Hydrological modelling of daily flow in two restored playa-lakes in southern Spain (Córdoba province)

Modelización hidrológica de paso diario en dos lagunas restauradas del sur de España (provincia de Córdoba)

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ABSTRACT

In this work, we estimated the water level from 2008 to 2023 at a daily scale in Rincon and Santiago playa-lakes (Southern Spain) by means of precipitation, total runoff and evaporation data. The results were compared to actual evolution of the water level during the same period in both wetlands. Historical hydrological data taken from previous studies was also evaluated to observe possible changes in total runoff onto the hydrological system. Our results suggest that Rincón and Santiago playa-lakes constitute a single through-flow hydrological system. In high water periods Santiago Lake, placed at a higher altitude, contribute to the water balance of Rincón and so the hydroperiod of the latter is longer. During low water periods Santiago Lake act as a recharge system. Finally, a 4.23% reduction in runoff was observed comparing the results from the study period to the historical (1972/1996) average.

Key-words: *Water balance, hydrogeology, endorheic watershed, playa-lake.*

RESUMEN

En este trabajo, se ha estimado el nivel del agua desde 2008 hasta 2023 a escala diaria en las lagunas de Rincón y Santiago (sur de España) mediante datos de precipitación, escorrentía total y evaporación. Los resultados se compararon con la evolución real del nivel del agua durante el mismo período en ambas lagunas. Asimismo, se evaluaron los datos hidrológicos históricos tomados de estudios anteriores para observar posibles cambios en la escorrentía total hacia las lagunas. Nuestros resultados sugieren que las lagunas de Rincón y Santiago constituyen un único sistema hidrológico de tránsito. En períodos de aguas altas, la laguna de Santiago, ubicada a mayor altitud, contribuye al balance hídrico de la laguna del Rincón y, por lo tanto, alarga su hidroperíodo. Durante los períodos de aguas bajas, la laguna de Santiago actúa como un sistema de recarga. Finalmente, se observó una reducción del 4.23% en la escorrentía total, al comparar los resultados del período de estudio con el promedio histórico (1972/1996).

Palabras clave: *Balance hídrico, hidrogeología, cuenca endorreica, laguna temporal.*

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Introduction

Playa-lakes in southerm Spain are mostly located in the so-called Andalusian countryside. Most of these wetlands are very shallow, and consequently, very highly sensitive to variations in their water balances. Small changes in water inputs or outputs may provoke changes in the flooded area and in the hydroperiod (Jiménez-Bonilla *et al,* 2023; Rodríguez-Rodríguez *et al*, 2016). Within this area, Rincón and Santiago playa-lakes are located in the Cordoba province, 6 km southeast of Aguilar de la Frontera town (Fig. 1).

Rincón Lake watershed is 295.7 ha, and its maximum flooded area is 10 ha. Meanwhile, Santiago Lake catchment is 135.5 ha, and its maximum flooded area is 8 ha (Fig. 1). Both receive water inputs only from precipitation and basin discharge (surface and subsurface runoff). Rincón Lake also overflows to anexhorheic drainage network towards the (Capellanía Stream, Fig.1) during extremely wet years.

During the 1940 decade, a drainage system connected Rincón and Santiago lakes. This anthropogenic modification was created for agricultural purposes. In 2003, a restoration program tried to disconnect both wetlands, clogging the drainage (Moral *et al*, 2008; Valero-Garcés *et al*, 2006). This restoration was made after the recognition as a protected Natural Reserve in order to re-establish their natural hydrological functioning.

The aim of this work is to perform daily modeling of the lake's water level to verify the effectiveness of the restoration, as recommended in previous hydrological studies in these wetlands (Confederación Hidrográfica del Guadalquivir [CHG], 2008). To do that, we modelled the water level in both lakes, following a methodology validated in previous hydrological studies (Moral *et al*, 2013).

