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Long-term water monitoring in two Mediterranean lagoons as an indicator of land-use changes and intense precipitation events (Adra, Southeastern Spain)

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A B S T R A C T

During recent historical times the Adra river delta, a detrital coastal aquifer of nearly 32 km^2 located in a semi-arid, mountainous area of SE Spain, has undergone different changes caused by human activity. Within this context, both the river dynamics in the plain and the geomorphology of the coastline have at various times resulted in the formation of small lagoons. At present only two small (<0.5 km^2) lagoons exist, at the eastern edge of the aquifer, which, although closely surrounded by commercial market-garden greenhouses, are protected under international agreements. During the last 30 years of the twentieth century traditional agricultural irrigation techniques have undergone significant changes to improve their efficiency. Surface-water resources in the Adra river basin are regulated via the Beninar reservoir. In addition, the use of groundwater is increasing progressively. Both these factors affect the recharge of the coastal aquifer. To monitor these changes measurements of electrical conductivity and water level fluctuations have been recorded in these lagoons for the last 35 years (1975–2010). A comparison of the hydrochemical characteristics of the water in the lagoons and of the surrounding groundwater from 2003 to 2010 shows marked differences induced by the different hydrological dynamics in each lagoon, as well as by the hydrogeological impact of changes in land use in the delta. The increase in water demand is a consequence of the extension of irrigated areas from the fluvio-deltaic plain to its slopes, originally occupied by unirrigated crops. A reduction in irrigation return-flow is linked to the use of new irrigation techniques. These modifications affect both the recharge regime of the aquifer and its water quality. Moreover, extreme precipitation events, which are characteristic of Mediterranean semi-arid environments, can affect the lagoons' hydrological dynamics to a considerable extent. One such example is the unusually rainy period from January to March 2010 (>600 mm). This event, along with other effects, has dramatically lowered the salinity of the water in both lagoons. This case study reveals the extreme vulnerability of deltaic environments and also how lagoons can reflect anthropogenic changes over the whole river basin.

1. Introduction

1.1. General remarks

Worldwide, many wetlands were lost or highly degraded by human pressure during the twentieth century (Maltby, 1986; Castañeda and García-Vera, 2008;). Since the Ramsar Convention in 1971 [http://www.ramsar.org] several initiatives and projects have been undertaken to increase conservation awareness about these habitats. Among all Spanish wetlands, coastal lagoons are highly vulnerable to urban pressure, tourism, agriculture and coastal dynamics (Rodríguez-Rodríguez, 2007; Durán et al., 2009). Therefore, to protect these vulnerable environments adequately it is essential to monitor the changes produced both in the short- and long-term with the aim of investigating their causes and predicting their consequences (Meshal, 1987).

This work describes an analysis of the implications of anthropogenic changes throughout recent decades on the hydrological regime of a small wetland - the Adra lagoons. Due to its situation at the seaward end of a river basin of several hundred km^2, this type of wetland acts as a good indicator of the main human activities affecting land and water use both upstream and in the delta itself. Some activities, the construction of a reservoir upstream and the

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increase of irrigated areas, for example, have modified the water budget of the aquifer and the groundwater quality downstream, affecting the lagoons. Thus the connection between land use, aquifer levels and the lagoons' hydrochemistry is evident. To determine the human influence on the hydrological changes detected in these water bodies we have analysed different types of water bodies in the Adra river delta (ARD) area (Fig. 1). In this way we have been able to interpret how local-scale factors, such as land-use changes and efficient irrigation systems add to large-scale climatic variations and medium-scale factors to progressively alter the water balance of the lagoons.

The following paragraphs summarise the main features of the study area: location and extension, geology and hydrogeology, climate and economy, and provide a brief description of the geomorphological evolution of the study area since pre-Roman times.

1.2. Study site

We have studied two lagoons located on the Mediterranean seaboard of south-eastern Spain (Almería province): the Honda (meaning "deep") and Nueva (meaning "new") lagoons (Fig. 1). In the 1980s the two lagoons were environmentally protected as nature reserves under the management of the Andalusian Autonomous Government. In 1994 they were included in the Ramsar Convention list, which affords maximum protection for wetlands, mainly due to their harbouring waterfowl and autochthonous ichthyofauna (Montes et al., 2004). At present this protected complex occupies less than 0.5 km^2 (Paracuellos, 2009). The Adra river basin extends for over 750 km^2 from the Sierra Nevada mountains (peak elevation of 2800 m.a.s.l.) to the Mediterranean sea (Fig. 1).

The climate follows a typical Mediterranean semi-arid regime, with an average annual temperature of 18 °C (minimum in January of 11 °C and maximum in August of 26 °C). There are 3000 h of sunshine per year on average. The average annual precipitation is around 300 mm with a coefficient of variation of 0.36 for the period 1943–2009. The seasonal distribution of average rainfall shows that most of the rainfall occurs during the autumn (100 mm) and winter (120 mm). The geographic and orographic position of the ARD determines the type of winds affecting the lagoons; cold,

