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Changes in water level, land use, and hydrological budget in a semi-permanent playa lake, Southwest Spain

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Abstract Medina playa lake, a Ramsar site in western Andalusia, is a brackish lowland lake of 120 ha with an average depth of 1 m. Water flows into Medina from its 1,748-ha watershed, but the hydrology of the lake has not previously been studied. This paper describes the application of a water budget model on a monthly scale over a 6-year period, based on a conceptual hydrological model, and considers different future scenarios after calibration to improve the understanding of the lake's hydrological functioning. Climatic variables from a nearby weather station and observational data (water-level evolution) were used to develop the model. Comparison of measured and predicted values demonstrated that each model component provided a reasonable output with a realistic interaction among the components. The model was then used to explore the potential consequences of land-use changes. Irrigation of olive groves would significantly reduce both the hydroperiod (becoming dry 15% of the time) and the average depth of the lake (water level <0.5 m 40% of the time). On the other hand, removal of an artificial overflow would double the average flooded surface area during high-water periods. The simulated water balance demonstrates that the catchment outputs are dominated by lake evaporation and surface outflow from the lake system to a creek. Discrepancies between predicted and observed water levels identify key areas of uncertainty for future empirical research. The study provides an improved basis for future hydrological management of the catchment and demonstrates the wider utility of this methodology in simulating this kind of system. This methodology provides a realistic appraisal of potential land-use management practices on a catchment-wide scale and allows predictions of the consequences of climate change.

Keywords Hydrological budget · Land use · Playa lake · Water level

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Introduction

In regions where intense runoff occurs over a short time period, closed topographic depressions with low permeability are filled because of a water surplus. This leads to the formation of ephemeral ponds or playa lakes with longer hydroperiods (Hayashi and Van der Kamp 2005). The water budget (the balance of water inputs into the system versus water outputs) controls changes in the water level of these water bodies, and depends on the hydrological processes that control these dynamic changes. In closed basins composed of materials with low permeability (e.g. marls, clays), water input comes from rainfall in the watershed that is not used by vegetation (evapotranspiration or ET) or evaporated from the foliage cover (interception).

Once these variables are estimated, the application of a simple water balance equation (inputs = outputs + storage change) can be used to obtain the theoretical water level of the lake (storage change = inputs − outputs). Once validated, this water-level model can predict future water-level evolution due, for example, to land-use changes, climatic shifts, droughts or mismanagement of ground- or surface-water resources.

Agricultural land management is one of the main reasons for wetland degradation and wetland loss since 1950 (Rodríguez-Rodríguez 2007; Green et al. 2002). The Andalusian Campiña (henceforth AC) is a strip of land between the Guadalquivir River Depression to the north and the foot of the Betic Mountain Range (BMR) to the south (Fig. 1). Nearly 100 temporary playa lakes (as defined by Arche 2008) are scattered through the AC (Montes et al. 2004). The watershed of these playa lakes is usually dominated by orchards of olive trees. Olive trees have traditionally been managed without irrigation, but in recent years many olive-tree plantations have been irrigated to increase profits. In most cases, irrigation methods require groundwater abstraction owing to a lack of available surface water. Medina (c. 120 ha) is the second largest inland playa lake of the AC. The largest is the Fuente-Piedra playa lake (c. 1300 ha). Medina lake is very important for waterbirds (Amat 1984; Martínez-Haro et al. 2011), which led to its protection as a Nature Reserve and declaration as a Wetland of International Importance under the Ramsar Convention in 1989. The closed basin or watershed (WS) of 1,748-ha is dedicated mainly to wheat cultivation (Fig. 1) and new plantations of olive-tree orchards. The WS of the playa lake is closed—endorheic—and made up by low-permeability materials such as clays and marls. The playa lake is located in the deepest part of the watershed, so all the rainwater falling onto it—that has not been previously evapotranspirated—feeds the lake. A progressive land-use change to drip-irrigated olive-tree orchards and the resulting groundwater withdrawal could modify the hydroperiod of this valuable lake in the future. The hydroperiod is already altered by an artificial overflow that is linked to a ditch. The playa lake overflows whenever the maximum depth surpasses 3.5 m.

The main goal of this study is to characterise water-level changes in the Medina playa lake using a water-budget model based on the morphometric characteristics of the WS, climate data and previous knowledge. Then, this model is used to simulate the evolution of water levels under different scenarios. Finally, land use in the Medina

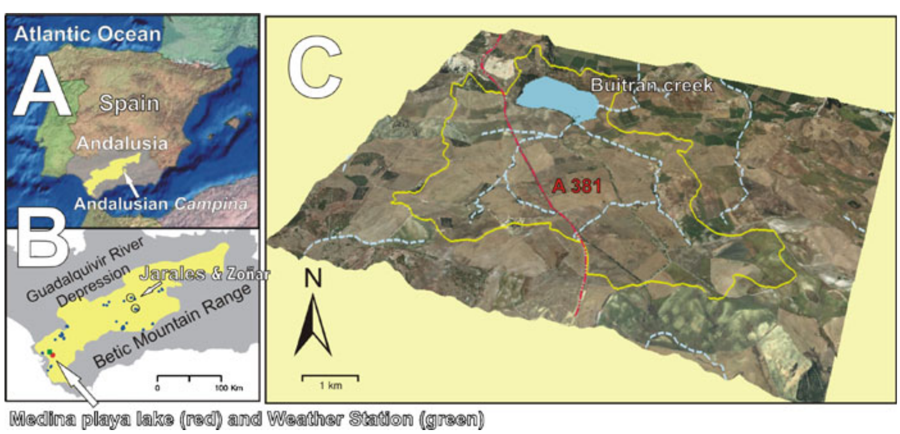

Fig. 1 **a** Location of the study area and the Andalusian Campiña; **b** location of the Medina playa lake, weather station and Jarales and Zoñar playa lakes. *Dots* indicate the position of other playa lakes in the Andalusian Campiña; **c** watershed of Medina playa lake (1,748.ha) and location of the Buitran creek (source of the image A.M.E. 2005)

WS from 1956 to 2003 is described in detail in this study.

