



# Groundwater salinity during 500 years of anthropogenic-driven coastline changes in the Motril-Salobreña aquifer (South East Spain)

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## Abstract

The freshwater–saltwater interface position in groundwater at coastal aquifers is determined by the location of the coastline. Anthropogenic-driven changes as modification of the land uses in catchments or the engineering construction in rivers can alter the transport of sediments to the coastal areas affecting to the coastline shape in detrital systems. This is the case of the Motril-Salobreña aquifer where the rapid coastline progradation over the last 500 years generated new land previously covered by the sea at a fast rate, 3 m year<sup>-1</sup> during hundreds of years. The effect of these changes in the salinity of the aquifer and the flushing time by freshwater has been examined with a paleo-hydrogeological model simulating the transient evolution of the groundwater salinity for the last 500 years with SEAWAT. The results of the model indicate a differentiated flushing time depending on the hydraulic properties in the region ranging from 50 years in the western sector to up to more than 200 years in the central sector for the shallower parts of the aquifer. In the deeper layers, the time can be highly increased but the uncertainties in the hydraulic properties generate different scenarios both in flushing time and water circulation in the aquifer. The sectors in the aquifer where changes took place at a faster rate are also the most sensitive to the effect of global changes, especially those associated to human activity as they occur at shorter time periods.

**Keywords** Groundwater numerical model · Salinity distribution · Flushing times · Paleohydrogeological model · SEAWAT

## Introduction

Global changes, as the anthropization of the environment, have been affecting to water resources for the last centuries. Coastal aquifers are indirectly affected not only by changes taking place in catchments but also by the contact with the sea and the risk of saltwater intrusion (Michael et al. 2017).

The equilibrium between freshwater and saltwater can easily be broken, triggering long-term contaminant processes for groundwater. The presence of a saline wedge occurs naturally in coastal zones as established by Ghyben–Herzberg (Drabbe and Badon Ghijben 1889; Herzberg 1901); however, changes in the hydrological system can influence its extension. Modification of recharge sources in aquifers will affect freshwater heads, while processes influencing sea level will change saltwater heads. Both can be generated by natural and/or anthropogenic processes such as sea-level oscillations (e.g., Saha et al. 2011; Rasmussen et al. 2013), climate variations (e.g., Bobba 2002), modification in the pumping regime (e.g., Adepelumi et al. 2009; Narayan et al. 2003) or decrease in the recharge as a consequence of urbanization or land uses changes (e.g., Uddameri et al. 2014; Akbarpour and Niksokahn 2018). These changes present different time scales that lead to hydrogeological variations from centuries/thousands of years for sea-level rising or climate modifications (Feseker 2007) to fast alterations in shorter terms like those performed by human intervention (Ferguson and Gleeson 2012; Duque et al. 2018).

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In coastal detrital aquifers, there is an additional element that can modify the equilibrium between saltwater and freshwater: the position of the sea border. The transport of sediments due to ocean currents moves the coastline position changing the location of the starting point where saltwater and freshwater interact. The sediment transport along coastlines (longshore drift) due to the longshore current not only is a fast process with significant alterations in the shoreline shape (Wijnberg and Terwindt 1995; Wang et al. 2010) but also it is the reason for the generation of detrital aquifers. In Mediterranean areas, the combination of precipitation regime, scarce vegetation, fragility of soils and the steep gradients of mountainous areas together with human interventions such as deforestation, fires and land use changes leads to high erosion rates and sediment transport (Poesen and Hooke 1997) affecting the shoreline location and shape.

The prediction of saltwater intrusion processes at coastal aquifers is usually calculated with numerical models including variable density. The most common approach to determine the salinity distribution and the initial salinity conditions when conducting variable-density simulations is to assume that the sea- and freshwater are in a steady-state condition. However, this assumption is often not correct, as the present conditions can be still a transient moment in the evolution of the aquifer leading to wrong conclusions. The historical modeling of landscape and the hydrogeology of an aquifer, here referred to as paleo-hydrogeological modeling, could be used as a method to better delineate the status of the salinity conditions in aquifers (Delsman et al. 2014). The amount of studies combining paleo-hydrogeological modeling with variable-density simulations has started to call the attention of researchers recently. Lebbe et al. (2008) modeled the historical evolution of saltwater distribution in the mouth of an estuary for the last 500 years. Delsman et al. (2014) modeled the evolution of saltwater intrusion in the Netherlands during the Holocene who pointed out that within the 8500-year modeled period, the coastal groundwater distribution never reached equilibrium with the contemporaneous boundary conditions. As changes in nature can take place slowly, the application of paleohydrogeological models can also be extended to understand freshwater problems. Zwertvaegher et al. (2013) simulated the phreatic groundwater level in an integrated archeological and geological study over a 12,000-year period to reconstruct the old paleo-landscape in Flanders, Belgium. van Loon et al. (2009) studied fen degradation in the Netherlands over a 2000-year period.

During the last centuries, the coastline in the Motril-Salobreña aquifer prograded thousands of meters offshore (Jabaloy-Sánchez et al. 2014) due to recent and rapid changes. As a result, the location where seawater starts the interaction with the aquifer has been migrating continuously and thereby modifying the equilibrium between freshwater and

saltwater. Previous researchers have presented uncertainties about the distribution of water salinity in the aquifer. Crespo (2012) using a geostatistical analysis over a hydrochemical database pointed to the possibility of traces of seawater trapped in areas located far away from the coast, without evidence of current saltwater intrusion like salinized wells between the coastline and the detected areas. A potential explanation could be old marine seawater trapped within sediments of low permeability (Duque et al. 2008) or sedimentological structures that prevents the flushing of the aquifer. Another would be a deeper connection between sea and aquifer (Crespo 2012). The use of paleo-hydrogeological modeling would be a solution for these questions, since the recent changes on the shoreline shape can be still affecting the configuration of the freshwater and saltwater equilibrium. A conventional groundwater model would not be able to reproduce the conditions existent in the study area. The inclusion of changes in the position of the sea border and the consideration of the salinity in groundwater when the aquifer was still under the sea level requires technical adaptations of the numerical models and the investigation about the past conditions based on historical documents and maps.

