundwater sample (1-GLP-2) shows a more depleted isotopic composition, probably due to the influence of recharge coming from the western area according to the general behavior of Pampean rainfalls.

The isotopic composition of recharge water/rainfall into the lake (δ recharge) is commonly estimated by the intersection of the LEL and the LMWL (δ^{18}O = −5.4% and δ^2H = −30%; e.g., Gat 1996; Gibson et al. 1993; Krabbenhoft et al. 1994). These isotopic values for rainfall are also similar to the mean values of the deepest groundwater sample (δ^{18}O = −5.4% and δ^2H = −30%). This is consistent with the fact that the isotopic composition of deep groundwater not affected by evaporation or mixing processes represents the average isotopic composition of rainfall in temperate climates (Fontes 1980).

Groundwater inflow into Lake Los Pocitos: stable isotope mass balance

The groundwater inflow into Lake Los Pocitos was estimated using Eq. (4) during the dry and wet seasons. The rainfall value corresponds to the monthly rainfall registered at INTA Villa Mercedes gaging station for September 2017 and March 2019, representing the dry and wet seasons respectively (P_{Dry} = 28.5 mm and P_{Wet} = 116 mm). In addition, as stated in the preceding, the evaporation rate from Lake Los Pocitos was estimated for the dry and wet seasons using the Penman method (E_{Dry} = 79.0 mm and E_{Wet} = 176.0 mm).

The δ^{18}O values for lake waters (δ_{L}) are −1.3 and 0.9% for the dry and wet seasons, respectively. Since Cabrera et al. (2019) observed a seasonal effect in the isotopic composition of rainfall at Río Cuarto city, two different δ_{P} values were used for mass balance calculations. During the dry season, rainfall is more depleted (δ_{P} = −5.7%), whereas in the wet period rainfall is more enriched in heavy isotopes, with a mean δ^{18}O value of −4.5% (Cabrera et al. 2019). The δ^{18}O value of groundwater (δ_{Gi} = −4.6%) used for calculation purposes corresponds to the mean isotopic composition of samples collected around the perimeter of the lake, except for sample 1GLP-6 which clearly shows the effects of capillary evaporation. Both δ^{18}O values (i.e., δ_{P} and δ_{Gi}) were multiplied by the lake surface area (0.2 km^2).

Finally, the δ^{18}O value of evaporating moisture (δ_{E}) was calculated for both seasons using the multilayered model (Eq. 5) developed by Craig and Gordon (1965) and considering the water salinity. Since δ_{E} also depends on humidity, mean monthly humidity values were obtained from INTA

Table 1 Physico-chemical parameters and isotopic composition of Los Pocitos Lake and groundwater samples. The groundwater sample depth is also included. *TDS* total dissolved solids; *EC* electrical conductivity; *T* temperature

Sample name	Depth (mbs)	T (°C)	EC (μS cm^{-1})	TDS (mg L^{-1})	δ^{18}O (%)	δ^{2}H (%)
1LLP-1		15.5	1,219	611	-1.1	-7
1LLP-2		15.8	1,218	611	-1.2	-8
1LLP-3		15.5	1,234	618	-1.0	-7
1LLP-4		16.3	1,169	587	-1.6	-10
1LLP-5		16.6	1,216	609	-1.5	-9
1LLP-6		16.7	1,333	668	-1.2	-7
2LLP-1		24.5	1,230	616	0.9	-1
2LLP-2		23.8	1,218	613	1.4	2
2LLP-3		23.7	1,218	610	1.1	2
2LLP-4		24.5	1,280	639	0.1	-5
2LLP-5		19.7	1,169	1,194	0.1	-3
2LLP-6		20.2	1,249	625	1.2	2
2LLP-7		23.6	1,238	620	1.3	3
2LLP-8		21.6	1,164	583	1.0	1
2LLP-9		21.1	1,180	591	1.3	2
2LLP-11		21.5	1,236	618	1.0	1
1GLP-2	2.20	25.2	89	177	-5.9	-35
1GLP-3	0.85	24.8	511	256	-3.7	-19
1GLP-4	7.60	19.4	472	236	-5.1	-27
1GLP-5	1.83	19.8	1,014	507	-5.2	-29
1GLP-6	2.21	Nd	1,651	826	0.1	-2
2GLP-3	0.95	Nd	332	166	-4.3	-27
2GLP-4	1.35	Nd	283	140	-3.2	-20

Villa Mercedes gaging station for September 2017 and March 2019. For the dry season, the δ_E is −18.5%, whereas for the wet season it is −7.8%.

Results obtained from the isotope mass balance using δ^{18}O values confirm that groundwater discharge into the lake occurs during both seasons (Table 2). During the dry season, a groundwater inflow of ~0.4 m month^{-1} to Lake Los Pocitos was estimated, whereas for the wet season a lower groundwater inflow was detected, in the order of ~0.2 m month^{-1}.

The groundwater discharge to Lake Los Pocitos during the dry season was previously demonstrated by Echegoyen et al. (2021) using the environmental tracer ^{222}Rn. This method revealed that Lake Los Pocitos exhibits a differential hydrogeological behavior along its perimeter. Groundwater inflow was detected at the northwestern sector of the lake, whereas surface water discharged into the aquifer at the southeastern sector of the lake. The different groundwater inflow values obtained with both methods can be explained by the fact that they indicate G_i rates at different timescales. While the stable isotope mass balance methods reflect the average conditions during months to several years (during the entire WRT), radon-based approaches reflect a maximum period of 20 days (Arnoux et al. 2017b; Petermann et al. 2018). Moreover, it was considered that this period could be even shorter due to degassing of ^{222}Rn to the atmosphere and wind-induced water mixing; thus, the authors consider that results obtained by means of both methods are consistent with different timescales of sensitivity.

