

Paleohydrogeological Model of the Groundwater Salinity in the Motril-Salobreña Aquifer

C. Duque, J. T. Olsen, J. P. Sánchez-Úbeda and M. L. Calvache

1 Introduction

The changes in groundwater systems can have both natural and anthropogenic origin such as sea-level rise, climate variations, excessive pumping or decrease in the recharge. These modifications present different time scales leading to hydrogeological variations that can impact in aquifers during hundreds or thousands of years (i.e. sea level rising or climate alterations) to fast modifications in a scale of years or decades (i.e. human intervention). If the changes are continuous, the groundwater might require a period to reach an equilibrium condition that, due to the slow flow of groundwater, can take a long period of time specially when considering the hydrochemical composition.

In coastal detrital aquifers, the equilibrium between saltwater and freshwater can be also affected by the variation in the position of the sea border. The aquifers composed by unconsolidated sediments can be exposed to the movement of the sediments and even, with a longer term perspective, can be connected to the genesis of the aquifer. In the Western Mediterranean areas, due to the combination of geological (high runoff associated with low infiltration of rain and slopes), biological (scarce vegetation) and climatic conditions (torrential rain), the transport of sediments

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by rivers can produce the progradation of the shoreline distances of thousands of meters. This would have an impact in the saltwater wedge location but the differences between geological and hydrogeological scales of time can be very different.

The simulation of future scenarios due to climatic change includes the modification of the water inputs to aquifers. Additionally, in coastal areas, this would affect to the salinity distribution in the aquifer with a change in the position of the saline wedge. The use of numerical models, as for example, variable-density modelling requires an initial steady-state condition. However the movement of groundwater with different salinities can be a slow process and the assumption of steady state condition from the current groundwater status can be erroneous.

The historical modeling of landscape and the hydrogeology of an aquifer or paleo-hydrogeological modeling, could be used as a method to improve the definition of the initial conditions. This has been developed in previous studies as Lebbe et al. (2008) with the historical evolution of saltwater distribution in the mouth of an estuary for the last 500 years, or Delsman et al. (2014) showing the changes in saltwater intrusion in the Netherlands during the Holocene using variable-density simulations. The last one pointed out that within the 8500 years modeled period, the coastal groundwater distribution never reached an equilibrium with the contemporaneous boundary conditions.

The Motril-Salobreña aquifer is located at the South of Spain (Fig. 1) and changed its geometry in very recent history. The deforestation of mountain areas

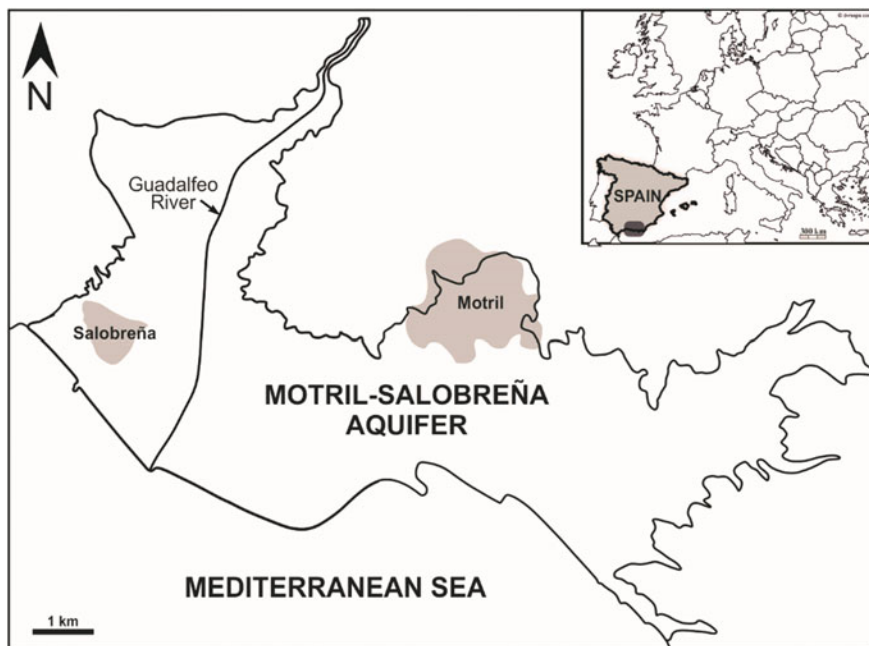


Fig. 1 Location of study area, boundaries of Motril-Salobreña aquifer and main urban areas