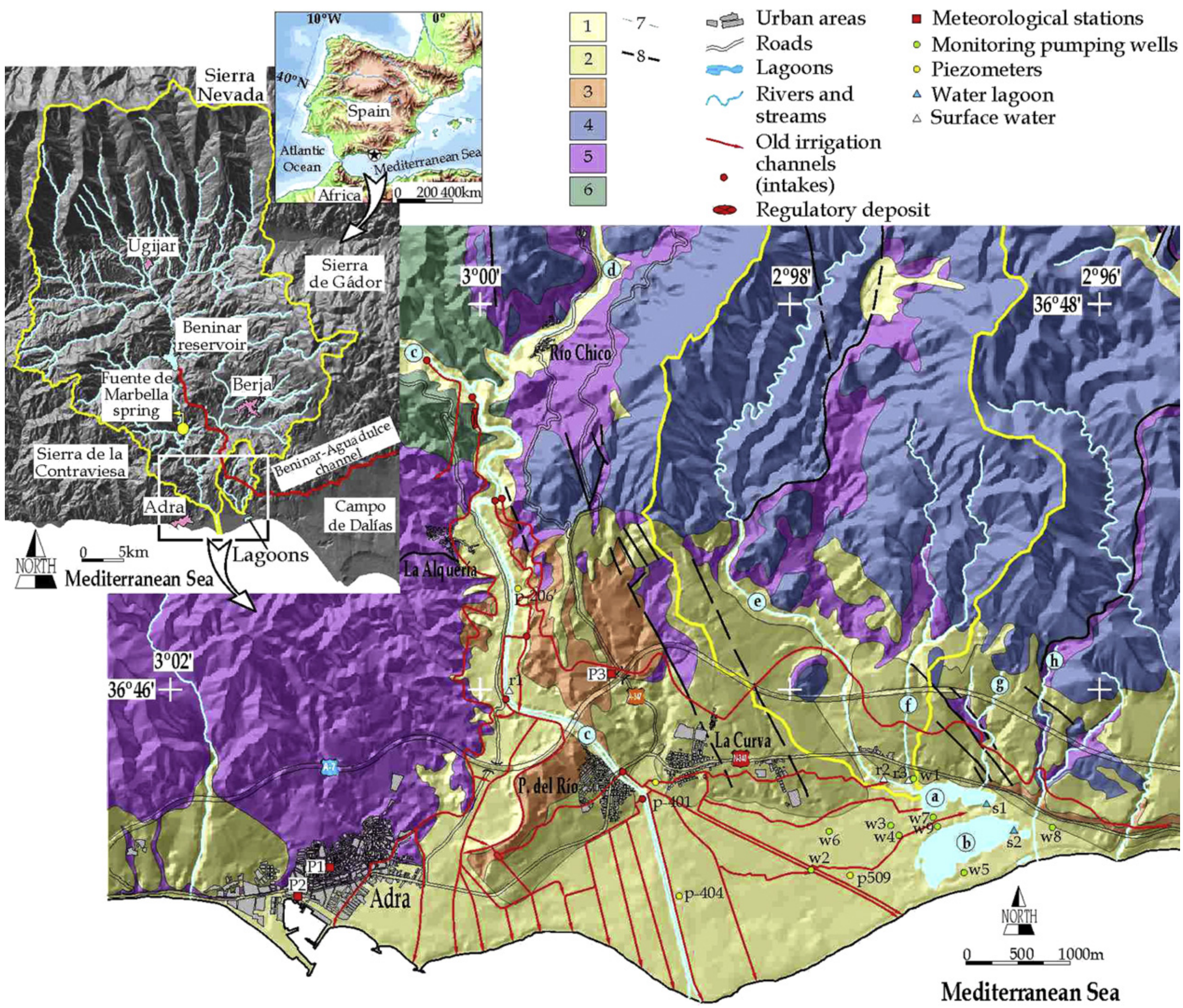

Fig. 1. Study area location showing sampling points and places of interest cited in the text. Geology: 1. Holocene deltaic, fluvial, marsh and aeolian facies; 2. Pleistocene glacis, marine terraces and colluvials; 3. Pliocene deltaic facies and upper-Tortonian calcarenites; 4. Permian to Triassic limestone and dolomites; 5. Permian to Triassic schists, phyllites and quartzites; 6. Palaeozoic schists and quartzites; 7. Geological contact; 8. Normal and thrust faults. Lagoons: a) Honda; b) Nueva. Rivers and streams: c) River Adra; d) River Chico; e) Estanquera stream; f) Adelfas stream; g) Malo stream; h) Infantes stream. The River Adra basin and the Estanquera stream catchment are singled out. Thermo-pluviometric stations: P1) Adra; P2) Adra-Faro; P3) Puente del Río Monitoring pumping wells: w1 to w9. Piezometers: p-216', p-401, p-404, p-509. Lagoon water sampling: s1) Honda; s2) Nueva. Runoff sampling: r1) River Adra; r2) Estanquera stream; r3) Adelfas stream.

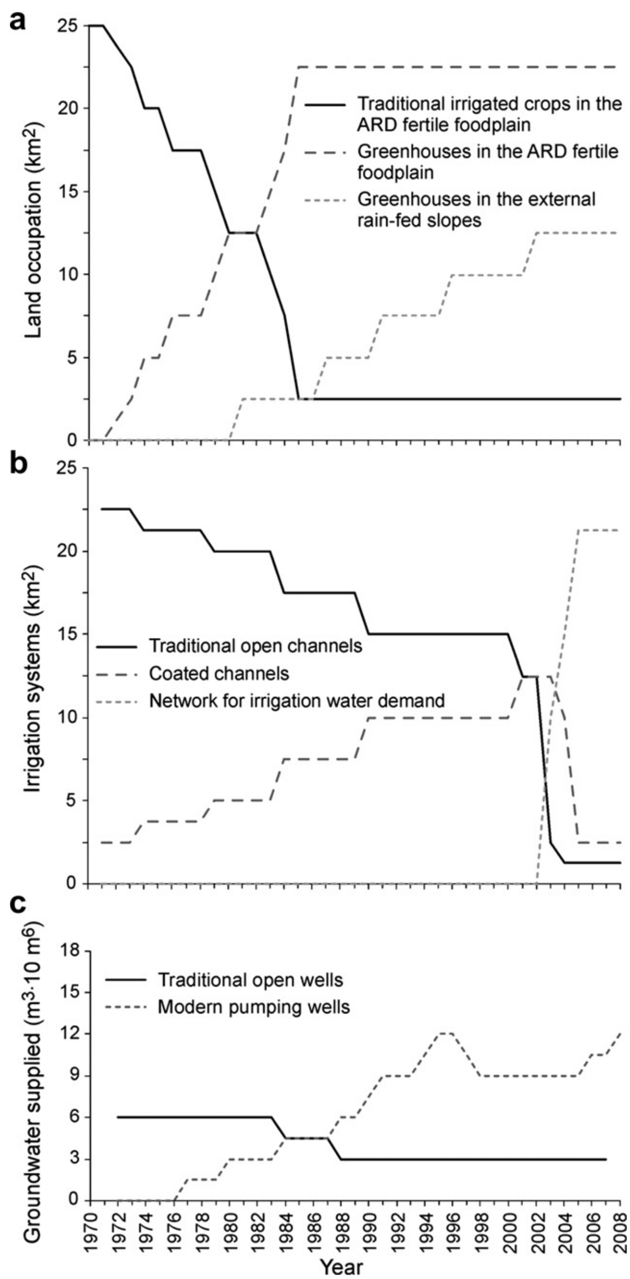

Fig. 2. Time-line of land use and implementation of irrigation systems in the ARD fertile floodplain and external rain-fed slopes: a) Land occupation by types of cropping systems. b) Surface covered by types of irrigation systems in the ARD fertile foodplain (data from the Adra river Water Users' Association). c) Groundwater supplied from scattered traditional open wells and modern pumping wells to complement irrigation allocation from the Adra river surface water.

northern and western, continental winds predominate in winter, whilst in summer and autumn a maritime wind blows mainly from the S and SE (Rodríguez-Rodríguez et al., 2004b).

The main geological features of the ARD are sketched out in Fig. 1. It is located within the Internal Zones of the Alpine Betic range, in the Alpujarride domain, a tectonic complex of low-to-medium-grade metamorphic rocks dating from the Palaeozoic to the Triassic (Sanz-de-Galdeano and Alfaro, 2004). Over this pre-orogenic metamorphic bedrock lie upper-Miocene to Quaternary marine and continental sediments filling a pronounced coastal depression (Goy and Zazo, 1986). The Holocene deposits where the lagoons in question are located are made up of sands, alluvial deposits from the river Adra and muddy silts (lagoon deposits).

The regional fault systems, which configure a sinking valley and delta, are the main reason for the presence of the wetland.

The lagoons are located at the south-eastern edge of the ARD area; the aquifer is located within this area. The ARD aquifer is a 32 km^2 unconfined groundwater body, 22 km^2 of which are of permeable outcrops made up of upper-Miocene calcarenites to Plio-Quaternary alluvial sediments, with an average saturated thickness of 100 m, overlying a fairly impermeable metamorphic bedrock.

Yearly average recharge is estimated to be 25 Mm^3 $year^{-1}$ (1 $Mm^3 = 10^6$ m^3); 1 Mm^3 is due to direct rainfall infiltration from permeable outcrops, 21.5 Mm^3 to preferential stream-bed infiltration in the river Adra alluvium and the remaining 2.5 Mm^3 to irrigation return flows (López-Geta et al., 1998). Water output is due to groundwater extraction for irrigation and urban water supply (16 Mm^3 $year^{-1}$), diffuse discharge through the coastline (7 Mm^3 $year^{-1}$) and evaporation from the surface of the lagoons (2 Mm^3 $year^{-1}$) (López-Geta et al., 1998). Diffuse discharge is evaluated as the residual of the aquifer water balance. These results were calibrated with piezometric maps and the mean values of the permeability and transmissivity of the materials along the coast.

