HYDRO(GEO)ENVIRONMENTAL CHANGES ASSESSMENT AFTER GUADALHORCE RIVER MOUTH CHANNELIZATION. AN EXAMPLE OF HYDROMODIFICATION AT 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 Malaga. The channel was bifurcated entering into the Mediterranean Sea, surrounding an isolated wetlands 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 tidal influence inland from the Mediterranean Sea through the Guadalhorce River and the subjacent coastal aquifers, but also 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 in 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.

KEYWORDS

River hydromodification, channelization works, groundwater dependent ecosystems, ecological impact, Guadalhorce River Mouth

1. INTRODUCTION

Prevention of floods in riverine areas is a great concern for the humankind because, for example, approximately 500,000 people were displaced between 1998 and 2004 (EEA, 2011), only in Europe, as well as about 25,000 million euros of material damages were estimated. This concern is increasingly higher in densely populated urban settlements and their associated facilities for residential, industry or entertainment uses. Several anthropogenic actions have been conducted worldwide to minimize flood risks, such as the construction of dams, dredging of rivers or 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 wetlands areas, among other purposes (Brookes, 1981; Schoof, 1980; 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, this type of engineering solutions usually has an important impact on the hydrology, causing changes in water velocity and sediment transport capacity (Brookes, 1988). There also exist impacts on the hydrogeology, as modifications in the groundwater discharge into streams (LaSage *et al*., 2008), marine intrusion (Petalas, 2013) or 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). Habitat of riverine areas can also be negatively affected (Brooker, 1985), because of 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.) as consequence of river channelization.

Hydromorphological pressures are the most commonly occurring 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 or 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 2,800 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 (3,150 km^2) that covers about 43% of the eastern territory of Málaga province. Historically, a Phoenician presence existed in all this zone, as demonstrated by an historical site built over a little hill in the Guadalhorce River mouth, to avoid the flooding risk. Likewise, many flood events have occurred in the mouth area, very often with catastrophic consequences, such as substantial material damages in adjacent urban and industrial areas and even human victims (Perles *et al*., 1999b). After the historical floods of 1989, when 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 left isolated a coastal wetlands complex (Guadalhorce Delta Wetlands) composed by 8 pools (Nieto, 2015, 2018).

Despite of some previous works studying impacts on the hydrology and the hydrogeology (Servicios Omicron, 1995; Lucena and Carrasco, 2000) or on the habitats

(Perles *et al.*, 1999a, 1999c), no additional assessment of the impacts of the channelization works has been carried out in this area. Also, there exists a lack of multidisciplinary and transversal approach studies regarding hydraulic infrastructures, and even less works involving hydrology, hydrogeology, biology, vegetation, habitats, etc.

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

2. BACKGROUND INFORMATION

2.1. Physical description of the Lower Guadalhorce River Basin (LGRB)

The Guadalhorce River mouth is located in the S-W edge of the Málaga city, in Southern Spain (Fig. 1). Land topography is practically flat, typical of a river delta physical setting, and it is surrounded of 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 of its high degree of human-induced modification, the Guadalhorce River mouth is environmentally protected since 1989 by the regional authorities because of its richness in biodiversity and hydrological and ecological values.

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 result, 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 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 (Consejería de Medio Ambiente, 2005) to reduce the number of dug depressions, as well as to perform the morphological adaptation of the land surface and re-vegetation environmental initiatives.

2.2. Land use changes

Several decades ago, farming has been predominantly developed throughout the entire LGRB (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 high water consumption.

The change in the land use between 1996 and 2015 is shown in figure 2. Numerous changes associated to the channelization are visible: all the farming lands existing in the Guadalhorce River shore and in the mouth disappeared, leaving place to a great artificial and controlled flooding area. Nevertheless, other relevant changes have taken place in this period in the territory, 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 entertainment urbanization, in both margins. So, agricultural use of land in the coastal area of the LGRB was reduced from 42% to 17%. In the other hand, naturalized areas increased from 23% to 32%, because the required flooding area of the river was no longer allowed for any different use than this.

Land cover changes associated with the Guadalhorce River channelization coincide with other cases in Europe, like the floodplain area along the Danube River, where almost 20,000 km^2 of 26,000 km^2 land surface were isolated by levees (Tockner *et al*., 2008). In Europe, the 95% of the original floodplain area of rivers has been converted to other uses (EEA, 2018). In some cases, the works were done for improving navigation, instead of controlling floods, but both goals are achieved in the most of them. Besides, new land uses around channelized rivers can affect negatively because of the discharge of diffuse or punctual pollutants.

Actually, 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, but also by an increasing urbanization (Perles *et al*., 1999b), which has supposed an increase of 9% in the urbanized area.

2.3. Geomorphology

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

The geomorphological changes associated to 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 50's, a noticeable flooded area can be observed in the previously named Carmen Marshes, but also the meander-like shape of the Guadalhorce River, at the North of the mouth, is visible. The depressions originated by the aggregates extractions are present from 1977, but after 1998 are appreciable the modifications of the morphology of some wetlands, as well as the isolation of the meander.

A considerable reducing of farming area in the surroundings of the mouth took place along the years, as well as the disappearing of some marshes and the increasing of the urbanized area. Channelization works took place between 1997 and 2003 and the resulting water facility is 7 km length, 350 m wide and 2 m depth, also at the mouth (the bottom of the channel is -2 m a.s.l.), leaving isolated the Guadalhorce Delta Wetlands, a protected natural area. The incision of the Guadalhorce river bed in all the length covered by the channelization has also supposed a great change in the morphology and hydrodynamics (Garrido and Alba, 2008), because it improves groundwater pathways towards the river and makes easier that sea tides can 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 geologic 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 conglomerates (confined aquifer), marl and sand layers, whose thickness achieves 300 m or more. The latter lithology (<20 m thickness), acting as semi-confined aquifer (IGME, 1983; Linares *et al*., 1995), is characterized by 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 in 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 have been historically exploited for traditional farming (Linares *et al*., 1988), but also for drinking water supply to Málaga city, which stopped in middle 90's. So, very often groundwater drawdown below the sea have been recorded during the summer season at the coastline, favoring the seawater intrusion inland, toward 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 hm3/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), 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 because the land use change has removed the most of the points measured by the IGME.

Rainfall data has 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, with an annual periodicity, 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 in different kinds of waters, for determining their hydrochemical composition. This was done in wetlands, with monthly periodicity, and in April 2017 in a groundwater sampling network composed by wells and piezometers over the LGRB. Groundwater was first pumped for several minutes to purge the well for having the most representative water before measuring and sampling it.

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

Due to the known interaction between groundwater and surface water, groundwater table has been measured in different points to determine the potential influence of the channelization on the Quaternary and Pliocene aquifers. To do this, a 50 m OTT Hydromet^{TM} KL010 sounding line with an accuracy of 0.01 m was used. Also, all the points surrounding the Guadalhorce Delta Wetlands were leveled.

Historical groundwater level measurements in 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 closed to each other (Fig. 6). These piezometers are named 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 that points 84 and 85 show, corresponding to the Pliocene and Quaternary aquifers, respectively, so is not possible to obtain coherent groundwater level measurements after 2001.

3.3. Statistical methods

The Mann-Kendall non-parametric test (Mann, 1945; Kendall, 1975) have been applied to check the existence of trends in selected water quality parameters and in birdlife metrics. Besides, this test allows the assessment of the magnitude of the trend due to the modifications made by Sen and Hirsch (Sen, 1968; Hirsch *et al*., 1991). The Mann-Kendall test has been traditionally used for the trend detection in weather and hydrological data but, in this study, it is 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) have also applied this method to verify temporal trends in this type of environmental parameters. Mann-Kendall test doesn't consider previous distribution of data and has a similar power than parametric methods (Serrano *et al.*, 1999).

The Mann-Kendall parameter (S) is calculated in this way:

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

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 serie. A positive S value indicates an increasing trend, while a negative S value indicates a decreasing trend.

4. RESULTS

4.1. Spatial-temporal variations of groundwater levels in 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 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 are also observed as consequence of discrete groundwater pumping in the coastal area of the LGRB, particularly in October 1996.

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

A more detailed view of groundwater surface waters' hydrodynamics allows to check some different behaviors between a wet (Fig. 4E) and a dry period (Fig. 4F) in the GDE of the Guadalhorce Delta Wetlands. Water table measured in wells is, generally, higher than in wetlands. In February 2017 (Fig. 4E), a flow from Grande and Costera Wetlands to the others is perceptible, as well as some flow from the Quaternary aquifer. Besides, all flows are going towards the Mediterranean Sea and the Guadalhorce River branches. This general flow changes in August 2017 (Fig. 4F), when Escondida and Casilla Wetlands are acting as recharge wetlands to the other ones, and to the aquifer. Nevertheless, it is difficult to establish a distinctive flow pattern between the Quaternary aquifer and the wetlands because several discharge, recharge and transit relationships are visible in both periods. Arrows indicating water fluxes help to understand in an easier way the functioning of the relationships between groundwater and wetlands in distinctive hydrodynamic situations.

Figure 5 reflects the variability of water table in both wells and 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).

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 are lower than 2 m all over the periods. Meanwhile, greater changes (> 6 m) were recorded in the Pliocene aquifer from 1977 to 1997, as consequence of its confinement, but also to the groundwater pumping. During and after the channelization works, pumping decreased in the area, for example because of the diminution of cultivated extension, 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, piezometric head in the Pliocene aquifer became higher (~1 m) than in the Quaternary one and is showing practically the same behavior.

Time series of electrical conductivity (EC) and chloride concentrations in groundwater (Fig. 6) show a very close behavior in both aquifers, with values higher than 2 mS/cm and 500 mg/l, respectively. Aquifers salinity was very similar and with narrow variations until mid-80's, when it started being higher and unstable in time. A similar fact started to occur in 90's, but with an apparent ascending trend corresponding with the channelization works period. From 2013, values are very stable and close to each other.

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

A slight increasing of the average ion concentration is perceptible (Fig. 7B), like Cl^- and Na^+, in both aquifers. Similarly, concentrations of HCO_3^- and K^+ have also increased in the Quaternary aquifer, but there exists a noticeable decreasing of Ca^{2+} (both aquifers) and Mg^{2+} (Quaternary aquifer) concentrations.

