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Hydro-environmental changes assessment after Guadalhorce River mouth channelization. An example of hydromodification in southern Spain

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ABSTRACT

The Guadalhorce River mouth (Málaga, Southern Spain) was channelized between 1997 and 2003 to reduce flooding potential in adjacent densely populated sections of Málaga. The channel was bifurcated near the Mediterranean Sea, surrounding an isolated wetland complex composed of eight different ponds. Groundwater-level and wetland-stage data, combined with water-chemistry data from wells and wetlands, collected since 1977, have documented the hydrological and ecological responses to channelization. The results show that channelization has extended the tidal influence inland from the Mediterranean Sea through the Guadalhorce River and the subjacent coastal aquifers, producing a change in groundwater hydrodynamics. The isolation of the wetlands resulting from channelization has provoked a significant salinization of both surface water and groundwater, the extent of which varies among wetlands. These decadal-scale changes in water chemistry have promoted the appearance or increase of halophilic vegetation and have caused a shift from diving birds to predominantly shorebirds in some wetlands. Documentation of these unexpected ecosystem responses is a necessary first step for land managers who need to consider groundwater and surface water as a single resource, particularly in groundwater-dependent ecosystems along the densely populated and ecologically sensitive Mediterranean coastal areas.

1. Introduction

Prevention of floods in riverine areas is a great concern for the humankind. For example, approximately 500,000 people were displaced between 1998 and 2004 (EEA, 2011), only in Europe, and about 25 billion euros of property damage were estimated. This concern is increasingly higher in densely populated urban settlements and their associated facilities for residential, industry and leisure uses. Several anthropogenic actions have been conducted worldwide to minimize flood risks, such as the construction of dams, dredging of rivers and modification of the original river courses, including their channelization, among others (USEPA, 2007). The latter comprises one of the most applied engineering practices for controlling river flood risk and draining wetland areas, among other purposes (Schoof, 1980; Brookes, 1981; Brookes and Shields, 1996).

USEPA (1993) defines the term *hydromodification* as the “alteration of the hydrologic characteristics of coastal and non-coastal waters, which in turn could cause degradation of water resources” induced by anthropogenic actions. Hydromodification activities are grouped into three categories (USEPA, 2007): channelization and channel modification, dams and streambank, and shoreline erosion. In this way, channelization and channel modification include actions such as straightening, widening, deepening, and clearing channels of debris and sediment.

However, these engineering solutions usually have an important hydrological impact (Watson et al., 1999), causing changes in water velocity and sediment transport capacity (Brookes, 1988). They also have hydrogeological effects, such as modifications in the groundwater discharge into streams (LaSage et al., 2008), marine intrusion (Petalas, 2013), tidal flooding and seawater encroachment (Carol et al., 2014). Regarding surface water/groundwater exchange, Constantz et al. (2016) demonstrated alterations in the biogeochemical processing and in the ecological systems.

Aquatic biodiversity can also be affected by hydromodification, with remarkable detrimental effects on fish populations, like changes in populations, biomass or total density (Swales, 1980, 1982), and changes in plant communities (Haslam, 1973, 1978) through deforestation and land-use conversion to agriculture (Shankman, 1996).

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Habitat of riverine areas can also be negatively affected (Brooker, 1985), due to the impact on river corridors, fish populations, macroinvertebrates, aquatic vegetation, birds or bankside trees. Although human-induced impact on river ecosystems is widely documented in the scientific literature (Middleton, 1999; Simenstad et al., 2006), little is known about hydrogeological changes (i.e., groundwater/surface water fluxes, salinization, etc.) derived from river channelization.

Hydromorphological pressures are the most commonly occurring type of pressure on surface waters in Europe, affecting 40% of all such bodies, which is approximately an overall number of 44,455 (EEA, 2018). Of this percentage, almost 60% corresponds to physical alterations in the channel, bed, riparian zone and shore, whose objective is flood protection and agriculture. In the Mediterranean European countries, close to 12,000 surface water bodies are affected by hydromorphological pressures (EEA, 2018). In Spain, around 2800 surface water bodies are under pressure (EEA, 2018), as can be observed in almost every river that passes through a city. One example is the Turia River, next to Valencia, which was completely diverted around the south edge of the city to avoid flood risk (Puertes and Francés, 2016).

The Guadalhorce River basin (S Spain) is a highly anthropized Mediterranean watershed (3150 km^2) that covers about 43% of the eastern territory of Málaga province. Historically, there was a Phoenician settlement in this area, as demonstrated by a historical site built over a little hill in the Guadalhorce River mouth, to avoid flood risk. Likewise, numerous flood events have occurred in the mouth area, very often with catastrophic consequences, such as substantial property damage in adjacent urban and industrial areas, and even human casualties (Perles et al., 1999b). After the historical floods of 1989, where several people died, regional authorities decided to channelize the Guadalhorce River, and split it in two branches at its ending stretch. These works took place between 1997 and 2003, and isolated a coastal wetland complex (Guadalhorce Delta Wetlands) composed of 8 pools (Nieto et al., 2015, 2018).

Apart from some previous works studying the impact of channelization on the hydrological and hydrogeological properties of natural water bodies (Servicios Omicron, 1995; Lucena and Carrasco, 2000) and their habitats (Perles et al., 1999a, 1999c), no additional studies have been carried out in this area. Moreover, there are very few studies with multidisciplinary and transversal approaches regarding hydraulic infrastructures, and even less works involving hydrology, hydrogeology, biology, vegetation, habitats, etc.

Thus, the aims of this investigation were: (1) to analyze the hydro (geo)logical impact of channelization works on the Lower Guadalhorce River Basin (LGRB), (2) to determine the hydrological interactions between surface water and groundwater in such coastal sector and, (3) to assess the influence of ecohydrological changes after the river hydromodification on the current birdlife and vegetation.

2. Study area

2.1. Location and general features of the study area

The Guadalhorce River mouth is located in the SW edge of Málaga city, in Southern Spain (Fig. 1). Its land topography is practically flat, typical of a river delta physical setting, and it is surrounded by urban and industrial areas and relevant transport infrastructures (i.e., international airport, motorways, etc.). The natural part of the delta is characterized by the existence of a wetland complex, which is physically constrained between the two branches of the Guadalhorce River at its end-reach. Despite its high degree of human-induced modification, the Guadalhorce River mouth is environmentally protected since 1989 by the regional authorities because of its rich biodiversity and hydrological and ecological value.

Initially, the Carmen Marshes (local name given to the original coastal wetlands) existed in the Guadalhorce River mouth until 1977 and usually got flooded by sea waves lashing, originated by the eastern winds. Since 1977, the extraction of sands and gravels started in this area to satisfy the emerging demand of construction materials in the city of Málaga. In 1982, the digging works stopped and, as a result of this, numerous land depressions remained in the ground, with a remarkable modification of the original Carmen Marshes. The man-made land holes, showing different sizes and depths, favored the modification in the dynamics of the preexisting lagoon system (Guadalhorce Delta Wetlands, hereafter GDW) as a consequence of the water infiltration from the Guadalhorce River, the groundwater flow from the underlying aquifers and the seawater intrusion from the Mediterranean Sea. After the declaration of the protected area, refilling and topographic restoration works have been implemented by the regional government (Andalusian Environmental Office, 2005) to reduce the number of dug depressions, as well as to perform the morphological adaptation of the land surface and to implement re-vegetation environmental initiatives.

2.2. Land use changes

Several decades ago, farming was predominantly developed throughout the entire LGRB with citrus, orchards and vegetables, as well as several other irrigation and non-irrigation crop modalities. Among these, the sugar cane crops prevailed near the coastal sector, requiring a large water supply.

The change in the land use between 1996 and 2015 is shown in Fig. 2. Numerous changes associated with the channelization are visible: all the farming lands existing in the Guadalhorce River shore and in the mouth disappeared, giving room for a great artificial and controlled flooding area. However, other relevant changes have taken place in this period in the territory, such as the enlargement of the Málaga airport and the industrial areas of the Guadalhorce River left margin, in addition to an increment of residential and leisure urbanization, in both margins. Thus, agricultural use of land in the coastal area of the LGRB was reduced from 42% to 17%. On the other hand, naturalized areas increased from 23% to 32%, since the required flooding area of the river was no longer allowed for any other uses.

Land cover changes associated with the Guadalhorce River channelization coincide with other cases in Europe, such as the floodplain area along the Danube River, where almost 20,000 km^2 out of 26,000 km^2 of land surface were isolated by levees (Tockner et al., 2008). In Europe, 95% of the original floodplain area of rivers has been converted to other uses (EEA, 2018). In some cases, works have been carried out to improve navigation instead of controlling floods, although both goals are achieved in most of them. Moreover, new land uses around channelized rivers can have negative effects due to the discharge of diffuse or punctual pollutants.

Nowadays, the land use of the last stretch of the Guadalhorce River, before its mouth, is characterized by the presence of industrial areas and the International Airport of Málaga, and also by a 9% increase of the urbanized area (Perles et al., 1999b).

2.3. Geomorphology

The LGRB has the typical relief of a fluvial valley in which the Guadalhorce River flows along a SE-NW axis. Although the altitude values in most of the valley are between 0 and 100 m a.s.l., with slopes lower than 5%, the entire coastal sector can be considered to be flat.

The geomorphological changes associated with the channelization of the Guadalhorce River mouth and its groundwater dependent ecosystems (GDW) can be observed in the selected aerial snapshots corresponding to the last 60 years (Fig. 3). In the 1950 s, a noticeable flooded area can be observed in the previously mentioned Carmen Marshes, although the meander-like shape of the Guadalhorce River, at the North of the mouth, is also visible. The depressions originated by the aggregates extractions are present from 1977, and the modifications in the morphology of some wetlands can be observed after 1998, as well as the isolation of the meander.