Description of the study area

Owing to former hunting activity, the playa sediments are highly contaminated with spent lead shot (Mateo et al. 2007). Medina lake has also suffered marked fluctuations in depth and salinity over the past 9,000 years (Reed et al. 2001). The lithology of the AC is fundamentally composed of clays and marls, although there is a considerable amount of evaporitic rocks, mainly gypsum. These sedimentary materials have been deposited in a marine environment since the Triassic and have different structural positions, from allochthonous (rocks deposited from the Triassic to the Middle Miocene that were moved from their original site by low-angle thrust faulting) to autochthonous (sedimentary rocks deposited from the Upper Miocene due to the complete immersion of the area). The allochthonous materials from the BMR include blocks of different sizes and ages (olistolites) with a very heterogeneous distribution (Vera 2004). Conversely, autochthonous rocks that fill the Guadalquivir River Basin are composed mainly of Upper Miocene marine materials, namely, marls and cross-stratified calcarenites. During the Pliocene and Quaternary, continental sedimentation was predominant (Viseras et al. 2005). Detailed information about the BMR's geology can be found elsewhere (Gibbons and Moreno 2002; Vera 2004). One of the main hydro-morphological characteristics of the AC is the predominance of low-permeability outcrops due to the abundance of marine clays and marls. Thus, in the majority of the playa lakes, the catchment area exhibits a shallow water table that is a subdued replica of the land surface. Given the low permeability (Haitjema and Mitchell-Bruker 2005), surface and ground water catchments are expected to resemble each other (Moral et al. 2008a). This is true for the Medina playa lake WS, >85% of which is occupied by low-permeability marls and clays deposited during the Triassic period and then thrusted, so these rocks are defined as olistolites (Benavente et al. 2005a). The substratum over which the playa lake formed inhibits downward percolation and groundwater recharge. This type of hydrogeological system has been defined as a discharge playa (Born et al. 1979; Yechieli and Wood 2002). The main water output in Medina lake is by evapotranspiration over the average water surface of 120 ha (including the riparian vegetation). The playa lake also overflows whenever the water level reaches 3.5 m. The overflow was constructed to prevent flooding of adjacent fields, and is dredged periodically. Past research, including field measurements in the majority of the AC playa lakes and climatic analyses of extensive data sets, have enabled us to develop a conceptual hydrological model of an AC playa lake (see Benavente et al. 2005a, b; Moral et al. 2006, 2008a, b; Rodríguez-Rodríguez 2007; Rodríguez-Rodríguez and Benavente 2008; Rodríguez-Rodríguez et al. 2006, 2008a, b).

This paper draws on previous experience and knowledge, an updated data set of water-level measurements, recent bathymetry of Medina lake and climate data (ET0-Penman and rainfall at a daily scale) from March 2002 to December 2008 to develop a numerical hydrological model that allows estimation of the expected future water-level evolution in the Medina playa lake in response to land-use changes (e.g. irrigation of olive trees). In addition, the model is used to predict hydrological functioning of the playa lake (i.e. expected AFS and hydroperiod) in the absence of human modification (overflow and drainage).

Methods

Conceptual model: the water budget

Water-level changes (dh) in any water body are governed by the balance between inputs and outputs (Hayashi and Van der Kamp 2005):

$$Q_{\text{in}} - Q_{\text{out}} = A \times (dh/dt)$$

where $Q_{\text{in/out}}$ is the sum of all the water inputs/outputs as a flow (L3·T-1), A is the surface area of the lake (L2) and (dh/dt) is the water-level change of the lake (L·T-1).

Applying such a water balance requires prior development of a realistic hydrological model to estimate both the water inputs and outputs with respect to the groundwater–surface water interactions. Based on a robust hydrological model, good estimations of $Q_{in/out}$ and the hypsometric curve (bathymetry) of the playa lake, it is possible to obtain the theoretical dh/dt by applying the water-budget model. Using the observed water-level changes in the playa lake for the same period, it is possible to calibrate and validate the model. Once validated, different scenarios may be simulated to predict the evolution of the water level if, for example, some of the inflows are removed from the system.

Based on a conceptual model that assumes a groundwater-discharge type playa lake with coincident surface and hydrogeological WSs (Moral et al. 2008b), Q_{in} is estimated by summing the surface and groundwater runoff from the WS and the direct precipitation over the lake surface. The latter value is easy to determine if the precipitation and the flooded area are known, which can be calculated by measuring the water level. Runoff from the WS, however, is not as straightforward to measure.

Runoff from the watershed: the soil water budget

A soil water budget is a simple method normally used to predict soil water storage, actual evapotranspiration (AET) and runoff as defined by Jensen et al. (1990). Runoff is synonymous to the surplus of the soil water budget. Thus, runoff is the fraction of precipitation that exceeds potential evapotranspiration (PET), calculated by the Thornthwaite and Mather (1955) method and is not stored whitin the soil. The soil water budget model does not distinguish between surface runoff and subsurface runoff, so surplus includes both these components. The estimation of runoff is important because it is the main water input—ground water and surface water flow—to the lake. In this work we calculated the runoff from the WS by assuming that the water input (in m^3) equals the surplus of the soil water budget in the WS, in mm ($m{\cdot}10^{-3}$), at a monthly scale. This can be formulated as follows:

Runoff from the soil water budget ($m{\cdot}10^{-3}$) $\times$ WS area (m^2) = Runoff from the WS (m^3) to the playa lake.