Regarding the sources of error of the stable isotope mass balance, previous works (e.g., Krabbenholft et al. 1990; Shaw et al. 2017) have demonstrated that this method is more sensitive to the estimation of the isotopic composition of the evaporation flux, which depends on humidity and the isotopic value of atmospheric moisture. Thus, the model uncertainty may be increased due to the fact that these parameters are estimated by indirect methods. Despite these sources of error, the employed method is adequate as a first assessment of groundwater inflow quantification in these types of lakes where previous studies have not considered the groundwater component.

Hydrologic conditions and lake water residence time

The proportion of the total water input that is lost through evaporation was calculated using Eq. (12). The *E*/*I* ratios of Lake Los Pocitos were 0.22 and 0.62 for dry and wet seasons, respectively, indicating that about 22% of lake water was lost through lake surface evaporation during the dry period, whereas during the wet period the lake water lost by evaporation increased to 62%. Values of *E*/*I* between 0 and

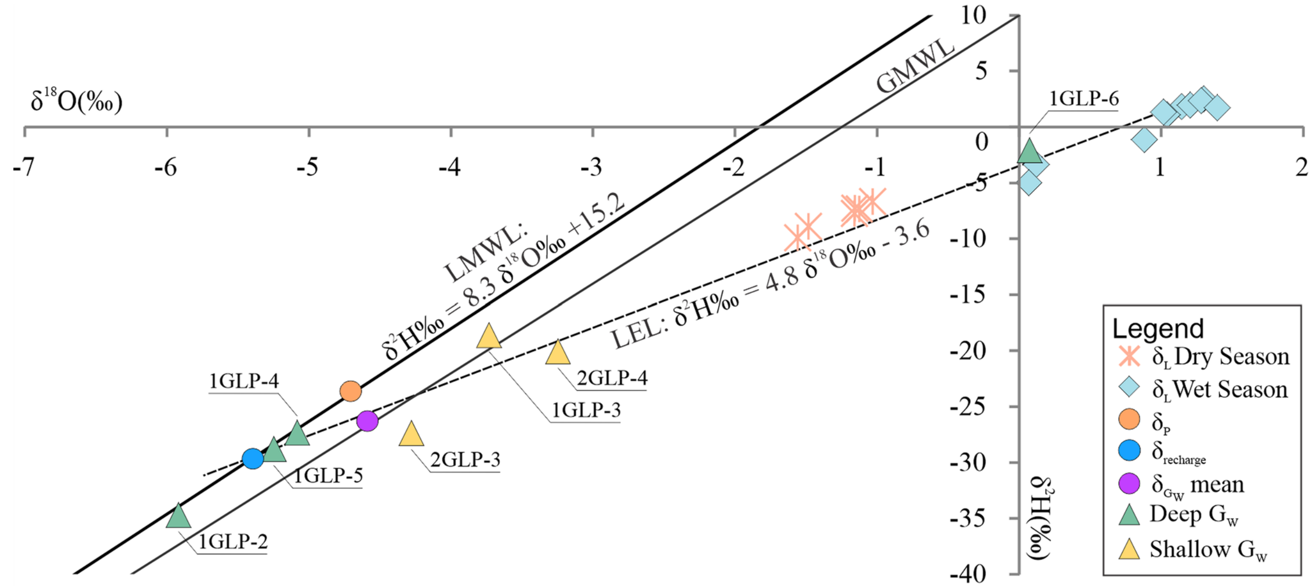

Fig. 4 Isotopic composition (δ^2H vs. δ^{18}O) of Lake Los Pocitos (δ_L) and associated groundwaters. The LMWL from the city of Rio Cuarto (Cabrera et al. 2019) and the mean isotopic composition of local rainfall (δ_P) are also included

approaching 1 (which corresponds to 0-100% respectively) reflect varying degrees of throughflow lakes (Gat 1995; Gibson et al. 2016; Turner et al. 2010), where inflow is continuous and balanced by outflow (Gibson et al. 2002).

In the PP, dunes, especially those without vegetation, act as preferential recharge areas where freshwater from rainfall can locally form important groundwater lenses in the upper part of the aquifer, surrounded by salty groundwater (Blarasin et al. 2014; Jobbágy et al. 2011). This occurs in the dunes of Los Pocitos area, where barchanoid dunes act as preferential recharge zones. Here, groundwater measurements show EC values <550 µS cm^{-1}. Regional studies performed on rainwater samples from Río Cuarto station (2006-2012) have shown EC values of ~54 µS cm^{-1} and that they correspond to the calcium sulfate or calcium carbonate type (Cabrera et al. 2013).

The throughflow condition of the lake, along with freshwater inputs from the dune, can explain the existence of a nonsalty lake like Los Pocitos (mean TDS 651 mg L^{-1}) in a semiarid region in which high evaporation rates would warrant a fast concentration of solutes in any stagnant water body.

Figure 5 corresponds to a schematic diagram depicting the different components of the hydrological budget for this lake system. Evaporation exceeds rainfall during both seasons. Although groundwater inflow occurs during both seasons, it is lower during the wet season. Despite the fact that this is the season when the highest rainfall is recorded, due to lower groundwater inflow in the lake and a greater loss of water by the intense evaporation, a decrease of 10 cm in the lake level was observed.