1.3. Geomorphological evolution of the ARD area

The present-day appearance of the ARD area is related to the recent geodynamic evolution of the Betic range and geomorphological changes due to natural factors and human activities over the last three thousand years (Paracuellos, 2006; Durán et al., 2009; Jabaloy et al., 2010). In the eighth century B.C., the littoral area was influenced by Phoenician trade. At this time the shoreline of the mouth of the Adra river estuary ran along the foot of the alluvial fans. Expansion of agriculture, grazing and incipient mining during the Roman period, however, led to an increase in deforestation and consequent erosion in the Adra river basin, triggering sedimentary processes at the mouth of the estuary, which was then transformed into a small delta, originating the present-day "Vega de Adra" or Adra fertile floodplain. At the eastern edge of the delta the coastal sedimentary infill remained incomplete, resulting in the formation of phreatic lagoons. These coastal wetlands are mentioned in 16th century documents.

From the late 18th century onward intense deforestation took place in the Adra river basin in order to make way for modern large-scale mineral mining. The mining of galena ores was particularly extensive during the first half of the 19th century, giving employment to around 20,000 people. These works favoured wide-scale deforestation and consequent floods and dramatic changes in the course of the river during storms, causing many deaths in the area. The course of the riverbed was modified during the second half of the 19th century to prevent infection from malaria and similar diseases in the town of Adra and its neighbourhood (see Fig. 1 for the location of urbanised areas) and thus the former delta was disrupted. In 1910, after a huge flood that caused such severe damage that nearly a third of the population had to move from the area, the river was channelled to its current position. Soon afterwards, a new delta formed to the east and a series of sand bars developed. The new coastline dynamics gave rise to the Nueva lagoon at the end of the 1930s.

Finally, when the Beninar reservoir (Fig. 1) came into service in 1982 sedimentation in the new delta was reduced considerably (Jabaloy et al., 2010). The present position of the river, the lagoons and the infrastructures of the area can be seen in Fig. 1. The description and historic development of the area given above is summarised from Paracuellos (2006).

1.4. Information on human activities in the ARD area

We gathered together and compared exhaustive information on human activities developed at different times and places in the region in order to interpret the hydrological dynamics of the ARD area and the lagoons over the last 4 decades. On a medium-scale, the construction of the Beninar reservoir has been the most important human action (García-López et al., 2009). We also obtained information from the Adra River Basin Water Users' Association and checked against old aerial photographs, land-use maps and documents related to agricultural practices and field campaigns. A detailed census of land use and the evolution of irrigation systems throughout recent decades was conducted to study the relevance of local-scale factors, such as land occupation and crop types, the evolution of irrigation systems and water distribution efficiency, and the increasing use of water pumped from wells, on the water dynamics in the lagoons.

2. Methods

2.1. Morphometric analyses

We measured six morphometric characteristics of the lagoons: maximum length, mean and maximum width, mean and maximum depth, shoreline length, shoreline development and overall volume (Hutchinson, 1957). The morphometric analysis of the catchment area was carried out using a digital terrain model developed by the Andalusian Agency for the Environment (A.M.E., 2005). We measured the maximum flooded surface, altitude and drainage-basin area of the lagoons by means of ArcGIS© (ESRI, 2004). Bathymetric data were processed by Surfer© (Bresnahan and Dickenson, 2002). Finally, we carried out field tests to check the results obtained.

2.2. Meteorological data

Meteorological data were obtained from three weather stations, which provided similar records due to their proximity (Fig. 1). We chose the Adra station (P1) to represent the study area due to its longest series and immediacy to the lagoons. Daily data from April 2003 to February 2010 were obtained from the Andalusian Agency of Fisheries and Agriculture webpage [www.juntadeandalucia.es]. These data were analysed to obtain precipitation (mm) and average air temperature (°C) in monthly steps. Monthly potential evaporation (ET_0) was computed using Penman's method (Chen et al., 2005).

2.3. Hydrochemical data

We chose to sample four different types of water bodies (Fig. 1): (1) groundwater samples of the ARD aquifer from seven pumping wells around the lagoons (w1-w7) in May 2007 – samples were taken after removing stagnant water from the wells and were preserved until laboratory analysis; (2) two samples of runoff from the Estanquera and Adelfas ephemeral streams (r2, r3) (which feed the Honda lagoon) during a rainy event on the same dates as the groundwater samples; (3) fourteen samples of water in the lagoons taken at a depth of 0.5 m at 5 m from the shore in the vicinity of the limnimetrical gauges (s1, s2); and (4) eight samples from the Adra river (r1). The last two groups of samples were taken during different visits to the study area between 2002 and 2007.

Water temperature and EC were measured *in situ* using a WTW® portable waterproof conductivity meter (model LF 318). Between 0.5 °C and 99 °C accuracy is ±0.1 °C for temperature and ±1 μS/cm for EC. Chloride, sulphate, calcium, magnesium, sodium and potassium were analysed in all these samples following EPA methods (Hautman and Munch, 1997). A Dionex-1000® liquid ionic chromatograph was used. Bicarbonates were obtained by titration. The charge imbalance among samples ranged from 0.8 to 4.0%. The hydrochemical data were then implemented as a database in AquaChem©.

A total of 83 monthly electrical conductivity (EC) values for each lagoon from 2003 to 2010 were provided by the Andalusian Agency for the Environment. Sixteen complementary EC measurements from between 1975 and 2010 were taken from the literature (Rodríguez-Rodríguez, 2002; Benavente et al., 2003; Rodríguez-Rodríguez et al., 2004b).

2.4. Water-level data

A monthly record of experimental water-level data in each of the two lagoons [limnimetric scales at sites s1 and s2 (see Fig. 1)] were provided by the Andalusian Agency for the Environment. Complementary data were used to enlarge the series. With regard to fluctuations in groundwater table, a monthly piezometric record from 1970 to 2008 was provided by the Andalusian Water Authority from 3 piezometers along the Adra riverbed and another near the lagoons (Fig. 1).

2.5. Water balance

The water budget in a given surface water body can be expressed in terms of volume per surface unit (i.e. mm) for a given time interval. Monthly time steps have been used to show water level fluctuations throughout a hydrological year, as follows:

$$V = P - E + S_I - S_O + G_I - G_O \quad (1)$$

where V = variation of water storage in the lagoon, as water level fluctuations measured in limnimetric scales divided by the average flooded surface, AFS; P = rainfall directly onto the lagoon as recorded by the Adra weather station (P1); E = actual evaporation from the flooded surface as recorded by the P1 weather station; S = surface water; G = groundwater.

The subscripts I and O mean water inputs to the lagoon and outputs from the lagoon respectively. S_I represents runoff events into the Honda lagoon from both the Estanquera and Adelfas ephemeral streams (Fig. 1), while S_O is overflooding events. G_I means ARD aquifer discharge into the lagoon and G_O ARD aquifer recharge from the lagoon.

There are two seasonal scenarios to solve the monthly water budget:

(1) Rainy periods from autumn to spring.

Sporadic runoff and ARD aquifer recharge events occur, producing variable quantities of S_I, S_O, G_I and G_O. The piezometric network in the ARD aquifer allows us to make a theoretical estimation of G_I and G_O. The quantification of S_I becomes unreliable, however, in the ungauged Honda lagoon catchment area. The curve-number (CN) procedure -aSCS-based method (McCuen, 1982) -was implemented to compute daily runoff in the catchment area. The method takes into consideration the antecedent soil-moisture condition (AMC), types and absence of soil and vegetation, natural and human land use, and slope gradient. Runoff accounts only for large and intense rainfall events.