This assumption has major hydrogeological implications, as we do not consider regional ground water inflow in the equation. In the study area, hydraulic conductivity of the materials is usually low. In this situation, low-permeability aquifers with a topography-controlled water table are expected to be found, instead of highly permeable aquifers with a recharge-controlled water table (Haitjema and Mitchell-Bruker 2005). Piezometric measurements throughout the study area reinforce this hypothesis, as the water table is a subdued replica of the topography of the WS (Benavente et al. 2005a).

One widespread approach for estimating evaporation is to get a PET from weather variables, such as air temperature and the number of hours of sunlight, and then to estimate AET as a fraction of PET, that depends on soil dryness. PET then represents an upper limit to the evapotranspiration rate. Knowing the precipitation inputs and the maximum storability of water in the soil (water-holding capacity, WHC) allows estimation of AET from the reference PET. Soil WHC can be defined as the difference between the water content at field capacity and the wilting point. Field capacity moisture is the amount of soil moisture or water content held in soil after excess water has drained away, which usually takes place within 2–3 days after rain or irrigation. A physical definition of field capacity is the bulk water content retained in soil at −33 J/kg of hydraulic head or suction pressure: θ33 kPa. The wilting point moisture is the minimal point of soil moisture the plant requires not to wilt or the bulk water content retained in soil at −1500 J/kg of hydraulic head or suction pressure: θ−1500 kPa (Vanderlinden et al. 2005). The WHC of the soil at Medina lake was estimated from previous analyses (Moral et al. 2008a) in which a lake water balance was calibrated on a monthly basis for two systems very similar to Medina in the AC (Jarales playa lake and Zoñar lake, see Fig. 1) to obtain a representative value for WHC in this type of soil. The calibrated WHC obtained was 187 and 191 mm (l/m^2), respectively. Since Medina's WS has similar soil characteristics to the other two watersheds (LuvisolsWRB), according to the Soil Map of Andalusia 1:400,000 (Monge et al. 2008), we used a value of 191 mm for the WHC. Furthermore, this value of 191 mm is very similar to that given for the area on the only WHC map published in the AC (Vanderlinden et al. 2005). This map was based on the 1:400,000 Soil Map of Andalusia and 521 soil profiles, including both analytical and morphological data, using pedotransfer functions (PTFs) and geostatistics. The PTF estimates for the WHC ranged from near 0 to 235 mm, with an average value of 110 mm. This reinforces our assumption that WHC = 191 mm in the calculations of the soil water budget to estimate runoff in the WS. No other water inputs have been considered in the water balance calculations, apart from direct precipitation onto the lake's surface.

Evapotranspiration and evaporation: Thornthwaite vs. Penman

Two of the most widely accepted methods to estimate PET are the Thornthwaite method (Thornthwaite and Mather 1955) and the Penman–Monteith (PM) equation, used by the American Society of Civil Engineers as a standard reference for PET (Drexler et al. 2004). In the PM equation, the daily mean temperature, wind speed, relative humidity, and solar radiation are used to predict the net evapotranspiration. As several authors (Chen et al. 2005; Penman 1948) have stated that PETPENMAN from bare soil is similar to evaporation from the surface of open water, we used PETPENMAN data from the Basurta–Jerez automated weather station (see Fig. 1, WS) to obtain evaporation flows from the lake's surface (open water) as explained below. We estimated the PET in the WS to calculate the runoff from the WA using the Thornthwaite method (Thornthwaite and Mather 1955). We used the PETThornthwaite to obtain reliable results in the soil water budget in Medina so as to be consistent with previous studies that also used PETThornthwaite. Nevertheless, there are potential problems of underestimation of PET using the Thornthwaite method. This method was developed for use in specific studies and is most appropriately applied in climates similar to that where it was developed. Large errors are possible when this method is extrapolated to other climatic areas without recalibrating the constants involved in the formulae. We chose this method only for an estimation of runoff, and not for an estimation of PET or AET.

Q_{out} occurs mainly because of evapotranspiration processes on the playa lake's surface. The ET flows have been estimated from daily PETPENMAN data and summed per month as a function of the lake's surface. In addition, Medina lake has an overflow channel on its eastern shore (Buitran creek, Fig. 1). Whenever the water level is higher than 3.5 m, the overflow is active and water flows out into the River Guadalete. Recent measurements have shown that the overflow can reach 0.084 m^3/s after 3 days of rain (as occurred during February 2009). More detailed information about the water budget can be found in Moral et al. (2009).