Water residence time, which was calculated taking into account evaporation, precipitation, the absence of an installed drainage network that flows into the lake, and the lake volume, indicates how rapidly the water in the system is replaced. WRT of 0.28 and 0.67 years were estimated for Lake Los Pocitos for dry and wet seasons, respectively. Low values (i.e., <1 year) indicate a short WRT in the system, which generates a constant exchange of water. Moreover, the low WRT inhibits the interaction between water and rocks,

Table 2 Input data for stable isotope mass balance and evaporation loss in Lake Los Pocitos

Season	Area (m^2)	T (°C)	h	P (mm m^{-1})	E (mm m^{-1})	δ_L ^{18}O (%)	δ_P ^{18}O (%)	δ_{Gi} ^{18}O (%)	δ_A (%)	δ_E (%)	G_i (m month^{-1})	G_i (mm day^{-1})
Dry	195,884	12.7	0.62	21	79	−1.3	−5.7	−4.6	−16	−19	0.4	12.8
Wet	195,185	17.9	0.74	116	176	0.9	−4.5	−4.6	−14	−7.8	0.2	5.5

T: air temperature; h: relative humidity; P: precipitation; E: evaporation; δ_L: δ^{18}O composition of lake waters; δ_P: δ^{18}O composition of precipitation; δ_{Gi}: δ^{18}O composition of groundwater; δ_A: δ^{18}O composition of atmospheric water vapor; δ_E: δ^{18}O composition of evaporated lake water; G_i: groundwater inflow

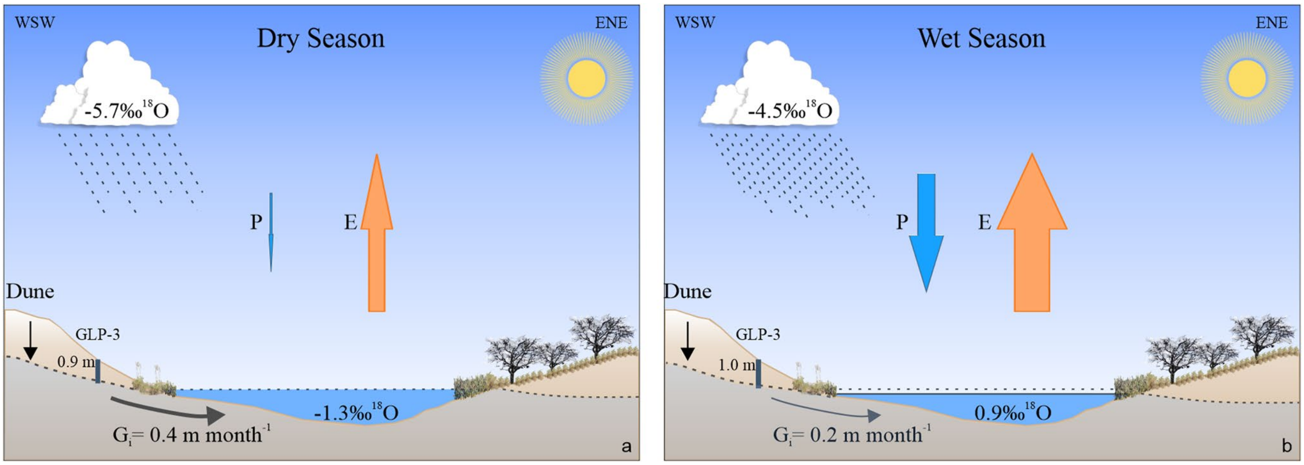

Fig. 5 Schematic hydrological model for Lake Los Pocitos during **a** dry and **b** wet seasons. The arrow thickness is proportional to the component contribution. The $\delta^{18}O$ values for rainfall (δ_P) are those reported by Cabrera et al. (2019) for Rio Cuarto station

reducing the intensity of weathering processes, which favors a low salt concentration. The WRT values calculated for Lake Los Pocitos were lower than those reported for other lakes in the HPP ($\tau = 1.11$ years) by Quiroz Londoño et al. (2020). These differences may be attributed to the existence of different climatic regimes in the PP. For instance, within the USA, aridity is an important factor controlling E/I and τ, with relative humidity and annual precipitation being the main drivers (Brooks et al. 2014).

Different studies (Brock et al. 1982; Wolfe et al. 2007) established that throughflow lakes and, to a lesser extent, those with relatively short WRT, show good biological conditions and low concentrations of nitrogen, phosphorus, and dissolved organic carbon. Thus, the hydrological conditions determined for Lake Los Pocitos could explain the good water quality observed in this water body.

Unfortunately, the environmental quality of water bodies in this region is at risk of deterioration in response to disturbances caused by human activities. Changes in the hydrologic balance as a result of the conversion of native vegetation to areas devoted to agriculture have been reported for instance in Australia, Southern High Plains in the USA, and the Sahel plains in North Africa (George et al. 1997; Leblanc et al. 2008; Scanlon et al. 2005). A widely observed pattern of rising water levels and soil salinity has been reported in such semiarid sedimentary plains. This does not only cause the loss of cultivable hectares, but also the deterioration of ecosystems that depend on groundwater (George et al. 1997; Williams 1999). A widespread water-table rise accompanied by incipient salinization of soils, phreatic groundwater, and surface waters has also been recorded in the DPP (Bogino and Jobbágy 2011; Jayawickreme et al. 2011; Santoni et al. 2010). Even the appearance of deep canyons and streams in the western edge of the DPP caused by sapping has been related to land use change (i.e., replacement of native vegetation by crops) and the consequent water-table rise (Contreras et al. 2013; Jobbágy et al. 2021). Particularly, in the study area, the anthropic activities have not significantly impacted the water quality and lake levels which have remained relatively constant during the last few years. However, if human activities continue without control and remediation policies, it is probable that these modifications could generate a negative impact on the ecosystem in a short time.