due to the colonization combined with the high slopes and the precipitation characteristics in Sierra Nevada, with annual strong storm events, increased the erosion rates.

It has been demonstrated that over the last 500 years the mean coastline advance of the aquifer is over 1200 m (Jabaloy-Sánchez et al. 2014); a progradation of over 2 m each year (Fig. 2). As a result, the location of the interaction sea-aquifer contact has been changing continuously and thereby modifying the natural equilibrium between saltwater and freshwater. Hence, the use of a paleo-hydrogeological model can be useful as a previous step to forecast future changes in the groundwater but also to explain the presence of seawater into the aquifer that could be related to old marine seawater trapped within sediments of low permeability (Duque et al. 2008) or the presence of preferential flow paths between sea and aquifer (Crespo 2012).

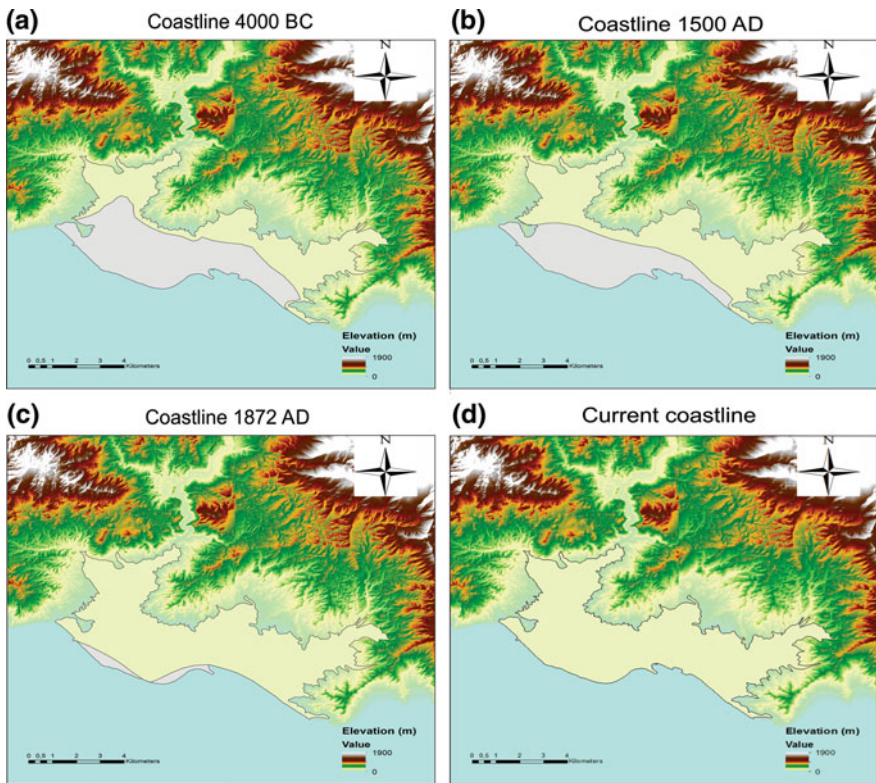


Fig. 2 Evolution of the coastline location in the Motril Salobreña aquifer for the last 6000 years. The grey areas indicate the areas covered by the sea