Hydrological indices

In any given playa lake, the average area of the flooded surface (AFS) is determined by two main factors: the morphometry of the lake basin and the average annual amount of water input. The amount of water input is controlled primarily by the size of the contributing areas (i.e. catchments) and the amount of runoff that is generated per unit area depending on climate conditions, vegetation cover and soil properties. The Medina playa lake's AFS and WS were determined by analysing the Digital Terrain Model of Andalusia with a horizontal resolution of 10 m and an accuracy of elevation of 1 m (A.M.E. 2005) and detailed field surveys. To define the AFS, we also used the position of the vegetation fringe as an indicator of the average position of the shore. The maximum depth of the playa lake was determined with a bathymetric map of Medina and by direct measurements within the lake. The bathymetry was studied during a hydrographic survey in April 2007 by Caribersa S.L. (unpublished), using Differential GPS. The bathymetry map obtained was used to produce the hypsometric curve. We calculated a hydrological function index (HFI) by combining the morphometry of the lake (WS and AFS) and the previously estimated runoff (Rodríguez-Rodríguez et al. 2010):

$$\mathrm{HFI} = (\mathrm{WS}/\mathrm{AFS}) \cdot (\mathrm{Runoff})\,/1{,}000.$$

This index allowed estimation of how the current playa lake differs from the established conceptual model for current conditions. The function of 1,000 in the equation is to obtain an index that ranges between 0.1 and 10, instead of ranging from 100 to 10,000.The physical meaning of this index relates to the theoretical AFS that a playa lake should reach as a function of the size of its WS and the available natural water resources in the area, or runoff. Runoff is a fraction of the mean precipitation in the region and depends on the soil type in the WS. This index is based on a simple working hypothesis: the surface and hydrogeological basins of a playa lake in the AC are coincident, i.e., the playa lake is the main discharge zone of a local system of groundwater flow, as defined by Tóth (1963). Another hydrological index is the temporality index (TI). We estimated this index by a simple formula that is a function of both the maximum depth of the lake and the average evapotranspiration: TI = Max. depth (m) / (11·ET(m)) × 100.

In the temporality index:

1. Maximum depth represents the point of maximum depth of the lake (i.e., the point of lowest altitude in the lake's basin). If the lake has an overflow, as is the case of Medina, the maximum depth is easy to define (3.5 m). If that is not the case, we have to assume that the maximum depth in a given lake is the highest depth that has been measured in the lake after a wet period.
2. The function of 11 and 100 in the TI is to normalize the results and to get an expression as a percentage. A lake with a depth of 11 m would not desiccate in summer, even with no rainfall at all, as the average potential evaporation in southern Spain is c. 1,100 mm (TI = 100%). Shallower water bodies can, thus, desiccate in summer.
3. ET is expressed in mm/year, and is an average value for a long period of measurement (at least 25 years). The TI represents the percentage of time during which a playa lake is flooded (considering an average hydrological year).

Thus, this index allows a comparison between different playa lakes of the same typology and indicates the probability of encountering summer inundation of the lake in any given year.

Future scenarios

The cover for different land uses in the Medina WS was calculated for 1956, 1999 and 2003 in ArcView GIS 3.2; the calculation was based on existing vegetation and land-use maps for the whole of Andalusia (prepared at a scale of 1:25.000 by the Red de Información Ambiental de Andalucía de la Consejería de Medio Ambiente).

We estimated the water budget for the period from March 2002 to February 2009 (i.e., estimation of change in water storage) we analyzed the regression line comparing Actual Water Level (measured) and Estimated Water Level and find that the correlation was satisfactory (see results). Two future scenarios were simulated as a next step. The first one considered progressive groundwater withdrawal due to the establishment of olive-tree irrigation within the WS. Currently, the WS of Medina lake is dedicated mainly to wheat and sunflower cultivation (see "Results" section). Given the progressive implementation of drip irrigation for olive trees in Andalusia, it is easy to imagine a land-use change of this type in the near future. This situation would involve drilling irrigation wells within the WS to extract groundwater, since there is no surface water available in the area: the surface waters of the nearby Guadalete River are already used for irrigation and urban supply; all the water rights for irrigation were given long ago.

Shallow aquifers or aquitards normally store groundwater at depths between 5–20 m in the AC, although the position of the groundwater level is very heterogeneous and depends on several factors such as the lithology (type of aquifer), topography and the existence of olistolites. As stated above, in areas where low permeable materials (e.g. clays or marls) outcrop abundantly, topography-controlled water tables are likely to be present (see Fig. 6).

Water requirements for olive-tree irrigation are almost 2,000 m^3/ha/year (i.e., a groundwater withdrawal of 332 m^3/ha/month from May to October). Whenever groundwater is withdrawn inside the watershed, there is a reduction of the total water inputs (baseflow in streams and subsurface runoff). The evolution of the water level in the playa lake would thus be affected, because the lake is the main zone of discharge of this local system of groundwater flow. The expected water-level evolution in Medina lake was simulated by assuming a 100 ha/year increment in the irrigation surface from May 2002 to February 2009.

The second simulation aimed to estimate the WL evolution and the resulting AFS if the playa lake's artificial drainage was deactivated. The simulation was run by simply omitting the 3.5-m overflow in the playa lake and extrapolating the hypsometric curve to 4.1 m, which was the original maximum water depth of Medina lake. Subsequently, a new AFS was estimated using the Digital Terrain Model (A.M.E. 2005).

Results

A summary of the main climate data statistics used in this study is given in Table 1. The air temperature ranged from 8.2 to 26.7°C. The frequency distribution of these data showed both a low asymmetry (0.1) and a low standard deviation/average (0.3). Mean annual precipitation during the study period (1/1/2002 to 1/1/2009) was 613 ± 187 mm/year, with an average and median value of 51.1 ± 55.2 mm/month and 41.0 ± 55.2 mm/month, respectively (Table 1). The runoff—henceforth "effective rainfall"—was estimated from the surplus of the soil water budget method, which assumes that this is the fraction of precipitation not evapotranspired. The effective rainfall consists of surface and groundwater flow. In reality, these water inputs are diffuse and therefore difficult to measure directly; thus, water inputs from the watershed are frequently estimated as in this study (Su et al. 2000).