In the CN procedure, the maximum instantaneous water-storage capacity (C) of a soil during a given rainfall event is quantified as:

$$C = (25,400/CN) - 254 \quad (2)$$

where C is a function of CN groups (McCuen, 1982; Boughton, 1989). After making appropriate assumptions, the daily S_I can be calculated via Equation (2) as follows:

Table 1
Morphometric characteristics of the lagoons.

	Honda lagoon	Nueva lagoon
Lagoon Area (A; hm^2)	9.4	27
Maximum length (L_{max}; m)	586	759
Shoreline length (L_o; km)	1.5	2
Maximum depth (z_{max}; m)	3.19	3.8
Volume (V; hm^3)	0.12	0.63
Catchment area (A_c; hm^2)	1300	50
Mean width ($B_m = A/L_{max}$; m)	160	357
Mean depth ($z_m = V/A$); m)	1.3	2.3
Relative depth ($z_r = 100{*}z_{max}/(A{*}p)^{1/2}$; %)	1.8	1.2
Shore development $DL = L_o/2(A{*}p)^{1/2}$)	1.4	1.1
z_m/z_{max}	0.4	0.6
A_c/A	138.7	1.8
(A_c/V; m^{-1})	110.3	0.8

$$S_I = 0 \quad \text{if} \quad P < 0.2C$$
$$S_I = (P-0.2C)^2/(P+0.8C) \quad \text{if} \quad < 0.2C < P < 4.2C$$
$$S_I = P - C \quad \text{if} \quad P > 4.2C$$

where P is daily rainfall.

The calculation of CN takes into account types of soil and land use described by Alcalá et al. (2001) and Martín-Rosales et al. (2007). In the studied area CN varies from 45 in areas without soil in limestone, 55 in lower alluvial deposits with Rendzic Leptosols, 65 in terraced floodplains and glacis with Eutric Cambisols, to 90 in areas covered by greenhouses. A weighted average of CN = 61 was obtained to compute runoff.

The AMC is a function of the total rainfall in the 5-day period preceding a storm. The CN is CN_{II}, which corresponds to a mean AMC value of soil. Whereas CN_{II} was used in the intermediate periods, new equations to evaluate CN_{II} dry periods (CN_I) and rainy periods (CN_{III}) were adopted from Boughton (1989):

$$CN_I = CN_{II}/(2.334 - 0.01334 \cdot CN_{II}) \tag{3a}$$

$$CN_{III} = CN_{II}/(0.4036 - 0.0059 \cdot CN_{II}) \tag{3b}$$

$CN_{II} = 61$, $CN_I = 40.1$ and $CN_{III} = 79.9$ were the values used to compute runoff in dry and rainy periods respectively.

S_O values were derived from direct observation of overflowing from the Honda into the Nueva lagoon in winter and numerical modelling of the water level.

(2) Dry periods in summer, from June to August.

During these periods, $P \sim 0$ results in $S_I = S_O \sim 0$. An aquifer hydraulic gradient of less than 0.001 produces negligible ARD aquifer discharges, which allows us to ignore the effect of G_I and G_O in the lagoon dynamics. Thus Equation (1) can be simplified to:

$$V = -E \tag{4}$$

Four consecutive hydrological years (2006–2009) were chosen to calculate a monthly water budget in both lagoons. During this period, assuming that steady hydrological conditions persist in the lagoons during the summer of two consecutive years, a comparison of the experimental values with the V values estimated from Equation (1) would give us the G_I and G_O magnitudes occurring in the lagoons during that period.

3. Results

3.1. Morphometric analyses

The morphometric characteristics of the lagoons are shown in Table 1. Both the Honda and Nueva lagoons are small bodies of water of 9.4 and 27 ha (1ha = 10^4 m^2) respectively. There is a considerable difference in the surface of their catchment areas (13 km^2 for the Honda lagoon compared to 0.5 km^2 for the Nueva lagoon). The catchment area draining into the Honda lagoon is shown in Fig. 1. The streams are mainly ephemeral and are only subject to flash flooding during very heavy rainfall events, as will be discussed later (Table 2).

3.2. Meteorological data

The precipitation record reveals a large-scale trend from 1980 onward for lower annual rainfall according to the overall average for the period 1970–2009. This dry period was particularly acute during the drought of 1990–1995, which was finally interrupted by the abnormally rainy year 1996. But once again, average to low precipitation has predominated since 1997. 2010 was an exceptional winter because of the very heavy rainfall registered from January to March (>600 mm), which is twice the annual average (Fig. 4).

3.3. Hydrochemical and physicochemical data

Fig. 3 shows the hydrochemical facies for the different water bodies sampled from 2002 to 2007.

The Adra river is the main source of recharge, which controls the hydrochemical baseline of the ARD aquifer (El-Amrani et al., 2007). Both the Adra river water and groundwater contain chloride-sulphate mixed-water facies and have EC values in the range of 2–3 mS/cm.

We could only obtain two runoff water analyses of ephemeral streams because of the difficulty of sampling during the sporadic runoff events. The EC values are 0.4 and 2 mS/cm, with mixed sodium- and calcium-type facies.

Table 2
Main statistics of the climatic variables used in the water balance calculations and actual depth of the lagoons (mm) from June 2006 to February 2010. GW: groundwater; OF: overflow ($m^3 \times 10^3$).

	$ET_{oPENMAN}$ (mm)	Rainfall (mm)	Air Temperature (°C)	Runoff (mm)	Honda Depth (mm)	Nueva Depth (mm)	Honda GW[a] ($m^3 \times 10^3$)	Nueva GW ($m^3 \times 10^3$)	Honda OF ($m^3 \times 10^3$)	Nueva OF ($m^3 \times 10^3$)
N° values used	47.0	47.0	47.0	45.0	47.0	47.0	45.0	45.0	45.0	45.0
N° values ignored	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
Minimum	51.3	0.0	10.9	0.0	2090.0	3650.0	−16.1	−85.4	0.0	0.0
25th Percentile	63.4	1.1	14.2	0.0	2640.0	3750.0	−14.6	−77.5	0.0	0.0
50th percentile (Median)	108.7	20.5	17.6	0.0	2760.0	3780.0	−5.5	−38.3	0.0	0.0
75th Percentile	156.7	43.5	22.0	0.3	2955.0	3830.0	4.0	−13.0	0.0	0.0
Maximum	170.8	250.2	26.0	50.9	3500.0	4530.0	674.9	108.3	584.1	1140.5
Average	108.5	32.0	18.2	2.0	2841.7	3822.8	19.0	−37.3	17.7	43.9
V.C.(St.deviation/Average)	0.4	1.4	0.2	3.8	0.1	0.0	5.5	−1.1	5.0	4.3

[a] GW > 0 = groundwater recharge, GW < 0 = groundwater discharge.

