Water balance in the playa-lakes of an arid environment, Monegros, NE Spain

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Abstract The playa-lakes of the Monegros desert in north-east Spain are saline wetlands in an arid environment, a rare phenomenon in Europe. These extremely valuable habitats are threatened by changes associated with agricultural expansion and incorporation of new irrigated areas. An understanding of the present hydrologic regime will enable changes to be identified, particularly those brought about by flooding and pollution caused by irrigation surplus. This study sets out to show the results of applying a daily water balance in three selected playa-lakes. The balance was in two parts and consisted of: (1) the average balance for all the endorheic basin using the BALAN_11 program, and (2) the water balance in some playa-lakes, applying discharge flows obtained from the previous balance. The resulting volumes of water were converted to water depths and contrasted with reference volumes taken from field and Landsat images. The model was calibrated by applying various hypotheses of function which enabled the results to be adjusted. The proposed balance is an acceptable reproduction of field water measurements during this period, and underlines the consistency of the conceptual model. The methodology used is appropriate for understanding the playa-lakes function and for monitoring them for conservation purposes.

Résumé Les playa-lakes (saladas) du désert de Monegros, situé au nord-est de l'Espagne, sont des zones humides salines en environnement aride, phénomène rare en Europe.

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Ces habitats inestimables sont menacés par les changements associés à l'expansion agricole et à la création de nouvelles zones irriguées. Une meilleure compréhension du régime hydrologique actuel permettra d'identifier ces changements, notamment ceux générés par les inondations et la pollution causés par le surplus d'irrigation. La présente étude expose les résultats de l'application de bilans en eau quotidiens sur trois playa-lakes sélectionnés. Les bilans étaient scindés en deux parties : (1) le bilan moyen sur l'ensemble du bassin endoréique, utilisant le programme BALAN_11, et (2) le bilan en eau dans quelques lacs asséchés, appliquant les débits de sortie obtenus par le bilan précédent. Les volumes d'eau obtenus ont été convertis en hauteurs d'eau, et mis en contraste avec les volumes de référence issus des observations sur site et des images Landsat. Plusieurs hypothèses ont été mises en œuvre pour calibrer le modèle, en ajustant au mieux les résultats. Le bilan proposé constitue une image satisfaisante des mesures de terrain sur la période considérée, et souligne la cohérence du modèle conceptuel. La méthodologie mise en œuvre est adéquate pour comprendre la fonction des playa-lakes, et pour les surveiller en vue de leur préservation.

Resumen Los playa-lakes (saladas) del desierto Monegros en el nororiente de España son humedales salinos en un ambiente árido, un fenómeno raro en Europa. Estos hábitats extremadamente valiosos están amenazados por cambios asociados con expansión agrícola e incorporación de nuevas áreas de riego. Un entendimiento del ámbito hidrológico actual permitirá identificar cambios, especialmente los cambios ocasionados por inundación y contaminación ocasionados por exceso de riego. Este estudio se propone mostrar los resultados de aplicar un balance hídrico diario en tres playa-lakes seleccionados. El balance se hizo en dos partes y consistió de: (1) el balance promedio para todas las cuencas endorreicas usando el programa BALAN_11, y (2) el balance hídrico en algunos lagos de playa, aplicando flujos de descarga obtenidos en base al balance anterior. Los volúmenes resultantes de agua se convirtieron a profundidades de agua y se contrastaron con volúmenes de referencia tomados del campo y de imágenes Landsat. El modelo se calibró mediante la aplicación de varias hipótesis de función lo cual permitió que se ajustaran los resultados. El balance propuesto es una reproducción aceptable de mediciones de agua en el campo durante este periodo y remarca la consistencia del modelo conceptual.

La metodología utilizada es apropiada para el entendimiento de la función de los playa-lakes y para su seguimiento con propósitos de conservación.

Introduction

Located in the centre of the Ebro Basin in north-east Spain, scattered playa-lakes and other closed saline depressions stand out as a group of isolated saline wetlands in an agricultural area of considerable scenic and scientific value. They support endemisms and other organisms of high biogeographical interest. Comparable in appearance to the playa-lakes and sebkhas (saline flat areas) of North Africa, these saline wetlands form a functional unit with a common geomorphological and hydrogeological evolution, and a geological formation that results from sedimentary processes in arid environments, common to all the Ebro Basin.

In Europe, wetlands in arid zones are rare. These playa-lakes differ from other Mediterranean wetlands in that they are ephemeral and frequently alternate between filling up and emptying phases. They are discharge playa-lakes (Yechieli and Wood 2002) associated with long-standing aquifers which present a high degree of salinity due to the chemical and lithological characteristics of the sediments.

Environmental protection policies of the European Union hindered the establishment of irrigation projects in Monegros for several years and contributed to the exclusion of some areas from irrigation. However, under the Monegros Plan II (Comisión Técnica Mixta 2002), these saline wetlands are now being affected by the incorporation of the new irrigated areas which will include the area hosting playa-lakes. This desert and arheic area will receive water diverted from Pyrenean rivers. Meanwhile, hydrological studies (Berga 1993; Samper and García-Vera 1998) assert that irrigation will modify the hydrologic balance and that new fresh and polluted water flows will discharge into the playa-lakes, resulting in the disappearance of valuable habitats.

It is necessary to understand how the hydrologic system functions in semi-arid areas and unaffected playa-lakes, especially with regard to groundwater–surface-water interactions, for irrigation management and ecological purposes (Schot and Winter 2006). The application of water balances in wetlands is essential to be able to describe their hydrologic functioning (Jacobson and Jankovski 1989; Malek et al. 1990; Goes 1999; Sophocleous 2005), understand the evolution of surface water and the basic principles controlling the interaction of lakes and groundwater (Euliss et al. 2004; Winter et al. 2005), and plan ecological studies of wetlands (Conly and Van der Kamp 2001; Trick and Custodio 2004). Very few studies apply to water balances in work on isolated wetlands (Winter and LaBaugh 2003).

In the Ebro Basin, agricultural intensification is a threat to the isolated saline wetlands. For this reason, the Ebro Basin water authority (Confederación Hidrográfica del Ebro, or CHE) applied BALAN_11 in Gallocanta, a saline wetland of international importance. BALAN _11 proved to be an apt method to assess surface water and groundwater resources (San Román et al. 2005). In arid environments characterized by irregular rains, daily water balance is a more suitable measure than monthly water balances (Ruston and Ward 1979; Samper and García-Vera 1997) and has been successfully applied to the estimation of groundwater recharge in different hydrogeological environments (García-Vera and Arqued 2004; Samper et al. 1991; Samper et al. 1999; Samper et al. 2005).

The objective of the present study is to apply a daily water balance in three Monegros playa-lakes using a theoretical model consistent with what is known about the lakes from previous studies. This work allows for the improvement of the hydrological conceptual model for these wetlands by applying a water balance which integrates the available meteorological, agronomical and geological information. In contrast to the flow model applied by García-Vera (1996) in a stationary regime, here, a detailed balance in a transitory regime was performed, i.e. taking into account the temporal evolution of three playa-lakes and estimates for an extended period. The usefulness of this balance lies in the hydrological and environmental interest of these wetlands, and especially in the need to foresee irrigation's hydrological impact within the framework of the protected habitats management.

Geology

The Monegros playa-lakes are locally called *saladas*, and form part of an endorheic complex with dozens of scattered saline depressions (Castañeda and Herrero 2008), formed on a structural platform of some 300 km^2, at a height of more than 100 m above the Ebro River (Fig. 1). The sediments of the platform, from the Miocene age, are of palustrine and lacustrine origin and are formed from gypsums, limestones and lutites. These alternate vertically and horizontally, contributing to the hydrogeological complexity of the area.

The lithostratigraphic units mapped by Salvany et al. (1996) were grouped by García-Vera (1996) into three lacustrine units—Upper, Intermediate and Lower–cropping out to the northern, central, and southern sectors of the platform, respectively. Most of the saladas are found in the Intermediate Lacustrine Unit (Fig. 2). The largest, of playa-lake type, have silt and clay bottoms with intercalations of evaporites, reflecting climatic changes during the Holocene (Pueyo and Inglès 1987; Valero et al. 2001). Away from the Intermediate Unit, some saladas have been found along the narrow strip of red lutites which separates this unit from the upper one. These saladas are of varying sizes, from 1 to 200 ha; they have no surface water throughout the year and are mostly covered by halophytic
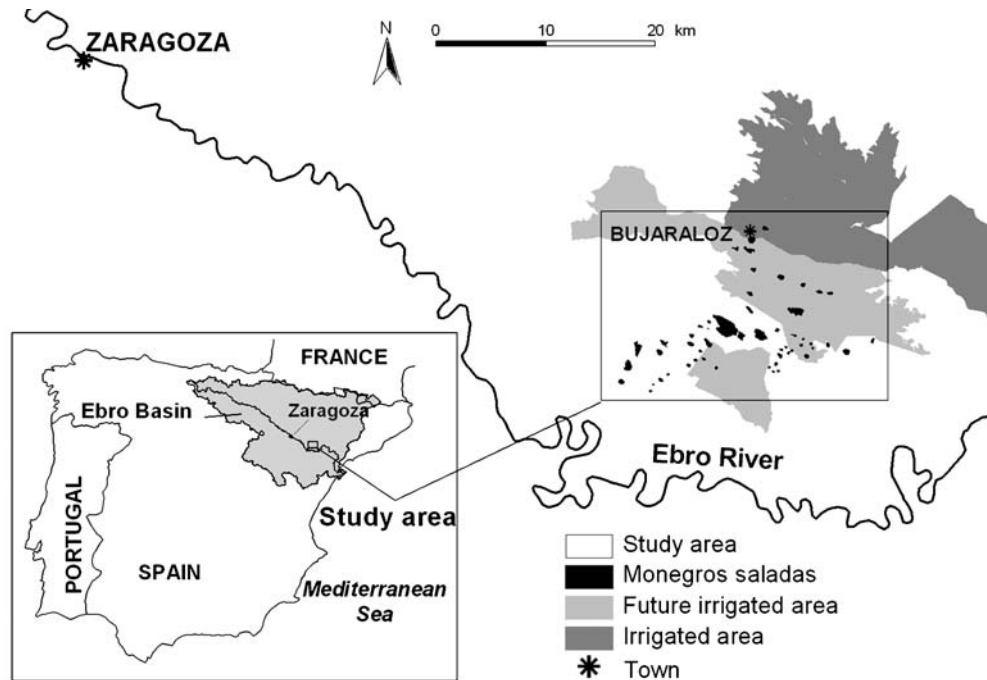
Fig. 1 Location of the Ebro Basin in Spain, the study area, and the Monegros playa-lakes (locally called saladas)

plants. Their bottoms are moist, indicating the proximity of the water table. In the Upper Unit, which is more lutitic and outcrops in the northern sector (Fig. 2), very few saladas have been detected; those that have been detected are just at the boundaries between two formations which differ because of the presence of gypsum. Of these, Salineta, the northernmost playa-lake stands out, with the greatest incidence of water and salts in all the playa-lakes studied.