The effective rainfall from 2002 to 2009 was 171 mm, with an average value of 8.6 mm/month (i.e. 16.8% of the total precipitation). Only during 14 of the 84 months considered was the effective rainfall greater than zero. Kurtosis or "peakness" of the frequency distribution is very high (19.2), as most of the variance is due to extreme, but infrequent, rainfall events generating runoff. The Penman–Monteith ET from the playa lake's surface (evaporation) was more intense in July (more than 200 mm/month) and declined abruptly in winter (e.g., 35.8 mm/month in December 2003). The mean value for the entire study period was 110.8 mm/month. Thornthwaite's potential and actual ET results showed that these values ranged from 14.2 to 161.7 mm/month and from 0 mm/month to 145.2 mm/month, respectively.

Table 1 Statistical results from the meteorological data and the soil water budget data (monthly values)

	Temperature (°C)	Rainfall (mm)	Effective rainf. (mm)	PETPenman (mm)	PETThornthwaite (mm)	AETThornthwaite (mm)
No used values	84	84	84	84	84	84
No ignored values	0	0	0	0	0	0
Minimum	8.2	0.0	0.0	35.8	14.2	0.0
Median	16.9	41.0	0.0	101.5	64.8	32.4
Maximum	26.7	283.8	171.8	213.3	161.7	145.2
Range	18.5	283.8	171.8	177.5	147.5	145.2
Average	17.4	51.1	8.6	110.8	73.3	40.4
Kurtosis or "peakedness"	−1.4	3.0	19.2	−1.4	−1.2	0.5
Asymmetry	0.1	1.5	4.0	0.2	0.4	0.9
Variation coefficient (St.deviation/aver.)	0.3	1.1	3.0	0.5	0.6	0.8
Variance	29.2	3,052.3	678.3	3,271.4	2,156.6	1,098.3
Standard deviation	5.4	55.2	26.0	57.2	46.4	33.1

Effective Rainf surplus from the soil water balance in Medina Watershed for a WHC of 191 mm, *PETPenman* potential evapotranspiration estimated by the Penman–Monteith method *PETThornthwaite* potential evapotranspiration estimated by the Thornthwaite method, *AETThornthwaite* actual evapotranspiration for a WHC of 191 mm

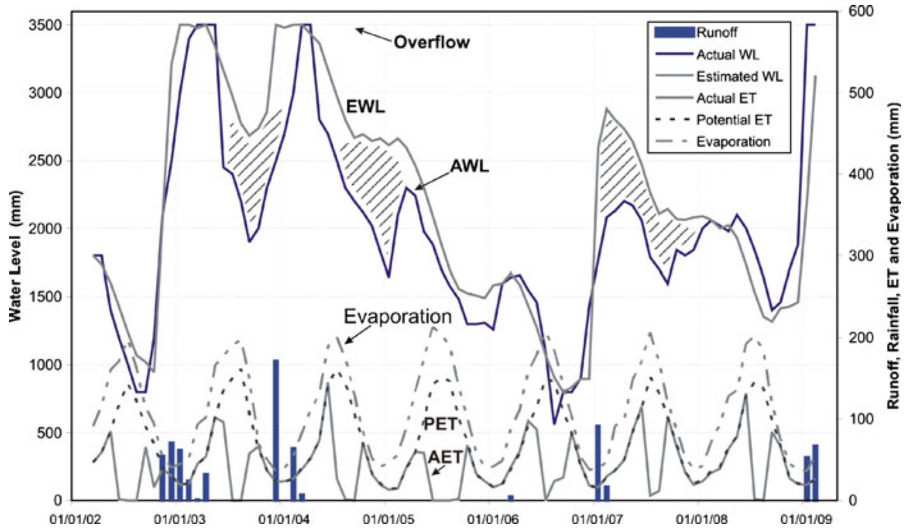

Fig. 2 Time series of the main climatic variables (evaporation, ET and runoff from the soil water budget) and the evolution of the measured water level vs. the predicted water level in Medina playa lake during the study period. *Vertical bars* represent monthly runoff values

Figure 2 shows the time series for the main climatic variables (evaporation, ET and runoff) together with the evolution of the actual (measured) water level vs. the predicted water level. The potential ET exhibits a cyclical behaviour, whereas the actual ET (both parameters are estimated by the Thornthwaite method) falls to zero whenever there is a lack of precipitation and when the soil water is depleted. The runoff, which was received from Medina lake's two main inflowing streams and by diffuse flow as well as subsurface flow, is responsible for the major rises in water level. Whenever, there are two consecutive vernal months (November to February) with a runoff higher than 50 mm/month, there is a rapid water-level rise and the playa lake overflows. During the study period, this occurred three times, in the winters of 2003, 2004 and 2009 (see Fig. 2).

