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title: **Modeling stream-groundwater interactions for different water extraction scenarios: the Almádena-Odeáxere case study**

author(s): **Rui T. Hugman**
CVRM-Geosystems Centre, Instituto Superior Técnico, Portugal,
ruitwohigh@yahoo.com

João Martins
CVRM-Geosystems Centre, Instituto Superior Técnico, Portugal,
joaoambiente@gmail.com

José P. Monteiro
CVRM-Geosystems Centre, University of Algarve, Portugal, jpmontei@ualg.pt

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INTRODUCTION

The Almádena-Odeáxere aquifer system (hereafter known as AO) extends over a 63.5 km^2 area, across the Lagos and Vila do Bispo municipalities (Almeida et al., 2000) in the southern region of Portugal, Algarve. Up until the end of the 20th century it was the main source of public water supply for these municipalities, and records show that it was the main source of supply for the city of Lagos as far back as the 15th century. In 1999 a multi-municipal water supply system entirely dependent on surface water provided by large reservoirs was implemented, leading to the abandonment of the AO (and other aquifer systems in the region) as sources of water supply. However, the extreme drought of 2004–2005 brought to light the serious limitations of this single-source strategy when several reservoirs reached their exploitation limit and could not satisfy water demand.

It is likely that in the near future, a water management approach that integrates the use of surface and groundwater in order to guarantee public water supply will be put into practice (Martins, 2007). However, in order to do so in a responsible manner, it is necessary to understand the implications of extracting water from these aquifer systems. In the particular case of the AO, it is known that there are several surface water bodies which are hydraulically connected to the aquifer system, the most significant of which are two wetlands linked to the aquifer's natural discharge areas (Almeida et al., 2000).

CONCEPTUAL FLOW MODEL AND NUMERIC FLOW MODEL

The AO has an area of 63.5 km^2 and stretches from Odeáxere (East) to Almádena (West). The aquifer system is a free to confined karstic system, which develops in carbonate Lias-Dogger outcrops and stretches in a NE-SW direction. The dominant lithologies are limestone, dolomite limestone and dolomite rock with thicknesses between 750 m and 60 m, and which present, in certain places, a well developed karst (Reis, 1993; Almeida et al., 2000). The average precipitation occurring in the area of the AO is 650 mm/year and there is an average recharge of 40.3% of the precipitation (Vieira, Monteiro, 2003), which corresponds to an average annual recharge of 16.6×10^6 m^3/year.

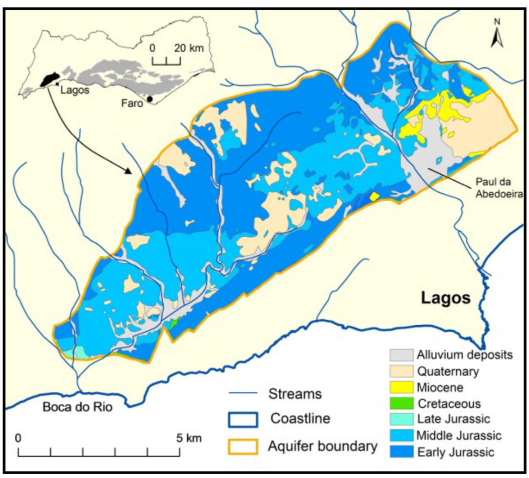

Figure 1. Geographic location and geology of the Almádena-Odeáxere aquifer system.

Regional groundwater flow occurs predominantly from the NE to SW. There are two main sources of recharge: indirect infiltration from streams flowing across the system and direct infiltration from rainfall over the entire system (Reis, 1993). The main natural discharge areas are located (1) along the final reach of the Bensafrim stream, which feeds into the wetland of the Paul da Abedoeira and (2) a second diffuse discharge area at the SW point of the system which feeds a second wetland area (Almeida et al., 2000).

The physical principals that are the basis of the simulation of the aquifer systems hydraulic behavior can be expressed by the following equation (1):

$$S_s \frac{\partial h}{\partial t} + div\left(-[K] grad h\right) = Q \qquad (1)$$

In which T [L^2 T^{-1}] is transmissivity, *h* is the hydraulic head [L], Q is the volumetric flux per volume unit [L^3 T^{-1} L^{-3}]. Representing sources and/or sinks and *S* is the storage coefficient [-]. In steady state conditions the variables are time-independent, and in this case equation (1) can be reduced to equation (2):

$$div\left(-[\mathrm{T}]\ grad\, h\right) + Q = 0 \qquad (2)$$

The total simulated budget will be equal to zero, because a medium permanent state of the aquifer is represented, i.e., recharge and discharge have the same value at the flow domain global scale.