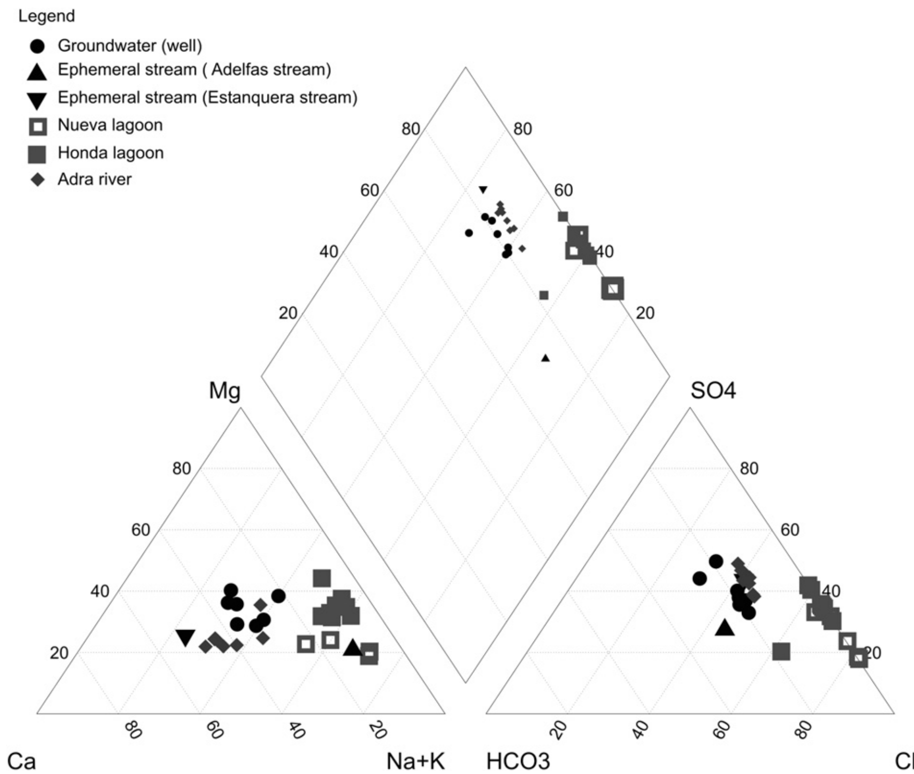

Fig. 3. Piper diagram showing the hydrochemical facies in the groundwater of the ARD aquifer, the two main ephemeral streams in the Honda lagoon basin, water from the lagoons and from the river Adra. Symbol size in the central diamond portion is proportional to the EC of the sample.

The lagoon water has sodium-chloride facies. In the Honda lagoon chloride ranges from 55% to 70% of the total ions, whilst in the Nueva lagoon it ranges from 60% to 80%. In the Honda lagoon EC ranges from 5 to 7 mS/cm and in the Nueva lagoon from 6 to 11 mS/cm. The historical evolution of EC in the lagoons and the main human impacts mentioned above are plotted in Figure 4A. It must be born in mind, however, that there are periods of several years with an absence of EC data. The monthly evolution of EC in the lagoon water and monthly precipitation from 2003 to 2010 are plotted in Figure 4B. There is a general seasonal pattern, with lower EC values following periods of high precipitation. Disregarding the abrupt decrease in EC at the end of the monitoring period, it may be inferred from Fig. 4 that there has been an increasing trend in EC in the Nueva lagoon. The opposite seems to be the case, however, in the Honda lagoon. The summer increases in EC (labelled as “summer trend” in Fig. 4B) are similar in both lagoons except for the unusual increase in summer 2007 in the Nueva lagoon (Fig. 4B).

3.4. Water-level data

An analysis of changes in the water level of both water bodies (Fig. 5) revealed six episodes of surface water entering into the Honda lagoon, causing rapid rises in the water level. When its depth rises to above 3.5 m the Honda lagoon overflows and the Nueva lagoon receives part of the $S_I + G_I$ as S_O, as shown in Fig. 5. This occurred in April 2008, January 2009 and January 2010. The most recent episode also resulted in the overflow of the Nueva lagoon (water depth > 4.5 m) and its artificial drainage into the sea to prevent flooding in the area. Maximum monthly overflow (OF) was quantified as 584 10^3 m^3 in the Honda lagoon (Dec. 2009) and 1140 10^3 m^3 in the Nueva lagoon (Feb. 2010).

The evolution of the ARD aquifer water table along the Adra riverbed shows that large phases of cyclicity coincide, allowing us to interpret at the main pulses of recharge on groundwater stored (Fig. 6). This is due to large-scale controls induced by climate and the lamination that the Beninar reservoir imposes on the groundwater flow. The effect at local-scale is observed as a decrease in the water table towards the discharge area (the coastline).

3.5. Water balances

A comparison between the real and expected water levels in the lagoons each summer during the hydrological years 2006–2009 is plotted in Fig. 7A. The monthly water budget allows us to interpret the water level fluctuations throughout a hydrological year. Monthly P and ET_O values from the weather station P1 were compared with computed S_I values, S_O observations and experimental G_I and G_O values to obtain monthly V values. Since these variables are needed to estimate the water balance in rainy periods, the water balance becomes simpler in the summer due to the absence of surface–groundwater interactions.

In dry periods, if the theoretical evolution shows a decreasing trend compared to the real measured evolution, it must be assumed that groundwater from the ARD aquifer (G_I) is entering the lagoons. In the case of the Nueva lagoon it can be seen that groundwater was discharging into the lagoon at a similar rate throughout the months of June to August of 2006–2009. In the Honda lagoon there were lower rates of groundwater discharge than in the Nueva lagoon during 2006 and 2007. Then the trend was reversed in 2008 and 2009 and the lagoon began to recharge the aquifer. So, the hydrological regime of each lagoon is different: the hydrological system of the Honda lagoon can act as a recharge or discharge water body, depending upon the relative position of its water level and the