Hydrogeology

Groundwater, with a salinity ranging from 10 to 100 g/L , has an average depth of 4.5 m and flows horizontally—perhaps along preferential pathways—discharging to the playa-lakes bottoms. These present temporary shallow brines, even in periods of hydric deficit, with a maximum water depth of 51 cm, as recorded for La Playa in December 1994 (Castañeda 2002). When they dry up,

Fig. 2 Study area with the saladas superimposed over the Landsat 5 TM image of the Bujaraloz-Sástago endorheic platform taken in August 2004. Also shown are the two main aquifers (Upper Unit and Intermediate Unit), as established by García-Vera (1996), and the location of the weather station "Bujaraloz-Petris". The playa-lakes studied from among those inventoried are identified. The irrigated fields appear in the northeastern part of the image
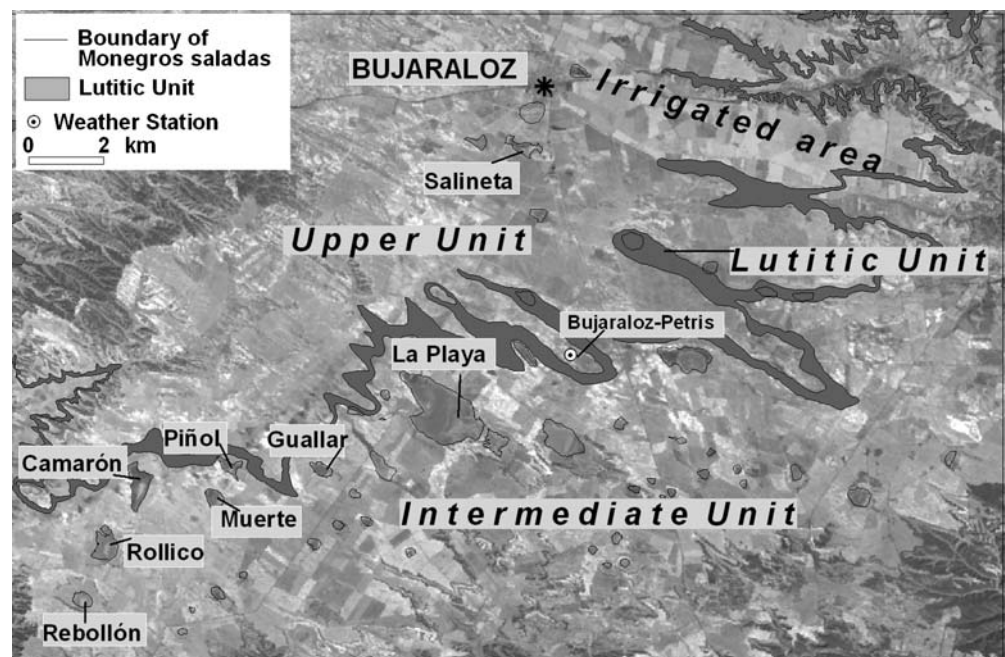
their bottoms remain moist, favouring the evaporation of groundwater near the land surface.

Water presence in the saladas rises after a rainfall event and lasts several days or weeks, depending on the evaporation. The role played by aquifers in the surface-water occurrence of such arid wetlands was confirmed in Castañeda and Herrero (2005) in several playa-lakes by studying the relationship between their water presence obtained from ground and satellite data and the previous accumulated rainfall (Fig. 3). These authors found the best relationship for the 180-day accumulated rainfall period previous to the date of the water measurements taken in the playa-lakes. In the same study, a close relationship is demonstrated between the inundation patterns of these wetlands and their location on hydrogeological units mentioned in the previous section.

The origin and evolution of the playa-lakes was initially related to a theoretical hydrological model of a regional nature (Sánchez et al. 1989). Later, their hydrologic function was studied using data collected in the field, which enables inflows and outflows of water to be quantified. Berga (1993) devised a hydrological classification and applied water balances to the principal playa-lakes in order to estimate the contribution made by the aquifer. She defined a hydrological function model in a multi-layered system, conditioned by the lithological heterogeneity of the area. She simulated various irrigation scenarios and estimated an increase in flooded areas of more than 100% in 21% of the saladas studied.

García-Vera (1996) defined the endorheic platform as a single hydrological system, consisting of two aquifers and their limits, and established a hydrogeological function model of the platform, on which he based a numerical model of groundwater flow capable of simulating irrigation. He describes two saline aquifer levels, an

Fig. 3 **a** Water depth in La Playa, recorded from 1993 to 1997, and the previous 30-day accumulated rainfall (P); **b** determination coefficients (R^2) for the total water surface in the largest playa-lakes, extracted from a series of Landsat images between 1984 and 2004, and the accumulated rainfall (P) for the 15, 30, 90, 180, and 365 days previous to the image date
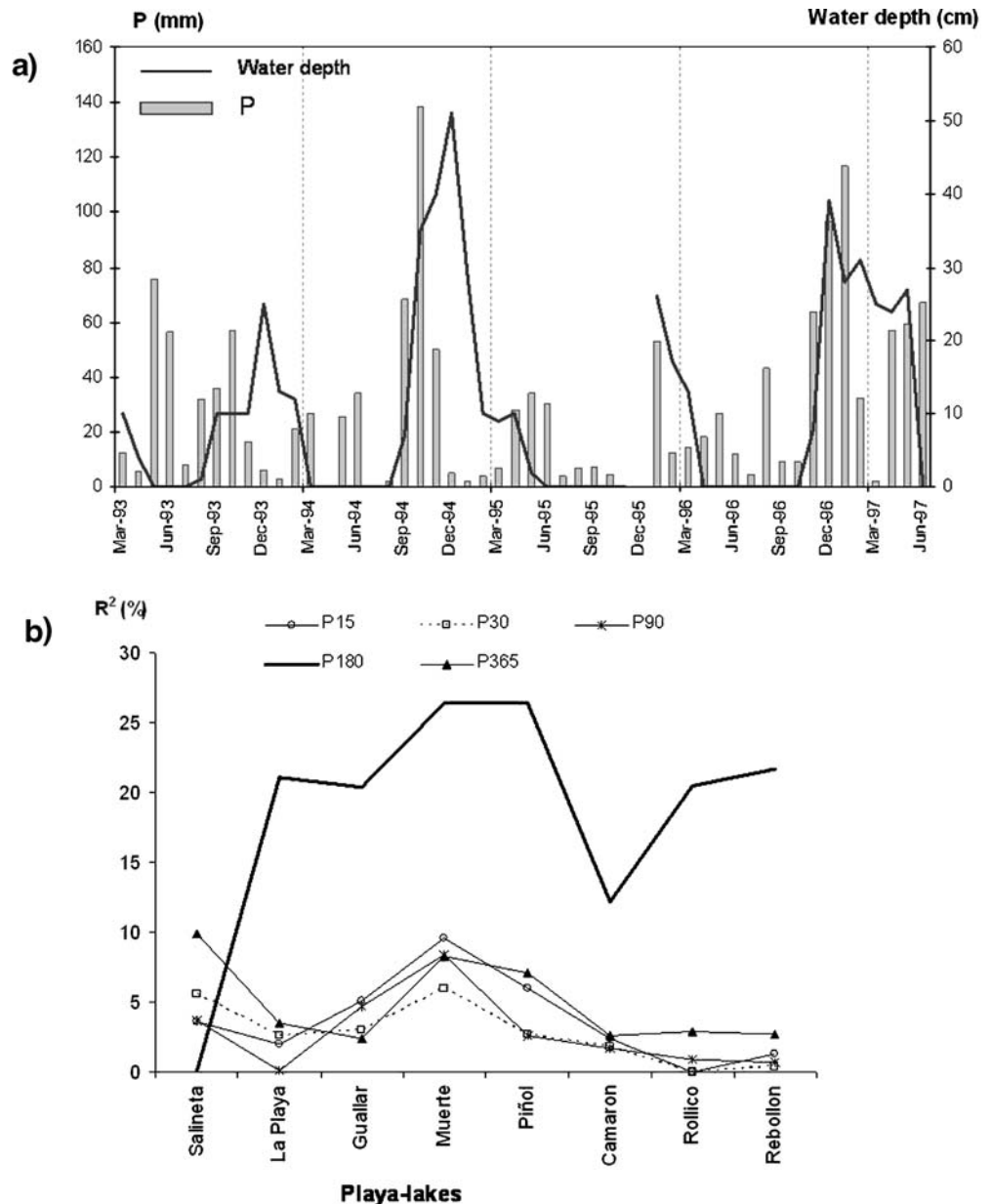
upper one and a lower one, associated with the upper and intermediate lithostratigraphic units, respectively; these aquifers are separated from each other by the above-mentioned strip of red lutites (Fig. 2). With regard to new irrigated areas, he emphasised the importance of establishing an efficient system of drainage on the platform in order to avoid flooding in the cultivated land near the depressions containing the saladas.