The direct solution of equation (2) was implemented using a standard finite element model based on the Galerkin method of weighted residuals. The model has a mesh based on the AOs geometry, with 7494 nodes and 14533 triangular finite elements for which the defined conceptual flow model was translated. The use of finite element models is currently a standard approach for solving problems in hydrogeology and is described in textbooks such as Huyakorn and Pinder (1983), Kinzelback (1986), Wang and Anderson (1982) and Bear and Verrujit (1987).

Over the last two decades, hydraulic parameters were obtained for AO via pumping tests in boreholes (Reis, 1993; Almeida et al., 2000); however these methods cannot provide sufficient data to carry out a realistic representation of regional aquifers (Martins, Monteiro, 2008). In order to overcome these limitations, simulations were performed, using a synthetic bi-dimensional numerical representation of the AO, in which *T* was estimated by inverse modeling. These results allowed a very important improvement on the reliability of the simulation of the regional flow pattern, in particular a better characterization of the spatial distribution of hydraulic head. The calibration of *T* undertaken by Martins (2007) was performed by inverse modeling using the Gauss-Marquardt-Levenberg method, implemented in the nonlinear parameter estimation software PEST (Doherty, 2002). This calibration approach has already been thoroughly described and implemented by authors such as Carrera et al. (2005) and Poeter and Hill (1997).

EXTRACTION SCENARIO SIMULATIONS

Data on the volume of water extracted per month from the eight main public water supply boreholes during the last decade was obtained. The data showed, as can be seen in Figure2, a steady increase in the number of boreholes as well as in the total extracted volume during the last few years prior to the implementation of the multi-municipal water supply system, in particular the year 1999 and the subsequent dip as of the year 2000. Extracted volume rose on average 3.08E+05 m³/year between 1989 and 1999.

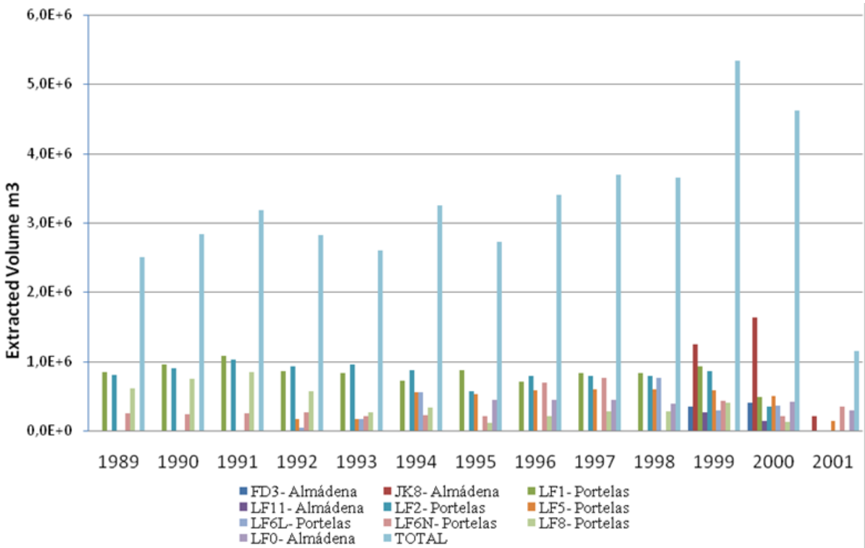

Figure 2. Yearly extracted volume from the main public water supply boreholes on the AO.

Simulations were performed for various extraction scenarios. Initially a simulation was run under natural conditions, with no artificial water extraction, the results of which represent the aquifer systems current state. Subsequently, several more scenarios were considered (1) in which the average pumping rates for the year 1999 (the year with the highest registered extraction) were applied and, (2) pumping rates were raised by 50%, 100% and 150% of the average pumping rates in 1999 (which correspond to potential rises in pumping rates for 10, 20 and 30 years).

ANALYSIS OF RESULTS

Groundwater Flow Patterns

Figure3 shows the simulated regional flow pattern under natural conditions, and with average pumping rates registered during the year 1999. The results of these simulations helped to validate the functionality of the model as the values of hydraulic head of the pumping scenario mode closely resemble the values measured during the year of 1999 than those of the no pumping scenario.

The effect of pumping for public water supply is easily visible, in particular around the area of Portelas, however the model suggests that discharge does not cease under these conditions. This refutes reports of the Paul de Abedoeira wetlands drying up during periods of intense pumping. On the other hand, this steady state model does not take into consideration the large seasonal variability of rainfall and water demand characteristic of this region. Considering that most pumping is concentrated during the dry months, it is possible that discharge could cease during these periods and recover during the rainy season.

