

# UNIVERSIDADE DO ALGARVE

Faculdade de Ciências e Tecnologia

## Transient-State Calibration of a Ground-Water Flow Model and Simulation of Scenarios of Development for the Almádena-Odeóxere Aquifer System

Dissertação elaborada no âmbito do Mestrado Integrado em Engenharia do  
Ambiente na área de Modelação Ambiental

**RUI TWOHIG HUGMAN**

**Faro, Setembro 2009**

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**Orientação: Dr. José Paulo P.G. Monteiro**

Faro, Setembro 2009

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O conteúdo deste trabalho é da exclusiva responsabilidade do autor

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Rui Twohig Hugman

## Abstract

The Almádena-Odeóxere aquifer system is a free-to-confined karstic system and extends over an area of 63.5 km<sup>2</sup>, in the Algarve (southern Portugal). The aquifer's two natural discharge areas are connected to two separate wetlands, which support environmentally important groundwater dependent ecosystems. Uncorroborated observations indicate that abstractions from municipal wells on the aquifer have led to a reduction in discharge in these areas.

Other authors have determined various hydrostratigraphic units of the Almádena-Odeóxere and the spatial distribution of the transmissivity parameter has been determined via inverse calibration techniques. The first section of the current work characterizes the spatial distribution of the storage coefficient in order to allow for the simulation of the aquifer's hydraulic behaviour under transient state conditions.

The calibration of the storage coefficient was carried out by trial-and-error methods. The relatively small span of physically possible values of storage coefficient was not considered sufficient to justify the effort required to implement inverse calibration methods. Calibration results provided the first estimate on the regional distribution of storage coefficient values, which range from 0.05 to 0.125 over 5 zones, resulting in a greater reliability of the spatial and temporal evolution of state variables for transient simulations.

The calibrated model was tested against historical data to verify its accuracy and stability under stress conditions. Simulated temporal and spatial distribution of hydraulic heads and natural discharge flow show a good fit with observed data.

In the second section, hypothetical scenarios of water withdrawal from the municipal boreholes were simulated to evaluate the effects of abstractions on the regional flow system and on the natural groundwater discharge. Results show that abstractions have an immediate effect on groundwater discharge, and rates of  $1.4 \times 10^4$  m<sup>3</sup>/day are enough to reduce flow to zero at one of the discharge areas. However, to properly determine the maximum safe yield, a more detailed analysis of the importance of the groundwater component to the streams and wetlands associated to the AO is required.

**Keywords:** Numerical groundwater flow models; groundwater-surface water interactions; groundwater dependent ecosystems; transient-state calibration; groundwater resource management.

## Resumo

O presente trabalho de investigação pretendeu caracterizar a distribuição espacial do coeficiente de armazenamento no sistema aquífero Almádena-Odeáxere (AO) através da calibração de um modelo numérico de elementos finitos, com o objectivo de aumentar a fiabilidade da simulação em regime transitório, do seu funcionamento hidráulico. Após a calibração e validação do modelo para a simulação do comportamento hidráulico do AO em regime transitório, procedeu-se à simulação e análise do impacto de vários cenários hipotéticos de exploração do sistema aquífero e assim, espera-se demonstrar a utilidade destes modelos como ferramentas para a gestão responsável destes recursos.

O sistema aquífero AO estende-se ao longo de 63.5 km<sup>2</sup> nos Municípios de Lagos e Vila do Bispo, no Algarve, e encontra-se hidraulicamente ligado a vários corpos de água superficial que suportam ecossistemas vulneráveis. Os mais significantes dos quais, são as duas zonas húmidas que se encontram nas áreas de descarga natural do aquífero: (1) ao longo da ribeira de Bensafrim e (2) na Boca do Rio no canto SW do sistema aquífero. Dada a variabilidade sazonal da disponibilidade de água superficial e a natureza efémera das ribeiras associadas a estas zonas húmidas, a exploração deste sistema aquífero poderá ter efeitos sobre a disponibilidade de água para estes ecossistemas.

Durante o último século o aquífero AO era a principal fonte de abastecimento de água para as cidades de Lagos e Vila do Bispo. Recentemente, em 1999 este, foi substituído como fonte de abastecimento público por um sistema suportado por fontes de água superficial (designadamente barragens). No entanto, as limitações desta estratégia, dependente de uma única fonte de abastecimento, tornaram-se evidentes durante a seca de 2004-2005 e iniciaram um movimento na direcção de integrar o uso de águas superficiais e subterrâneas na estratégia de gestão dos recursos hídricos. É portanto fundamental compreender os impactos que a exploração destes recursos subterrâneos poderão ter sobre os aquíferos e outros sistemas que deles dependem.

Foi implementado um modelo regional de elementos finitos de forma a investigar as relações quantitativas entre os dados históricos disponíveis sobre a exploração do aquífero, realizada pelas Câmaras Municipais e, as variáveis de estado resultantes da monitorização do AO (medições piezométricas e do caudal de fontes e ribeiras). Numa fase prévia, a distribuição espacial do parâmetro hidráulico transmissividade foi determinado para o AO usando métodos

de calibração inversa do modelo e integrando informação disponível no que concerne à geometria do sistema, às condições de fronteira, à cartografia geológica e aos dados hidrológicos relevantes.

De modo a permitir a simulação do comportamento hidráulico do AO em regime transitório, foi necessário proceder à caracterização da distribuição espacial do coeficiente de armazenamento. Comparado com o parâmetro transmissividade, o coeficiente de armazenamento considera uma gama de valores fisicamente possíveis bastante menor que a transmissividade, apresentando valores na ordem de  $1 \times 10^{-5}$  a  $1 \times 10^{-3}$  para aquíferos confinados e valores na ordem de  $1 \times 10^{-2}$  até valores de porosidade total para aquíferos livres. Considerou-se que esta menor gama de valores a considerar não justificava o esforço e tempo necessários para a aplicação de métodos de calibração inversa em regime transitório. Assim, foi aplicado um método de tentativa e erro na calibração do modelo numérico para determinar a distribuição espacial do coeficiente de armazenamento.

Os resultados da calibração forneceram a primeira estimativa da distribuição regional do coeficiente de armazenamento, com valores entre 0.05 e 0.125 obtidos em cinco zonas, o que resultou numa maior fiabilidade na evolução espacial e temporal de variáveis de estado para simulações em regime transitório, quer em regimes naturais, quer considerando diferentes cenários de utilização do recurso de água.

Após esta calibração foi necessário proceder com a validação do modelo em regime transitório, o que contribuiu não só para averiguar a sua precisão e estabilidade mas também para a análise do impacto de vários cenários de exploração a que o aquífero foi exposto ao longo das últimas décadas. Estes cenários simulados do período entre 1997 e 2003 permitiram a análise do impacto das alterações significativas nas políticas de gestão dos recursos hídricos da região, não só a nível da dinâmica hidrogeológica numa escala regional mas também numa escala mais local nas áreas de descarga natural do sistema aquífero e as relações com as águas superficiais associadas. Os resultados obtidos mostraram um bom ajuste entre valores de potencial hidráulico e de descarga natural simulados e valores medidos no terreno.

Com o estado actual do modelo foi possível avançar com a simulação de vários cenários hipotéticos de exploração do aquífero a partir dos furos municipais existentes no AO de modo a determinar os seus potenciais impactos. Para a realização destas simulações tomou-se em conta a recarga calculada a partir de valores de precipitação de Setembro de 2003 a Setembro de 2006, um período que cobre uma das épocas mais secas em registo. Os regimes de

extracção considerados para cada simulação foram calculados com base no valor de capacidade de extracção máxima dos furos. Os caudais dos regimes foram variados entre 0% e 100%, em passos de 10%, da capacidade máxima de cada furo. Apesar destes regimes hipotéticos não serem representativos da variabilidade sazonal da procura de água, considera-se que representam casos de “pior cenário”.

Os resultados destas simulações de cenários hipotéticos demonstraram que a extracção de água subterrânea dos furos municipais tem um impacto significativo na dinâmica hidrogeológica regional e sobretudo nas zonas de descarga e subseqüentemente sobre os corpos de água superficial associados, reduzindo a contribuição do aquífero para as ribeiras e zonas húmidas. De facto, as simulações sugerem que a descarga natural na zona das Portelas seria efectivamente nula com regimes de exploração que consideram apenas caudais de extracção de  $1.4 \times 10^4$  m<sup>3</sup>/dia (cerca de 35% da capacidade total dos furos municipais).

No entanto, para quantificar o impacto desta redução de descarga é necessário um estudo mais detalhado acerca da importância da componente de água subterrânea para o funcionamento destes corpos de água superficial e os seus ecossistemas associados.

Sugere-se que seja levada a cabo uma pesquisa futura que coordene modelos de escoamento de água subterrânea, modelos de água superficial e modelos ecológicos, de forma a otimizar os regimes de exploração do aquífero de forma a resultar no menor impacto possível sobre estes sistemas e os seus ecossistemas associados.

Em suma, espera-se que o presente trabalho consiga demonstrar a utilidade e importância destes modelos como ferramentas para uma gestão mais eficiente e racional dos recursos hídricos. Além disso, pretende-se que as conclusões apresentadas reforcem a possibilidade da gestão de reservas de água subterrânea do sistema aquífero AO poder vir a ser efectuada utilizando este tipo de modelos.

**Palavras-Chave:** Modelos numéricos de escoamento subterrâneo; interacções águas superficiais-subterrâneas; ecossistemas dependentes de água subterrânea; calibração em regime transitório; gestão de recursos hídricos subterrâneos.

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"All Models Are Wrong But Some Are Useful" - **George E.P. Box**



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## 1. Introduction

The Almádena-Odeóxere aquifer system (hereafter known as AO) extends over a 63.5 km<sup>2</sup> 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 20<sup>th</sup> 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 year 1521 (Paradela, 1959).

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 public water supply. The extreme drought of 2004-2005 brought to light the serious limitations of this single-source strategy when several reservoirs reached their limit and could not satisfy water demand (Nunes *et al.*, 2006b).

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, namely two wetlands located at the aquifer system's main natural discharge areas (Almeida *et al.*, 2000). It is important to understand the effects of extracting water on the regional groundwater flow patterns in order to protect these vital groundwater dependent ecosystems.

Many aquatic ecosystems which are classified as surface water bodies are partially or wholly dependent on interactions with groundwater to sustain ecological structure and function. This includes springs, wetlands, karst and cave systems, rivers and estuaries with a strong baseflow component especially in the dry season. In the case of the AO, the two wetlands known as the Paul da Abedoeira and the Boca do Rio.

Quite often, the interaction between groundwater and surface water is not adequately quantified. This may be because the interaction is complex and difficult to measure, or it may be simply because people haven't considered that the interaction might be important and so don't give it sufficient attention in their research or field measurement programmes. Another reason why the interaction is poorly understood is because groundwater and surface water hydrologists have generally worked separately in the past. Hydrological models have often been developed

independently, with a resulting mismatch in scale and resolution (both temporal and spatial) between surface water and groundwater models, and often substantial inaccuracies in estimates of the groundwater contribution to surface water flow, or the surface water recharge to groundwater. Groundwater and surface water hydrologists tend to use different terminology, leading to confusion when trying to build integrated conceptual models.

Poor or inadequate quantification of the groundwater-surface water interaction means that management decisions (for example the abstraction of groundwater in the riparian zone of rivers) may be made without sufficient information on the potential impacts on aquatic ecosystems.

The issue of groundwater interactions with aquatic ecosystems is becoming the subject of increasing attention, as the body of research into determination of the water requirements of ecosystems grows, and as more emphasis is placed on integrated water resource management.

### **1.1. Scope and Purpose**

Numeric flow models are fundamental in analyzing the accuracy of hypothetical explanations for an aquifer's hydraulic behaviour, and at a later stage in predicting the effects of changes in natural conditions or due to anthropogenic activities likely to interfere with groundwater flow (Monteiro and Silva, 1998). The use of numerical models in describing the hydraulic behaviour of aquifer systems is one of the most advanced methods for understanding events controlling water flow and contaminant transport in the subsoil, and therefore is an invaluable tool for water management (Martins, 2007). According to Monteiro *et al.* (2002), these models can be fundamental in answering questions such as: (1) Where and how much water can safely be extracted for public water supply; (2) What the effects of certain extraction scenarios will be on regional piezometric levels; (3) The importance of the extracted volume when compared to the aquifer system's water budget; (4) What influence various exploitation scenarios will have on the intensification of undesirable phenomena. Considering that the AO is hydraulically connected to surface water bodies which are home to sensitive ground water dependant ecosystems, such as wetlands, understanding the effects of water withdrawals on this system could be fundamental in protecting them.

Over the last few years researchers at the University of the Algarve have developed various models to simulate the AO within the framework of the study of regional groundwater flow of

aquifers in the Algarve. These efforts have led to the construction of the numerical model on which the work undertaken during this thesis is based. In this fashion, the presented research represents the next step in an ongoing body of work in the development of a potentially invaluable tool to ground water research and management alike.

The methodology for the development of numeric models can be summarized in four basic steps: (1) Analysis and description of conceptual models; (2) Calibration; (3) Validation; (4) Predicting possible future scenarios. Step (1), (2) and (3) have been completed for the physical distribution of the hydraulic parameter transmissivity under steady-state conditions for the case of AOs numeric flow model. To perform simulations under transient conditions a second calibration, of the storage coefficient parameter, is required. And subsequently, in order to guarantee the applicability of this model to simulating ground water flow under transient conditions it is necessary to validate it by comparing its results, under various stress conditions, with field data so as to allow for the next step, the simulation of hypothetical scenarios.

The proposed research intends to demonstrate the potential impacts of certain water extraction scenarios on the Almádena-Odeáxere aquifer system and water bodies to which it is connected, and hopefully demonstrate the value of these models as a tool for water management schemes which incorporate ground water as a source of supply.

## **1.2. Numerical Ground Water Flow Modeling in Karst Aquifers**

The lithological support of the AO consists of carbonate rocks, therefore it is important to refer to some of the particular aspects related to modelling ground water flow in this kind of media.

Numerical groundwater models are amongst the most important tools available for the management of groundwater resources. The models can be used to test or refine different conceptual models, estimate hydraulic parameters, and, most importantly for water-resource management, predict how an aquifer might respond to changes in pumping and climate change (Scanlon *et al.*, 2003).

Numerous models have been successfully developed for porous aquifers; however their application in karst aquifers has been more problematic. Karst aquifers are generally highly heterogeneous, being dominated by secondary (fracture) or tertiary (conduit) porosity and may exhibit hierarchical permeability structure or flow paths (Scanlon *et al.*, 2003). The major difficulty faced is that karst aquifers typically exhibit dual groundwater flow regimes, that is, fast (conduit-dominated) flow and slow (diffuse) flow (Taylor and Greene, 2001), and therefore are

likely to have a turbulent flow component, which may be problematic since most numerical models are based on Darcy's law, which assumes laminar flow (Scanlon *et al.*, 2003)

At present, great difficulties exist in accurately simulating karst flow systems at the local or sub regional scale because of the difficulty in developing numerical models that realistically represent boundary conditions for conduit networks. Nevertheless, according to Taylor and Greene (2001), numerical models are among the best quantitative tools for gaining a better understanding of the functioning of individual karst hydrology components and for predicting how the system works as a whole. However, as stated by Quinlan *et al.* (1996): "Although modeling of karstic processes is often possible and numerical flow models can sometimes simulate hydraulic heads, groundwater fluxes, and spring discharge, they often fail to correctly predict such fundamental information as flow direction, destination, and velocity." Therefore, when discussing the relevance of numerical modeling in a karst aquifer, it is crucial to identify what type of model (i.e. flow model or transport model) is being proposed (Scanlon *et al.*, 2003).

It is important to consider the various modeling approaches available for simulating groundwater flow and contaminant transport in karst aquifers and to be aware of the advantages and limitations of each approach. According to Scanlon *et al.* (2003), one of the simplest approaches is the lumped parameter model, which has also been termed black box or mixing cell model. The spatial dimension in the equations is omitted in these models; therefore, only ordinary linear differential equations must be solved. The system is assumed to behave like an equivalent porous medium. These models generally result in good agreement between measured and simulated spring discharge (Yurtsever and Payne, 1986; Wanakule and Anaya, 1993; Barrett and Charbeneau, 1996; Zhang *et al.*, 1996). The advantages of using lumped parameter models are that data requirements are minimal and simulations are rapid. The main disadvantage is lack of information on spatial variability in hydraulic head and directions and rates of groundwater flow (Scanlon *et al.*, 2003).

Distributed parameter models are required to obtain detailed information on spatial variability in groundwater flow (Scanlon *et al.*, 2003). Equivalent porous media distributed parameter models include single continuum and double continuum approaches. Single continuum models have generally been applied to aquifers characterized as predominantly diffuse (Teutsch, 1993), and some studies have found this approach to be inadequate for simulating regional flow in highly karstified aquifers (Teutsch, 1993; Keeler and Zhang, 1997). However, although accurate simulation of transport processes is still problematic, certain single continuum models have



proved adequate for simulating regional groundwater flow (Ryder, 1985; Kuniatsky, 1993; Teutsch, 1993; Angelini and Dragoni, 1997; Keeler and Zhang, 1997; Greene *et al.*, 1999 and Larocque *et al.*, 1999); and Scanlon *et al.* (2003) suggest that this modeling approach is acceptable for the simulation of systems in which the conduit networks are fairly uniformly distributed and well interconnected.