With respect to water-level (WL) evolution, the estimated WL and the measured WL show a reasonable correlation (Fig. 3). The estimated WL (i.e., based on the conceptual model under current natural conditions) was almost systematically higher than the measured WL, with an average difference of 22 cm during the study period. The variation in observed water levels matched our estimates well during dry periods. However, our estimates were not nearly as accurate during rainy

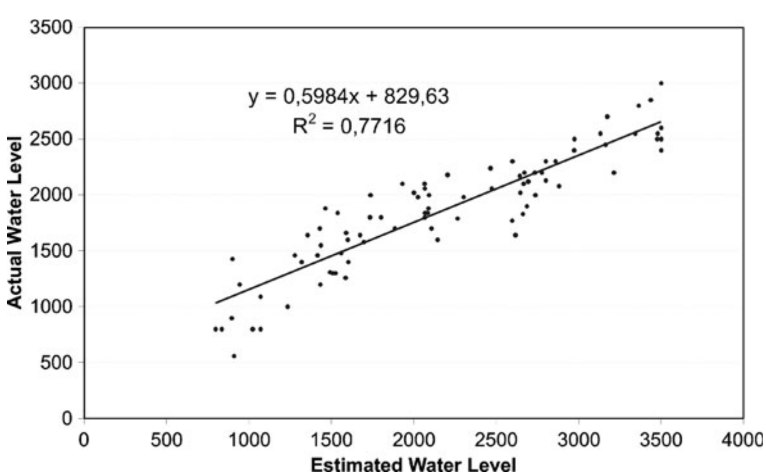

Fig. 3 Correlation between predicted vs. measured water level in Medina lake from 2002 to 2009

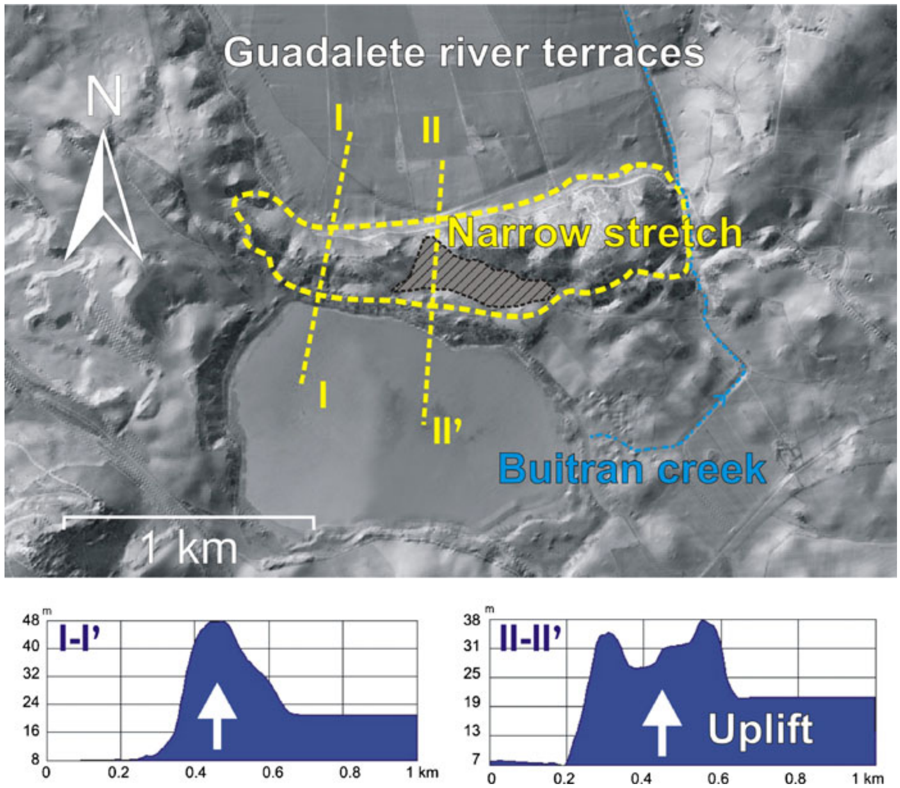

Fig. 4 Sketch of the diapiric uplift and subsequent doline formation in the northern sector of the watershed of Medina playa lake. The *hatched area* represents gypsum-rich Triassic material

periods and in winter (Fig. 3). For example, during the period from May to September 2006, the R2 between estimated and observed water levels was 0.93. In contrast, between November and March 2007 the R2 was 0.82.

This can be explained by several factors.

1. Most importantly, during the summers of rainy years when the streams are fed by base flow, farmers pump some water directly from the streambed (author's own observations). This water withdrawal is not considered in our modelling. In contrast, during the summer months of dry years, the base flow equals zero; thus, there is no possible surface-water withdrawal.
2. It has previously been suggested (Benavente et al. 2005a) that groundwater recharge may be taking place from the Medina lake to the alluvial materials of the Guadalete River, in a northerly direction. This assumption is supported by geological features observed in the northern sector of the basin, i.e. a narrow band of Triassic materials rich in gypsum and slightly epi-karstified. Some small dolines are formed in that sector (Fig. 4). Nevertheless, there is no hydrogeological demonstration of such a process of groundwater recharge, so it is only a hypothesis.
3. A subestimation of the actual ET could account for the apparent overestimation of the water inputs into the playa lake, although this factor is probably not important.

Morphometry and hydrological indexes

In Table 2, the morpho-climatic parameters obtained for Medina playa lake are compared with results for the 48 main playa lakes of Andalusia (Rodríguez-Rodríguez and Benavente 2008). Medina is one of the biggest remaining continental water bodies in the region, although its median salinity, maximum depth and temporality index are very similar to those of the

Table 2 Comparison between the morpho-climatic parameters in the 48 main playa lakes of Andalusia and Medina playa lake

	AFS (ha)	WS (ha)	Effective Rainfall (mm)	Median salinity (g/l)	Maximun Depth (m)	Slope of the watershed (%)	Evaporation $ET_{0-\mathrm{Penman}}$ (mm)	HFI (mm/1000)	Temporality index (%)
No used values	48	48	48	48	48	48	48	48	48
Minimum	1.6	30.2	50.5	0.1	0.1	1.7	1,150.0	0.3	0.6
Median	8.1	112.9	102.0	2.9	1.9	6.0	1,579.7	1.6	12.7
Maximum	1,271.6	14,299.1	334.4	41.2	16.0	17.4	1,694.2	6.3	90.7
Average	42.8	543.4	126.0	6.8	2.5	6.7	1,526.1	1.9	16.8
Variation coefficient (St.deviation/aver.)	4.3	3.8	0.6	1.3	1.1	0.5	0.1	0.6	1.2
Medina playa lake	120.0	1,748.3	142.0	2.9	3.5	6.1	1,490.6	2.1	21.2

