Integrating improved conceptual knowledge into a 3-D variable density numerical model for a heavily exploited coastal aquifer with submarine spring discharge in South Portugal

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ABSTRACT

The *Albufeira-Ribeira de Quarteira* aquifer system on the south coast of Portugal is an important source of groundwater for agriculture and tourism, as well as contributing to significant freshwater discharge along the coast in the form of inter- and sub-tidal springs, and maintaining groundwater dependent ecosystems along the Quarteira stream. During the last period of heavy abstraction in the late 1990s, water quality deteriorated significantly. This has alerted to a need to better understand the system, both in terms of quantifying available freshwater and the behavior of the fresh/saltwater interface. Towards this end, a variable density model that accurately represents the complex 3D geologic structure of the aquifer system is under development. The configuration and extent of the aquifer system is still subject to a certain amount of uncertainty. In an initial phase, several hypotheses of the system's structure are tested with a numerical 2D profile model to simplify 3D model development. Results support a conceptual model that includes a connection between the various layers of the aquifer system and confirms the potential for an extensive freshwater lens several km offshore.

INTRODUCTION

The study area is in the Algarve, a Mediterranean region in the south of Portugal, where several uses already compete for groundwater resources, including coastal groundwater dependent ecosystems. At the beginning of the 21st century, surface water replaced groundwater for public supply and currently all publicly owned boreholes are either inoperative or held in reserve in case of emergency. The limitations of this single source strategy, demonstrated during the drought in 2004-05, have induced a move towards including groundwater as part of a more complex concept of integrated water resource management (Stigter et al. 2009). This requires quantifying and understanding available resources to avoid repeating the past mistakes of overexploitation. This paper focuses on the initial phase in the development of a 3D numerical model of the *Albufeira-Ribeira de Quarteira* (ARQ) aquifer system. The end goal for this model is to serve as one of several tools under development to aid in the efficient and effective management of groundwater resources in the region.

Hydrogeological Background

The ARQ aquifer system is described in Almeida et al. (2000). These last authors defined the limit of the ARQ, as shown in Figure 1, with the aim to define inventory and management units. The aquifer systems develop mostly within lithologies dating from the Miocene and Jurassic, believed to be occasionally separated by low permeability Cretaceous formations. Dolomites and occasionally limestones, karstified to a certain degree and depth, make up the

Jurassic formations, reaching up to 700m thickness. In both aquifer systems, these formations crop out in the north, with a Miocene and Cretaceous cover to the south. The Miocene formation is composed of sands and fossiliferous sandy limestones (occasionally karstified), almost entirely covered by low permeability clayey consolidated sand and gravel deposits of the Plio-Quaternary, which can reach 40m thickness.

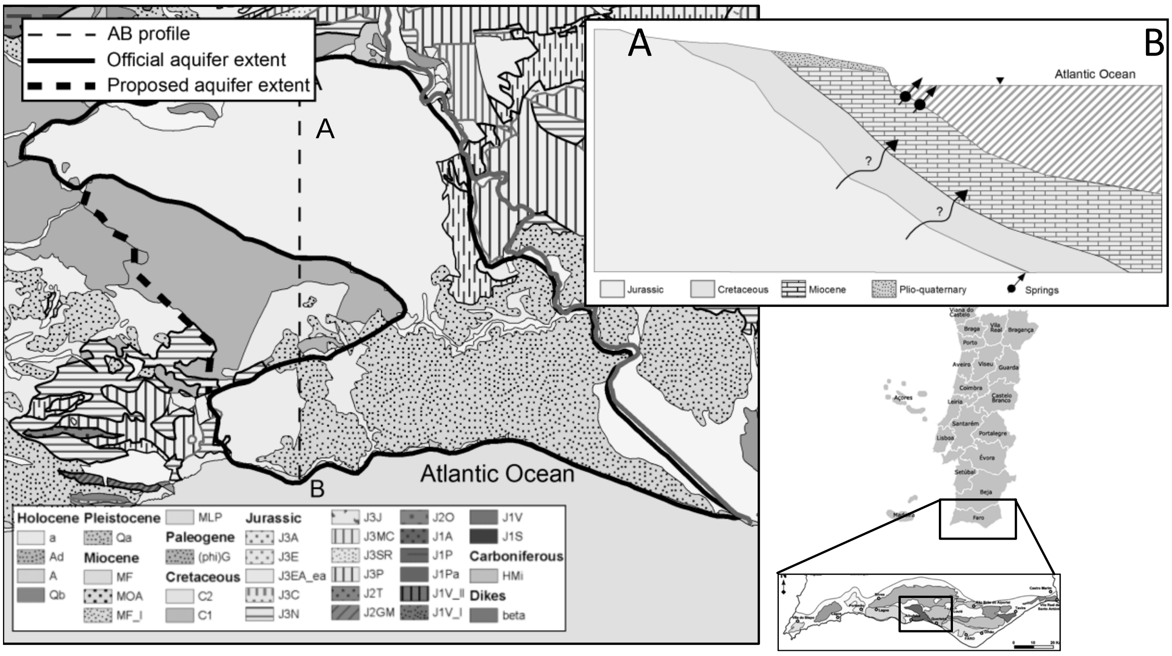

Figure 1. Location and geological map of the study area (adapted from Manupella, 1992).

We have previously applied geophysical methods to update the current hydrogeological conceptual model, along with an analysis of available borehole logs and water level and quality data (Francés et al. 2014). This new data points to the need to increase the extent of the current conceptual model of the system to include the (area marked by thick dotted line in Figure 1). The outcropping formation in this area is the low permeability Cretaceous, however the underlying Jurassic formation connects the northern and southern parts of the system. Results also verify the existence of the confining cretaceous formation in the south; however, we were unable to confirm explicitly the connection between Jurassic and Miocene formations in this part of the system. Furthermore, during several offshore field campaigns submarine springs and indications of freshwater discharge were found a couple of kilometers from the shoreline.