The objectives of this work are:

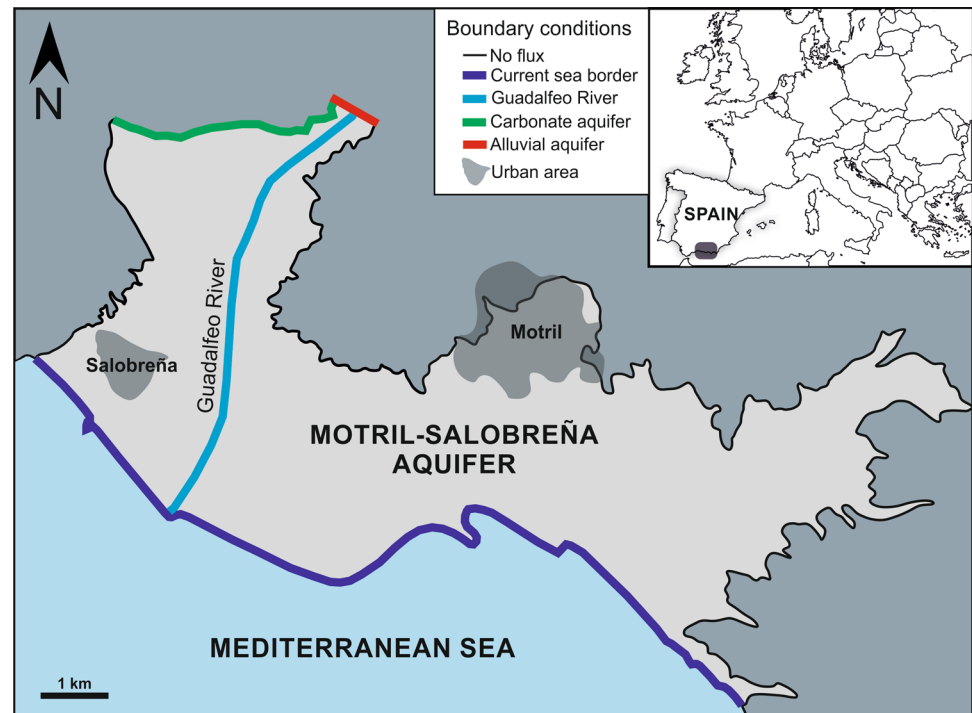
- Review the Motril-Salobreña aquifer sedimentary history to locate the sea border position in the last centuries and differentiate sedimentological units that would affect the hydraulic properties.
- Develop a paleo-groundwater numerical model including variable density to assess the effect of a migrating coastline and the evolution of groundwater salinity.
- Analyze the time for the aquifer to reach steady-state condition under century scale changes and define the flushing times for saltwater in the different hydrofacies.

## Study area

### Location and climatic setting

The Motril-Salobreña aquifer is located in the south of Spain, at the coast of the Mediterranean Sea (Fig. 1). The climate in this region is sub-tropical mediterranean with irregular periods of rain, usually concentrated in the winter months. The average annual temperature is 17–19 °C with warm summer months reaching over 25 °C and mild winters with average over 12 °C. The aquifer has mountainous reliefs in its inland borders and extends for 42 km<sup>2</sup>. The thickness of the aquifer varies, ranging from 30 to 50 m in the north to more than 250 m in the south near the coastline (Duque et al. 2008). In the west sector, it is crossed by the Guadalfeo river (Fig. 1) whose catchment has an extension of 1150 km<sup>2</sup> and reaches up to 3479 m.a.s.l.

**Fig. 1** Location of study area and boundaries used for the numerical model



in the nearby Sierra Nevada range. Because of the high elevation differences, the amount of precipitation varies within the catchment, from 400 mm year<sup>-1</sup> near the coast to over 1000 mm year<sup>-1</sup> at higher elevations (mean 717.3 mm year<sup>-1</sup>) (Liquete et al. 2005). The region is characterized by climatic variations alternating wet periods with droughts and high seasonality with dry summers and relatively wet winters.

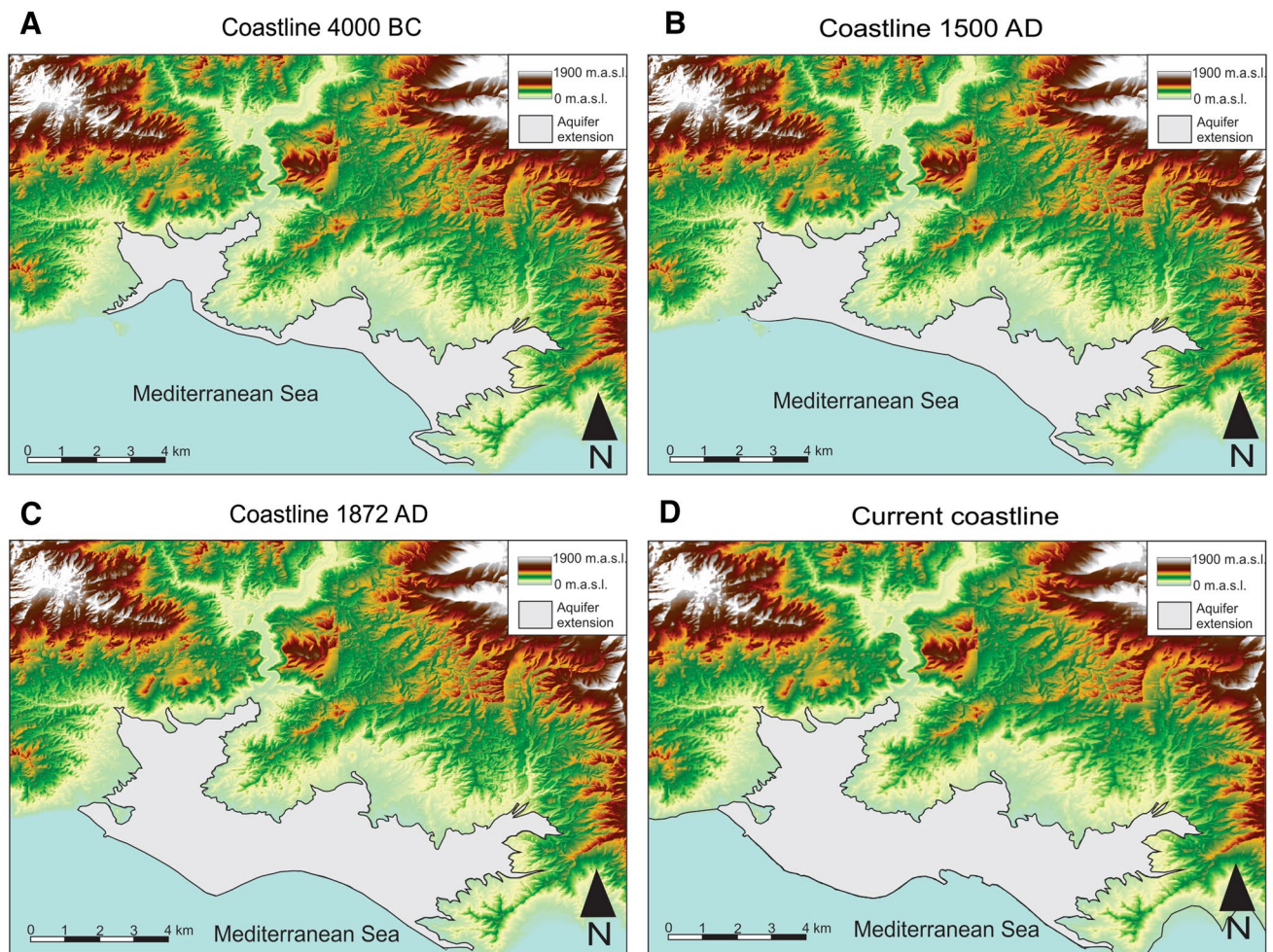
### Hydrogeological setting

The Motril-Salobreña aquifer is an unconfined aquifer (Calvache et al. 2009) composed of detrital sediments where groundwater flows predominantly from north to south. It is surrounded by metapelitic rocks that provide scarce recharge except in the area where it is in contact with a carbonated and an alluvial aquifer that provides a constant inflow (10–12% annual inflow). Other sources of recharge are the Guadalfeo River (20–32% annual inflow) (Duque et al. 2010), typically characterized by seasonal variability and two peaks in flow associated to winter rainfall, and snow melt in the catchment, and the recharge due to the irrigation excess with water derived from the river (40–54%) (Duque et al. 2011). The outputs of the system are dominated by the groundwater flow to the sea along the south border of the aquifer (73–77%), the pumping for water supply and irrigation (22–25%) and the discharge to the Guadalfeo river in the proximity of the river mouth (0–1%).