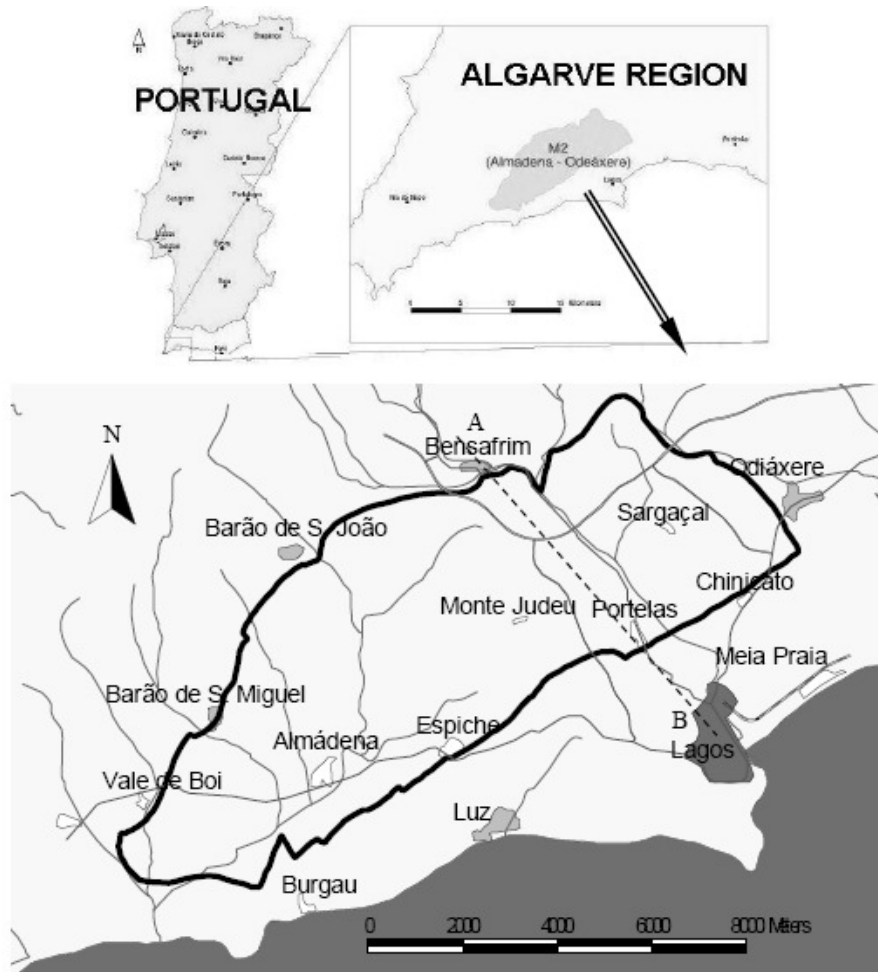
According to Monteiro (2001), double continuum and discrete continuum modeling approaches allow for a more realistic description of flow processes in carbonate aquifers, in which the regional flow pattern is strongly influenced by the conduit network. However, these methods are not commonly applied in hydrogeology outside of research and academic circles, mainly due to the large data requirements needed to describe karstic systems (Scanlon *et al.*, 2003).

Although a discrete continuum model would be the most adequate to simulate this karstic aquifers' hydraulic behaviour, there is currently insufficient data to develop such a model. However, as will be discussed in more detail in a subsequent chapter, the fact that regional piezometry of the AO is characterized by low gradients denotes the existence of a well developed conduit network controlling flow at a regional level. And therefore a single continuum model should be sufficient for the task as long as it's' limitations are appreciated and respected.

## 2. Hydrogeological Setting

### 2.1. Location and Geological Setting

The Almádena-Odeóxere aquifer system (hereafter known as the AO) is located to the west of the river Arade, between the towns of Odeóxere (to the east) and Almádena (to the west) as can be seen in Figure 1. It encompasses the Lagos and Vila do Bispo municipalities in the Algarve, the southernmost region of Portugal and extends over an area of 63.5 km<sup>2</sup> (Almeida *et al.*, 2000).



**Figure 1 - Geographic location of the Almádena-Odeóxere aquifer system. From Martins (2007)**

The aquifer system is a free-to-confined karstic system, which occurs in carbonate Lias-Dogger outcrops and stretches in a NE-SW direction (Almeida *et al.*, 2000). The dominant lithologies in which it occurs are limestone, dolomite limestone and dolomite rock with thicknesses between

60m and 1000m, and which appear in certain places as a well developed karst (Almeida et al., 2000). These formations are covered in some places by Faro-Quarteira sands and gravels, as well as alluvial deposits associated with the Almádena and Bensafrim streams. The distribution of these lithologies, as well as the geographic boundaries of the AO can be seen in Figure 2.

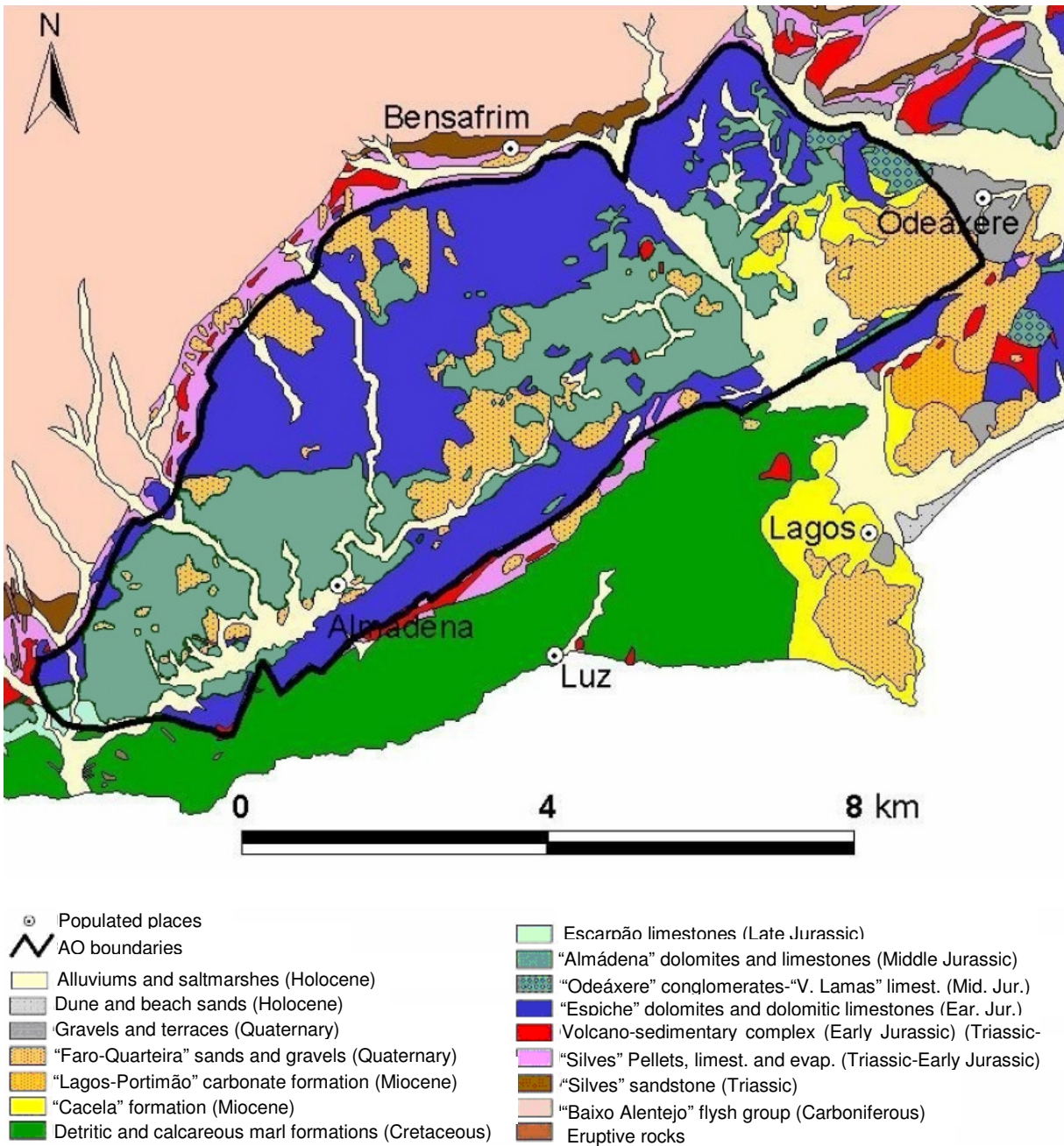


Figure 2 - Lithologies supporting the AO and its' geometric boundaries; From: Almeida et al. (2000)

As can be seen in Figure 3, the aquifer formations present a synclinal structure, with a NE-SW direction, compressed between the Barão de S. João fault to the northwest, and the Espiche fault to the southeast (Reis, 1993).

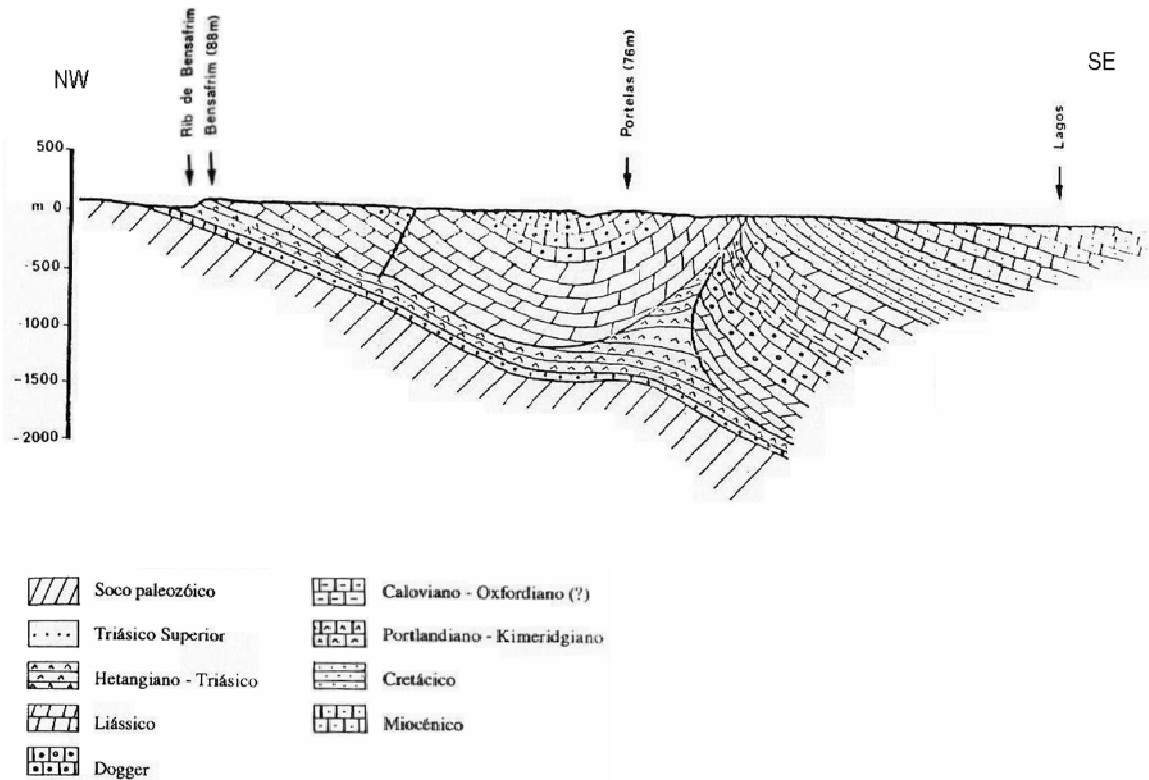
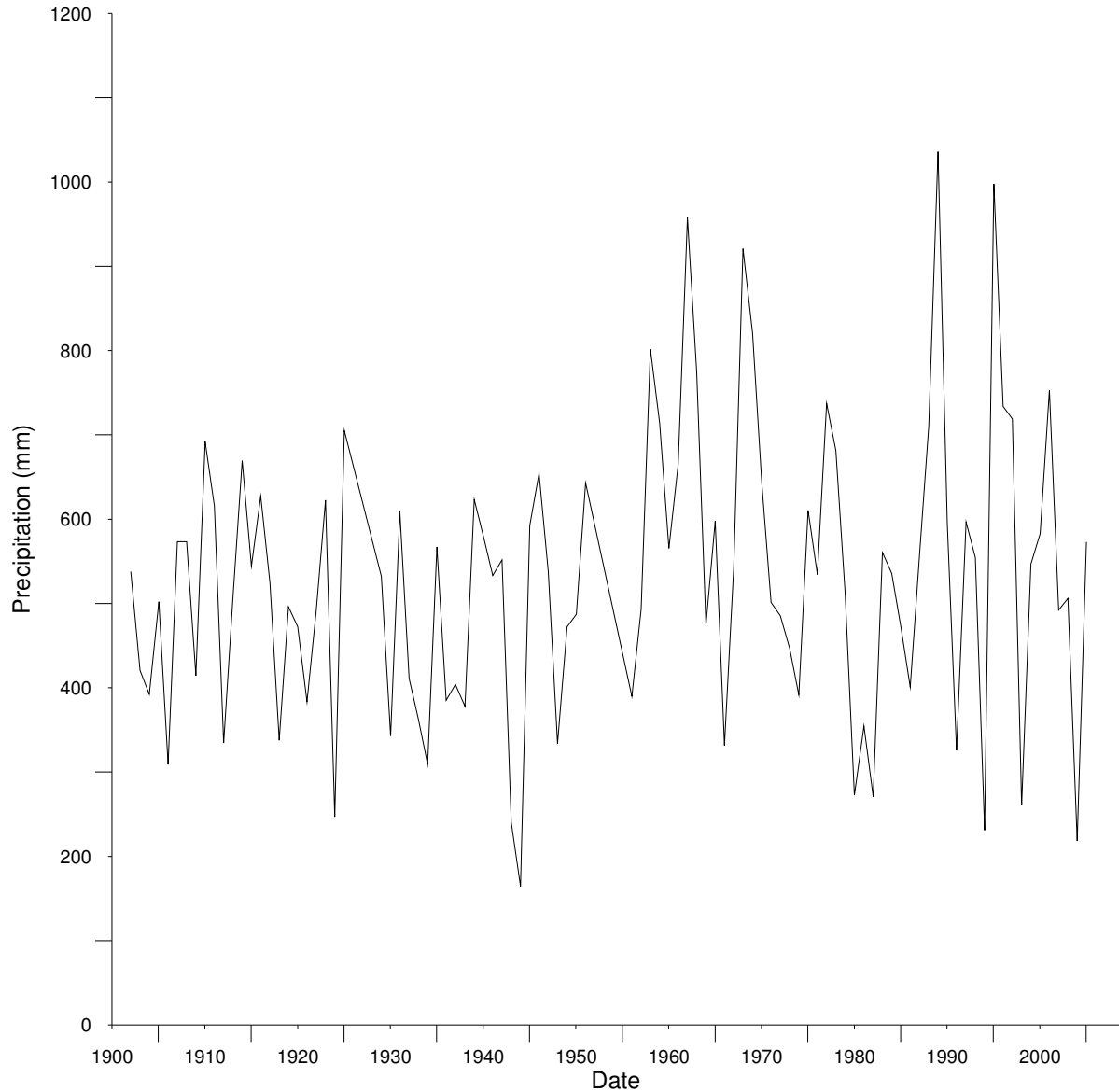


Figure 3 - Geological cross section between Bensafrim and Lagos. From Reis (1993)

## 2.2. Precipitation

Precipitation is the main source of recharge for the AO aquifer system. Daily precipitation values for the Lagos gauge (31E/01UC), the closest gauge to the AO, can be obtained for as far back as 1902 up to the present day from the SNIRH (National Service of Information on Water resources) (SNIRH, 2009). As can be seen in Figure 4, yearly precipitation values range from 203.8 mm (2004/05) to 1035.9 mm (1989/90), with a pattern of alternating dry and wet periods every 2 to 5 years.



**Figure 4 – Yearly precipitation values registered at the Lagos gauge from 1902 to 2005. Source SNIRH (2009).**

Precipitation is distributed throughout the year as expected for a Mediterranean climate, mainly occurring between October and April. The remaining summer months are mostly dry and hot.

Nicolau (2002), estimated the average precipitation occurring in the area of the AO to be 650 mm/year, based on the 1959/60 to 1991/91 period. This value was obtained using an orthogonal grid of 1 km x 1km calculated by the Kriging method and using elevation as an

external drift. This method has proven to be the most suitable for the characterization of physiographic factors affecting the spatial distribution of rainfall in Portugal (Nicolau, 2002).

## **2.3. Water Budget**

### **2.3.1. Ground-Water Recharge**

The two main sources of recharge for the AO occur through direct infiltration over the entire area of the aquifer system and through indirect infiltration from water in the streams that cross it (Reis, 1993).

The first estimates of recharge in the AO area were undertaken by Reis (1993). For the areas where carbonate rocks are covered by sedimentary deposits, she estimated the recharge to be between 28.9% and 35.6% of the precipitation from 1955 to 1985 based on calculations of evapotranspiration and varying field capacity values. In areas with outcrops of carbonated rock, the percentage of precipitation that corresponds to recharge was calculated based on the Kessler method for values from the Lagos gauge between 1960 and 1985, and range from 44.4% to 83.4%.

In a more recent report, Almeida *et al.* (2000) estimated the recharge rate between 40% and 60% of the yearly precipitation. Given the aquifers area of 63.5 km<sup>2</sup>, this would result in an estimated renewable resource of between 16x10<sup>6</sup> m<sup>3</sup>/year and 24x10<sup>6</sup> m<sup>3</sup>/year. It is of note that these values do not take into consideration the effect of indirect infiltration from streams crossing the system, which may include a significant amount of runoff generated upstream from the aquifer area.

Vieira and Monteiro (2003) proposed an average recharge of 40.3% of the precipitation over the entire 63.5km<sup>2</sup> of the aquifer system. This value was obtained from the weighted average, taking into account the presence of sub-areas in which the recharge rates vary between 5% and 50% depending on the lithology which outcrops in that sub-area. This average recharge value is within the range proposed by Almeida *et al.* (2000), and corresponds to an average annual recharge of 16.6x10<sup>6</sup> m<sup>3</sup>/year. As will be discussed further on (chapter 4.2.2) these average values of annual recharge were applied to the individual recharge episodes during the considered climacteric data series, in order to estimate the transient recharge to be incorporated in the model.

### 2.3.2. Natural Discharge

The main natural discharge areas, which can be seen in Figure 5, are located near Portelas on the Bensafrim stream, which forms the main drainage axis of the AO system; with a second, diffuse natural discharge area located at the SW point of the system, which feeds a wetland area (Almeida *et al.*, 2000).