The hydrological regime of these wetlands is closely linked to the evolution of these two aquifers that feed them (Samper and García-Vera 1998). The rise in the water table from future irrigation return flows threatens these habitats, as the ephemeral brine will not only change to permanent, but will also become non-saline and polluted. Several authors consider the rising of the groundwater levels as the greatest threat, not only to the conservation of the playa-lakes but also to agricultural exploitation. For this reason, it is intended that irrigation not be located in the versant basins of the playa-lakes. The understanding of the current hydrogeological balance of the playa-lakes is a key to detecting future disturbances.

Description of the model BALAN: equations and parameters used

The version of the BALAN program used in this study was an adaptation of the first definitive BALAN V10.0 version (Samper and García-Vera 1992) devised for the Ebro Basin water authority. The basic terms in the balance are: (1) inflows from precipitation and irrigation; (2) outflows from surface run-off, evapotranspiration, subsurface and groundwater flows; and (3) variation in the moisture content of the soil, and (4) variation of the water table levels in the saturated zone (Fig. 4). Initial conditions relating to moisture are specified in the input data.

The program enables both the piezometric levels and the flow of streams in the basin to be calculated. In addition, it allows the balance of a chemically inert solute to be established. As with most programs for calculating
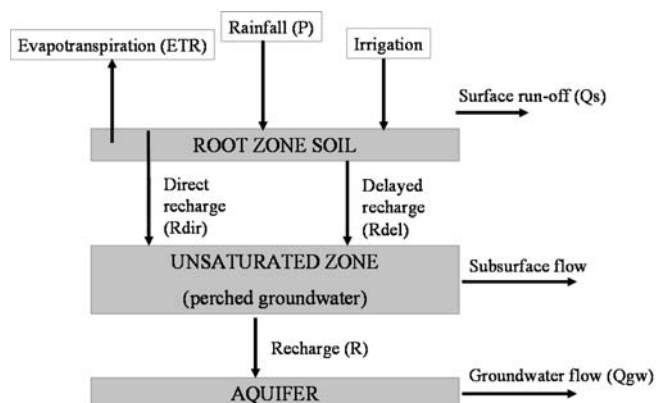
Fig. 4 Diagram of the principal components of the water balance in the root zone soil, the unsaturated zone and the aquifer, considered in the BALAN program

water balances in the ground, BALAN uses fundamentally semi-empirical correlations where some parameters appear that have to be estimated for each individual case.

It was considered that daily precipitation was the only inflow of water in the balance, since to date there are no irrigated areas in the drainage basin associated with the studied playa-lakes. The hydrological effectiveness of the saturated zone was limited. The piezometric level was an average of 4.5 m below ground level with a maximum oscillation of 1.67 m, and the hydrograms of García-Vera (1996) showed a very small delay. For these reasons, it was assumed that the saturated zone did not exist. Piezometric levels in the basins of the studied playa-lakes were not available.

The components of the balance were calculated for each day, i, sequentially along the following lines: potential evapotranspiration (ETP_i); direct recharge ($Rdir_i$), i.e. the part of rainfall which, in dry soil conditions, enter the aquifer directly through cracks and fractures; surface run-off (Rf_i); real evapotranspiration (ETR_i); indirect or delayed recharge ($Rdel_i$), i.e. the recharge produced when the soil moisture is higher than the field capacity; and balance in the aquifer (Q_i).

Rainfall (P_i), is the only input to the system. In order to distribute P_i between the different components of the balance, a secondary term called "inflows" (I_i) was defined. In every step of the balance, I_i represents the rainfall not assigned to each component of the balance. Therefore, at the beginning of the daily balance ($I_i = P_i$), and at the end of the daily balance ($I_i = 0$).

The *potential evapotranspiration* for the corresponding day (ETP_i) was calculated using the Thornthwaite method (Custodio and Llamas 1983). Although this method underestimates the ETP, and therefore overestimates the recharge in semi-arid zones (Jain and Sinai 1985), it has been used because it is the most commonly employed method for groundwater balances.

The *direct recharge* ($Rdir_i$)—the recharge which enters the aquifer directly—was calculated from the total amount of water that could potentially enter the ground before undergoing evaporation. It is considered that direct recharge takes place through cracks when the soil moisture is low. $Rdir_i$ only occurs when daily rain $P_i > ETP_i$ and is applied to water that will not be evapotranspirated ($P_i - ETP_i$). The direct recharge factor (DRF) is defined as a fraction of the available storage after which direct recharge ceases to exist. Therefore, direct recharge occurs whenever

$$\theta_{i-1} \leq WP + DRF \times (FC - WP) \qquad (1)$$

where θ_{i-1} is the soil moisture content the previous day, WP is the wilting point and FC is the field capacity of the soil. The magnitude of direct recharge $Rdir_i$ is given by:

$$Rdir_i = DRKC \times (P_i - ETP_i) \times F \qquad (2)$$

where DRKC is an empiric factor indicating the magnitude of the recharge and F is a decreasing exponential function of the degree of moisture, F, (Fig. 5) which has a

value of 1 when b) If $\theta_i\theta_{i-1} = WP$, and zero when $\theta_{i-1} = WP + DRF \times (FC - WP)$. When $Rdir_i$ was produced, its magnitude was subtracted from the inflows I_i, the value of I_i changing accordingly with the expression:

$$I_i = P_i - \text{Rdir}_i \qquad (3)$$

Surface run-off (Rf_i) was determined from the soil infiltration capacity (IC_i) and generated with mechanisms based on Horton's law. Its maximum value, ICM1, was reached when the soil was at WP (wilting point), and it decreased as θ_i increased, in accordance with a second degree parabolic function (Fig. 6). It reached its minimum value ICM0 when $\theta_i \geq FC$. Thus, the value I_i is updated again.

Real evapotranspiration (ETR_i) was calculated using the modified Penman-Grindley method (Rushton and Ward 1979). If the available water in the soil the previous day, $\theta_{i-1} - WP$, together with the input during day i, I_i, are greater than ETP_i, then $ETR_i = ETP_i$. Otherwise, the ratio $ETR_i = ETP_i$ is calculated in function of θI_{i-1} (Fig. 7) in accordance with two soil behaviors:

a) If $\theta_i > (FC - K_1)$; $\qquad ETR_i/ETP_i = 1 \qquad (4)$

b) If $\theta_i < (FC - K_1)$;

$$ETR_i = I_i + K_2 \times (ETP_i - I_i) \qquad (5)$$
$$\times (1 - [(FC - \theta_{i-1})/(FC - WP)])$$

where K_1 is the root constant and represents the value of soil moisture content at which the above a) or b)
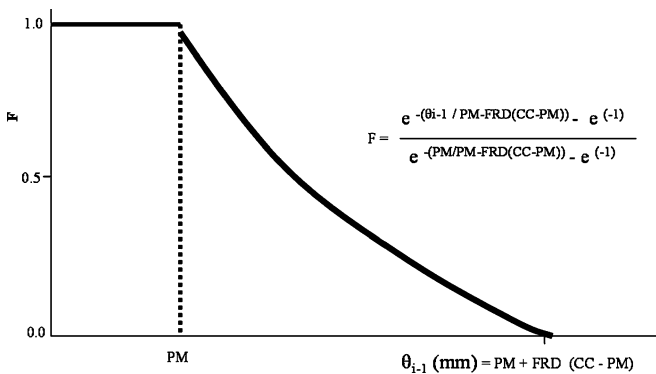

Fig. 5 Evolution of the degree of moisture, F, with respect to the moisture content of the soil to determine direct recharge (Rdir) through cracks. WP is the wilting point and FC is the field capacity of the soil; θ_{i-1} is the soil moisture content the previous day and DRF is the direct recharge factor
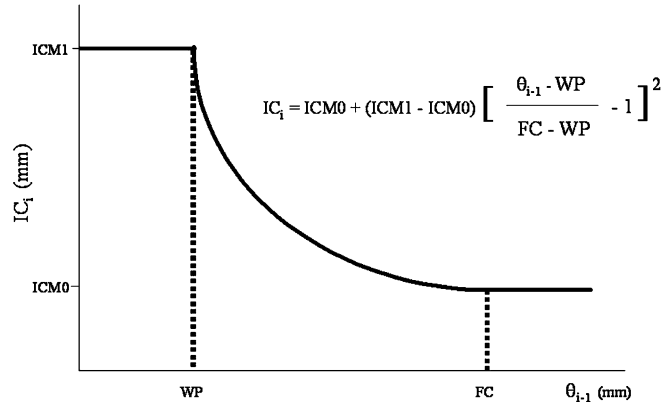

Fig. 6 Evolution of the infiltration capacity with soil moisture content according to Horton's law. Soil infiltration capacity (IC_i) maximum ICM1 and minimum ICM0 values; θ_{i-1} is the soil moisture content the previous day, WP is the wilting point and FC is the field capacity of the soil

mechanisms will take place, and K_2 is a coefficient indicating the magnitude of the ETR_i. The mechanism a) occurs when the soil is wet enough, i.e. $\theta_i > (FC - K_1)$, and there is no water retention; in mechanism b), soil water retention occurs due to the soil moisture deficit. The values of K_1 and K_2 must be calibrated, and these depend on vegetation cover and soil properties. After calculating ETR_i, I_i and θi are updated.

