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Articles

Topo-bathymetric and hydrological study of the water system "lagoon La Picasa", Argentina

Estudio topo-batimétrico e hidrológico del sistema hídrico "laguna La Picasa", Argentina

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Abstract

Knowledge of the water balance of lagoons, surface, and underground basins is essential not only to use water resources more rationally in space and time but also to improve their control and redistribution.

The La Picasa lagoon basin is an inter-jurisdictional endorheic basin in the Argentine Republic at the intersection of Córdoba, Santa Fe, and Buenos Aires provinces. This basin has recently gone through recurrent floods caused by an increase in the level of the lagoon, which has affected infrastructure, transport, and agricultural activity.

In the present work, a lagoon-scale approach is proposed. For the topo-bathymetric study, the lagoon's Digital Elevation Model (DEM) was defined using data collection, fieldwork, and data processing. In contrast, a 0D water balance model was developed in the hydrological study. Based on these two models, the rainfall excesses that impacted the lagoon were analyzed and quantified for evacuation through gravity discharge, a pumping system, or a combination of both systems.

The main objective was to define a 0D water balance model that represents the La Picasa lagoon and then uses it as a tool to evaluate future hydrological situations that may occur.

Keywords: La Picasa lagoon, inter-jurisdictional basin, water balance, lagoon environments, topo-bathymetry, digital elevation model, water model.

Resumen

El conocimiento de la estructura del balance hídrico de lagunas, cuencas superficiales y subterráneas es fundamental para conseguir un uso más racional de los recursos de agua en el espacio y en el tiempo, así como para mejorar su control y redistribución.

La cuenca Laguna La Picasa es una cuenca endorreica interjurisdiccional entre las provincias de Córdoba, Santa Fe y Buenos Aires, en la República Argentina, que ha sufrido en los últimos tiempos inundaciones recurrentes causadas por crecimientos del nivel de la laguna, y que afectaron a la infraestructura, el transporte y la actividad agrícola.

En el presente trabajo se planteó un enfoque a escala lagunar. Para el estudio topo-batimétrico se definió un modelo digital de elevación (MDE) de la laguna mediante recopilación de antecedentes, trabajos de campo y procesamiento de datos, y en el estudio hidrológico se desarrolló un modelo de balance hídrico 0D. Con base en estos dos modelos se analizaron y cuantificaron los excesos pluviales que impactaron en la laguna para su evacuación con un sistema de gravedad, de bombeo o combinado.

El objetivo principal fue definir un modelo de balance hídrico 0D que represente a la laguna La Picasa y luego utilizarlo como una herramienta para evaluar futuras situaciones hidrológicas que ocurran.

Palabras clave: laguna La Picasa, cuenca interjurisdiccional, balance hídrico, ambientes lagunares, topobatimetría, modelo digital de elevación, modelo hídrico.

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Introduction

The knowledge of water balance is considered one of the primary objectives of hydrology since it is a means to solve important problems during floods or droughts periods. From the study of water balance, it is possible to quantitatively assess water resources, their modifications caused by the influence of human activities, and to predict how artificial changes affect the regime of rivers, lagoons, and underground basins (Sokolov & Chapman, 1981).

A literature review suggests that an attempt is often made to represent how a system functions through distributed or semi-distributed hydrological models. However, Viessman and Lewis (cited by Rodríguez *et al*., 2006) indicate that a water balance model should be the first to analyze any basin.

Currently, several water balance studies are applied to lagoons and wetlands in the province of Córdoba. In particular, the studies by Plencovich *et al*. (2005) and Curletto (2014) used the Mar Chiquita lagoon, and the work carried out by the National Water Institute (INA) (INA, 2018) applied to the La Picasa lagoon.

This work presents a study about La Picasa lagoon situated in the South of the province of Santa Fe and fed by an endorheic basin that includes the provinces of Buenos Aires and Córdoba in the Argentine Republic. This basin has 5 346 km^{2,} with 51 % of this area located in the province of Córdoba, 9 % in the province of Buenos Aires, and 39 % in the province of Santa Fe.

The analyzed region is characterized by a high agricultural and livestock production. The surrounding area of the lagoon is one of the most productive areas in the country in terms of agriculture, dairy farming, and livestock. The lagoon has changed at its level, and its water flow oscillates over time because of variations in the rainfall amount, land topography, and speed of water runoff.

The water leaves the system through evaporation and two pumping systems: South and North stations. Their flows finally converge in the Salado River. The pumps operate with a yield of approximately 3-4%.

From 1973 to 2019, the area under study went through a humid period with average annual rainfall above the historical mean value of 900 mm/year (Universidad Nacional del Litoral, 1999). The lagoon level gradually increased, and consequently, several problems arose, such as the flooding of urban and productive areas, provincial roadblocks, and most importantly, the blockage of National Route No. 7 and the railroad since both connect Buenos Aires with the provinces of the Cuyo Region.

As the lagoon is the final receptor of the water surpluses of an inter-jurisdictional basin, its integral management is carried out by the provinces involved. Therefore, developing knowledge about how the lagoon and the basin operate is of great importance.

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Initially, this work included the definition of a Digital Elevation Model (DEM) that was later used as the basis for developing a Mass Balance Water Model (0D) applied to the body of water. This model aimed to show the hydrological variables without considering the influence of runoff and underground infiltration. In this model, two kinds of variables were differentiated: a) purely atmospheric variables (precipitation and evaporation), and b) variables intervened by man (entry of flows through channels and egress by pumping). The time window was five years, from 2012 to 2017, with a monthly time step.