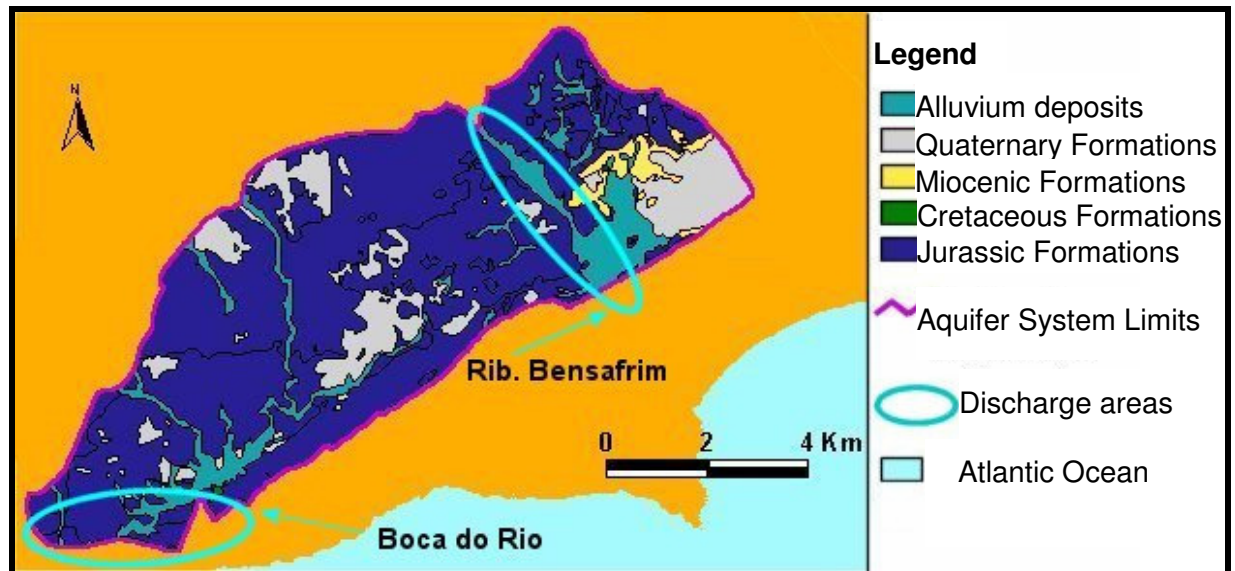


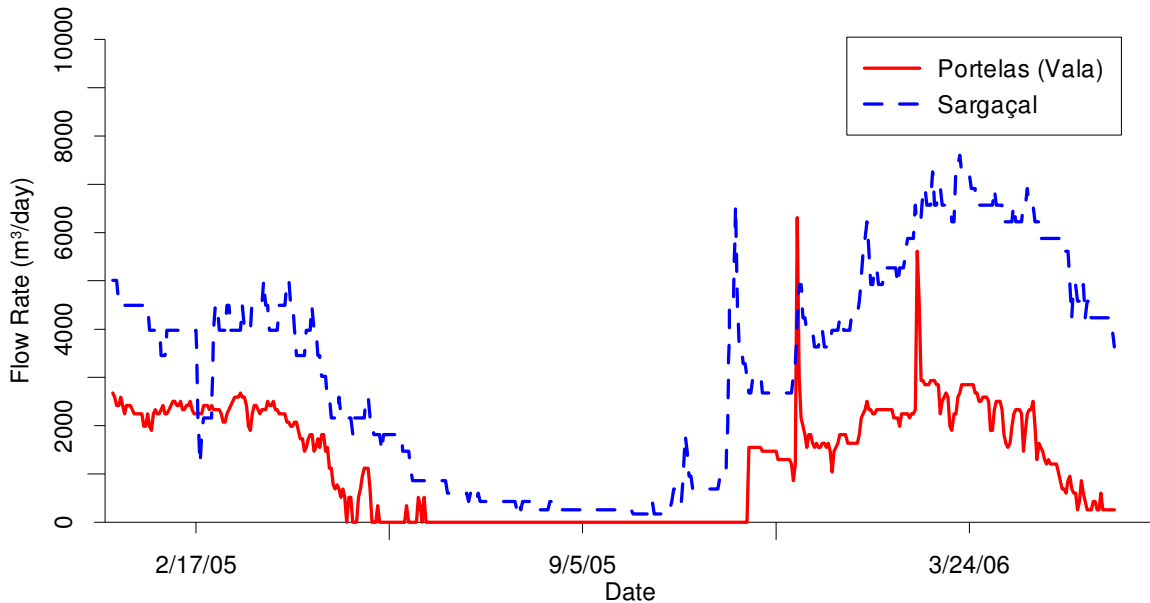
Figure 5 – Geological setting and main discharge areas of AO. From Vieira and Monteiro (2003).

The Portelas (Vala) gauge monitored the flow in a drainage system which collects the water from some of the springs at Portelas, one of the natural discharge areas. These springs dried up while the boreholes in the area were in use, however flow has restarted since 2000 (Reis, 2007). Between January and September 2005, the total flow registered was 290608 m<sup>3</sup>, and 429667 m<sup>3</sup> for the hydrological year of 2005/06.

On the east bank of the Bensafrim stream at Sargaçal, the ground water level is very close to the surface, sometimes causing flooding during winters with heavy rainfall (Reis, 2007). There are various springs which are collected by a drainage system. Between January and September 2005 the total flow registered for these springs was 598646 m<sup>3</sup> and 1141356 m<sup>3</sup> for the hydrological year of 2005/06.

According to Reis (2007) when water was being extracted for the city of Lagos from boreholes in the vicinity of Portelas these springs dried up, however since they were taken out of service in the year 2000 the springs have become active once more. This was confirmed by the simulations, as will be shown further on (chapter 5.2), as the simulation of the maximum

pumping capacity installed in the boreholes provokes an inversion of the gradient between the aquifer and the Bensafrim stream, with the consequent interruption of the baseflow in this watercourse. Reis (2007) notes that the influence of periodic water extraction for public water supply has a noticeable effect on the springs flow as can be seen during the summer of 2005 on the spring hydrographs in Figure 6. For the other main discharge area, along the Boca do Rio, there is currently no available data, due to difficulties in installing sensors in this area (Reis, 2007).



**Figure 6 – Spring hydrographs for the Portelas (vala) and Sargaçal springs from January 2005 to June 2006.**

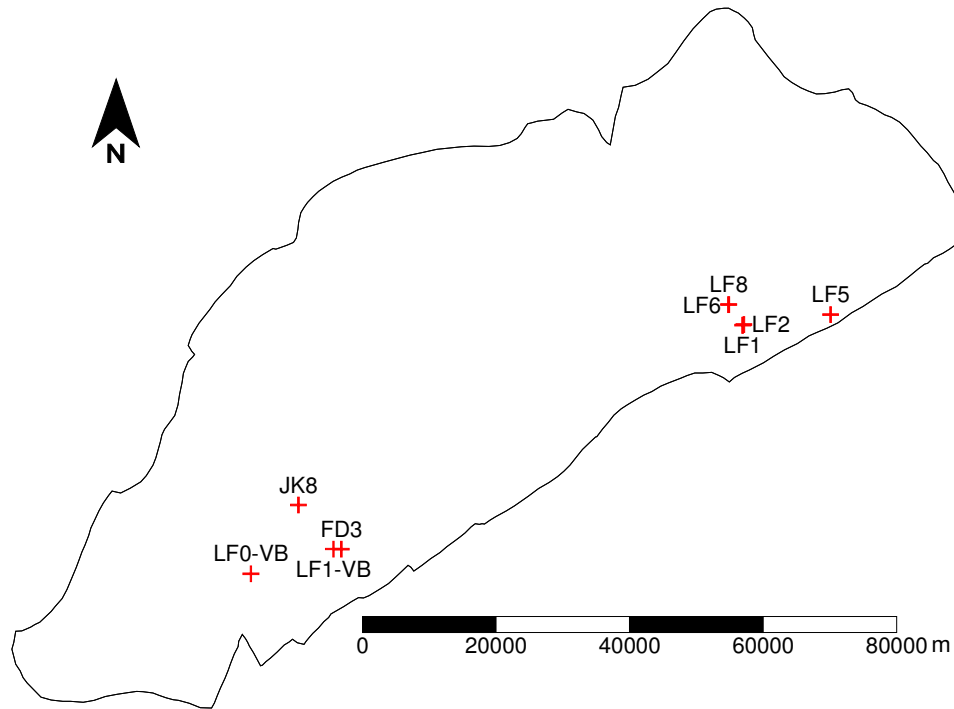
### **2.3.3. Ground-Water Withdrawals**

The use of the AO aquifer system as a source of urban water supply goes as far back as the year 1521. At that time, a spring at Paul da Abedoeira (also known as the Paul de Lagos) on the right bank of the Bensafrim stream, from which water was brought by gravity, was the sole source of water supplying the city of Lagos and remained so until the 1960's (Paradela, 1959).

In the early 1960s, due to the increased demand for water created by the rise in tourism, three well-fields were drilled in the proximity of springs in the area to the north of Lagos. Most of the boreholes were not particularly deep, with depths in the range of 21m to 39m. Registered flow rates were generally in the 20-30 l/s range; however two boreholes in one of the well-fields had



flows of 95 l/s and 100 l/s (Paradela, 1959). Slightly earlier, in 1957, the municipality of Vila do Bispo was already supplied by a single borehole in the vicinity of the town of Almádena (Paradela, 1959). The location of the main boreholes extracting from the AO used for public water supply can be seen in Figure 7.

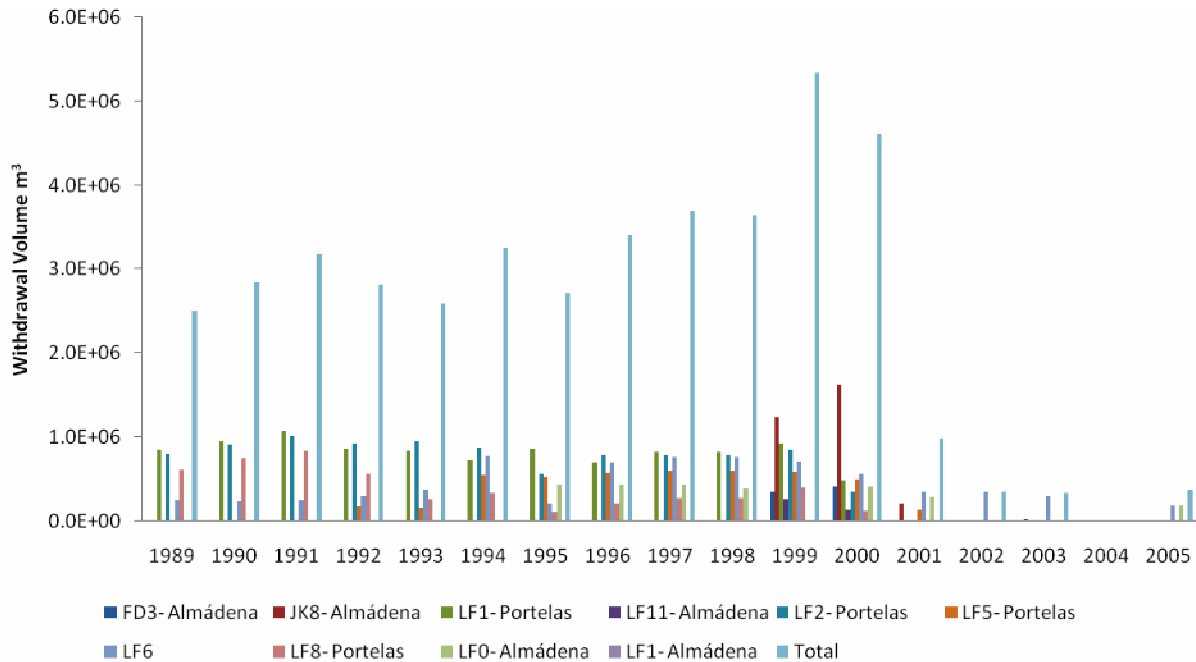


**Figure 7– Location of the main public supply boreholes in use from 1989 to 2005.**

Until 1999 the AO was the main source for the public water supply of the municipalities of Lagos and Vila do Bispo, but after the Algarve multi-municipal water supply system was implemented, withdrawals from the AO diminished dramatically. Currently this aquifer system is held as a strategic reserve for use in case of a disruption to the municipal water supply as happened recently during the 2004/2005 drought. There is, however, a strong possibility that some of the existing boreholes could be used in the future in an integrated public water supply management scheme (Martins, 2007).

Data on the volume of water extracted per month from the eight main public water supply boreholes during the last decade was gathered from the Municipal Councils in the scope of the OPTEXPLOR project (Nunes *et al*, 2006b). As can be seen in Figure 8, the data shows a steady increase in the number of boreholes in use as well as in the total extracted volume

during the last few years prior to the implementation of the multi-municipal water supply system, peaking in the year 1999 and then the subsequent dip in 2000. As is to be expected the highest registered extractions occurred during tourist season.



**Figure 8 - Yearly extracted volumes from the main public water supply boreholes on the AO from 1989 to 2005.**

An inventory of extractions for irrigation and private supply, produced by the “Direcção Regional do Ambiente e Ordenamento do Território” (DRAOT) Algarve and which covered approximately half of the known extraction points, indicates that these extractions are responsible for approximately  $1.3 \times 10^6$  m<sup>3</sup>/year. Almeida *et al.* (2000) considered it safe to assume that therefore, the total of ground-water withdrawals for private supply and irrigation to be approximately  $2.6 \times 10^6$  m<sup>3</sup>/year.

Indirect methods, such as remote sensing, should be applied to better estimate these values based on the area of irrigated land such as already been done for the Querença-Silves aquifer system in this region (Nunes *et al.*, 2006a)

**Table 1– Water budget and estimation of withdrawal/recharge ratio for the AO considering average annual precipitation and pumping data from 1989 to 2005.**

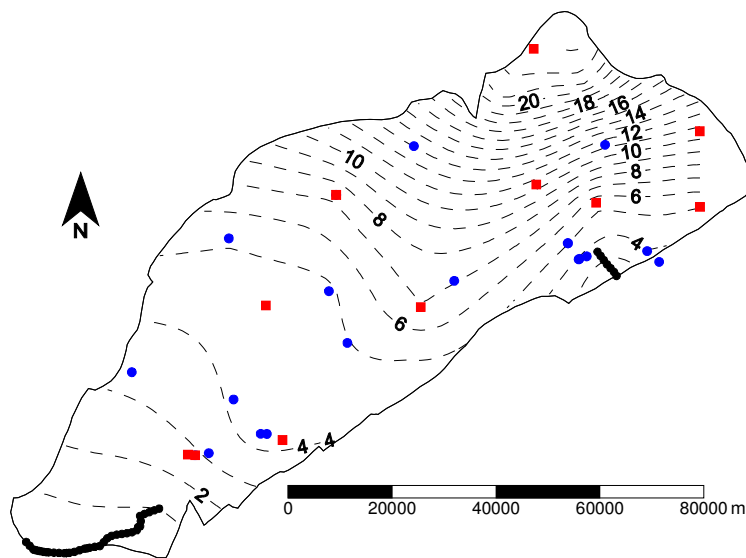
Year	Withdrawals			Precipitation (mm)	Recharge (m <sup>3</sup> /year x10 <sup>6</sup> )	Withdrawal/Recharge (%)
	Public Supply (m <sup>3</sup> /year x10 <sup>6</sup> )	Private Supply (m <sup>3</sup> /year x10 <sup>6</sup> )	Total (m <sup>3</sup> /year x10 <sup>6</sup> )			
1989	2.51	2.60	5.11	1097.70	28.02	18.22%
1990	2.84	2.60	5.44	553.90	14.14	38.47%
1991	3.18	2.60	5.78	436.50	11.14	51.88%
1992	2.82	2.60	5.42	422.00	10.77	50.35%
1993	2.59	2.60	5.19	638.40	16.30	31.87%
1994	3.25	2.60	5.85	317.00	8.09	72.35%
1995	2.72	2.60	5.32	498.80	12.73	41.81%
1996	3.41	2.60	6.01	1016.60	25.95	23.15%
1997	3.69	2.60	6.29	787.90	20.11	31.27%
1998	3.64	2.60	6.24	354.60	9.05	68.97%
1999	5.33	2.60	7.93	399.20	10.19	77.84%
2000	4.61	2.60	7.21	611.20	15.60	46.22%
2001	0.99	2.60	3.59	720.00	18.38	19.56%
2002	0.36	2.60	2.96	590.90	15.08	19.60%
2003	0.34	2.60	2.94	602.40	15.38	19.14%
2004	0.02	2.60	2.62	254.80	6.50	40.24%
2005	0.37	2.60	2.97	361.50	9.23	32.19%

The estimates presented in Table 1 indicate that a deficit in the water balance between inflow and outflow from the aquifer system has yet to occur. However it is likely that, if groundwater had continued to be the main source of public water supply up to the year 2005, the withdrawal/recharge ratio would have come close to reaching, or even surpassing 100%. The consequences of such a scenario would not necessarily have been drastic on the availability of water at a regional scale due to the high regulatory capacity of the aquifer system, however there is no indication of what effects these abstraction ratios would have at a local scale or on the quality of the water due to the lessening of the dilution effect. These estimates show that water management should take into account the high climate variability of the region, and not be based merely on values of average yearly budgets as has been the case for most management practices of ground-water resources.

## 2.4. Spatial and Temporal Evolution of Hydraulic Head

Historical data used to characterize the spatial distribution and temporal evolution of ground-water levels in the AO aquifer system were obtained from the observation points shown in Figure 9. The interpretation of this data allows us to define the predominant directions of ground-water flow which forms the basis of the conceptual model of the aquifer system.

Part of this data consists of historical data collected by the CCDRA (Commission for the Coordination and Development of the Algarve), and is publicly available from the SNIRH website (SNIRH, 2009). This set of data is available, for some observation points, as far back as 1978 up to the present day. However, the spatial distribution of the observation points is insufficient to properly characterize the hydraulic behaviour of the aquifer (Martins, 2007). Piezometric data from automatic monitoring of ten observation points between March of 2007 and July 2007 was obtained, and is also available *online* as part of the “Groundwater Flow Modelling and Optimization of Groundwater Monitoring Networks at the Regional Scale in Coastal Aquifers” research project undertaken at the University of the Algarve and funded by the Science and Technology Foundation “POCTI/AMB/57432/2004” (Martins and Monteiro, 2008a).



**Figure 9 – Location of the Piezometric observation points and piezometric map of the AO (dotted lines). Red dots represent data provided by CCDRA, Blue dots represent data supplied by “POCTI/AMB/57432/2004” research**

project. Thick black lines represent the aquifer systems main discharge areas.

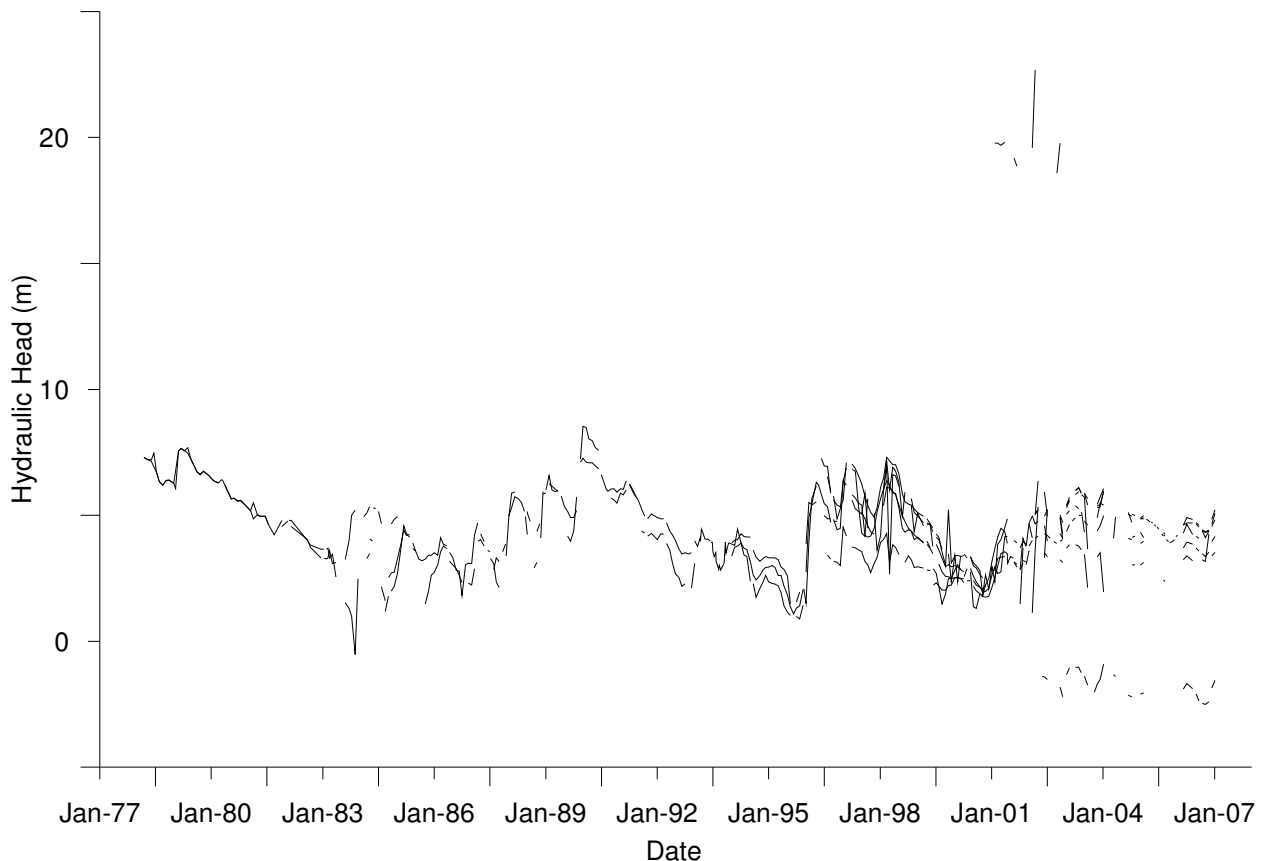
**Table 2 – Piezometric data observation points. Ref. CCDR (reference number used by the CCDRA on their monitoring networks). Ref. UALG (reference number used by the University of the Algarve on their monitoring network).**

Ref. UALG	Ref. CCDR	M	P Coordinate	Max.	Min.	Average	Amplitude
	593/5	149150	22050	22.73	18.48	19.79	4.25
-	594/400	152345	20470	4.10	1.77	3.15	2.33
-	602/32	142640	14260	7.68	1.56	5.64	6.12
-	602/36	142500	14270	7.65	1.09	4.52	6.56
-	602/43	144320	14550	6.12	1.75	3.86	4.37
-	602/76	149200	19450	8.53	0.88	3.89	9.05
AO-02	602/178	145350	19250	7.23	2.51	5.45	4.72
-	602/187	150350	19100	5.33	1.13	3.11	4.20
-	602/242	146980	17100	6.98	1.86	4.67	5.12
-	602/311	144000	17130	7.31	1.48	4.53	5.83
-	603/38	152350	19020	5.00	0.25	2.56	4.75
-	602/9	144016	14667	4.27	3.30	3.90	0.97
-	602/10	143898	14670	4.57	3.72	4.24	0.85
-	602/78	151336	18176	3.95	-0.28	1.93	4.23
-	602/4	150021	18019	5.76	3.92	5.03	1.84
-	602/5	150038	18028	5.89	3.76	5.19	2.13
AO-13	602/6	149814	18328	5.27	4.10	5.04	1.17
-	602/8	149810	18328	5.27	4.11	4.58	1.16
AO-08	-	143286	18416	5.14	4.10	4.77	1.04
AO-09	602/79	151565	17965	0.85	0.45	0.65	0.40
AO-17	602/112	143376	15328	8.54	4.36	5.7	4.18
AO-19	-	142900	14298	5.09	4.52	4.82	0.57
AO-20	-	141418	15851	5.16	4.24	5.03	0.92
AO-21	-	147622	17601	3.95	3.44	3.66	0.51
AO-22	-	146846	20185	4.55	4.11	4.23	0.44
AO-23	-	150524	20210	5.33	3.34	3.88	1.99

The interpretation of the data in Table 2 and in Figure 9 shows that the hydraulic gradients are relatively low across most of the aquifer system except for in the north-eastern corner, and

regional flow occurs predominantly from NE (recharge area) to SW (discharge area at the Boca do Rio). A north to south flow can also be identified on the eastern side of the aquifer system, related to the discharge area at the estuary of the Bensafrim stream.

In order to complement the spatial distribution of hydraulic heads represented by the piezometric map in Figure 9, the temporal variation of hydraulic heads for the 11 observation points with the longest time series (data provided by CCDRA) are represented in Figure 10. As can be seen, this data does not reveal significant variations of the water level. This behaviour could be a result of a high regulating capacity of the aquifer system, as well as being due to the well developed karst network of the aquifer system which allows for good hydraulic connections between all of the aquifers sectors and the natural discharge areas (Almeida *et al.*, 2000).



**Figure 10 – Historical data on hydraulic heads obtained from piezometers with the longest time series of data (data obtained from SNIRH, 2009).**

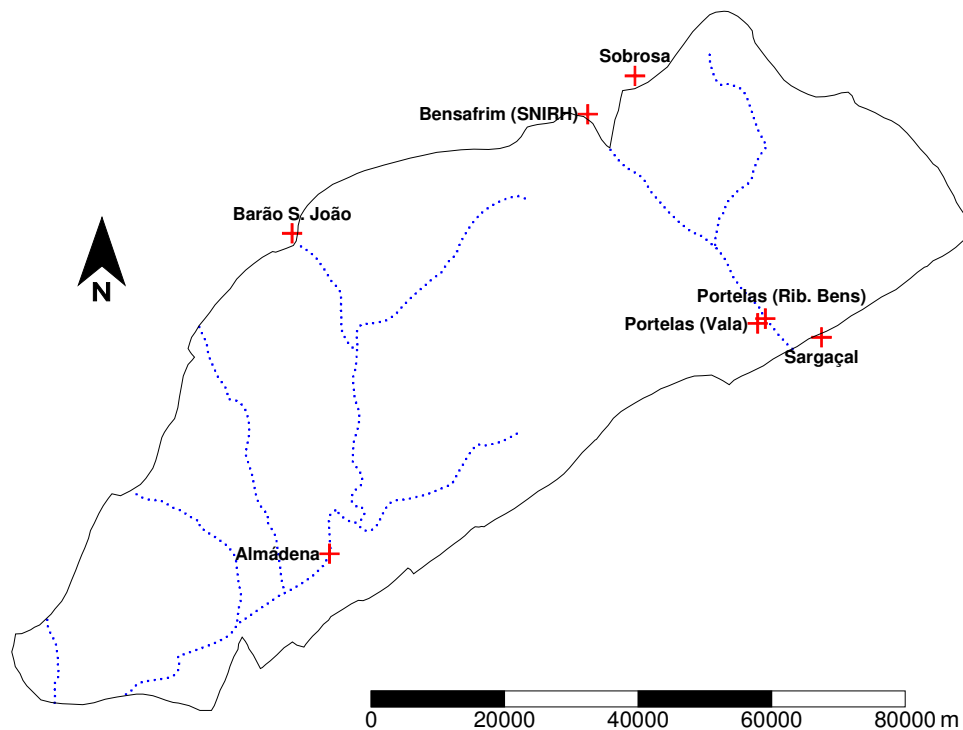
Of note are the values registered by the two piezometers which are significantly different from the rest. Unfortunately these are the only piezometers in their respective areas, and therefore there is currently no other data to corroborate these readings. Future monitoring planning

should consider the option of selecting extra observation points in these areas to obtain a more accurate understanding of these anomalous readings.

## 2.5. Stream Network and Surface Water flow

The system is crossed by various water lines originating in the hills to the north (the streams Vale do Barrão, Almádena and Bensafrim), and when these streams intersect the carbonated Jurassic formations which make up the aquifer system, most of the flow infiltrates. This is largely due to groundwater level below the stream bed which, as was mentioned previously, is in the range of 40-60m over most of its extension only coming close to the surface at the discharge areas due to the formations which cause a barrier at the southern limits of the aquifer system.

Data on stream flow was collected by the CCDRA starting January 2005 to October 2006 from gauges on the Almádena and Bensafrim streams, the location of which can be seen in Figure 11. Gauges on a drainage system which collects water from springs at Portelas and Sargaçal (one of the natural discharge areas for the AO) collected data on spring flow for the same period.



**Figure 11 – Main streams (dotted blue lines) and hydrometric stations and monitored springs (red crosses) on the Almadena-Odeáxere aquifer system.**

From January 2005 to the end of the 2004/05 hydrological year, the stream at Almadena was always dry. For the same period of time, a total flow of 6480 m<sup>3</sup> was registered at the Barão de S.João gauge. The entirety of that flow was registered before March, with the stream being dry from that month to the end of the hydrological year, in September. Downstream from the Barão de S.João gauge there is a discharge point for a sewage treatment plant, which registered a discharge of 12440 m<sup>3</sup> for the same period (Reis, 2007). This corresponds to a total flow of 18720 m<sup>3</sup> which, apart from a small portion loss to evapotranspiration, will have infiltrated into the aquifer system.

During the 2005/06 hydrological year, total flow at Almadena was 189130 m<sup>3</sup>, whilst at Barão de S. João, including discharge from the sewage treatment plant was 221155 m<sup>3</sup>. This indicates that about 32025 m<sup>3</sup> will have infiltrated, which is relatively insignificant at the scale of the AOs water budget (Reis, 2007). It is important to refer that there is no estimate of the flow from the tributaries which connect to this stream in-between the hydrometric stations. Therefore the impact of potential recharge from the tributaries is unknown.

It is of note that, near Barão de S. João there are alluvium deposits on top of the limestone formations, which form a small aquifer which is mostly recharged by the stream. It is therefore likely that the volume of water from the stream that reaches the karst aquifer is even less significant (Reis, 2007).

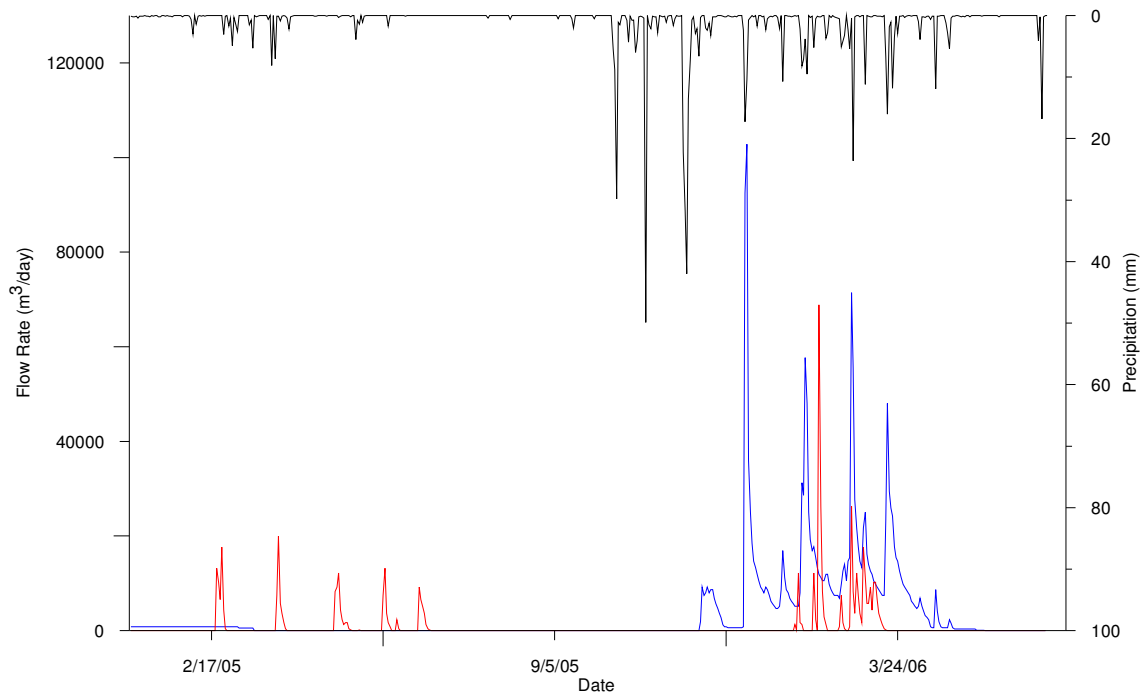
Unfortunately, due to technical difficulties in installing the sensor, there is no data for stream flow downstream from Almadena, at the Boca do Rio discharge area.

The Bensafrim stream was monitored in three places, on the Machada and Sobrosa streams (which join together to form the Bensafrim stream, slightly upstream from the AO) and at Portelas at one of the AOs natural discharge areas. The difference between the volume of flow registered at Sobrosa and Machada and at Portelas was 716256 m<sup>3</sup> for the hydrological year of 2004/05 and 2192000 m<sup>3</sup> for 2005/06 (Reis, 2007). This value of recharge from this stream is significant considering it represents approximately 13% of the AOS average annual water budget.

Unfortunately this data only covers a short period, and is insufficient for a comprehensive analysis of surface water behaviour. However, as can be seen in Figure 12 the flow in both



these streams is dependent on rainfall, only occurring after precipitation episodes and drying up during dry periods. Therefore it can be supposed that the wetlands which are associated with them depend on the presence of ground water discharge to maintain their functionality.



**Figure 12 – Stream hydrographs measured at the Portelas-Bensafrim gauge (blue line) and Almádena gauge (red line) compared to precipitation (black line; top axis) registered at the Lagos gauge (31E/01UC); Almádena gauge was inoperative during part of 2005.**

## 2.6. Wetlands

The AO aquifer system is hydraulically connected to two wetlands which are formed by upward seepage at the aquifers diffuse discharge areas, as was previously mentioned in chapter 2.3.2. Wetland ecosystems hold an important part of Europe's biodiversity. They provide ideal conditions for a vast diversity of habitats and species. They are especially important for birds, providing vital nesting and migratory flyway areas, as well as for fauna species and countless specialist plant species (Silva *et al.*, 2007). Wetlands support a wide range of public goods and services, such as providing fresh water and recreational tourism opportunities. In addition they act as carbon sinks and are therefore fundamental asset in our efforts to reduce levels of greenhouse gases in the atmosphere. However, despite their importance, wetlands are

disappearing or are being polluted at an alarming rate and are among Europe's most threatened ecosystems (Silva *et al.*, 2007).

The wetland known as the Paúl de Lagos (or Paúl da Abedoeira) is located at the mouth of the Bensafrim stream, to the North-east of the city of Lagos and within a short distance from the protected Ria do Alvor. It is considered one of the most important wetlands in the Western Algarve due to its rich biodiversity. This wetland covers an area of 297 hectares and has an interesting mix of flora and fauna (Costa, 2001). The vegetation found here, as well as the various channels which cover it, attract numerous species of birds which come to nest, as well as many reptiles and other animals which proliferate in the undergrowth (Costa, 2001). Over 373 species of plants, 37 types of butterflies, 15 different mammals as well as 190 species of birds have been documented. Of particular note is the Monarch Butterfly (*Danaus plexippus*), which is extremely rare in Europe and the only known breeding colony in Portugal is at the Paúl de Lagos (Costa, 2001).

Human occupation and alteration of the Paúl is well documented as far back as the XV century, during which a channel system was built in order to drain the marsh as well as provide water to the city of Lagos (Barata, 2003). Since then the Paúl has mostly been used as agricultural land up until the 1970s, when it was occupied by rice paddies. With the decline of agricultural activities in the recent past, they have been mostly abandoned and are currently reduced to a few small farms (Domingos *et al.*, 2008).

This area was recently the focus of a study by the Portuguese Society for the Protection of Birds (SPEA) and the British Royal Society for the Protection of Birds (RSPB) to determine the present state of its wildlife and steer a proposed habitat creation opportunity supported by the Lagos Municipal council. They determined that the flow from the springs in the area, which is currently flowing along ditches into the sea, could be viably harnessed for habitat creation (Costa, 2001). It was established that the Paúl de Lagos would be suitable for creating a large self-sustaining fresh water lagoon which would enhance this areas already large ornithological significance.

The Boca do Rio wetlands (also known as the Vale de Barao wetlands) form at the confluence of the Ribeiro de Budens, Ribeiro de Boi and Ribeiro de Vale Barao, west of Lagos. The wetlands occupy a fault-bounded valley at the coast, extending inland for approximately 1 km before dividing into the three tributary valleys (Allen, 2003). Land use in the catchment is at present largely agricultural, but with much uncultivated land. Much of the wetland area is

supratidal, separated from the sea by a narrow beach which prevents marine ingress even during severe storms (Allen, 2003). Consequently a well-developed creek system, such as that associated with many coastal marshes, is absent. The major outflow of the rivers has been canalized as it crosses the wetlands, but periodically there are extensive floods from precipitation in the catchment (Allen, 2003).

Land-use activity in the catchment inevitably influences the ecology of the wetlands giving rise to the transience of the varying ecological status of the wetlands. Recognition of this is important given that wetlands are among the most threatened of Mediterranean ecosystems and environments. Major threats come from development pressures and reclamation; a Council of Europe survey in 1984 found that 80 per cent of Portuguese wetlands were vulnerable to reclamation (Hollis, 1992). The threat comes from tourism and recreation, and unsustainable abstraction of drinking water. For the Mediterranean basin as a whole, estimates suggest that by 2025 there will be about 380 million tourists per year if economic growth is weak, but about 760 million if it is strong and that almost half of these tourists will be concentrated along the coast, many in Portugal (Stanners and Bourdeau, 1995). Although there have been no major tourist developments in the Boca do Rio catchment, there are some small villa complexes and the wetlands themselves are reportedly now threatened by the development of a marina.

While not a site of prime conservation value in the Algarve (in comparison, for example, with the much larger and more varied habitats of the Rio Formosa National Park further east), the Boca do Rio wetlands provide valuable habitat for wildlife, especially as attempts at reclamation for agriculture have been abandoned and marsh conditions have become re-established (Allen, 2003). Populations of some wetland species are high, especially of the European pond turtle (*Emys orbicularis*) and the viperine water snake (*Natrix maura*). It is also believed that there are important populations of freshwater birds such as rails (Rallidae) and crakes (Porzana spp.) (Pullan, 1988).

Considering the significance and fragility of these surface water bodies, it is of utmost importance to properly understand any potential threats to their existence and function. Taking into account the dependence of these two wetlands to ground water discharge, any water resource management plan which takes into account the use of ground water as a source of supply must consider the impacts this could have on these surface water bodies and their associated ground-water dependent ecosystems.

### 3. Numerical Modelling Method

In this chapter, a brief description will be given of the physical principals underlying the simulation of the hydraulic of the aquifer system, followed by a brief description of the numerical method to be applied.

The following description is adapted from Monteiro (2001):

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + Q = S_s \frac{\partial h}{\partial t} \quad (1)$$

In which:

$K_{xx}$ ,  $K_{yy}$  and  $K_{zz}$  are values of hydraulic conductivity [ $LT^{-1}$ ] along the x, y and z Cartesian axis which are assumed to be parallel to the directions of greater hydraulic conductivity,  $h$  is the hydraulic potential [L],  $Q$  is the volumetric flux per unit of volume [ $L^3T^{-1}L^{-3}$ ] that represents fluid gains and losses and  $S_s$  is the storage coefficient, necessary to simulate transient variations on the reserved volume of water [ $L^{-1}$ ].

Hydraulic conductivity is defined by the expression:

$$K = \frac{\rho g k}{\mu} \quad (2)$$

In which  $\rho$  is the density of water [ $ML^{-3}$ ],  $g$  is gravitic acceleration [ $LT^{-2}$ ],  $k$  is the intrinsic or geometric permeability [ $L^2$ ] and  $\mu$  is the dynamic viscosity [ $ML^{-1}T^{-1}$ ].

The piezometric level, also known as hydraulic potential ( $h$  [L]), corresponds to the energy per unit of mass of the fluid, if kinetic energy is disregarded, as is expressed as the sum of the elevation potential,  $z$  [L] of the fluid and the pressure potential,  $p$  [ $ML^{-1}T^{-2}$ ] at a given point:

$$h = \left( \frac{p}{\rho g} \right) + z \quad (3)$$

The storage coefficient [ $L^{-1}$ ] is defined by the expression:

$$S_s = \rho g (\alpha + n\beta) \quad (4)$$

In which  $\alpha$  represents the compressibility of the porous media [ $LT^2M^{-1}$ ],  $n$  is the effective porosity (non-dimensional) and  $\beta$  is the waters compressibility [ $LT^2M^{-1}$ ].

Equation (1) is often expressed in a more compact manner, using the divergence and gradient differential operators:

$$S_s \frac{\partial h}{\partial t} + \text{div}(-[K]\overrightarrow{\text{grad}h}) = Q \quad (5)$$

The equation describing groundwater flow can be solved for particular boundary conditions by the finite element method, which is a particularly well suited approach for integrating partial differential equations over space and thus to simulate flow in complex geometry flow domains. The use of finite element models is currently a standard approach for solving problems in hydrogeology and is described in textbooks such as HuyakomandPinder (1983), Kinzelbach (1986), WangandAnderson (1982) and BearandVerujit (1987).

The finite element method is implemented in several commercial and public domain codes to solve problems in hydrogeology. The most employed method to assemble the element matrix is the Galerkin method of weighted residuals. The description of the principles of this method is adapted from Monteiro (2001):

The flow domain is divided into discrete elements, each of which is characterized by its shape, hydraulic conductivity and storage coefficient. Equation (5) is presented in the form:

$$L(h) = 0 \quad (6)$$

Where  $L$  is a differential operator and  $h$  is the dependant variable (hydraulic head).

A trial solution  $\hat{h}$  for the unknown variable is defined as a function of a set of quadratic or linear polynomial functions, expressed by the Equation (7).

$$\hat{h} \cong \sum_{j=1}^n N_j h_j \quad (7)$$

, where  $h_j$  are the unknown nodal values,  $N_j$  are the interpolation (or basis) functions and  $n$  is the total number of nodes defining the elements in a mesh representing the geometry of the flow domain. When  $h$  is substituted by  $\hat{h}$  in equation (7) an approximate solution is defined. Therefore residuals  $r$ , defined by equation (8) will occur:

$$r = L(h) \neq 0 \quad (8)$$

To minimize the residual over the entire flow domain an integral equation is written to ensure that the basis functions satisfies the partial differential equation of flow. This is accomplished by defining a weighted integral of  $r$  over the elements of the flow domain and then setting this integral equal to zero. As a consequence of this the weighted integral will be zero over the entire flow domain  $V$  and thus over the entire set of  $n$  weighting functions ( $W$ ):

$$\int_V W_i L(\sum_j N_j h_j) dV = 0 \quad \text{for } i = 1, 2, \dots, n \quad (9)$$

Thus the method of weighted residuals seeks to determine the unknown  $h_j$  in such a way that the error is minimized in the flow domain  $V$ . In the Galerkin method the employed interpolation (or basis) functions and weighted residual functions are the same ( $M_i = W_j$ ). After the definition of these functions (usually linear or quadratic polynomials) the values of  $\hat{h}$  calculated by equation (7) are combined with equation (9) to provide a set of simultaneous equations where the unknown variable  $\hat{h}$  is defined for each of the  $n$  nodes of the finite element mesh (equation 10):

$$[A] \cdot \left\{ \hat{h} \right\} = \{ f \} \quad (10)$$

Where  $[A]$  is the global stiffness matrix and  $\left\{ \hat{h} \right\}$  is the vector of unknown variables and  $\left\{ f \right\}$  is the source term. Once the values of all elements are combined, including prescribed boundary conditions, the resulting set of simultaneous linear algebraic equations is solved using different solution algorithms. Different direct and iterative solvers based in matrix solution techniques are available to solve the resulting assembled algebraic equations.

## **4. Ground-Water Flow Model**

In Chapter 2, an overview was given of the current knowledge, data and information available on the AOs hydrogeological behaviour.

The following chapter aims to describe the steps taken in the construction of the model which lead to the version applied in this thesis. It is important to point out that some of this work was carried out by researchers from the University of the Algarve prior to the beginning of this thesis, namely the generation of the finite element mesh, definition of boundary conditions and definition of spatial distribution of transmissivity.

### **4.1. Conceptual Model**

The AO has an area of 63.5 km<sup>2</sup> and stretches from Odeóxere (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 1000m and 60m, and which present, in certain places, a well developed karst (Reis, 1993; Almeida *et al.*, 2000).

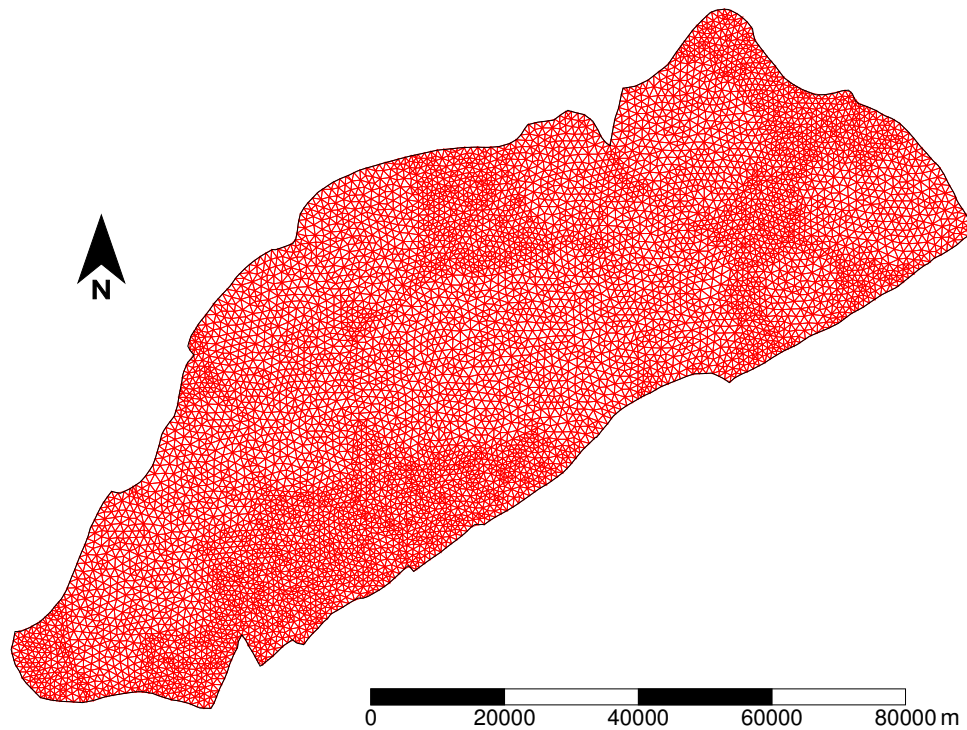
Regional groundwater flow occurs predominantly from the NE to SW. There are two main sources of recharge: indirect infiltration from streams flowing across the system (the Bensafrim and Odeóxere being the most significant) and direct infiltration over the system (Reis, 1993). The system is traversed by various water lines originating in the hills to the north (the streams Vale do Barrão, Almádena and Bensafrim), and when these streams intersect the carbonated Jurassic formations which make up the aquifer system, most of the flow infiltrates. The main natural discharge areas are located (1) along the Bensafrim stream, which forms the main drainage axis for the AO system and (2) a second diffuse discharge area at Boca do Rio the SW point of the system which feeds a wetland area (Almeida *et al.*, 2000).

### **4.2. Numerical Model**

Ground water flow was simulated by the use of FEFLOW (Finite Element Subsurface Flow and Transport Simulation System). This is sophisticated software and consists of an interactive simulation model of groundwater flow in 3D and 2D, using the numeric method of resolving partial differential equations through finite elements mesh (FEM).

#### 4.2.1. Finite Element Mesh

The first step taken in the development of the current model was the creation of a 2D non-structured finite element mesh (FEM). The mesh was generated using the Delaunay TMesh method, which was developed at the Swiss Institute of Technology (Laboratory of Geology, Lausanne, Switzerland) and is composed of 7494 nodes and 14533 triangular finite elements, which can be seen in Figure 13. In order to generate the mesh, the aquifer's limits, the system's geological cartography and a database containing important water points were taken into consideration.



**Figure 13 - Finite element mesh based on the geometry of the Almádena-Odeóxere aquifer system.**

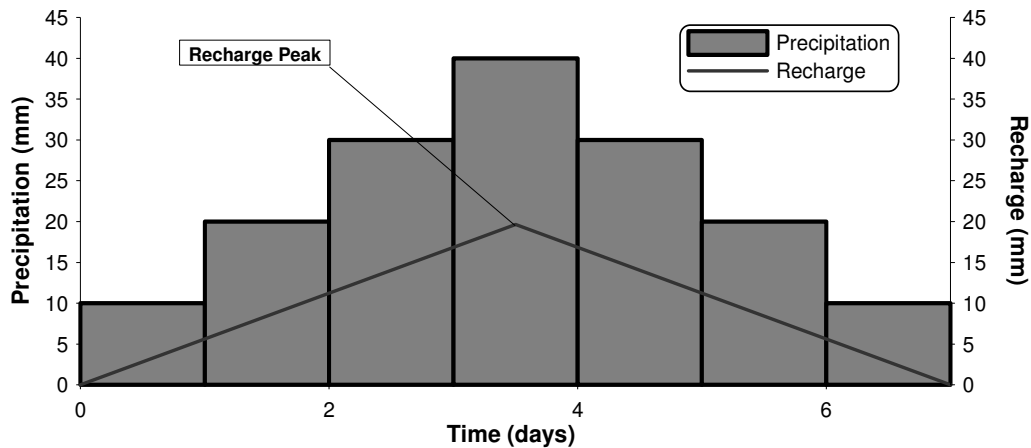
#### 4.2.2. Simulation of Transient Ground-Water Recharge

As discussed in Chapter 2.3.1, Vieira and Monteiro (2003) proposed an average recharge of 40.3% of the precipitation over the entire 63.5km<sup>2</sup> of the aquifer system. This value was obtained from the weighted average, taking into account the presence of sub-areas in which the recharge classes vary between 5% and 50% depending on the lithology which outcrops in that



sub-area. This value was considered adequate for use in transient state simulations by Martins and Monteiro (2008b).

In order to perform transient simulations, recharge was calculated using average daily precipitation values, obtained at the Lagos (31E/01UC) meteorological station. These values consist of abrupt point inputs and were converted into smoother continuous recharge inputs before being introduced in the AO finite-element model in an attempt to minimize a potential source of numeric instability into the model, as is illustrated in Figure 14.



**Figure 14 - Illustrated example of the transient recharge input method based on measured precipitation values of a typical precipitation episode. Adapted from Martins and Monteiro, (2008b).**

Given an episode of precipitation (consisting of one or more days of significant precipitation), equation (11) is used to calculate the highest value of recharge,  $h_{rec}$ , attained during the episode:

$$h_{rec} = \frac{2 \times R \times P}{n} \quad (11)$$

In which  $R$  is recharge rate,  $n$  is the number of days of the precipitation episode and  $P$  is the total precipitation occurring at the episode.

Values of transient recharge were distributed linearly increasing from the beginning of the episode until  $h_{rec}$  and decreasing afterwards until reaching the last day of the episode. This method had been previously implemented by Martins and Monteiro (2008b).

### 4.2.3. Boundary Conditions

Hydraulic potentials were imposed along the areas in which natural discharges are known to occur (Monteiro *et al.*, 2003). Potentials were imposed on discharge areas, along the stream watercourses, where it is known that historical piezometric values in the surrounding area are above ground level as can be seen in Figure 15.

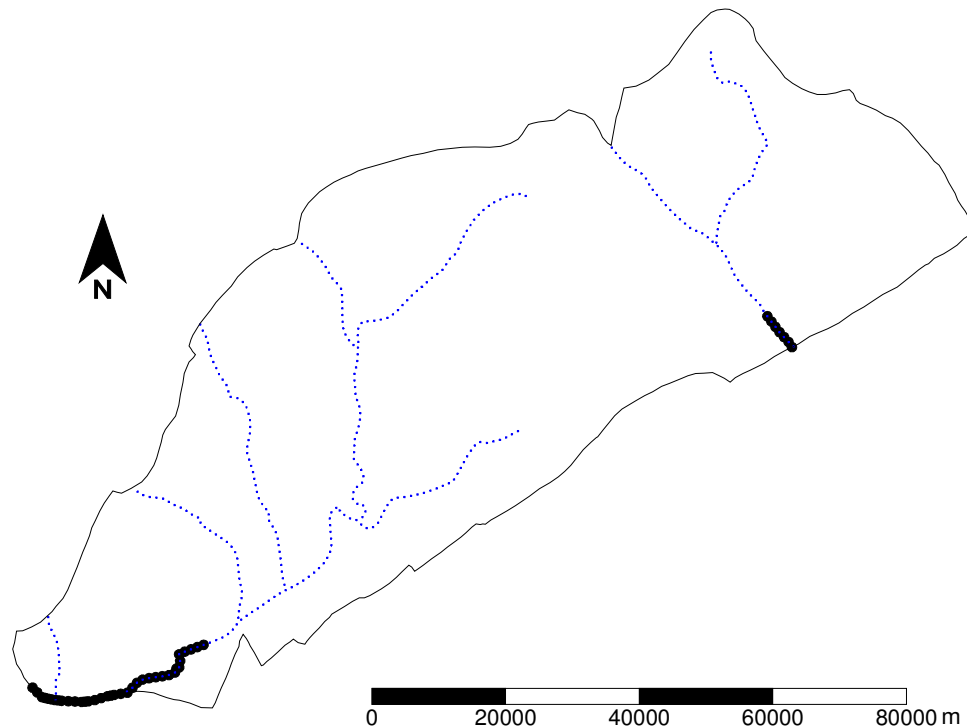


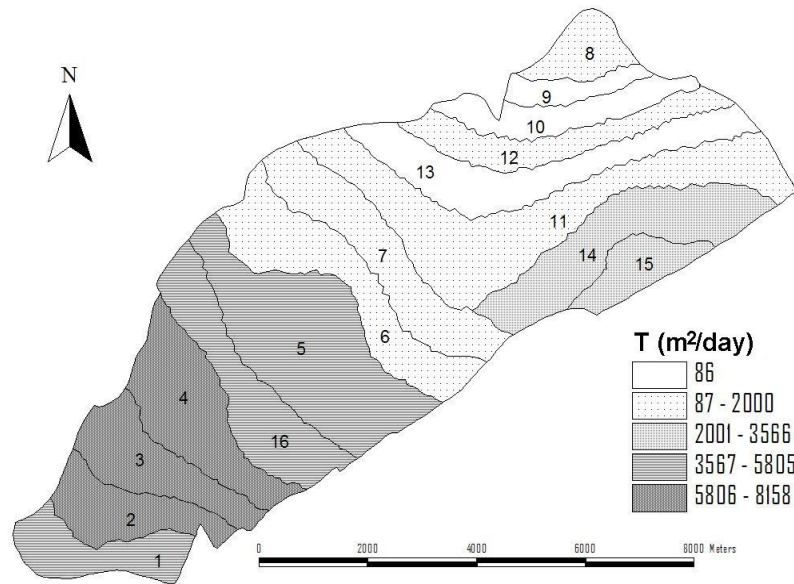
Figure 15 – Imposed potentials (thick black lines) along the known natural discharge areas and stream network (dotted blue lines).

### 4.2.4. Previously Calibrated Hydraulic Parameter: Transmissivity

Over the last two decades, hydraulic parameters were obtained for the 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 and Monteiro, 2008b).

In order to enhance the reliability of the simulation of AO's hydraulic behaviour, Martins (2007) performed a calibration of the physical parameters which control groundwater flow. The calibration of the transmissivity (T) parameter was performed by inverse modelling, using the Gaus-Marquadt-Levenberg method, implemented via the non-linear parameter estimation

software PEST. Individual values of transmissivity were defined for 16 zones which can be seen in Figure 16, where the behaviour registered by piezometers allows for a reasonable fit between field data and the model's results. The optimization of the results was based on numerous steady-state runs of the model, in which several variants of the model were tested to search for the best possible reproduction of the varying pattern of the hydrographs at the effluent reaches of the Bensafirim and Almádena streams (Martins, 2007; Martins and Monteiro, 2008a).



**Figure 16 – Spatial distribution of T values for each of the 16 predefined zones obtained using inverse calibration. From Martins (2007).**

The variant with the best fit showed a correlation coefficient, R, of 99.7% and a value of 4.56m for the sum of squared weighted residuals between model results and corresponding field data. The model's calibration results provided the first estimate of the regional transmissivity values distribution, which range from 86 m<sup>2</sup>/day to 8158 m<sup>2</sup>/day, allowing for a higher precision in future simulations of spatial distribution and temporal evolution of state variables (Martins, 2007).

It should be noted that this variant of the model at the time of the current thesis had not been validated for use under stress conditions such as ground water withdrawals in transient-state simulations.

### **4.3. Transient State Calibration: Storage Coefficient**

Martins and Monteiro (2008b) undertook an initial analysis of the values of the storage coefficient (S) which best represented the aquifer systems behaviour over time. However at the time, they reduced their analysis to a uniform value of S for the entire area of the aquifer system not taking into account the spatial heterogeneity of hydraulic properties. This procedure is common practice due to the complex and time consuming nature of the calibration process under transient conditions. They determined that 0.1 was the most adequate uniform value of S in reproducing the variations of hydraulic head over time (Martins and Monteiro, 2008b).

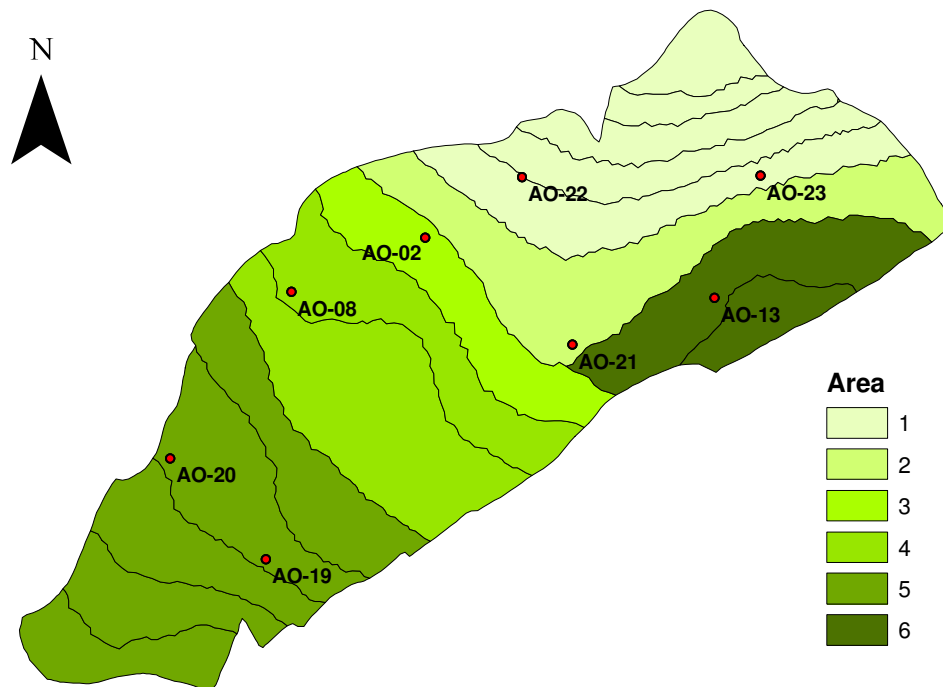
As part of the work undertaken for the current thesis, an attempt was made to refine the results obtained by these authors by obtaining a higher resolution of the spatial distribution of the storage coefficient (S). Even though physically possible values of S cover a much smaller span than those of the transmissivity parameter, the complexity of this process justifies by itself the time investment necessary to undertake the calibration of the parameter S. In fact, S can vary between values in the order of  $1 \times 10^{-5}$  to  $1 \times 10^{-3}$  for confined aquifers and  $1 \times 10^{-2}$  to much higher values (reaching close to values of total porosity) for unconfined aquifers. Considering the smaller span of possible values of S, a trial and error based method is likely to take less time to undertake than the use of inverse calibration techniques, however it must be kept in mind that this method brings with it certain limitations as will be discussed in chapter 4.5.

Unfortunately the data made available by the CCDRA is not detailed enough for a proper analysis of the storage coefficient due to its insufficient temporal resolution. The data supplied by the CCDRA is comprised of measurements taken once per month from each observation point; therefore it does not show the aquifers response to short term recharge events which can last merely a few days or even a few hours.

On the other hand, the data provided by the “Groundwater Flow Modelling and Optimization of Groundwater Monitoring Networks at the Regional Scale in Coastal Aquifers” research project (Malgar) is comprised of readings from 9 observation points taken every 2 hours from March 2007 to July 2007, the location of which can be seen in Figure 17. Although this is a relatively short period of time, it is sufficient to analyse the aquifer system’s response to several recharge events as well as emptying periods of the system.

#### 4.3.1. Calibration Process

The aquifer system was divided into zones based on the constant transmissivity zones proposed by Martins (2007), which are based on the character of the piezometric contours as there is little variation in the geology of the study area, and are shown in Figures 16-17. Due to the limited spatial distribution of data, and to reduce the amount of necessary iterations, these zones were subsequently grouped into areas according to the geographical location of observation points as can be seen in Figure 17.



**Figure 17 – Location of the selected observation points and proposed areas of constant storage coefficient.**

Once the different areas had been obtained, the storage coefficient values were estimated by trial and error method by varying the value of storage coefficient for each area between 0.01 and 0.15, with steps of 0.025 in search of the value that obtained the best fit between simulated and measured hydraulic heads at the chosen observation points for the time period under consideration. The simulations took into account recharge calculated from precipitation values March 2007 to July 2007, as explained in chapter 4.2.3.

It was found that the behaviour of the simulated hydraulic head was not significantly influenced by the changes in the values of storage coefficient in down-gradient areas. Therefore, to reduce

the amount of necessary iterations, the values of storage coefficient for the up-gradient areas were varied first, whilst keeping the values in the down-gradient areas static

#### 4.3.2. Calibration Results

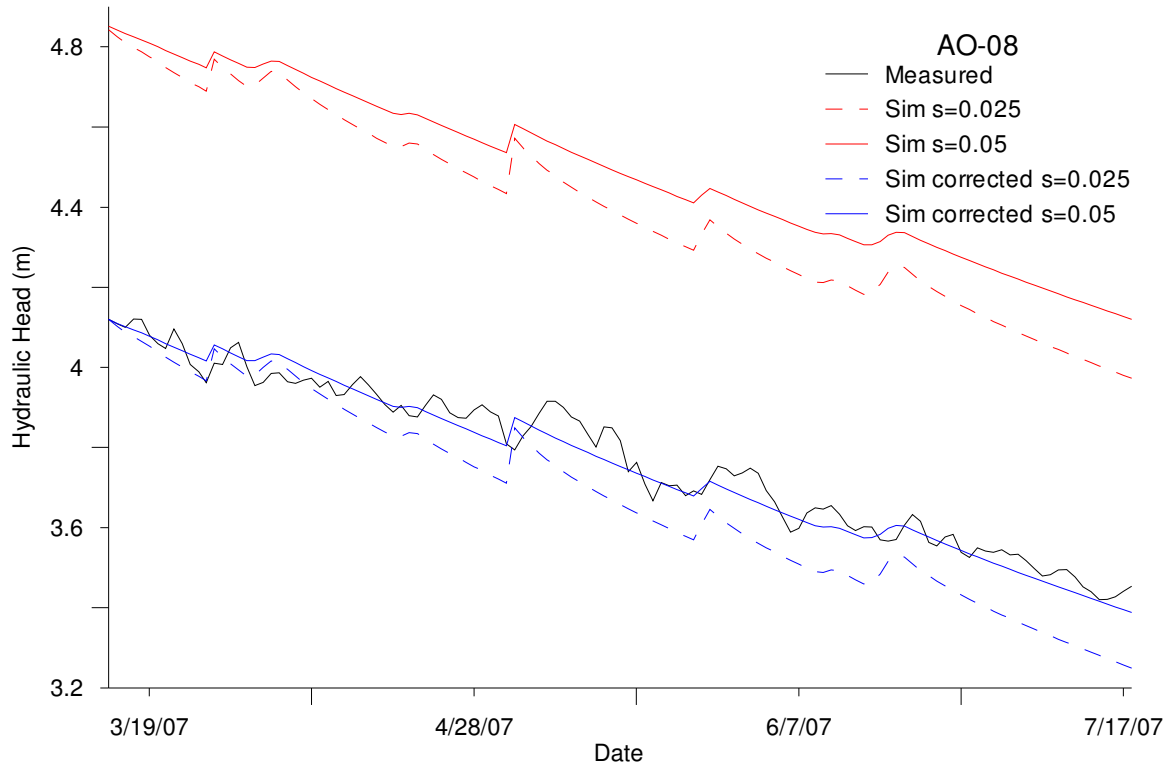
The results of each iteration were evaluated based on their root mean square error (RMSE) which is defined by the expression (Belitz et al., 1993):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (h_{meas} - h_{sim})^2}{n}} \quad (11)$$

In which  $h_{meas}$  is the hydraulic head registered at the observation points,  $h_{sim}$  is the hydraulic head simulate with the model and  $n$  is the number of measurements.

There is however a limitation to this method when evaluating how well a model simulates the transient behaviour of hydraulic head measured at a given piezometer. In some cases due to inaccuracies in the model, values of hydraulic head are systematically simulated with a certain offset to the measured values. An example of this can be seen in Figure 18 in which results from simulations at AO-08 with different values of  $S$  in the respective area are both “above” measured values. Considering that RMSE is essentially the average of the differences between simulated and measured values of hydraulic head, in these cases the value of RMSE would be a measure of which simulated values are “closer” to measured values and not necessarily the ones which better simulate the transient behaviour observed at the piezometer. In the example presented in Figure 18, simulations with an  $S$  of 0.025 resulted in the lowest values of RMSE compared to simulations with an  $S$  of 0.05; however if the plots were transposed so as to make the initial heads of the simulated and measured plots coincide, it was clear that the simulation with an  $S$  of 0.05 was a better representation of the transient behaviour of the observed hydraulic head.

It was therefore necessary to adjust the values obtained for simulated hydraulic head; this was done by subtracting the difference between the initial values of simulated and measured hydraulic head, from the simulated heads at each respective observation point. This effectively cancelled the previously mentioned offset, and guaranteed that the RMSE was an effective measurement of how well the simulations represented the transient behaviour observed at the piezometers.

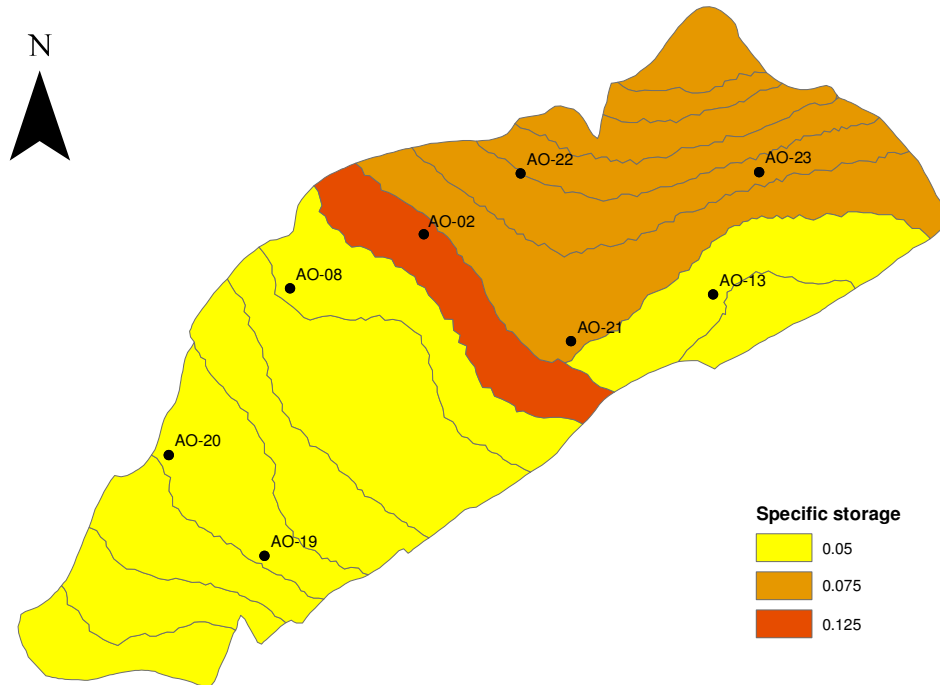


**Figure 18 – Comparison between corrected and non-corrected simulation results and their similarity to measured values for observation point AO-08.**

The spatial distribution of storage coefficient values which resulted in the lowest values of RMSE is shown in Figure 19. The values of RMS obtained for each observation point with this distribution are presented in Table 3. The values obtained for AO-19, 20, 22 and 23 are significantly higher than the rest.

**Table 3 – Values of RMSE for the best spatial distribution of storage coefficient.**

Observation Point	RMSE (corrected)
AO 02	0.042
AO 08	0.040
AO 13	0.030
AO 19	0.162
AO 20	0.186
AO 21	0.054
AO 22	0.133
AO 23	0.337
Total	0.984



**Figure 19 – Proposed spatial distribution of storage coefficient.**

The data measured at AO-20, 22 and 23 shows an overall rise in ground water levels over the entire sample of data, contrary to the trends seen at all the other observation points and suggested by the model. This could be due to various reasons: measurement errors, an inadequate conceptual model for this area of the aquifer or, considering the location of these observation points, the influence of recharge from the hills to the North which is not considered by the numerical model. It is clear that a better description of this area is needed for further refinements of the model; however the currently available data is insufficient to refine it much further.

#### **4.4. Model Validation**

None of the previously described versions of the AO numeric model have yet been tested for use under stress conditions such as pumping. In order to carry out the analysis proposed in this thesis it was necessary to verify the models' functionality under the aforementioned stress conditions, as well as its ability to accurately simulate hydraulic heads and flows at the natural discharge areas.



Unfortunately there is a discrepancy in the timeline of available data as can be seen in Table 4. Data on pumping rates is only available from 1989 up to 2003; and hydrometric and spring flow data is only available from 2004 until 2006. It was therefore necessary to analyse two separate periods (1) to verify both the models functionality under stress conditions and (2) its ability to simulate flows at the natural discharge areas under transient conditions.

A first variant was used, based on recharge values from January 1997 until December 2003 and pumping rates from the same period to test the models stability under stress conditions and the accuracy in simulating the temporal evolution of hydraulic heads.