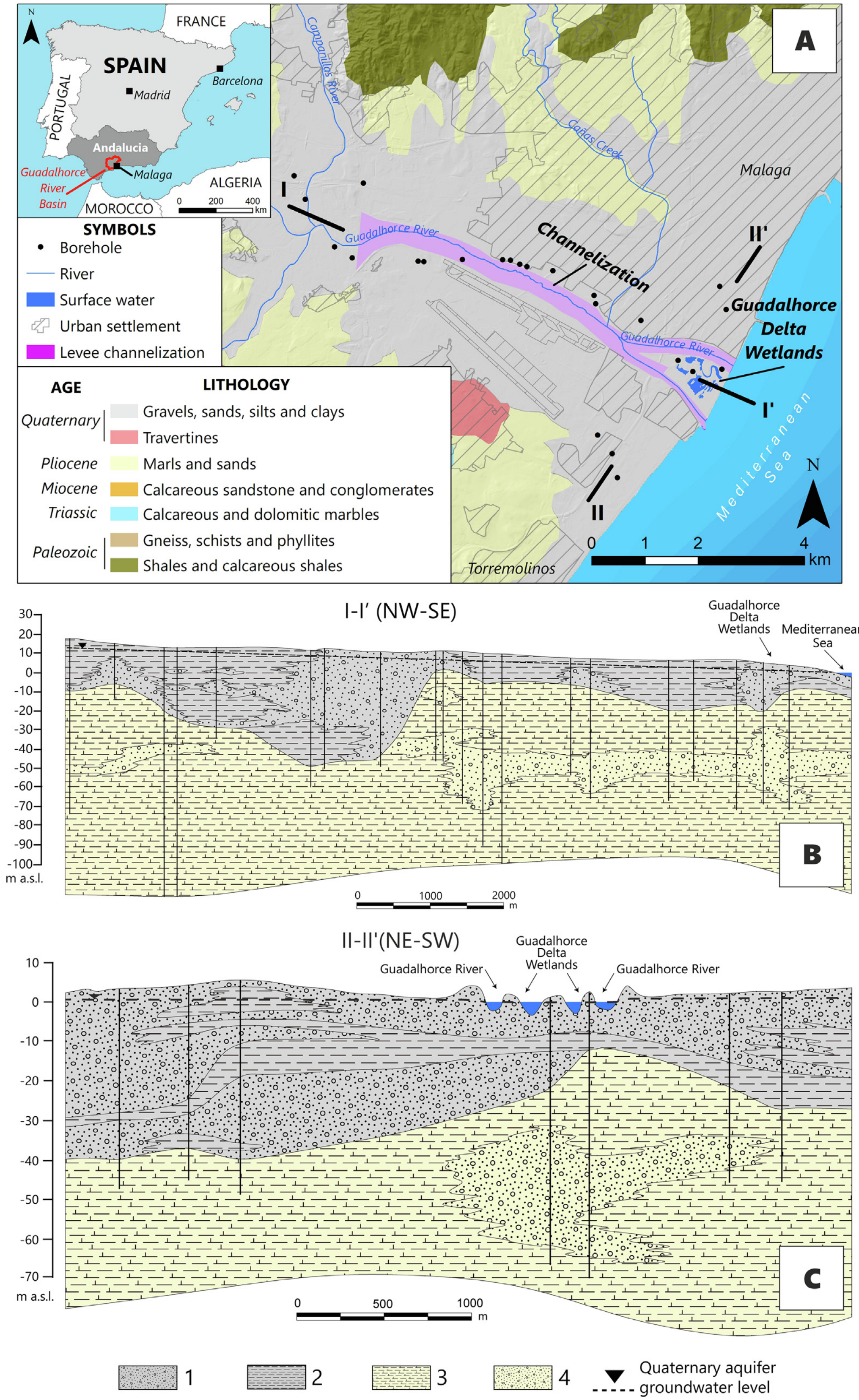

Fig. 1. Location and lithological map of the study area (A). Hydrogeological sections I-I' and II-II' (B and C) are also shown (modified from IGME, 1983; Linares et al., 1995). Legend: 1: Quaternary aquifer with predominance of gravels and gross sands. 2: Quaternary aquifer of sands, silts and clays. 3: Low permeability Pliocene of clays and marls. 4: Pliocene aquifer composed of gravels and sands. Note the different scale bars matching both hydrogeological sections.

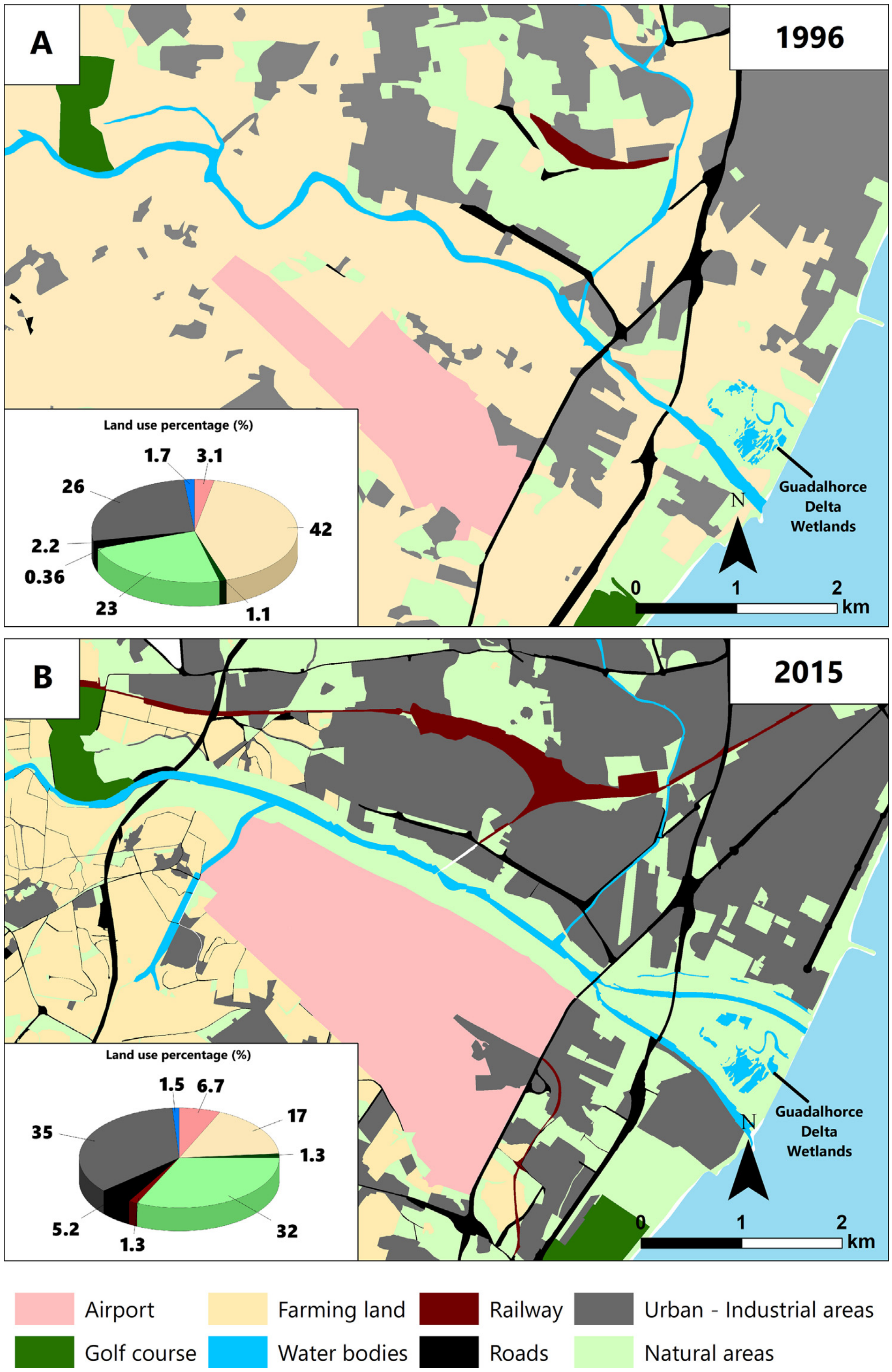

Fig. 2. Topic cartography displaying land use assessment in the Guadalhorce River mouth in 1996 (A) and 2015 (B) snapshots (REDIAM, 1996 and SIOSE, 2015).

A considerable reduction of the farming area in the surroundings of the mouth took place along the years, as well as the disappearance of some marshes and the expansion of the urbanized area. Channelization works took place between 1997 and 2003 and the resulting water facility is 7 km long, 350 m wide and 2 m deep, also at the mouth (the bottom of the channel is −2 m a.s.l.), thus isolating the Guadalhorce Delta Wetlands, which is a protected natural area. The incision of the Guadalhorce River bed throughout the length covered by the channelization has also posed a great change in the morphology and hydrodynamics of the area (Garrido and Alba, 2008), as it improves groundwater pathways towards the river and makes it easier for sea tides to advance inland through it.

2.4. Geology and hydrogeology

In the LGRB (Fig. 1A), the shallower Quaternary (unconfined) aquifer is composed of alluvial sediments (gravels, sands, silts and clays) that crop out over 115 km^2 of land surface. It is the most recent geological formation of the Málaga sedimentary basin (Fig. 1B-C), whose infilling is constituted by slightly deformed sediment layers (Sanz de Galdeano and López-Garrido, 1991). The underlying rocks are Upper Miocene calcareous sandstones and conglomerates, and Pliocene

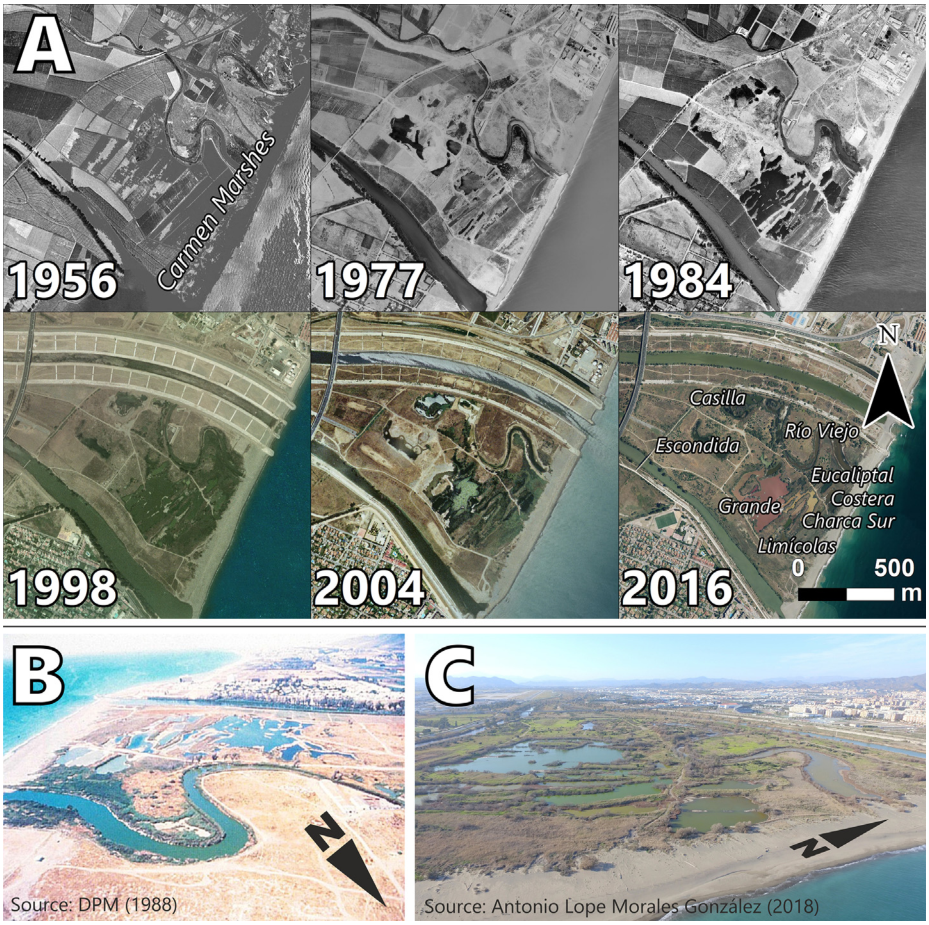

Fig. 3. (A) Mosaic of aerial photos showing the geohydromorphological evolution of the Guadalhorce River mouth and wetlands during the last sixty years (REDIAM, 2018). See reference of each wetland in the 2016 frame. North arrow and scale are the same for each photo. B-C) Aerial photographs of the Guadalhorce River mouth and its wetland complex (GDW), before (B) (courtesy of DPM, 1988) and after (C) (courtesy of Antonio Lope Morales González – 2018) the river hydromodification.

conglomerates (confined aquifer), marl and sand layers, which can be over 300 m thick. The latter lithology (< 20 m thick), acting as a semi-confined aquifer (IGME, 1983; Linares et al., 1995), is characterized by a very low specific yield (10^{-3}-10^{-4}) and average hydraulic conductivity values of 8–16 m/day. The Quaternary alluvial aquifer (30–50 m thick) is found stratigraphically over the former sediments (IGME, 1983; Linares et al., 1995) and its hydraulic properties are higher than those of the Pliocene aquifer (specific yield of 10^{-2}-10^{-3} and hydraulic conductivity of 7–1,300 m/day) (IGME, 1983; Nieto et al., 2016).