The slope of the watershed was calculated by means of the Digital Terrain Model of Andalusia (A.M.E. 2005)

average lowland playa lake. The HFI is 2.1 and the catchment-to-area ratio is 14.6. The HFI is considerably higher than the average for the region (1.6), owing to water overflow. The expected average flooded surface for Medina playa lake in the absence of overflow is higher than 120 ha. The expected flooded surface, or "equilibrium" flooded surface (EFS), can be calculated from the following expression: EFS = (WS·Eff. Rainfall/1,000). This expression is derived from the assumption that HFI = 1 in the equation, so AFS can be recalculated, giving a value of 248 ha for Medina playa lake.

Future scenarios

Considerable land-use change occurred within the watershed between 1956 and 2003, especially with regard to the transformation of natural grassland and shrubland into cereal agriculture, which increased from 47% of the total watershed in 1956 to 83% in 2003 (see Table 3). Not surprisingly, there were relatively few changes between 1999 and 2003, although by 2003 a neighbouring quarry had expanded into the watershed and the construction of a new motorway between Jerez and Algeciras (A-381) had begun. The A-381 was completed by 2006 and bisected the watershed.

Once calibrated, the water budget or water-level model can be applied to different scenarios. New inundation conditions or different water budgets can be simulated. Two scenarios have been considered. Scenario A represents equilibrium in the absence of overflow. Assuming an AFS of 248 ha (EFS), the water-level evolution after refilling of the overflow of the lake was simulated (Fig. 5). In this scenario, the period of water level rise is increased and the minimum WL is 0.8 m higher. The maximum simulated WL slightly exceeds 4.0 m.

Scenario B considers conditions of increasing irrigation and groundwater withdrawal within the Medina WS of 100 ha/year and 2,000 m^3/ha/year, respectively (Fig. 5). In the Andalusian lowlands, there is an increasing demand for and interest in drip irrigation of olive trees because, although the tolerance of this species to drought and soil salinity is high, drip irrigation produces a substantial increase in yield. Many hectares of cultivated

Table 3 Surface of Medina playa lake (m^2) devoted to different land uses during years 1956, 1999 and 2007

	1956 (m^2)	1999 (m^2)	2007 (m^2)
Endorreic playa lake	1,194,500 (6.61%)	1,210,500 (6.7%)	1,210,500 (6.70%)
Artificial ponds	26,100 (0.14%)	57,500 (0.32%)	57,500 (0.32%)
Forestry plantations	208,400 (1.15%)	235,200 (1.30%)	220,700 (1.22%)
Grasslands	5,839,300 (32.32%)	454,600 (2.52%)	332,000 (1.84%)
Non-irrigated cereals	8,433,200 (46.68%)	14,914,500 (82.55%)	14,507,600 (80.30%)
Olive groves	44,300 (0.25%)	44,300 (0.25%)	159,600 (0.88%)
Vineyards	–	172,000 (0.95%)	172,000 (0.95%)
Other crops	102,600 (0.57%)	116,300 (0.64%)	335,200 (1.86%)
Riparian habitats	91,600 (0.51%)	122,100 (0.68%)	122,100 (0.68%)
Shrubland	2,035,400 (11.27%)	580,000 (3.21%)	580,000 (3.21%)
Rock formations	21,900 (0.12%)	12,400 (0.07%)	12,400 (0.07%)
Quarry	–	–	9,200 (0.05%)
Roads	–	–	200,500 (1.11%)
Urban areas	69,600 (0.39%)	147,300 (0.82%)	147,300 (0.82%)

wheat fields are progressively being transformed into olive-tree fields in southern Spain, even in shallow and low-quality soils. In this scenario, the hydroperiod is drastically reduced and the lake changes from being dry 0% of the time (actual conditions) to 15.5%. In addition, the predicted water level is <0.5 m for 40% of the time (Fig. 5).

Morphology and the possible origin and formation of the playa lake

In the area surrounding the playa lake, the relief is characterised by a contrast between the northern flat, low terraces of the Guadalete River (6 m ASL) and the southern hilly lands of the watershed, where the altitude is progressively higher towards the south (100 m ASL). The area with the greatest slope (>20%) and the most abrupt relief is constituted by a narrow stretch of material situated between the lake and the Guadalete River terraces (Fig. 4). The alignment of the materials is crossed by the Buitran creek, which forms a valley (Fig. 1). The outcropping materials are mainly Triassic-aged clays and marls with an abundance of gypsum. These plastic rocks are topped by alluvial materials: Quaternary terraces of the Guadalete River at an altitude of 50 m ASL. The relative position of these quaternary terraces, more than 40 m above the recent (Holocene) Guadalete River terraces reveals the

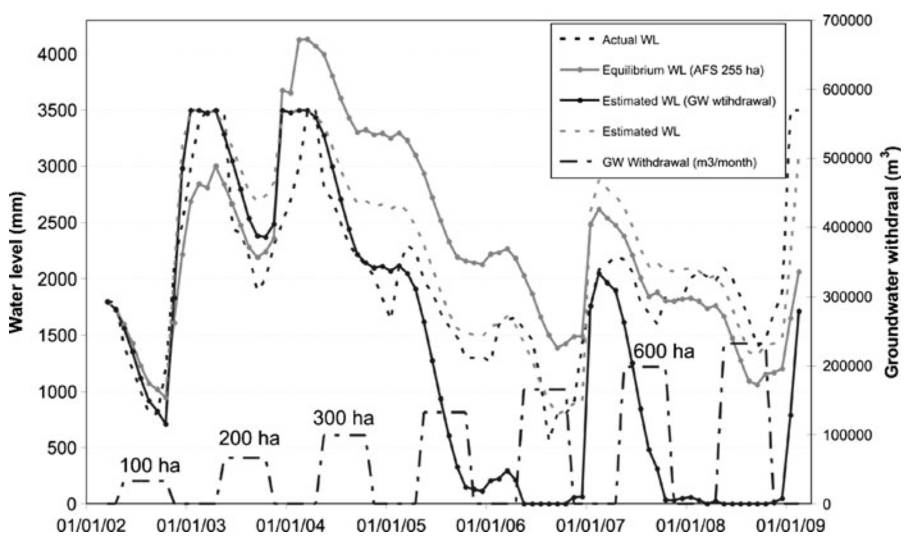

Fig. 5 Observed water level (WL), WL predicted by our model, and simulations of WL under future scenarios of groundwater (GW) extraction or removal of the overflow. Figures in ha refer to the surface area of irrigated olive groves in that year

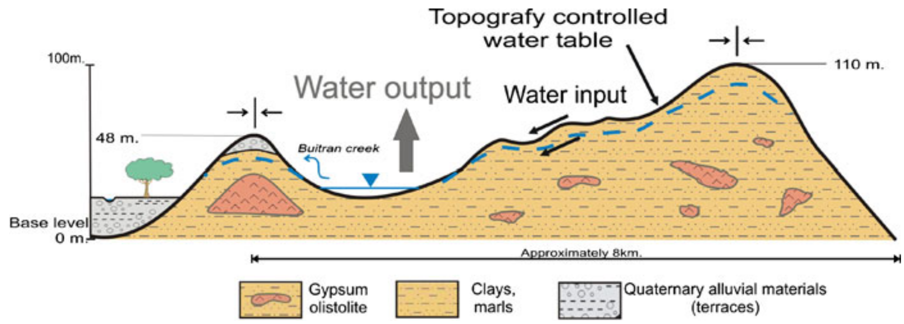

Fig. 6 Conceptual hydrogeological function model in Medina playa lake

process of vertical tectonic movements related to diapiric phenomena during the quaternary. The diapirism is favoured by the high plasticity and low density of the Triassic gypsum and also by the transformation of anhydrite into gyspsum (Moral et al. 2006).

The vertical movement is probably responsible for the formation of the closed basin that formed Medina playa lake. Another morphological aspect of these materials is evidenced by the formation of an epikarst of gypsum materials at the top of the narrow band, which is not topped by alluvium (Fig. 4). Whenever the gypsum-rich Triassic materials outcrop, they appear in large, pure regions as depicted in Fig. 4, in which karstiphication phenomena are observed. Thus, in the northern border of the Medina playa lake an epikarst is observed, with several dolines and numerous sinkholes.

Discussion and conclusions

In many situations, lake-management schemes that do not take into account the detailed hydrogeological setting have had detrimentally effects (Born et al. 1979). The hydrological regime must be adequately assessed to facilitate management of playa lakes. In the AC and elsewhere in the Mediterranean region, groundwater–surface water interactions have often received limited attention because hydrogeological data are scarce and difficult to collect, and adequately measuring different components of the water cycle is a complex process. In the absence of detailed data, it is necessary to use simple conceptual schemes to estimate the hydrological balance for a simple water body. In the case of the Medina playa lake, this hydrological balance has been used to develop a model that predicted water-level evolution in a satisfactory way for a 6-year period at a monthly scale, although some discrepancies were found.

In the WS of Medina lake (1,748 ha), the primary mechanisms of water loss are evapotranspiration and evaporation; in addition, large proportions of the evaporated water may come from the shallow aquifer. Similar findings have been reported previously in other playa lakes (Cooper et al. 2006; Moral et al. 2008a, b; Rodríguez-Rodríguez 2007; Rodríguez-Rodríguez et al. 2008a; Sanderson et al. 2008; Yechieli and Wood 2002). Due to overflow during high-water periods, some water outputs are evacuated through Buitran creek. Also, it is possible that the karstified materials of the northern part of the watershed, including the Triassic gypsum and marls (20 m ASL) and the Guadalete River terraces (5 m ASL), could be hydraulically connected. Our results should be taken into account in order to correctly manage this type of ecosystem from a basin perspective, as outlined in the Water Framework Directive.

The conceptual hydrogeological model developed in this study is summarised in Fig. 6. It has been possible to simulate two different situations regarding water management. Firstly, a scenario in which the overflow is filled up and the original basin of the playa lake is restored. Secondly, a progressive land-use change (irrigation of olive trees) was simulated. Both simulations showed that this kind of methodology is a powerful tool to assess water management in playa lakes. However, our model currently has a degree of uncertainty. Therefore, the results must be treated with caution, and further research is required to improve the model (e.g. by investigating possible connectivity between Medina lake and the Guadalete River terraces).

Finally, this study has shown the importance of protecting playa lake watersheds against changes caused by ditching, draining or groundwater exploitation. These types of activities can trigger the modification of the hydrological regimes over short or medium time scales because playa lake basins always adjust to average water inputs from the watersheds.

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