

Quantification of the water balance and hydrogeological processes of groundwater–lake interactions in the Pampa Plain, Argentina

E. Bocanegra · O. M. Quiroz Londoño ·
D. E. Martínez · A. Romanelli

Received: 5 December 2011 / Accepted: 16 August 2012 / Published online: 1 September 2012
© Springer-Verlag 2012

Abstract This paper gives an account of the assessment and quantification of the water balance and the hydrogeological processes related to lake–groundwater interaction in the Pampa Plain by using hydrogeochemical, isotopic and flow numerical modeling techniques. La Salada is a permanent shallow lake, with an area of 5.8 km², located on the SE of Buenos Aires Province. A total of 29 lake water samples and 15 groundwater samples were collected for both hydrochemical analysis and environmental stable isotope determination. Water table depths were measured in wells closed to the lake. Groundwater samples appear grouped on the Local Meteoric Water Line, suggesting a well-mixed system and that rainfall is the main recharge source to the aquifer. Water evaporation process within La Salada is also corroborated by its isotopic composition. The model that best adjusts to La Salada Lake hydrochemical processes includes evaporation from groundwater, calcite precipitation with CO₂ release and cationic exchange. The annual water balance terms for the lake basin indicates for each hydrological component the following values: 1.16 E⁰⁸ m³ rainfall, 8.15 E⁰⁷ m³ evapotranspiration,

1.90 E⁰⁶ m³ runoff, 1.55 E⁰⁷ m³ groundwater recharge, 6.01 E⁰⁶ m³ groundwater discharge to the lake, 9.54 E⁰⁶ m³ groundwater discharge to the river, 5.00 E⁰⁵ m³ urban extraction and 4.90 E⁰⁶ m³ lake evaporation. Integrated analysis of hydrochemical and isotopic information helped to calibrate the groundwater flow model, to validate the conceptual model and to quantitatively assess the basin water balance.

Keywords Environmental isotopes · Hydrogeochemistry · Flow modeling · Water balance · Shallow lake

Introduction

Lakes are integrated into the global water cycle and are therefore influenced by precipitation, evaporation and water fluxes by groundwater or surface water (Mook 2002; Burkert et al. 2004; Froehlich et al. 2005). Understanding these hydrologic processes is a fundamental key, since lake exists in the landscape where the water balance ensures an adequate water supply. Therefore sustained lakes functioning require proper land use and water management. To achieve this, an integrated understanding of the spatial dynamics and hydrological balance of the lake ecosystem is required. An important note is that lakes are linked through the hydrological system to upstream and downstream areas. What happens upstream will affect a lake, while what happens in a lake will affect the environment and people living downstream (Price and Maloney 1994).

Hydrologic alterations of lakes may affect the spatial and temporal fluctuations in the water table and the interaction with hydrological events. The spatiotemporal changes in groundwater elevation would directly affect the flow characteristics of water and nutrients within, and

E. Bocanegra · O. M. Quiroz Londoño (✉) ·
D. E. Martínez · A. Romanelli
FCEyN, Instituto de Geología de Costas y del Cuaternario,
Universidad Nacional de Mar del Plata, Funes 3350-Nivel 1,
7600 Mar del Plata, Argentina
e-mail: qlondono@mdp.edu.ar

E. Bocanegra
Scientific Research Commission of the Buenos Aires
Province (CIC), La Plata, Argentina

O. M. Quiroz Londoño · D. E. Martínez · A. Romanelli
Instituto de Investigaciones Marinas y Costeras, National
Council of Scientific and Technical Research (CONICET),
Mar del Plata, Argentina

from, the lake (Litaor et al. 2008). Moreover, lakes represent significant natural environments, since they deliver a wide range of ecosystem services including provisioning (habitat for species, water supply), regulating (regulation of local climate and hydrological flows, groundwater recharge and discharge), cultural and supporting (nutrient cycling) services (MA Millennium Ecosystem Assessment 2005). Therefore, their sustainable utilization for the benefit of mankind in a combined way, compatible with the maintenance of the natural properties of the ecosystem is necessary.

The hydrogeochemical interpretation of representative water-sample analyses is a useful tool developed for the analysis of hydrological systems (Martínez et al. 2000; Wang et al. 2006). This is based on the thermodynamic principles which determine the chemical composition of natural waters. Its evolutionary concepts were first put forward by Cheveratev (1955), and its thermodynamic bases more accurately developed by Garrels and Christ (1965). Glynn and Plummer (2005) have recently published a synthesis of the evolution of geochemistry applied to the understanding of groundwater systems. Custodio (1991) makes reference to the difficulty connected with the piezometric definition of complex areas as well as to the relative advantages of hydrochemical methods, such as their reasonably low cost and independence from hydrodynamic methods. This tool allows characterizing different water sources identifying and verifying flow lines, identifying mixing processes and quantifying the interaction between different water sources.

Moreover, the contribution of isotopic techniques to the study of lakes includes water balance, dynamics (vertical and horizontal mixing processes), lake–groundwater interaction, sedimentation processes and paleoclimatic and paleohydrological problems (Froehlich et al. 2005). The use of environmental isotopes for the study of groundwater dynamics in hydrologic systems was successfully developed in the works of Craig (1961) and Dansgaard (1964). Likewise, isotopic determinations may have a number of further applications such as recharge estimation, age determination, end members mixing, etc as can be seen in several reviews (Clark and Fritz 1997; Cook and Herczeg 1999; Geyh 2000).

Easily usable hydrology models, generally available, would be quite valuable to predict hydrologic conditions. Furthermore, modeling water budgets in terms of hydrologic processes is extremely important for the maintenance of lake structure and function; biotic introductions, organic accumulation and export, nutrient cycling and vegetation dynamics can only be determined in the context of accurate lake hydrological fluxes (Zhang and Mitsch 2005).

The Pampa Plain in Argentina is characterized by a geomorphological environment which corresponds mostly

to that of gently sloped plains. Shallow lakes are common in the area due to the slow slopes and drainage density that dominate the landscape. Pampean ponds are very shallow plain lakes, without thermal stratification and highly fluctuating in salinity and water renewal time. Due to the shallowness of lakes their hydrology is highly dependent on in situ rainfall (Quirós et al. 2002).

Processes and relationships between aquifers and shallow lakes in the Pampa Plain can be easily identified in conceptual models. However, the quantification of them is still unknown in most cases. There are several tools that combined can quantify that processes in order to compensate the lack of information. The aim of this study is to assess and quantify the water balance and the hydrogeological processes related to lake–groundwater interaction in the Pampa Plain by using hydrogeochemical, isotopic and numerical modeling techniques. It is expected that this methodological proposal could be applied in other shallow lakes located in plain areas with similar characteristics, bringing useful information in order to improve water resource and land use planning.