Delayed recharge, $Rdel_i$, was calculated taking into account that (1) recharge only exists when $\theta > FC$, (2) it cannot exceed the vertical permeability of the soil, K_v, and (3) it increases with the difference between θ_i and FC (Fig. 8). Thus:

a) If $\theta_i < FC \qquad Rdel_i = 0 \qquad (6)$

b) If $FC < \theta_i < FC + K_v \qquad Rdel_i = \theta_i - FC \qquad (7)$

Once delayed recharge was calculated, the soil moisture content was updated. Finally, a *water balance in the aquifer* was carried out. The sum of the direct and delayed recharge, R_i, raised the water volume in the aquifer (Vaq_i) every day, and from that volume daily outflows from the aquifer were determined from the groundwater discharge, Dgw,

$$R_i = Rdir_i + Rdel_i; \quad Vaq_i = Vaq_{i-1} + R_i;$$
$$Dgw = \alpha \times Vaq_i \qquad (8)$$

where α is the depletion coefficient of the aquifer, expressed in days^{-1}. With the daily recharge value, R_i, the volume of the aquifer, Vaq_i, is updated from the surface of the basin.
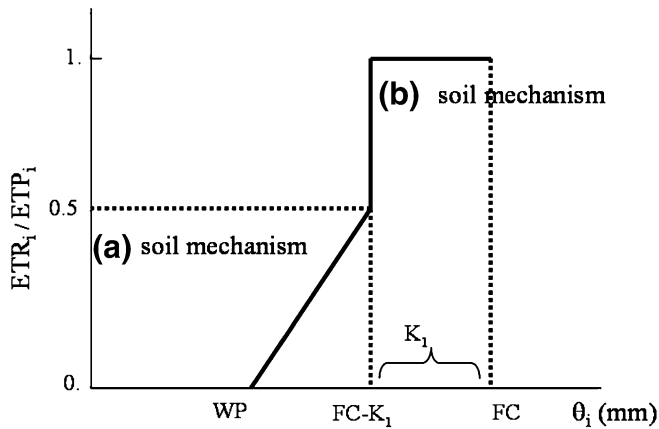
Fig. 7 Evolution of ETR_i/ETP_i for different values of soil moisture content θ_i, being WP the wilting point and FC the field capacity of the soil. The coefficient K_1 is the root constant and represents the value of θ_i from which the **a**) or **b**) mechanisms will take place

Once the balance for day i had been carried out, the volume of the aquifer for day i and the total outflow into the playa-lakes (Q_i), surface flow (Qs_i) and groundwater flow (Qgw_i) was calculated. Then:

$$Q_i = Qs_i + Qgw_i \tag{9}$$

Input data

Using meteorological data—precipitation and average temperature—and specific parameters relating to the ground, the aquifer and the geometry of the bottom of the playa-lakes, the proposed model calculates the heights of the water (or depths) for each day. The meteorological data were recorded at the nearest weather station (Fig. 2). Rainfall was taken at "Bujaraloz-Petris" situated at 345 m above sea level on UTM co-ordinates 738480°E and 4590710°N in grid zone 30. Average precipitation over the 28 years studied was 364 mm/year. The wettest year of this period was 1997 with 535 mm, and the driest 1995 with 176 mm. The daily temperature was obtained from "Candasnos2", at 280 m above sea level, on UTM co-ordinates 755480°E and 4598670°N in grid zone 30. Average temperature for the period of application of the balance was 14.2°C.
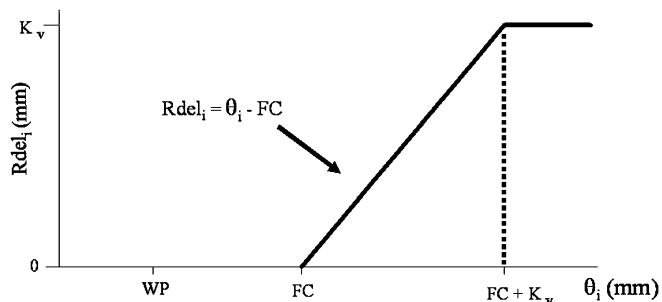

Fig. 8 Variation in delayed recharge $Rdel_i$ with soil moisture content θ_i, where WP is the wilting point, FC the field capacity, and K_v the vertical permeability of the soil

The soil parameters were taken from 25 different soil profiles made in the area (García-Vera 1996). The grain-size analyses showed that the field capacity varied from 15 to 35%, and the wilting point varied from 75 to 20%. Average values were used, i.e. a porosity of 0.3, a field capacity of 0.24, and a wilting point of 0.14. The thickness of the soil, reported in the García-Vera study between 0.25 m and 1.5 m, in this study was the object of several calibration analyses, with values between 50 and 1,550 mm, accounting for an available storage of 5 and 155 mm, respectively. The vertical permeability of the soil gave values of between 1.4 and 0.5 m/d in the field (García-Vera 1996). Therefore, an average of 1m/d was set. The magnitude of superficial run-off was maintained between 1% and 3% of total precipitation, accordingly to what had been established in previous studies.
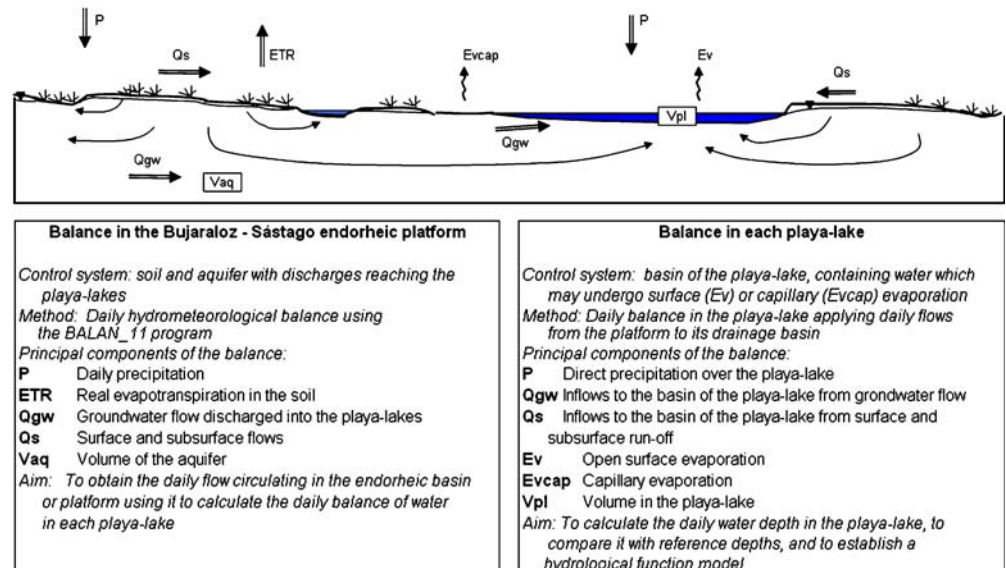
Methodology

The hydrologic balance of the Monegros playa-lakes was calculated on a daily basis in two successive phases (Fig. 9), corresponding to two systems' control, which were clearly differentiated. Firstly, the BALAN programme (Samper and García-Vera 1992) was used to estimate the average water balance in the soil and in the aquifer for the entire endorheic basin or Bujaraloz-Sástago platform where the playa-lakes are situated. This simulation was extended to the entire period covered by the available meteorological data, between January 1973 and December 2000, in order to determine a representative hydrological behavior of the entire area.

Second, the daily balance is applied to the three selected playa-lakes—Salineta, La Playa and Guallar—shown in Fig. 2 and sketched in Fig. 9. The main criterion for selecting these playa-lakes was the availability of topographical data on their bottoms. La Playa was chosen as a typical example of the lower aquifer and as the largest playa-lake. Salineta was selected because some of its cycles relating to the presence of water are different from the rest, as well as because it is the northernmost playa-lake situated on clayey materials, and because it is the only one which may show a hydrological connection with both aquifers on the platform (Samper and García-Vera 1998). Guallar is connected to the same aquifer as La Playa and was chosen as a contrast with this lake because of its smaller size.

Although data were available for discharge into the playa-lakes resulting from the BALAN simulation between January 1973 and December 2000, this balance was undertaken between 1993 and 1997 as this was the period which had the only continuous records of water presence in the field (Castañeda 2002). The discharge flows obtained from the water balance in the soil and the aquifer were applied, producing a flow (mm/d) discharged into the playa-lakes, $Q_i = Qs_i + Qgw_i$, which was converted to m^3/s when the surface of the drainage basin associated with each of them is applied. According to Berga (1993), the basin areas are 20.52 km^2 for La Playa, 0.275 km^2 for Salineta, and 0.325 km^2 for Guallar. The balance was

Fig. 9 Sketch of the two successive phases of the balance corresponding to two systems control: *on the left* the endorheic basin or Bujaraloz-Sástago platform where the playa-lakes are situated; *on the right*, the daily balance in an isolated playa-lake

Balance in the Bujaraloz - Sástago endorheic platform

Control system: soil and aquifer with discharges reaching the playa-lakes
Method: Daily hydrometeorological balance using the BALAN_11 program
Principal components of the balance:
P   Daily precipitation
ETR   Real evapotranspiration in the soil
Qgw Groundwater flow discharged into the playa-lakes
Qs   Surface and subsurface flows
Vaq   Volume of the aquifer
Aim: To obtain the daily flow circulating in the endorheic basin or platform using it to calculate the daily balance of water in each playa-lake

Balance in each playa-lake

Control system: basin of the playa-lake, containing water which may undergo surface (Ev) or capillary (Evcap) evaporation
Method: Daily balance in the playa-lake applying daily flows from the platform to its drainage basin
Principal components of the balance:
P   Direct precipitation over the playa-lake
Qgw Inflows to the basin of the playa-lake from grondwater flow
Qs   Inflows to the basin of the playa-lake from surface and subsurface run-off
Ev   Open surface evaporation
Evcap Capillary evaporation
Vpl   Volume in the playa-lake
Aim: To calculate the daily water depth in the playa-lake, to compare it with reference depths, and to establish a hydrological function model

carried out for every day i in every playa-lake (*pl*) and was based on the equation for water conservation

$$In(pl)_i - Out(pl)_i = \left(V(pl)_i - V(pl)_{i-1}\right) + \varepsilon \qquad (10)$$

where, $In(pl)_i$=inflows of water; $Out(pl)_i$=outflows of water; $V(pl)_i$=volume of water; $V(pl)_{i-1}$=volume of water in playa-lake at the end of day $i-1$; ε=balance error. An analysis of the inflows and outflows of water in playa-lake gives:

$$In(pl)_i = P(pl)_i \times S(pl)_{i-1} + Q(pl)_s \qquad (11)$$

$$Out(pl)_i = Ev(pl)_i \times S(pl)_{i-1} + Evcap(pl)_i \times Scap(pl)_{i-1} \qquad (12)$$

where $P(pl)_i$ is the precipitation falling on day i over (pl); $S(pl)_{i-1}$ is the surface of water in (pl) at the end of day $i-1$; $Q(pl)_i$ the inflows of water into the playa-lake (pl) calculated by BALAN for the surface of the drainage basin, according to Eq. (9); $Ev(pl)_i$ the volume of evaporation from the surface water in (pl), $Evap(pl)_i$ the volume of capillary evaporation, and $Scap(pl)_{i-1}$ the surface susceptible to evaporation. Considering ε=0, a reasonable adjustment can be obtained taking into account the complex natural environment. Joining Eqs. (11) and (12) and calculating the daily water volume for each playa-lake, $V(pl)_i$, gives:

$$\begin{aligned} V(pl)_i = {} & P(pl)_i \times S(pl)_{i-1} + Q(pl)_i - Ev(pl)_i \\ & \times S(pl)_{i-1} - Evcap(pl)_i \times Scap_{i-1} \\ & + V(pl)_{i-1} \end{aligned} \qquad (13)$$