### Historical evolution

A succession of historical events in the region close to Motril-Salobreña aquifer triggered the fast movement of the coastline. During the period between the sixteenth and nineteenth century, the mountainous regions constituting the catchment of the Guadalfeo River were colonized as a defensive system from the north-African incursions and to obtain natural resources as wood and metals. The area was occupied by farmers that deforested extensive areas for farming, livestock and mining (García-Ruiz 2010; Sánchez Ramos 1995) leading to decreased soil stability and thereby increasing erosion and sediment transportation by rivers. The last five centuries have been particularly crucial but human interventions have been traced back to 2000 BC (García-Ruiz 2010).

The evolution of the Motril-Salobreña aquifer coastline from 4000 BC to present time was reconstructed (Jabaloy-Sánchez et al. 2014), based on previous studies (Hoffmann 1987), using radiocarbon-dated organic matter extracted from boreholes, archaeological data and historical maps of the area. Three stages of coastline evolution characterized by different rates of progradation were proposed: (1) 4000–2000 BC to 1500 AD, (2) 1500 AD to 1872 AD and (3) 1872–2011 (Fig. 2). During the first period, the coastline advanced at a mean rate of 0.09–0.15 m year<sup>-1</sup>. It started out as an estuary environment changing into a narrow coastal plain (Fig. 2a, b). In the second period, from 1500 AD to 1872 AD, the delta was in a highly constructive phase with a mean coastline advance of 3.3 m year<sup>-1</sup>. At the end of this period, coastline approached its current location (Fig. 2c)



**Fig. 2** Evolution of the coastline location in Motril-Salobreña aquifer for the last 6000 years based on Hoffmann (1987) and Jabaloy-Sánchez et al. (2014)

but continued expanding until around 1957 when it reached a quasi-stationary condition. From then and until 2011, different parts of the coastline experienced different growth rates, with some sections along the eastern segment even regressing (Fig. 2c, d). In the late 1940s, the Guadalfeo River track was changed and channeled to its current position to prevent flooding events. This modified the discharging point of the sediments transported by the river that can be tracked by the softening of the pointy shape of the delta (Fig. 2c, d) and the generation of a small new starting deposition point (Fig. 2d).

## Methods

The study of the groundwater salinity in the Motril-Salobreña aquifer required the development of a numerical model based on the geological information of the area. A sedimentological analysis of the aquifer was completed with

new information provided by recent drilling campaigns. The hydrogeological data were collected in previous surveys.

## Hydrofacies analysis

The available lithological columns in the aquifer (26 in total) were interpreted based on the sedimentological model of the region to define hydrofacies with differentiated hydraulic properties. For each of them, a range of hydraulic conductivity (horizontal and vertical) and storage/specific yield were assigned with the information provided by grain size analysis of samples collected in the cores extracted from drilling, and the review of previous studies using numerical models in the region. For the grain size analysis, a set of 24 samples was collected from cores collected in recent drilling campaigns in the area. Following the Hazen method (Hazen 1892), the effective grain size diameter obtained from the cumulative grain size curve was used to estimate hydraulic conductivity. This method allowed a quantitative estimation of hydraulic

conductivity at depths where until now, no information was available. It is based on:

$$K = C(d_{10})^2,$$

where  $K$  is hydraulic conductivity ( $\text{cm s}^{-1}$ ),  $d_{10}$  is the effective grain size (cm) and  $C$  is an empirical coefficient based on the degree of sorting.

Grain size analysis can be considered as a local estimation because it only represents a small fraction of the sediments. For this reason, the hydraulic conductivity was calibrated later considering the information provided by this analysis and preceding studies. Previous numerical models in the aquifer suggested different simplifications in the distribution of hydraulic properties in the aquifer and the values proposed have been considered during the calibration process. The first numerical model reproducing the Motril-Salobreña aquifer was steady state (Heredia et al. 2003), followed by transient models for a 1-year period (Ibáñez 2005; Calvache et al. 2009). A model with a more extended period (6 years) was developed but without considering variable density (Duque 2009).

### Numerical model and boundary conditions

A numerical model with variable density (SEAWAT) (Guo and Langevin 2002) was constructed based on the data presented by Duque (2009) including groundwater heads, flow in the river and recharge from irrigation and precipitation for the period 2001–2007. The grid used in the model had 16,921 cells with 100 m, 100 m, and 20 m in the  $X$ ,  $Y$  and  $Z$  dimensions, respectively, distributed in ten layers. SEAWAT uses a variable-density groundwater flow equation:

$$\nabla \left[ \rho \frac{\mu_0}{\mu} K_0 \left( \nabla h_0 + \frac{\rho - \rho_0}{\rho_0} \right) \right] = \rho S_{s,0} \frac{\partial h_0}{\partial t} + \theta \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} - \rho_s q'_s,$$

where  $\rho_0$  is the fluid density ( $\text{M L}^{-3}$ ),  $\mu$  is the dynamic viscosity ( $\text{M L}^{-1} \text{T}^{-1}$ ),  $K_0$  is the hydraulic conductivity tensor

of the material saturated with reference fluid ( $\text{L T}^{-1}$ ),  $h_0$  is the hydraulic head of the reference fluid (L),  $S_{s,0}$  is the specific storage ( $\text{L}^{-1}$ ),  $t$  is time (T),  $\theta$  is porosity (dimensionless),  $C$  is salt concentration ( $\text{M L}^{-3}$ ) and  $q'_s$  is the source or sink of fluid with density  $\rho_s$  ( $\text{T}^{-1}$ ).

The boundary conditions were defined based on the hydrogeological knowledge collected in previous studies (Table 1). The sea border was defined as a constant head with also constant salinity ( $35 \text{ g L}^{-1}$ ) that could be moved for simulating other locations of the shoreline. Most of the aquifer is surrounded by rocks that have been simplified as impermeable due to the assumption that they provide a reduced amount of flow. In the borders where the aquifer was in contact with carbonate rocks or alluvial sediments, water table measurements in that geological units were used in combination with the conductance for each of them. For recharge, a soil balance was established considering the daily precipitation combined with the irrigation excess based on crops maps and agricultural practices. The river was simulated using the flow measurements collected by the local water management agency and the characteristics of the river channel. The abstractions in the aquifer were obtained based on the surveys developed by the geological survey of Spain (IGME). The model was run under transient conditions with time steps of 1 month (72 steps in total). The first time step was set up as steady state.