EC spatial distribution in the Quaternary aquifer in the 90's (Fig. 8A) shows values lower than 5 mS/cm in almost all its area, excepting in the eastern sector, where there exist greater values (10-20 mS/cm). Chloride concentrations (Fig. 8B) present, in general, values below 1,000 mg/l, but it is possible to observe a higher concentration in the area that corresponds to the high EC values, so EC is conditioned by the chloride concentration.

However, by using a different sampling network, due to changes in land use (airport, channelization, etc.), this hydrochemical setting has suffered great changes in 2017 (Fig. 8C and 8D), with EC values higher than 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 than 15,000 mg/l in some points, more than 5 times higher than in 90's.

4.2. ***Guadalhorce Delta Wetlands***

Time evolution of wetland stage and EC measurements of Guadalhorce Delta Wetlands is shown in figure 9 (see reference of each wetland in figure 3). Seasonal variations are observed, with higher levels during the rainfall season (November-April) and lower ones at the end of the summer. However, it seems that no appreciable interannual trend exists. Average EC from 2008 to 2017 is shown in figure 10 (Charca Sur Wetland is not included in the EC measurements because of the lack of data between 2008 and 2013). It is possible to observe the influence of rainfall in the EC values of the wetlands, being lower in very wet years (2010).

It is possible, as well as in the water table time series, to observe the seasonality of EC, with maximum values in summer and minimum ones during the rainfall season. One of the most prominent facts that can be observed in figures 9 and 10 is the great EC increasing in almost all wetlands (Table 2), with an ascendant trend statistically probed by the Mann-Kendall test (Table 3). Actually, there are wetlands with EC values 30 times higher than the recorded before and during the channelization works (Figure 9). However, in the Escondida and Casilla Wetland this increment has been lower, and its seasonal variations are slighter. Whereas, other wetlands like Grande and Eucaliptal show greater seasonal increases and variations, but they are different than Limícolas, Río Viejo, Charca Sur and Costera Wetlands, because these show even higher values and variations.

Regarding to the chemical composition of wetlands' waters (Fig. 11), some significant changes have been detected. So, the earliest measurements, corresponding to the channelization works period (1997-1998), present Cl^- and Na^+ concentrations considerably lower than the actual ones. It is also visible the seasonality of the water chemistry, with higher values in dry periods and lower ones in wet periods.

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

4.3. *Guadalhorce Delta birdlife and vegetation*

Global birdlife census, carried out between 1997 and 2017 by the Andalusian Environment and Water Agency in the Guadalhorce River mouth, are shown in figure 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 the double than in 1997. After 2004 the variations have been lower. Some ascending trends can also be observed in the number of breeding pairs.

Within the censed species there are several ones which are endangered and catalogued in the Red Book of Birds of Spain (Madroño *et al*., 2004), like the Red-Crested Pochard (*Netta rufina*) or 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). It started to nest in the wetlands complex after 2003. It lives, usually, in 1.5 to 3 m depth wetlands, with slightly saline and eutrophicated waters (Torres and Arenas, 1985). Escondida and Casilla Wetlands are the unique which accomplish these conditions and where *Oxyura leucocephala* is usually seen, among other diving birds.

Figure 13B shows the evolution of two different bird species in the Grande Wetland: Common Mallard (*Anas platyrhynchos*) and Black-winged Stilt (*Himantopus himantopus*), a diving bird and a shorebird, respectively. There is no *Himantopus himantopus* population until 2001, when it started to nest there, and it is going back and forth, with an increasing trend. However, *Anas platyrhynchos* populations present a noticeable decreasing trend (see Mann-Kendall results in fig. 13B and table 4) until its disappearance in 2012. Some individuals nested here in 2015 and 2016, disappearing again in 2017.

Mann-Kendall trend analysis (Table 4) was carried out for the time series of reproductive species, breeding pairs, *Anas platyrhinchos* and *Himantopus himantopus*, to check the existence of trends and their nature. Results show increasing trends for every time series excepting for *Anas platyrhinchos*, as said before.

5. DISCUSSION AND CONCLUSIONS

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

A lot of wetlands are related with groundwater (Töth, 1963; LaBaugh, 1986; González-Bernáldez, 1992; Winter and Rosenberry, 1995; Menció *et al*., 2017) and are, partially or totally dependent of it, so any groundwater change can affect their functioning (Winter *et* al., 1998; Rosenberry and Masaki, 2013; Custodio, 2017). Coastal wetlands are, probably, the most related because: (1) water table is close to the ground surface, so it can feed, temporary or constantly, topographic depressions that may exist, and (2) groundwater discharges in coastal areas, following medium and large scale flowpaths.

However, wetlands around the world are endangered because of 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 because all the implications that the morphological change has had (hydrological and biological isolation).

The EU Water Framework Directive 2000/60/EC (EU, 2000) aims for getting a good state in the ecological and chemical status of surface water and groundwater in Europe, which includes hydromorphology, hydrology or the biological state, among others. So, land use changes, river channelization and their negative influence on the fluvial ecosystems is a challenge for the present.

5.2. Hydrological 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 Pliocene and Quaternary aquifers, with higher levels in the first one, revealing its confining character (Fig. 6).

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

The detailed groundwater surface of the river mouth and the wetlands shows distinctive behaviors (Fig. 4), and allow to check a wide range of relationships between the hydrological systems. So, in wet periods (Fig. 4E), some wetlands like Grande or Eucaliptal Wetlands act as recharge features to the aquifer, while other ones as Limicolas or Casilla Wetlands are fed by groundwater. In dry periods, the opposite occurs: recharge wetlands act as discharge ones and Casilla and Escondida Wetlands are feeding the aquifer.

This is explainable because Escondida and Casilla Wetlands present slighter variations than the other wetlands (Fig. 5), so they will act as recharge or discharge wetlands depending on the water stage in the other ones. The slighter water table range and coefficient of variation that Escondida and Casilla Wetlands present, respecting to the other wetlands and to the aquifer, allow to suppose a better hydraulic connection with the last one, because these pools became deeper than the rest after the aggregate extractions (Servicios Omicron, 1995). This supposed the removing of the organic material (low hydraulic conductivity), which made easier the connection with the Quaternary aquifer. The other wetlands are more rainfall dependent.

Channelization works have generated a kind of estuary in the river mouth, with a very perceptible influence of the Mediterranean Sea over it. So, a serious affection to the chemical quality of both aquifers has taken place, where the noticeable increase of EC and some ions like Cl^- or Na^+ prove an increasing marine influence over them (Fig. 11 and 12). Moreover, this increase in Na^+ has supposed a relevant diminution 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 even taking in account the decreasing of the pumping in the area, because of the land use change, so 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 this one over the other hydrological systems.

This new hydrodynamic situation, in both surface and groundwater, looks to be the responsible of the salinization of Guadalhorce Delta Wetlands (Fig. 9 and 10; tables 2 and 3) what can be due to the change of the groundwater flow: years ago freshwater flowed through wetlands to the Guadalhorce River, acting as a transitional element but actually no freshwater flow exists, at least in a noticeable magnitude, which feed the wetlands from the NE. The lack of freshwater supply has originated a progressive salinization of wetlands by evapoconcentration of sodium chloride waters (Cl-Na and $ClHCO_3$-Na water types) (Fig. 11), due to the relevant relationship existing between the Mediterranean Sea, the Quaternary aquifer and wetlands, which is also accentuated by the greater influence of the sea over the Guadalhorce River. Before the channelization, Grande and Eucaliptal wetlands had lower Cl^-/HCO_3^- (Fig. 12), which indicates more freshwater influence. However, salinity in Escondida Wetland is not increasing with time but instead is decreasing.

Some other interpretations could be made about the reason of the salinization of these wetlands, like guessing a natural salinization in a coastal area, but in the elapsed time between their origin (1977-1982) and the first measurements of EC, didn't occurred such an increase like during and after the channelization works.

Servicios Omicron (1995) and Lucena and Carrasco (2000) studied the potential environmental impacts of the channelization over the Guadalhorce River, particularly those regarding to the groundwater dependent ecosystems, as well as the local groundwater hydrodynamic and they concluded that no severe alteration of the hydrology was going to take place. In other studies (Perles *et al.*, 1999a, 1999c), the occurrence of impacts on hydrology and the habitat was predicted.

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

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 in account is the known impact that channelizations have over the biodiversity (Brooker, 1985) or wetlands (Wilcock, 1991). So, when wetlands got isolated, it is of a great concern to assess the possible impact on them. An increase in reproductive species and breeding pairs has been recorded (Fig. 13A), fact associated to the removing of farming areas in the vicinity of wetlands and to the new isolation from the city and other lands, being more attractive for birdlife. It is important to sum 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. It is also very relevant the increase of threatened species, which gives also more value to this recovery.

The disappearance of diving birds as *Anas platyrhynchos* and the appearance of shorebirds as *Himantopus himantopus* and others in the Grande Wetland (Fig. 13B) can be explained by the change in the water quality and mineralization of water. So, *Anas platyrhynchos* shows a preference for freshwater (Madge and Burn, 1988) and, when the salinity of waters became too high, it stopped nesting in this wetland. *Himantopus himantopus*, in the other hand, likes 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 (Johngard, 1981), saltpans and coastal marshes (Del Hoyo *et al*., 1996). So, when the EC of the wetland started to increase, this bird found an ideal habitat for breeding but is also nesting in the other saline wetlands in the area. There occurred a transition towards a different ecosystem (from freshwater to saline wetlands), in an Anthropocene context, creating novel, non-expected, ecosystems.

Vegetation changes have been analyzed along years in this area. The first studies were done by Díez-Garretas (1977) and Asensi & Nieto (1981). They were focused in the recognition and characterization of the Málaga province coastal, halophytic and wetland vegetation, respectively and, more specifically, in the phytosociology of plants. In these works, the vegetal association *Scirpetum compacto-littoralis phragmitetosum isiaci* was detected, composed by *Typha angustifolia*, *Scirpus maritimus var. compactus* or *Phragmites communis* subsp. *isiacus*, among others. A recent study, carried out by Casimiro-Soriguer Solanas & García-Sánchez (2017), has demonstrated the lack 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 ones associated to 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, as *Chara canescens*, *Chara aspera*, *Chara vulgaris* subsp. *envulgaris* or *Najas marina* (Nieto-Caldera *et al*., 1997; Casimiro-Soriguer Solanas & García-Sánchez, 2017). In the other hand, some species, growing in saline soils and waters, have appeared in the last years, as *Elymus elongatus* subsp. *elongatus* or great prairies of *Sarcocornia perennis* subsp. *alpini* (Casimiro-Soriguer Solanas & García-Sánchez, 2017).