To determine the rate of evaporation $Ev(pl)_i$, the daily ET_0 was calculated using the Reference Evapotranspira-tion Calculator REF-ET v.2.0 (Allen 2000) which uses the FAO-56 Penman-Monteith formula recommended by the UN's Food and Agriculture Organisation (FAO; Allen et al. 1998). A coefficient of 1.67 was applied in order to correct this value to that of a class A evaporation tank, and in accordance with (1) the average meteorological conditions—relative humidity between 40 and 70%, and wind speed between 2 and 5 m/s—and (2) the fact that there are no cultivated areas in the vicinity of the water surface (Doorenbos and Pruitt 1977). The overestimation of evaporation, due to the effects of heating on the edge of the tank, were corrected by multiplying by 0.70, the typical value for arid areas (ASCE 1996), and the negative effect of the salinity was corrected using a factor of 0.87 (García-Vera 1996). Therefore, the ET_0 value obtained from Penmam-Monteith is transformed to evaporation rate using the coefficient 1.02, which is equal to 1.67×0.7×0.87. During the period studied, between 1993 and 1997, the average value for ET_0 equalled 3.44 mm/day.

The daily water volumes obtained for the three playa-lakes were converted into surfaces for estimating precip-itation and evaporation for the following day, and into water depths in order to have comparable data with the existing field records of water depths. To carry out the volume-surface-depth conversion, it was necessary to know the bathymetry of the playa-lake, or at least to have simultaneous water depth and surface data available for a relationship between the two to be established. Taking into account the field and remotely sensed observations related to the shape and look of the playa-lakes, and the very few topographical data that exist, it was assumed that the shape of the bottom of the playa-lakes is likened to an inverted cone, similar to the estimation of water depths from remotely sensed water surface areas in ephemeral wetlands proposed by Bryant and Rainey (2002). A base surface S, height h, equivalent radius r, and slope φ, gives the relationship $tan\varphi = h/r$, and $r = (S/\pi)^{1/2}$, from which

the water surface in each playa-lake, S, and the water depth, h, is obtained from:

$$h = \left[\left(3 \times V \times \tan^2 \varphi\right)\big/\pi\right]^{0.33} \qquad (14)$$

$$S = 3 \times V\big/\left[\left(3 \times V \times \tan^2 \varphi\right)\big/\pi\right]^{0.33} \qquad (15)$$

The value of φ was estimated from the topography at the bottom of the depressions, although this was subject to change due to the constant action of the wind and to sedimentary processes. Therefore, in Salineta, water depth recordings coinciding with or approximating surface data obtained by remote sensing (Castañeda 2002) were also examined.

A detailed understanding of the evaporation process is an essential aspect of the hydrologic balance of wetlands (Drexler et al. 2004; Zapata and Martínez-Cob 2001), and an exact valuation would require the use of specific instruments. Field observations indicate that even if there is no surface water the bottoms of the playa-lakes are always moist, even in summer. Moreover, evaporation in the capillary fringe can take place up to a depth of 2 m (García-Vera 1996). Because it was not possible to define this factor from field data, several tests were carried out for each application of BALAN, these being: (1) with no capillary evaporation, (2) with capillary evaporation in surface areas exceeding the surface water body limits in the playa-lakes in 10, 20 and 50 m; (3) with capillary evaporation taking place throughout the year over all the bottom of the playa-lakes, taking into account that evaporation in the soil is 33% less than on the open water surface. Due to the lack of field data on capillary evaporation in the study area, the data obtained in Gallocanta Lake (a playa-lake located in NE Spain 100 km from Monegros) were employed. Those measurements of real evaporation in the weather station located at the edge of the lake, 10 m above the maximum flooding border, are based on the surface renewal method (Spano et al. 1997 and 2000) and were the only available experimental data in similar environments throughout the Mediterranean area. Those ETR values indicated that the water evaporation occurs in the capillary fringe with a value of two thirds of the free water evaporation.

Model calibration

The calculated water depths were compared to the field data registered from scale readings taken weekly in the field by the DGMN (Natural Environment Department of the Government of Aragon, Spain) between 1993 and 1997 and compiled in Castañeda (2002). On the one hand, the criteria used to calibrate the model were:

1. Graphical analysis of both series of values, discussing the goodness-of-fit between measured and estimated water depths and indicating the parameters that gave the best result.

2. Statistical analysis of the two series of previous data, using (1) the root mean square error (RMSE) given by Eq. (16) and (2) the determination coefficient (r^2).

$$RMSE = 100 \times \sqrt{\sum_{i=1}^{N} \frac{(Y_i - X_i)^2}{N}} \qquad (16)$$

where N is total number of data from the X (measured) and Y (estimated) series.

On the other hand, the consistency of calculated data compared to those obtained in previous studies was taken into account. Samples in the field and hydrogeological tests from previous campaigns (García-Vera 1996) endorse the values of parameters used in this study and enable an assessment of the reliability of different hypotheses applied to the balance.

The calibration of the BALAN program was carried out using six hypotheses or scenarios—from MON_1 to MON_6—which represent different models of hydrological behaviour of the aquifer. Those scenarios were defined during the iterative calibration process in order to examine the parameters that reproduce possible flow functions through the ground and the aquifer, especially the importance of the direct flow mechanism. The calibration was performed iteratively for the available storage of the soil (soil thickness), depletion coefficient α of the aquifer, direct recharge, and infiltration coefficients. To calculate real evapotranspiration the K_1 and K_2, values were fixed at 16.05 mm and 1.5, respectively, for all the scenarios. The volume corresponding to the first water depth measured in the field was considered as the initial state of the balance in each playa-lake (Table 1). It was calculated following Eqs. (14) and (15).

Available storage of the soil

The analysis of the available storage of the soil was performed in three different scenarios—MON_1, MON_3 and MON_6—each followed by the other three parameters mentioned above. In the first scenario (MON_1), values from 5 to 55 mm were taken, corresponding to soil thicknesses of between 50 and 550 mm. Increasing the available storage reduced the discharge of water from the aquifer to the lakes. In the playa-lakes, the resulting

Table 1 Initial conditions for the water balance application to each playa-lake. Values were calculated for 03 March 1993

	Depth	Volume	Surface
	m	m³	m²
La Playa	0.10	1,537	46,116
Salineta	0.11	111	3,026
Guallar	0.05	17.4	1,042

Table 2 Maximum water depth (h_{max}), maximum surface area (S_{max}) and maximum volume (V_{max}) estimated from topographic data. Those values were used to calculate equivalent radius (r) and slope (α)

Playa-lakes	h_{max} (m)	S_{max} (m²)	V_{max} (m³)	α	Equivalent radius (m)
Salineta	0.95	226,250	71,646	0.20300	268
La Playa	0.70	2,200,000	513,333	0.04729	848
Guallar	0.60	149,862	29,972	0.1573	218.4

discharged volumes $I(pl)_i$ (Eq. 10) produce much higher water levels than the measured values and the resulting discharge is too slow. To improve the adjustment, it was necessary to modify the aquifer depletion, α (Eq. 8), in the next step MON_2, before continuing the tuning of the available storage.

In a following scenario MON_3, the available storage increased from 55 to 105 mm/day, with the aquifer depletion being $\alpha=0.033$ d^{-1}. With this analysis, the volume of discharge $I(pl)_i$ (Eq. 10) into the playa-lakes decreased. However, this discharge becomes zero in the first years, which did not correspond to the measured values of water depth in the field. For this reason the analysis of the direct recharge, $Rdir_i$ (Eq. 2) was introduced in MON_4.

With the third iteration of the analysis of the available storage of the soil (MON_6) the model was tuned with the following adjustment: the soil thickness was varied between 105 and 155, and 135 cm was finally adopted. The final aim was to improve the result so that the flow discharged into the streams had a reasonable value, approximating 20 mm/year, likely the flow obtained in previous studies (García-Vera 1996). To do this, the infiltration coefficients ICM0 and ICM1 were fixed at 30 and 55 mm/day, respectively.

Aquifer depletion

The analysis of the aquifer depletion was performed in MON_2. With a soil thickness of 550 mm, α ranged from 0.0077 to 0.2 d^{-1}, resulting in times for emptying half the aquifer of between 4 and 90 days. This mechanism

improved noticeably the adjustment because the velocity of discharge of the aquifer is increased. A better adjustment was produced applying $\alpha=0.033$. With this value, the calculated water depths are similar to the measured values. This adjustment was not modified in the following scenarios, but rather retained for α.

Direct recharge of the aquifer

The direct recharge, $Rdir_i$, was regulated by the DRKC coefficient (Eq. 2), up to a maximum value fixed by the DRF coefficient (Eq. 1), which was fixed for all the hypotheses in 75% of the available storage. In the analysis of the direct recharge of the aquifer performed in MON_4, DRKC coefficient took the following values: 0, 0.05, 0.1, 0.15, 0.2 and 0.25. The minimum value was adopted for $Rdir_i$, i.e. DRKC=0.05. This mechanism produced a significant improvement of the adjustment. When direct recharge was introduced into the balance, the weight of direct precipitation onto the lake was increased, this being a contribution to the flow, undergoing neither evaporation nor run-off.