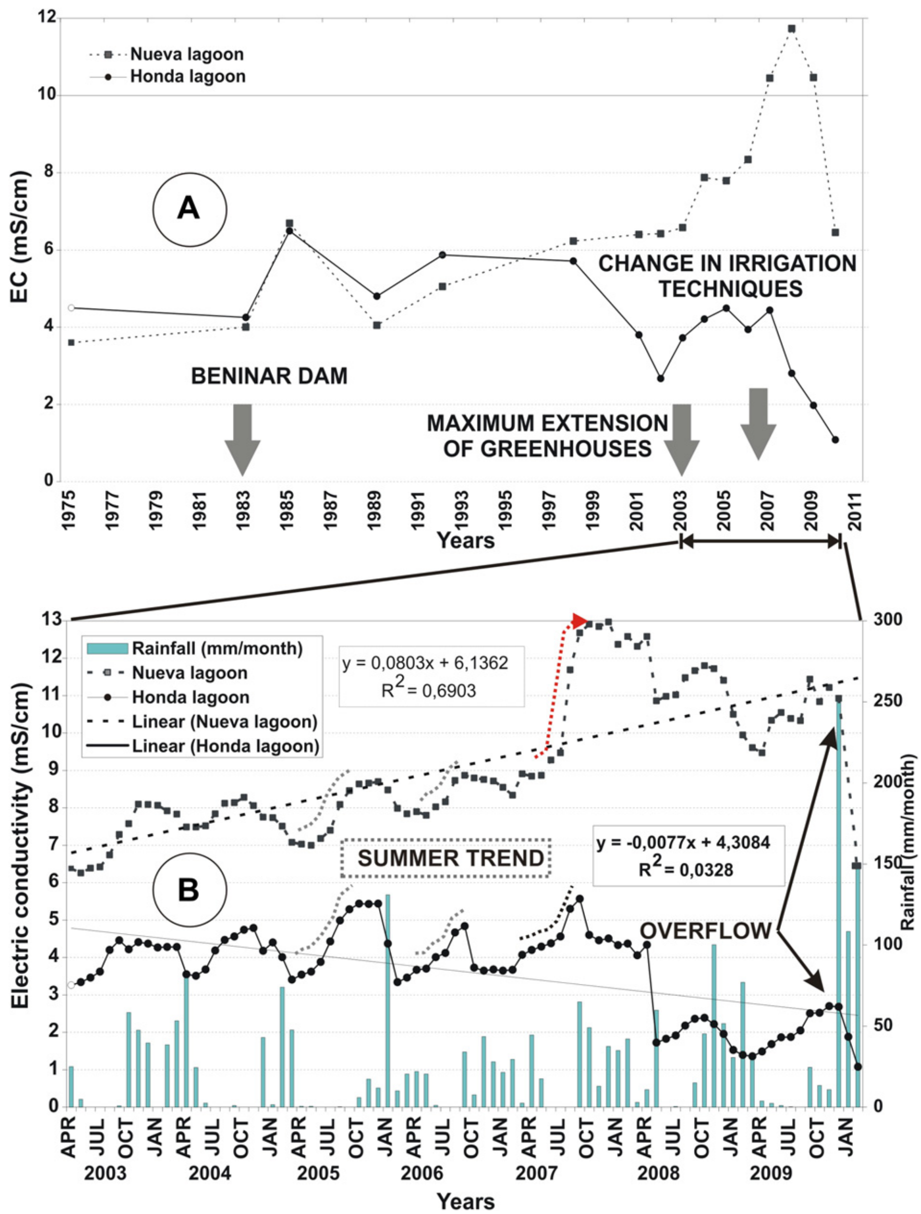

Fig. 4. A) Evolution from 1975 to the present of the EC of the water in the Honda and Nueva lagoons. The main changes in land use are indicated with arrows and specified within the figure. B) Evolution from 2003 to 2010 of the EC of the water in the Honda and Nueva lagoons. Dotted grey lines indicate summer salt concentrations; the red line shows the effect of a transient episode of seawater intrusion into the Nueva lagoon in summer 2007. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

phreatic level of the ARD aquifer in the sector. The Nueva lagoon undergoes a lower range of changes in water level due to its proximity to the coast. The piezometric levels of the ARD aquifer in that sector are also fairly stable. In this situation water loss by evaporation in the lagoons is compensated by groundwater discharge into the lagoons, at least during summertime.

Finally, an estimation of two components of the water balance in both lagoons, groundwater (GW) and overflow (OF), can be seen in Fig. 7B. Groundwater discharge (negative values) is predominant in the Nueva lagoon, with an average monthly discharge of 37.3 10^3 m^3 and a median monthly discharge of 38.3 10^3 m^3. Significant episodes of groundwater recharge are common during rainy periods in the Honda lagoon. The data show an average monthly recharge of 19.0 10^3 m^3 but a median monthly discharge of 5.5 10^3 m^3 during the study period. This means that the Honda lagoon is normally receiving groundwater discharge from the ARD aquifer, except during rainy periods.

4. Discussion

4.1. Using tracers to assess the impact of human activity on the lagoons

The use of physical tracers such as the electric conductivity (EC) of water has proven to be an efficient tool for the understanding of the hydrological regime in this type of ecosystem (Laudon and Slaymaker, 1997). In fact, a multivariate approach has shown itself to be successful in studies of these types of lagoon in both undisturbed and altered systems (Medina-Gomez and Herrera-Silveira, 2003; Tapia-Gonzalez et al., 2008).

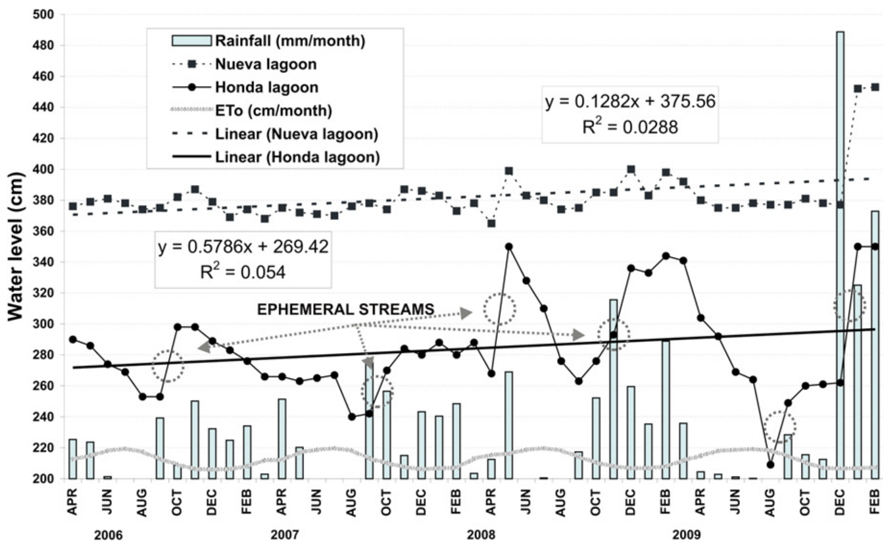

Fig. 5. Evolution from 2006 to 2010 of the water levels in the Honda and Nueva lagoons. Circles show episodes of surface water entering the Honda lagoon.

Dilution processes, produced by inland freshwater are conspicuous in the Honda lagoon. We have recorded six dilution episodes due to incoming water ($G_I + S_I$) from April 2006 to February 2010 (Fig. 5). In the Nueva lagoon we have not recorded these dilution processes so clearly. The catchment area of the Honda lagoon is 26 times bigger than that of the Nueva lagoon (see Table 1) and the generation of runoff is the main hydrological process causing its dilution. Nevertheless, the exceptionally high increase in EC

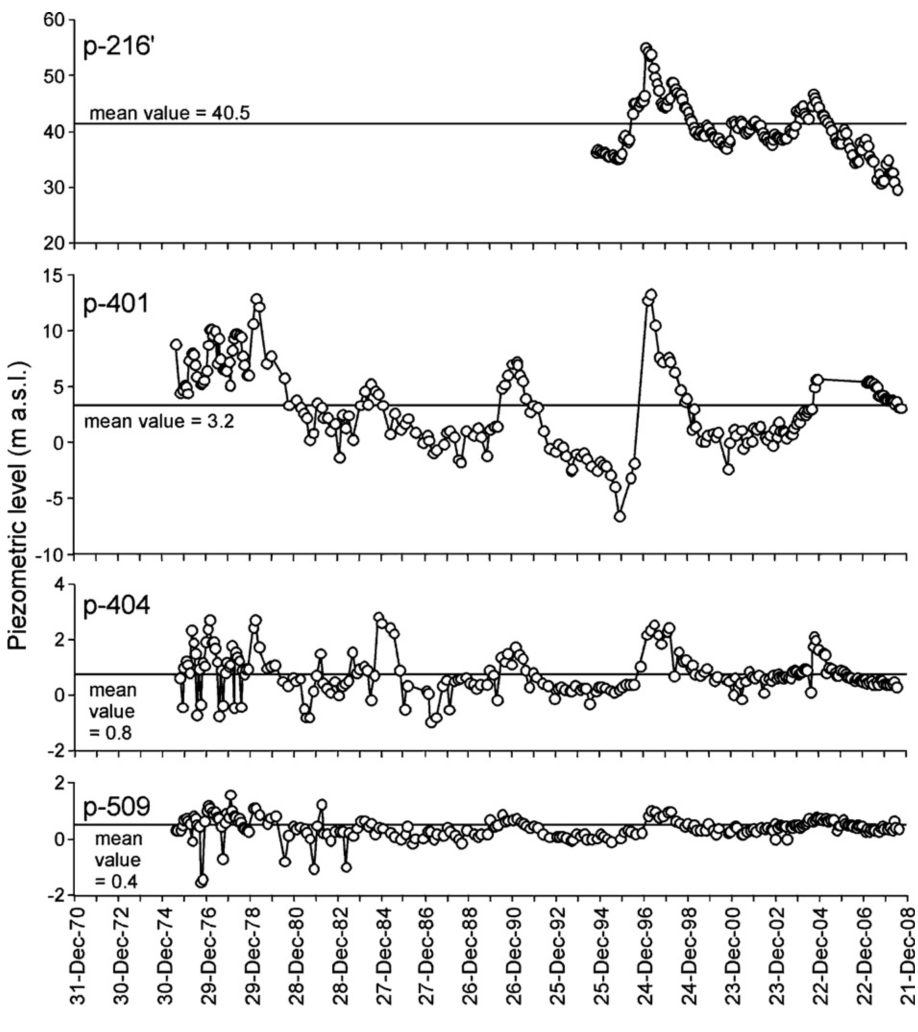

Fig. 6. Piezometric evolution of the ARD aquifer (siting of piezometers in Fig. 1).