This remarkable increase of saline water/soil-related species as *Sarcocornia perennis* subsp. *apini* or *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 groundwater dependent ecosystems associated has permitted to confirm that a river hydromodification, as a channelization is, as well as land use changes, can cause relevant alterations on the hydrology of surface water and groundwater, and consequently on the biodiversity.

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

In this way, Guadalhorce River is always in a gaining relationship with the Quaternary aquifer but in the Guadalhorce Delta Wetlands this relationship is very changeable, 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 in the environment: isolation and improvement of birdlife. So, an increase of birds 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 have caused the salinization of the whole mouth area and the related wetlands, in a bigger magnitude in some of them, what has made some bird populations to switch wetlands for nesting. These high saline waters have also made saline vegetation to grow in a bigger surface around wetlands

Consistent hydrogeological reports about channelization works can help to avoid important damages not only on the environment, but also on human being (raw materials and food, tourism, etc.). So, we strongly encourage land managers to take in account rigorous multidisciplinary approach assessments of hydraulic infrastructures to avoid negative impacts.

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FIGURES AND TABLES CAPTIONS

Figure 1. Geographical location and geological map of the LGRB (A). Hydrogeological sections I-I' and II-II' (B and C) are also shown (modified from IGME, 1983 and 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

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

Figure 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) the river hydromodification.

Figure 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 figure 6. E-F) Groundwater levels in wells and wetlands and groundwater table of the Guadalhorce River mouth in February (A) and August (B) 2017

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

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

Figure 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

Figure 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

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

Figure 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

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

Figure 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

Figure 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

Figure 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 1. Source of hydrological data taken in the LGRB

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

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

Table 4. Results of the Mann-Kendall test over some bird censuses

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

Table 1. Source of data
Click here to download Table: Table 1. Source of data.eps

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

Table 2. Chemistry of wetlands

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		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	71332	10491	33470	2874	5014	1086
	Average	53.6	8.6	252	33986	4935	18476	1303	2684	468
	CV	46.8	5.3	30	58	55	56	56	57	55
	SD	25.1	0.5	75	19679	2720	10355	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	30776	6176	16361	2126	2739	317
	Average	29.4	8.0	266	16449	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	13701	1893	6877	568	1066	137
	Maximum	168.8	9.7	391	152063	17176	85237	4281	13122	1769
	Average	69.5	8.1	283	50820	6475	27775	1612	4207	619
	CV	50.3	4.8	20	72	64	69	53	72	67
	SD	35.0	0.4	56	36839	4173	19212	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	74164	9150	40832	2296	5554	1000
	Average	55.7	8.2	238	36357	4440	20788	1259	2769	519
	CV	46.9	6.1	19	55	52	53	50	53	52
	SD	26.1	0.5	45	20074	2319	11030	623	1469	267
Río Viejo	n	91	81	34	34	34	34	34	34	34
	Minimum	17.1	7.4	156	12344	1649	7102	576	1000	182
	Maximum	185.0	9.7	331	170746	15105	109986	3699	15757	2638
	Average	81.6	8.5	230	63126	7140	35109	2030	4967	861
	CV	49.8	6.2	21	69	50	69	41	72	67
	SD	40.7	0.5	47	43510	3561	24375	838	3601	579
Costera	n	90	81	32	32	32	32	32	32	32
	Minimum	3.7	7.1	161	22149	2804	13352	624	1700	402
	Maximum	150.2	9.5	332	115293	14609	63683	2804	7989	1845
	Average	85.5	8.3	250	66707	8181	37321	1689	4761	1054
	CV	37.3	5.5	17	37	35	34	30	34	33
	SD	31.9	0.5	43	24925	2839	12711	504	1631	349
Charca Sur	n	40	32	33	33	33	33	33	33	33
	Minimum	28.6	7.6	172	11152	1529	6438	460	889	169
	Maximum	170.0	9.1	478	140877	15219	80449	3669	10504	1807
	Average	91.9	8.2	288	57047	6687	31444	1645	4172	756
	CV	38.2	4.5	25	65	58	63	51	63	58
	SD	35.1	0.4	73	37123	3894	19868	835	2624	438

Table 3. Mann-kendall wetlands

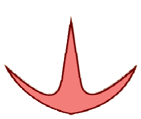
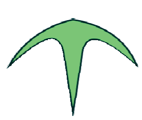
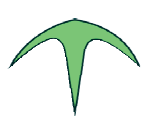
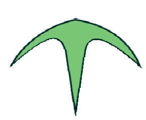
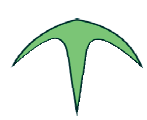
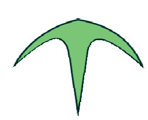
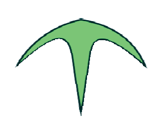
Variable	Escondida	Grande	Casilla	Limícolas	Eucaliptal	Río Viejo	Costera
Observations	91	103	92	90	96	91	90
Minimum	12.25	2.78	2.43	3.39	2.58	17.09	3.66
Maximum	21.3	102.5	40	168.8	102.8	185	150.2
Mean	15.76	53.63	29.37	69.53	55.67	81.63	85.49
Std. deviation	2.23	25.12	6.69	34.96	26.14	40.69	31.92
S	-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

Table 4. Mann-Kendall birds

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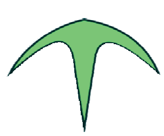
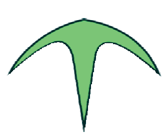
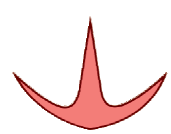
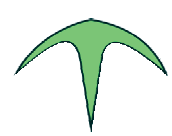
Variable	Breeding pairs	Reproductive species	*Anas Platyrhinchos*	*Himantopus himantopus*
Observations	21	21	21	21
Minimum	65	6	0	0
Maximum	209	13	50	41
Mean	121.7	10.5	16.7	13.9
Std. deviation	46.4	2.1	14.2	12.6
S	87	98	-28	47
Var(S)	1096	983	407	332
p-value (Two-tailed)	0.009	0.002	0.181	0.012
alpha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

Table 5. Vegetal species

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	✓	✓

Figure 1. Geology
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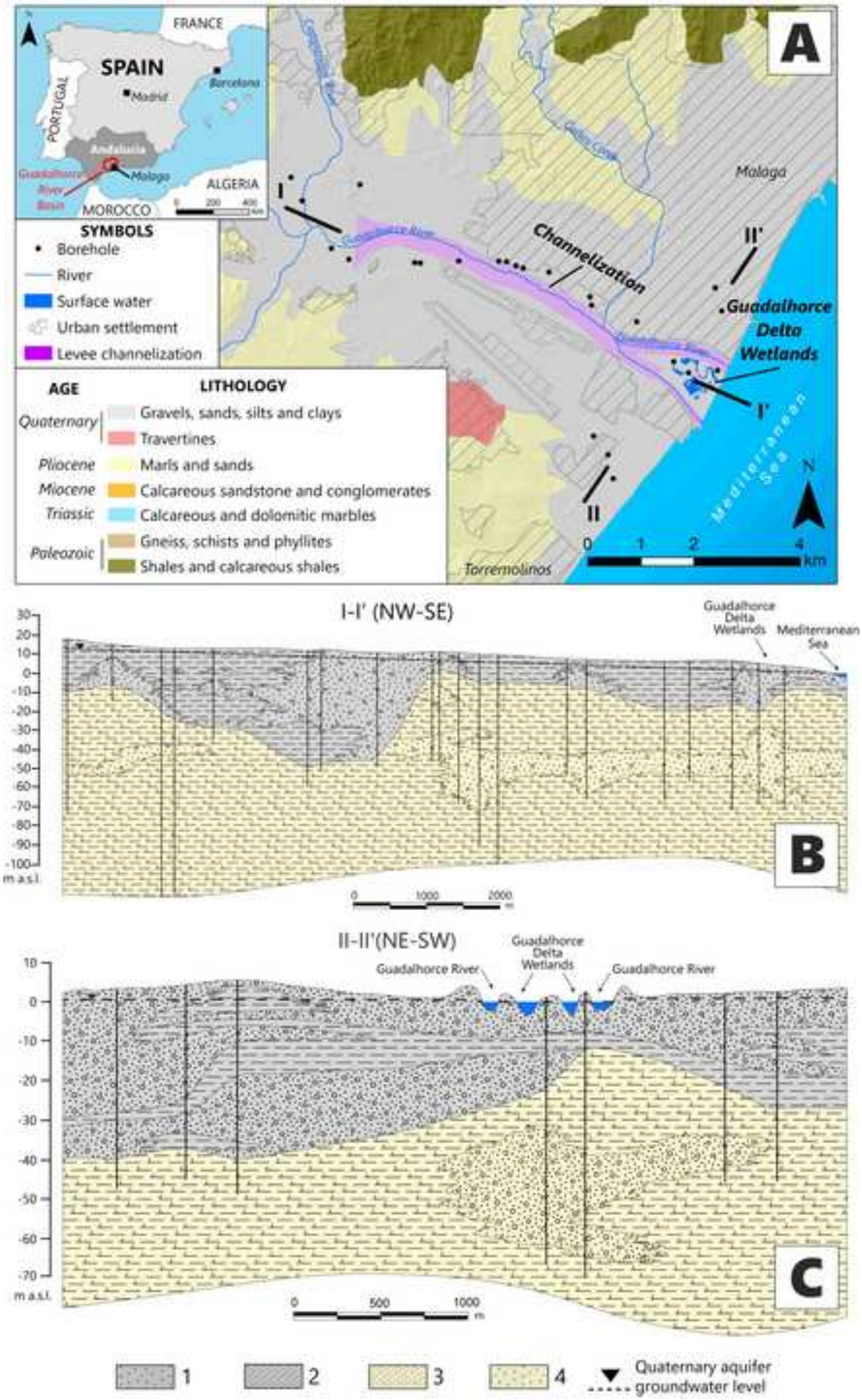