Surface run-off

The effect of the infiltration coefficients ICM0 and ICM1 (MON_5) was analysed in order to approximate the surface run-off value to 1% of precipitation. By making ICM0 equal to 30 mm/d, the ICM1 coefficient was varied with the following values: 30, 35, 40, 45, 50 and 55 mm/d. Finally, for ICM1 the value 55 mm/d was adopted, because it produced the best results.

Results and discussion

Volume–surface area–depth relationship

With data from the maximum depth and maximum flood surface area in the three playa-lakes, taken from the existing topography, the maximum volume and the

Table 3 List of depths (h) corresponding to water surface area (S) estimated using Landsat images between 1993 and 1997 for the three playa-lakes studied

Date	La Playa		Salineta		Guallar	
	S(m²)	h(m)	S(m²)	h(m)	S(m²)	h(m)
06/03/93	403,130	0.30	87,500	0.59	3,800	0.10
12/07/93	503,750	0.33	84,400	0.58	0	0
28/05/94	17,500	0.06	0	0	7,500	0.13
29/06/94	0	0	0	0	10,000	0.15
16/08/94	0	0	0	0	10,000	0.15
07/01/95	726,260	0.40	91,900	0.61	33,800	0.28
18/04/96	1,238,750	0.52	75,000	0.55	3,800	0.10
15/06/96	0	0	0	0	6,900	0.13
20/07/96	0	0	0	0	3,100	0.09
02/04/97	1,500,630	0.57	135,600	0.74	67,500	0.40
07/07/97	523,750	0.34	68,100	0.52	40,000	0.30

Fig. 10 Comparison between simulated and measured daily water depths for the three playa-lakes: **a** La Playa, **b** Salineta, and **c** Guallar. *Solid lines* represent model values obtained from the best calibration in each hypothesis of the balance; *dots* represent measured values. Satellite estimated values are also represented (*circles*). Legend shows the adopted value in each hypothesis
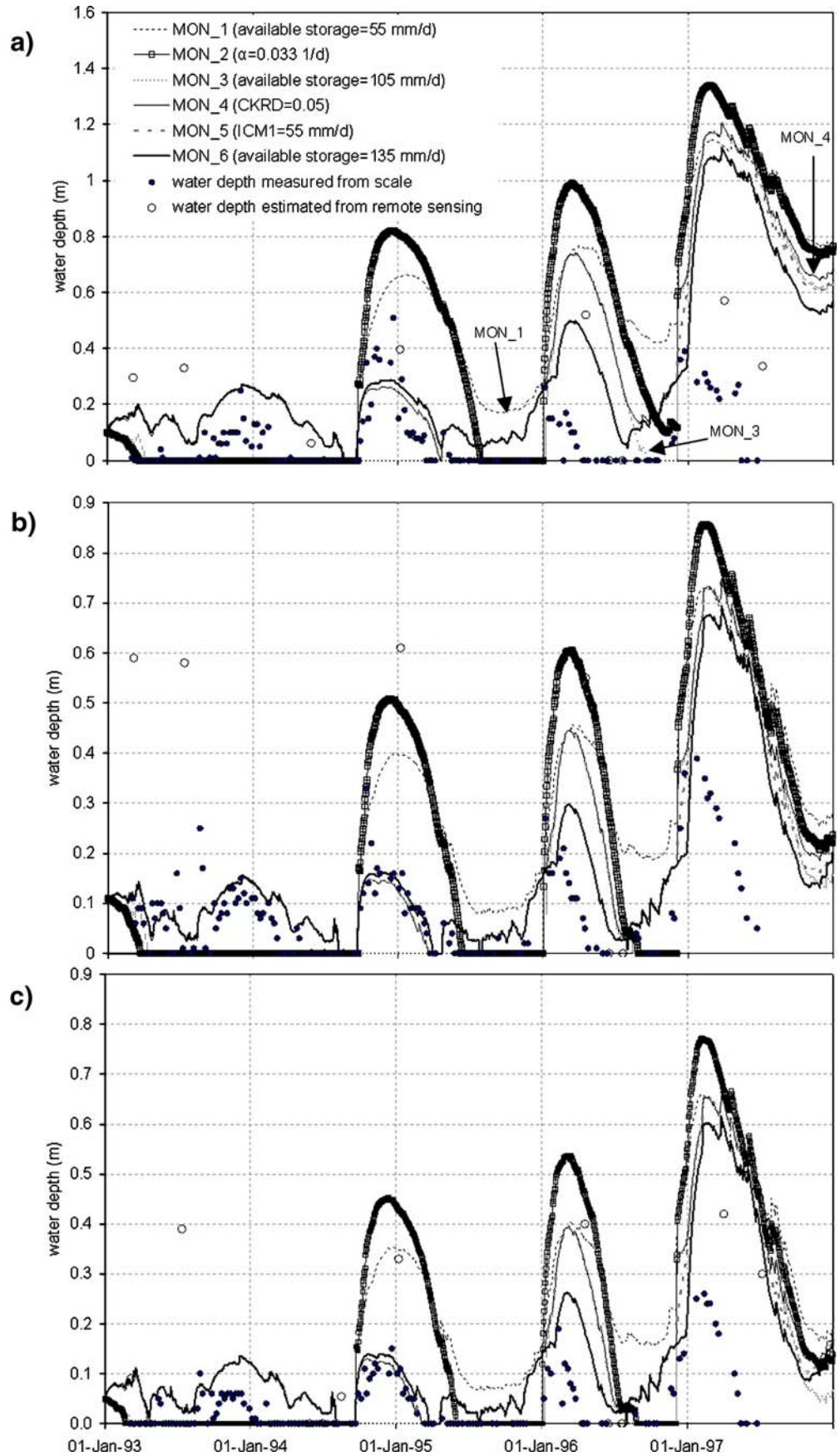
slope of the bottom of the lakes, φ, were calculated (Table 2).

These φ values were compared with those obtained from examining simultaneous recordings from water depths in the field and water surfaces from satellite images. Only Salineta gave valid water depths on four comparable dates, with very variable φ values, reflecting an increase in the slope of the bottom towards the centre of the salt lake. This variability may be due to (1) the time that lapsed between the water depth reading and the viewing of the image; (2) the fact that the scale for measuring water depth was not always installed in the area of greatest depth in the salt lake, and (3) the topographical complexity of the bottom.

In view of the lack of field data for establishing a reliable empirical surface-depth relationship for Salineta, and the lack of similar comparative data for La Playa and Guallar, values obtained from the topography were adopted. As angle φ has a very small value in the playa-lakes, the error introduced for this factor in the calculation of the water balance may be ignored.

Reference water depth

With the surface-depth correlation established for each playa-lake, based on the data in Table 2, open water surfaces obtained from Landsat images on 26 different dates (Castañeda et al. 2005) were converted into depths. Table 3 shows these depths between 1993 and 1997, this being the only period when water depths were measured in the scales. Maximum expanses of water in the playa-lakes were registered during this time interval; these occupied 85% of the bottom in La Playa, 71% in Salineta and 50% in Guallar, responding to depths of 0.57, 0.80 and 0.42 m, respectively.

The 184 depths measured by scale during a period of 4 years and 3 months between 1993 and 1997, together with the water depths from Table 3 were considered as reference water depths. It will be noted that depths obtained from satellite images are appreciably greater than those registered in the field. This is because: (1) the image can detect water surfaces not found at the site of the scale, and (2) topographical data are scarce and unevenly distributed in the playa-lakes, with the result that the conversion of surface areas to depths is of limited accuracy; moreover, it would be necessary to update the topography since it undergoes changes in character caused by the effects of the wind. This situation is most noticeable in Salineta, which has the greatest topographical depth of the three lakes and an asymmetrical bottom aligned in the direction of the wind. Observations in the field show that, due to the wind, the mass of water is frequently found leeward of the area of greatest depth.

Due to the different kind of data sets and to the fact that the water surface data include surfaces not measurable with a ruler but noticeable on the satellite images, only the measured water depths were used to contrast the results of the applications of the model with the different hypotheses.

Water balance

For each of the six hypotheses applied, the average daily flows for the entire platform were obtained over 28 full years, from January 1973 to December 2000. Taking into account that hydrological series are representative from 30 years onwards, this first part of the balance allows properly representative values of the working model to be obtained. From these discharge flows to the Monegros playa-lakes, it was possible to calculate the water balance in the three selected playa-lakes. Successive applications of the balance in each playa-lake have enabled calculated depths to be adjusted to measured depths, taking into account the characteristics of the soil obtained from previous hydrogeological studies. Figure 10 shows the best performance of every hypothesis of the balance into these three playa-lakes, for the period 1993–1997, which is the period with field data for validation. This work is to be considered as a calibration on the whole; from a new field monitoring exercise it will be possible to obtain the validation for a new period of time.

The main considerations obtained during the adjustment process are as follows:

1. The depth–surface– volume relationship used in this study enabled a correlation to be established between the volumes of water discharged in the playa-lakes and the resulting water depth.
2. With successive applications of six BALAN hypotheses, the calculated water flow for the entire platform decreased from 188 mm/year in the first application to 22 mm/year in the last one. At the same time, real evapotranspiration in the soil increased from 173 to 338 mm/year.
3. This reduction in the discharge flow to the playa-lakes from their drainage basin was basically due to the reduction in groundwater flow, from 177 to 119 mm/year, while surface run-off remained almost constant at 11 mm/year, except in the last two applications following the increase in soil infiltration capacity.
4. Excess flow was corrected throughout the applications using the increase in the available storage (which varied between 5 and 155 mm). This mechanism was useful for reducing the value of the calculated depths, but different results were observed depending on the rainfall registered. As the available storage increased, the calculated depths clearly decreased in the driest years, while in the wettest years they did not decrease at the same rate.
5. The increase in the depletion coefficient of the aquifer improved the calculated depths in the dry phase of the playa-lakes, resulting in faster emptying.
6. Direct recharge from the aquifer considerably improved the results, giving water discharges to the playa-lakes in the driest years. With DRKC coefficient values of 0.05, the consequences of this resulting in an excessive increase in calculated depths were avoided.
7. The increase in infiltration coefficients hardly affected the calculated depths and considerably improved the distribution between groundwater flow and surface run-off.