Transport parameters used in the model were assigned based on the values estimated by Calvache et al. (2009): longitudinal dispersivity (30–65 m), ratio between longitudinal dispersivity and transverse dispersivity (10), retardation coefficient ( $1 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$ ), and diffusion coefficient ( $1 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ ) that corresponded to the diffusion coefficient of  $\text{Cl}^-$  and  $\text{Na}^+$ .

**Table 1** Boundary conditions used in the numerical model of the Motril-Salobreña aquifer

Name	Boundary type	Description	Characteristic
(1) Sea	Dirichlet boundary	Ocean/aquifer boundary	Constant head and concentration ( $0 \text{ m } 35 \text{ g L}^{-1}$ )
(2) Impermeable schist	Neumann boundary	Surrounding impermeable schist	Constant flow (no flow)
(3) Carbonate aquifer	Cauchy boundary	Carbonate aquifer	Head dependent based on observation well, constant concentration ( $0 \text{ g L}^{-1}$ )
(4) Alluvial aquifer	Dirichlet boundary	Limit applied where Guadalfeo alluvial starts	Constant head (varying between stress periods) based on observation well, constant concentration ( $0 \text{ g L}^{-1}$ )
(5) Guadalfeo River	Cauchy boundary	Exchange along the Guadalfeo River	River stage varies accordingly to measured field data, constant concentration ( $0 \text{ g L}^{-1}$ )
(6) Wells	Neumann boundary	Extraction through pumping	Monthly withdrawal from wells according to field surveys
(7) Recharge	Neumann boundary	Irrigation and precipitation	Excess rainfall after soil balance and irrigation return flow, constant concentration ( $0 \text{ g L}^{-1}$ )

## Calibration

The hydraulic conductivity of the model was calibrated using the pilot points technique (Doherty 2003) and PEST (Doherty and Hunt 2010) to represent the hydraulic conductivity heterogeneity in each of the hydrofacies defined. The mean error (ME), the mean absolute error (MAE) and the root mean squared error (RMSE) were minimized for observed groundwater heads during the period 2001–2004 based on:

$$ME = \frac{1}{n} \sum_{i=1}^n (h_m - h_s)_i,$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |(h_m - h_s)_i|,$$

$$RMSE = \left[ \frac{1}{n} \sum_{i=1}^n (h_m - h_s)_i^2 \right]^{0.5},$$

where  $n$  is the number of targets,  $h_m$  is the measured head (m) and  $h_s$  is the simulated head (m)

In total, 15 wells distributed along the aquifer with monthly or continuous measurements were used for the calibration and validation. A set of 43 pilot points was established in intermediate locations between the observation wells. The anisotropy ratio (horizontal and vertical), the specific yield (for the top layers) and the specific storage (for the deeper layers) were calibrated with PEST for each of the hydrofacies defined. The maximum and minimum hydraulic conductivities for each pilot point were constrained spatially by the hydrofacies assigned. The conductance of the carbonate aquifer and the Guadalfeo River were also calibrated based on the water budgets calculated by Calvache et al. (2009) and Duque (2009). Afterwards, the model was validated using the groundwater head data from 2004 to 2007.

## Sensitivity analysis

The calibration process considered only the physical processes in the aquifer (groundwater heads). A sensitivity analysis was completed for the unit with the lowest hydraulic conductivity in the aquifer (marine sediments at deep location) as it was observed that could have a major impact in the flushing time results and the uncertainty associated. Further details can be found in Olsen (2016).

## Coastline changes into the model

To implement the coastline movement in the Motril-Salobreña aquifer and to study the salinity changes of

the aquifer, the model simulation was divided in two time slices, each corresponding to distinct conditions in the location of the coastline motivated by the historical reconstruction of the coastline. This simplification was decided for operative reasons because it was required to deactivate and activate cells in the numerical model. The first time slice starts with the location of the sea border at 4000 BC as the first known reference point of the coastline until 1500 AD that is also used to reach a steady-state condition. The second time slice corresponds to the change from 1500 AD to 2007 AD. This division is based on the acceleration of the changes happening in the last 500 years in comparison with the previous thousands of years. The boundary conditions of the aquifer for the past conditions (paleohydrogeological model) are unknown and several assumptions were done:

1. *Precipitation* For the climatic characteristics, it was considered precipitation and temperature distributions recorded in the period 2001–2007 in a loop, since this period included droughts and wet years.
2. *Irrigation* The agriculture irrigation return distribution and quantity were assumed constant in the last 500 years until the last 50 years. It is documented that this region has been under agricultural influence of the Arabs with flooding irrigation system for the sugar cane with water derived from the Guadalfeo River (Lopez de Coca Castañer 1987) until the last decades when other crops were introduced.
3. *Pumping* It has only been considered for the last 40 years when wells started to be drilled and pumping systems were installed for abstraction of water.
4. *River* The characteristics for the period 2001–2007 were considered a good estimate of the river flow since it included a dry and a wet period and they were repeated in a loop.
5. The hydrogeological properties were considered constant for all the period excepting the areas that were covered by the sea that were deactivated/activated with the progradation of the coastline.

## Analysis of results

The model results were studied based on the salinity distribution for the last 500 years that is the period with a higher variability in the location of the coastline and when there is better knowledge about what can be the hydrological conditions in the region. Salinity maps and cross sections considering the correlation with hydrofacies locations were compared for different time periods. The flushing times from different locations were calculated also as indicators of risk for processes that can affect the aquifer in the future.

## Results

### Hydrofacies distribution and hydraulic properties

The sedimentological study of the aquifer showed lithological spatial variations throughout the aquifer resulting from different depositional processes. The west sector was classified as a delta with the classic sedimentary structure including topset, foreset and bottomset fed with sediments deposited predominantly by the Guadalfeo River. The East area was considered a coastal plain coupled to the outlet of several dry streams in the area, locally known as ramblas. These ramblas present high flow during periods of hours to days due to storms that generate flash floods with high sediment transport energy. Most of the years, they are dry. Coastal plains are derived from a number of deltas that have coalesced laterally and/or prograded at the same time (Alexander 1989). The evolution of the coastal plain in the east and the delta in the west is interconnected, but they show different depositional characteristics due

to the type of genetic processes that have influenced their development (Maldonado 2009). In the north sector, the aquifer is composed by coarse alluvial sediments deposited by the Guadalfeo River. Resuming the sedimentological interpretation, 6 hydrofacies units were proposed (Fig. 3): (Unit 1) channel and paleochannel of the river characterized by coarse sediments and elongated shapes (Unit 2) heterogeneous alluvial sediments dominated by gravel and sand, (Unit 3) deltaic environment with gravel, sand and some silt, (Unit 4) marine sediments (clay and silt), (Unit 5) coastal plain environment with gravel, sand and silt and (Unit 6) fan delta with also a wide range of grain size sediments.