Figure 2. Land use change
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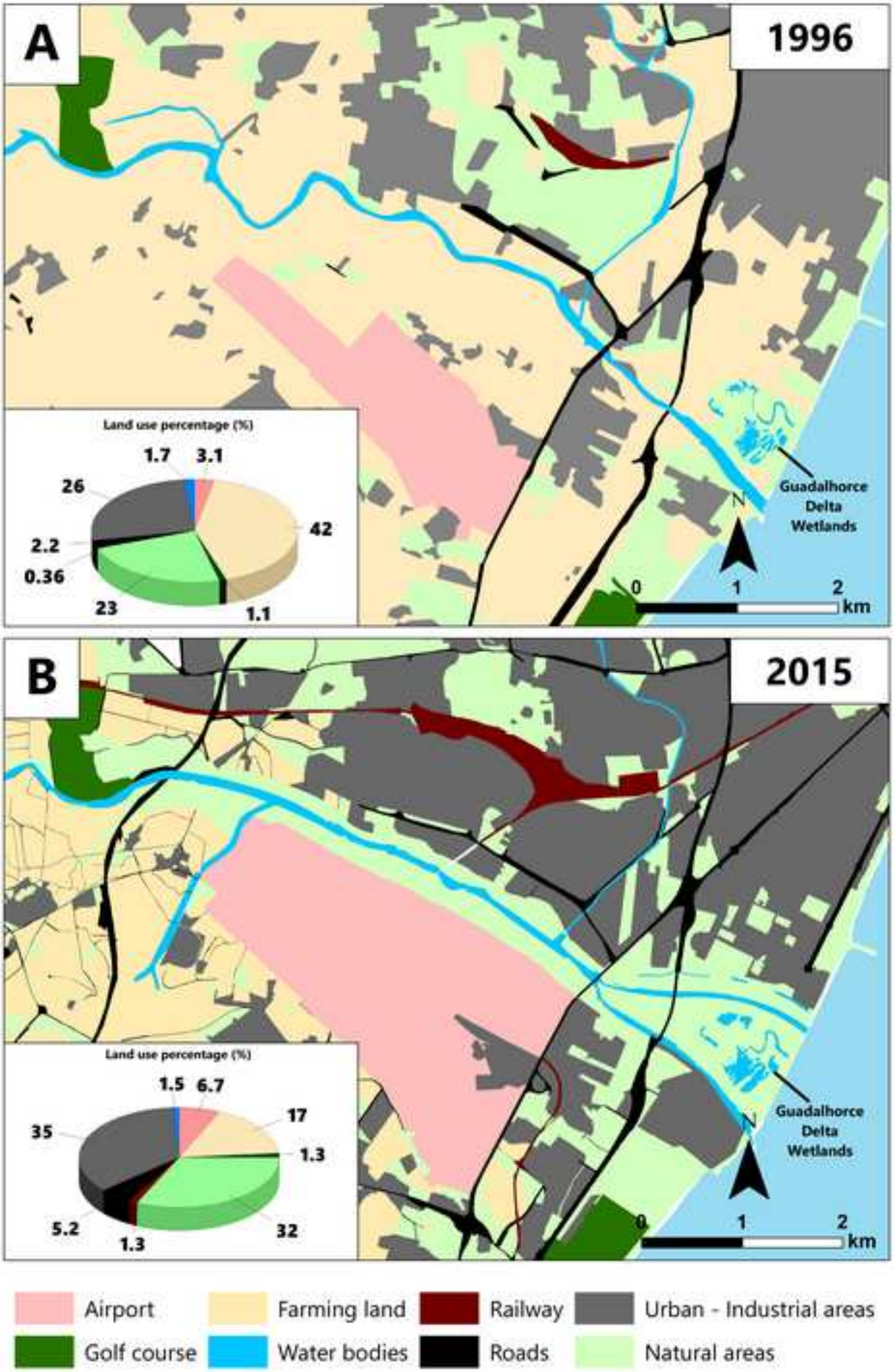

Figure 3. Wetlands timeline
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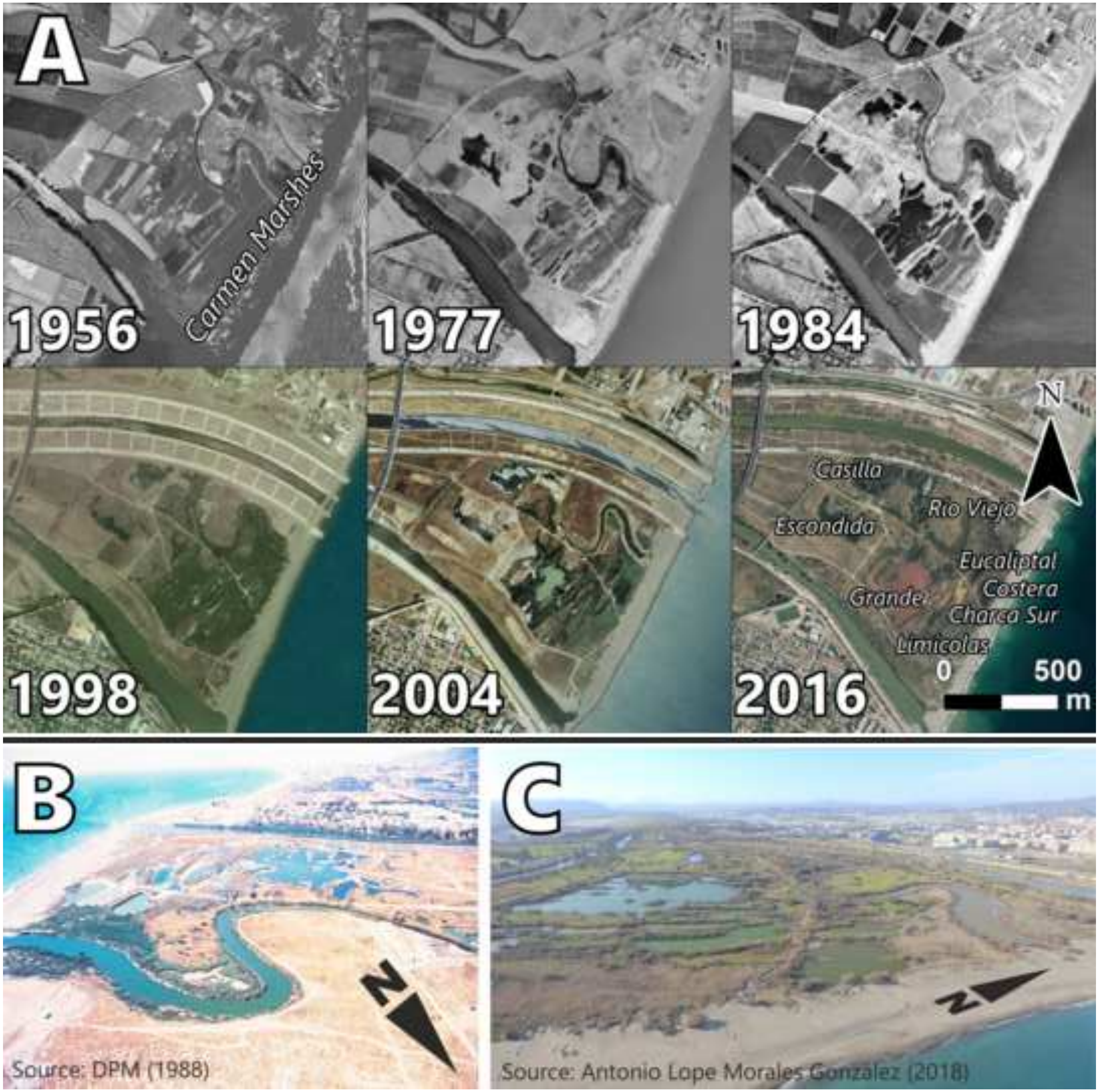