The surface-water and groundwater degradation due to the use of fertilizers is another risk associated with agriculture expansion that has become an environmental problem in many regions of the world. In Argentina, N-containing fertilizers have been utilized inefficiently, and large quantities are frequently discharged into aquatic ecosystems causing eutrophication (e.g., Licursi et al. 2016). N-degraded groundwater and lakes have been recognized in the PP (Blarasin et al. 2020; Romanelli et al. 2020). Lakes receive water inputs from nitrate-contaminated groundwater, which can cause ecosystem deterioration. WRT is an important factor related to the nitrogen (N) self-purification capacity of aquatic systems (e.g., Finlay et al. 2013; Tong et al. 2019). For instance, a longer WRT results in higher N removal efficiency via denitrification or permanent burial in water bodies (Finlay et al. 2013).

The results obtained in this work give an idea of the hydrological functioning of water bodies emplaced in the DPP and their possible response to anthropic disturbances. Thus, establishing the surface-water/groundwater interactions, the type of lake, and the WRT in Lake Los Pocitos results in a relevant consideration of the changes in land use that have occurred in the DPP in the last few decades. For instance, the ecosystem N removal efficiency via denitrification or permanent burial would be affected by the short WRT in Lake Los Pocitos. The preservation of groundwater quality is crucial in this region, where a high percentage of total inflow to surface-water bodies comes from this source.

Concluding remarks

Lakes where the evaporation rate exceeds rainfall are usually desiccating ponds. However, Lake Los Pocitos has maintained its water level through the last decade, showing a relatively minor seasonal fluctuation. The δ^{18}O mass balance model suggests a groundwater inflow of ~0.4 and ~0.2 m month^{-1} to Lake Los Pocitos during the dry and the wet season, respectively. These results confirm that groundwater discharge into the lake occurs during both seasons, allowing a relatively constant water level throughout the year. During the wet season, in spite of the highest rainfall rate, the lowest groundwater inflow and the most intense evaporation causes a lake-level decrease of ~10 cm compared to the dry season, when it increases again.

Based on the ratio of water inputs to the lake and surface evaporation, Lake Los Pocitos is classified as a throughflow lake with uninterrupted inflows that exceed loss by evaporation, and yield a WRT of approximately half a year. These hydrologic conditions, along with freshwater inputs from the dune, explain why, in spite of the aridity of the region, low water salinity and stable lake levels prevail.

This study constitutes a first approach to the quantification of the groundwater inflow for a large group of lakes located in the DPP, helping researchers to understand the lake sensitivity to changes in groundwater resulting from the ongoing climate and land-use changes and supporting decision-makers in the development of water management policies in these landscapes. In addition, the results indicate that these lakes offer an ideal opportunity to observe the impact of land-use changes in this semiarid region, which is part of one of the major agricultural regions in the world. Future research efforts should address the effects of land-use change on the hydrological cycle of the DPP.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Ala-aho P, Rossi PM, Kløve B (2013) Interaction of esker groundwater with headwater lakes and streams. J Hydrol 500:144-156. https://doi.org/10.1016/j.jhydrol.2013.07.014

Arnoux M, Barbecot F, Gibert-Brunet E, Gibson JJ, Rosa E, Noret A, Monvoisin G (2017a) Geochemical and isotopic mass balances of kettle lakes in southern Quebec (Canada) as tools to document variations in groundwater quantity and quality. Environ Earth Sci 76(3). https://doi.org/10.1007/s12665-017-6410-6

Arnoux M, Gibert-Brunet E, Barbecot F, Guillon S, Gibson JJ, Noret A (2017b) Interactions between groundwater and seasonally ice-covered lakes: using water stable isotopes and radon-222 multilayer mass balance models. Hydrol Process 31(14). https://doi.org/10.1002/hyp.11206

Blarasin M, Cabrera A, Matteoda E, Aguirre M, Giuliano Albo J, Becher Quinodoz F, Maldonado L, Frontera H, (2014) Recursos hídricos subterráneos, parte II: aspectos geoquímicos, isotópicos, contaminación y aptitudes de uso [Groundwater resources, part II: geochemical, isotopic, contamination and usability aspects]. In: Martino R, Guereschi A (eds) Report of the XIX Argentine Geological Congress: Geology and Natural Resources of the Province of Córdoba. XIX Cong Geol Arg Actas. https://doi.org/10.13140/2.1.4625.184. pp 1263-1287

Blarasin M, Cabrera A, Matiatos I, Becher Quinodóz F, Giuliano Albo J, Lutri V, Matteoda E, Panarello H (2020) Comparative evaluation of urban versus agricultural nitrate sources and sinks in an unconfined aquifer by isotopic and multivariate analyses. Sci Total Environ 741. https://doi.org/10.1016/j.scitotenv.2020.140374

Bocanegra E, Quiroz Londoño OM, Martínez DE, Romanelli A, London OMQ, Romanelli A (2013) Quantification of the water balance and hydrogeological processes of groundwater-lake interactions in the Pampa plain, Argentina. Environ Earth Sci 68(8):2347-2357. https://doi.org/10.1007/s12665-012-1916-4

Bogino SM, Jobbágy EG (2011) Climate and groundwater effects on the establishment, growth and death of Prosopis caldenia trees in the pampas (Argentina). For Ecol Manag 262(9). https://doi.org/10.1016/j.foreco.2011.07.032

Bouchez C, Goncalves J, Deschamps P, Vallet-Coulomb C, Hamelin B, Doumnang J-C, Sylvestre F (2016) Hydrological, chemical, and isotopic budgets of Lake Chad: a quantitative assessment of evaporation, transpiration and infiltration fluxes. Hydrol Earth Syst Sci 20(4). https://doi.org/10.5194/hess-20-1599-2016

Brock TD, Lee DR, Janes D, Winek D (1982) Groundwater seepage as a nutrient source to a drainage lake: Lake Mendota, Wisconsin. Water Res 16(7):1255-1263. https://doi.org/10.1016/0043-1354(82)90144-0