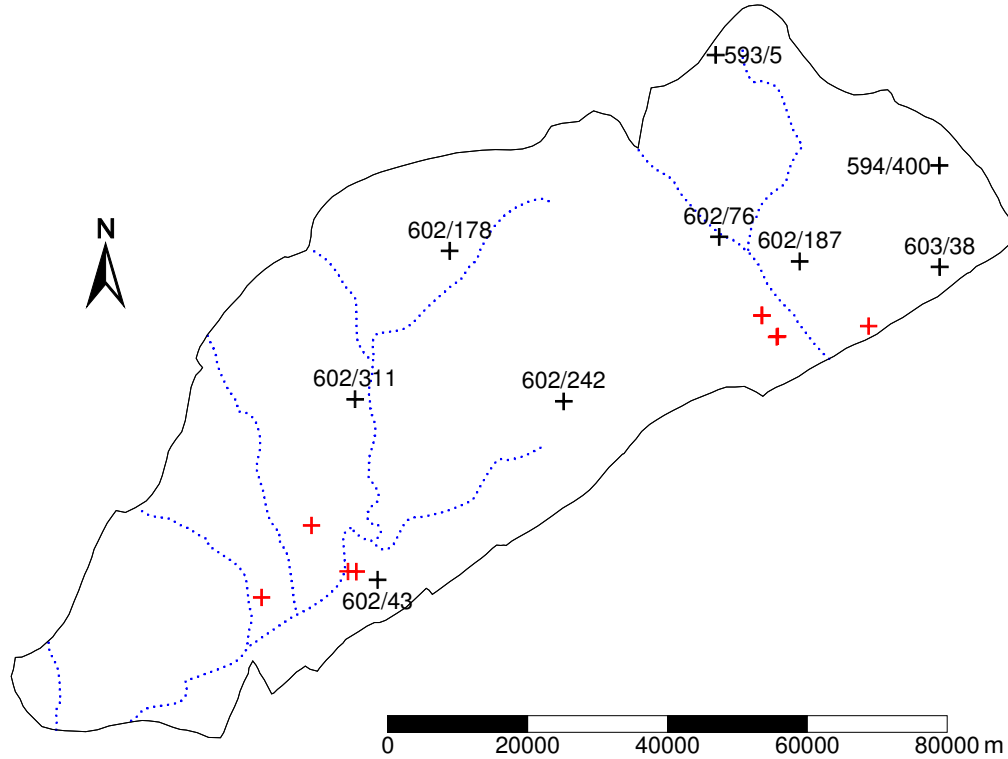
The second variant was based on recharge values from January 2005 until September 2006, in order to compare the models results to spring flows measured at the natural discharge areas.

**Table 4 – Temporal distribution of available data series relative to the AO.**

Precipitation								
Piezometric (Malgar)								
Piezometric (SNIRH)								
Pumped Volumes								
Hydrometric and Spring Flow								
	<1989	1989	1990-2002	2003	2004	2005	2006	2007

#### **4.4.1. Temporal Evolution of Hydraulic Heads**

The aquifers response was simulated from January 1997 until the end of December 2003. This period was chosen for various reasons: being the period for which the largest amount of piezometric data is available, during which extraction for public water supply was in effect; and due to it covering both a period of high ground water levels (1997) followed by a drought period (1998-1999), as can be observed in Figure 10 and Table 1. Water extraction for public water supply was simulated based on monthly values supplied by the Municipal Councils, previously described in chapter 2.3.3. The location of the observation points with data for this period as well as that of the extraction points in use can be seen in Figure 20.

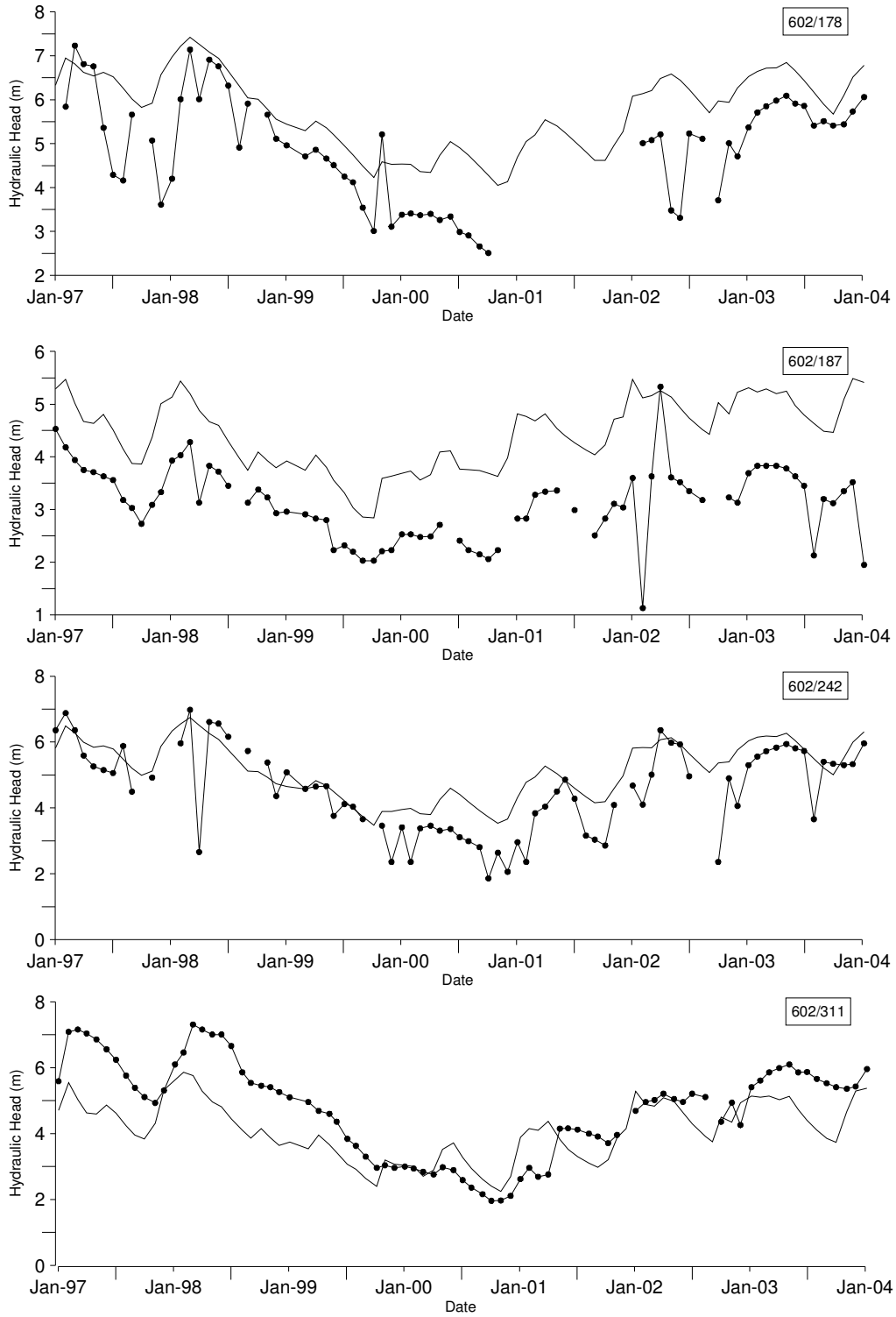


**Figure 20 – Location of piezometric observation points with data from January 1997 until December 2003 (black crosses) and boreholes for public water supply (red crosses).**

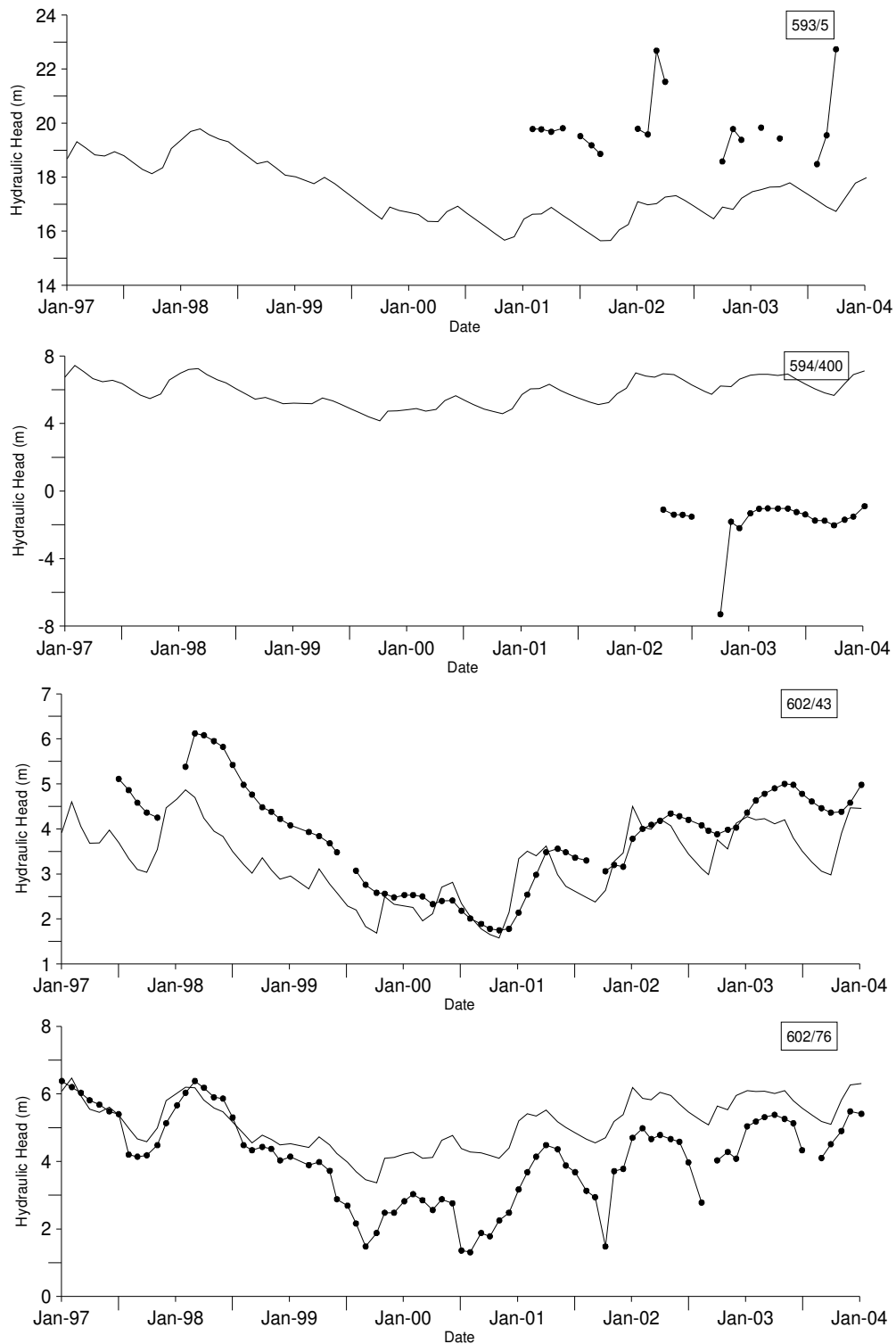
The plot of the measured and simulated values of hydraulic head for each observation point is shown in Figures 21-22, along with the respective values of RMSE in Table 5.

**Table 5 – Values of RMSE obtained for the simulated ground water levels between January 1997 and December 2003.**

Observation Point	RMSE
593/5	3.280
594/400	8.369
602/43	0.936
602/76	1.306
602/178	1.282
602/187	1.451
602/242	1.020
602/311	1.123
603/38	1.152



**Figure 21 - Measured (dotted line) and simulated (continuous line) hydraulic heads for the period between January 1997 and December 2003.**



**Figure 22 – Measured (dotted line) and simulated (continuous line) hydraulic heads for the period between January 1997 and December 2003.**

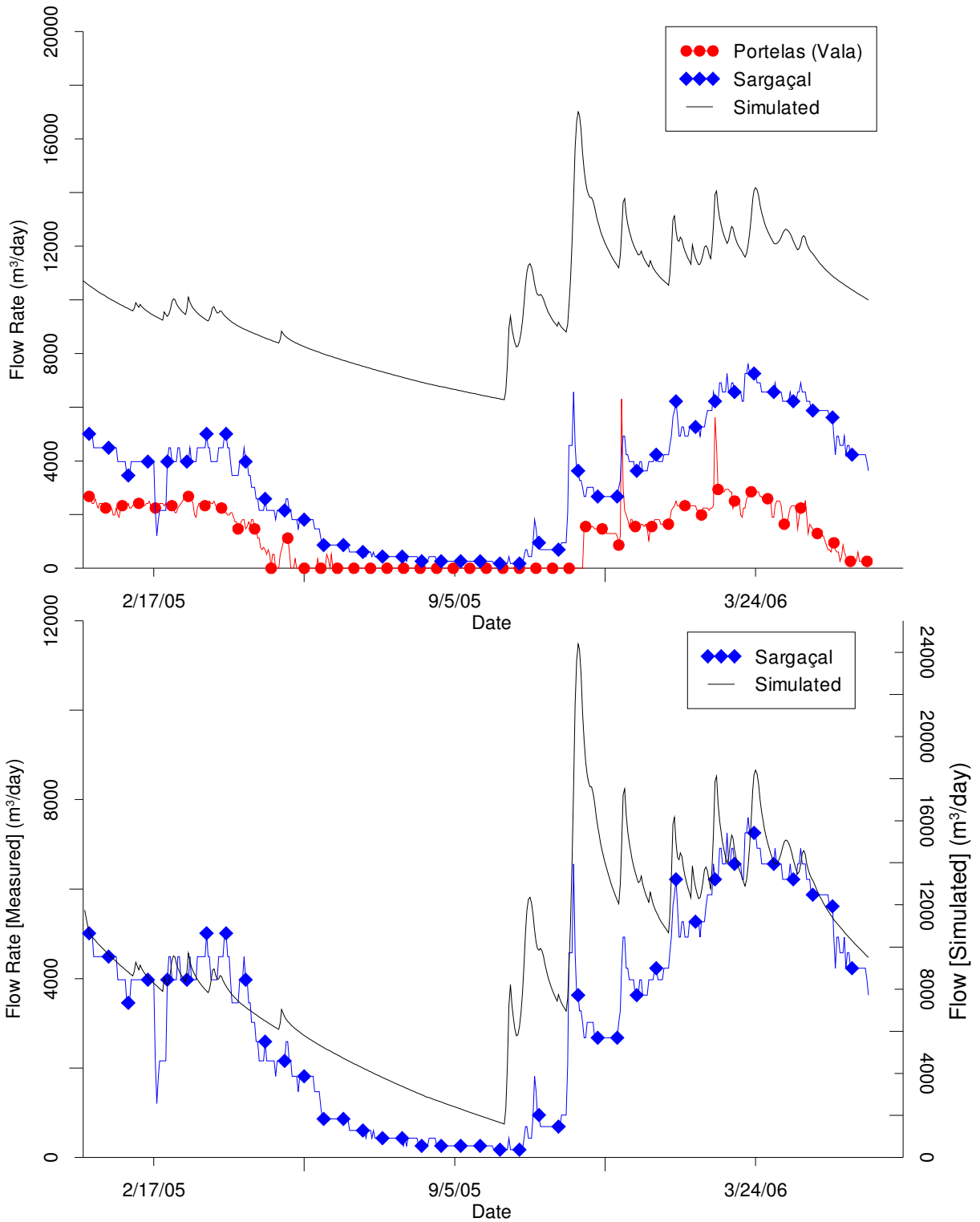
Overall the model simulates the ground water levels adequately. There is however a significant discrepancy in North-eastern area of the aquifer system. At the observation point 594/400 the model consistently overestimates the ground water level; however there are certain uncertainties about the validity of the data for this piezometer as was discussed in chapter 2.4.

#### **4.4.2. Natural Discharge**

Unfortunately there is no data on spring flow for the period of time between 1997 and 2003. In fact available data on spring discharge is limited to a period from January 2005 to September 2006, and only for certain springs' in the area of Portelas. A second simulation was run for this period in order to verify the models ability to replicate spring discharge.

As can be seen from Figure 23 the model simulates the behaviour of the springs relatively well, although the emptying rate is somewhat slower in the model than measured at the springs. The model shows significantly higher flow rates than those measured at the springs; this is likely due to the flow rates shown for the simulation being spread out over a much larger area than the two springs for which there are data. The lack of available spring discharge data and the difficulty in quantifying diffuse discharge in the area makes it difficult to accurately verify the numerical model ability to simulate the volumes of discharge.

As explained in a previous chapter, there is no available data on spring flow rates for the Boca do Rio discharge area making it impossible at this time to verify the validity of the model in simulating discharge at this area.



**Figure 23** – Flow rates measured at the two springs [Sargaçal and Portelas (vala)] and simulated discharge at the Portelas natural discharge area (top); measured flow rates at the Sargaçal spring and displaced plot of simulated discharge at Portelas (bottom).

#### 4.5. Remarks on Model Limitations

As well as the difficulties related to the modelling of ground water flow in karst aquifers discussed in a previous chapter, numerical flow models suffer from various other limitations. Despite the reasonable results obtained with the steady state and transient conditions, the use of this model as a management tool must be done taking into account the potential limitations inherent to such models.

A ground-water-flow model represents a complex, natural system with a set of mathematical equations that describe the system. Intrinsic to the model is the error and uncertainty associated with the approximations, assumptions, and simplifications that must be made. Hydrologic modelling errors typically are the consequence of a combination of (1) input data, (2) representation of the physical processes by the algorithms of the model, and (3) parameter estimation during the calibration procedure (Troutman, 1985).

(1) The number and distribution of piezometers monitoring the AO is limited. In particular piezometers with data with a sufficient temporal resolution to observe and analyse transient behaviour in the aquifer is severally limited. Added to which this data does not cover a period during which withdrawals for public supply were in effect.

There is a significant lack of data on both surface water crossing the AOs surface as well as limited data on the spring flows at the discharge areas (in the case of Boca do Rio there is currently no data). Although this data is perhaps not fundamental for the ground water flow model, it would certainly contribute to its validation and a better understanding of the AOs hydraulic properties and behaviour in particular at the local scale of the discharge area.

(2) A numerical model cannot represent completely, or "capture" all the physical processes of a watershed. Determining if a weakness in a simulation is attributable to input data error or model shortcomings is almost impossible, but the simplifying assumptions and generalizations that are incorporated into a model undoubtedly affect the results of the simulation.

(3) Errors in parameter estimates occur when improper values are chosen during the calibration process. Various combinations of parameter values can result in low residual error, yet improperly represent the actual system. An acceptable degree of agreement between simulated and measured values does not guarantee that the estimated model parameter values reasonably represent the actual parameter values. The use of nonlinear regression and associated statistics could remove some of the effects of non-uniqueness, but certainly would

not eliminate the problem entirely. Considering that the methods applied for the transient calibration of the AO model were trial and error based, it must be kept in mind that there could be significant error in the geographical distribution of the storage coefficient parameter.