Because of the heterogeneous composition observed within each depositional environment, for each hydrofacies unit was assigned a possible range of hydraulic properties to be applied during the calibration process based on the grain size analysis (Table 2). The maximum values were determined for the channel and paleochannel (Unit 1) of Guadalfeo river as pumping tests and drilling have shown very coarse facies (Duque 2009). Units 2, 3, 4 and

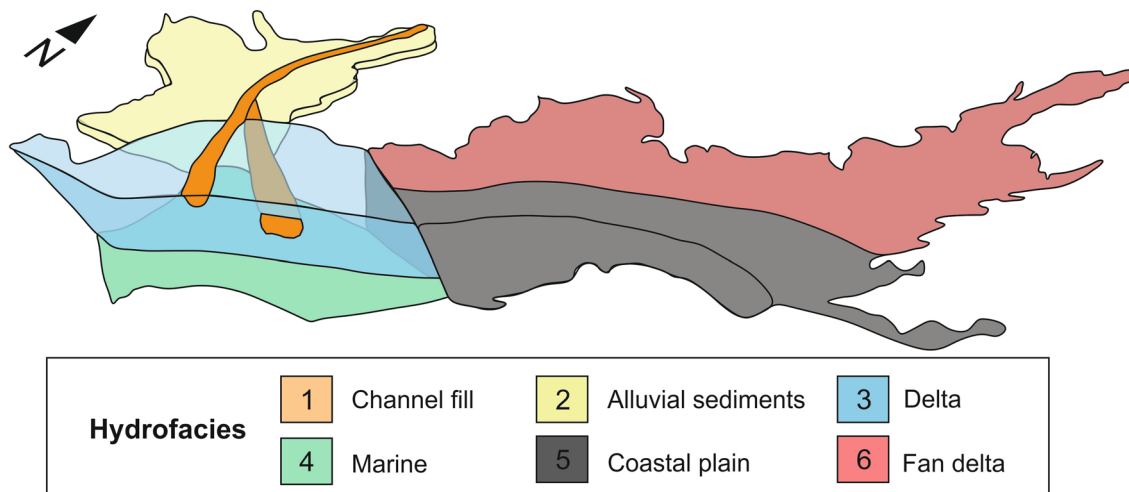


Fig. 3 3D representation of the hydrofacies units within the Motril-Salobreña aquifer

**Table 2** Description of the different hydrofacies in the Motril-Salobreña aquifer and hydraulic properties based on field data

Unit	Description	K initial values/calibrated (m day <sup>-1</sup> )	Calibrated Sy/Ss	Calibrated anisotropy horizontal/vertical
1	Channel fill	200–900/245	0.3/1 × 10 <sup>-2</sup>	3/3
2	Alluvial sediments	45–200/45–150	0.1/1 × 10 <sup>-4</sup>	0.48/10
3	Deltaic deposits	3–27/3–27	0.3/1.5 × 10 <sup>-3</sup>	0.1/6.49
4	Marine deposits	0.0001–12/1	–/1.5 × 10 <sup>-3</sup>	3/3
5	Coastal plain deposits	5–50/5–50	0.26/4 × 10 <sup>-3</sup>	1.65/10
6	Fan delta deposits	20–60/20–60	0.3/4 × 10 <sup>-3</sup>	3/10

K hydraulic conductivity, Sy specific yield, Ss specific storage

5 presented heterogeneous properties with a variable range of hydraulic conductivities. The unit 4, corresponding to marine deposits, had the lowest values as a consequence of the presence of clay, but still, due to the detection of gravel/sandy layers, higher values of hydraulic conductivity can be considered.

### Calibration and model results

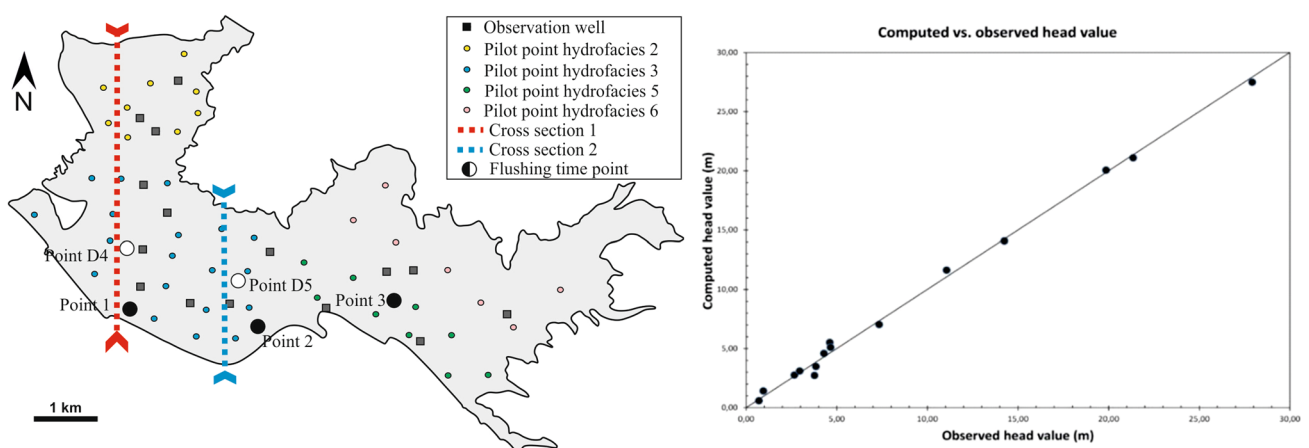
During the calibration process, the spatial distribution of hydraulic conductivity for each of the sedimentological units, the conductance for the river ( $0.2730 \text{ m}^2 \text{ day}^{-1}$ ) and the carbonated aquifer ( $0.1201 \text{ m}^2 \text{ day}^{-1}$ ), the storage properties and the anisotropy factor both for the vertical and horizontal dimension were estimated (Table 2). The unit 4 presented very low sensitivity to the changes in hydraulic conductivity, as flow will be much lower than in the more surficial layers. This process required multiple iterations combining automatic calibration tools (PEST) (Doherty and Hunt 2010), and manual calibration depending on the level of detail and information of the tested parameter. The final optimization showed a MAE = 0.54 m, ME = -0.03 m and RMSE = 0.77 m for the calibration period. After this, the dataset for the validation period was also tested with MAE = 0.63 m, ME = 0.05 m and RMSE = 0.83 m indicating that the calibration was robust enough to allow the use of the model for the simulation of other scenarios as the changes in coastline locations. The wells used for the calibration and validation were distributed along all the extension of the aquifer from the proximity of the sea to the highest topographical areas (the heads in the observation wells ranged from 35.71 to 0.49 m) (Fig. 4). The RMSE relative to the observed head

was 2.2% for the calibration period and 2.9% for the validation period.

### Salinity changes

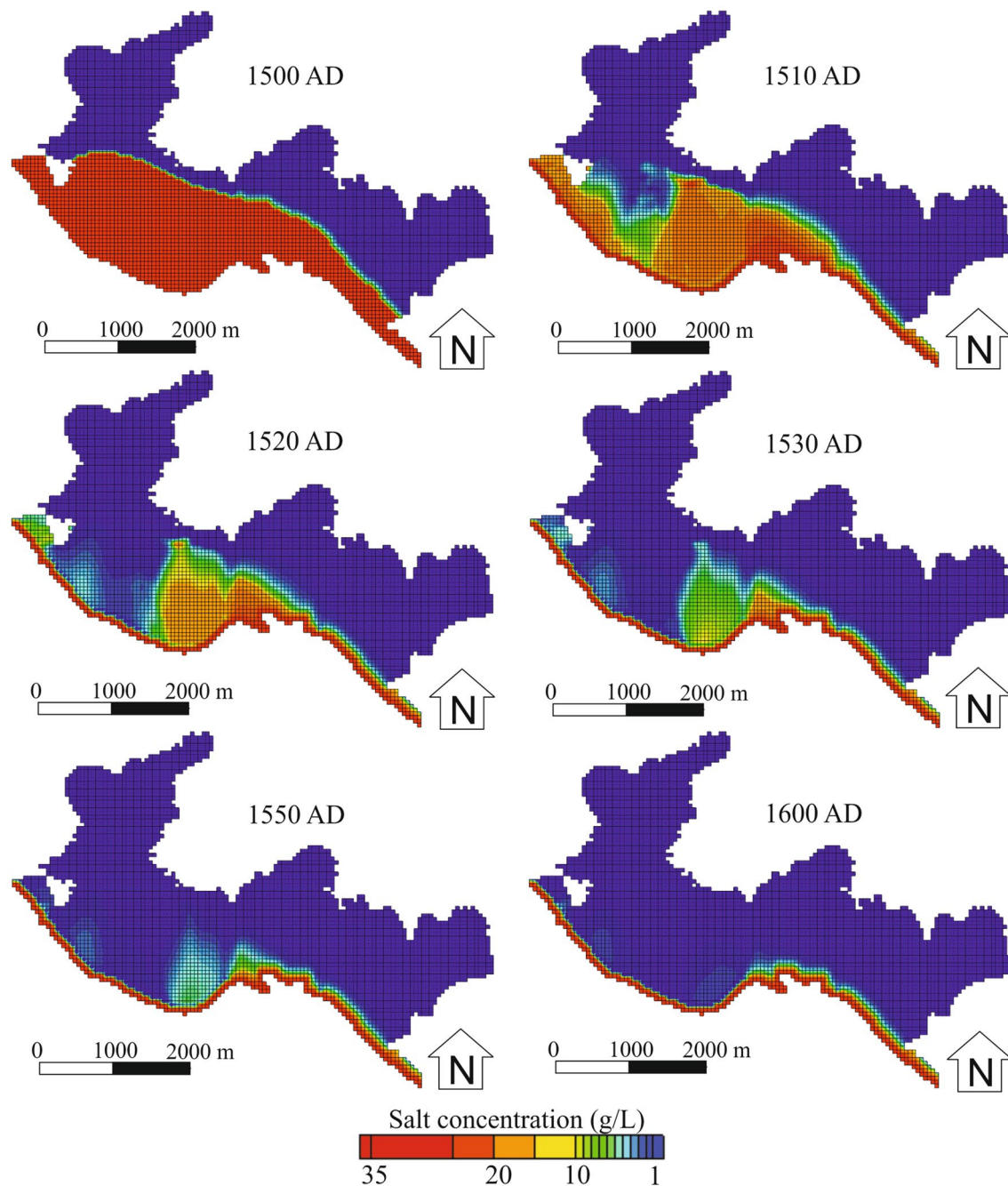
The salinity distribution based on the paleohydrogeological model showed a fast movement of the saline front when the coast starts to prograde around year 1500 AD (Fig. 5). The change in the boundary conditions produce an immediate reaction with freshwater flushing the areas previously occupied with saltwater. This process is not homogeneous due to the changes in hydraulic and transport properties between the different hydrofacies but also because of the intra-unit heterogeneity generated by the pilot points calibration. Based on the model results, in the western sector where the Guadalfeo River is located, the freshwater front moves several hundred meters towards the coastline in 20 years (Fig. 5). In the meanwhile, the central zone remains salty or slightly diluted probably because of the freshwater recharge from the top of the aquifer. The flushing of this zone lasts for more than 50 years and it is not completely finished until 100 years later (Fig. 5). After this period, a stationary condition is reached very similar to what is observed nowadays in the aquifer and the saltwater is located only in deeper layers due to the higher density (Fig. 5). In the eastern sector, the coastline has suffered less changes since its shape is more similar to what is currently observed in the aquifer. The system reached a steady-state situation at a shorter time in spite of the lower hydraulic properties due to the similarity with the current boundary conditions. The changes between 1600 AD and 2007 AD are minor in the most surficial part of the aquifer in this sector.

The top view showed an overview of the shallower sectors of the aquifer but the differences in hydraulic conductivity at deeper sectors offered a different perspective in the



**Fig. 4** Left: distribution of pilot points, observation wells, points where flushing time was calculated and cross sections to visualize salinity changes. Right: computed vs observed head in the model after calibration