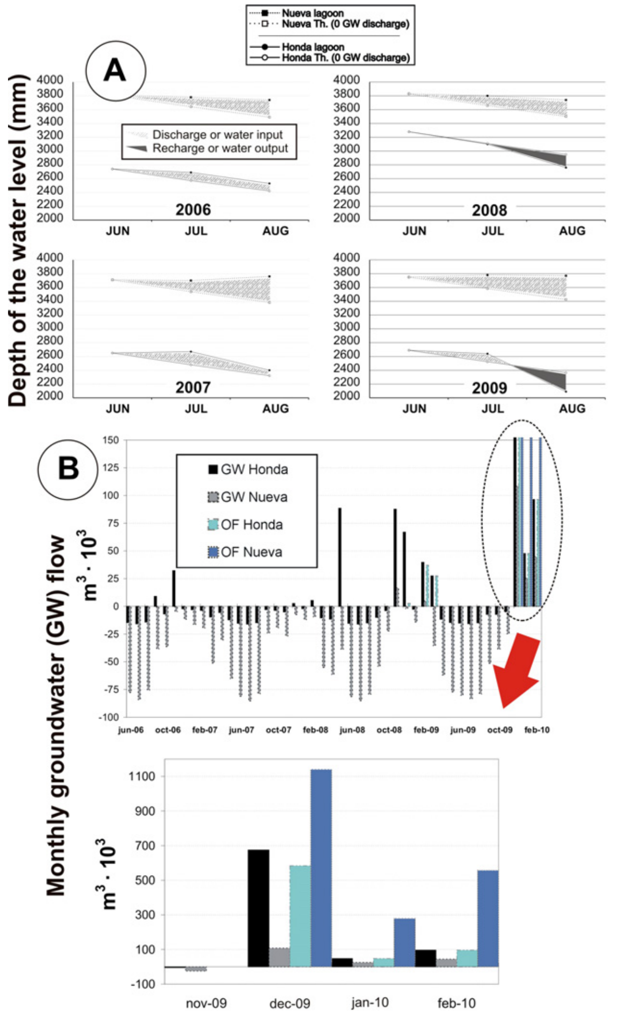

Fig. 7. A) Actual *vs*. Expected water levels (WL) during dry periods considering no GW discharge/recharge from the ARD aquifer (June–August 2006 to 2009). WL: water level (mm). Th.: theoretical. B) Estimation of the monthly GW discharge/recharge from ARD aquifer to the lagoons (i.e. discharge means water input to the lagoons and recharge means water output from the lagoons to the aquifer) and overflow into the Mediterranean sea (June 2006 to February 2010). GW: groundwater; OF: overflow.

observed in summer 2007 in the Nueva lagoon (see Fig. 4B, “summer trend”) is likely due to a transient episode of marine intrusion during which the subsurface seawater–freshwater transition zone moved inland and upwards in the lagoon area. This marine intrusion was caused by a local decrease in the recharge/pumping ratio brought about by the operation of new deep wells to complement the supply of irrigation water.

The existence of a thick brackish–freshwater transition zone below the lagoons was confirmed by means of an exploratory geoelectrical survey (Benavente and Rodriguez 2000). Groundwater salinity decreases inland and is therefore less pronounced in the Honda lagoon.

A general inverse relationship between EC data and volume of water storage in the two lagoons was observed in a previous work (Benavente et al., 2003). We have corroborated this trend with a more exhaustive series of data collected systematically since 2006 (Fig. 10). This data has allowed us to clarify the hydraulic behaviour of the two lagoons. In the Honda lagoon the high water levels and reduction in salinity are linked to the influx of large volumes of freshwater. We have recorded higher EC values, between 4 and 7 mS/cm, in the Nueva lagoon. Variations in EC are not related to changes in the volume of water stored in the lagoon. The increase in EC in the Nueva lagoon is particularly evident from 2002 to 2008. During this time, both traditional and waterproofed irrigation channels, which discharge comparatively freshwater into the Nueva lagoon, were removed (Fig. 2).

The different functioning of each lagoon was revealed clearly by analysing the monthly water levels of the lagoons and EC data from 2006 to 2009 (Figs. 4 and 5). A range of more than 1500 mm in water level was recorded in the Honda lagoon, whilst the Nueva lagoon only altered by some 500 mm during the same period. The Honda lagoon overflowed more than three times and after the rainy period that ended in May 2008 the EC of the water dropped from more than 4 mS/cm to less than 3 mS/cm. Water EC in the Nueva lagoon increased progressively during 2006 and 2007 but showed signs of a decreasing trend in 2008 and 2009. After the heavy rainfalls that ended in February 2010 the Nueva lagoon overflowed, flooding the nearby agricultural terrains, and had to be artificially drained towards the sea.

4.2. Implication of natural and human factors on the local water budget

A conceptual hydrological model for the Adra lagoons is depicted in Fig. 8. The model includes the magnitude of major water-budget terms and the relationship of both lagoons with the ARD aquifer in the framework of a brackish–freshwater transition zone, which fluctuates landward according to the reduction in freshwater fluxes and increases in local pumping and evaporation in dry periods, and seaward in rainy periods.

In the dry season aquifer hydraulic gradients of less than 0.001 and transmissivities in the range of 200–900 m^2/day (Pulido et al.,

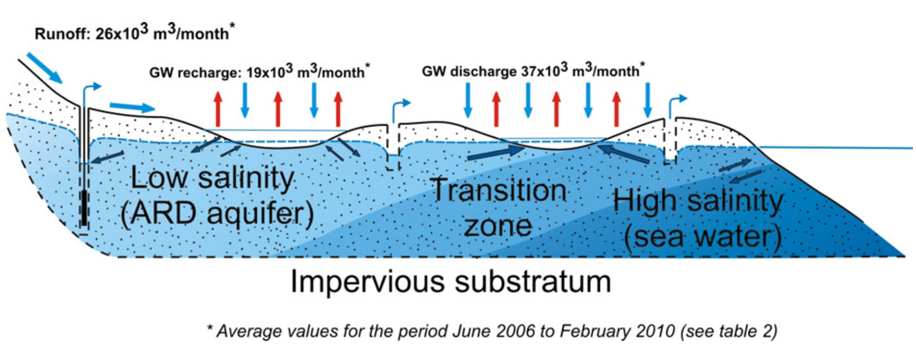

Fig. 8. Hydrogeological simplified sketch of the ARD aquifer in the sector of the lagoons. Limits for low-to high-salinity waters are often blurred and subject to seasonal groundwater dynamics. Blue arrows: surface water inputs; dark blue arrows: groundwater interactions; red arrows: water evaporation from the lagoons. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

1988) result in negligible aquifer discharges, which allow us to ignore the effect of G_I and G_O on the lagoon dynamics. In rainy periods the hydraulic gradient of the aquifer rises to produce an ARD aquifer discharge of about 8000 m^3 into the sea, as has been found previously by Alcalá et al. (2008).