Table 4 Average annual values of the balance components in the platform for the 1973–2000 period

The balance components in the endorheic platform	mm/year
Precipitation	364
ETR	338.8
Discharge flow into the playa-lakes	22.4
Surface flow	3.0
Groundwater flow	19.4
Aquifer recharge	19.2
Direct recharge	5.9

The parameters giving the best agreement in the three playa-lakes are: (1) soil thickness of 1.35 m, which gave an available storage of 135 mm; (2) the presence of direct recharge through cracks, allowing a rapid circulation of water without waiting for the soil to become saturated, with DRF and DRCK coefficients of 0.75 and 0.05, respectively; (3) infiltration coefficients of 30 and 55 mm/d; and (4) an aquifer depletion coefficient of 0.033 d^{-1}. The average annual values of the components of the balance in the endorheic platform are shown in Table 4, which gives the balance in the platform between 1973 and 2000, and Table 5, which gives the balance in the three playa-lakes between 1993 and 1997.

Of the three validation criteria used, graphical analysis was the most useful for adjusting calculated and reference depths in each application, which clearly demonstrated the acceptability of the adjustment achieved with the MON_6 application (Fig. 10). The determination coefficient (r^2) and the root mean square error (Eq. 16) served as descriptive criteria, allowing differences in results for the three playa-lakes to show up. The RMSE was reduced when discharge flow into the lakes was restricted, giving 0.28 m in La Playa, 0.14 m in Salineta, and 0.13 m in Guallar. The determination coefficient between calculated and measured water depths gave low values in all three playa-lakes and only a slight variation between the first and the last application, with 0.23 in La Playa, 0.48 in Salineta and 0.50 in Guallar. Probably the loss of adjustment observed in the wettest years (1996 and 1997) influences these low values; therefore, an improvement of the results would be conditioned to the availability of more field measurements, instead of to the model improvement itself.

The parameters of the balance obtained were consistent with previous studies, this being a criterion used in the choice of the most suitable application procedure and in the reliability of the final results. The balance undertaken confirmed that with an average recharge to the aquifers on the order of 20 mm/year and a surface run-off of about 1% of total precipitation (values given in García-Vera 1996) the function observed in the three playa-lakes analysed was reproduced to an acceptable degree.

With this, balance advances have been made in the study of the correlation between water depths of the Monegros playa-lakes and meteorological variables as water discharges produced in the platform and introduced by BALAN have been taken into account. Better adjustment to reference data must be based on greater accuracy of the starting data used such as soil parameters of the platform, the topography of the playa-lake bottoms and precipitation.

Capillary evaporation

In the daily water balance in each playa-lake, the volume evaporated was calculated from the water surface that was present each day. Considering that evaporation from each lake is made up of open water surface evaporation and capillary evaporation (Winter 1999), according to Eq. (3), the effects of capillary evaporation were tested in all the results of the balance.

In order to assess the influence of these two evaporation components on the daily balance, capillary evaporation was progressively increased by gradually extending the evaporation surface within a radius of 10, 20, and 50 m around the flooded area, and, ultimately, in all the floodplain. In this case, the correction factor for evaporation in the ground was taken into account. The upper limit of the volume evaporated was determined by the maximum floodable area in each playa-lake; data are shown in Table 2.

In each BALAN hypothesis, and for the three playa-lakes, the increase in evaporation resulted in a decrease in calculated water depths and a more rapid emptying. In general, the hypothesis of capillary evaporation in a ring ranging from 10 to 20 m around the water-surface edge implied a lowering of the depths, which is broadly consistent with the rate of lowering of the reference depths (Fig. 11). Other hypotheses of capillary evaporation involved much faster reductions than those observed. Constant evaporation from all the playa-lake bottoms inferred an excessive outflow of water from the system.

Generally, consideration of capillary evaporation improved the agreement between calculated and measured water depths, but field data for calibrating the importance of this component in the balance were not available. In the most favourable case, that is, using hypothesis MON_6 and assuming 135 mm of available storage, the RMSE for

Table 5 Average annual values of the balance components in each studied playa-lake for the 1993–1997 period

The balance components in each playa-lake		m^3/year		
		La Playa	Salineta	Guallar
Inflow	Precipitation	636,889	8,535	10,087
	Surface run-off + groundwater flow	426,126	7,132	8,846
Outflow	Open water surface evaporation	1,010,000	15,556	18,804
ΔVolume	$V_{final} - V_{initial}$	53,015	111	128

Fig. 11 Root mean square error (*RMSE*) value between estimated and measured daily water depth obtained from the six hypotheses for each of the three playa-lakes: La Playa (**a**), Salineta (**b**), and Guallar (**c**). For this purpose, increments in evaporation were considered by extending the evaporation surface within a radius of 10, 20, and 50 m around the flooded area and the entire playa-lake surface bottom. In La Playa, an extra surface area increment of 100 m around the flooded area was considered due to its large size
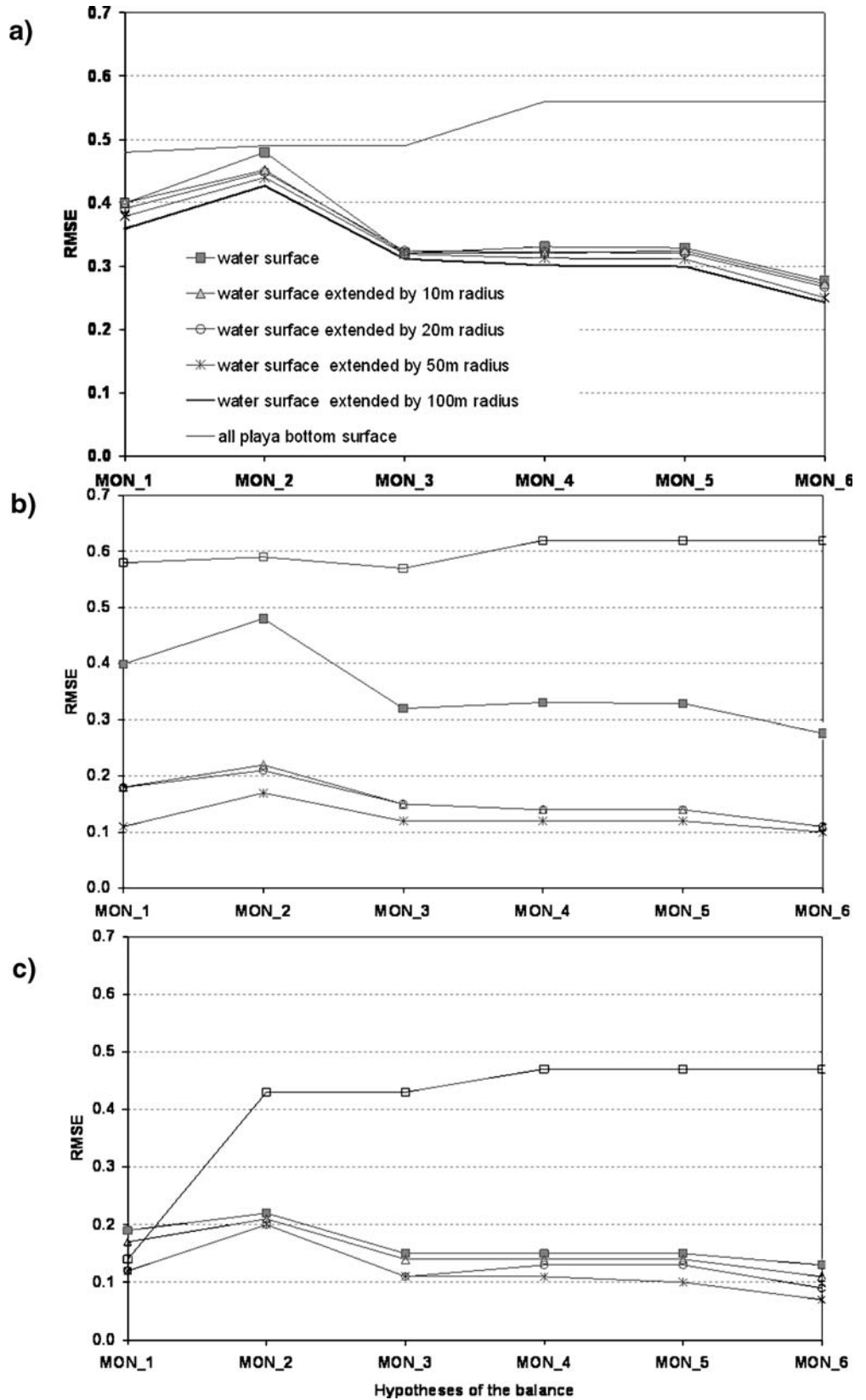
the three playa-lakes was: 0.24 m in La Playa, 0.10 m in Salineta and 0.07 m in Guallar.

From 1996 until the present day, as far as is known, there have been no significant advances in the understanding of the hydrogeology of the Monegros playa-lakes, nor any new contributions to their hydrologic model.

Conclusions and recommendations

The daily water balance applied in this work to the Monegros playa-lakes is a suitable methodology for assimilating hydrometeorological data with the heights of water observed in those wetlands. The uncertainness of the recordings of free water—the daily levels and volumes—during periods with minimum water presence, together with the knowledge of the water content in the capillarity fringe, are difficulties associated with this type of environment.

The present study provides an update of the water balance in the Bujaraloz-Sástago platform carried out by García-Vera (1996). In the present work, the water depth records of three playa-lakes have allowed a detailed balance to be carried out which takes into account the temporal evolution of these wetlands, performing their modeling in a transitory regime for an extended period of 4 years and 3 months, a period containing the driest and wettest years registered in the area. This balance is a useful tool to assess whether the future hydrological regime of these playa-lakes is the consequence of a natural behavior, or if it is influenced by irrigation.