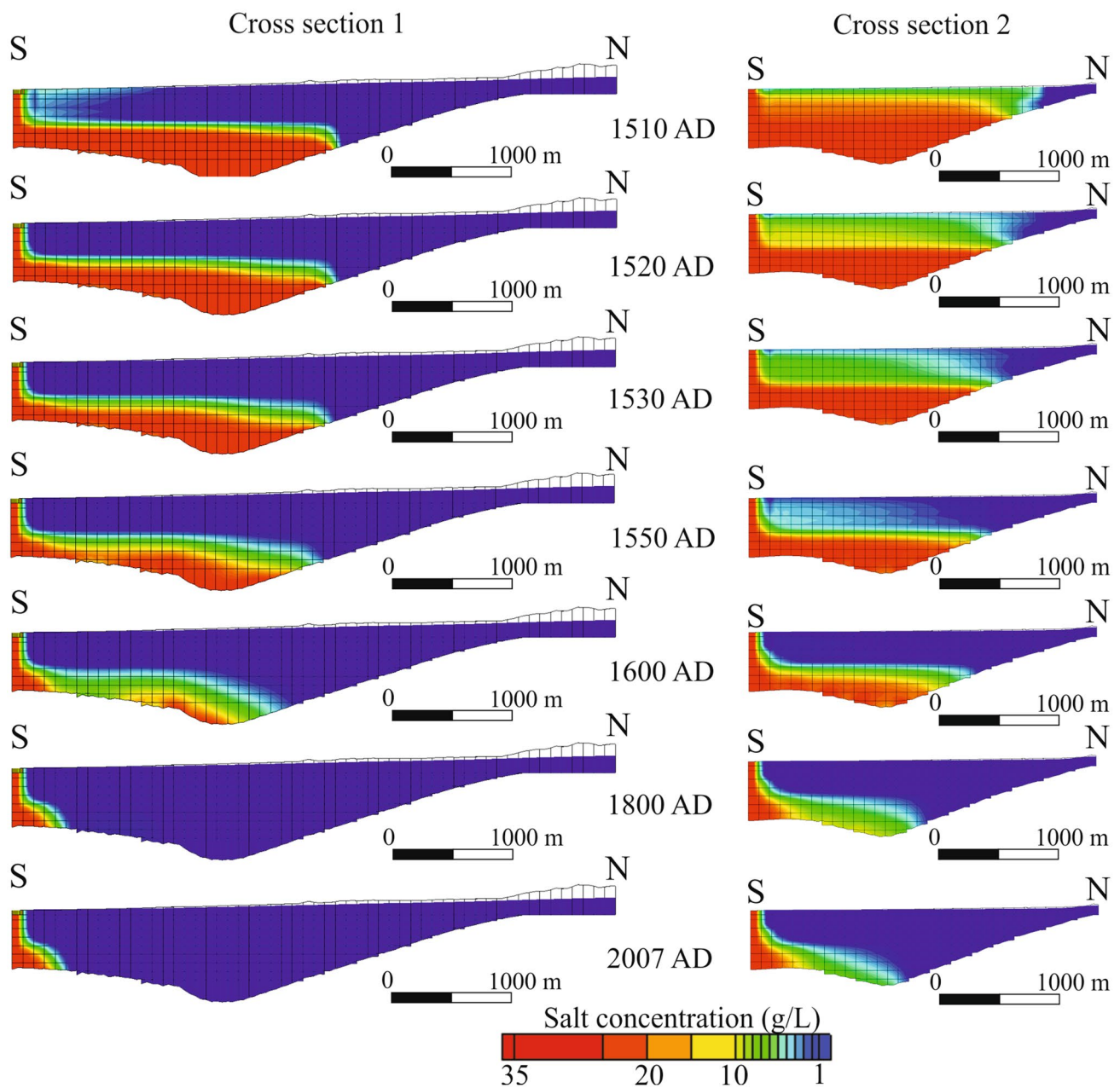


**Fig. 5** Transient evolution of the salinity distribution in the Motril-Salobreña aquifer from 1500 AD to 1600 AD

flushing of saltwater. Along cross section 1, oriented N–S in the western sector where the Guadalfeo River is located, the top layers indicated a fast reaction (Fig. 6). In 20 years, all the salt is flushed and the freshwater–saltwater front moves hundreds of meters. The western sector is characterized by high hydraulic conductivity due to the presence of the channel and paleochannel and high recharge because of the infiltration taking place along the riverbed. In the deeper layers of the aquifer, the changes are almost not detectable

visually in 20 years and only slight changes in the shape and the interface width can be seen (Fig. 6). It takes more than 140 years to start detecting the flushing effect and the maximum salinities are confined to the area more proximal to the coast. According to the model results, the total flushing time in this sector would take around 300 years.

The central sector presents different characteristics both due to the sediment composition and recharge. The flushing time in the more surficial sectors of the aquifer



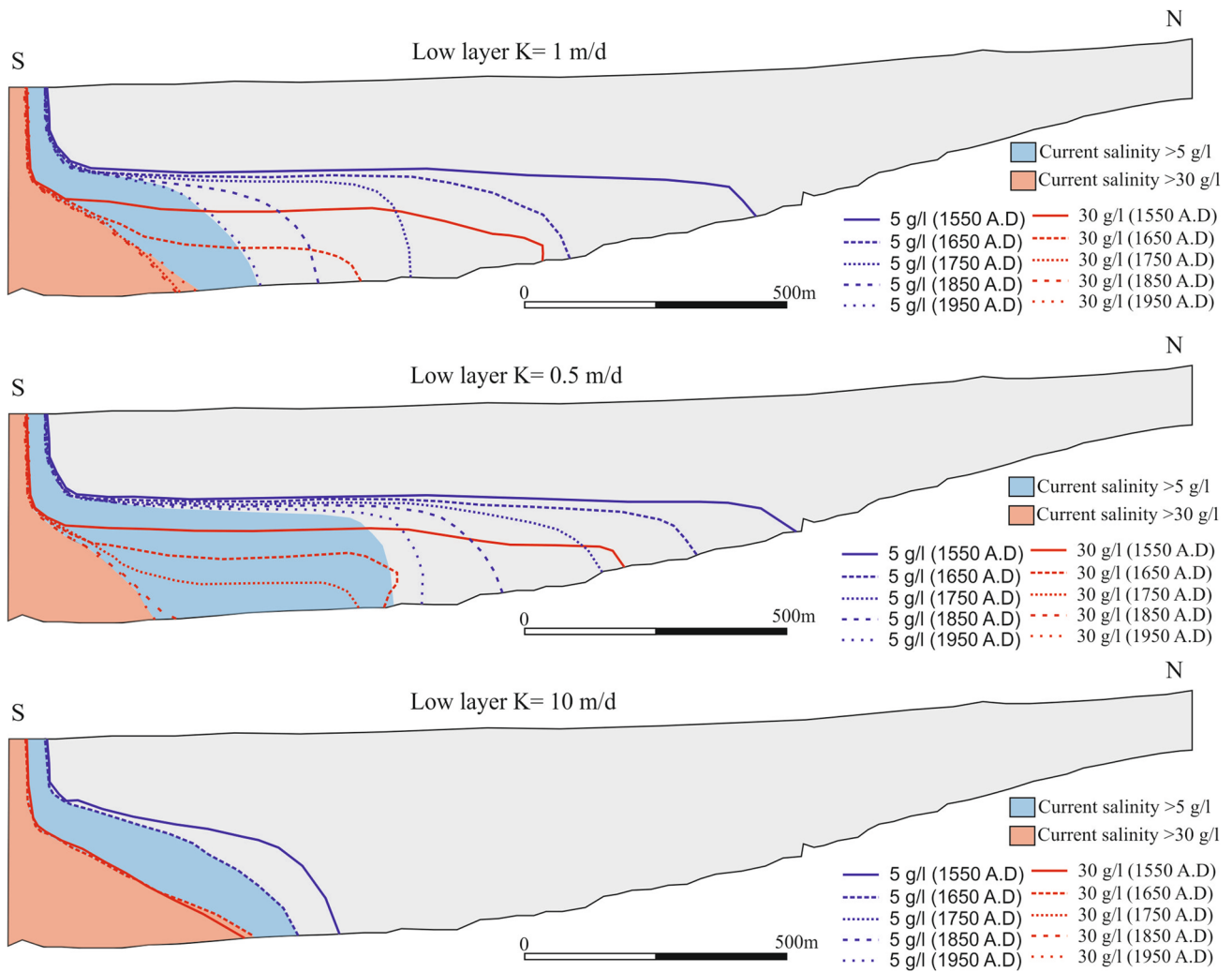
**Fig. 6** Cross-sectional view of the evolution of the salinity distribution along the two cross sections presented in Fig. 5, vertical exaggeration 5:1

takes several decades; after 50 years, there are still some residuals of slightly salty water (Fig. 6). Here, the sources of recharge are limited to the rain (constrained to the wet season of the year) and irrigation return. At deeper locations, the combination of lower hydraulic conductivities and the lower recharge produced a flushing process at a century scale; after 100 years, the salty water is extending for hundreds of meters into the aquifer and only after 300 years, the salinities calculated with the model in the deeper parts of the aquifer can be considered as brackish

water (Fig. 6). The results even can indicate that a stationary condition has not been reached yet in the deepest parts of the aquifer.