An investigation into the hydrological regime using piezometric measurements and water balances, and physical limnology in the Adra lagoons carried out in 2004 (Rodríguez-Rodríguez et al., 2004a) found that the presence of the two water bodies at the south-eastern edge of the ARD aquifer reduces groundwater discharge to the sea in that sector of the aquifer because of the high evapotranspiration rates in the flooded and vegetated surface area of this wetland.

4.3. Processes acting on different spatio-temporal scales that control the water dynamics of the lagoons

The hydrological dynamics of the ARD coastal lagoons can be suitably evaluated in the framework of the well-known evolution of anthropogenic activities that took place in the Adra river basin and the ARD area. As with other Mediterranean areas, these shallow lakes are characterized by their fast dynamics and subsequent lack of predictability, caused by both climate variability and the effects of human activity (Becares et al., 2004).

Several factors on both large to local spatio-temporal scales appear to control the magnitude of changes observed in the lagoons. The large-scale factors are determined by climate variability. Global precipitation and air-temperature patterns, as well as stream flow and drought recurrence in terrestrial mid-latitudes are shown to be control by global climate cycles. The global models predict a reduction in overall precipitation but an increase in sporadic, intense rainfall events in some areas (Alcalá et al., 2008). The medium-scale factors may be catalogued as human actions which permanently affect the hydrological regime downstream, such as the construction of the Beninar reservoir in the 1980s. The Beninar reservoir (Fig. 1) has a potential storage capacity of 63 Mm^3, although its actual storage capacity is no more than 30 Mm^3 due to water loss through a Triassic karstic aquifer, a problem that remains unresolved (García-López et al., 2009). The water losses have significantly increased the discharge of an important spring downstream, the Fuente de Marbella (Fig. 1). In fact most of the Adra river baseflow through the ARD area corresponds to this spring's discharge, which, in addition, is quite saline (around 2 g/L) due to the dissolution of gypsum interbedded within the Triassic carbonate rocks. The reservoir was intended to provide additional water resources for irrigation and human consumption in areas located farther to the east of the Adra river basin, through the Beninar-Aguadulce channel (Fig. 1). Before the Beninar reservoir came into operation, the average flow rate of the river Adra through the ARD area was a maximum of 3–6 m^3/s in springtime (García-López et al., 2009), due to melt-water from the Sierra Nevada mountains (Fig. 1). The baseflow in late summer was around 0.4–0.8 m^3/s. This flow was diverted at the entrance of the ARD area by a network of irrigation channels (Fig. 1). The operation of the Beninar reservoir has led to the lamination of higher flow rates downstream and the above-mentioned increase in the Fuente de Marbella discharge. The consequence has been a general reduction in the natural recharge from the Adra river to the aquifer that has brought about a deterioration in the chemical quality of both the river Adra surface water and the groundwater of the ARD aquifer, especially in the sectors with most intensive groundwater recycling for irrigation [increase in agricultural pollutants, and nitrates in particular (García-López et al., 1991)]. Fortunately, in the vicinity of the lagoons this increase in pollutants may be limited by natural denitrification processes induced by the presence of organic matter caught up in the sediments (El-Amrani et al., 2007). This process seems to decrease the bicarbonate content of the water in the lagoons (Fig. 3). An overall modulation of water-table fluctuations occurred after the Beninar reservoir was put into service, as shown at point p-401. Rainy periods, such as the one that occurred in 1996, resulted in high, but not extreme, phreatic levels, while local pumping effects produced negative values in the water level at p-404 and p-509 (Fig. 6).

The local-scale factors caused by changes in land use, improvements of irrigation systems and the increase in groundwater supplied from the ARD aquifer over recent decades (Fig. 2) have had negative effects on the water level of the lagoons.

The progressive tendency to replace traditional irrigated crops for intensive crops grown in plastic greenhouses started in the 1970s and was almost complete by the late 1980s (Fig. 2a). Today, greenhouses extend out of the fertile floodplain along the rain-fed slopes of the delta valley. This trend has levelled off in recent years due to the Andalusian government's prohibition of new greenhouses. The new irrigated areas have not meant an increase in the demand for water, since a parallel tendency to improve the irrigation systems was promoted by the water authorities and users as a water-saving measure (Fig. 2b). Nevertheless, this combination of actions has reduced the returns of irrigation water to the aquifer. The measure was taken to prevent huge water wastage by progressively replacing traditional, gravity-fed, open channels dug directly into the soil with channels with a waterproof coating. Since early 2000 both the open channels and the waterproof channels were replaced by a so called "demand-oriented" irrigation system. This system starts at a single regulatory deposit that derives water for irrigation from the beginning of the ARD aquifer (Fig. 1) and conducts it through pressure-driven pipes.

Since in summer the flow of the river Adra is insufficient to cope with water demand, groundwater is used to complement allocation, especially at the south-eastern side of the delta. Groundwater was usually pumped from open wells before being diverted into the irrigation channels, but from the mid-1980s these wells have been phased out in favour of deeper, more efficient, drilled pumping wells (Fig. 2c).

5. Conclusions

In Mediterranean, semi-arid, seaboard environments the impact of human activities such as deforestation, grazing and changes in agricultural land use has been very significant, causing relatively rapid changes in coastal morphology by the deposition of considerable loads of sediment. Coastal and fluvial dynamics control the generation of wetlands (lagoons), their migration, or even their disappearance. The case in hand is a paradigmatic example of this situation. From the mid 20th century to the present day the Adra lagoons have witnessed urban and agricultural growth, the development of tourism, the introduction of modern irrigation systems and the conversion of irrigation schemes, which have involved regulating water resources either by building dams or by increasing the pumping of groundwater. These actions have had particularly striking effects on the hydrological regime of the lagoons.

The estimation of the water balance in the Adra lagoons indicates that groundwater discharge from the Adra river delta (ARD) aquifer is predominant in the Nueva lagoon. The Honda lagoon normally receives groundwater discharge from the ARD aquifer, although during periods of intense rain the lagoon supplies the aquifer with a significant recharge - or water output.

The study of series of water levels and electrical conductivity in the lagoons, together with hydrochemical data concerning these lakes and of the ARD aquifer, has served to trace:

(1) the major effects of anthropogenic activity in the Adra river basin; and
(2) the consequences of sequences of drought and heavy rainfall deriving from the semi-arid climate of the region.

The Beninar reservoir has modified the recharge of the ARD aquifer because it has denied the input of surface melt-water deriving from the spring thaw. The transformation of traditional farming systems to greenhouses, both inside and outside the floodplain, has been accompanied by additional groundwater withdrawal. This has affected the old wells and galleries that used to capture water from the alluvial aquifer in this sector. In addition, there has been an increase in recycling processes from irrigation water (pumping-irrigation-percolation-pumping), especially in the eastern half of the aquifer, where irrigation with groundwater is most important. The extension of the brackish–freshwater transition zone has increased. Finally, the replacement of irrigation channels with piped systems under pressure has resulted in general in a reduction in the recharge to the ARD aquifer and also of the water inputs into the lagoons, although the effects differ: whereas the salinity of the Nueva lagoon has increased that of the Honda lagoon has decreased.

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