Study area

The study area includes the surface bounded by La Picasa lagoon, its inlet channels, and its pumping systems. This area includes the towns of Laboulaye, Melo, Rosales and Villa Rossi in the province of Córdoba, and the towns of Rufino, Aarón Castellanos, Amenábar, Lazzarino and Diego de Alvear in the province of Santa Fe (Figure 1).

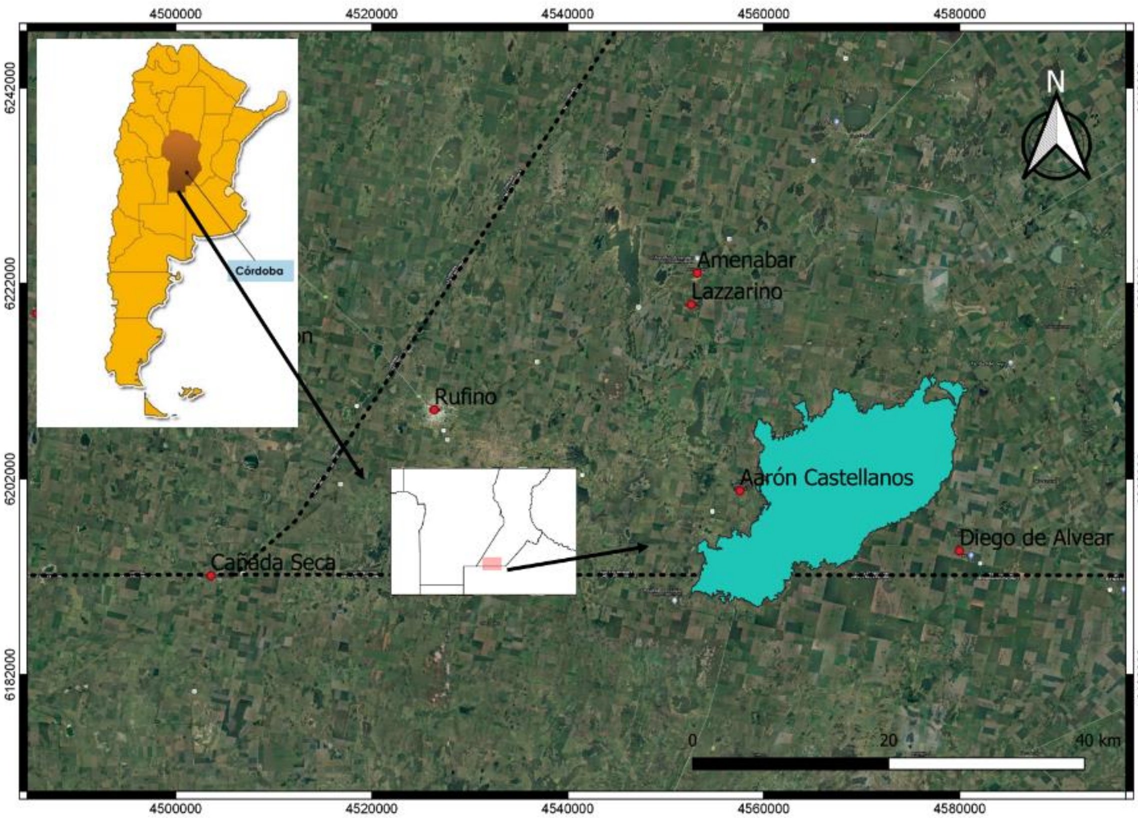

Figure 1. Study zone - La Picasa lagoon.

As mentioned before, the lagoon is located in the province of Santa Fe - Argentina, between the latitudes 34° 22.69'-34° 15.74' South (558525.38-577696.967 UTM-20) and the longitudes 62° 21.8'-62° 9.36' west (6195727.899-6208440.766 UTM-20).

It is located on a sunken block which is 20 kilometers long East-West and 10 kilometers wide North-South. Under ordinary hydrological conditions, the lagoon occupies slightly more than half of the sunken block. However, in recent decades, it has overflowed and has covered twice as much as the block area (Iriondo, 2010).

The flows in and out of the lagoon are controlled by two pumping stations and a diversion channel from reservoir No. 7 to the Salado River basin in the Buenos Aires province (Figure 2). One of the pumping stations is located in the South of the lagoon (EB South) and the other in the North (EB North). Below the 105.80 m IGM (Geographic Military Institute) elevation, the only significant discharge pathway from the lagoon is evaporation.