Figure 4. Groundwater surface 1996-2017 and detail

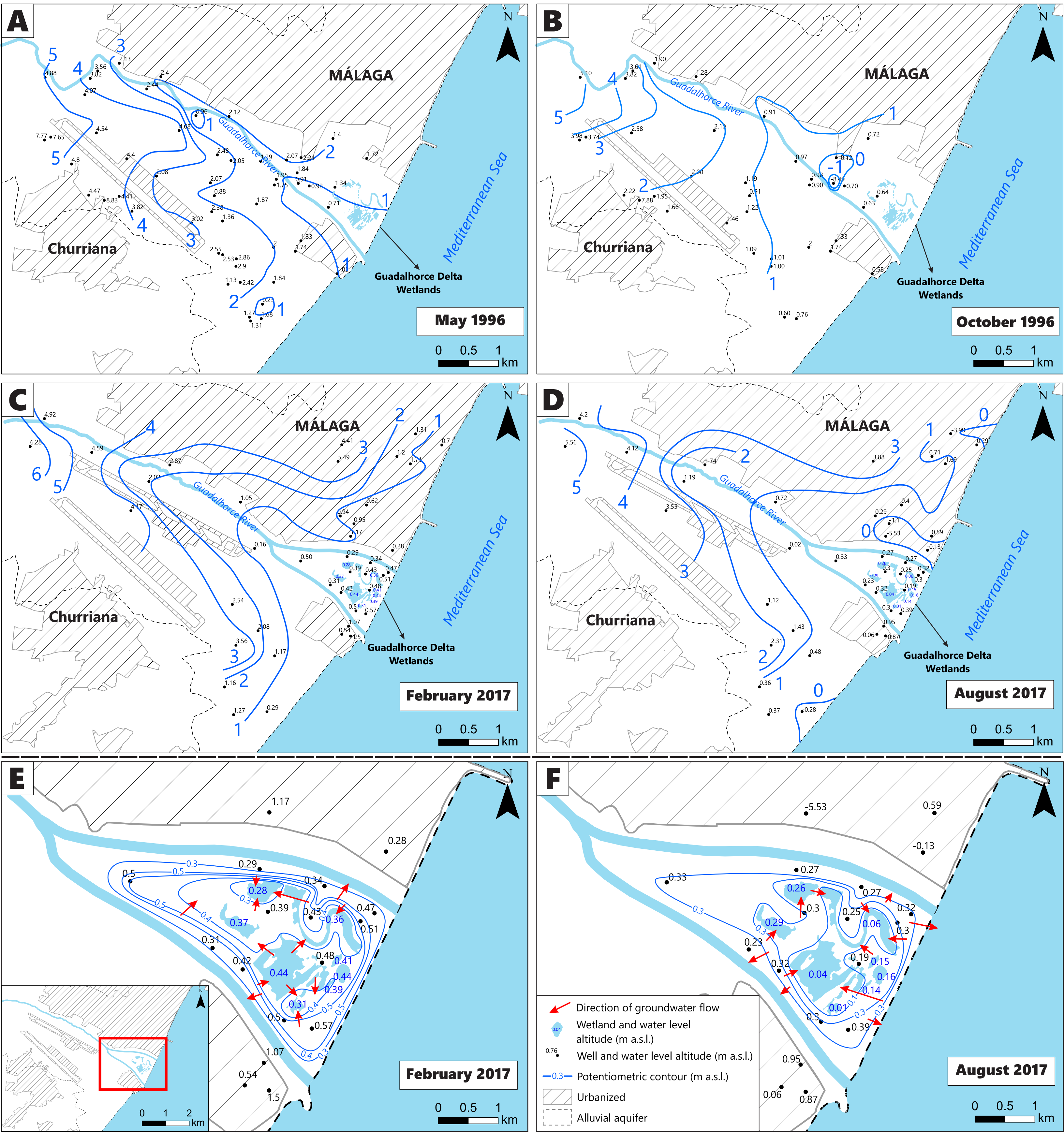

Figure 5. Water levels variability

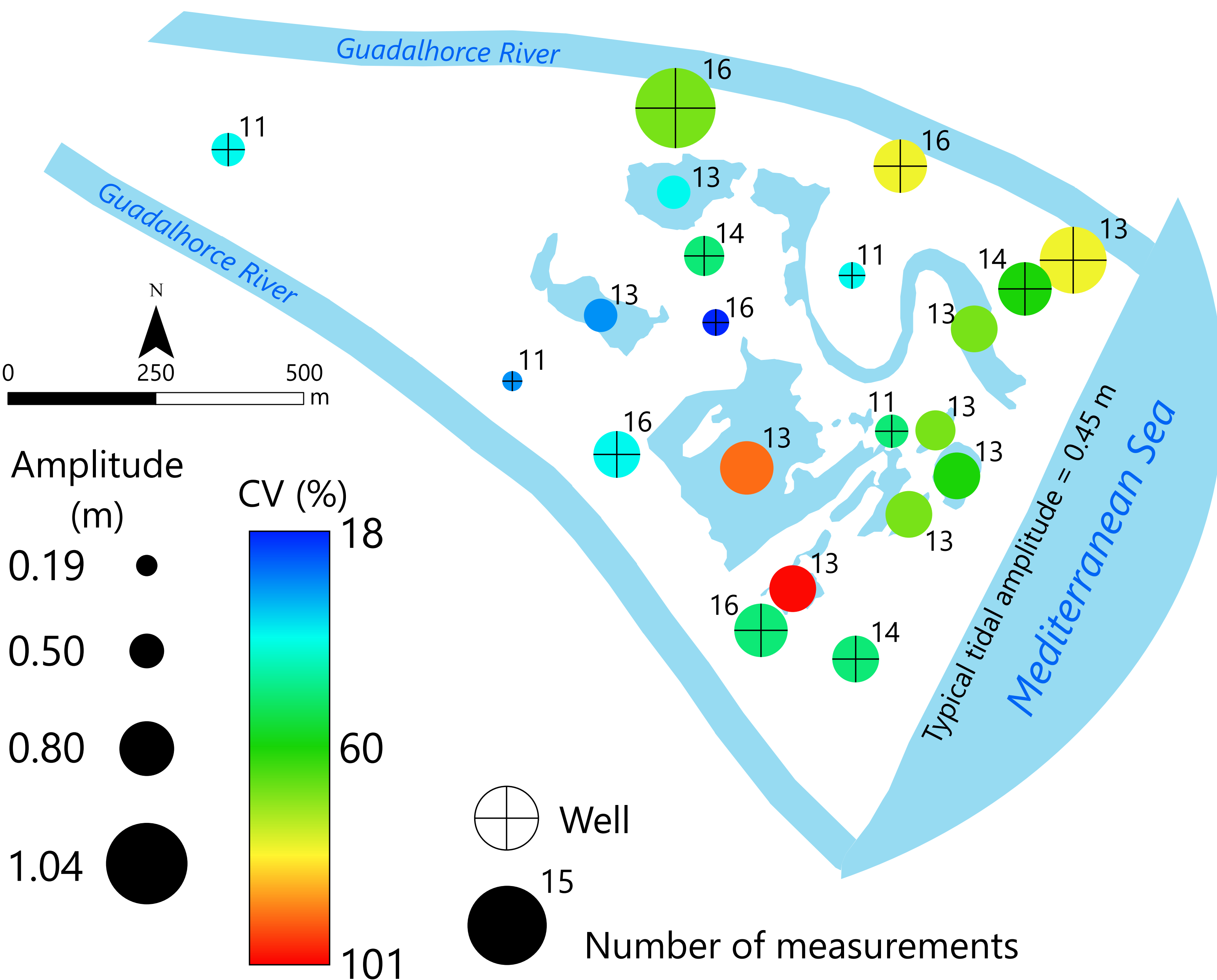

Figure 6. Groundwater levels and chemistry
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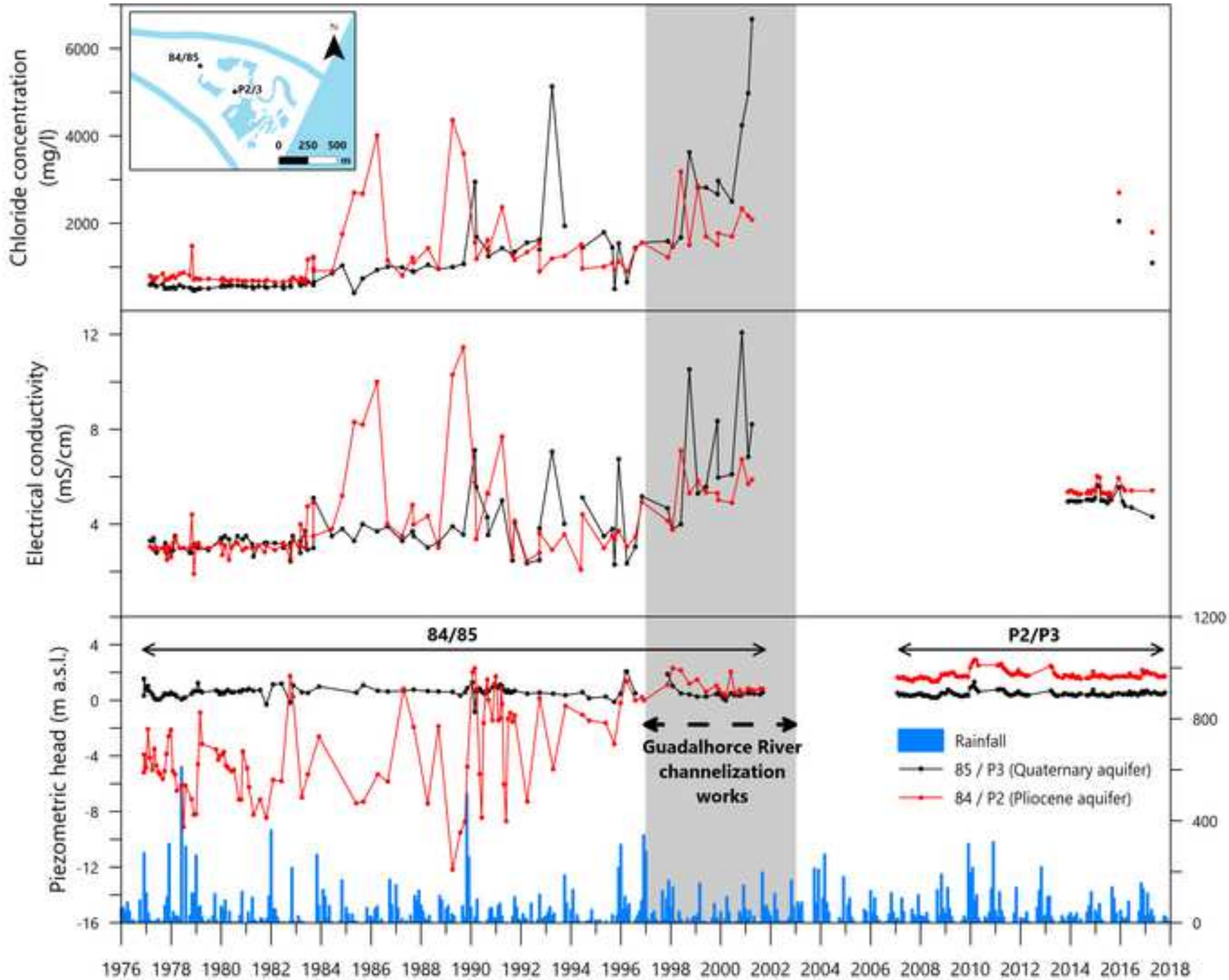