Geological and hydrogeological background

The Pampa Plain in Argentina is a large plain of about 1,500,000 km², characterized by gently sloped plains (<0.5 %) crossed by a block mountain system called Tandilia Range System. This system has a maximum altitude of about 510 m above sea level (m asl). It consists of two big geological units a Precambrian crystalline bedrock called Complejo Buenos Aires (Marchese and Di Paola 1975) with no outcrops in the study area, and a set of sedimentary rocks of Precambrian–Lower Paleozoic origin which lithologically constitutes the ranges, grouped under the name of Balcarce Formation (Dalla Salda and Iñiguez 1979). Hills and plains are formed by Cenozoic loess-like sediments (especially of Pleistocene–Holocene age).

The Upper Pleistocene–Holocene cover of the area is a sequence of silt, silt-clayed and fine sand sediments of aeolian and fluvial origin that constitutes an aquifer system known as Pampeano aquifer (Sala 1975). The Pampeano aquifer in the area is an unconfined aquifer, with a thin unsaturated zone ranging from 0.50 to 25 m. Most typical values of unsaturated zone thickness are in the range from 2 to 10 m. Recharge is due to infiltration of precipitation excess, and discharge occurs towards surface streams, river and water bodies, and directly to the Atlantic Ocean. Recharge in the Pampeano aquifer has been calculated from different approaches, giving results as different as 50 or 200 mm/year. On the other hand, an important discharge takes place in the streams (Massone 2003; Quiroz Londoño 2009).

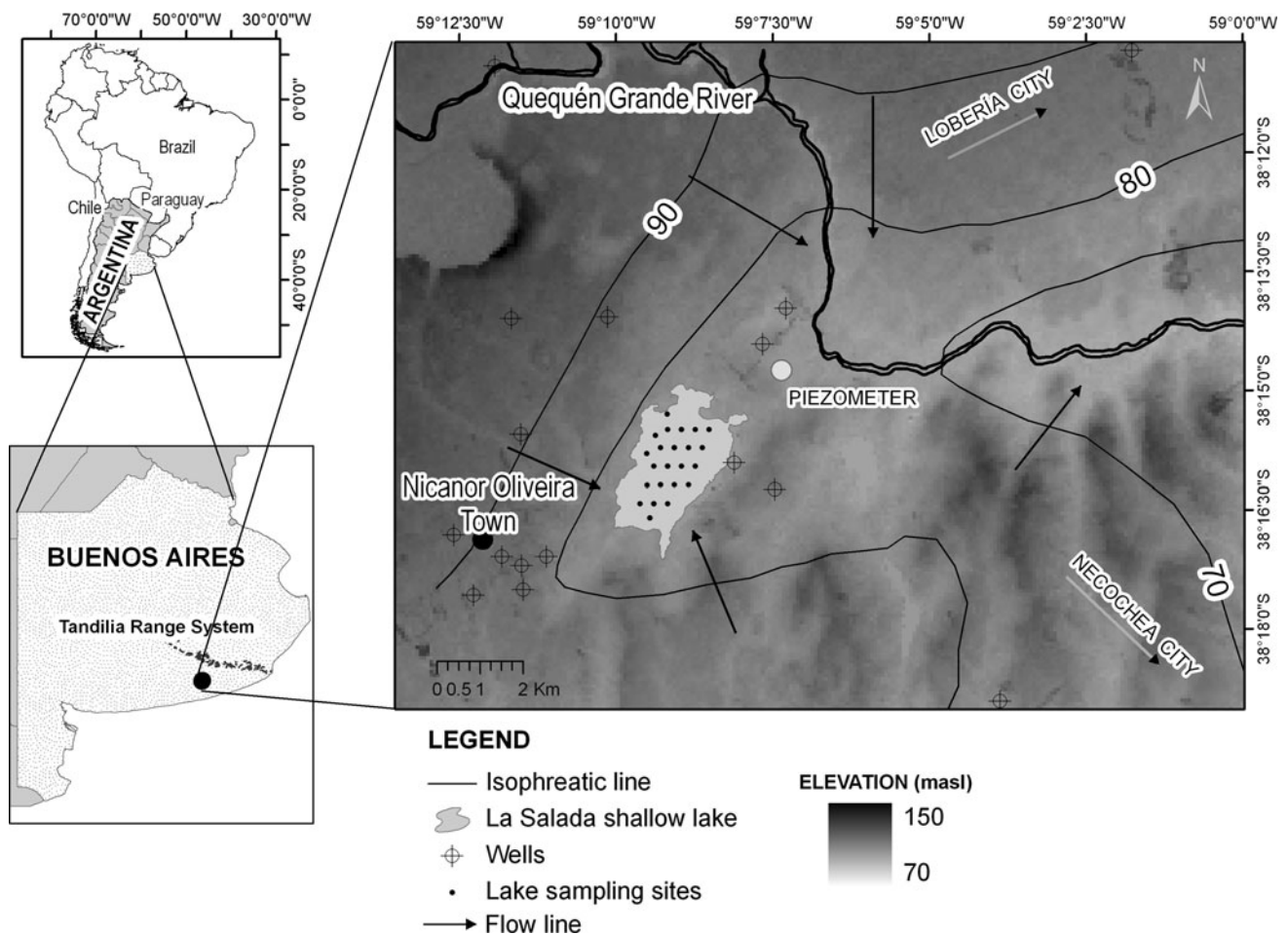


Fig. 1 Location map and sampling sites

Over the past 15 years, annual precipitation values in the region have ranged from 703 to 1,400 mm/year, with an average of 943 mm/year. The highest precipitation values are recorded between September and March. As regards evapotranspiration potential values, calculated for the same period using Thornthwaite method, ranged between 750 and 833 mm/year, with an average of 786 mm/year. In particular, the hydrological systems of the plains in the Argentinean Pampas present peculiar features: they are vast areas which show small changes in slope, eolic paleomorphology, scarce river courses and permeable materials, where the processes of infiltration and evaporation become dominant (Zimmerman 2004). In the area rainfall water is the main recharge source to the hydrologic system, meanwhile evaporation and groundwater flow are the main outputs of it.

La Salada Lake is a shallow permanent lake (maximum depth of 2.8 m), with an area of 5.78 km². It is located in the southeastern of Buenos Aires Province, in a hill environment called “watershed area with shallow lakes”, from a geomorphologic point of view (Fig. 1). Its drainage basin has an area of 120 km² with an elevation of 70–150 m asl

without inflow or outflow streams. This aquatic system has an effluent-influent behavior with the aquifer, receiving concentric flows from the high sectors of the basin and discharging its waters to the Quequén Grande River (QGR) and other waterbodies near to it (Romanelli et al. 2010). The piezometric line equidistance suggests a permeability increase from the highest to the slowest slopes. The hydrogeological conceptual model for La Salada Lake establishes groundwater evaporation as the responsible for its physical–chemical features.