Brooks JR, Gibson JJ, Birks SJ, Weber MH, Rodecap KD, Stoddard JL (2014) Stable isotope estimates of evaporation: inflow and water residence time for lakes across the United States as a tool for national lake water quality assessments. Limnol Oceanogr 59(6). https://doi.org/10.4319/lo.2014.59.6.2150

Cabrera A, Blarasin M, Bécher Quinodoz F, Lutri V, Felizzia J, Eric C, Matteoda E, Giacobonne D (2019) The local meteoric water line in the Pampean Plain of Córdoba, Argentina. J Appl Geol Geophys 7:19-25

Cabrera A, Blarasin M, Dapeña C, Maldonado L (2013) Composición físico-química e isotópica de precipitaciones del Sur de Córdoba [Physico-chemical and isotopic composition of precipitation in the south of Córdoba]. In: González N, Kruse E, Trovatto M, Laurencena P (eds) Agua subterránea recurso estratégico Tomo II. VIII Cong. Arg. de Hidrogeología y VI Seminario Latinoamericano sobre Temas Actuales de la Hidrología Subterránea. Editorial of the National University of La Plata, La Plata, Argentina, pp 35-42

Campodonico VA, Dapeña C, Pasquini AI, Lecomte KL, Piovano EL (2019) Hydrogeochemistry of a small saline lake: assessing the groundwater inflow using environmental isotopic tracers (Laguna del Plata, Mar Chiquita system, Argentina). J S Am Earth Sci 95:102305. https://doi.org/10.1016/j.jsames.2019.102305

Cao X, Wu P, Zhou S, Han Z, Tu H, Zhang S (2018) Seasonal variability of oxygen and hydrogen isotopes in a wetland system of the Yunnan-Guizhou plateau, Southwest China: a quantitative assessment of groundwater inflow fluxes. Hydrogeol J 26(1):215-231. https://doi.org/10.1007/s10040-017-1635-8

Ceci JH, Coronado MD (1981) Recursos hídricos subterráneos [Groundwater resources]. In: Irigoyen M (ed) Geología de La Provincia de San Luis, VIII Cong. Geol. Arg., San Luis, Argentina, pp 301-322

Colazo JC (2012) Recursos físicos y ambientales de los territorios de la provincia de San Luis [Physical and environmental resources of the San Luis province territories]. INTA Ediciones, INTA, Buenos Aires, Argentina

Contreras S, Santoni CS, Jobbágy EG (2013) Abrupt watercourse formation in a semiarid sedimentary landscape of Central Argentina: the roles of forest clearing, rainfall variability and seismic activity. Ecohydrology 6(5):794-805. https://doi.org/10.1002/eco.1302

Córdoba FE, Guerra L, Rodríguez CC, Sylvestre F, Piovano EL (2014) Una visión paleolimnológica de la variabilidad hidroclimática reciente en el centro de Argentina: desde la pequeña edad de hielo al siglo XXI [A Paleolimmological perspective of recent hydroclimate variability in central Argentina: from the Little Ice Age to the 21st century]. Lat Am J Sedimentol Basin Anal 21(2):139-163

Craig H, Gordon LI (1965) Deuterium and oxygen 18 variations in the ocean and the marine atmosphere. In: Tongiorgi E (ed) Stable isotopes in oceanographic studies and Paleotemperatures. Laboratory Di Geologia Nucleare, Pisa, Italy, pp 9-130

Drago E, Quiros R (1996) The hydrochemistry of the inland waters of Argentina: a review. Int J Salt Lake Res 4:315-325. https://doi.org/10.1007/BF01999115

Echegoyen CV, Lecomte KL, Campodonico VA, Yaciuk PA, Jobbágy EG, Heider G, Sepúlveda LD, Pasquini AI, De Micco G, Bohé AE (2021) Use of radon-222 to assess the groundwater inflow in a phreatic lake of a dune field (San Luis, Argentine). Bol Inst Geol Min Esp 132(1-2):99-106. https://doi.org/10.21701/bolgeomin.132.1-2.010

Fernández Cirelli A, Miretzky P (2004) Ionic relations: a tool for studying hydrogeochemical processes in Pampean shallow lakes (Buenos Aires, Argentina). Quat Int 114(1):113-121. https://doi.org/10.1016/S1040-6182(03)00046-6

Finlay JC, Small GE, Sterner RW (2013) Human influences on nitrogen removal in lakes. Science 342(6155):247-250. https://doi.org/10.1126/science.1242575

Fontes JC (1980) Environmental isotopes in groundwater hydrology. Vol. 1. In: Fritz P, Fontes J (eds) Handbook of environmental isotope geochemistry. Elsevier, Amsterdam, pp 75-140

Gat JR (2010) Isotope hydrology: a study of the water cycle. Imperial College Press, London. https://doi.org/10.1142/p027

Gat JR (1995) Stable isotopes of fresh and Saline Lakes. In: Lerman A, Imboden DM, Gat JR (eds) Physics and Chemistry of Lakes, Springer, Berlin, pp 139-165. https://doi.org/10.1007/978-3-642-85132-2_5

Gat JR (1996) Oxygen and hydrogen isotopes in the hydrologic cycle. Annu Rev Earth Planet Sci 24(1):255-262. https://doi.org/10.1146/annurev.earth.24.1.225

George R, McFarlane D, Nulsen B (1997) Salinity threatens the viability of agriculture and ecosystems in Western Australia. Hydrogeol J 5(1):6-21. https://doi.org/10.1007/s100400050103

Gibson JJ, Edwards TWD (2002) Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lakes in northern Canada. Glob Biogeochem Cycles 16(2):10-1-10-14. https://doi.org/10.1029/2001GB001839