Figure 7. Piper and schoeller diagrams
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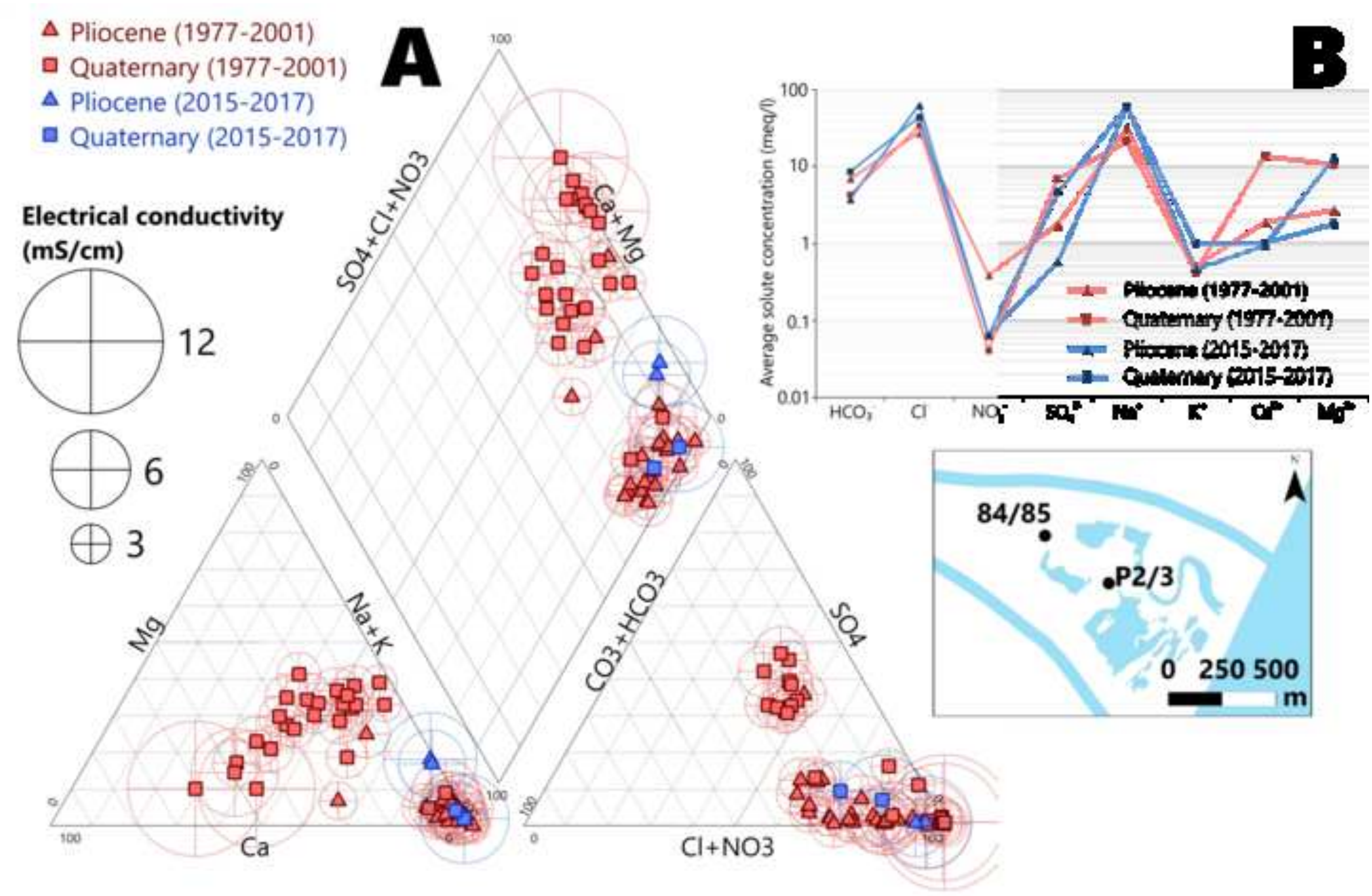

Figure 8. CE and chloride
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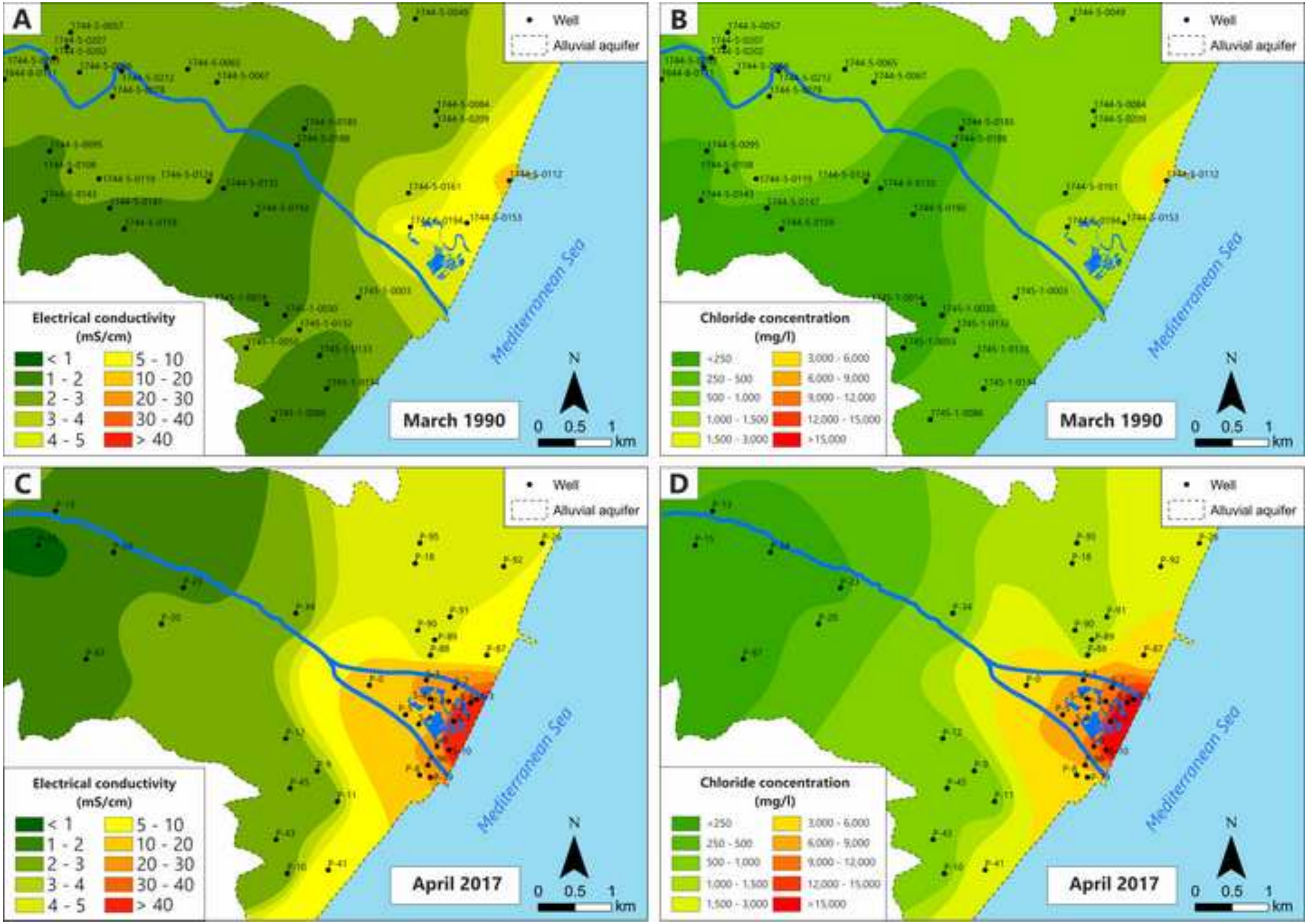

Figure 9. Wetlands stage and CE

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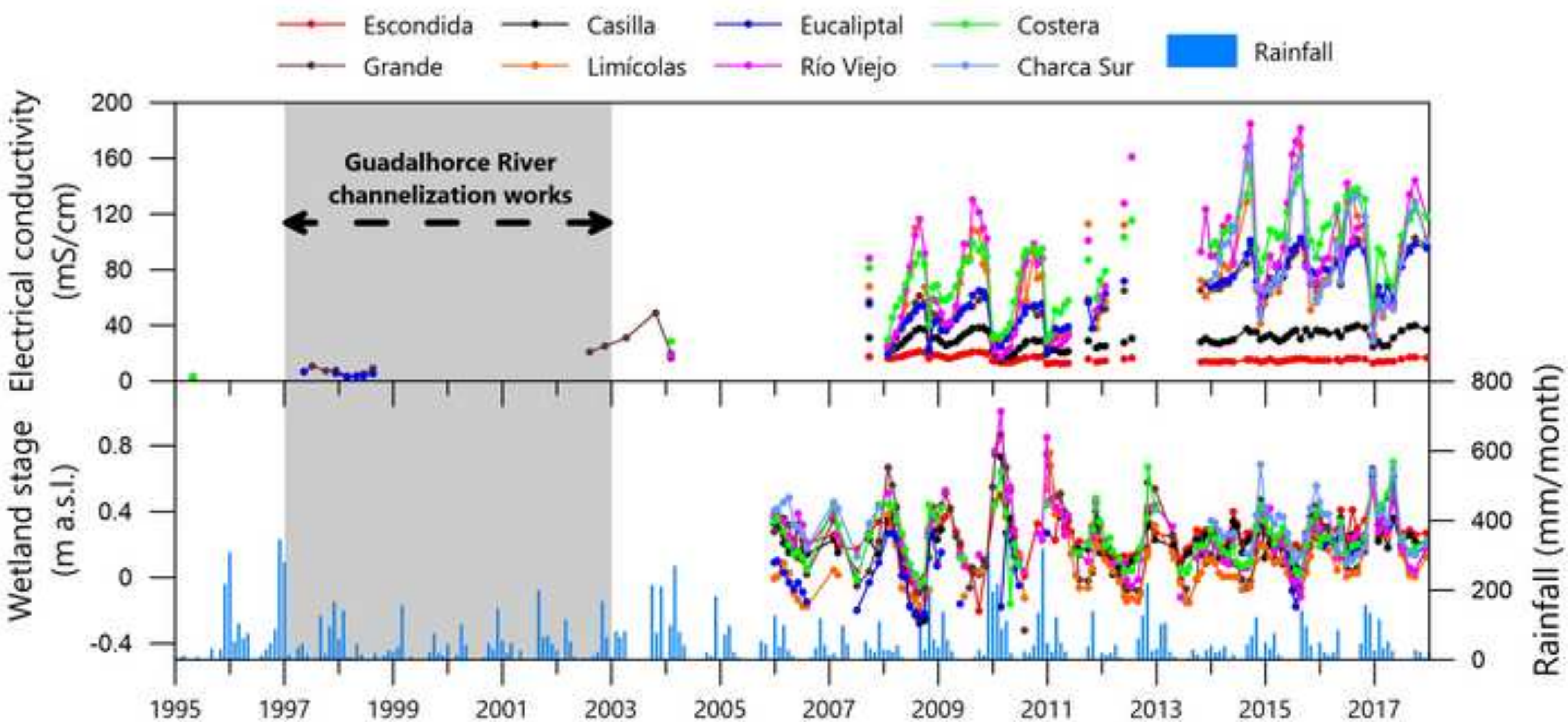