Groundwater from the Quaternary and Pliocene aquifers has been historically exploited for traditional farming (Linares et al., 1988), human consumption for Málaga city, which stopped in the mid-1990 s. Thus, groundwater drawdown below the sea has been recorded in numerous cases during the summer season at the coastline, favoring the seawater intrusion inland, towards both aquifers. However, the channelization works (1997–2003) in the river favored the change in land use, reducing the irrigated areas and, consequently, the groundwater pumping of about 15 hm^3/year (Andreo et al., 2002).

3. Methodology

3.1. Source of existing data

Groundwater table (Quaternary and Pliocene aquifers), wetland stage (Guadalhorce Delta Wetlands), electrical conductivity (EC) and hydrochemical data have been collected over the years in different locations of the LGRB (Table 1). These data have been obtained from field measurements and water sampling campaigns by the Spanish Geological Survey -IGME- between 1977 and 2003, the Andalusian Environment and Land Management Office (1997–1998) (Andalusian Environmental Office, 1998), the Andalusian Environment and Water Agency (2002–2013) and the Center of Hydrogeology of the University of Málaga -CEHIUMA- (1996). It is important to mention that the groundwater monitoring network has changed over the years, since the land use change has removed most of the points measured by the IGME.

Rainfall data have been obtained from the Spanish Weather Agency (AEMET) and from the Farming and Fishing Research Institute of Andalusia (IFAPA) between 1976 and 2017.

Bird species censuses are being carried out annually since 1997 by the Andalusian Environment and Water Agency, always accounting pairs and chicks in the nesting period (April-August) for each wetland.

3.2. Field work and analytic determinations

Between 2013 and 2017, several parameters were measured (wetland stage, groundwater levels, electrical conductivity, temperature, pH and dissolved oxygen) and 359 samples were taken from different kinds of waters, to determine their hydrochemical composition. This was carried out in wetlands, with monthly periodicity, and in April 2017 in a groundwater sampling network composed of wells and piezometers over the LGRB. Groundwater was first pumped for several minutes to purge the well in order to obtain the most representative sample.

The electrical conductivity and temperature of the water samples were measured using a WTW™ Cond 3310 device, with ± 0.5% and ± 0.1 °C accuracy, respectively. The pH and dissolved oxygen levels were measured with a ± 0.002 pH accuracy HACH™ HQ40d device. For the determination of the major ions in the waters between 2014 and 2017, with 2% accuracy, an ion chromatography METROHM® equipment, model 881 Compact IC pro, was used. The HCO_3^- concentration was calculated by H_2SO_4 0.02 M titration until reaching pH 4.45.

Due to the known interaction between groundwater and surface

Table 1
Source of hydrological data taken in the LGRB.

Data source (institution)	Type of data*	Sampling period	Sampling periodicity
Spanish Geological Survey (IGME)	GWT, GWHD	1977–2003	Monthly, bi-annual
Andalusian Environment and Land Management Office	WHD	1997–1998	Bi-monthly
Andalusian Environment and Water Agency	WS, WHD	2002–2013	Monthly
Center of Hydrogeology of the University of Málaga (CEHIUMA)	GWT, GWHD, WS, WHD	1996, 2013–2017	Monthly

* GWT: Groundwater table data; GWHD: Groundwater hydrochemical data; WS: Wetland stage; WHD: Wetland hydrochemical data.

water, groundwater table was measured in different points to determine the potential influence of the channelization on the Quaternary and Pliocene aquifers. To this end, a 50 m OTT Hydromet™ KL010 sounding line, with an accuracy of 0.01 m, was used. Moreover, all the points surrounding the Guadalhorce Delta Wetlands were leveled.

Historical groundwater level measurements in the Quaternary and Pliocene aquifers have been carried out in two different periods (1977–2001 and 2006–2017) and in two different pairs of piezometers, located very close to each other. These piezometers are called 84 and 85 (1977–2001) and P-2 and P-3 (2006–2017). They are screened at different depths from the surface, to sample water coming from the two subjacent aquifers; 84: 22–66 m, 85: 5–27 m, P2: 35–70 m and P3: 0–30 m. This combination of data is due to the structural damage shown by points 84 and 85, corresponding to the Pliocene and Quaternary aquifers, respectively, thus coherent groundwater level measurements cannot be obtained after 2001.

3.3. Statistical methods

The Mann-Kendall non-parametric test (Mann, 1945; Kendall, 1975) was applied to verify the existence of trends in selected water quality parameters and in birdlife metrics. This test also allows analyzing the magnitude of the trend, thanks to the modifications made by Sen and Hirsch (Sen, 1968; Hirsch et al., 1991). The Mann-Kendall test has been traditionally used for trend detection in weather and hydrological data; however, in this study it was applied to the time series of individual hydrological and ecological target parameters. Several authors (Hirsch et al., 1982; Esterby, 1996; Grath et al., 2001; Lee and Lee, 2003; Mendizabal et al., 2012; Urresti et al., 2012) have also applied this method to verify temporal trends in this type of environmental parameters. The Mann-Kendall test does not consider previous distributions of data and its power is similar to that of parametric methods (Serrano et al., 1999).

The Mann-Kendall parameter (S) is calculated as follows (Gilbert, 1987):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$$

where

$$sgn(x_j - x_i) = \begin{cases} 1; \; if x_j > x_i \\ 0; \; if x_j = x_i \\ -1; \; if x_j < x_i \end{cases}$$

and x_i and x_j are the data values for times *I* and *j*; *n* indicates the length of data series. A positive S value indicates an increasing trend, while a negative S value indicates a decreasing trend. A value close to 0 will indicate that no trend exists.

4. Results

4.1. Spatial-temporal variations of groundwater levels and properties of water in the Quaternary and Pliocene detrital aquifers

The spatial distribution of groundwater levels in the Quaternary aquifer during 1996 and 2017 (Fig. 4) evidences distinctive hydrodynamic conditions. In 1996, the piezometric surface shows a generalized flow towards the Guadalhorce River and the Mediterranean Sea in May –high water conditions– (Fig. 4A) and October –low water conditions– (Fig. 4B), as well as the presence of a preferential flow (western sector), only in May 1996, which matches a more transmissive aquifer zone coinciding with palaeochannel sedimentary structures. Several depressions in the potentiometric surface were also observed as a consequence of discrete groundwater pumping in the coastal area of the LGRB, particularly in October 1996.

In 2017, the groundwater flow in the Quaternary aquifer distributed towards the river and to the sea in its ending stretch, regardless of high water (February) or low water (August) conditions. However, there was a noticeable decrease of levels (> 1 m a.s.l. in some points) in the entire vicinity of the mouth in 2017 (Fig. 4C and 4D) compared to 1996 (Fig. 4A and B). The groundwater flow throughout the palaeochannel structure presents now a different morphology.

A more detailed view of groundwater and surface water hydrodynamics shows different behaviors between a wet (Fig. 4E) and a dry period (Fig. 4F) in the GDE of the Guadalhorce Delta Wetlands. The water table measured in wells was, generally, higher than in the wetlands. In February 2017 (Fig. 4E), there was a flow from the Grande and Costera Wetlands to the other wetlands, as well as some flow from the Quaternary aquifer. Moreover, all flows moved towards the Mediterranean Sea and the Guadalhorce River branches. This general flow changed in August 2017 (Fig. 4F), when the Escondida and Casilla Wetlands acted as recharge wetlands to the other wetlands and to the aquifer. Nevertheless, it is difficult to establish a distinctive flow pattern between the Quaternary aquifer and the wetlands, since there were several discharge, recharge and transit relationships in both periods. Arrows indicating water fluxes help to understand the functioning of the relationships between groundwater and wetlands in distinctive hydrodynamic situations.

Fig. 5 reflects the variability of the water table in both the wells and the wetlands for the June 2016-December 2017 period. In this way, points closer to the Mediterranean Sea and to the north branch of the river show higher amplitudes (max level – min level) and coefficients of variation (CV). The typical tidal amplitude, which influences groundwater level measurements at the local scale, is also shown. Nieto et al. (2016) demonstrated that the Mediterranean Sea tidal regime affects local groundwater levels in the studied coastal wetlands, hindering the accurate delineation of potentiometric maps.

Distinctive groundwater dynamics in the Quaternary and Pliocene aquifers have been observed along the years (Fig. 6). The variations of the water table in the Quaternary aquifer were lower than 2 m throughout the periods. Meanwhile, greater changes (> 6 m) were recorded in the Pliocene aquifer from 1977 to 1997, as a consequence of its confinement, and also due to the groundwater pumping. During and after the channelization works, pumping decreased in the area, as a result of the decrease of cultivated area, and narrow head variations occurred in both Pliocene and Quaternary aquifers, showing an ascending response favored by rainfall (Fig. 6). Coinciding with the starting of the works, the piezometric head in the Pliocene aquifer became higher (~1 m) than in the Quaternary aquifer, showing practically the same behavior.