### Sensitivity analysis

The hydraulic conductivity of the marine sediments located in the base of Motril-Salobreña aquifer was modified to lower ( $0.5 \text{ m day}^{-1}$ ) and higher values ( $10 \text{ m day}^{-1}$ ) than the optimal calibrated value ( $1 \text{ m day}^{-1}$ ). A lower hydraulic



**Fig. 7** Salinity contours for the hydraulic conductivity sensitivity analysis of the marine sediments unit

conductivity showed a more gradual flushing process that extends over more than 500 years (Fig. 7). Even the last part of the flushing process (represented as the 5 g L<sup>-1</sup> contour line) would be still under transient conditions according to this simulation. An increase of the hydraulic conductivity of ten times generated a flushing of the saltwater in a shorter period of time and the system would reach stationary conditions after less than 50 years for the 30 g L<sup>-1</sup> isoline; while it would take more than 100 years for the 5 g L<sup>-1</sup> isoline (Fig. 7).

**Discussion**

The results of the model showed a variable flushing time after the progradation of the coastline not only highly dependent on the hydraulic properties and the recharge sources (both variable along all the extension of the

aquifer) but also affected by the depth. This can be analyzed by the calculation of the saltwater flushing times at different locations in the aquifer (Fig. 4), assumed as the time that takes to reach 1 g L<sup>-1</sup> in a point occupied with saltwater. In the western sector, the flushing time in the shallower part of the aquifer is around 20 years; while in the central sector, it is more than 70 years (Table 3). In the Eastern sector, since there is a smaller progradation of the coastline, the boundary conditions were less modified and therefore, the flushing time is lower, around 18 years (Table 3). For the deeper sector of the aquifer, the flushing time is longer as a consequence of the relatively reduced amount of flow circulating due to the low hydraulic conductivity. These values should be considered carefully for the transport of salt and the flushing times: for example, in points located less than 1 km from the current coastline at more than 150-m depth (Fig. 4), the flushing time can be increased more than 200 years with slight changes

**Table 3** Flushing time in years for the sensitivity analysis of hydrofacies 4 ( $K_1=0.5 \text{ m day}^{-1}$ ,  $K_2=1 \text{ m day}^{-1}$ ,  $K_3=10 \text{ m day}^{-1}$ )

	Point 1	Point 2	Point 3	Point D4	Point D5
Flushing time for $K_1/K_2/K_3$ (years)	23.8/19.2/52.0	82.2/72.6/109.6	23.3/17.8/23.3	389.0/206.8/28.8	387.7/241.1/78.6

Points 1, 2 and 3 are located in the upper layer of the model; while Points D4 and D5 are located at 160 m below the topographic surface

in hydraulic conductivity (Table 3). The uncertainty generated by the hydraulic properties in the deeper parts of the aquifer can generate two effects. The first one is an extension or shortening of the flushing time in the deep areas of the aquifer, from close to 400 years reducing the hydraulic conductivity to half of the initially estimated up to a decrease to decades for an increment to  $10 \text{ m day}^{-1}$  (Points D4 and D5) (Table 3). The other consequence is that the flow in the deeper sectors of the aquifer would reduce the amount of water circulating by shallower layers. Therefore, the flushing time will be increased in the shallower layers as it can be seen in points 1 and 2 (Table 3) to almost double. These changes indicate the interconnection between all different properties in the study area and non-unidirectional consequences of a better knowledge of the hydraulic properties and the boundary conditions in the aquifer.

These results, considering the uncertainties in the boundary conditions and hydraulic properties, indicate that some areas of the Motril-Salobreña aquifer could be still reaching an equilibrium derived from the changes in the coastline over the last 500 years. The distribution of sediments can be also critical and it cannot be discarded that some geomorphological and sedimentological conditions as well as the presence of clays and low hydraulic conductivity sediments could hinder washing or diluting ancient saline water in the aquifer.

The flushing time of the salt is not only showing the capacity of the aquifer to be flushed in case of saltwater intrusion but also it can be considered as an indicator of how fast it would affect future changes. According to the model, the western sector reacted in a scale of a few decades to variations in the recharge and boundary conditions while the central region is less reactive. The local water resources managers should take into account this consideration, as the use of groundwater would have a different impact depending on the sector and depth in the aquifer. As an example, urbanization of agricultural land would reduce precipitation recharge triggering long-term (but slow) saltwater intrusion in the central sector or shorter-term and faster changes in the aquifer salinity in the western sector. Sea-level rise would also have a different impact depending on the location in the aquifer. In the western zone, it might be detected in a short period and actions against it could be implemented; but in the Eastern sector, once saltwater intrusion is detected, it could be

challenging to implement strategies to reverse the process as it can take several hundred years.

## Conclusions

A paleohydrogeological model of the Motril-Salobreña aquifer was developed to reproduce the historical changes that took place in the coastline shape as a consequence of anthropogenic activity in the catchment of the Guadalfeo River. The impact on salinity distribution in the aquifer was assessed with the analysis of historical information and the application of changing boundary conditions in SEAWAT.

The sedimentological analysis of the lithological columns in the study area allowed to determine a series of hydrofacies that can be applied to optimize the calibration process of the numerical model and reduce the uncertainties in its results. The flushing times for saltwater in the aquifer ranged from a few decades to hundred years depending on the hydraulic properties along the aquifer. The flushing is much faster in the shallower parts of the aquifer compared with the deeper layers. The paleohydrogeological model of the Motril-Salobreña aquifer indicates likely the aquifer in under a steady-state condition in spite of the changes over the coastline. However, the presence of saline water is possible due to the difficulties flushing saltwater in specific sedimentological structures and in sediments with low hydraulic conductivity.

The use of paleohydrogeological models represents a useful tool for understanding the current conditions in aquifers, but, at the same time, the boundary conditions should be constrained based on approximations since it is rear to find data older than several decades in most of the places of the world. In this study, a first approximation to the processes than took place in the last centuries is presented but processes as the salt retention in the aquifer and the scale dependence of the transport parameters are potential improvements that could be considered in future studies.

These results showed the impact of anthropogenic action over salinization of water resources in the Motril-Salobreña aquifer. The areas where the flushing time was faster are also prone to have a quicker reaction if the recharge sources are reduced triggering saltwater intrusion problems. Global changes are affecting the sources and potential use of water in the aquifer for centuries and considering them will contribute to establish a better and more sustainable management of the water resources of the region.

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