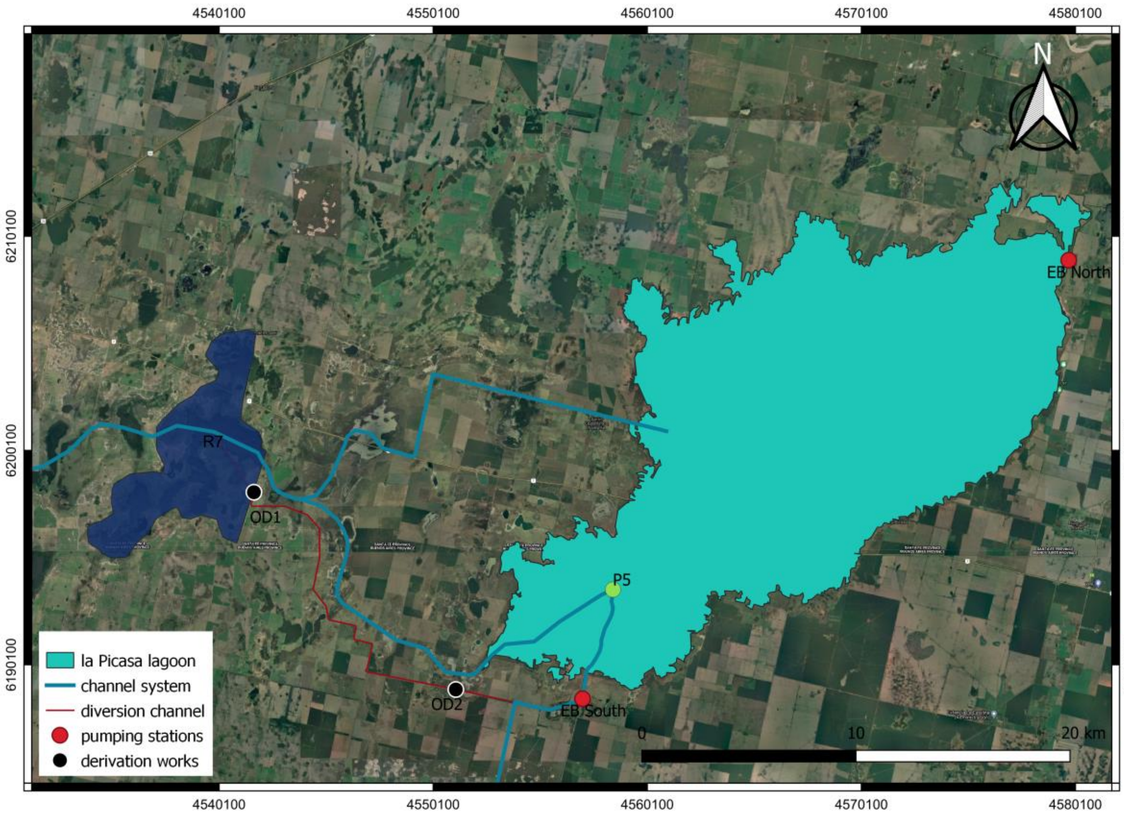

Figure 2. La Picasa lagoon, diversion channel, and pumping stations.

The control points for the inflows analysis were located at the Regulation Work of reservoir 7- OR7 (the last reservoir before discharging into the lagoon) and two sewers (A45-A35) found after OR7. The measured flow rates were analyzed, and the highest values were considered.

The southern pumping station derives the flow to other lagoons in the province of Buenos Aires through canalizations and lagoon systems. The northern pumping station derives the water to the north of the lagoon in the province of Santa Fe. Each station has 5 (five) pumps of 1 m^3/s capacity and 6 m of loading height for a maximum evacuation of 5 m^3/s.

The diversion channel begins inside regulation lagoon 7 and conducts runoff to the Salado River basin in the province of Buenos Aires. In addition, there is a second Derivation Work (OD2) to carry out a second flow control.

Materials and methods

Bathymetric survey and digital elevation model

A Digital Elevation Model is a numerical representation of the topographic surface of the Earth. To construct the model, the territory is divided into cells of a specific size, which are grouped in the form of an ordered grid. The numerical representation can be processed to reproduce geometric surface properties and spatial relationships digitally, The DEM of La Picasa lagoon was defined based on the bathymetry obtained from field tasks for elevations below 98.5 meters above sea level (masl). Above 98.55 m, the antecedent bathymetry of the INA (Bathymetric survey, March 2007) was used. In addition, satellite images linked to scale readings were used together with contour lines related to the water level obtained in-field tasks. The working coordinate system used was UTM 20 South with DATUM WGS-84.

The bathymetry obtained from the field tasks was defined by comparing depths obtained from different instruments. Field measurements were carried out during two campaigns in April and May 2018. A SOUTH SDE-28S Echosounder, a Geographic Positioning System with Real-time Extension (GPS RTX), and two Doppler Acoustic Current Profilers (ADCP) M9 were used. The latter was developed by the firm YSI/Sontek and provided by the Secretariats of Water Resources of the provinces of Córdoba and Santa Fe (Figure 3). The raw data was processed by filtering outliers.

Figure 3. Instruments. Left: GPS equipment and submerged echosounder; right: ADCP Sontek M9.

Echosounder measurements included ellipsoidal heights, water depths, and bottom elevation. The measures with ADCP-M9 included water depths, bottom level, and altitudes obtained with its GPS. Using the "GEOIDE-Ar16" web tool, the ellipsoidal heights were transformed into orthometric heights, as referred to in the 2016 National Vertical Reference System. This tool is based on the national Geodetic Reference Framework POSGAR07. This transformation is carried out because all the coordinates and heights measured on the Earth's surface concerning sea level are referred to in a mathematical model known as the geoid, which is adapted to the shape of the Earth.