2 Methods

The study of the saltwater distribution in Motril-Salobreña aquifer is strongly linked to the aquifer properties. The aquifer presents differentiated sedimentological origins that would generate differences in hydraulic characteristics. The aquifer geometry was defined based on previous geophysical studies (Duque et al. 2008), the thickness of the aquifer increases from the borders of the aquifer towards the coastline where it reaches more than 250 m in depth (Fig. 3a). An analysis of 26 lithological columns together with a sedimentological interpretation of the different origin of the materials composing the aquifer was accomplished to establish different hydrofacies (Fig. 3b). For each of them it was assigned a range of hydraulic

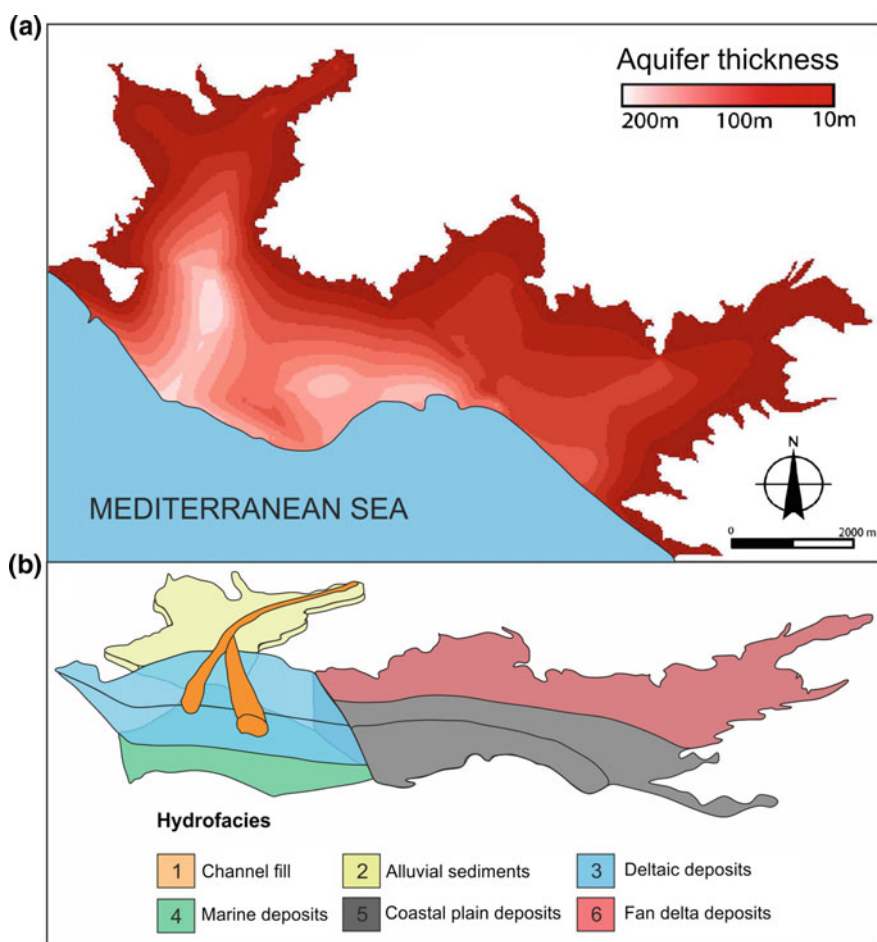


Fig. 3 **a** Motril-Salobreña aquifer thickness based on previous studies (Duque et al. 2008). **b** Hydrofacies within the Motril-Salobreña aquifer based on the sedimentological models

properties based on pumping test data, grain size analysis, bibliography and the review of previous studies using numerical models.