Figure 10. Wetlands CE mosaic

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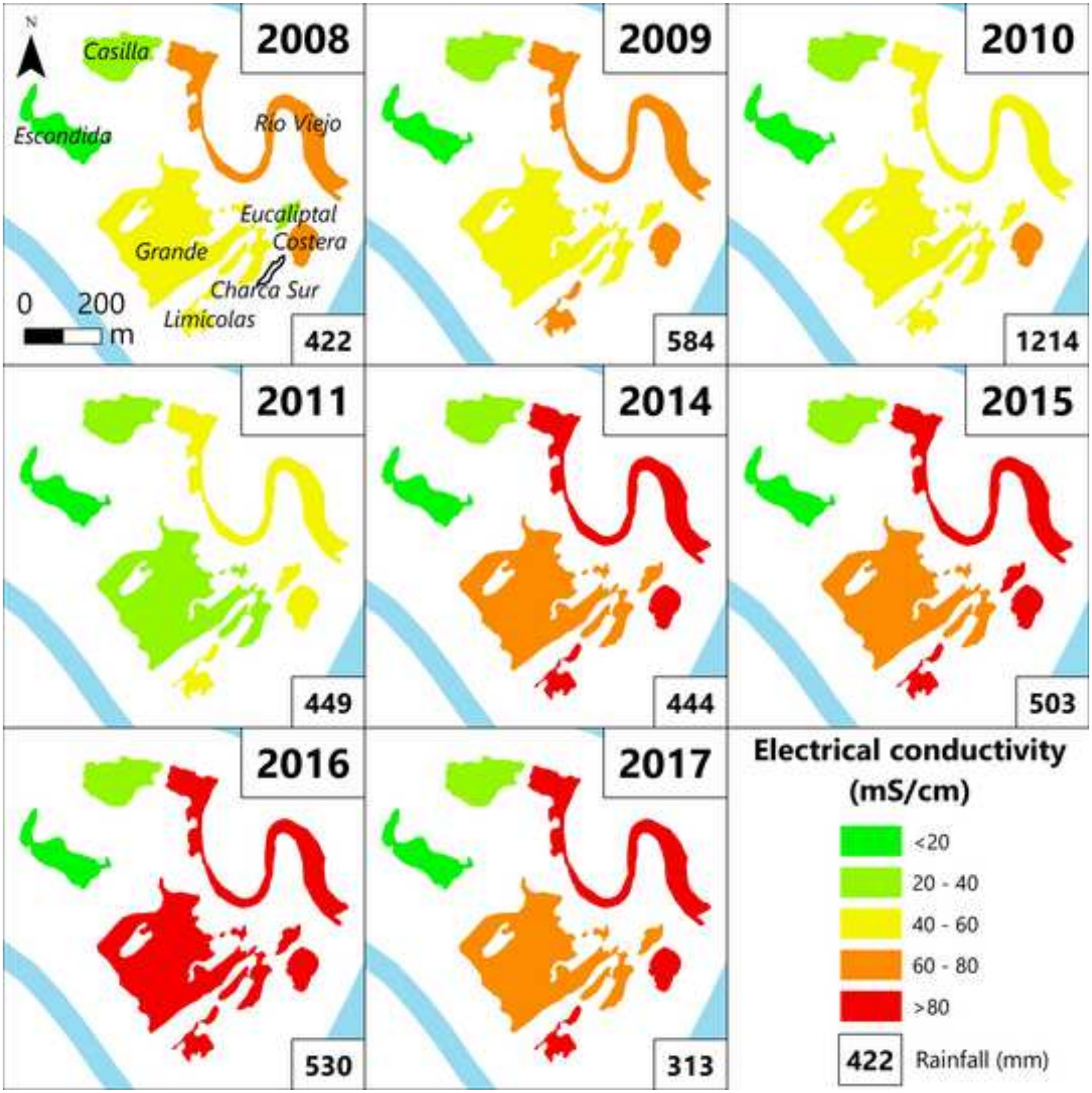

Figure 11. Wetlands Cl and Na
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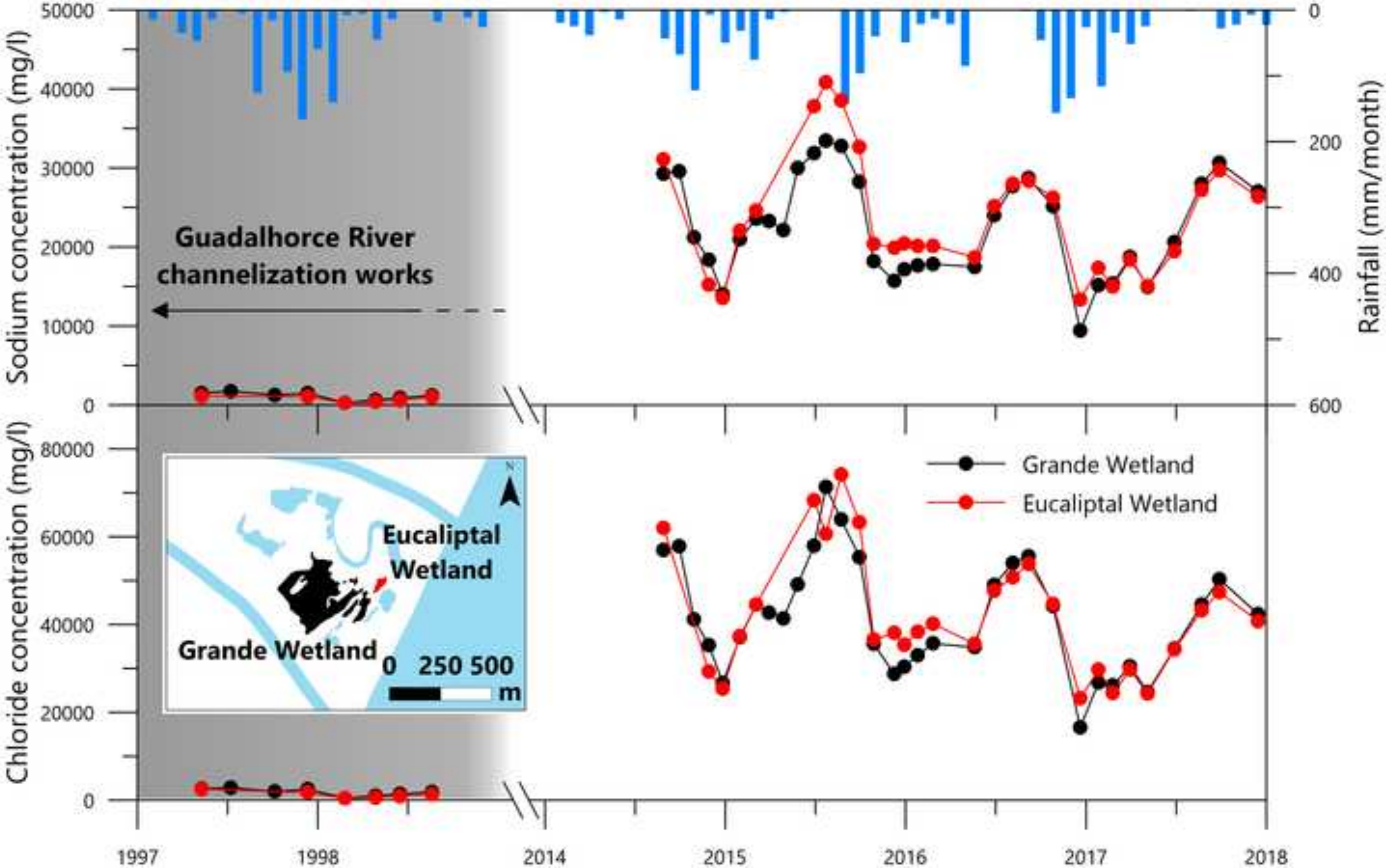

Figure 12. Biplot

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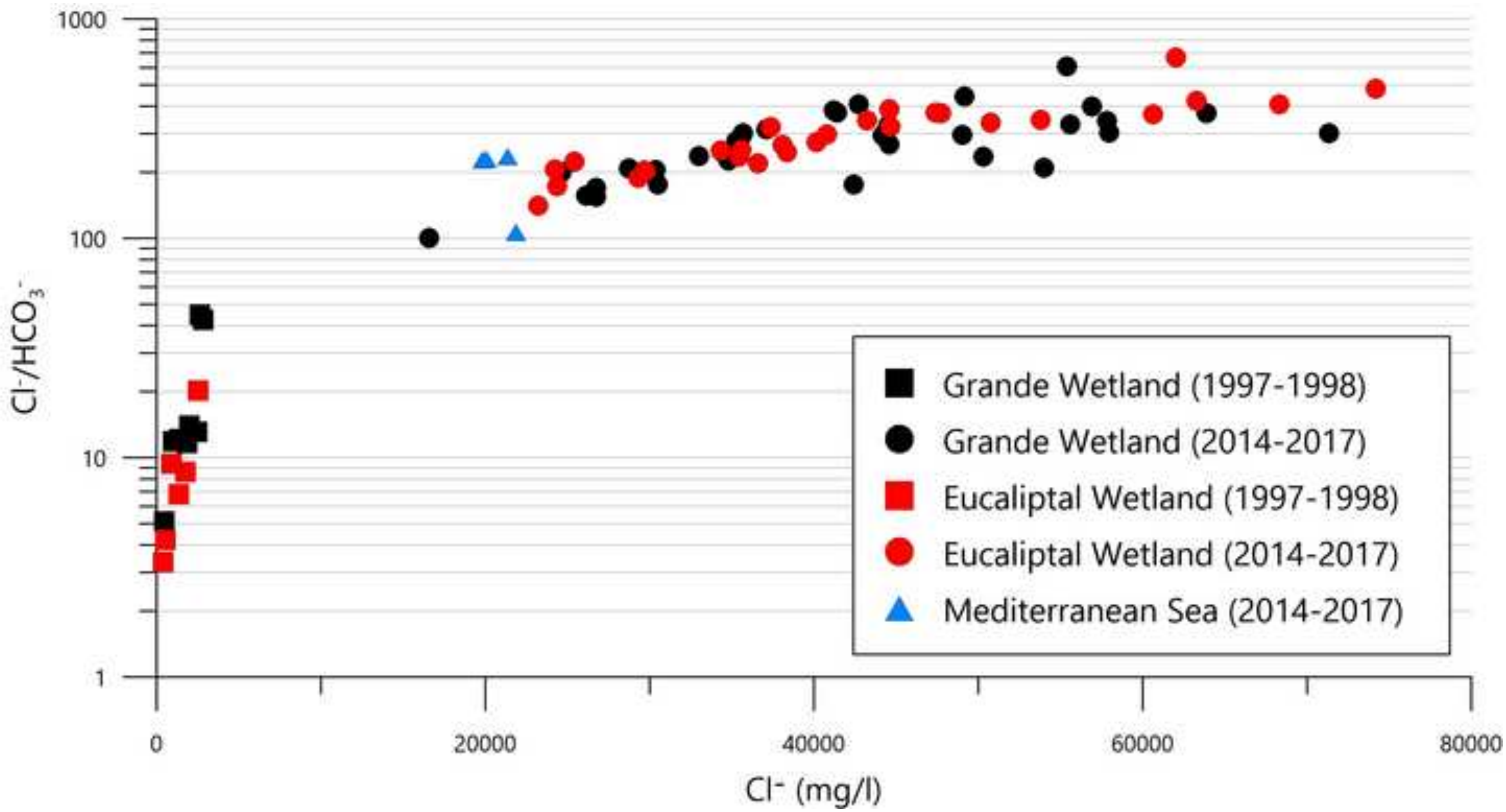