The model used in this study can be refined, and the ground water flow system can be better represented as more data becomes available to constrain it.



## **5. Simulated Effects of Hypothetical Ground Water Withdrawals**

### **5.1. Hypothetical Scenarios**

The transient calibrated ground water flow model as described in previous chapters was used to evaluate the effects of hypothetical withdrawals from boreholes previously used as a source of public water supply on the regional flow system and on ground water discharge at the Portelas and Boca do Rio wetlands.

Recharge for these simulations was calculated based on the precipitation values for the period between September 2003 and September 2006. This period was chosen as it covers the drought year of 2005, as well as a prior and subsequent year of average rainfall.

As was previously described, head values are imposed on the nodes which correspond to the stream reaches at the natural discharge areas; this implies that the amount of water flowing between the stream and the aquifer depends on the heads in the nodes that surround the specified head boundary representing the stream. Considering the intermittent nature of these streams the existence of water flow is not constant, only occurring after rainfall. Therefore, for the purposes of these simulations, constraints (maximum and minimum flow rates) were imposed on the specified-head boundaries to avoid the streams becoming a source of recharge for the aquifer at these locations.

Constant pumping rates were imposed on nodes corresponding to the location of the main boreholes used for public supply for the entire period of the simulation, even though this is not representative of observed seasonal variations in pumping rates. Scenarios were simulated by varying the pumping rate on these boreholes for each scenario. The pumping rates were varied between 0% and 100% with steps of 10% of the maximum yield of each borehole. An additional scenario with pumping rates of 35% of the maximum yield was added later, so as to have a better distribution of results when the natural discharge at Portelas reached zero. It should be noted that pumping rates of 100% of the maximum yield are not very realistic over the long term, and in fact the model simulated drawdown's around several boreholes which resulted in water depths lower than the depth of the pumps. Constraints could also be have been defined here (in terms of maximum/minimum drawdown), however they were not applied at this time. Future variants of the model should take this into consideration.

The values of maximum yield were obtained from various sources, namely technical reports elaborated at the time of the boreholes construction which were collected by Paradelo (1959) and values supplied by OPTEXPLOR.

**Table 6 – Hypothetical ground water withdrawal scenarios and their respective pumping rates based on percentages of the maximum yield for each borehole; \*Almádena well-field; \*\*Portelas well-field.**

	<b>Sim 1</b>	<b>Sim 2</b>	<b>Sim 3</b>	<b>Sim 4</b>	<b>Sim 5</b>	<b>Sim 6</b>	<b>Sim 7</b>	<b>Sim 8</b>	<b>Sim 9</b>	<b>Sim 10</b>	<b>Sim 11</b>
	10%	20%	30%	35%	40%	50%	60%	70%	80%	90%	100%
<b>Borehole</b>	<b>Pumping Rate (m<sup>3</sup>/day)</b>										
FD3*	216	432	648	756	864	1080	1296	1512	1728	1944	2160
JK8*	518	1037	1555	1814	2074	2592	3110	3629	4147	4666	5184
LF0*	104	207	311	363	415	518	622	726	829	933	1037
LF11*	259	518	778	907	1037	1296	1555	1814	2074	2333	2592
LF1**	605	1210	1814	2117	2419	3024	3629	4234	4838	5443	6048
LF2**	432	864	1296	1512	1728	2160	2592	3024	3456	3888	4320
LF5**	207	415	622	716	829	1037	1244	1452	1659	1866	2074
LF6**	821	1642	2462	2873	3283	4104	4925	5746	6566	7387	8208
LF8**	864	1728	2592	3024	3456	4320	5184	6048	6912	7776	8640
<b>TOTAL</b>	<b>4026</b>	<b>8053</b>	<b>12079</b>	<b>14092</b>	<b>16105</b>	<b>20131</b>	<b>24157</b>	<b>28184</b>	<b>32210</b>	<b>36236</b>	<b>40262</b>

Additionally two more scenarios were simulated, one with no pumping which corresponds to the natural state of the AO (Sim 0) and one based on the historically highest daily pumping rate measured at each borehole during the period of 1989 until 2003 (Sim 12) the values of which are presented in Table 5.

**Table 7 – Pumping rates based on historical data for hypothetical ground water withdrawal Scenario 12.**

<b>Borehole</b>	<b>Scenario 12 (m<sup>3</sup>/day)</b>	<b>% of Maximum Yield</b>
FD3- Almádena	1108.4	51%
JK8- Almádena	4455.7	86%
LF11- Almádena	721.5	28%
LF1- Portelas	2944.6	49%
LF2- Portelas	2786.4	65%
LF5- Portelas	1645.4	79%
LF6- Portelas	2081.3	25%
LF8- Portelas	2294.4	27%
LF0- Almádena	1036.8	100%
<b>TOTAL</b>	<b>32918.4</b>	

## 5.2. Results

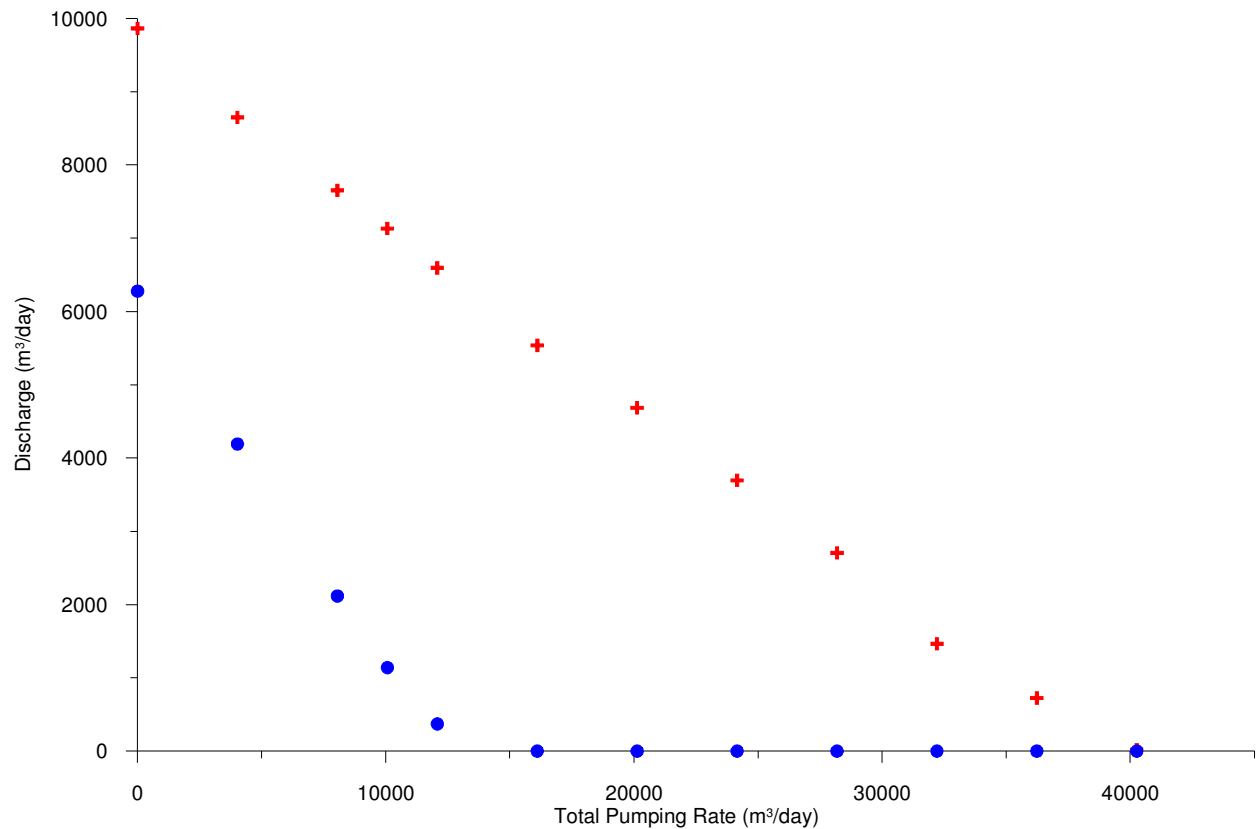
The results from the various scenarios were compared based on the lowest simulated outflow rate at both discharge areas for the period of the simulation, which are presented in Table 8 and Figure 24. The discharge at Portelas is the most rapidly affected, having reached values close to zero with pumping rates of 35% of the maximum yield, whilst the discharge at Boca do Rio only reaches zero at maximum yield pumping rates. This is to be expected, as the well field in this area (LF1 to LF8) has significantly higher values of maximum yield (approximately 3x higher) than the values of maximum yield of the well field at Almádena which is closer to the Boca do Rio discharge area.

Scenario 12 (Sim 12), which measured ground water abstraction based on the highest historical pumping rates also caused flow from the discharge area at Portelas to cease. When considering this result it is important to keep in mind that the applied pumping regime is not realistic as it does not take into account seasonal variation and assumes all pumps to be working at all times. However, at their peak, values of annual volume of abstracted ground water (previously presented in Table 1) were at an average rate between 30% (2000) and 36% (1999) of the maximum yield. Taking into account that these are average values and seasonal variation of pumping rates it is safe to assume that pumping rates during the driest seasons would be even higher. Considering the growing demand for water in the last few years, it is possible that had public water supply continued to be dependent on ground water it is likely that discharge at Portelas would have ceased during the drought of 2005. This corroborates information provided by inhabitants of the area who describe the local springs as drying up during summers in which pumping occurred.

**Table 8 – Lowest registered flow rates at the natural discharge areas for hypothetical ground water withdrawal scenarios.**

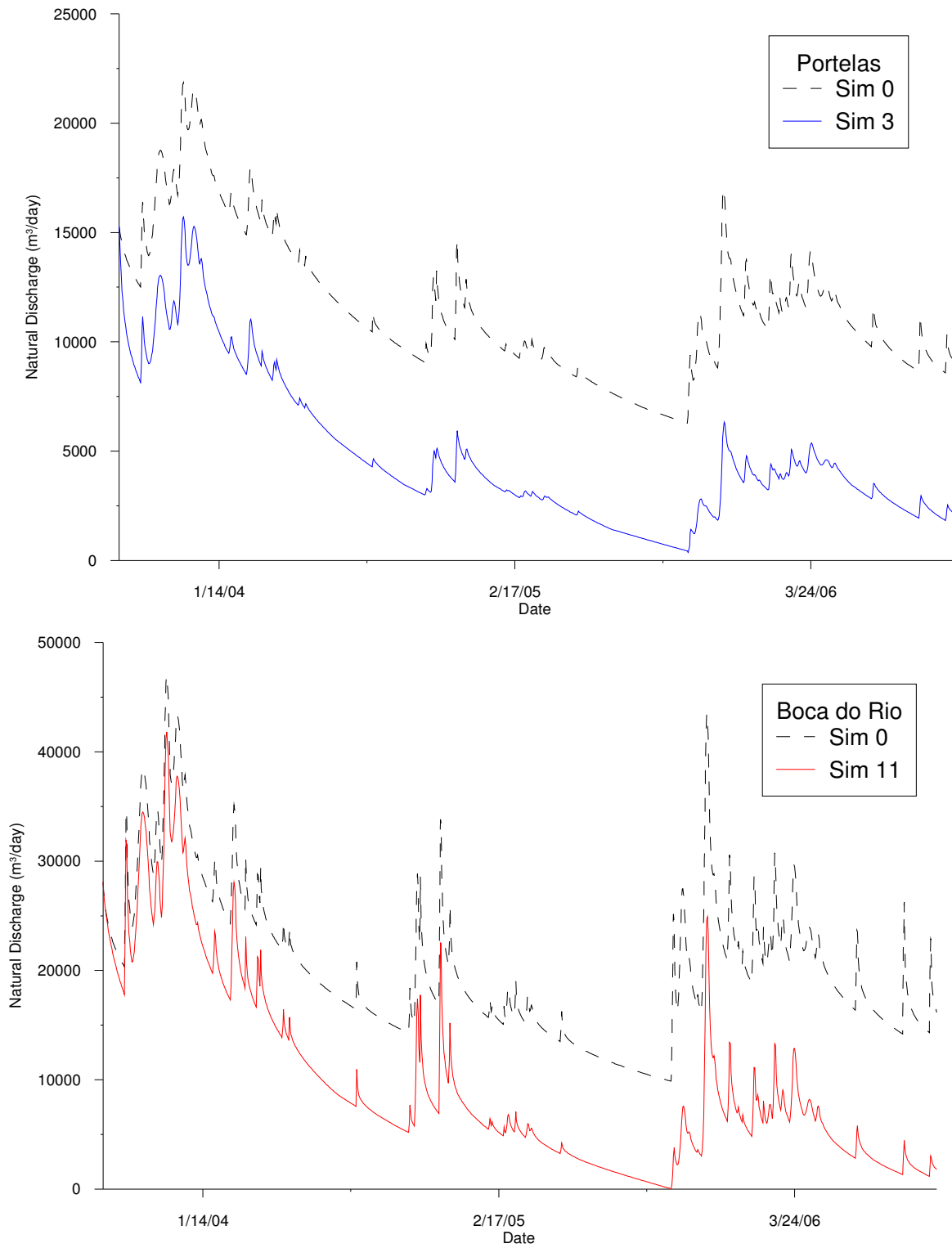
Scenario	Total Pumping Rates (m <sup>3</sup> /day)	Discharge	
		Boca do Rio (m <sup>3</sup> /day)	Portelas (m <sup>3</sup> /day)
Sim 0	-	9.86E+03	6.28E+03
Sim 1	4.03E+03	8.65E+03	4.19E+03
Sim 2	8.05E+03	7.65E+03	2.12E+03
Sim 3	1.21E+04	6.59E+03	3.71E+02
Sim 4	1.41E+04	6.18E+03	0.00E+00
Sim 5	1.61E+04	5.54E+03	0.00E+00
Sim 6	2.01E+04	4.69E+03	0.00E+00
Sim 7	2.42E+04	3.70E+03	0.00E+00
Sim 8	2.82E+04	2.71E+03	0.00E+00
Sim 9	3.22E+04	1.47E+03	0.00E+00
Sim 10	3.62E+04	7.25E+02	0.00E+00
Sim 11	4.03E+04	2.06E+01	0.00E+00
Sim 12	3.29E+04	3.79E+03	0.00E+00

An almost linear relationship can be clearly observed between the rise in pumping and decrease in discharge rates as shown in Figure 24. Should future research be carried out which quantifies the minimum discharge required for the sustainability of the ground water dependant ecosystems associated to the AO aquifer system, this linear relationship should make it relatively simple to couple a ground water flow model with ecological model of the wetlands in order to estimate a safe pumping rate from the AO.



**Figure 24 – Plot of discharge rates at the two natural discharge areas (blue crosses for Portelas and red crosses for Boca do Rio) versus total pumping rate.**

As can be seen in the simulated discharge hydrographs presented in Figure 25, discharge is immediately influenced by pumping, in particular at Portelas. The effects on the Boca do Rio area are more gradual and to some extent less pronounced, likely due to both to being physically farther away from the closest well field at Almádena and this well field having a significantly smaller abstraction capacity than the Portelas well field.



**Figure 25** – Examples of simulated discharge at the natural discharge areas (Portelas top and Boca do Rio bottom); discharge under natural (SIM0, black dotted lines) and under pumping conditions (SIM3 and 11, blue and red continuous lines respectively).

## Final Remarks

Prior to the work presented in this thesis, the various hydrostratigraphic units of the AO had been defined and the spatial distribution of the transmissivity parameter had been determined via inverse calibration techniques, allowing for accurate simulations under steady-state conditions.

The work presented in this thesis represents the next step in the evolution of the AO numerical model. In order to carry out transient simulations which consider the variation in recharge and water withdrawals over time, a second calibration was carried out to determine the spatial distribution of the storage coefficient. This was done by trial and error methods, as the relatively small span of physically possible values of storage coefficient was not considered sufficient to justify the time and effort required to implement inverse calibration methods under transient conditions.

The models calibration results provided the first estimate on the regional distribution of storage coefficient values, which range from 0.05 to 0.125 over 5 zones based on the hydrostratigraphic units, resulting in a greater reliability of the spatial and temporal evolution of state variables for simulations.

The models stability and ability to accurately simulate groundwater flow in the AO in transient state and under stress conditions (such as pumping) was put to test so as to validate the model to be used in simulating hypothetical scenarios. The results were quite satisfactory both from the simulation of hydraulic heads, as well as the behaviour of groundwater discharge at the natural discharge areas which accurately depicts the variations in spring flows measured at the natural discharge areas.

The validation of the models ability to accurately simulate the behaviour of groundwater flow under transient conditions allowed the simulation of several hypothetical scenarios of abstractions for public water supply. These simulations were based on precipitation values for 3 years which cover a drought period. Abstraction regimes were chosen based on the maximum yield of boreholes historically used as sources for public water supply.

Results from the hypothetical scenario simulations showed that abstractions from these boreholes significantly impact the flow at the natural discharge areas. In particular at Portelas, likely due to the close proximity and high yield of the closest well-field, the increase in abstractions rapidly reduces the natural discharge in this area. These simulations suggest that if

the well-fields reach 35% of their maximum capacity, discharge at Portelas would effectively cease during dry years, however for the discharge area at Boca do Rio to reach these conditions all boreholes would have to be extracting at their maximum capacity. They also demonstrated that the analysis and management of these resources must be done taking into account the large seasonal variability of the region, as variations in the amount and temporal distribution of rainfall will significantly affect the availability of groundwater.

These simulations did not allow for a quantitative analysis of the impact of water abstraction. To do so, a detailed analysis is required of the importance of the groundwater component of the flow in the streams and wetlands as well as the effects of its variations on the groundwater dependent ecosystems associated to the AO.

Future research could attempt to couple surface water and ecological models to this groundwater model in order to better understand the relationships which exist between them, as well as properly quantify the impacts of their use. Additionally, optimization techniques can be applied to determine the abstraction regimes likely to result in the least negative impacts.

It is hoped that the present work will contribute to demonstrating the usefulness of such models as tools for a more efficient management of groundwater resources, as well as contribute to the development of a future potential model-based regional management of the AOs water reserves.



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