Time series of electrical conductivity (EC) and chloride

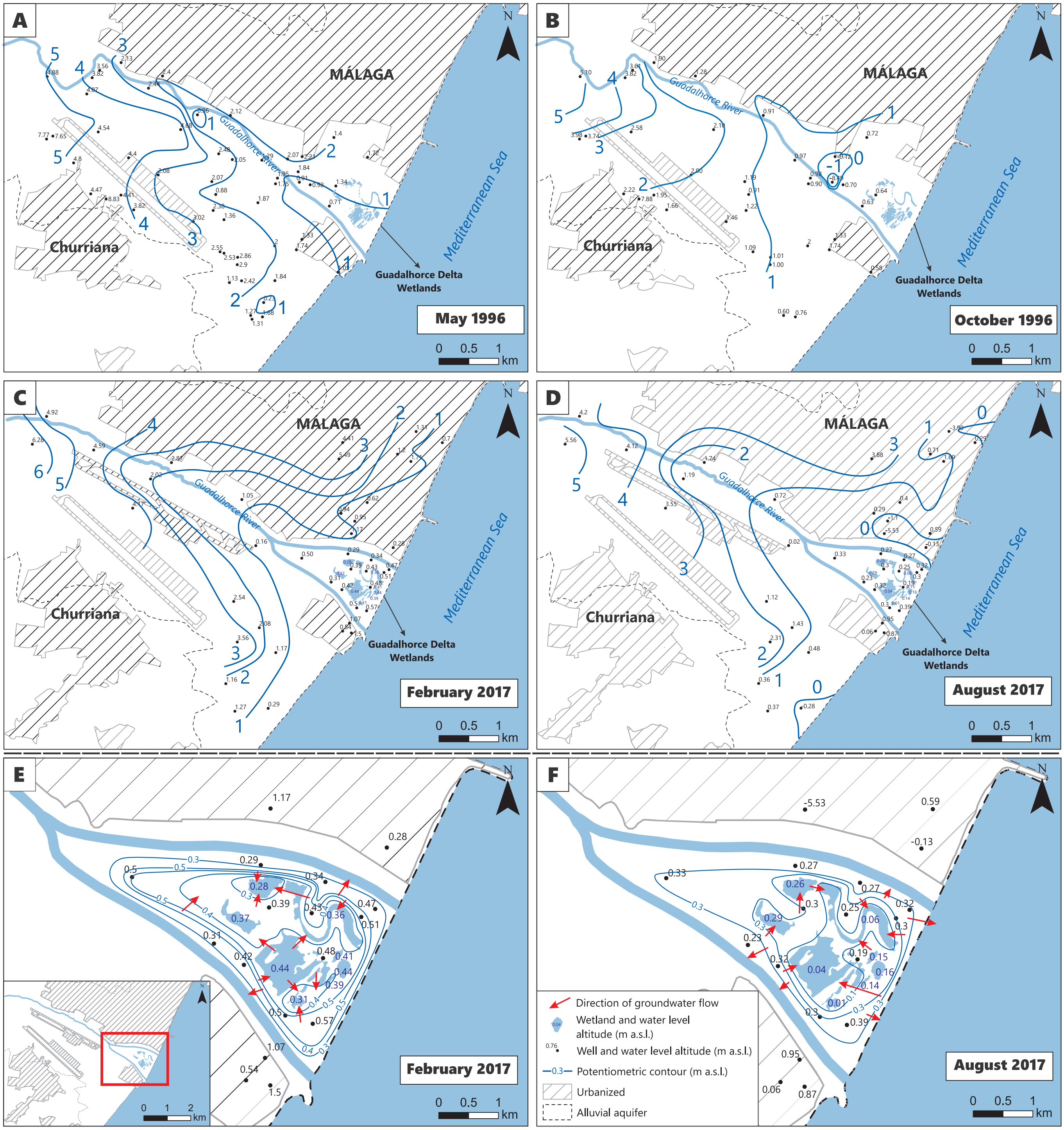

Fig. 4. (A-D) Piezometric surface (m a.s.l.) of the Quaternary aquifer in the LGRB under different hydrodynamic conditions during May-October 1996 (A and B, respectively) (modified from GHUMA-EMASA, 1996) and February-August 2017 (C and D, respectively). See piezometric maps of the zoomed area of Guadalhorce Delta Wetlands in Fig. 6E-F) Groundwater levels in wells and wetlands and groundwater table of the Guadalhorce River mouth in February (A) and August (B) 2017.

concentrations in groundwater (Fig. 6) show a very similar behavior for the two aquifers, with values higher than 2 mS/cm and 500 mg/l, respectively. The aquifers salinity was very similar and with narrow variations until the mid-1980 s, when it started to increase and destabilize in time. A similar fact started to occur in the 1990 s, but with an apparent ascending trend coinciding with the channelization works period. From 2013, the values are very stable and close to each other.

Regarding groundwater quality, Fig. 7 shows a combination of Piper and Schöeller-Berkalof diagrams. The Quaternary aquifer presents, between 1977 and 2001, mixed sulphate-chloride facies, although in some cases sodium chloride facies are detected. On the other hand, samples from the Pliocene aquifer usually present sodium chloride facies, as well as some unusual calcium sulphate-chloride facies. Samples taken after 2015 show sodium chloride facies in both Quaternary and Pliocene aquifers.

A slight increase in the average ion concentration (Fig. 7B), such as Cl^- and Na^+, can be observed in both aquifers. Similarly, concentrations of HCO_3^- and K^+ have also increased in the Quaternary aquifer,

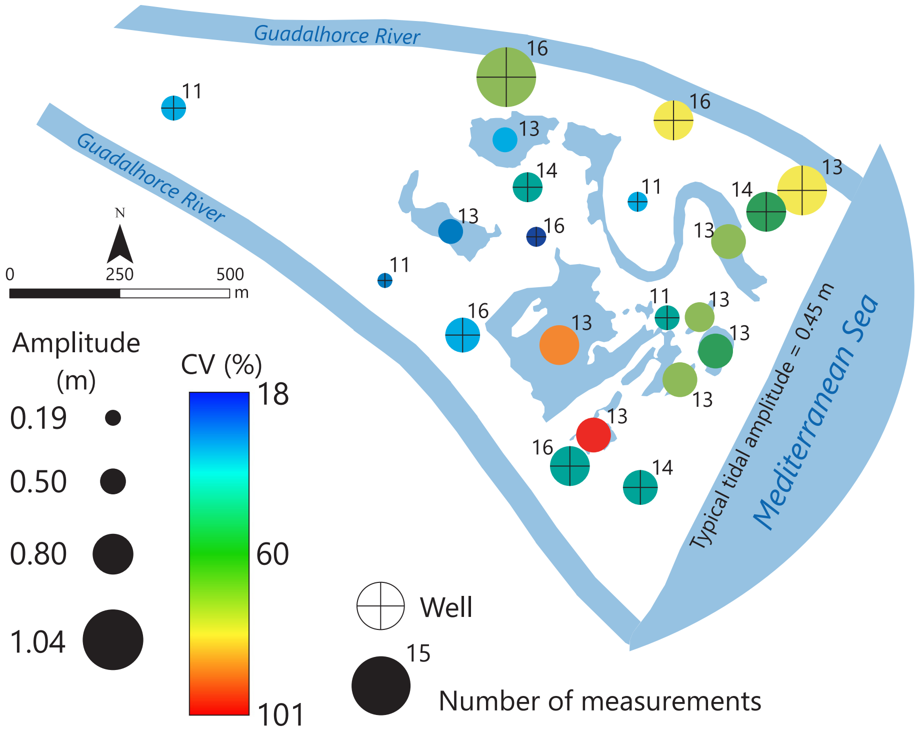

Fig. 5. Amplitude of water table fluctuations in wells and wetlands of the Guadalhorce River mouth and coefficient of variation (CV).

although there exists a noticeable decrease of Ca^{2+} (both aquifers) and Mg^{2+} (Quaternary aquifer) concentrations.

EC spatial distribution in the Quaternary aquifer in the 1990s (Fig. 8A) shows values below 5 mS/cm in almost all of its area, except in the eastern sector, where there were greater values (10–20 mS/cm). Chloride concentrations (Fig. 8B) presented, in general, values below 1000 mg/l, although it is possible to observe a higher concentration in the area that corresponds to the high EC values, thus EC is conditioned by chloride concentration.

However, by using a different sampling network, due to changes in land use (airport, channelization, etc.), this hydrochemical setting underwent great changes in 2017 (Fig. 8C and D), with EC values above 40 mS/cm in the coastal area, inside the isolated territory of wetlands between the two arms of the river. Chloride follows the same spatial distribution, with concentrations above 15,000 mg/l in some points, over 5 times higher than in the 1990s.

4.2. Guadalhorce Delta wetlands

The time evolution of the wetland stage and EC measurements of the Guadalhorce Delta Wetlands is shown in Fig. 9 (see the reference of each wetland in Fig. 3). Seasonal variations are observed, with higher levels during the rainfall season (November-April) and lower levels at the end of summer. However, there was no appreciable interannual trend. The average EC from 2008 to 2017 is shown in Fig. 10 (the Charca Sur Wetland is not included in the EC measurements due to the lack of data between 2008 and 2013). It is possible to observe the influence of rainfall in the EC values of the wetlands, which were lower in very wet years (2010).

As in the water table time series, the seasonality of EC can also be observed, with maximum values in summer and minimum values during the rainfall season. One of the most prominent facts that can be observed in Figs. 9 and 10 is the great EC increase in almost all the wetlands (Table 2), with an ascending trend statistically proved by the Mann-Kendall test (Table 3). Nowadays, there are wetlands with EC values 30 times higher than those recorded before and during the channelization works (Fig. 9). However, in the Escondida and Casilla Wetlands, this increment was lower, and their seasonal variations were slighter. At the same time, other wetlands, such as Grande and Eucaliptal, had greater seasonal increases and variations, although these were different from those of the Limícolas, Río Viejo, Charca Sur and Costera Wetlands, since these show even higher values and variations.

Regarding the chemical composition of the wetlands' waters (Fig. 11), some significant changes were detected. The earliest measurements, corresponding to the channelization works period (1997–1998), present Cl^- and Na^+ concentrations considerably lower than the current concentrations. The seasonality of the water chemistry can also be observed, with higher values in dry periods and lower values in wet periods.

Furthermore, in the Eucaliptal and Grande Wetlands, the Cl^-/HCO_3^- ratio (Fig. 12) was lower in the samples taken between 1997 and 1998, and higher in modern samples. Also, a higher chloride concentration, even higher than that of the Mediterranean Sea, was present in samples taken between 2014 and 2017.

4.3. Guadalhorce Delta birdlife and vegetation

Global birdlife censuses, carried out between 1997 and 2017 by the Andalusian Environment and Water Agency in the Guadalhorce River mouth, are shown in Fig. 13A.

The number of reproductive species that nest in wetlands has increased during the census period. This increment was more accelerated until 2004, when the number of species was as twice as large compared to 1997. After 2004, the variations were lower. Some ascending trends can also be observed in the number of breeding pairs.

Among the censed species, some are endangered and catalogued in the Red Book of Birds of Spain (Madroño et al., 2004), such as the red-crested pochard (*Netta rufina*) and the Kentish plover (*Charadrius alexandrinus*), typified as vulnerable (VU). This is also the habitat for the white-headed duck (*Oxyura leucocephala*), typified as endangered (EN). These started to nest in the wetland complex after 2003 and live, usually, in 1.5 to 3 m deep wetlands, with slightly saline and

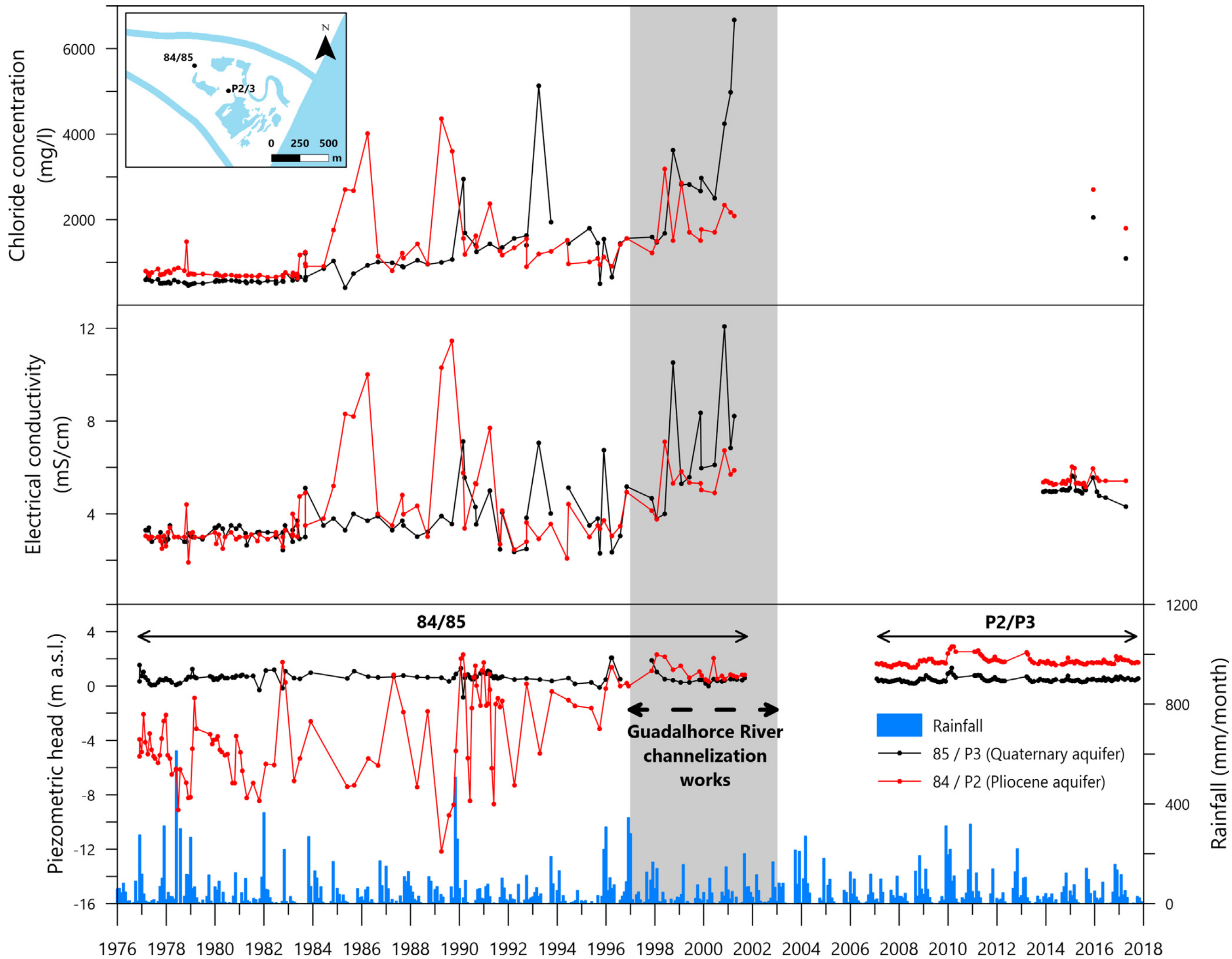

Fig. 6. Time series of groundwater level, electrical conductivity and chloride concentration of groundwater from the Pliocene and Quaternary aquifers of the LGRB.

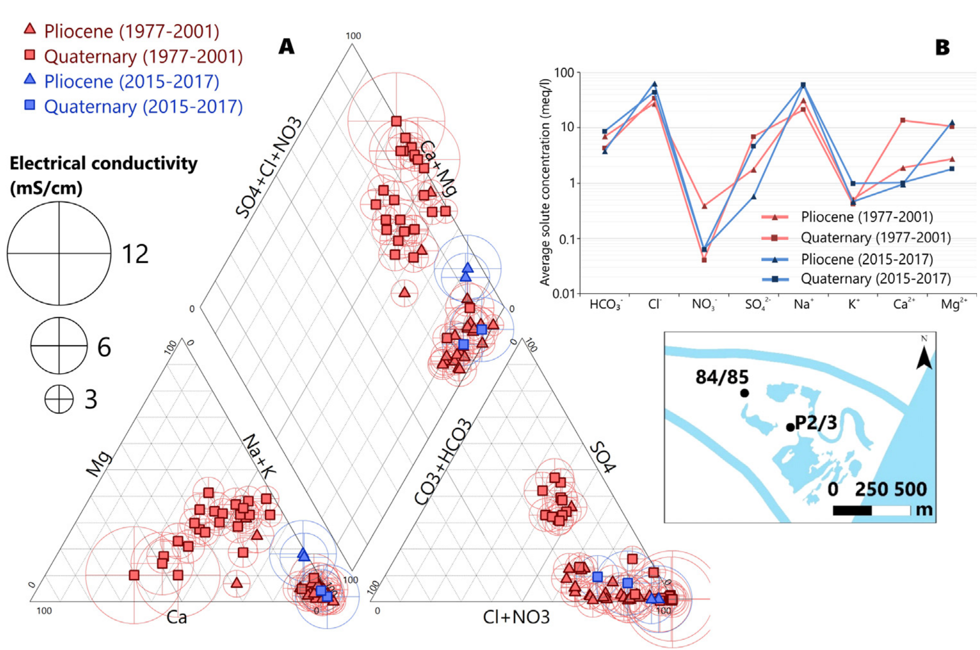

Fig. 7. Piper (A) and Schöeller-Berkaloff (B) diagrams showing average solute concentration of water samples taken in two pairs of piezometers (84/85 – P2/3), corresponding to the Lower Guadalhorce Pliocene and Quaternary aquifers, respectively. Circles in Piper diagram show the proportional scale of the EC of each sample.

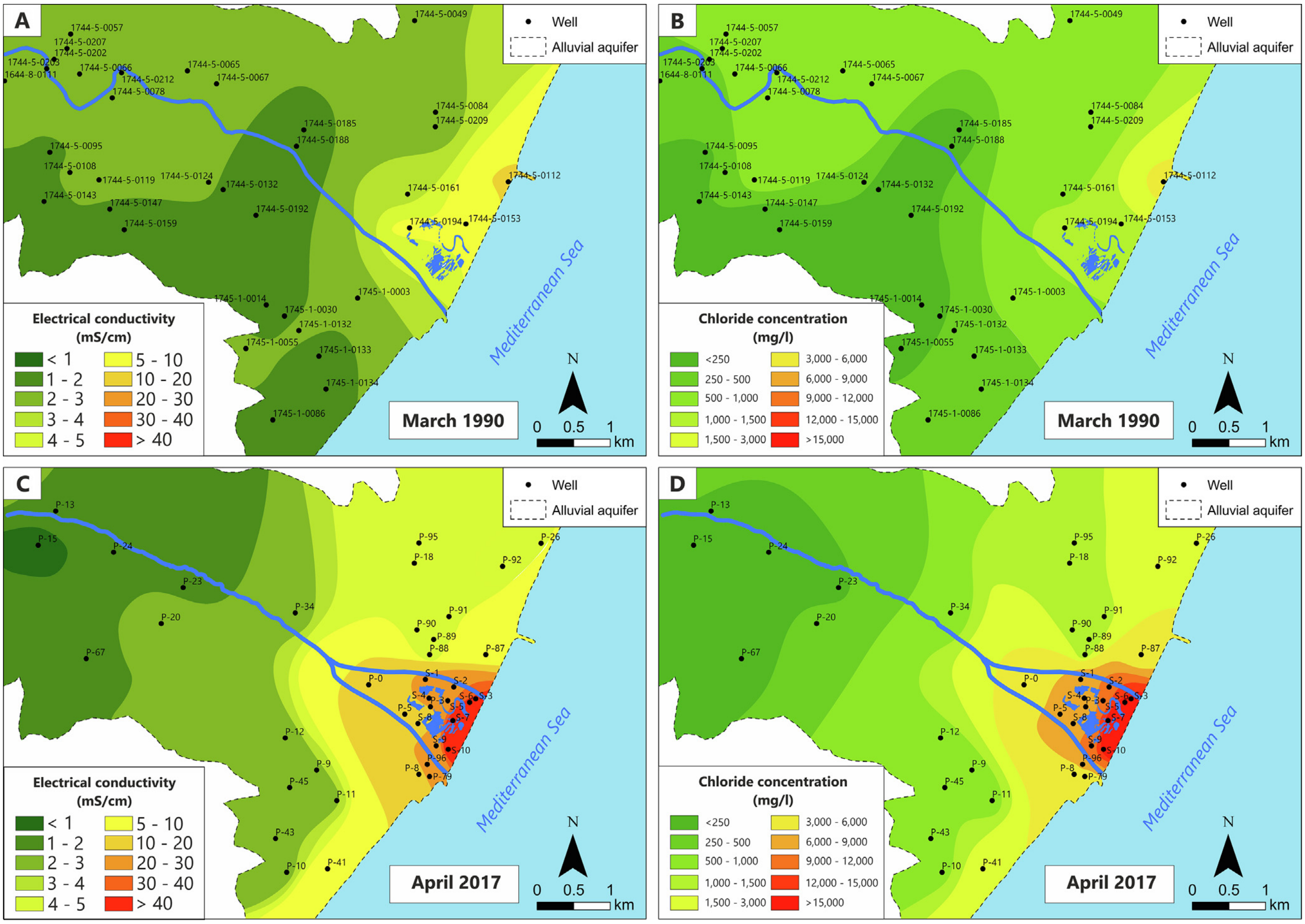

Fig. 8. Spatial distribution of electrical conductivity (mS/cm) and chloride concentration (mg/l) measured in March 1990 (A and B, respectively) and May 2017 (C and D, respectively) in groundwater of the Lower Guadalhorce Quaternary aquifer. Note that the monitoring network for groundwater and wetland water quality changes from 1990 to 2017.

eutrophicated waters (Torres and Arenas, 1985). Such conditions are only present in the Escondida and Casilla Wetlands, where *Oxyura leucocephala* is usually seen, among other diving birds.

Fig. 13B shows the evolution of two different bird species in the Grande Wetland: the common mallard (*Anas platyrhynchos*) and the black-winged stilt (*Himantopus himantopus*), a diving bird and a shorebird, respectively. There were no populations of *Himantopus himantopus* until 2001, when it started to nest there, going back and forth with an increasing trend. However, *Anas platyrhynchos* populations had a noticeable decreasing trend (see Mann-Kendall results in Fig. 13B and Table 4) until its disappearance in 2012. Some individuals nested there in 2015 and 2016, disappearing again in 2017.

A Mann-Kendall trend analysis (Table 4) was carried out for the time series of reproductive species, breeding pairs, *Anas platyrhinchos*

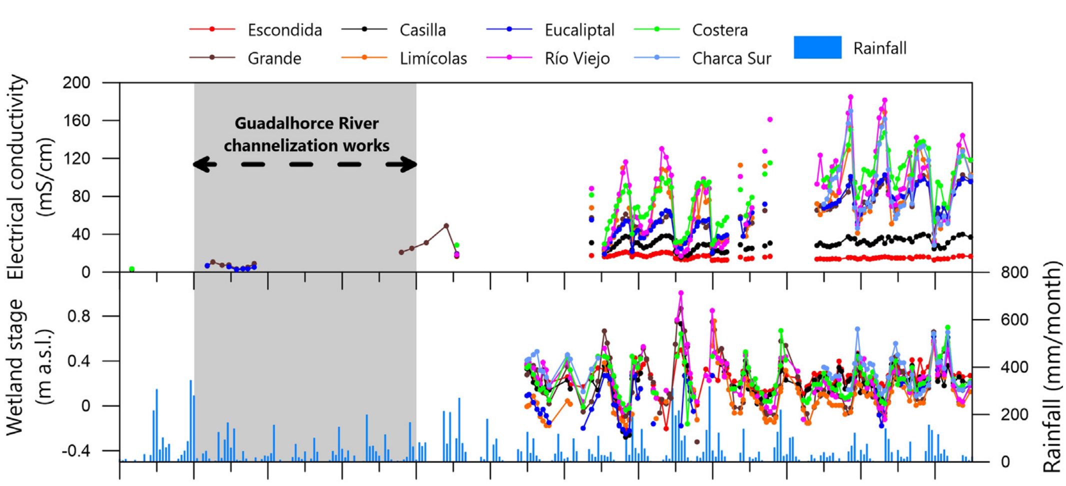

Fig. 9. Time series of water table and electrical conductivity of Guadalhorce Delta Wetlands' waters.

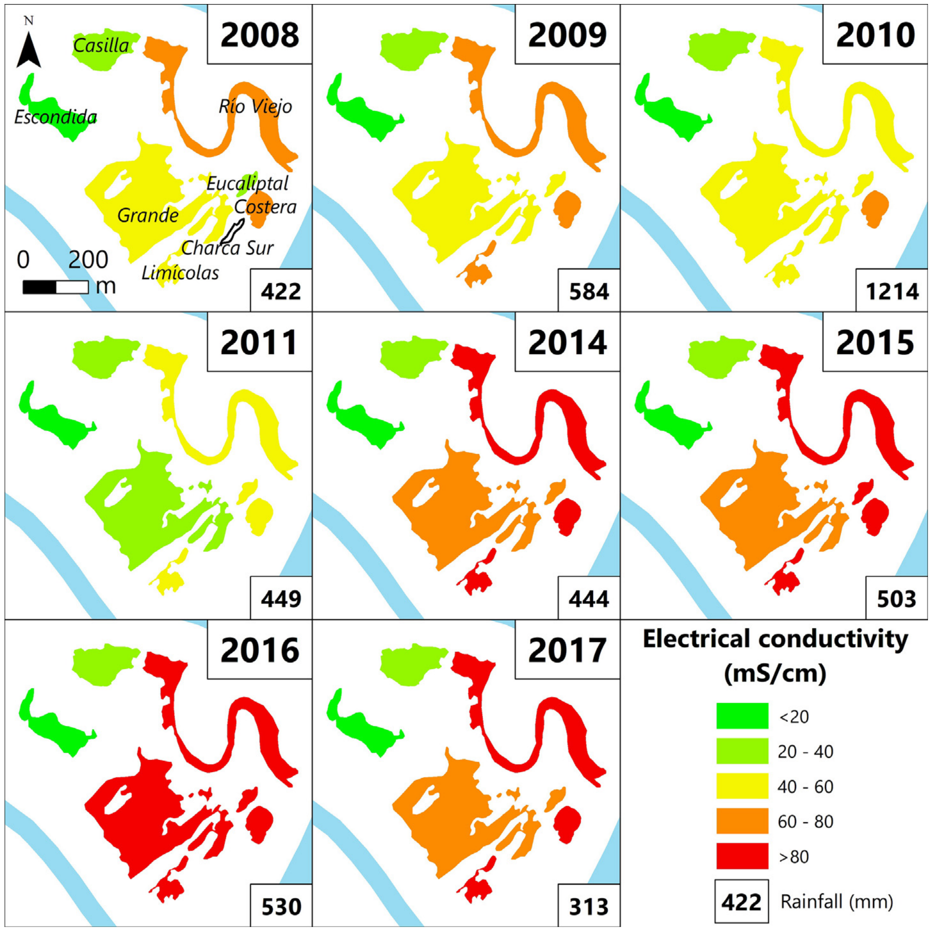

Fig. 10. Yearly average electrical conductivity of Guadalhorce Delta Wetlands from 2008 to 2017. Annual rainfall is shown in the down-right corner of each mosaic.

and *Himantopus himantopus*, to verify the existence of trends and their nature. The results show increasing trends for every time series, except for *Anas platyrhinchos*, as previously commented.

5. Discussion and conclusions

5.1. The role of land use change in the Guadalhorce river hydromodification

Numerous wetlands are related to groundwater (Töth, 1963; LaBaugh, 1986; González-Bernáldez, 1992; Winter and Rosenberry, 1995; Menció et al., 2017), on which they partially or totally dependent, thus any groundwater change can affect their functioning (Winter et al., 1998; Rosenberry and Hayashi, 2013; Custodio, 2017). Such relationship is especially strong in coastal wetlands, since (1) the water table is close to the ground surface, thus it can feed, temporarily or constantly, topographic depressions that may exist, and (2) due to groundwater discharges in coastal areas, following medium and large scale flowpaths.

However, wetlands around the world are endangered due to some drivers of change (MEA, 2005), which modify the ecological state of ecosystems and their capability to produce services. Main drivers of change that affect wetlands are infrastructures and human development (land use/habitat change), water abstraction or pollutants spilling, among others. In the Guadalhorce Delta Wetlands case, habitat change has been the most important driver due to all the implications derived from the morphological change (hydrological and biological isolation).

The EU Water Framework Directive 2000/60/EC (EU, 2000) aims to obtain a good ecological and chemical status of surface water and groundwater in Europe, including the hydromorphological, hydrological and biological state, among others. Thus, land use changes, river channelization and their negative influence on the fluvial ecosystems is a challenge for the present.

5.2. Hydrological and hydrochemical changes after channelization works

Land changes in the LGRB (channelization, reduction of irrigated land, new infrastructures) have provoked a fast recovery of groundwater levels in the Pliocene and Quaternary aquifers, with higher levels in the former, revealing its confining character (Fig. 6). Moreover, the increase of the impermeable area can cause a decrease in the infiltration rate and, therefore, a rise in the groundwater table.

The new course of the Guadalhorce River, located north to the wetland complex, and whose riverbed is 2 m b.s.l., acts as another drain of the Quaternary aquifer, thus the northern groundwater flows that previously went to the historical course of the river and passed through the wetlands are now circulating towards this new course (Fig. 14).

The detailed groundwater surface of the river mouth and the wetlands shows distinctive behaviors (Fig. 4) and allows evaluating a wide range of relationships between the hydrological systems. Thus, in wet periods (Fig. 4E), some wetlands, such as Grande and Eucaliptal, act as recharge wetlands to the aquifer, while others, such as Limicolas and Casilla, are fed by groundwater. In dry periods, the opposite situation occurs: recharge wetlands act as discharge wetlands and the Casilla and Escondida Wetlands feed the aquifer.

This is due to the fact that the Escondida and Casilla Wetlands present slighter variations compared to the other wetlands (Fig. 5), thus they will act as recharge or discharge wetlands depending on the water stage in the other wetlands. The slighter water table range and coefficient of variation of the Escondida and Casilla Wetlands with respect to the other wetlands and to the aquifer, suggest a better hydraulic

Table 2
Electrical conductivity (EC), pH and hydrochemical data collected in some of the Guadalhorce Delta Wetlands between 1995 and 2017. n = number of measurements/samples; CV = Coefficient of variation; SD = Standard deviation.

		EC	pH	HCO_3^-	Cl^-	SO_4^{2-}	Na^+	Ca^{2+}	Mg^{2+}	K^+
		mS/cm					mg/l			
Escondida	n	91	81	33	33	33	34	34	34	34
	Minimum	12.3	7.8	227	4166	1369	1753	366	379	44
	Maximum	21.3	9.5	319	9476	3308	5536	858	1153	252
	Average	15.8	8.4	268	5707	1890	3278	489	548	118
	CV	14.2	4.5	9	21	25	20	25	25	28
	SD	2.2	0.4	25	1205	476	658	124	138	33
Grande	n	103	92	41	41	41	41	41	41	41
	Minimum	2.8	7.7	101	479	192	299	50	50	11
	Maximum	102.5	10.1	442	71,332	10,491	33,470	2874	5014	1086
	Average	53.6	8.6	252	33,986	4935	18,476	1303	2684	468
	CV	46.8	5.3	30	58	55	56	56	57	55
	SD	25.1	0.5	75	19,679	2720	10,355	724	1523	257
Casilla	n	92	81	33	34	34	34	34	34	34
	Minimum	2.4	7.2	190	9047	1646	5315	539	817	90
	Maximum	40.0	8.8	363	30,776	6176	16,361	2126	2739	317
	Average	29.4	8.0	266	16,449	3219	8776	1056	1456	180
	CV	22.8	4.1	14	31	34	27	34	28	26
	SD	6.7	0.3	37	5143	1084	2381	363	411	46
Limícolas	n	90	78	31	31	31	32	32	32	32
	Minimum	3.4	6.9	173	13,701	1893	6877	568	1066	137
	Maximum	168.8	9.7	391	152,063	17,176	85,237	4281	13,122	1769
	Average	69.5	8.1	283	50,820	6475	27,775	1612	4207	619
	CV	50.3	4.8	20	72	64	69	53	72	67
	SD	35.0	0.4	56	36,839	4173	19,212	847	3026	412
Eucaliptal	n	96	87	37	38	38	39	39	39	39
	Minimum	2.6	7.4	161	397	154	267	44	42	10
	Maximum	102.8	9.8	348	74,164	9150	40,832	2296	5554	1000
	Average	55.7	8.2	238	36,357	4440	20,788	1259	2769	519
	CV	46.9	6.1	19	55	52	53	50	53	52
	SD	26.1	0.5	45	20,074	2319	11,030	623	1469	267
Río Viejo	n	91	81	34	34	34	34	34	34	34
	Minimum	17.1	7.4	156	12,344	1649	7102	576	1000	182
	Maximum	185.0	9.7	331	170,746	15,105	109,986	3699	15,757	2638
	Average	81.6	8.5	230	63,126	7140	35,109	2030	4967	861
	CV	49.8	6.2	21	69	50	69	41	72	67
	SD	40.7	0.5	47	43,510	3561	24,375	838	3601	579
Costera	n	90	81	32	32	32	32	32	32	32
	Minimum	3.7	7.1	161	22,149	2804	13,352	624	1700	402
	Maximum	150.2	9.5	332	115,293	14,609	63,683	2804	7989	1845
	Average	85.5	8.3	250	66,707	8181	37,321	1689	4761	1054
	CV	37.3	5.5	17	37	35	34	30	34	33
	SD	31.9	0.5	43	24,925	2839	12,711	504	1631	349
Charca Sur	n	40	32	33	33	33	33	33	33	33
	Minimum	28.6	7.6	172	11,152	1529	6438	460	889	169
	Maximum	170.0	9.1	478	140,877	15,219	80,449	3669	10,504	1807
	Average	91.9	8.2	288	57,047	6687	31,444	1645	4172	756
	CV	38.2	4.5	25	65	58	63	51	63	58
	SD	35.1	0.4	73	37,123	3894	19,868	835	2624	438

connection with the latter, since these pools became deeper than the rest after the aggregate extractions (Servicios Omicron, 1995). This involved the removal of organic material (low hydraulic conductivity), which facilitated the connection with the Quaternary aquifer. The other wetlands are more strongly related to rainfall.

Channelization works have generated a kind of estuary in the river mouth, with a very perceptible influence of the Mediterranean Sea over it. Thus, the chemical quality of both aquifers has been seriously affected, where the noticeable increase of EC and some ions, such as Cl^- or Na^+, prove an increasing marine influence over them (Figs. 11 and 12). Moreover, this increase in Na^+ has posed a relevant decrease of Ca^{2+} and Mg^{2+} concentration in the waters of the Quaternary aquifer, due probably to cationic exchange reactions (Andersen et al., 2005; Appelo and Postma, 2005; Giambastiani et al., 2013). This is happening despite the decreasing pumping in the area, due to the land use change, thus we can assume that the salinization of the coastal sector of the alluvial aquifer is due to the new hydrodynamics. This fact favors a greater exchange of freshwater-saline water between the Quaternary aquifer, the Guadalhorce River and the Mediterranean Sea, with a higher influence of the latter over the other hydrological systems.

This new hydrodynamic situation, in both surface water and groundwater seems to be responsible for the salinization of the Guadalhorce Delta Wetlands (Figs. 9 and 10; Tables 2 and 3), which can be due to the change of the groundwater flow; years ago freshwater flowed through the wetlands to the Guadalhorce River, acting as a transitional element, and now there is no freshwater flow, at least in a

Table 3
Results of the Mann-Kendall test over the Guadalhorce Delta Wetlands water electrical conductivity from 1995 to 2017. Highlights and arrows in green correspond to ascending trends; red correspond to descending trends.

Variable	Escondida	Grande	Casilla	Limícolas	Eucaliptal	Río Viejo	Costera
Observations	91	103	92	90	96	91	90
Minimum	12.25	2.78	2.43	3.39	2.58	17.09	3.66
Maximum	21.3	102.5	40	168.8	102.8	185	150.2
Mean	15.76	53.63	29.37	69.53	55.67	81.63	85.49
Std. deviation	2.23	25.12	6.69	34.96	26.14	40.69	31.92
S	-922	3350	1303	1311	2865	1048	1932
Var(S)	85074	123147	87884	82323	99808	85082	82324
p-value (Two-tailed)	0.0016	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0003	< 0.0001
alpha	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Trend							
Sen's slope (mS/cm/year)	-0.2	3.4	0.5	4.3	3.4	4.1	3.2

noticeable magnitude, to feed the wetlands from the NE. The lack of freshwater supply has originated a progressive salinization of the wetlands by evapoconcentration of sodium chloride waters (Cl-Na and $ClHCO_3$-Na water types) (Fig. 11), due to the relevant relationship between the Mediterranean Sea, the Quaternary aquifer and the wetlands, which is also accentuated by the greater influence of the sea over the Guadalhorce River. Before the channelization, the Grande and Eucaliptal Wetlands had lower Cl^-/HCO_3^- (Fig. 12), which indicated a greater freshwater influence. However, the salinity of the Escondida Wetland is not increasing with time, but decreasing.

The salinization of these wetlands could have also occurred naturally, although there was no such increase in the time between their origin (1977–1982) and the first EC measurements, as shown in previous sections during and after the channelization works. Further hypotheses about wetland water salinization could be associated with the influence of the sea level rise during the last decades, which accounted for 5.775 cm from 1992 to 2017 in the nearby Málaga port (Puertos del Estado, 2019).

Servicios Omicron (1995) and Lucena and Carrasco (2000) studied the potential environmental impact of the channelization on the Guadalhorce River, particularly those regarding the groundwater-dependent ecosystems, as well as the local groundwater hydrodynamics, and they concluded that no severe hydrological alterations would take place. Other studies (Perles et al., 1999a, 1999c), predicted the impact of the channelization on the hydrology and habitat of the area.

Despite these previous works, no assessment has been carried out, from a multidisciplinary approach, about the possible impact of the channelization on the hydrogeology, surficial hydrology or habitat of these wetlands. Therefore, there is a general lack of hydrological/hydrogeological studies regarding this issue, which are completely necessary to achieve the goals stablished by the EU Water Framework Directive.

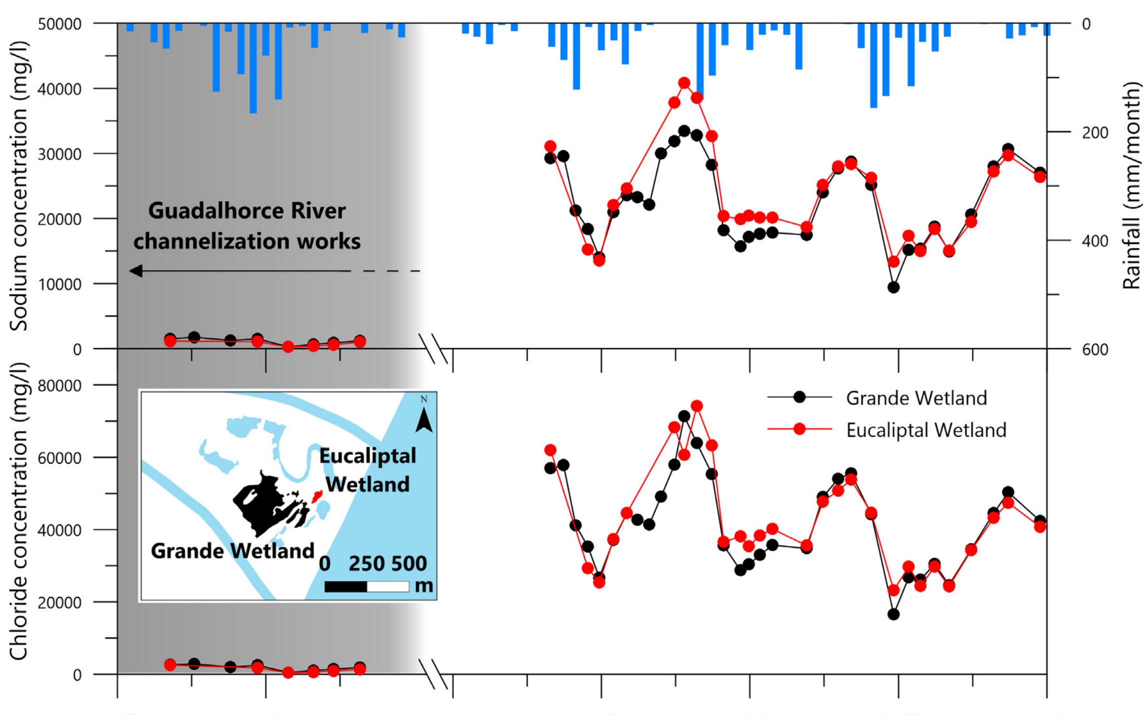

Fig. 11. Cl^- and Na^+ concentrations (mg/l) of Grande and Eucaliptal Wetlands waters between 1995 and 2017.

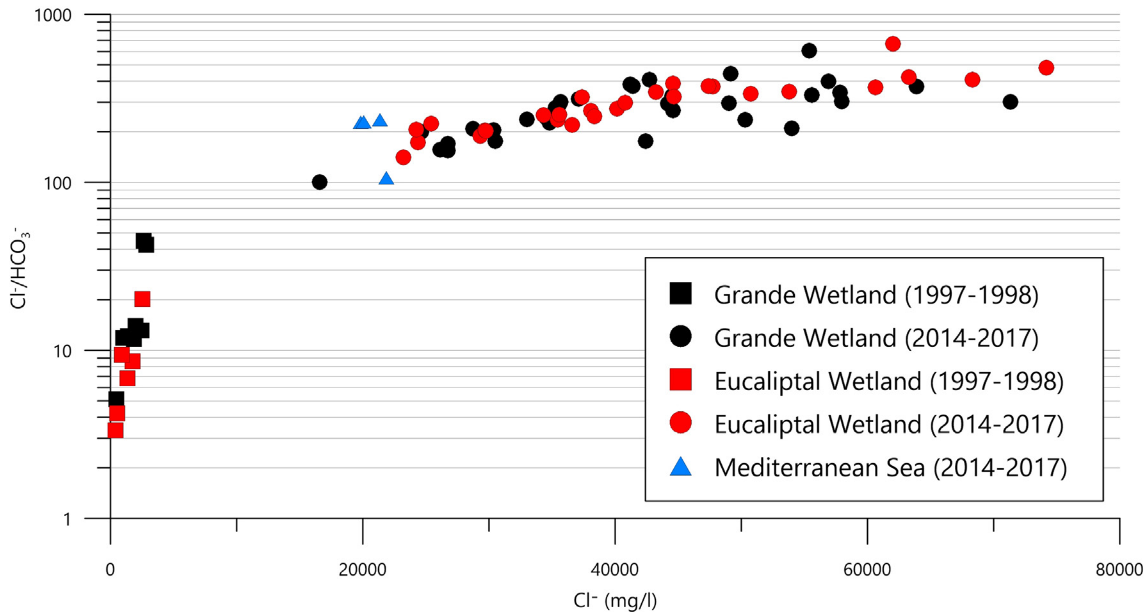

Fig. 12. Cl^-/HCO_3^- ratio versus chloride concentration (mg/l) of Grande and Eucaliptal Wetland waters and in the Mediterranean Sea between 1997 and 2017.

5.3. Impact on biodiversity

The reason for protecting the Guadalhorce Delta Wetlands was the presence of migratory and protected birds, which found in these wetlands a resting place in their travel between Africa and Europe (Andalusian Environmental Office, 2005) and, in general terms, their biodiversity in a natural-urban area.

In this context, an important feature to take into account is the known impact of channelization on biodiversity (Brooker, 1985) and wetlands (Wilcock, 1991). Thus, as the wetlands were isolated, it

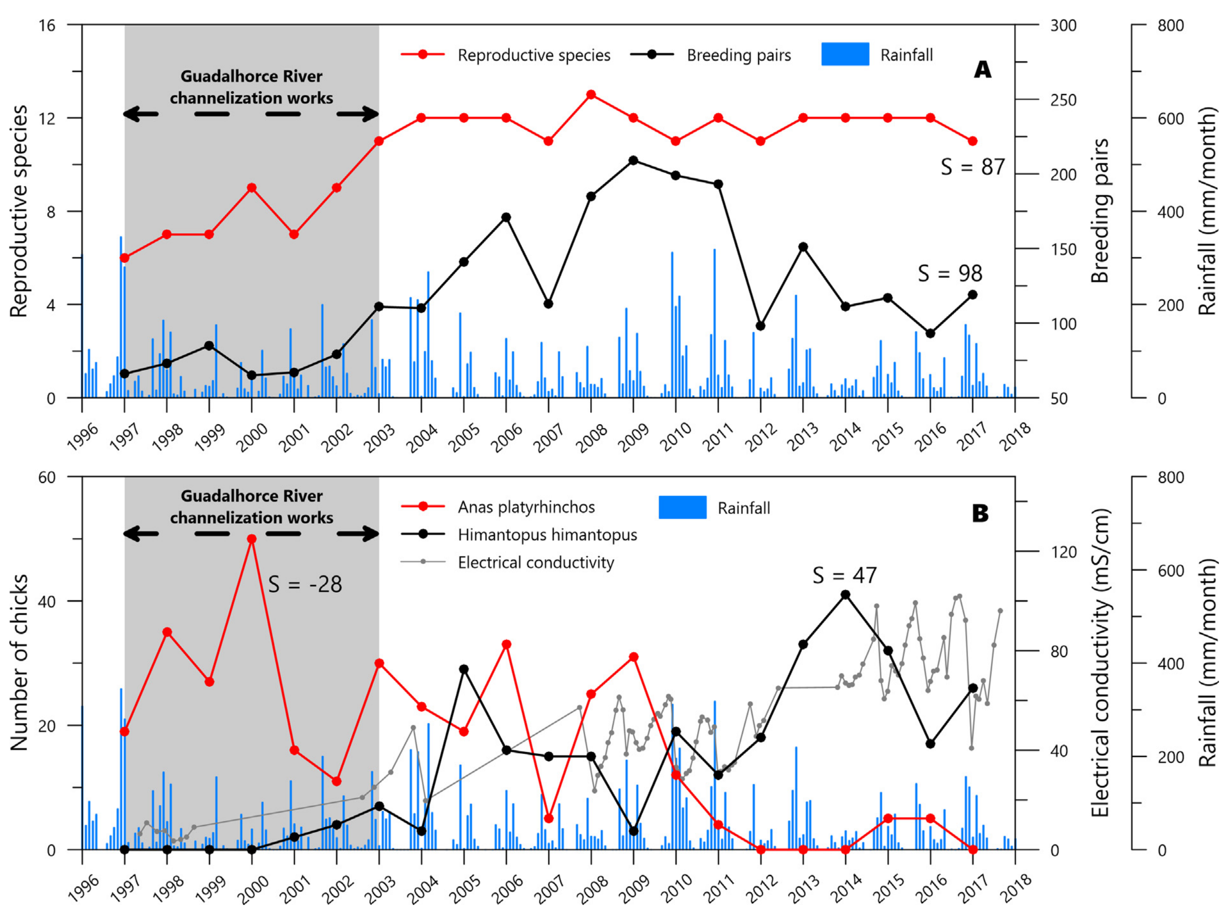

Fig. 13. (A) Results of the birdlife censuses carried out in the Guadalhorce Delta Wetlands between 1997 and 2017. (B) *Anas platyrhinchos* and *Himantopus himantopus* chicks in the Grande Wetland between 1997 and 2017. S = Mann-Kendall's statistical descriptor.

Table 4
Results of the Mann-Kendall test over some bird censuses from 1997 to 2017.

Variable	Breeding pairs	Reproductive species	*Anas Platyrhinchos*	*Himantopus himantopus*
Observations	21	21	21	21
Minimum	65	6	0	0
Maximum	209	13	50	41
Mean	121.7	10.5	16.7	13.9
Std. deviation	46.4	2.1	14.2	12.6
S	87	98	−28	47
Var(S)	1096	983	407	332
p-value(Two-tailed)	0.009	0.002	0.181	0.012
alpha	0.05	0.05	0.05	0.05
Trend				
Sen's slope (unit/year)	3.3	0.2	−1.4	1.5

became imperative to assess the possible impact of such isolation on them. An increase in reproductive species and breeding pairs has been recorded (Fig. 13A), which coincides with the removal of farming areas in the vicinity of the wetlands and with the new isolation from the city and other lands, becoming more attractive for birdlife. It is important to add the important re-vegetation and topographical remodeling, carried out by the environmental authorities (Andalusian Environmental Office, 2005) to create new habitats (shallower/deeper wetlands) and to improve the existing ones. The increase in the populations of threatened species is also a relevant aspect, which gives more value to this recovery.

In the Grande Wetland, the disappearance of diving birds, such as *Anas platyrhynchos*, and the appearance of shorebirds, such as *Himantopus himantopus* and others (Fig. 13B), can be explained by the change in the water quality and mineralization. Thus, *Anas platyrhynchos* shows a preference for freshwater (Madge and Burn, 1988) and, when the salinity became too high, it stopped nesting in this wetland. On the other hand, *Himantopus himantopus* prefers saline environments such as river deltas, estuaries (Snow and Perrins, 1998), coastal lagoons (Johnsgard, 1981; Snow and Perrins, 1998) and shallow coastal pools with extensive areas of mudflats, salt meadows (Johnsgard, 1981), saltpans and coastal marshes (Del Hoyo et al., 1996). Thus, when the EC of the wetland started to increase, this species found an ideal habitat for breeding, although it is also nesting in the other saline wetlands in the area. There was a transition towards a different ecosystem (from freshwater to saline wetlands), in an

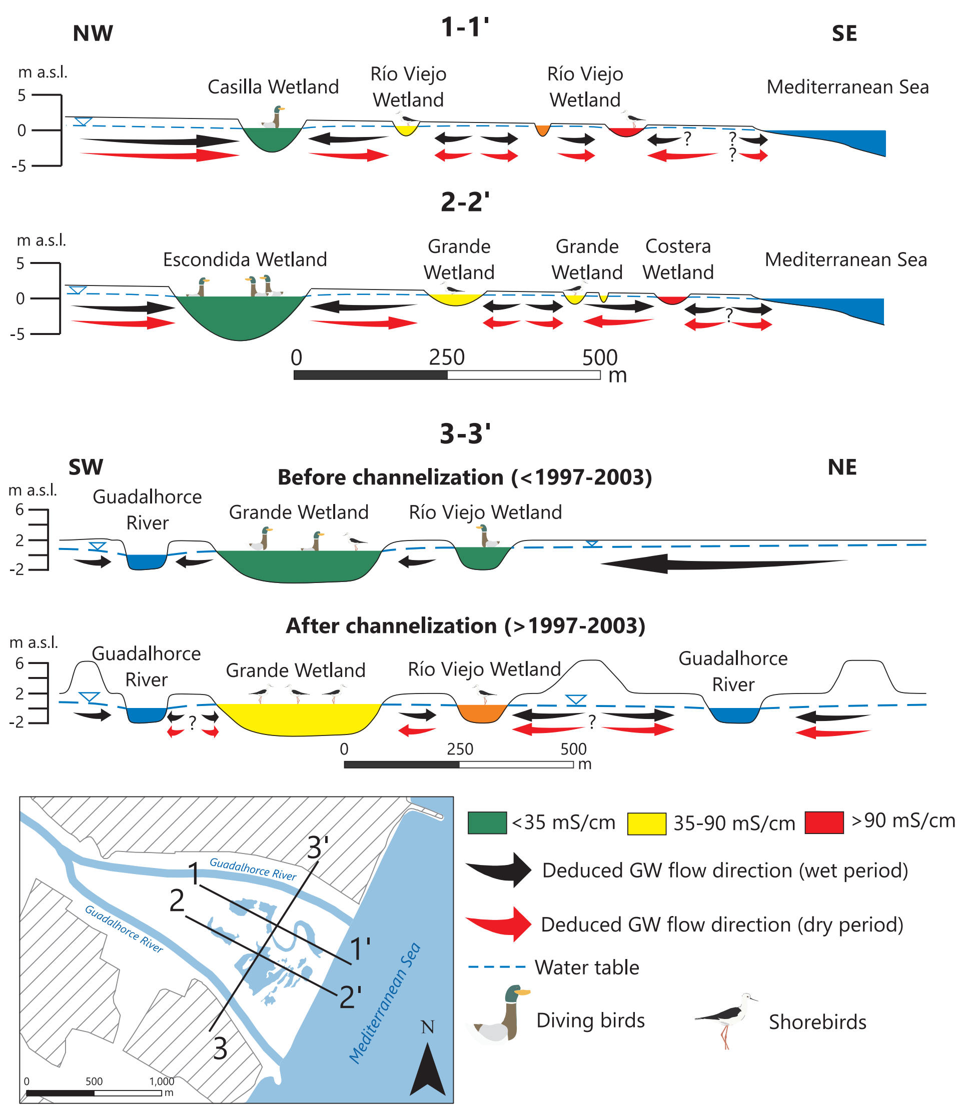

Fig. 14. Hydrogeological sketches of the Guadalhorce Delta Wetlands functioning before and after the channelization works. Sketches 1-1′ and 2-2′ correspond to the post-channelization setting. GW = Groundwater. Number of represented birds is relative to the amount of censed population.

Table 5
Summary of vegetal species inventoried in the Guadalhorce Delta Wetlands area before and after the river hydromodification.

Species	Díez-Garretas (1977), Asensi & Nieto (1981)	Casimiro-Soriguer Solanas & García-Sánchez (2017)
Scirpus maritimus var. *compactus*	✓	✓
Typha angustifolia	✓	✓
Lythrum junceum	✓	–
Alisma plantago-aquatica	✓	–
Samolus valerandi	✓	–
Lycopus europaeus	✓	–
Polypogon maritimus	✓	–
Scirpus pungens	✓	–
Phragmites communis subsp. *isiacus*	✓	–
Paspalum vaginatum	✓	–
Centaurium spicatum	✓	–
Juncus maritimus	✓	✓
Juncus acutus	✓	✓

Anthropocene context, creating novel, unexpected ecosystems.

Vegetation changes have been analyzed along the years in this area. The first studies were conducted by Díez-Garretas (1977) and Asensi & Nieto (1981). They were focused on the recognition and characterization of the Málaga province coastal, halophytic and wetland vegetation, respectively, and, more specifically, on the phytosociology of plants. In these works, the vegetal association *Scirpetum compacto-littoralis phragmitetosum isiaci* was detected, constituted by *Typha angustifolia*, *Scirpus maritimus* var. *compactus* and *Phragmites communis* subsp. *isiacus,* among others. A recent study, carried out by Casimiro-Soriguer Solanas & García-Sánchez (2017), has demonstrated the absence of some of the species (Table 5) that composed this association in this area. To achieve this, they studied the psammophilic, halophilic, halonitrophyl and hygrophilic communities, as well as those associated with very saline waters, in several sampling campaigns carried out between 2015 and 2017.

Additionally, other freshwater/brackish water-related species are no longer located in this area, such as *Chara canescens*, *Chara aspera*, *Chara vulgaris* subsp. *envulgaris* and *Najas marina* (Nieto-Caldera et al., 1997; Casimiro-Soriguer Solanas & García-Sánchez, 2017). On the other hand, some species, growing in saline soils and waters, have appeared in the last years, such as *Elymus elongatus* subsp. *elongatus* and great prairies of *Sarcocornia perennis* subsp. *alpini* (Casimiro-Soriguer Solanas & García-Sánchez, 2017).

This remarkable increase of saline water/soil-related species, such as *Sarcocornia perennis* subsp. *apini* and *Elymus elongatus* subsp. *elongatus*, can be explained by the salinization of almost all the wetlands.

5.4. Final remarks

The application of classical hydrological/hydrogeological field methods in the context of a coastal aquifer with associated groundwater-dependent ecosystems has allowed confirming that a river hydromodification, such as channelization and land use changes, can cause relevant alterations in the hydrology of surface water and groundwater and, consequently, on the biodiversity of the area.

Interactions between surface water and groundwater in the coastal sector of the study area were detailed using greater than 20 years of hydrodynamic and hydrochemical data and several statistical analyses, conducted for a better understanding of water behavior and the changes that have taken place over time.

In this way, the Guadalhorce River has always been in a gaining relationship with the Quaternary aquifer, although in the Guadalhorce Delta Wetlands this relationship has varied considerably, depending on the stage of each wetland and the groundwater table: lagoons can act as recharge, transitional or discharge elements of the aquifer.

Depending on the characteristics of the infrastructure, this influence can turn into a positive effect on the environment: isolation and improvement of birdlife. Thus, an increase of bird populations has been verified in the overall surface of the Guadalhorce Delta Wetlands, while other bird species have started to nest in some pools. Nevertheless, the impact on groundwater has caused the salinization of the whole mouth area and the related wetlands, to a greater extent in some of them, which has led some bird populations to switch wetlands for nesting. These high saline waters have also driven saline vegetation to grow in a larger surface around the wetlands.

Consistent hydrogeological reports about channelization works can help to avoid important damage not only to the environment, but also to human populations (raw materials and food, tourism, etc.). Thus, we strongly encourage land managers to take into account rigorous multidisciplinary studies on hydraulic infrastructures to avoid negative impacts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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