A numerical model with variable density (SEAWAT) (Guo and Langevin 2002) was constructed considering a database with hydrogeological measurements (groundwater heads and flow in the river and recharge from irrigation and precipitation) for the period 2001–2007. The grid used in the model has 16,921 cells with $100\text{ m} \times 100\text{ m} \times 20\text{ m}$ in the X, Y and Z dimensions respectively distributed over ten layers. A full description of the boundary conditions can be found in Olsen (2016). The model was calibrated using the pilot points technique with data from 2001 to 2004, and the values for each pilot point was constricted by the hydrofacies unit it was placed in. The model was validated using the data from 2004 to 2007. Once the model was considered valid, the boundary conditions were modified to reproduce the paleoscenarios inferred from the historical data and previous studies. The model was used to determine if the aquifer has reached an equilibrium condition and to study the flushing time for the different hydrogeological units. The model calibration was carried out matching measured groundwater head observations with the calculated heads from the model, and comparing the flow budget of the aquifer with obtained from previous studies (Calvache et al. 2009; Duque 2009). To quantify the agreement it was used the mean error (ME), mean absolute error (MAE) and root mean squared error (RMSE).

To implement the coastline changes in the Motril-Salobreña aquifer and study the salinity evolution of the aquifer the model simulation was divided in two time slices, each corresponding to distinct changes in the location of the coastline motivated by the historical reconstruction of the coastline (Jabaloy-Sánchez et al. 2014). The transitional movement of the coastline was simplified in 2 steps. The first time slice starts with the location of the sea border at 4000 BC as the first known reference point of the coastline (Mean coastline advance $0.09\text{--}0.15\text{ m year}^{-1}$) until to 1500 AD. The second time slice corresponds to the change from 1500 AD to 2007 AD (Mean coastline advance 3.3 m year^{-1}). This division is made based on the acceleration of the changes happened in the last 500 years in comparison with the previous thousands of years that can also help to reach a stationary position of the saline wedge.

The boundary conditions of the aquifer for the past conditions (paleohydrogeological model) are unknown so several assumptions were needed: for the recharge it was considered the rain average and temperatures for the period 2001–2007 while the agriculture irrigation return distribution and quantity was assumed constant in the last 500 years with high fluxes entering the aquifer due to the dominant presence of sugar cane. This region has been under agricultural influence of the Arabs with flooding irrigation system to maintain the sugar cane with water derived from the Guadalfeo River. The pumping was eliminated excepting for the last part of the simulation when was technically possible and the current river characteristics for the period 2001–2007 were considered a good estimate of the river flow since it included a dry period and a wet period and they were repeated in a loop. The hydrogeological properties were considered the same for all the time periods.

Transport parameters used in the model were assigned based on the values estimated by Calvache et al. (2009) in a previous numerical model of the aquifer. They calibrated the parameters by matching the simulated saline wedge with geochemistry data from seven observation points in the aquifer. Depending on location, they estimated that longitudinal dispersivity ranges from 30 to 65 m, the ratio between longitudinal dispersivity and transverse dispersivity was 10 and the retardation coefficient was $1 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$. For the diffusion coefficient it was used a value of $1 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ which corresponds to the diffusion coefficient of Cl^- and Na^+ , the dominating ions in seawater. The only source of high salinity was the sea border, the rest of the inputs to the aquifer were considered freshwater.

3 Objectives

The objectives of this work are:

- Characterize the Motril-Salobreña aquifer sedimentary history to define both the sea border progradation and the hydraulic properties based on a sedimentary analysis.
- Develop a groundwater numerical model with variable density to define the impact of the changing position of the coastline.
- Analyze the time for the aquifer to reach steady state condition under big scale changes and define the flushing times for saltwater in the different hydrofacies.

4 Results

The sedimentological study of the aquifer showed spatial variations in lithology throughout the aquifer resulting from different depositional processes. It was distinguished four major depositional environments: (1) heterogeneous alluvial sediments in the northern parts of the aquifer with mostly gravel and sand, (2) deltaic deposit in the western part with mostly gravel and sand and some silt, (3) alluvial fans/coastal plain environment in the eastern parts with gravel, sand and silt and (4) marine deposition in the shallow parts, mostly clay and silt. From this the aquifer where delineated into 6 hydrofacies units (Fig. 3). Because of the heterogeneous grain composition observed within each depositional environment, each hydrofacies unit where assigned a possible range of hydraulic properties and the spatial distribution within each unit where estimated using pilot points (Fig. 4).