Gibson JJ, Edwards TWD, Bursey GG, Prowse TD (1993) Estimating evaporation using stable isotopes: quantitative results and sensitivity analysis for two catchments in northern Canada. Hydrol Res 24(2-3):79-94. https://doi.org/10.2166/nh.1993.0015

Gibson JJ, Prepas EE, McEachern P (2002) Quantitative comparison of lake throughflow, residency, and catchment runoff using stable isotopes: modelling and results from a regional survey of boreal lakes. J Hydrol 262(1-4):128-144. https://doi.org/10.1016/S0022-1694(02)00022-7

Gibson JJ, Birks SJ, Edwards TWD (2008) Global prediction of δ_A and δ^2H-δ^{18}O evaporation slopes for lakes and soil water accounting for seasonality. Glob Biogeochem Cycles 22(2):1-12. https://doi.org/10.1029/2007GB002997

Gibson JJ, Birks SJ, Yi Y (2016) Stable isotope mass balance of lakes: a contemporary perspective. Quat Sci Rev 131:316-328. https://doi.org/10.1016/j.quascirev.2015.04.013

Gonfiantini R (1978) Standards for stable isotope measurements in natural compounds. Nature 271(5645):534-536. https://doi.org/10.1038/271534a0

Gonfiantini R (1986) Environmental isotopes in lake studies. In: Fritz P, Fontes J (eds) Handbook of environmental isotope geochemistry. Elsevier, New York, pp 113-168. https://doi.org/10.1016/B978-0-444-42225-5.50008-5

Guerra L, Piovano EL, Córdoba FE, Sylvestre F, Damatto S (2015) The hydrological and environmental evolution of shallow Lake Melincué, central Argentinean Pampas, during the last millennium. J Hydrol 529:570-583. https://doi.org/10.1016/j.jhydrol.2015.01.002

Gurrieri JT, Furniss G (2004) Estimation of groundwater exchange in alpine lakes using non-steady mass-balance methods. J Hydrol 297(1-4):187-208. https://doi.org/10.1016/j.jhydrol.2004.04.021

Harvey FE, Swinehart JB, Kurtz TM (2007) Ground water sustenance of Nebraska's unique Sand Hills peatland fen ecosystems. Groundwater 45(2):218-234. https://doi.org/10.1111/j.1745-6584.2006.00278.x

Heider G, Jobbágy EG, Tripaldi A (2019) Uso del espacio semiárido por poblaciones prehispánicas: el papel de los paisajes de dunas como eco-refugios en el Centro de Argentina [Use of semi-arid space by prehispanic population: the role of dune landscapes as eco-refuges in Central Argentina]. Bol Soc Geol Mex 71(2):229-248. https://doi.org/10.18268/BSGM2019v71n2a1

Hofmann H, Knöller K, Lessmann D (2008) Mining lakes as groundwater-dominated hydrological systems: assessment of the water balance of mining Lake Plessa 117 (Lusatia, Germany) using stable isotopes. Hydrol Process 22(23):4620-4627. https://doi.org/10.1002/hyp.7071

Horita J, Wesolowski DJ (1994) Liquid-vapor fractionation of oxygen and hydrogen isotopes of water from the freezing to the critical temperature. Geochemica Cosmochim Acta 58(16):3425-3437. https://doi.org/10.1016/0016-7037(94)90096-5

Iriondo M, Kröhling DM (1995) El sistema eólico pampeano [The Pampean Aeolian system]. Comunicaciones Museo Provincial de Ciencias Naturales. Comunicaciones Museo Provincial de Ciencias Naturales "Florentino Ameghino," Santa Fe

Iriondo M, Brunetto E, Kröhling D (2009) Historical climatic extremes as indicators for typical scenarios of Holocene climatic periods in the Pampean Plain. Palaeogeogr Palaeoclimatol Palaeoecol 283(3-4):107-119. https://doi.org/10.1016/j.palaeo.2009.09.005

Jayawickreme DH, Santoni CS, Kim JH, Jobbágy EG, Jackson RB (2011) Changes in hydrology and salinity accompanying a century of agricultural conversion in Argentina. Ecol Appl 21(7):2367-2379. https://doi.org/10.1890/10-2086.1

Jobbágy EG, Nosetto MD, Villagra PE, Jackson RB (2011) Water subsidies from mountains to deserts: their role in sustaining groundwater-fed oases in a sandy landscape. Ecol Appl 21(3):678-694

Jobbágy EG, Lorenzo S, Buono N, Páez R, Diaz Y, Marchesini V, Nosetto MD (2021) Plants versus streams: their groundwater-mediated competition at "El Morro," a developing catchment in the dry plains of Argentina. Hydrol Process 35(5). https://doi.org/10.1002/hyp.14188

Kidmose J, Nilsson B, Engesgaard P, Søndergaard M, Jeppesen E (2013) Focused groundwater discharge of phosphorus to a eutrophic seepage Lake (lake Væng, Denmark): implications for lake ecological state and restoration. Hydrogeol J 21(8):1787-1802. https://doi.org/10.1007/s10040-013-1043-7

Krabbenholft DP, Bowser CJ, Anderson MP, Valley JW (1990) Estimating groundwater exchange with lakes: 1. the stable isotope mass balance. Water Resour Res 26(10):2445-2453. https://doi.org/10.1029/WR026i010p02445

Krabbenhoft DP, Bowser CJ, Kendall C, Gat JR (1994) Use of Oxygen-18 and deuterium to assess the hydrology of groundwater-Lake systems. In: Baker LA (ed) Environmental chemistry of lakes and reservoirs, advances in chemistry, Washington, DC, pp 67-90. https://doi.org/10.1021/ba-1994-0237.ch003