This hydrological model advances the understanding of the hydrologic regime in the Monegros playa-lakes and their associated aquifers. This work contributes to delimit the values of the components needed for the balance estimation. It has been confirmed that an average recharge of 20 mm/year gives a satisfactory explanation of the levels observed in the lakes during the 1993–1997 period. The role of groundwater as the main source of supply to the lakes is clearly prominent. When capillary evaporation is taken into account, evaporation in the balance of the playa-lakes increases, with a slight improvement in the balance.

More accurate results will be obtained with improvements in the quality and temporal and spatial accuracy of the data. To achieve greater future understanding of the hydrologic functioning of the playa-lakes, it is recommended that available information relating to the following components be improved: meteorological data from a greater number of stations, measurements of free-water evaporation with a standard class "A" evaporation pan, instrumentation geared to the determination of capillary evaporation in the playa-lakes, detailed topography of playa-lake bottoms, an improvement in the understanding of soil parameters using field data, and a network of controls for both water levels in the playa-lakes and piezometric levels.

References

Allen RG (2000) Crop Evapotranspiration. Manual of reference evapotranspiration calculator v.2.0 for support of ASCE manual 70 (1990) and 1999 ASC standardizations and FAO irrigation and drainage paper 56, University of Idaho, USA

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Papers 56, FAO, Rome

ASCE, American Society of Civil Engineers (1996) Hydrology handbook. ASCE manuals and reports on engineering practice no 28. ASCE, New York, 784 pp

Berga A (1993) Relaciones clima-agua-suelo-subsuelo en Monegros II [Climate-water-soil-subsoil relations in Monegros II]. PhD Thesis, University 7 of Lleida, Spain

Bryant RG, Rainey MP (2002) Investigation of flood inundation on playas within the Zone of Chotts, using a time-series of AVHRR. Remote Sens Environ 82:360–375

Castañeda C (2002) El agua de las saladas de Monegros sur estudiada con datos de campo y de satélite [The water of the saladas de Monegros, studied with field and satellite data]. Consejo de Protección de la Naturaleza en Aragón, Zaragoza, Spain

Castañeda C, Herrero J (2005) The water regime of the Monegros playa-lakes established from ground and satellite data. J Hydrol 310:95–110

Castañeda C, Herrero J (2008) Assessing the degradation of saline wetlands in an arid agricultural region in Spain. CATENA 72:205–213

Castañeda C, Herrero J, Casterad MA (2005) Landsat monitoring of playa-lakes in the Spanish Monegros desert. J Arid Environ 63:497–516

Comisión Técnica Mixta (2002) Plan Coordinado de Obras de la zona regable de Monegros II. [Coordinated Plan for the irrigated area of Monegros II]. Unpublished document elaborated by the Ebro Water Authority, the Ministry of Agriculture, and the Government of Aragón, Spain, Zaragoza

Conly FM, Van der Kamp G (2001) Monitoring the hydrology of Canadian prairie wetlands to detect the effects of climate change and land use changes. Environ Monit Assess 67:195–215

Custodio E, Llamas, MR (1983) Hidrología subterránea [Groundwater Hydrology]. Omega, Barcelona, Spain

Doorenbos J, Pruitt WO (1977) Guidelines for predicting crop water requirements. Irrigation and Drainage Paper 24, FAO, Rome

Drexler JZ, Snyder RL, Spano D, Paw U KT (2004) A review of models and micrometeorological methods used to estimate wetland evapotranspiration. Hydrol Proc 18(11):2071–2101. (http://www3.interscience.wiley.com/cgi-bin/abstract/ 108562476). Cited 03 October 2007

Euliss NH Jr, LaBaugh JW, Fredrickson LH, Mushet DM, Murray KL, Swanson GA, Winter TC, Rosenberry DO, Nelson RD (2004) The wetland continuum: a conceptual framework for interpreting biological studies. Wetlands 24:448–458

García-Vera MA (1996) Hidrogeología de zonas endorreicas en climas semiáridos. Aplicación a Los Monegros [Hydrogoelogy of endohreic areas in semiarid environments. Application to Monegros site]. Consejo de Protección de la Naturaleza en Aragón, Zaragoza, Spain

García-Vera MA, Arqued V (2004) Evaluación de los recursos subterráneos en el dominio hidrológico Alto Jalón-Alto-Jiloca [Groundwater resource assessment in Alto Jalón-Alto Jiloca hydrogeological basin]. Geotemas 1:87–91

Goes BJM (1999) Estimate of shallow groundwater recharge in the Hadejia-Nguru Wetlands, semi-arid northeastern Nigeria. Hydrogeol J 7:297–304

Jacobson G, Jankovski J (1989) Groundwater-discharge processes at a central Australian playa. J Hydrol 105:275–295

Jain PK, Sinai G (1985) Evapotranspiration model for semiarid regions. J Irrig Drain Eng 111:369–379

Malek E, Bingham GE, McCurdy GD (1990) Evapotranspiration from the margin and moist playa of a closed desert valley. J Hydrol 120:15–34

Pueyo M-JJ, Inglès M (1987) Substrate mineralogy, interstitial brine composition and diagenetic processes in the playa-lakes of Los Monegros and Bajo Aragón (Spain). In: Rodríguez C-R, Tardy Y (eds) Geochemistry and Mineral Formation in the Earth Surface. Geochim Cosmochim Acta 52(10):351–372

Ruston KR, Ward RC (1979) The estimation of groundwater recharge. J Hydrol 41:345–361

Salvany JM, García-Vera MA, Samper FJ (1996) Geología e Hidrogeología de la zona endorreica de Bujaraloz-Sástago (Los Monegros, provincias de Zaragoza y Huesca) [Geology and hydrogeology of the Bujaraloz-Sástago endhorreic area (Los Monegros, Zaragoza and Huesca)]. Acta Geol Hispán 30:31–50

Samper FJ, García-Vera MA (1992) BALAN v.10: Programa para el cálculo de balances de agua y sales en el suelo [BALAN v.10: programme for calculating water and salt balances in soil]. Departamento de Ingeniería del Terreno. Universidad Politécnica de Cataluña, Spain

Samper FJ, García-Vera MA (1997) Estimación de la recarga producida por la lluvia y los excedentes de riego mediante balances diarios de agua en el suelo: experiencias en diferentes zonas climáticas [Rain and irrigation flow recharge estimate by using daily water balances in soil]. Paper presented at Congress of Aquifer recharge assessment in Hydrological Planning, Las Palmas de Gran Canaria, Spain, January 1997

Samper FJ, García-Vera MA (1998) Inverse modeling of ground-water flow in the semiarid evaporitic closed basin of Los Monegros, Spain. Hydrogeol J 6:33–49

Samper FJ, Poncela R, Custodio E, García-Vera MA (1991) Estimation of infiltration recharge from a combination of meteorological and hydrogeological data. Paper presented at the XXIII Congress on Aquifer overexploitation, Canary Islands, Spain, April 1991, pp 85–88

Samper FJ, Huguet L, Ares J, García-Vera MA (1999) Modelos interactivos de balance hidrológico [Interactive models of hydrological balance]. In: Muñoz C R, Ritter A, Tascón C (eds) Estudios de la zona no saturada del suelo [Studies of the unsaturated soil zone], vol 4. Instituto Canario de Investigaciones Agrarias, Tenerife, Spain, pp 187–193

Samper FJ, García-Vera MA, Pisani B, Alvares D, Espinha M J, Varela A, Losada JA (2005) Hydrologic models and geographic information systems for water resources evaluation. Aplication of GIS-BALAN to Atlantic basins in Spain and Portugal. Paper presented at the Fourth Inter-Celtic Colloquium on Hydrology and Management of Water Resources, Portugal, July 2005

Sánchez NJA, Martínez GFJ, Miguel CJL, San Román J (1989) Hidrogeoquímica de la zona endorreica de las lagunas de Monegros, provincias de Zaragoza y Huesca [Hydrogeochemistry of the endohreic area of the Monegros saladas, Zaragoza and Huesca]. Bol Geol Miner 100:876–885

San Román J, García-Vera, MA, Blasco, O, Coloma, P (2005) Toma de datos, modelación y gestión del agua subterránea en la cuenca endorreica de la Laguna de Gallocanta (España) [Proceedings of the AIH-GE International Workshop: from data gathering and groundwater modelling to integrated management (Alicante, Spain). Hidrogeol Aguas Subterrán (IGME) 21:551–558

Schot P, Winter T (2006) Ground water-surface water interactions in wetlands for integrated water resources management. J Hydrol 320:261–263

Sophocleous M (2005) Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA. Hydrogeol J 13:351–365

Spano D, Zinder RL, Duce P, Paw U KT (1997) Surface renewal analysis for sensible heat flux density using structure functions. Agri For Meteorol 86:259–271

Spano D, Zinder RL, Duce P, Paw U KT (2000) Estimating sensible and latent heat flux densities from grapevine canopies using surface renewal. Agri For Meteorol 104:171–183

Trick T, Custodio E (2004) Hydrodynamic characteristics of the western Doñana Region (area of El Abalario), Huelva, Spain. Hydrogeol J 12:321–335

Valero G-BL, Martí C, García R-JM, González S-P, Lorente A, Beguería S, Navas A, Machín J, Delgado H-A, Stevenson T, Davis B (2001). Lateglacial and early Holocene paleohydrological and environmental change along a humid-arid transect from the central Pyrenees to the Ebro valley (Spain). Terra Nostra 3:211–218

Winter TC (1999) Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeol J 7:28–45

Winter TC, LaBaugh JW (2003) Hydrologic considerations in defining isolated wetlands. Wetlands 23:532–540

Winter TC, Rosenberry DO, Kelly E, LaBaugh JW (2005) Comparison of wetlands in different hydrogeologic settings under conditions of extreme climate variability. Paper presented at the symposium of Dynamics and Biogeochemistry of River Corridors and Wetlands, Foz do Iguaçu, Brazil, April 2005, Int Assoc Hydrol Sci Publ 294:139–147

Yechieli Y, Wood WW (2002) Hydrogeologic processes in saline systems: playas, sabkhas, and saline lakes. Earth Sci Rev 58:343–365

Zapata N, Martínez-Cob A (2001) Estimation of sensible and latent heat flux from natural sparse vegetation surfaces using surface renewal. J Hydrol 254:215–228