This paper presents a modeling exercise that aims to determine whether a connection is reasonable, taking into account realistic values of hydrogeological parameters. At the same time, the potential extent of offshore freshwater discharge is analyzed. Results will serve to define how far a future 3D model must be extended beyond the shoreline.

METHODS

Existing borehole log data was complemented with new data from the geophysical methods to determine the depths and thicknesses of the various formations. Constant head boundary conditions were set along the top of the Miocene layer, coinciding with the sea floor. Prior to introducing transport and density effects into the models, conductivity (k) values of the

Cretaceous formations (k_{Cret}) was varied over several orders of magnitude (1e^{-6} m.d^{-1} to 1 m.d^{-1}). Results from each variant are then compared against measured values of k for the Miocene (k_{mio}) and Jurassic (k_{jur}) to constrain the range of acceptable values of k_{Cret}. The calibration process was carried out using the parameter estimation software PEST (Doherty, 2002). Post calibration, mass transport was included. Hydrogeological parameters for the area, reported in the literature were assigned (Almeida et al. 2000). Longitudinal and transversal dispersivity were defined as 5 m and 0.5 m respectively, according to the empirical relationship suggested by Neuman (2005). The models were constructed with the FEFLOW code (Diersch& Kolditz, 2002), and run until reaching quasi-steady state conditions.

PRELIMINARY RESULTS

Sensitivity of the flow model to k_{Cret} is relatively low, and allows for a range of values over several orders of magnitude (0.001 m.d^{-1} to 0.1 m.d^{-1}) before values in the other two formations are forced beyond an acceptable range. The k values that gave the best fit at each end of the range were applied to the variable density transport model. Figure 2 shows the salinity distribution obtained from the model variant with the k_{Cret} = 0.001 m.d^{-1}. Results from other end of the k_{Cret} range are similar, however the freshwater lens extends significantly less offshore.

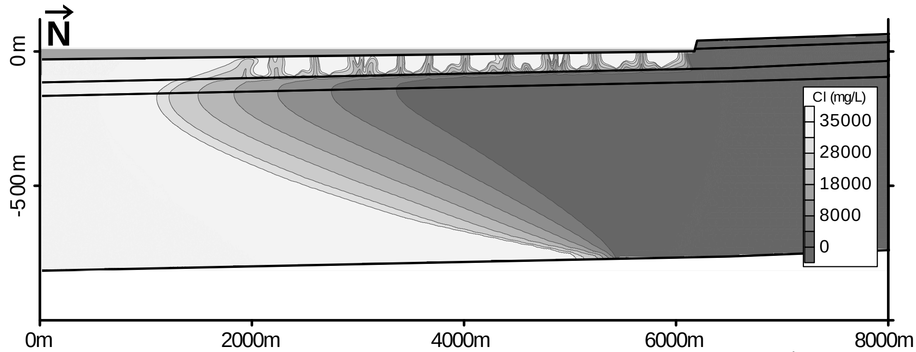

Figure 2. Example of Cl distribution (k_{Cret} 0.001 m.d^{-1}).

Depth and extent of the salt-water toe in the upper-Miocene layer are a similar to results from geophysical profiles taken perpendicular to the beach (Figure 3). The Miocene formations with seawater are characterized by low resistivity <15 ohm.m, and by 30-50 ohm.m when saturated with freshwater (Francés et al. 2014). The presence of low resitivities further inland than simulation results can be explained by tidal and wave pumping effects. Data on the salinities in the deep Jurassic layers are unavailable, however model results confirm the potential for brackish discharge over 4 km from the shore.

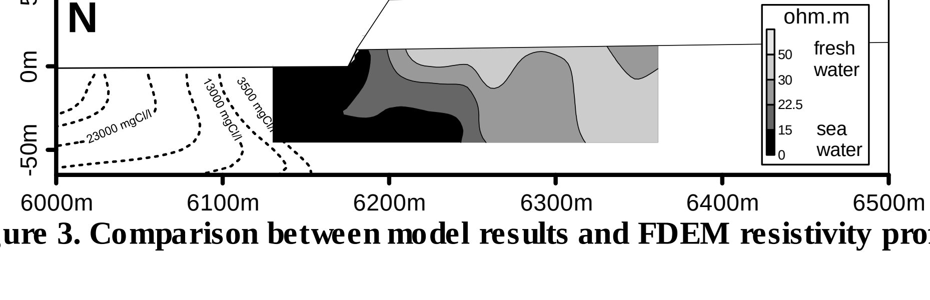

Figure 3. Comparison between model results and FDEM resistivity profile.

DISCUSSION AND CONCLUSIONS

Simulation results are far from being a definitive representation of the ARQ system, however they do give us first look at how the system might work. Despite the model results not giving a conclusive answer in regards to the connection between the Jurassic and Miocene, they do point to the affirmative. The question remains of how well connected they are. These preliminary results indicate that the chosen parameter values are within an acceptable range to represent the aquifer system, confirmed by both an adequate fit with measured hydraulic head and distribution of the saline groundwater wedge. These preliminary simulations also explain the occurrence of submarine freshwater discharge up to 4 km offshore. Together with the presence of fractures or karstified conduits, this can explain the occurrence of freshwater discharge several kilometers from the shore found during the field-campaigns. Confirming the existence of this potential storage of freshwater would be of interest from a management perspective, as it could represent a significant volume available at less risk from saltwater intrusion.

ACKNOWLDEGMENTS

The first author wishes to thank the FCT for the PhD grant SFRH/BD/80149/2011.

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