Leblanc MJ, Favreau G, Massuel S, Tweed SO, Loireau M, Cappelaere B (2008) Land clearance and hydrological change in the Sahel: SW Niger. Glob Planet Change 61(3-4):135-150. https://doi.org/10.1016/j.gloplacha.2007.08.011

Lewandowski J, Meinikmann K, Nützmann G, Rosenberry DO (2015) Groundwater-the disregarded component in lake water and nutrient budgets, part 2: effects of groundwater on nutrients. Hydrol Process 29(13):2922-2955. https://doi.org/10.1002/hyp.10384

Liao F, Wang G, Shi Z, Cheng G, Kong Q, Mu W, Guo L (2018) Estimation of groundwater discharge and associated chemical fluxes into Poyang Lake, China: approaches using stable isotopes (δD and δ^{18}O) and radon. Hydrogeol J 26(5):1625-1638. https://doi.org/10.1007/s10040-018-1793-3

Licursi M, Gómez N, Sabater S (2016) Effects of nutrient enrichment on epipelic diatom assemblages in a nutrient-rich lowland stream, Pampa Region, Argentina. Hydrobiologia 766(1):135-150. https://doi.org/10.1007/s10750-015-2450-7

Liu C, Liu J, Wang XS, Zheng C (2016) Analysis of groundwater-lake interaction by distributed temperature sensing in Badain Jaran Desert, Northwest China. Hydrol Process 30(9):1330-1341. https://doi.org/10.1002/hyp.10705

Liu H, Yin Y, Piao S, Zhao F, Engels M, Ciais P (2013) Disappearing Lakes in semiarid northern China: drivers and environmental impact. Environ Sci Technol 47(21):12107-12114. https://doi.org/10.1021/es305298q

Marchesini VA, Nosetto MD, Houspanossian J, Jobbágy EG (2020) Contrasting hydrological seasonality with latitude in the south American Chaco: the roles of climate and vegetation activity. J Hydrol 587. https://doi.org/10.1016/j.jhydrol.2020.124933

Meinikmann K, Hupfer M, Lewandowski J (2015) Phosphorus in groundwater discharge: a potential source for lake eutrophication. J Hydrol 524:214-226. https://doi.org/10.1016/j.jhydrol.2015.02.031

Miretzky P, Conzonno V, Fernández Cirelli A (2000) Hydrochemistry of pampasic ponds in the lower stream bed of Salado River drainage basin, Argentina. Environ Geol 39(8):951-956. https://doi.org/10.1007/s002549900063

Miretzky P, Conzonno V, Fernández Cirelli A (2001) Geochemical mechanism controlling pampasic ponds hydrochemistry: Salado River Drainage Basin, Argentina. Rev Bras Recur Hídricos 6:29-39. https://doi.org/10.21168/rbrh.v6n4.p29-39

Montalván FJ, Heredia J, Ruiz JM, Pardo-Igúzquiza E, García de Domingo A, Elorza FJ (2017) Hydrochemical and isotopes studies in a hypersaline wetland to define the hydrogeological conceptual model: Fuente de Piedra Lake (Malaga, Spain). Sci Total Environ 576:335-346. https://doi.org/10.1016/j.scitotenv.2016.10.048

Nosetto MD, Paez RA, Ballesteros SI, Jobbágy EG (2015) Higher water-table levels and flooding risk under grain vs. livestock production systems in the subhumid plains of the pampas. Agric Ecosyst Environ 206:60-70. https://doi.org/10.1016/j.agee.2015.03.009

Oliveira Ommen DA, Kidmose J, Karan S, Flindt MR, Engesgaard P, Nilsson B, Andersen FØ (2012) Importance of groundwater and macrophytes for the nutrient balance at oligotrophic Lake Hampen, Denmark. Ecohydrology 5(3):286-296. https://doi.org/10.1002/eco.213

Petermann E, Gibson JJ, Knöller K, Pannier T, Weiß H, Schubert M (2018) Determination of groundwater discharge rates and water residence time of groundwater-fed lakes by stable isotopes of water (^{18}O, ^{2}H) and radon (^{222}Rn) mass balances. Hydrol Process 32(6):805-816. https://doi.org/10.1002/hyp.11456

Poca M, Nosetto MD, Ballesteros S, Castellanos G, Jobbágy EG (2020) Isotopic insights on continental water sources and transport in the mountains and plains of southern South America. Isot Environ Health Stud 56(5-6):586-605. https://doi.org/10.1080/10256016.2020.1819264

Quiroz Londoño OM, Romanelli A, Martínez DE, Massone HE (2020) Water exchange processes estimation in a temperate shallow lake based on water stable isotope analysis. Isot Environ Health Stud 56(5-6):465-479. https://doi.org/10.1080/10256016.2020.1803857

Rice EW, Baird RB, Eaton AD, Clesceri LS (2012) Standard methods for the examination of water and wastewater, 22nd edn. American Public Health Association, Washington, DC

Romanelli A, Quiroz Londoño OM, Martínez DE, Massone HE, Escalante AH (2014) Hydrogeochemistry Wet Pampa Plain, Argentina. Environ Earth Sci 71(4):1953-1966. https://doi.org/10.1007/s12665-013-2601-y

Romanelli A, Soto DX, Matiatos I, Martínez DE, Esquius S (2020) A biological and nitrate isotopic assessment framework to understand eutrophication in aquatic ecosystems. Sci Total Environ 715. https://doi.org/10.1016/j.scitotenv.2020.136909

Rosenberry DO, Winter TC, Buso DC, Likens GE (2007) Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA. J Hydrol 340(3-4):149-166. https://doi.org/10.1016/j.jhydrol.2007.03.018

Rosenberry DO, Lewandowski J, Meinikmann K, Nützmann G (2015) Groundwater-the disregarded component in lake water and nutrient budgets, part 1: effects of groundwater on hydrology. Hydrol Process 29(13):2895-2921. https://doi.org/10.1002/hyp.10403