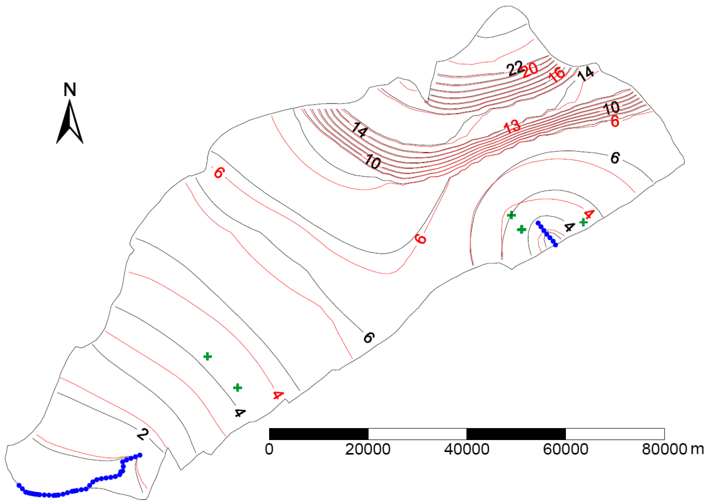

Figure 3. Simulated groundwater flow patterns: no extraction scenario (black lines), average pumping rates for 1999 (red lines). Main boreholes for public water supply (green crosses); main discharge areas (blue lines).

Three hypothetical scenarios were simulated in which the pumping rates were raised by 50%, 100% and 150%, which correspond to periods of 10 years considering the average yearly rise in water demand observed between 1989 and 1999, in order to estimate the impacts of extraction for public water supply. As was to be expected, there was a significant drop in values of hydraulic head around the discharge area at Portelas with the raising of the pumping rates, and although natural discharge at this area is significantly reduced it does not cease completely until pumping rates are higher than 200% of average rates in 1999. As can be seen in Figure4, for 250% of the pumping rate the reduction in hydraulic head is significant, causing the discharge to cease at Portelas. On the other hand, although there is a decrease in discharge, the south-western natural discharge area is not significantly affected by the rise in pumping rates.

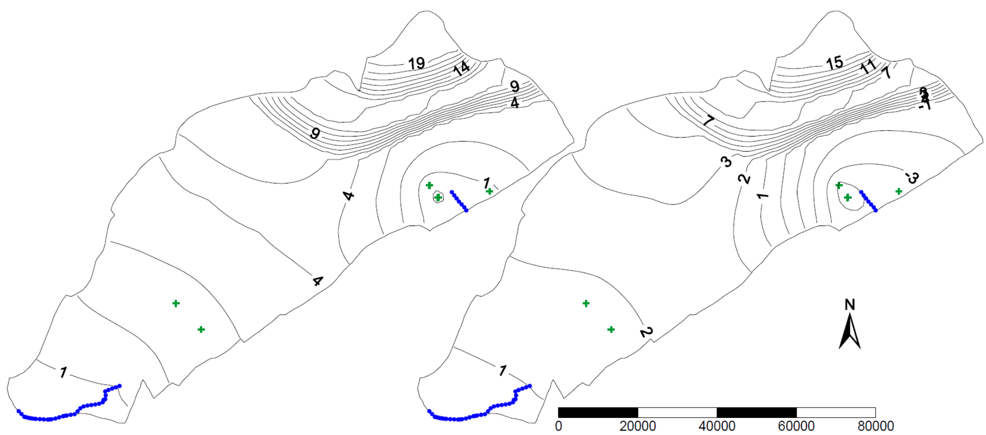

Figure 4. Simulated groundwater flow patterns: 200% (left) and 250% (right) of average pumping rates during 1999.

FINAL REMARKS

It was found that water extraction from the main existing public water supply boreholes could affect the surface water bodies hydraulically connected to the AO by reducing the amount of groundwater flow from the aquifer to the streams. However, to properly quantify the effects of this reduction on groundwater discharge, a more detailed study of the importance of the groundwater component to the streams flow is needed.

It also demonstrated that should the extraction rates rise to 250% of average values during 1999, discharge at Portelas would effectively cease allowing for current values of average recharge. Future research should be carried out to better determine where and how much water can safely be extracted for public water supply, as well as to determine the importance of the groundwater component for the surface water bodies to which the AO is hydraulically connected. Considering the high seasonal variability of the region, this research should involve the development of transient variations of the AO model, in order to consider the variation of recharge and withdrawals over time.

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