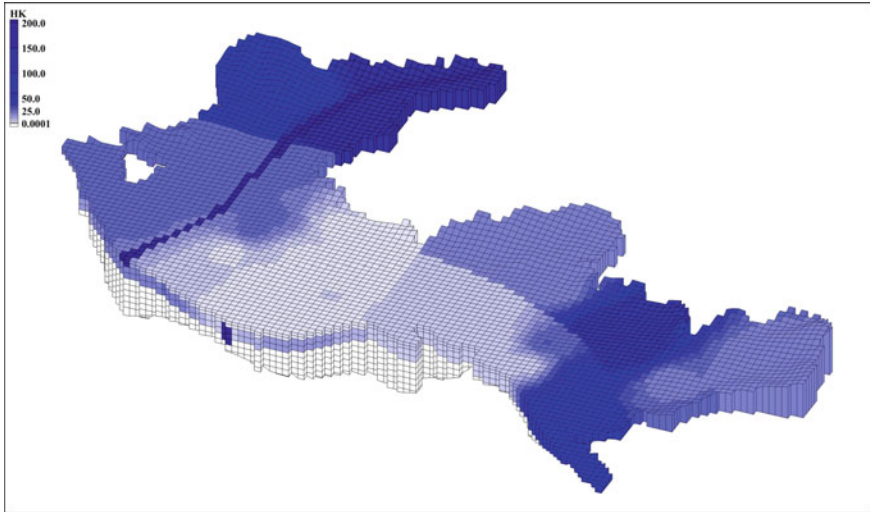


Fig. 4 Hydraulic conductivity distribution for the numerical model based on zones connected to the sedimentological study and the use of pilot points to include the natural variability in each of them

The calibration period of the model has a MAE of 0.54 m, ME of -0.03 m and RMSE of 0.77 and the validation period has MAE of 0.63, ME of 0.05 and RMSE of 0.83. The heads in the observation wells ranged from 35.71 to 0.49 m for the calibration period, and from 29.28 to 0.48 m for the validation period. Therefore, the RMSE relative to the observed head is 2.2% for the calibration period and 2.9% for the validation period.

The salinity distribution based on the paleohydrogeological model shows a fast movement of the saline wedge 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 heterogeneous due to the changes in hydraulic properties and transport between the different hydrofacies but also due to the heterogeneity introduced in each unit. The area with higher hydraulic conductivity is along the channel of the Guadalfeo River and in 20 years the freshwater front moves several hundred meters towards the coastline while the central zone remains salty or slightly diluted probably due to the effect of freshwater recharge from the top of the aquifer. The top view of the model shows that in 50 years, all the saltwater in the areas with higher hydraulic conductivity can be washed and reached a stationary condition very similar to the current status of the aquifer. For the same period, in the central region the salinity concentration still can remain over 10–20 g/l at several hundred meters from the coastline.