Materials and methods

Water samples were collected for both hydrochemical analysis and environmental stable isotope determination during 2007–2009. Lake samples (*N* = 29) were obtained at two different depths subsurface (0.5 m) and maximum depth (2.8 m). Groundwater samples (*N* = 15) were collected from mills domiciliary and irrigation wells, with 12–24 m of depth, which get water from the shallow aquifer. Water table levels were measured in 14 of these wells.

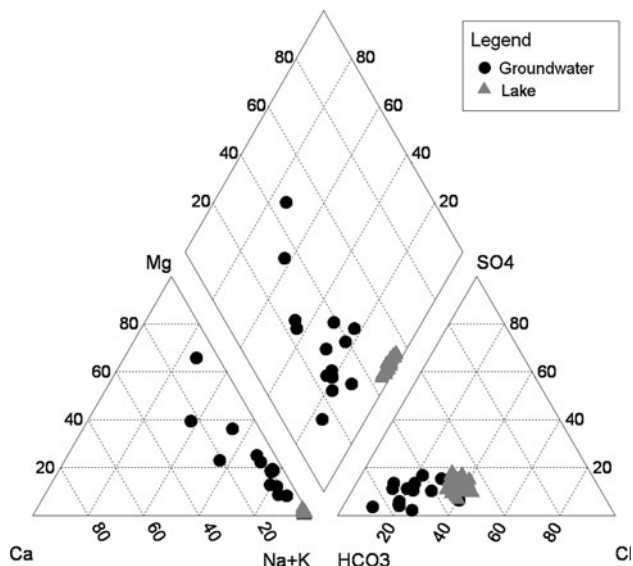


Fig. 2 Major water ionic content in La Salada Lake Basin

Chemical analyses were performed applying standard methods (APHA American Public Health Association 1998); chloride following Mhor method, sulfate by turbidimetry, calcium and magnesium by complexometric titrations with EDTA, sodium and potassium by flame spectrometry and carbonate-bicarbonate by potentiometric titrations. Water temperature, pH and electrical conductivity (EC) were in situ estimated using one Hanna HI9828 sonde. Hydrogeochemical inverse mass balance models were numerically tested by using NETPATH software (Plummer et al. 1991).

Stable isotopes (^{18}O and ^2H) were analyzed by using a laser spectrometry DLT-100 Liquid–Water isotope analyzer, automated injection designed by Los Gatos Research at the Hydrochemical and Isotopic Hydrology Laboratory (National University of Mar del Plata). The results were expressed like δ (‰), defined as:

$$\delta = \left(\frac{R_s - R_p}{R_p} \right) \times 1,000 \text{‰}$$

where δ is the isotopic deviation in ‰, s is the sample, p the international reference and R is the isotopic ratio ($^2\text{H}/^1\text{H}$, $^{18}\text{O}/^{16}\text{O}$). All δ values of water samples are conventionally reported relative to the international standard VSMOW (Vienna standard mean ocean water) (Gonfiantini 1978). The analytical uncertainties were ± 0.3 and ± 2.0 ‰ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively.

Surface runoff and potential evapotranspiration was determined by the Curve Number (CN) (USDA-SCS 1964) and the Penman–Monteith methods (Allen et al. 2006), respectively. Groundwater recharge estimation was performed by using two methods, the first one, the Thornthwaite–Mather Soil–Water–Balance (Thornthwaite and

Mather 1957) which only requires monthly temperature and rainfall data. The second one is the Water Table Fluctuation method (WTF) (Healy and Cook 2002), a simple and low cost method applicable to shallow aquifers with rapid response to recharge events. It requires the previous estimation of the specific yield and temporal water table measurements. According to several studies of the Pampean aquifer in different areas of the region (Venecio and Varni 2003; Auge 2004; Ruiz de la Garreta et al. 2007; Ferreira et al. 2009) a constant specific yield value of ten was selected for the calculation. Daily water level data was obtained by the automatic datalogger Gérica LF325, installed in a 12 m depth well between the lake and the QGR, since 2007.

The groundwater flow numerical model was done applying the Visual Transin code (Medina and Carrera 2005), an inverse model based on the estimation of parameters using water table data, which solves the flow equations by the method of finite elements. A steady state regime model was performed by using information of 14 wells. The transitory regime model was simulated by using the temporal recharge variations, estimated from the two methods mentioned above, and the daily water table records obtained with the installed datalogger.

Aster satellite images with 15 m of spatial resolution were used for the geomorphological characterization of the basin in order to obtain a transmissivity zoning map (input of the numerical modeling). Finally, in order to facilitate data handling and ensure reliability, a geographical database managed with GIS tools was created.

Results and discussion

Hydrochemistry

Hydrochemical facies analysis was conducted by Piper diagrams (Fig. 2). Table 1 shows the statistical parameters of the water ionic content in groundwater and the lake. According to the physico-chemical parameters lake water is classified as oligohaline, with a mean EC of 6121.4 $\mu\text{S}/\text{cm}$ and pH values ranging from 9.61 to 9.73. La Salada Lake water type is $\text{Na}-\text{CO}_3-\text{HCO}_3-\text{Cl}$, with a homogeneous chemical composition even in area and depth (Fig. 2).

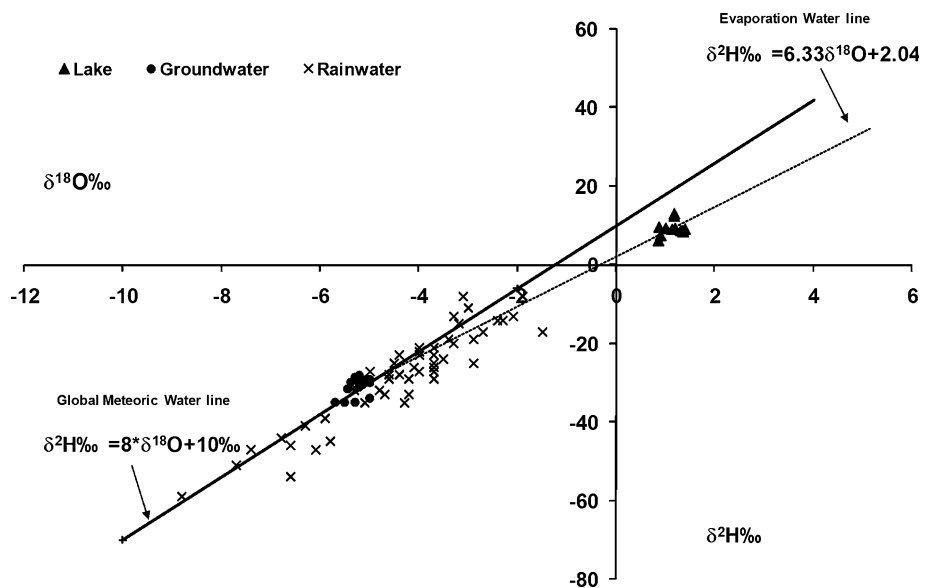
Groundwater is mainly $\text{Na}-\text{HCO}_3$ although some chloride-enriched water was detected to the QGR. Ca/Na and Mg/Na exchange processes can be recognized from the alignment of the samples from the magnesium-calcium area to the sodium extreme in the Piper diagram. A mean EC of 953.6 $\mu\text{S}/\text{cm}$, pH of 7.8 and a temperature value of 17.4 °C characterize groundwater. In all cases mean values of hardness, pH and EC are lower in comparison to the lake.

Table 1 Water ionic composition and main physico-chemical parameters in La Salada Lake Basin

Parameter	Groundwater (N = 15)				Lake (N = 29)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Ca ⁺² (mg/l)	11.0	57.2	27.6	15.3	16.0	45.1	27.2	6.7
Mg ⁺² (mg/l)	12.3	103.2	50.1	29.5	8.3	54.2	28.0	9.6
Na ⁺ (mg/l)	26.8	345.0	187.1	87.1	2,036.6	2,970.0	2,642.3	191.5
K ⁺ (mg/l)	3.7	10.3	7.4	1.8	10.3	52.0	29.7	7.6
Cl ⁻ (mg/l)	55.0	237.0	98.2	56.1	1,033.1	1,595.5	1,243.3	128.0
HCO ₃ ⁻ (mg/l)	372.7	992.0	546.4	175.1	2,479.0	3,260.1	2,907.6	195.0
CO ₃ ⁻² (mg/l)	0.0	610.0	87.1	230.6	1,154.6	1,765.9	1,475.5	128.2
SO ₄ ⁻² (mg/l)	8.1	166.0	50.2	45.6	305.0	872.2	597.9	143.6
EC (μS/cm)	630.0	1,670.0	953.6	296.3	6,000.0	6,280.0	6,121.4	78.6
pH	7.5	8.7	7.8	0.34	9.6	9.7	9.6	0.03
Hardness (mg/l)	87.3	553.5	277.9	157.8	117.0	276.6	184.8	31.9

Min minimum, Max maximum, SD standard deviation

Fig. 3 Environmental isotopic composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) in groundwater, lake and rainwater samples



Environmental isotopes

The isotopic composition of seven groundwater and 12 lake water samples were plotted in a conventional diagram $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ jointly with the global and local meteoric water lines (GMWL/LMWL) (Fig. 3).

Groundwater samples appear grouped around a mean value ($\delta^{18}\text{O} = -5.32$ and $\delta^2\text{H} = -32.77$ ‰) showing relatively constant isotopic composition. Groundwater isotopic composition is closed to the average isotope composition of rainfall in the area, indicating that it is a well-mixed system only recharged by rain water. Monthly rainfall sampling from 2005 to 2009 in the region (Quiroz Londoño et al. 2008) allows to define the local water line $\delta^2\text{H} = 7.98 \delta^{18}\text{O} + 9.78$, which results similar to the GMWL.

The values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ from samples of La Salada Lake are located in an evaporation water line which has its origin in the mean groundwater composition. An evaporation line for the lake was calculated and defined by the following equation: $\delta^2\text{H} = 6.33 \delta^{18}\text{O} + 2.04$. The mean isotopic content in the lake is $1.14 \delta^{18}\text{O}$ and 9.27 ‰ $\delta^2\text{H}$.

Hydrogeochemical modeling

In order to achieve a better conceptual model of the processes that determine lake chemical composition, and taking into account the obtained hydrochemical and isotopic information, a mathematical hydrogeochemical modeling was performed. Analyzing Schoeller diagram can give an easy and fast first approximation to the understanding of the hydrogeochemical processes. In this sense,

one set of samples from La Salada Lake and groundwater was represented in a Schoeller diagram (Fig. 4). This analysis yields a water type variation from Na–HCO₃ (well) to Na–HCO₃–Cl (lake), being well grouped in both cases. The trend and slope of Na⁺, Cl⁻, HCO₃⁻ and SO₄²⁻ lines suggest that an evaporation process is responsible for the increasing in similar proportion of most of the major ions. Calcium and magnesium remain with little change, indicating some different processes limiting their increase. A closer view of the other ions allows identifying a smaller increase in HCO₃⁻ and a higher increase in Na⁺ respecting those of Cl⁻, evidencing that more processes can be involved.

To complete this first approach, the saturation indexes of the most common minerals were obtained by using PHR-REQC (Parkhurst and Appelo 1999). Calcite saturation index is around equilibrium values for groundwater, ranging from -0.291 to 0.464, on the other hand supersaturation values are observed for lake water, usually higher than 1.4. Gypsum saturation indexes show under saturation conditions both for groundwater and lake water, being around -2 to -3. These values indicate that calcite precipitation is possible in the lake, but not gypsum precipitation.

Taking into account these observations, the simplest model to explain, how groundwater composition may evolve towards lake water composition should include groundwater evaporation, calcite equilibrium and probably cationic exchange (with Ca²⁺ adsorption and Na⁺ release, and, to a lesser extent, Na/Mg exchange). The easiest way to test this hypothesis is a geochemical inverse model

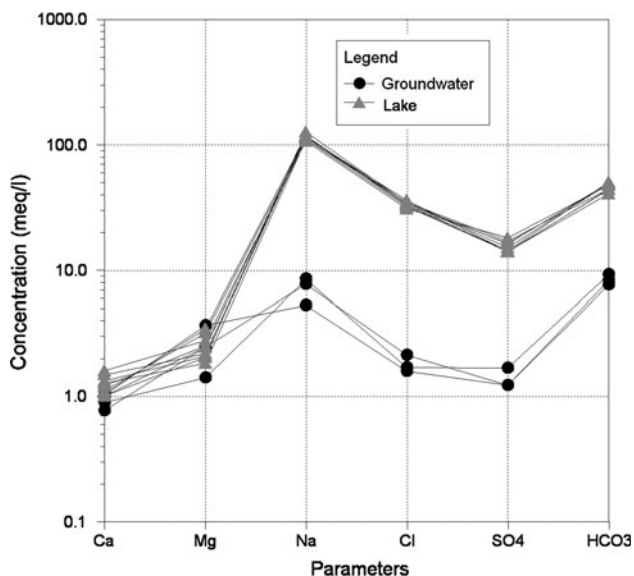


Fig. 4 Schoeller diagram showing the ionic composition of groundwater and La Salada Lake samples

Table 2 Hydrogeochemical model

Solutions		Processes					
Initial	Final	Evaporation factor	Calcite	CO ₂ gas	Fe-S	Ca/Na EX	Mg/Na EX
Well	Lake	11.4	-1.226	-2.099	-0.400	-0.937	1.138

(mass balance model) that has been performed by using NETPATH code (Plummer et al. 1991). One representative groundwater sample was taken as the initial solution, while a lake sample was the final one.

The model that best adjusts to the lake hydrochemical processes includes groundwater evaporation, calcite precipitation with CO₂ release, and cationic exchange. The last reaction consists in calcium release and sodium uptake by a hand, and magnesium uptake and sodium release to the solution on the other side (Table 2). The net effect of cationic exchange is a little variation in sodium in solution and major magnesium adsorption. Calcite precipitation controls calcium maximum concentration. Some sink for sulfate should be included. As gypsum precipitation is not possible according the saturation indexes, sulfate reduction to sulfide was considered including iron monosulfides, according to the pathway of sulfides formation in sediments (Berner 1970; Morse et al. 1987). Nevertheless, the amount of transferred moles of S is quite small (-0.400) and probably it is in the analytical error range (5 %).

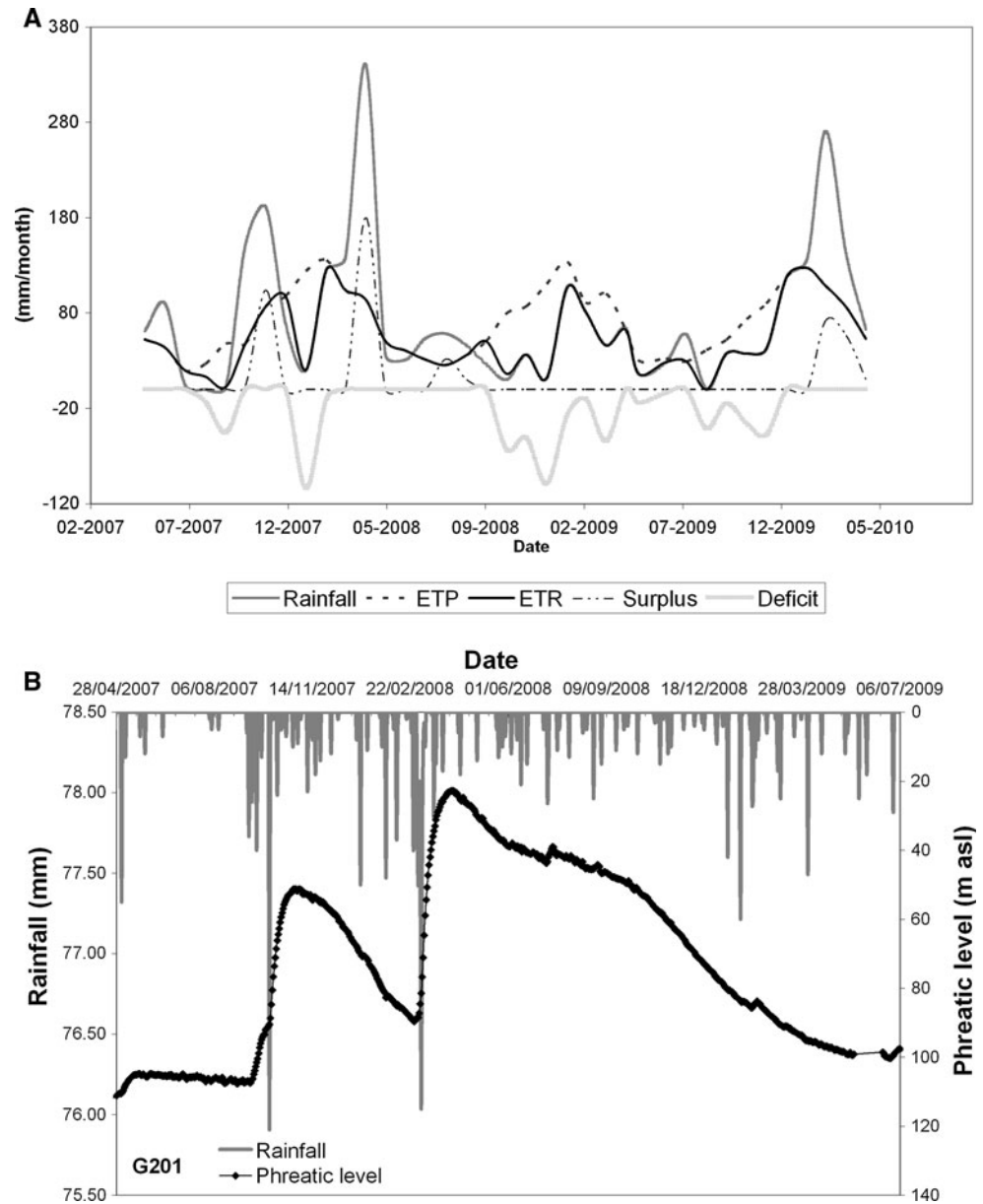
The estimation of evaporation process by using Cl⁻ was performed, obtaining an evaporation factor of 11.4 (11.4 l of groundwater are required to obtain 1 l of lake water). The Cl⁻ ion was used, because of its conservative nature and the absence of external sources of it in the area. The Na/Cl molar ratio is around 3 both for groundwater and lake water indicating that groundwater evaporation is the main process determining La Salada water composition, followed by the other geochemical processes mentioned above.

Groundwater recharge estimation

Thornthwaite-Mather soil–water-balance method

A field capacity value of 100 mm/year was considered in this method, since it is an adequate volume to meet the soil requirements. A mean recharge of 14 % of total rainfall was estimated from the mean rainfall and evapotranspiration values of the last 3 years. A runoff value of 1.7 % of the total rainfall was also calculated. Fluctuations of the obtained hydrologic parameters by using this method are displayed in Fig. 5a.

Fig. 5 **a** Fluctuations of the hydrologic parameters obtained by the Thornthwaite-Mather Soil–Water-Balance method, and **b** mean water table fluctuation in relation to daily rainfall values in the area



Water table fluctuation method (WTF)

Water table fluctuation in relation to daily rainfall values in the area are shown in Fig. 5b. Data analysis indicates a total aquifer recharge of 14.5 % of total rainfall. The obtained hydrogram evidences that water table presents a maximum variation value of 2.08 m. A quick water table response to rainfall events is detected, especially when the latter is preceded by less intense precipitation and high soil moisture exists. The lowest water table levels were recorded during 2008, coinciding with a dry period in which the total rainfall value was 300 mm below the historical average of the area. Field work during this period allowed identifying that the lake level was also low.

Groundwater flow numerical modeling

A 2D monolayer model with 863 elements and 417 nodes was constructed. One advantage of the utilized software is that it allows defining both expected transmissivity values and a maximum variation range of them, automatically adjusting the best values (Fig. 6a). Transmissivity zoning was obtained from the geomorphologic differences observed on the terrain, which allowed defining zones with different textures and spectral response associated to water content (Fig. 6b). The lowest transmissivity values correspond to loess sediments located in the upper basin, whereas the highest values were assigned to the lower basin, close to the QGR, where a sandy layer was found

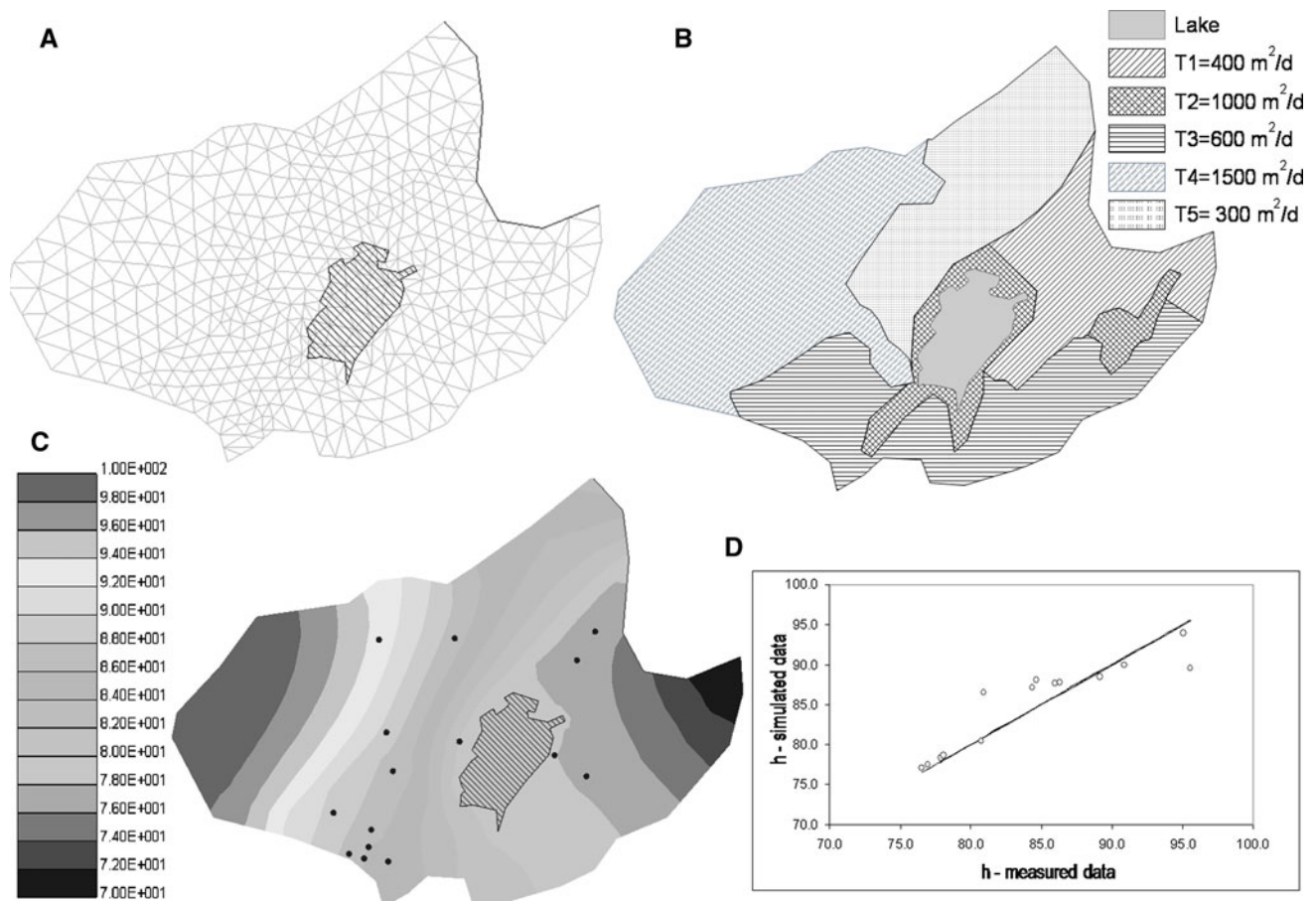


Fig. 6 **a** Model structure, **b** transmissivity zoning, **c** obtained piezometric map and, **d** measured and simulated heads in the steady state regime

during a research perforation. The adjusted values of transmissivities are shown in Table 3.

The steady regime was simulated with a temporal step of 30 days. The aquifer recharge obtained from the two mentioned methodologies coincides with a recharge value of 14 % of the total rainfall. The boundary conditions considered in the numerical model were a leakage condition for La Salada Lake and the QGR, a null flux for the other boundaries and a prescribed flux for the extraction wells due to urban consumption in Nicanor Oliveira Town.

The model described a surface water/groundwater interaction, according to the observed isophreatic map. In general, piezometric lines showed a groundwater flow towards the river (Fig. 6c). Regarding the lake, an effluent-influent behavior is evidenced. A mean absolute error of 1.85 m, between the computed and observed water table levels was obtained. The mean error value was 0.56 m (Fig. 6d). Although, these values were low with reference to the total aquifer thickness, they may become significant due to the topographic conditions of the area, i.e., a water table level fluctuation of this magnitude can produce significant changes in water dynamics. The aquifer water balance estimated by this model considered a net recharge

Table 3 Estimated and calculated transmissivities

Hydrogeological zones	Calculated transmissivity (m ² /day)	Previous transmissivity estimate (m ² /day)
T1	401	400
T2	1,645	1,000
T3	892	600
T4	3,037	1,500
T5	333	300

value of 14 % of total rainfall ($1.61 \text{ E}^{07} \text{ m}^3/\text{year}$), while the main outputs were groundwater discharge to the lake ($6.01 \text{ E}^{06} \text{ m}^3/\text{year}$) and to the QGR ($9.54 \text{ E}^{06} \text{ m}^3/\text{year}$) and $5.50 \text{ E}^{06} \text{ m}^3/\text{year}$ from well extraction.

Measured and simulated heads reasonably fit to the general aquifer system trend in the performed transitory model (Fig. 7). A mean error of 0.49 m was obtained by using the recharge data estimated by the WTF method. As a result, the simulated heads reproduced the different aquifer responses being mostly higher than the real value. Meanwhile, when using the recharge values estimated by the soil–water–balance method (mean error of 0.34 m), the

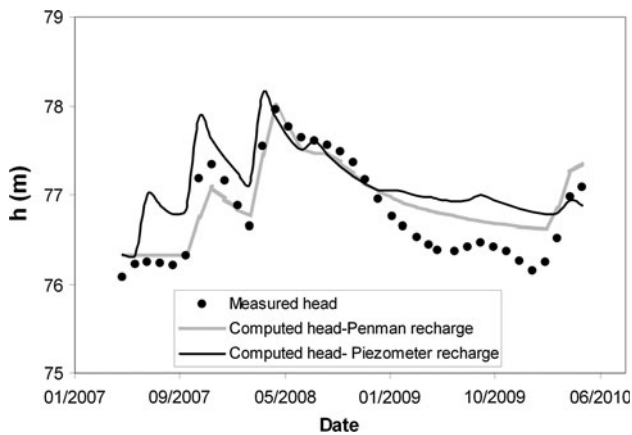


Fig. 7 Simulation of transient regime in a daily record piezometer

computed heads were closer to the observed values although, they did not properly represent some water table variations.