Rossman NR, Zlotnik VA, Rowe CM (2019) Simulating lake and wetland areal coverage under future groundwater recharge projections: the Nebraska Sand Hills system. J Hydrol 576:185-196. https://doi.org/10.1016/j.jhydrol.2019.06.046

Sacks LA, Lee TM, Swancar A (2014) The suitability of a simplified isotope-balance approach to quantify transient groundwater-lake interactions over a decade with climatic extremes. J Hydrol 519:3042-3053. https://doi.org/10.1016/j.jhydrol.2013.12.012

Santoni CS, Jobbágy EG, Contreras S (2010) Vadose zone transport in dry forests of Central Argentina: role of land use. Water Resour Res. 46(10). https://doi.org/10.1029/2009WR008784

Scanlon BR, Reedy RC, Stonestrom DA, Prudic DE, Dennehy KF (2005) Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. Glob Chang Biol 11(10):1577-1593. https://doi.org/10.1111/j.1365-2486.2005.01026.x

Shaw GD, White ES, Gammons CH (2013) Characterizing groundwater-lake interactions and its impact on lake water quality. J Hydrol 492:69-78. https://doi.org/10.1016/j.jhydrol.2013.04.018

Shaw GD, Mitchell KL, Gammons CH (2017) Estimating groundwater inflow and leakage outflow for an intermontane lake with a structurally complex geology: Georgetown Lake in Montana, USA. Hydrogeol J 25(1):135-149. https://doi.org/10.1007/s10040-016-1500-1

Stets EG, Winter TC, Rosenberry DO, Striegl RG (2010) Quantification of surface water and groundwater flows to open- and closed-basin lakes in a headwaters watershed using a descriptive oxygen stable isotope model. Water Resour Res 46(3):1-16. https://doi.org/10.1029/2009WR007793

Tao Y, Yuan Z, Fengchang W, Wei M (2013) Six-decade change in water chemistry of large freshwater Lake Taihu, China. Environ Sci Technol 47(16):9093-9101. https://doi.org/10.1021/es401517h

Tong Y, Li J, Qi M, Zhang X, Wang M, Liu X, Zhang W, Wang X, Lu Y, Lin Y (2019) Impacts of water residence time on nitrogen budget of lakes and reservoirs. Sci Total Environ 646:75-83. https://doi.org/10.1016/j.scitotenv.2018.07.255

Tripaldi A, Forman SL (2007) Geomorphology and chronology of Late Quaternary dune fields of western Argentina. Palaeogeogr Palaeoclimatol Palaeoecol 251(2):300-320. https://doi.org/10.1016/j.palaeo.2007.04.007

Tripaldi A, Ciccioli PL, Alonso MS, Forman SL (2010) Petrography and geochemistry of late Quaternary dune fields of western Argentina: provenance of aeolian materials in southern South America. Aeolian Res 2:33-48. https://doi.org/10.1016/j.aeolia.2010.01.001

Tripaldi A, Zárate MA, Forman SL, Doyle ME, Ciccioli PL, Badger T, Doyle ME, Ciccioli PL (2013) Geological evidence for a drought episode in the western pampas (Argentina, South America) during the early-mid 20th century. The Holocene 23(12):1731-1746. https://doi.org/10.1177/0959683613505338

Turner JV, Townley LR (2006) Determination of groundwater flow-through regimes of shallow lakes and wetlands from numerical analysis of stable isotopes and chloride tracer distribution patterns. J Hydrol 320(3-4):451-483. https://doi.org/10.1016/j.jhydrol.2005.07.050

Turner KW, Wolfe BB, Edwards TWD (2010) Characterizing the role of hydrological processes on lake water balances in the Old Crow Flats, Yukon territory, Canada, using water isotope tracers. J Hydrol 386(1-4):103-117. https://doi.org/10.1016/j.jhydrol.2010.03.012

Viglizzo EF, Jobbágy EG (2010) Expansión de la Frontera Agropecuaria en Argentina y su Impacto Ecológico-Ambiental [Expansion of the Agricultural Frontier in Argentina and its Ecological-Environmental Impact]. INTA Ediciones, Buenos Aires, Argentina

Vilanova I, Schittek K, Geilenkirchen M, Schäbitz F, Schulz W (2015) Last millennial environmental reconstruction based on a multi-proxy record from Laguna Nassau, Western pampas, Argentina. Neues Jahrb Geol Paläontologie 277(2):209-224. https://doi.org/10.1127/njgpa/2015/0502

Wetzel RG (2001) Limnology: Lake and river ecosystems, 3rd edn. Springer, Heidelberg, Germany. https://doi.org/10.1016/C2009-0-02112-6

Williams WD (1999) Salinisation: a major threat to water resources in the arid and semi-arid regions of the world. Lakes Reserv Res Manag 4(3-4):85-91. https://doi.org/10.1046/j.1440-1770.1999.00089.x

Winter TC, Harvey JW, Franke OL, Alley WM (1998) Ground water and surface water: a single resource. US Geol Surv Circ 1139. https://doi.org/10.3133/cir1139

Wolfe BB, Karst-Riddoch TL, Hall RI, Edwards TWD, English MC, Palmini R, McGowan S, Leavitt PR, Vardy SR (2007) Classification of hydrological regimes of northern floodplain basins (Peace-Athabasca Delta, Canada) from analysis of stable isotopes (δ^{18}O, δ^{2}H) and water chemistry. Hydrol Process 21(2):151-168. https://doi.org/10.1002/hyp.6229

Zárate MA, Tripaldi A (2012) The aeolian system of central Argentina. Aeolian Res 3(4):401-417. https://doi.org/10.1016/j.aeolia.2011.08.002