Given the extension of the lagoon, the fluctuations caused by the waves in the altitudes measured by the ADCP-M9 GPS are considered to have been eliminated during the bathymetric survey. The information collected in a matrix format with pixels of 50 x 50 m was the average of the points included. The descriptive statistical analysis showed that the deviations were in the order of 5 and 6 cm, and in the most unfavorable case, a range of 60 cm was observed. This range represents the difference between the maximum and minimum values recorded throughout the campaign (Table 1).

Table 1. Mean, deviation, maximum, minimum variation coefficient, and range of the analyzed series.

	Campaign 1-18/04/2018	**Campaign 1-19/04/2018**	**Campaign 2-8/05/2018**
Mean	104.47	104.49	104.75
Deviation	0.05	0.06	0.06
COV	0.0005	0.0006	0.0005
maximum	104.67	104.82	105.09
minimum	104.23	104.22	104.54
Range	0.44	0.60	0.55

For each campaign, the Surface Water Level SWL was obtained from the average of the orthometric heights. In turn, the bottom levels of the lagoon were obtained from the SWL, orthometric heights, water depths, and wave fluctuations. The results of the bottom levels obtained with different instruments were compared. This comparison allowed the choice of one instrument as a reference.

Water balance model 0D: Mass balance

The study of the 0D water balance is based on applying the principle of mass conservation, where there must be a balance between inputs and outputs mathematically represented by the continuity equation. For any arbitrary volume during any period, the difference between the input and the output will be related to the variation in the volume of stored water.

Water inputs refer to precipitation from rain and surface water, while outputs include evaporation and surface runoff. Evaporation was defined in terms of potential evapotranspiration, based on the Thornthwaite method (Figure 4). The infiltration and underground flow processes were assumed as non-significant variables to the rest of the intervening variables; therefore, they were not considered in the balance.

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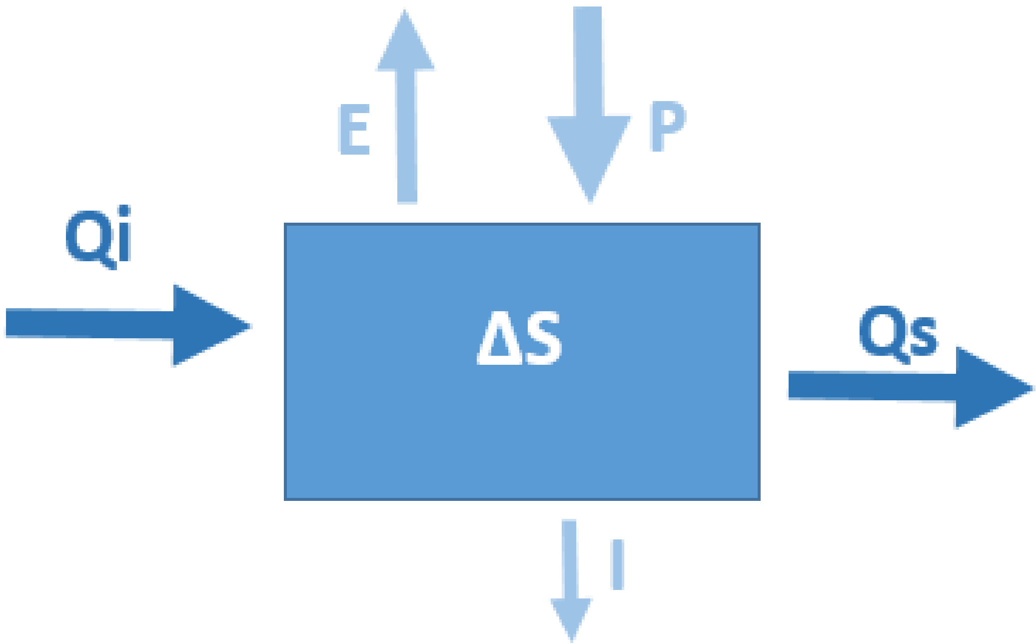

Figure 4. General scheme of mass balance.

In its most general form, the water balance is represented by the following equation:

$$\Delta V/\Delta T = (Q_i - Q_s) + AL(P - E) \quad (1)$$

Where ΔV is the variation in the volume of the lagoon (L); ΔT is the time interval; Q_i is the inflows from the tributaries of the system, and Q_s

the outflows; *AL* is the area of the lagoon; *P* is the average areal precipitation over the lagoon; *E* is the areal evaporation.

In terms of volume, the balance equation is:

$$\Delta S = Q_i . \Delta t + AL . (P - E) - Q_s . \Delta t (2) \quad (2)$$

Where Δ*S* is the storage volume.

Therefore, the model describes the balance between water that enters and leaves the system per unit of time from a combination of **natural** variables (entry of water by precipitation and exit of water by potential evapotranspiration-ETP) and **anthropic** (entry of water through channels, the exit of water through pumping stations, and diversion channels). An adjustment coefficient (μ) considered the measurement or estimation errors.

The adjustment coefficient, which is applied to the difference between the volumes that entered through channels and the volumes pumped out, was obtained by searching through data for the smallest error between the estimated and measured volumes:

$$V_{est} = A(P - Ev) + Coef(V_i - V_b) \quad (3)$$

Where V_{est} is the estimated volume; *A* the lagoon area that varies with the level; *P* is the precipitation; *Ev* is the evaporation; V_i is the entry volume through channels; V_b is the volume pumped out, and *Coef* is the adjustment coefficient to account for uncertainties.

The precipitation variable was obtained from the set of stations closer to the lagoon, and care was taken to evaluate the quantity and quality of data. The Thiessen polygon method was applied to determine the mean precipitation.

The evapotranspiration variable was obtained by using the Thornthwaite method (Aparicio-Mijares, 1989), the observed ETP, and the ETP isoline maps proposed by the National Institute of Agricultural Technology (INTA) (Rubí-Bianchi & Cravero-Silvia, 2010).

The analysis of natural variables shows small differences between rainfall and evapotranspiration (Figure 5a). On the other hand, the analysis of anthropic variables shows significant differences. The income flows are higher and sometimes exceed the pumping flows by a factor of ten (Figure 5b). Therefore, it was of great importance to know the inflow and outflows.

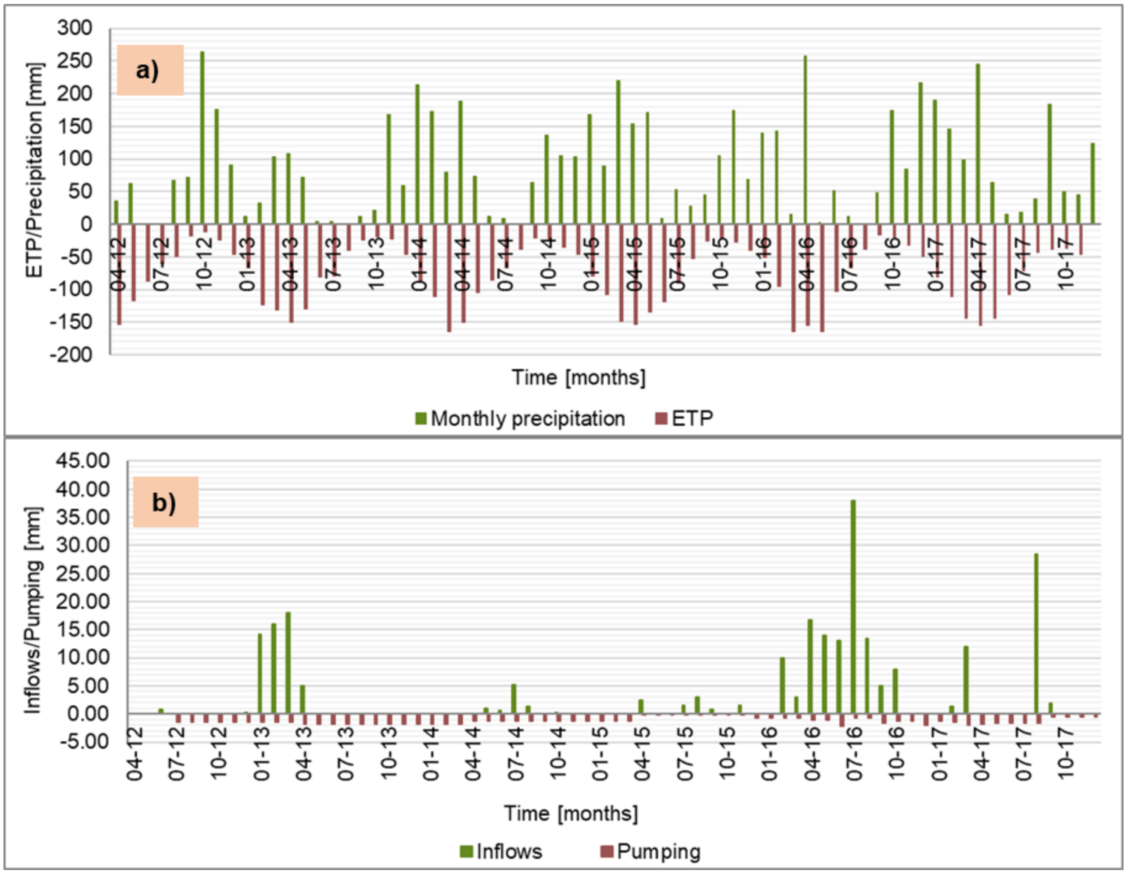

Figure 5. a) Comparison of natural variables in mm: precipitation and ETP; b) comparison of anthropic variables in mm: income flows and discharged flows.

An analysis of natural and anthropic variables shows an increase in the volume stored in the lagoon since there was a net flow into the lagoon (59 % inflows *versus* 41 % outflows). Consequently, there was an increase in the water level (Figure 6).

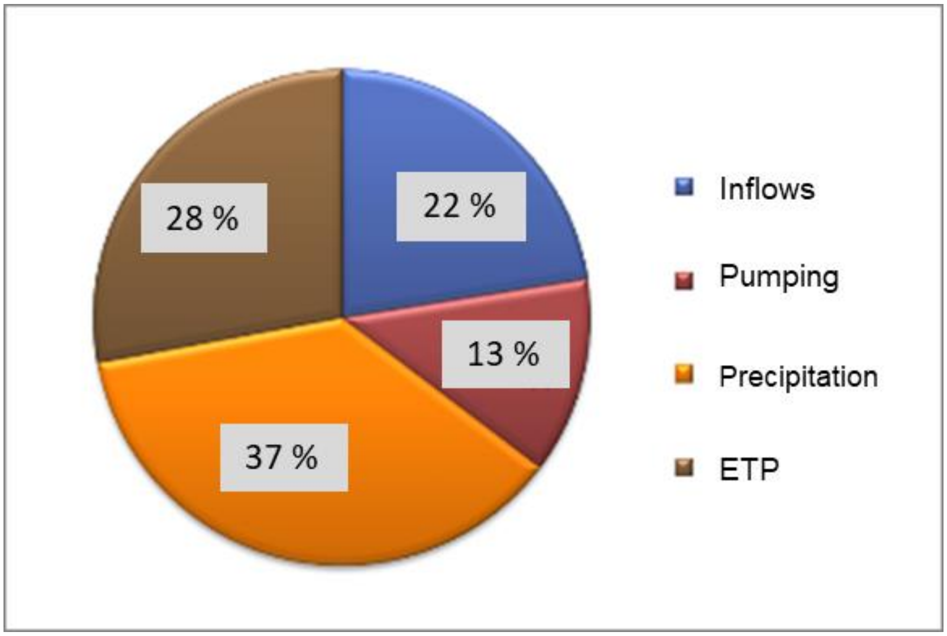

Figure 6. Percentage of the contribution of each variable to the water balance.

The model was calibrated by optimizing the water level parameter, comparing the values obtained from the model with the database provided by the Subsecretaría de Recursos Hídricos (2017) and Villauría (2003).

Results and discussion

Digital elevation model

The results of DEM of La Picasa lagoon included two stages. First, the DEM was defined based on measurements taken during the campaign tasks for elevations below 98.5 masl, the existing bathymetry from INA in March 2007 for elevations above 98.5 masl, and satellite images. In the second stage, a DEM was defined considering only existing bathymetry from INA in March 2007 developed for elevations lower than 98.5 masl. Wherever an overlapping between both DEMs was found, it was corrected using an algebraic subtraction between the pixel values as follows:

$$MDE_{resta} = MDE_{INA} - MDE_{UNC} \qquad (4)$$

Where DEM_{resta}, is the result of the subtractions between the DEMs obtained through linear interpolation of the points surveyed by the INA (DEM_{INA}) and those surveyed by the team from the National University of Córdoba (DEM_{UNC}).

The differences were taken from the deepest area of the lagoon where the campaign tasks have been carried out for levels lower than 98.5 masl. Table 2 shows that the mean values of the differences are 30 cm with a deviation of 55 cm. These values are acceptable when they are compared either with the maximum depth in the lagoon (6.65 m) or with the obtained average depth of 1.48 m.

Table 2. Statistical values of the differences.

Values (m)	
Minimum	-1.05
Maximum	2.03
Mean	0.30
Deviation	0.55

Finally, the Kriging method (Williams, 1998) was used to interpolate the points obtained in the campaign tasks, and the bathymetric points collected by the INA in March 2007. Figure 7 shows the level curves obtained in the area where campaign tasks were carried out. The figure also shows the Digital Elevation Model that represents La Picasa lagoon.

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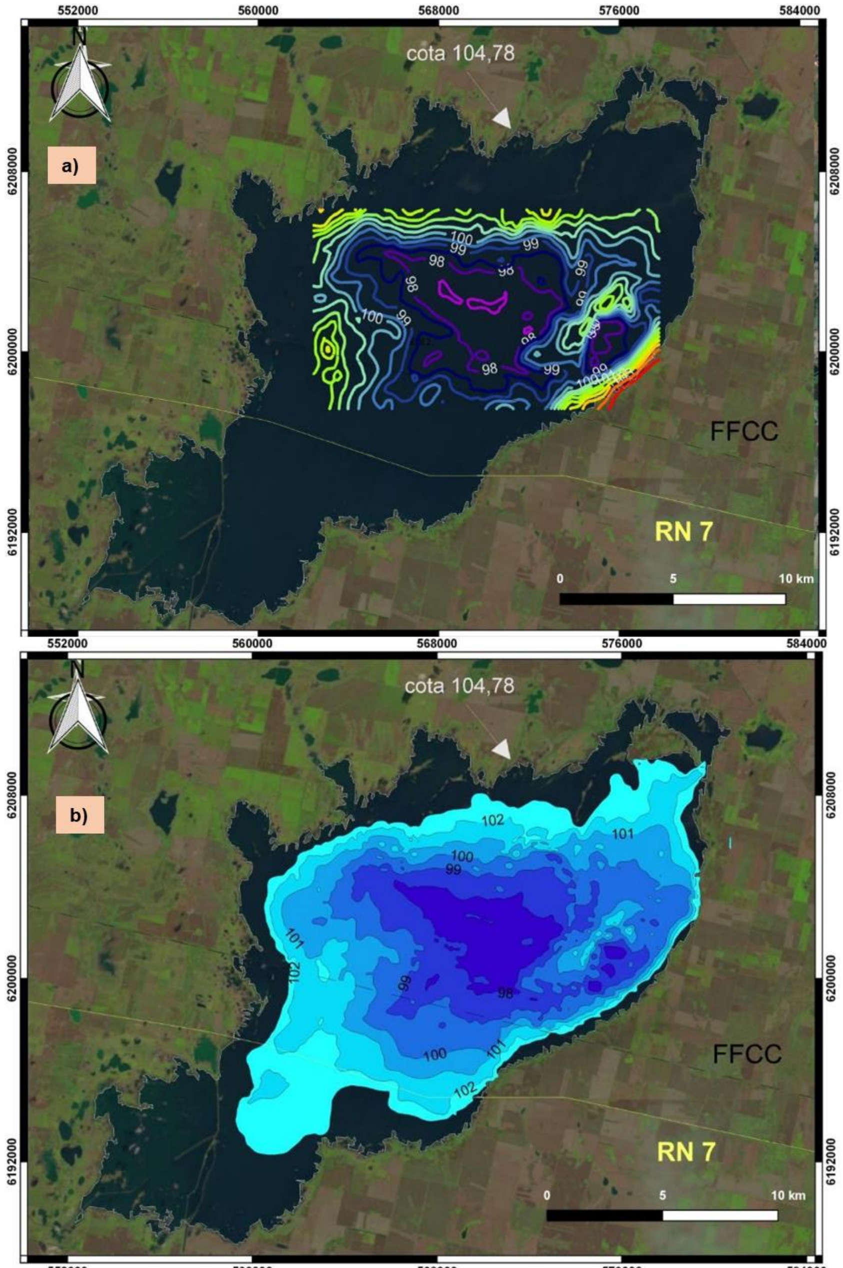

Figure 7. a) Level Curves of the area surveyed in the campaigns; b) DEM of La Picasa lagoon.

Elevation-area-volume curves

The elevation (H)-area (A)-volume (V) curves were obtained from the topo-bathymetry results. These curves describe the reception capacity of the lagoon in response to different input scenarios that can occur. The H-A-V curves and their respective trend lines are shown in Table 3 and Figure 8.

Table 3. H-A-V curve for La Picasa lagoon.

H (m)	A (km^2)	V (hm^3)
97.50	0.60	0.04
98.00	14.78	5.09
98.50	28.21	17.28
99.00	46.01	38.24
99.50	61.24	67.04
100.00	80.11	108.16
100.50	98.99	155.70

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H (m)	A (km^2)	V (hm^3)
101.00	119.34	212.95
101.50	135.47	277.84
102.00	156.38	352.30
10250	183.39	439.73
103.00	203.23	539.78
103.50	217.29	646.25
104.00	244.91	764.44
104.50	278.52	897.52
104.78	299.73	978.18

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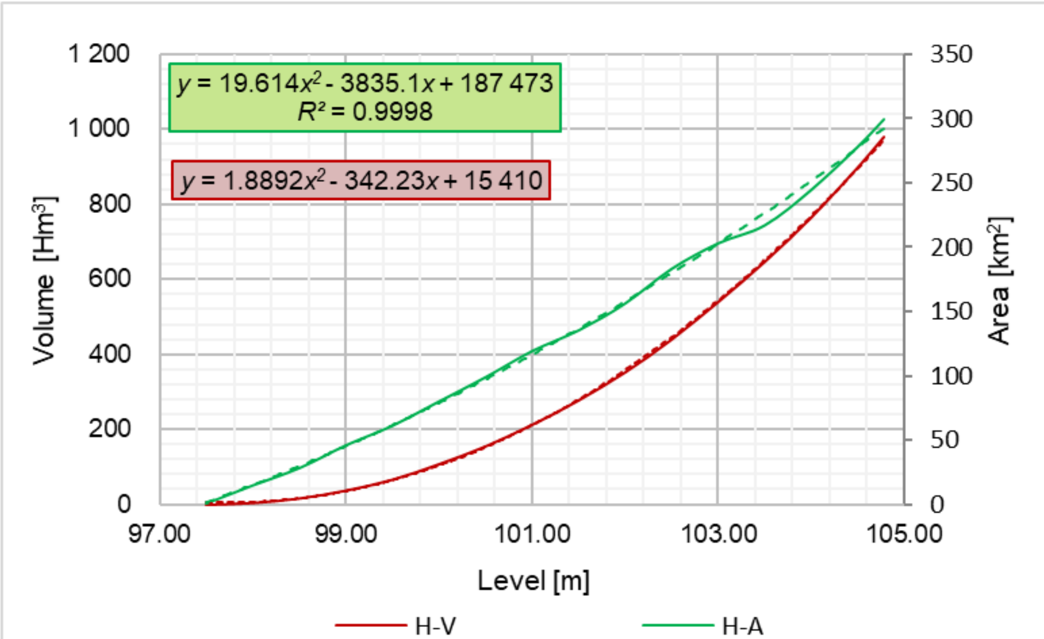

Figure 8. H-A-V curve for La Picasa lagoon.

0D water balance model

The water balance results for the water levels are observed in Figure 9, where the levels obtained from the 0D balance model are compared with the levels measured in the lagoon. An underestimation is observed in the levels obtained from the model with a maximum of 1.15 m difference, which corresponds to August 2017. In addition, since July 2015, there has been a significant increase in the lagoon level, which is related to both an increase in surface runoff and rainfall. In Figure 9, the water balance results are also observed for the volumes stored in the lagoon, which allows a comparison between the volumes obtained from the H-V curves and those obtained from the 0D balance model.