Quantification of the lake basin water balance

Based on the conceptual model developed for this catchment, the general water balance (Schicht and Walton 1961) is defined as:

$$R = ETR + RF + GR + FC + LE$$

where *R* is rainfall, *ETR* is evapotranspiration, *RF* is runoff, *GR* is groundwater recharge, *FC* is field capacity and *LE* is lake evaporation. All the terms are expressed as m³/year.

By using the above equation, the water balance of the lake basin was quantified for 2007. All these terms were previously estimated; however, the lake evaporation component is still unknown. It can be obtained from the general water balance formula. The estimated hydrologic outputs of the system were 70.9 % returned to the atmosphere through evapotranspiration, 14.0 % reaches the aquifer, 9.9 % is absorbed by the soil to satisfy its field capacity and 1.6 % is attributed to surface runoff (Fig. 8). According to these values, the lake evaporation parameter

corresponded to 3.6 %, which is equivalent to 4.10 E⁰⁶ m³/year with a total rainfall of 1.16 E⁰⁸ m³/year (958 mm/year).

The evaporation factor (11.4) calculated through hydrogeochemical modeling can also be used to corroborate the evaporated volume from the water body. This result also yielded a value of 4.10 E⁰⁶ m³/year.

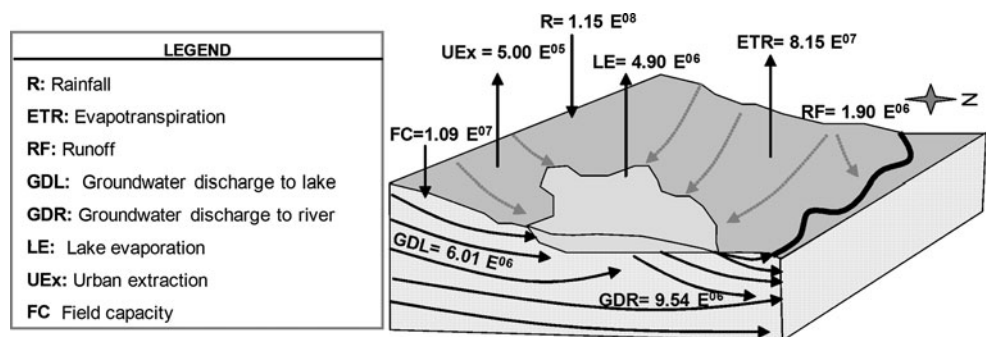
Conclusions

Hydrogeochemical, isotopic and hydrodynamic interpretation allowed redefining and adjusting the lake conceptual model. Moreover, water balances for the aquifer and the lake basin were obtained. La Salada Lake presents an effluent-influent behavior, operating as a discharge and recharge area of both surface water and groundwater. These techniques allowed explaining the water origin of this water body suggesting that it receives groundwater discharge subject to evaporation processes. δ¹⁸O and δ²H values establishes a specific lake fingerprint evidencing a evaporation process from groundwater with more enriched isotopic values in comparison to the rest of the water sources. The model that best adjusts to La Salada Lake hydrochemical processes include evaporation from groundwater (11.4 factor; i.e., 11.4 l are evaporated from groundwater in order to obtain 1 l of lake water) it calcite precipitation with CO₂ release and cationic exchange.

An aquifer recharge estimation of 14 % of the total rainfall was obtained by using two methods with different input data, hydro-climatic parameters (soil–water-balance method) and water table variations (WTF method). In this sense, they reasonably validate the aquifer recharge value. However, the monthly recharge estimation by these two methods used as input data in the transient simulation model showed markedly differences.

The numerical model had a good fitness in both the steady state and the transient simulations. It allowed defining the main outputs of the aquifer system quantifying a natural discharge of 59 and 37 % of the infiltrated water to the QGR and La Salada Lake, respectively.

Fig. 8 Water balance in La Salada Lake Basin (values in m³)



The calculation of the volume of water evaporated directly from the lake was performed by two different methods. The first one, the water balance equation, which uses hydrologic information and the second one, combine the results of the mathematical and the hydrogeochemical models. In both cases the volume obtained was similar, allowing the calculation of a 0.09 m increase in the level of La Salada Lake for 2007.

References

- Allen RG, Pruitt WO, Wright JL, Howell TA, Ventura F, Snyder R, Itenfsu D, Steduto P, Berengena J, Beselga J, Smith M, Pereira LS, Raes D, Perrier A, Alves I, Walter I, Elliott R (2006) A recommendation on standardized surface resistance for hourly calculation of reference ET by the FAO56 Penman–Monteith method. *Agric Water Manag* 81:1–22
- APHA (American Public Health Association) (1998) Standard methods for the examination of water and wastewater, 20th edn. American Public Health Association, American Water Works Association, Water Environment Federation, Washington
- MA (Millennium Ecosystem Assessment) (2005) Ecosystems and human well-being: wetlands and water synthesis. Millennium Ecosystem Assessment report to the Ramsar Convention, World Resources Institute, Washington
- Auge M (2004) Vulnerabilidad de acuíferos (Aquifer vulnerability). *Revista Latino-Americana de Hidrogeología* 4:85–103. <http://ojs.c3sl.ufpr.br/ojs2/index.php/hidrogeologia/article/view/2652/2193>
- Berner RA (1970) Sedimentary pyrite formation. *Am J Sci* 268:1–23
- Burkert U, Ginzler G, Babenzien HD, Koschel R (2004) The hydrogeology of a catchment area and an artificially divided dystrophic lake—consequences for the limnology of lake Fuchskuhle. *Biogeochemistry* 71:225–246
- Chevoratev II (1955) Metamorphism of natural water in the crust of weathering. *Geochim Cosmochim Acta* 8:22–48
- Clark I, Fritz P (1997) Environmental isotopes in hydrogeology. Lewis Publisher, New York, p 328 (ISBN: 1566702496)
- Cook P, Herczeg A (1999) Environmental tracers in subsurface hydrology. Kluwer Academic Press, Boston, p 529
- Craig H (1961) Standard for reporting concentrations of deuterium and oxygen-18 in natural waters. *Science* 133 (N3467): 1833–1834
- Custodio E (1991) Hydrogeochemical interpretation as a tool in the study and quantification of aquifer systems. In: *Hidrogeología estado actual y prospectiva*, CIMNE, Barcelona, pp 121–162
- Dalla Salda L, Iñiguez RM (1979) “La Tinta”, Precámbrico y Paleozoico de Buenos Aires (La Tinta, Precambrian and Paleozoic in Buenos Aires). VII Congr Geol Arg I, Neuquén, Argentina, p 539–550
- Dansgaard W (1964) Stable isotopes in precipitation. *Tellus* 16: 438–468
- Ferreira G, Rodríguez L, Vonnet C, Choque J, Marano P (2009) Avances en el conocimiento del acuífero libre de la cuenca del arroyo Cululú (provincia de Santa Fe). VI Congreso Nacional de Hidrogeología y IV Seminario hispanoamericano de Temas Actuales de la Hidrogeología Subterránea, Santa Rosa, La Pampa, Argentina 24–28 de agosto (ISBN 978-987-1082-36-7)
- Froehlich KFO, Gonfiantini R, Rozanski K (2005) Isotopes in lake studies: a historical perspective. In: Aggarwal PK, Gat JR Froehlich KFO (eds) *Isotopes in the water cycle. Past, present and future of a developing science* pp 139–150
- Garrels RM, Christ CL (1965) *Solutions, minerals and equilibria*. Harper, New York, p 450
- Geyh MA (2000) *Environmental isotopes in the hydrological cycle: principles and applications/groundwater-saturated and unsaturated zone*, vol 4. Technical documents in hydrology 39, UNESCO/IAEA
- Glynn PD, Plummer LN (2005) Geochemistry and the understanding of groundwater systems. *Hydrogeol J* 13(1):263–287
- Gonfiantini R (1978) Standards for stable isotope measurements in natural compounds. *Nature* 271:534
- Healy RW, Cook PG (2002) Using groundwater levels to estimate recharge. *Hydrogeol J* 10:91–109
- Litaor MI, Eshel G, Sade R, Rimmer A, Shenker M (2008) Hydrogeological characterization of an altered wetland. *J Hydrol* 349: 333–349
- Marchese H, Di Paola E (1975) Miogeosinclinal Tandil. *RevAsoc Geol Arg* 30(2):161–179
- Martínez D, Bocanegra EM, Manzano M (2000) La modelación hidrogeoquímica como herramienta en estudios Hidrogeológicos (Hydrogeochemical modeling as a tool in hydrogeological studies). *Boletín geológico y Minero*. Vol 111-4. pp 83–98 (ISSN 0368-0176)
- Massone H (2003) *Geología y planificación territorial en la cuenca superior del arroyo grande (provincia de Buenos Aires)*. Tesis doctoral. Universidad Nacional de La plata, Facultad de Ciencias Naturales y Museo, La Plata
- Medina A, Carrera J (2005) Transin IV. Fortran code for solving the coupled flow and transport inverse problem. User’s guide E.T.S.I. Caminos Canales y Puentes, Barcelona, p 248
- Mook WG (2002) *Isótopos Ambientales en el Ciclo Hidrológico. Principios y Aplicaciones*. Publicaciones del Instituto Geológico y Minero de España Serie: Guías y Manuales N1 2002 IGME, Madrid
- Morse JW, Millero FJ, Cornwell JC, Rickard D (1987) The chemistry of hydrogen sulfide and iron sulfide systems in natural waters. *Earth Sci Rev* 24:1–42
- Parkhurst DL, Appelo C (1999) User’s guide to PHREEQC (version 2) A computer program for speciation, batch reaction, one dimensional transport, and inverse geochemical calculations, USGS Water Resources Investigations Report 99-4259, pp 1–312
- Plummer L, Vallejos W, Mazza C, Pugliese M (1991) An interactive code (NETPATH) for modelling net geochemical reactions along a flow path. USGS Water Resources Investigations Report 91-4078, pp 1–94
- Price JS, Maloney DA (1994) Hydrology of a patterned bog–fen complex in southeastern Labrador, Canada. *Nordic Hydrol* 25: 313–330
- Quirós R, Rosso JJ, Rennella A, Sosnovsky A, Boveri M (2002) Estudio sobre el estado trófico de las lagunas pampeanas (The trophic status of pampean ponds). *Interciencia* 27:584–591
- Quiroz Londoño OM (2009) *Hidrogeología e Hidrogeoquímica de las Cuencas de los Arroyos Tamangueyú y El Moro Provincia de Buenos Aires (Hydrogeology and hydrogeochemistry in Tamangueyú and El Moro Creek Basins)*. Tesis doctoral, Universidad Nacional de Río Cuarto, p 292
- Quiroz Londoño OM, Martínez DE, Dapeña C, Massone H (2008) Hydrogeochemistry and isotope analyses used to determine groundwater recharge and flow in low-gradient catchments of the province of Buenos Aires, Argentina. *Hydrogeol J* 16(6):1113–1127 (ISSN 14310-2174)
- Romanelli A, Quiroz Londoño OM, Massone HE, Martínez DE, Bocanegra EM (2010) El agua subterránea en el funcionamiento hidrológico de los humedales del Sudeste Bonaerense, Provincia de Buenos Aires, Argentina (Groundwater in the hydrological

- functioning of wetlands). *Boletín Geológico y Minero* 121(4): 373–386
- Ruiz de la Garreta A, Varni M, Banda N R, Barranquero R (2007) Caracterización Geohidrológica Preliminar en la Cuenca del Arroyo Langueyú, partido de Tandil, Buenos Aires. V Congreso Argentino de Hidrogeología, pp 119–128
- Sala JM (1975) Recursos Hídricos (especial mención de las aguas subterráneas) [Water Resources (special reference to groundwater)]. *Relatorio Geología de la Provincia de Buenos Aires*, IV Congreso Geológico Argentino, Buenos Aires, September 1975
- Schicht RJ, Walton WC (1961) Hydrologic budgets for three small watersheds in Illinois. *Ill State Water Surv Rep Invest* 40:40
- Thornthwaite CW, Mather JR (1957) The water balance. Drexel Institute of Technology, Centerton, p 104
- USDA-SCS (1964) Hydrology. Section 4, Part I, Watershed planning. In: *National Engineering Handbook*, US Department of Agriculture, Soil Conservation Service, Washington
- Venecio M, Varni M (2003) Estimación de la Recarga y del Almacenamiento Específico a través de Análisis de Registros de Nivel Freático (Recharge estimation and specific yield through water table measurement analysis). III congreso Argentino de Hidrogeología y I seminario Hispano-latinoamericano sobre temas actuales de la hidrología subterránea, Rosario, Argentina, pp 153–160. ISBN 950-673-395-3
- Wang Y, Guo Q, Su C, Ma T (2006) Strontium isotope characterization and major ion geochemistry of karst water flow, Shentou, northern China. *J Hydrol* 328:592–603
- Zhang L, Mitsch W (2005) Modelling hydrological processes in created freshwater wetlands: an integrated system approach. *Environ Model Softw* 20:935–946
- Zimmerman E (2004) Análisis de Sistemas Hidrológicos. Desarrollo de contenidos. Facultad de Ciencias Exactas, Ingeniería y Agrimensura, Rosario, República Argentina