Study site

Rincón and Santiago Playa-Lakes are located in the external fold-and-thrust belt of the Betic Cordillera, which involves Guadalquivir basin-derived units and Betics paleomargin-derived units. The Guadalquivir Basin itself was formed as a foreland basin during the Neogene, primarily composed of marine deposits from the Tortonian to Messinian epochs. Following the collision between the Iberian and African plates, the basin accumulated terrestrial and shallow marine sediments during the Pliocene to Holocene periods, which include sandstones and clays, marking a transition from a marine to a continental environment.

The tectonic compression in this region has shaped complex stratigraphy and influenced hydrogeological dynamics, particularly in the Playa-Lakes systems, where interactions between surface and subsurface water are affected by the geological substrate, significantly impacting the lakes topography and hydroperiods (Junta de Andalucía, 2005, 2006; IGME, 2009).

In the studied area, upper Miocene calcarenites and sandstones with variable permeability overly a clayey-evaporitic megabreccia dominated by Triassic origin materials with low permeability (Moral *et al*, 2013).

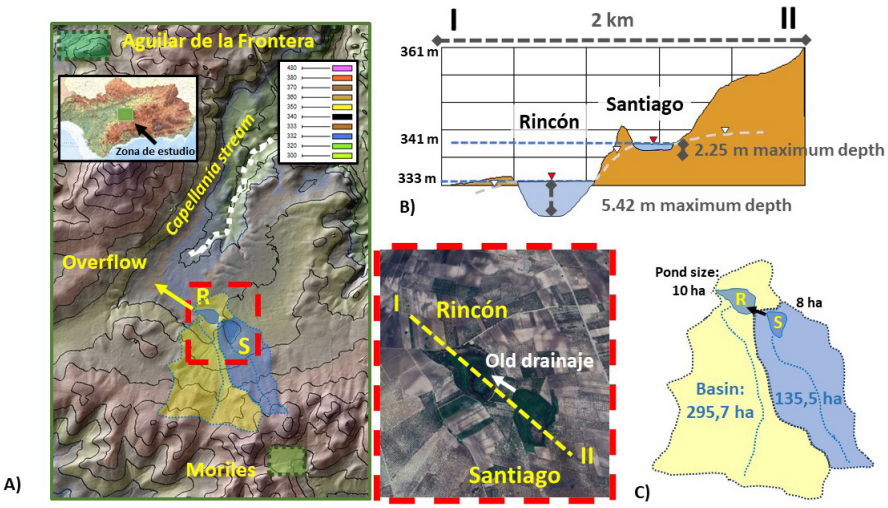

Fig.1.- A) Topographic map of Santiago and Rincón playa-lakes. B) Hydrologic cross-section of both playa-lakes. C) Basin of each lake and drainage streams. See color figure in the online version.

Fig. 1.- A) Mapa topográfico de las lagunas de Santiago y del Rincón. B) Corte hidrológico de ambas lagunas. C) Cuenca hidrográfica de cada laguna y arroyo en el que desemboca. Ver figura en color en la versión web.

Espejo and Romero (2009), classified the different horizons presented in the soil below the lakes, distinguishing an AB horizon of about 50-70 cm, along with another horizon of detrital-clay nature (BC), with features characteristic of Vertisols. The study area is characterized by a semiarid Mediterranean climate, where evapotranspiration largely excesses precipitations (Rodriguez-Rodriguez *et al*, 2011).

Both Rincón and Santiago playa-lakes are located in N-S elongated endorheic watersheds (Fig. 1). Rincón Lake (333 m ASL) is placed 8 m lower than Santiago Lake altitude (341 m ASL). In the top right of figure 1A, it shows the different colors of the maps according to the altitude. Because of the salinity value reported in a study by the CHG in 2008, which was 1.89 g/L, the water of Rincón Lakes can be considered brackish. Before the restoration, water varied between 0,6 and 1,9 g/l and the conductivity was between 1 and 3 mS/cm during the period March 1999 to October 2003 (CHG, 2008).

Both wetlands are of great ecological importance due to the wide variety of flora and fauna. In fact, Rincón Lake is one of the breeding and wintering areas for the white headed duck (*Oxyura leucocephala*), a species of waterfowl that was recognized as endangered in the Red List of Threatened Species by the IUCN, in 2017. Therefore, Rincón Lake was integrated into the Natura 2000 Network, as a Special Protection Area for Birds and Special Conservation Area (Junta de Andalucía, n.d.).

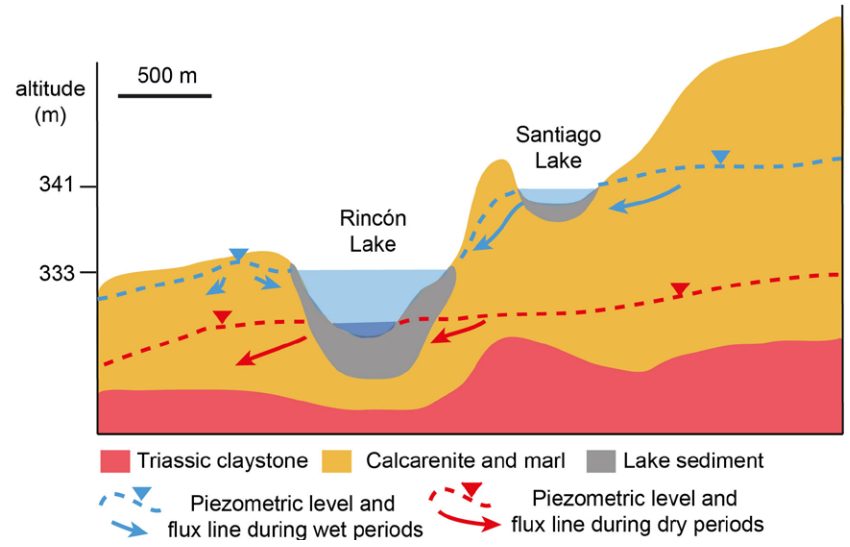

Fig. .2.- Hydrogeological model of Santiago and Rincón Lake with flux lines during dry (red lines) and wet periods (blue lines) according to our study. See color figure in the online version.

Fig. 2.- Corte litológico de las lagunas de Santiago y Rincón con líneas de flujos y niveles piezométricos. Ver figura en color en la versión web.

Methodology

The methodology applies in this work includes water level monitoring and water level modelling.

Water level monitoring

This task was conducted monthly by recording water level measurements from calibrated rulers on the deepest areas of Santiago and Rincón Lakes, from October 2008 to September 2023. Data was collected by the "Agencia de Medio Ambiente de la Junta de Andalucía". However, there are some gaps in the series due to the ruler of Santiago Lake.

This ruler has a maximum measure of 2 meters, so when the water level was over it, it could not be measured.

Water level modelling

Modelling was applied for a 15-year period of water level measurements. To do that, we used the methodology applied in previous studies (Jiménez-Bonilla, 2023; Moral *et al*, 2013; Rodríguez-Rodríguez *et al,* 2016;). The model considers local groundwater discharge, related to the playa-lake basin (Fig.2), simplifying lake water storage (Hs) as follows. The model considers low lake-groundwater connections (Fig 2), simplifying lake water storage (Hs) as follows:

$$Hs = P + BD \pm O - E, \text{ (eq. 1)}$$

where *Hs* represents the daily change in water level. *P* and *BD* are water inputs: *P* is the increase in lake level due to precipitation, and *BD* is the increase due to basin discharge (surface runoff and groundwater discharge). *O* represents surface overflow, and *E* is the water level decrease due to direct evaporation. Climatic parameters such as precipitation, temperature, and direct evapotranspiration/evaporation were sourced from a weather station (Santaella) within the Andalusian Agroclimatic Information Network (RIA) by the Junta de Andalucía's meteorological monitoring system. The Santaella station was chosen for its extensive data and proximity to the lakes (aprox. 22 km away). There were several data which did not appear in the series. To complete it, it was used the data from the Cabra station because it was the second closer.

P (mm) was directly obtained from the data series, representing the increase in the lake due to direct rainfall. *BD* was determined by a daily soil water balance in both basins, assuming a water holding capacity of 180 mm for the clayey soils (Aljibe, 2013). *BD* in mm was multiplied by the basin/flooded surface ratio to obtain the increase in water level in mm, consistent with previous studies (e.g., Jiménez-Bonilla, 2023; Rodríguez-Rodríguez *et al*, 2016). To estimate *E,* Penman *ETP* (in mm) was used, correcting these values by multiplying by 1.15.

We took into account the maximum water level in the lake. Above this level, water overflows from Santiago to Rincón or from the latter to the drainage network. Rincón Lake overflow threshold is located at 5.42 m from the lake bed (Fig. 1). Santiago Lake maximum water level was estimated aprox. 2.25 m from the lake bed. To start modelling procedure, Santiago Lake was completely dry at the beginning of the modelling period, and Rincón Lake had a height of 1.73 m (Fig. 2).

Results

Based on the observation of actual water level data in both wetlands, two periods were distinguished: a wet period from 2008 to 2014, during which the water level exceeded 5 m in Rincón Lake and 2 m in Santiago Lake; and a dry period from 2014 to 2023, during which both wetlands dried up.

Additionally, precipitation data from the RIA were analysed, revealing alternating dry and wet periods. The years with the highest precipitation were 2009, 2015, 2019, and 2021.

Following the water level modelling, a wet period was identified from 2008 to 2014, during which simulated water levels reached up to 5.5 m in Rincón and 2.2 m in Santiago. Subsequently, water levels decreased to 0.5 m in Rincón, while Santiago dried up, marking the beginning of a dry period. In early 2018, water levels increased again, reaching a maximum of 5.5 m in Rincón and 2.2 m in Santiago.

The water balance of both playa-lakes was determined by the relationship between inputs (precipitation and total runoff) and outputs (evaporation).

When comparing the climatological parameters from the study period with the values calculated by CHG in 2008 (Table 1), it was obtained an average annual precipitation of 557 mm was obtained for the historical period (1972-1996), while during the study period (2008-2023), this value was 422.3 mm/year. About the temperature, it increased 0.4 ºC from the period 1972-1996 to 2008-2023. Regarding the total runoff, 127.4 mm was recorded for the earlier period, compared to 122 mm/year in the more recent period, indicating a reduction of 4.23% in runoff when comparing both periods.

First year	Last year	Num. years	P (mm/year)	T (ºC/year)	EVAP (mm/year)	Total Runoff (Run)
1972	1996	25	557.0	17.4	-	127,4
2008	2023	15	436.0	17.6	1602.6	113,4

Table 1.- Climatic characteristics of the area during this study (2008-2023) and a historic series in the same area. (1972-1996, CHG, 2008).
Tabla 1.– Características climáticas de las lagunas Rincón y Santiago durante el periodo de estudio 1972-1996 (CHG, 2008) y el periodo 2008-2023.

As for evaporation, the only significant output, a value of 1587.8 mm/year was obtained for the period 2008-2023.

It was highlighted that runoff values were higher in Rincón Lake than in Santiago one, corresponding to longer hydroperiods in Rincón.

Finally, the meteorological parameters show a precipitation drop and an increase in temperatures during the last decades (Table 1).

To evaluate the model's performance in simulating water levels, the Pearson correlation coefficient was calculated between observed and simulated water height data. The resulting value was 0.34, reflecting a low correlation between the observed and modelled data.

This result suggested that the model had limitations in accurately capturing the variations in water levels in the playa-lakes. This low correlation could be due to factors not fully represented in the model, such as potential underground connections between the lakes, local runoff variability, or climatic factors not included in the input calculations.

In relation to the height water level. Figure 3 shows results of the water level modelling for Santiago and Rincón lakes, from November 1, 2008, to October 20, 2023.

Some significant variations occurred during the studied period. The 2008-2014 period could be considered as wet. 2014-2018 and 2020-2023 were considered dry periods (Fig. 3). This figure shows the results from the modelling and actual water level of Rincon Lake. It is the same for the modelling and actual water level of Santiago Lake. In this figure, it has been represented with unfilled orange dots the values the days when the water level in Santiago Lake was higher than 2 m. We do not have these measures because it was conditioned by the maximum calibrated ruler, as explained in the methodology section.

The water level modelling is in accordance with the climatologic conditions. It means that the maximum water level coincides with extremely wet periods, and both lakes should be dry during the dry

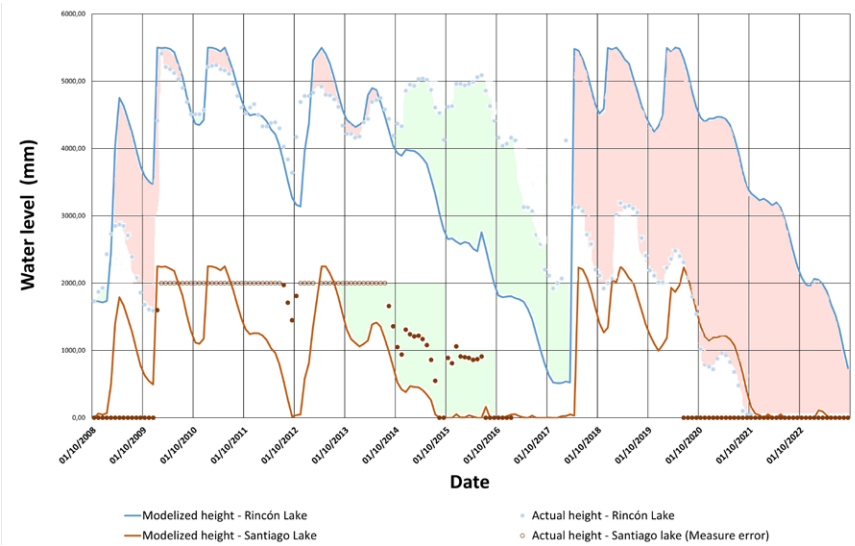

Fig. 3.- Water level (mm) vs date during the period 01/10/2008 to 30/10/2023. See color figure in the online version.
Fig. 3.- Nivel de la lámina de agua (mm) vs fecha durante el periodo 01/20/2008 al 30/10/2023. Ver figura en color en la versión web.

periods (Fig. 3). When compared actual data and modelling results of both lakes, we observed a low correlation, especially during the 2014-2023 period (Fig. 3).

Discussion

The use of this modelling has been considered successful due to its capacity to simulate the hydrological functioning of the system, in accordance with its conceptual model (Moral *et al*, 2008; Rodríguez-Rodríguez et al, 2010).

Related to this, it was created another graphic (Fig. 4) where it was represented the monthly accumulated precipitation and the actual water level.

In this figure, it can be observed that in the early years, when precipitation is more frequent, the levels of both lakes are stable or high, especially in Rincón Lake. However, starting in 2017, a decrease in the levels of both lakes is observed, coinciding with periods of lower precipitation. This suggests that the water levels in both lakes largely depend on precipitation, as when it decreases, the water levels also drop significantly.

Although both Rincón and Santiago lakes were initially considered as two independent hydrological systems after their restoration, they seem to remain connected. The results obtained throw the modeled (Fig. 3), could indicate the existence of groundwater discharge from Santiago watershed to Rincón watershed (see blue line in Fig. 2), but it would have to be contrasted with a piezometric study.

In contrast, from 2017 to 2023, values of actual data are lower than the modelled data in Rincón and Santiago lakes; this may be explained by a significant drop in the groundwater level within the aquitard (see red line in Fig. 2). Several factors could contribute to this decline. One possibility is the overexploitation of groundwater resources in the surrounding agricultural areas, which may have reduced the recharge to the aquitard. Additionally, the prolonged drought periods during these years may have limited natural recharge, as decreased precipitation and increased evaporation put further stress on the system. Another factor to consider is the geological characteristics of the region; greater permeability in the underlying strata or the presence of undetected fractures could facilitate water loss from the aquitard into deeper layers. It would be interesting to have into account in future investigations.

Additionally, we have observed that the transition from a discharge lake to a recharge lake in Rincón Lake coincides with Santiago Lake being dry during this period (Winter, 1988). This supports the hypothesis of Santiago and Rincón lakes behaving as a single hydrogeological system. Hence, in spite of the restoration carried out in 2003, our work shows that both lakes continue hydrogeologically connected.

Conclusions

The results of this work provide significant information about the hydrological functioning of Santiago and Rincón lakes. In this work, we modelled both lakes as independent hydrogeological systems, considering the analyses of the sheet hydrographs. However, taking into account our study, a close relationship between both lakes is observed, pointing to the existence of a single through-flow hydrological system.

In high water conditions Santiago Lake acts as a recharge system, probably contributing to the water balance of Rincón Lake. In addition to the water that may come from Santiago, the hydroperiod of Rincón is also influenced by the fact that its basin is at a lower elevation, which promotes greater water exchange with the geological substrate. On the other hand, during low water periods, groundwater level drops and Santiago Lake dries out.

In the future, the monitoring of lakes must be continuous, to avoid long register gaps. Moreover, the maximum depth of Santiago Lake should be constrained. It will be also important to observe the evolution of the piezometric level in the surrounding area, to check out the possibility of an affection in the water level of the lakes due to the aquitard overexploitation for irrigation purposes.

Author contributions

Below are the tasks performed by each author:

Martínez-Caro, M.: Review and structure of the work, and creation of table 1, figure 3 and 4, manuscript writing, laboratory analysis.

Jiménez-Bonilla, A.: Supervision, review and editing of the work structure, coordination, methodology, creation of figure 2, field data collection, and laboratory analysis.

Rodríguez-Rodríguez, M.: Supervision, review and editing of the work structure, creation of figure 1, and coordination.

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References

Winter, T. C. (1988). *Environmental Management*, 12, 605-620.

Espejo, J. M. R., and Romero, D. G. (2009). *Boletín de la Real Academia de Córdoba de Ciencias, Bellas Letras and Nobles Artes*, 89 (156), 183-190.

Jiménez-Bonilla, A., Rodríguez-Rodríguez, M., Yanes, J.L. and Gázquez, F. (2023). *Science of The Total Environment*, volume, 905, 1-14.

Junta de Andalucía. (2006). G*eodiversidad y patrimonio geológico de Andalucía* (Capítulo 14).

Junta de Andalucía. (n.d.). *Reserva Natural Laguna del Rincón*. Junta de Andalucía - Consejería de Sostenibilidad, Medio Ambiente y Economía Azul.

Moral, F., Rodriguez-Rodriguez, M., Beltrán, M., Benavente, J., and Cifuentes, V. J. (2013). W*ater environment research*, 85(7), 632-642.

Moral. F., Rodriguez-Rodriguez. M., Beltrán Miralles, M., Benavente Herrera, J. and Ortega Gonzalez., F. (2008). *Confederación hidrográfica del Guadalquivir*, *Tomo II*, 158-186.

Padilla, A., Delgado, J., Castillo, E., (2005). Aljibe Consulting, Rodríguez-Rodríguez, M., Montes-Vega, MJ and Maldonado-Jiménez, J. (2022). *Magazine of the Spanish Geological Society*, 72, 3-6.

Rodríguez-Rodríguez, M., Benavente, J., Alcalá, F. J., and Paracuellos, M. (2011). *Estuarine, Coastal and Shelf Science*, 91(3), 400-410.

Rodriguez-Rodriguez, M., Martos-Rosillo, S., and Pedrera, A. (2016). *Journal of Hydrology*, 543, 462-476.

Rodríguez-Rodríguez, M., Moral, F. and Beltrán, M. (2010). *Magazine of the Spanish Geological Society*, 48, 135-138.

Valero-Garcés, B. L., González-Sampériz, P., Navas, A., Machín, J., Mata, P., Delgado-Huertas, A., and González-Barrios, A. (2006). J*ournal of Paleolimnology*, 35, 441-465.