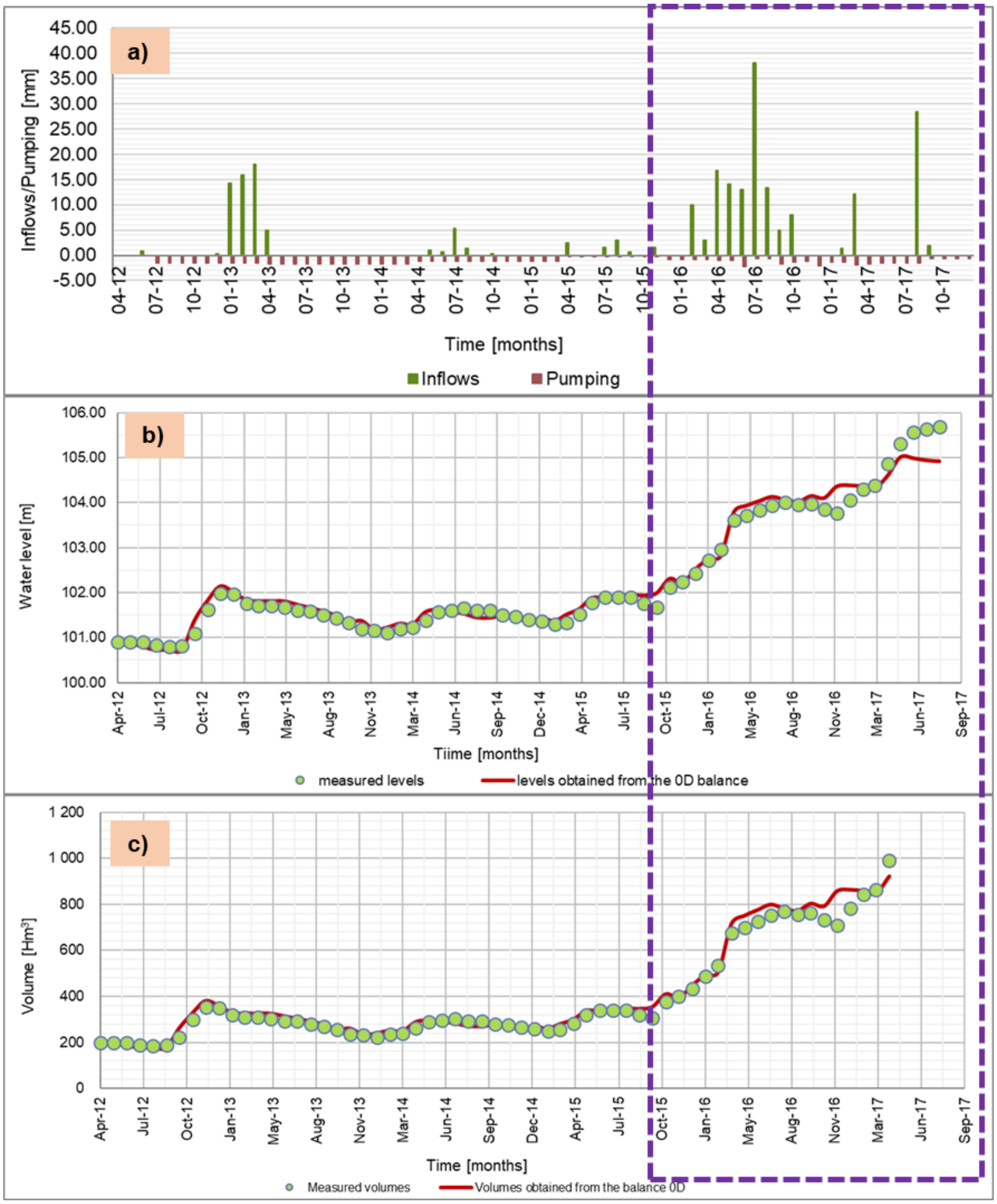

Figure 9. a) Inlet and pumping flows measured over the Picasa lagoon; b) comparison between measured and estimated levels for the different

pumping scenarios - Laguna La Picasa; c) comparison between measured and estimated volumes for the different pumping scenarios - Laguna La Picasa.

The adjustment coefficient involves the measurement uncertainties in the data collected for capacity (inflow and pumping flows), which results in 1.024 in this case. When this coefficient is applied, the 0D model becomes representative of the situation in which the lagoon was found from 2012-2017. It is assumed that this coefficient can be used for other hydrological conditions that may arise.

Conclusions

The results of the 0D model for the water balance are encouraging since a maximum difference between measured and estimated levels of 1.15 m was found, representing only about 1 % of the measured level of the lagoon. The application of the adjustment coefficient obtained from the analysis of errors between predictions and measurements makes the model a good representation for the 2012-2017 period.

It should be noted that it is necessary to analyze the individual flows to distinguish those with greater significance or more significant uncertainties, such as the inflow and outflow flows. The incoming flows play a significant role in the changes observed in the level of the lagoon. Pumping maneuvers are carried out in an attempt to regulate this level.

The water balance model applied to the lagoon could become a useful tool for predicting effects caused by hydrological situations that may occur around the lagoon environment; however, it is interesting to note that these predictions can be made from a 0D vision at the local level. The modeling was carried out with a limited amount of hydrometric data from gauges and water levels in the system. Initially, a monthly balance was proposed, and results were obtained with an acceptable degree of certainty for the analyzed period.

To achieve more precise results, it is necessary to have weather stations located close to the lagoon system to obtain representative atmospheric variables such as evaporation. Furthermore, it is crucial to have continuous flow gauges in canals since the main problem is in both entry and exit flow uncertainties.

Acknowledgments

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