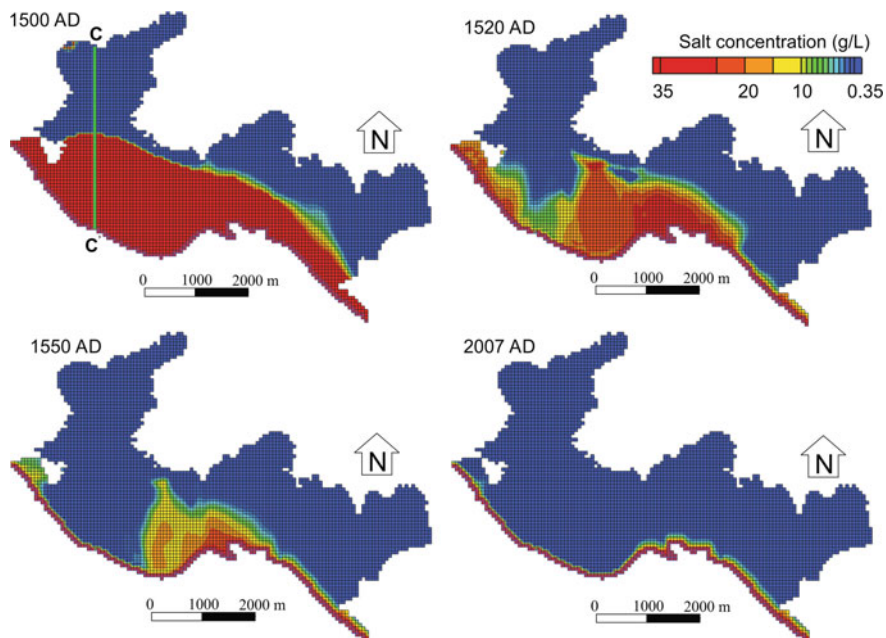


Fig. 5 Transient evolution of the salinity distribution in the Motril-Salobreña aquifer from 1500 AD to 2007

The paleohydrogeological model shows that there is a very distinct pattern in the reactions to the progradation of the sea border depending on the hydraulic properties of the aquifer. This is a good indicator that the aquifer can have a good recovery capability in case of potential saltwater intrusion processes but at the same time indicates that the aquifer can be very sensitive if the recharge is reduced. The area of the river can be flushed in a few decades while the central region can be more in the order of magnitude of 100 years.

The spatial distribution from the top view is not showing all the characteristics. The model results presented in cross section demonstrate also a differentiated pattern depending of the depth. The top part of the aquifer has a much faster reaction to the freshwater flushing that the deeper areas, and reaching a new equilibrium condition can take more than 300 years (Fig. 6). These results, considering the uncertainties in the boundary conditions 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 can not be discarded that some geometrical configurations could hinder the washing of ancient saline water in the aquifer.

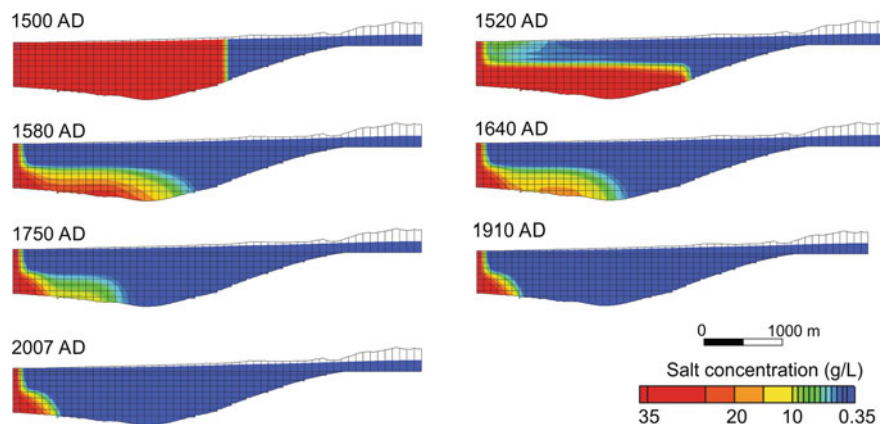


Fig. 6 Cross sectional view of the evolution of the salinity distribution along a S-N profile (in the *left* is located the sea border). Vertical exaggeration 5:1. The location of the cross section is presented in Fig. 5 C–C'

5 Conclusions

The paleohydrogeological model of the Motril-Salobreña aquifer indicates that most likely the aquifer is under steady state conditions in spite of the changes during the last centuries. However, it is possible the presence of saline water that has not been flushed depending on the geometric configuration of the different hydrogeological units or in case of presence of sediments with very low hydraulic conductivity. The flushing times for saltwater in the aquifer ranged from a few decades to a few hundred years depending on the zones that were considered and the hydraulic properties of them. There is a very distinct pattern of the aquifer with depth with very fast flushing in the top layers and much slower in the deeper zones. The areas where the flushing time is faster are also prone to have a quicker reaction if the recharge sources are reduced and generate saltwater intrusion problems due to future climatic changes or anthropogenic actions as intensive use of the water resources in the region.

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