Figure 13. Censuses

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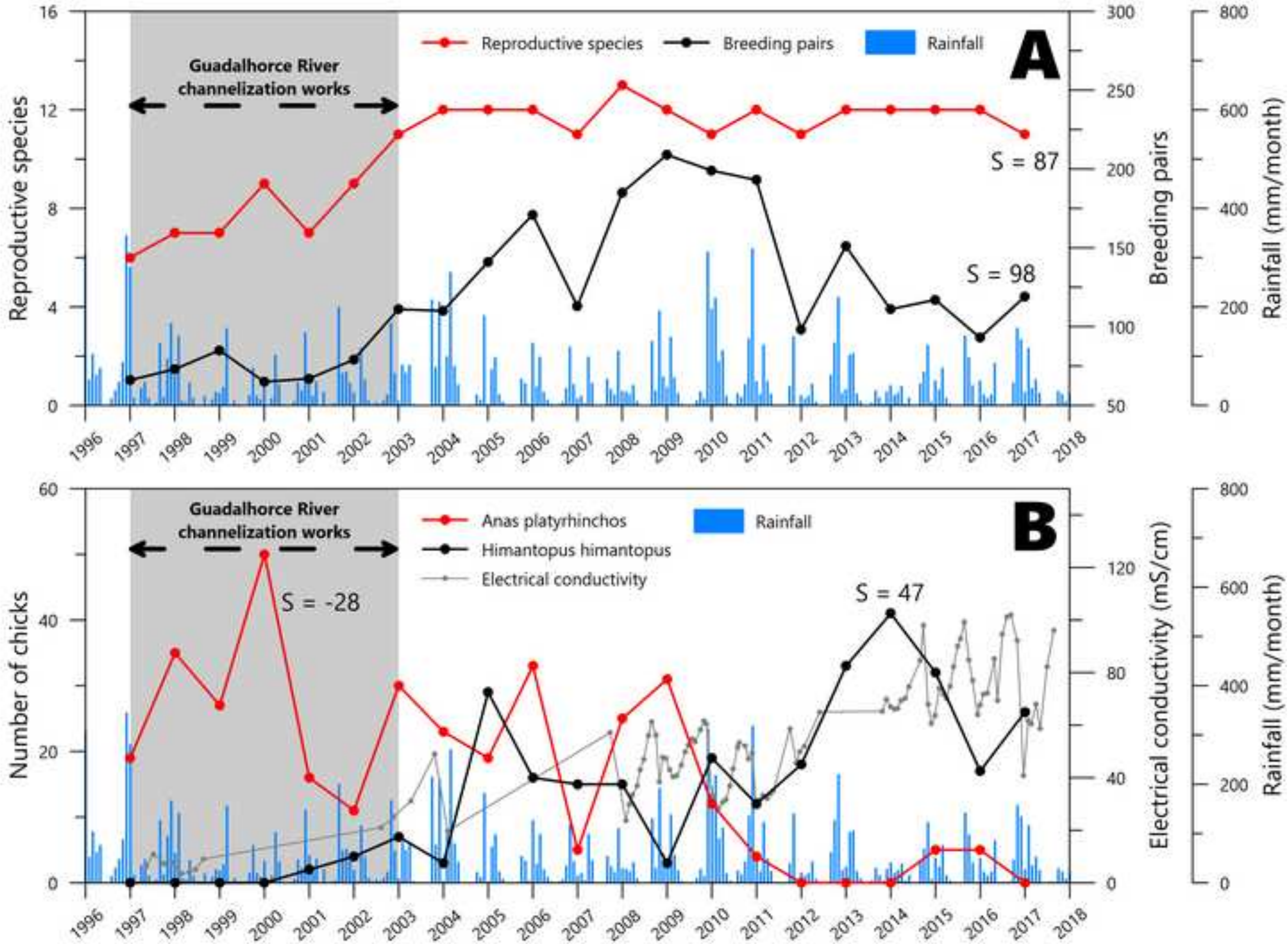

Figure 14. Summary figure

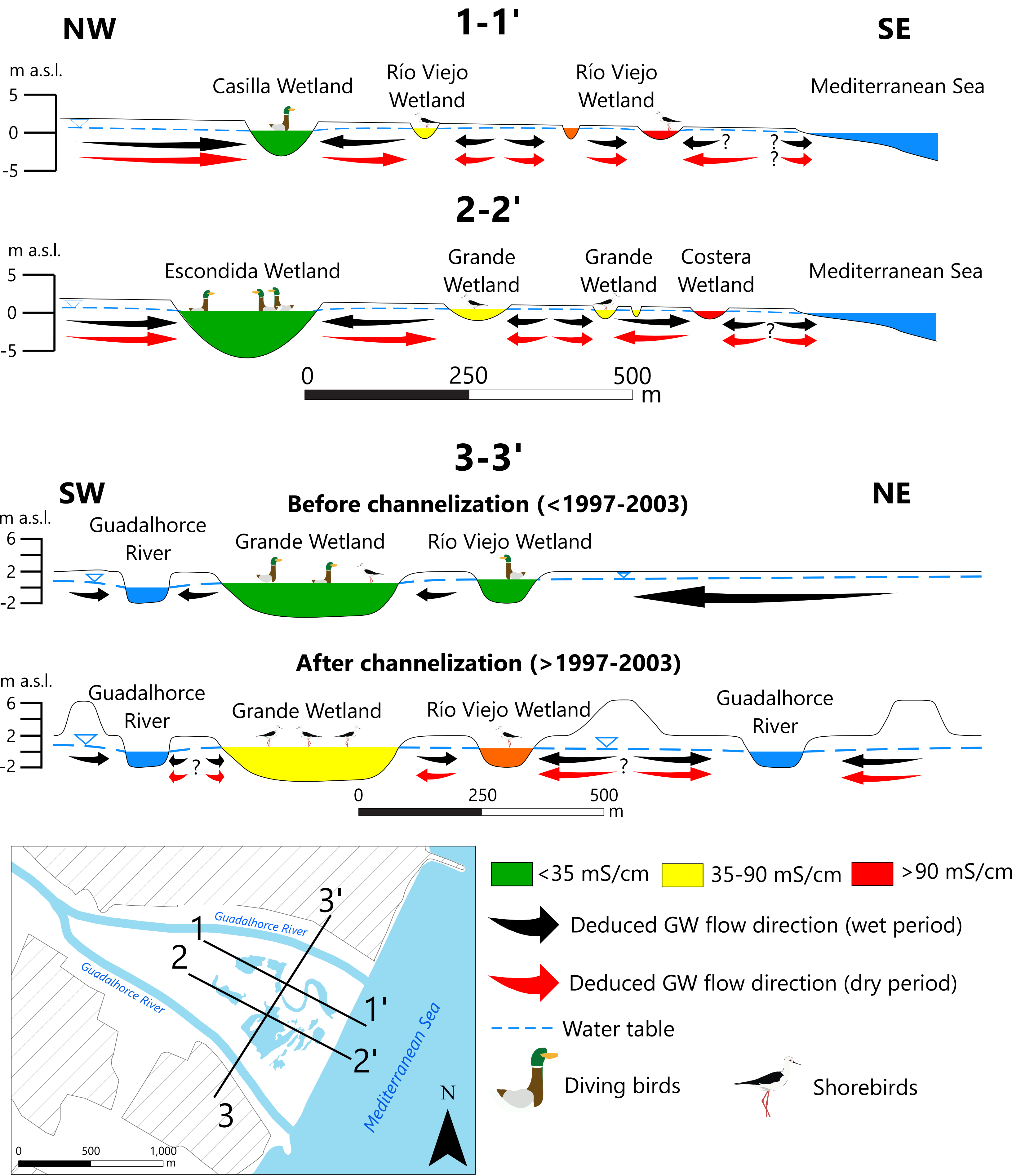

Figure 1. Location and lithological map of the study area (A). Hydrogeological sections I-I' and II-II' (B and C) are also shown (modified from IGME, 1983 and Linares *et al*., 1995). Legend: 1: Quaternary aquifer with predominance of gravels and gross sands. 2: Quaternary aquifer of sands, silts and 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

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

Figure 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.

Figure 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 figure 6. E-F) Groundwater levels in wells and wetlands and groundwater table of the Guadalhorce River mouth in February (A) and August (B) 2017

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

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

Figure 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

Figure 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

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

Figure 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

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

Figure 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

Figure 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

Figure 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 1. Source of hydrological data taken in the LGRB

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

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

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

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

***Declaration of Interest Statement**

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: