Hydrogeological characteristics of a groundwater-dependent ecosystem (La Lantejuela, Spain)

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Abstract
By means of a simple water balance model, together with hydrogeochemical and morphological interpretation, the hydrogeological characteristics of a series of playa lakes forming an endorheic complex within the Guadalquivir river basin in Southern Spain (La Lantejuela) have been evaluated. The lakes are demonstrated to be groundwater-dependent ecosystems. The main source of groundwater input to the lakes is from an unconfined detritic aquifer, the playa lakes being the natural discharge points from the aquifer within the endorheic complex. High rates of evaporation from the lakes induce a centripetal groundwater flow pattern. This water body has been disturbed by a combination of extensive drainage works and intensive groundwater abstraction. There is a need for a sustainable water management strategy for the whole catchment area. It is hoped this will be an issue addressed within the Guadalquivir river basin management plan in accordance with the requirements of the European Water Framework Directive (WFD).

Introduction
Throughout southern Spain, there exist numerous closed basins hosting playa lakes, where small mountain ranges or hills separate semi-arid basins (García et al. 1997; Montes et al. 2004). Ephemeral playa lakes occur in arid to semi-arid environments whenever internally drained basins are formed by tectonic activity or dissolution processes, and the floor of such basins intersects the water table (Duffy & Al-Hassan 1988). Rainfall onto the related aquifers or the catchment area of the playas enters the groundwater through permeable materials overlying the impervious substratum. Normally, the substratum is related to the presence of Triassic sediments, which outcrop abundantly in the Betic Cordillera (Vera 2004) and present very low hydraulic conductivity. The groundwater returns to the surface in the form of springs, rivers or discharge to the playa lake system. However, a second type of circulation, which is unique to a closed basin, may also occur. Evaporation concentrates the playa lake water, which turns into a brine. This brine, which is much denser, may flow into the fresher groundwater. As long as brine is supplied, cellular flow circulation may take place below the playa lake bottom until it reaches the impermeable substratum. This scenario is known as ‘free convective flow’ (Fan et al. 1997).

The surface–groundwater relation between the playa lakes and the unconfined aquifers in the area is of evident interest in the correct management of such ecosystems, which are very sensitive to hydrological alterations such as groundwater pumping or surface drainage. The Water Framework Directive (WFD), which is applicable in all the member states, encourages the investigation of groundwater-dependent ecosystems (WFD-CISNo.2 2002, 2003). Finally, this type of methodology could help close the present gap that exists between water managers and researchers (Borowski & Hare 2007), thanks to its simplicity. The main objectives to be addressed in this work are (i) to describe the detritic aquifer Osuna-La Lantejuela (O-LL), about which only a few hydrogeological studies have previously been published; (ii) to investigate the hydrological relations between this aquifer and the playa lakes of La Lantejuela by means of a simple water budget and (iii) to carry out a preliminary hypothesis on the genesis of these systems.

Main exposition

Methods

Study site

The study zone is located near the town of Osuna in the southeast of the province of Seville (Andalusia, Spain) (Fig. 1).
The topography is characterized by a plain that smoothly descends towards the north, from an altitude of about 300 m above sea level (a.s.l.) in the proximity of Osuna to 150 m near La Lantejuela. Hills bordering the flood plain include Palomarejo (309 m a.s.l.), which is in the northern part of the study zone (Fig. 1). Surface drainage is towards the west-located Corbones River and towards the east-located Blanco River (Fig. 2). The study area belongs to the Subbetic Units of the Betic Cordillera (External Zones) and to the sedimentary filling of the Guadalquivir river basin. Nine water bodies formed the endorheic complex of La Lantejuela, but the majority of these lakes are nowadays threatened by drainage and filling and so only two of them are preserved and hydrologically functional (Calderón and Ballestera playa lakes, see Fig. 2). Other anthropogenic stresses such as pollution, eutrophication, catchment cultivation, road construction and groundwater pumping affect these ecosystems.

**Field surveys, analytical procedures and water balance calculation**

Sampling campaigns were carried out in 2004. Subsequently, occasional morphological surveys were made in 2005. Surface water samples were taken at a distance of 4 m from the shore of the playa lakes. Groundwater samples were collected from the uppermost part of the 47 wells that were included in the inventory. Field parameters measured in surface and groundwater were electric conductivity (EC25), water temperature and pH. Major ions and nitrates were measured using ion chromatography and spectrophotometry techniques, at the hydrochemistry laboratory of Pablo de Olavide University (Seville). Geographic information system (GIS) was used to determine flooded surface and catchment area characteristics; several hydro-morphological surveys were undertaken to check the results obtained. The Osuna weather station, located at an altitude of 255 m a.s.l., was selected to obtain meteorological data. A 29-year series of mean temperatures and precipitation was used. Data on daily evaporation were obtained using a ‘Class A’ evaporation tank located at ‘Torre del Aguila’ reservoir weather station (55 m a.s.l.).

The equation of the water budget (Mansell & Rollet 2006) for average climatic conditions can be expressed as

\[
\Delta V = P - E + (S_i + G_i) - S_o - G_o, \tag{1}
\]

- \(\Delta V\) refers to the change in playa lake storage and is the result obtained from the water budget model (unknown...
variable). This component may not change on an interannual scale but important variations may be expected on a monthly scale. The model can be validated by comparing its results (theoretical water level) with the time series data for the water level of the playa lake.

- $P$ is direct precipitation onto the playa lake, estimated by multiplying monthly $P$ (mm) by the average flooded area at each time interval to obtain $P$ (m$^3$).
- $E$ is evaporation from the flooded surface. This component of the water budget is estimated from Class A tank evaporation data (mm), compared by correlation analyses with other evaporation data from reservoirs of the Guadalquivir river basin and scaled to obtain $E$ (m$^3$).
- $S_i$ is surface water inflow (i.e. surface runoff) and $G_i$ is subsurface runoff. These two components of the playa lake water balance are equal to 50% of the surplus of the soil–water budget. The remaining 50% infiltrates to recharge the aquifer. Previous studies (CHG-IGME 2001) have shown a relatively high transmissivity for the materials of the aquifer (10–100 m$^2$/day). Additionally, water balances in other playa lakes of Andalusia have been calculated using similar infiltration rates (Carrasco et al. 2004). A soil–water budget in the catchment area was calculated to determine the water surplus. The soil–water budget is a simple accounting scheme used to predict soil–water storage, actual evapotranspiration (ET) and water surplus by means of precipitation and potential ET at a given water-holding capacity (Thornthwaite & Mather 1955; Jensen et al. 1990). Water surplus is the fraction of precipitation that exceeds potential ET and is not stored in the soil. The simple model used here does not distinguish between surface and subsurface run-off, and so water surplus includes both.

- $S_o$ is surface water outflow. As the playa lakes are located at the centre of a closed basin without any water-discharging river or outlet, $S_o$ is zero.
- $G_o$ is groundwater output (i.e. recharge or infiltration) from the lake to the aquifer. This term is not computed in the equation because it is already included in the soil–water budget (50% recharge).

If the evolution of the water level in the playa lake is similar to that observed in the field, then it is assumed that the water budget is correct. In that situation, the only water inputs to the lake are $P$ and $S_i+G_i$. If regional groundwater discharge or hydrological alterations of the catchment area such as drainage or over pumping take place, then the result will not fit the average evolution of the water level observed in the playa lake. The
methodology of the water budget model presented in this work has been validated by successful previous applications in other Andalusian wetlands (Benavente et al. 2006a, b).

Discussion

Geological features

Sedimentation in the Betic Cordillera took place during the Neogene in two tectonically different phases. From the Early to Middle Miocene, the Betic basin evolved with the main movements of orogenic structuring of the Cordillera, which were the collision between the Alborán Microplate (Internal Zones) and the South-Iberian Paleomargin (in which deformed rocks of Mesozoic age made up the External Zones). In this synorogenic phase, a number of basins formed within the orogene as well as in the foreland basin outside it, such as the Proto-Guadalquivir basin. The sediments filling these basins were deformed by the Betic orogenic. The second tectonic phase took place during the Late Miocene to Quaternary. The main features of the orogene were already determined and this was the context in which the postorogenic basins formed, located in both the Internal and External Zones and at the contact (Viseras et al. 2005).

Simultaneously, diapiric movements associated with Mesozoic evaporitic materials occurred, leading to the formation of elevations and karstification throughout the External Zones of the Cordillera. From the different regional geologic studies carried out in the study zone (Cruz-Sanjulián 1974, 1986; Crespo 1977; Pignatelli & Crespo 1977), the geologic materials outcropping in the area can be grouped into three units:

- Alochthonous Formations (Subbetic and Olistostromic Unit): multicoloured marls and clays of Triassic age that include, in a chaotic mixture, blocks (olistolits) of varied nature and ages between the Triassic and Miocene (dolomites, volcanic rocks, limestones, marls, sandstones, etc.). These outcrop to the east and the south of the study zone and constitute the impervious substratum above which the youngest materials were deposited. The tectonics of the Alochthonous Units is determined by the gravitational displacement of these materials, of plastic behaviour, that took place in a SE–NW direction towards the Miocene marine basin. These materials exhibit a low level of hydraulic conductivity (Fig. 2).
- Para-autochthonous Formation: white marls and marly limestones, locally with sandy bars, from Upper Burdigalian to Messinian age. They show abundant remnants of marine microfauna (sponge spicules, diatoms, etc.) and display a thickness of almost 100 m. The most extensive outcrop is that of the Palomarejo hill, to the north of the playa lake complex of La Lantejuela. These materials display a medium level of hydraulic conductivity (Fig. 2).
- Autochthonous Formation (Upper Miocene and Plio-Quaternary): these appear discordant to the other Units described and are postorogenic. The main lithologies are conglomerates, gravels, sands, clays and evaporites that sometimes appear cemented. These materials are permeable, and have a high level of hydraulic conductivity (Fig. 2).

O-LL aquifer

The O-LL aquifer (Fig. 2) consists of a detritic unconfined hydrogeological system made up by Plio-Quaternary alluvial materials. The aquifer has an average thickness of 4–8 m in the northern part (near the playa lakes) and about 40 m near Puebla de Cañada and the Corbones River. Permeable outcrops occupy a surface area of 350 km² and the aquifer materials display a heterogeneous hydrogeological behaviour. The impermeable substrate of the aquifer contains clayey-evaporitic materials of Triassic age, which are responsible for the relatively high salinity of the groundwater (CHG-IGME 2001). Recharge takes place by the infiltration of rainwater and occasional flooding of the rivers. Discharge takes place by evaporation from the playa lakes and also by groundwater discharge to the main streams and rivers of the area. Present-day discharge is also produced by the pumping activities carried out in numerous irrigation wells throughout the area.

According to our measurements, the piezometric level is close to the surface (3–4 m). Absolute altitudes a.s.l. range from 142 to 155 m a.s.l. The piezometric levels measured in the 47 wells of the inventory (Table 1) lead us to conclude that the directions of the groundwater flow have an approximate component N330°E, from the proximity of Osuna towards the playa lakes (Fig. 3).

Piezometric measurements indicate the existence of a single groundwater system and that the base level of the playa lakes represents the phreatic level of the aquifer. However, each lacustrine basin displays its own separate characteristic hydrogeological behaviour as is discussed below.

The groundwater in the O-LL aquifer has nonhomogeneous electrical conductivities, ranging from 1.2 mS/cm in wells located in sandy conglomerates of Pliocene age to 16 mS/cm in wells located on the Quaternary clays and limes near the playa lakes. The salinity of the groundwater increases towards the lacustrine basins. This hydrochemical pattern seems to indicate that in a natural regime, transport processes take place towards the playa lakes (the discharge zones of the O-LL aquifer) where evaporative brines are generated (Fig. 4).
This brine infiltrates through the sediments of the playa lakes by diffusion and probably by advection processes, creating a zone of high-salinity groundwater below the system (Figs 3 and 5).

La Lantejuela playa lake endorheic complex

This playa lake system consists of eight ephemeral lakes that have been considerably altered by human activities.

### Table 1

<table>
<thead>
<tr>
<th>Code</th>
<th>UTMX</th>
<th>UTMY</th>
<th>Z (m a.s.l.)</th>
<th>DWL (m)</th>
<th>WL (m a.s.l.)</th>
<th>EC25 (mS/cm)</th>
<th>$T_{\text{water}}$ (°C)</th>
<th>Date recorded</th>
<th>Observations</th>
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<tr>
<td>O-LL-1</td>
<td>0312251</td>
<td>4132435</td>
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<td>4132849</td>
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<td>3.95</td>
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<td>5.16</td>
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<tr>
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<td>4133024</td>
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<td>18.8</td>
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<td>19.3</td>
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<td>30 Sept. 2004</td>
<td>Submersed pump</td>
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</table>

Z, position (m a.s.l.) of the wells with an accuracy of 1 m (AME 2005); DWL, depth of the water level with an accuracy of 0.01 m; WL, water level with an accuracy of 1 m; O-LL, Osuna-La Lantejuela; a.s.l., above sea level.

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La Lantejuela playa lake endorheic complex

This playa lake system consists of eight ephemeral lakes that have been considerably altered by human activities.
Formerly, it was a large endorheic area of more than 300 km² that extended around the town of Osuna. The Salado River ended at this area, creating a continental fan delta. Nowadays, most of the playa lakes are drained and the Salado River has been canalized to a tributary of the Corbones River, in accordance with the Agricultural Plan for Osuna, established in 1967.

The only playa lakes that have remained well preserved are Ballestera and Calderón, declared Natural Reserves, while the others are flooded only sporadically or have been transformed into agricultural lands (Fig. 7).

The playa lakes of the endorheic complex of La Lantejuela exhibit high water salinity, although there is a large degree of variation during each hydrological cycle. In the Ballestera playa lake, the concentration of solids correlates strongly with water volume and varies between 10 and

**Fig. 3.** Flow direction (a) and groundwater salinity (b) in the study area (September 2004).

**Fig. 4.** EC and depth of the water table in six wells (O-LL42 to O-LL47) located in the studied area plotted against distance from Consuegra playa lake (see Fig. 3). EC, electric conductivity; O-LL, Osuna-La Lantejuela.

**Fig. 5.** EC log in well No. 46 (O-LL 46, see Fig. 3). EC, electric conductivity; O-LL, Osuna-La Lantejuela.

**Fig. 6.** Piper diagram showing the hydrochemical facies in six wells located in the studied area. The arrows indicate the geochemical evolution path of the groundwater: increasing concentrations of Cl⁻ and Na⁺ from well 43 to the playa lake.
90 g/L. Similar salinity values have been measured in the Calderón playa lake.

With respect to hydrochemistry (Fig. 6), brine dominated by Na and Cl develops in both systems, although concentrations of sulphate and magnesium are also important. Playa lake brines are interpreted as the endmembers of local groundwater flow lines moving slowly towards the centre of each endorheic basin.

Table 2 shows the results for the water budgets in the playa lakes and the soil, together with meteorological data. The surplus from the soil–water budget totals 107.8 mm for a water-holding capacity of 100 mm (Table 2A), representing 20.5% of annual precipitation.

The monthly water balance of the Calderón and Ballestera playa lakes was determined in accordance with the methodology described above. We have assumed that, a priori, there is no water interchange between the playa lakes and the O-LL aquifer. If the results obtained from this theoretical balance for the average hydrological year (basically, the duration of the average flooding period of the playa lake) are similar to the data known about the hydroperiod of the lagoon, then the resulting net volume of the water interchange between the O-LL aquifer and the playa lakes would be considered negligible. Otherwise, a remarkable contribution of groundwater to the playa lakes (discharge) or groundwater recharge from the playa lakes to the aquifer must occur.

The runoff (surplus) was estimated by applying the precipitation and temperature records from the Osuna weather station (Table 2A) to the monthly water balance. Because the catchment area of the playa lakes is located over relatively permeable materials, it is assumed that half of the runoff infiltrates, constituting a part of the recharge of the O-LL aquifer. The other 50% produces direct surface runoff to the playa lakes.

Table 2B shows the results of the monthly water balance for the Calderón playa lake. The direct precipitation (P) onto the surface area of 3.9 ha is $31.1 \times 10^3$ m$^3$/year. Excluding the flooded area, the catchment area has a surface of 75.1 ha. The surface runoff and subsurface groundwater recharge to the playa lake ($S_i + G_i$) total $40.5 \times 10^3$ m$^3$/year. The ET estimated in the model is $71.6 \times 10^3$ m$^3$/year. The model predicts a flooding period with an average duration of almost 8 months, from January to the end of August, and a maximum water level of 65 cm.

According to the literature (Moreira & Montes 2005) and field observations, the playa lake remains flooded for <6 months each year. Thus, the hydroperiod observed is shorter than that predicted by the model. These differences
could be explained by regional groundwater recharge from the playa lake to the O-LL aquifer. Piezometric data (Figs 3, 7 and 8) support this idea, because the Calderón playa lake is situated at 157 m a.s.l. Piezometric measurements (September 2004) indicate that the water level in this sector is close to 150 m a.s.l. Therefore, this playa lake is perched with respect to the saturated zone of the O-LL aquifer and can contribute to the recharge of the groundwater body.

The Ballestera playa lake has an average flooded surface area of 25.4 ha and a catchment area of 145 ha. The
average precipitation onto the surface is $134 \times 10^3 \text{ m}^3/\text{year}$. Surface runoff from the catchment area is estimated to be $64.5 \times 10^3 \text{ m}^3/\text{year}$. The model predicts $198.3 \times 10^3 \text{ m}^3/\text{year}$ of ET (Table 2C). Under these conditions, the hydroperiod would last from January to the end of June, and the water level would reach a maximum of 25 cm in the months of February and March. A remarkable similarity exists between the forecasts of the model and the existing information about the actual hydroperiod of the playa lake. The position of the playa lake (145.5 m a.s.l.) with respect to the piezometric level of the O-LL aquifer in this sector (145 m a.s.l.) indicates that a hydraulic connection between the two systems may exist. The hydraulic potential may be greater in the playa lake or in the aquifer depending on the hydrological season. In such a situation, the water of the playa lake could recharge the aquifer in winter and vice versa. A simple scheme of the hydrological regime in both playa lakes and their relation with the O-LL aquifer is presented in Fig. 7. Systematic piezometric information and detailed geochemical investigation of this system are needed in order to confirm this hypothesis.

**Geomorphologic features: the fluvial network**

The main rivers of the study zone flow in a N–NW direction, from the southern highlands to the Guadalquivir river basin. From west to east, these rivers are the
Corbones, the Peinado, the Salado (of Osuna) and the Blanco. Around the Palomarejo hill, with a subcircular shape and a diameter of more than 10 km, a remarkable distortion in the general disposition of the drainage network can be observed (Fig. 9). A fluvial network of radial-annular shape has developed in the hill, although this network is very disorganized and presents numerous endorheic areas, where the playa lake complex of La Lantejuela is located. The morphology of the relief and the distribution of the fluvial network seem to indicate the existence of a diapiric structure. Accordingly, the Palomarejo hill would correspond to a diapiric dome and the lacustrine complex, the filling of the peripheral basin formed in the southern part of the diapir. The existence of active diapiric processes would explain the modification of the fluvial network pattern and the formation of the lacustrine basins as well as the detritic O-LL aquifer (Moral et al. 2006) due to fluvial-lacustrine sedimentation in the great endorheic river basins formed (such as that of the Salado River continental fan delta) formed in the river trajectory before the diapiric structure (Fig. 9).

Diapiric processes can be justified by the presence of Triassic evaporitic materials, as reported by several authors for nearby areas (García et al. 1991; Pérez & Sanz 1994; Calaforra & Pulido-Bosch 1999).

Conclusions

(1) To the north of Osuna (southern Spain), Triassic evaporitic materials (Keuper) are abundant. In many places, Neogene and Quaternary materials are located above the Triassic clays, and in this area they constitute the O-LL aquifer.

(2) In the northern sector of the aquifer is the endorheic complex of La Lantejuela, comprising nine playa lakes. The analysis of hydrogeological measurements serves to detect the existence of local groundwater feeding to the playa lakes. These are related to the O-LL aquifer, constituting local discharge zones and inducing a centripetal groundwater flow into the playa lakes.

(3) However, drainage works in these wetlands and intensive groundwater pumping have considerably modified the hydrological relations between the aquifer and the playa lakes. Advances in understanding these interactions and pressures are needed for a correct hydrological management of this type of groundwater-dependent ecosystem in the framework of the European WFD.

(4) The geologic and geomorphologic characteristics – the radial-annular fluvial network – of the area seem to indicate that a diapiric structure is responsible for the formation of the relief of the Palomarejo hill, of the basins where the playa lakes are located and of the O-LL Plio-Quaternary detritic aquifer.

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