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DAMS GROUNDWATER MODELLING AND WATER MANAGEMENT AT THE REGIONAL SCALE IN A COASTAL MEDITERRANEAN AREA (THE SOUTHERN PORTUGAL REGION – ALGARVE)

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I. INTRODUCTION

Actual water demand in the Southern Portuguese coastal area (Algarve ≈ 5400km^2) is in the order of 250×10^{6}m^3/year, distributed by agriculture (72%), gardening (8%) and public supply (20%). This value rose dramatically in the last 30 years, mainly due the increase of irrigated area (about 200 km^2) and tourism (about 10×10^6 visitors per year with an average sojourn of about 10 days).

Until very recently water use in the Algarve region was almost entirely supported by groundwater wells. However, the policy defined by the Portuguese central administration consists actually in the development of public water supply schemes entirely based in the use of dam waters. The efforts to abandon groundwater as a source for public supply started in 1999, after a large investment in infrastructures related with the exploitation of the Bravura, Funcho, Odeleite, Beliche dams (and the Odelouca dam, which is not yet in operation). However the practical implementation of the water supply scheme showed from the start that the complete abandon of the water wells is very difficult due to quantitative, qualitative and practical problems related with the management of surface waters.

The mentioned policy defined by the central Portuguese administration, regarding water management in this region allows us to define three periods: (1) a period when water use was almost entirely supported by groundwater (past); (2) a period characterised by large investments, settled with the aim to substitute groundwater by dam waters in the public supply of the region (present) and (3) a period where the prevailing hydrological conditions will force the administration to define an integrated policy for water resources management based in the conjunctive use of groundwater and surface water (future).
The actual knowledge about the hydrogeology of the Algarve region allows the identification of 17 aquifer systems at the regional scale ALMEIDA et al. (2000). The carbonate rocks (mainly Jurassic and Miocene in age) are the support of the most important aquifers, both by its extension and by the volume of water stored. After a general Hydrological setting of the studied area, some simulations performed with finite element models, implemented for 6 of these regional aquifers, will constitute the basis for discussing the possible role of this kind of methodology in the future of the water management in the Algarve Region.

KEY WORDS: conjunctive use, integrated water management, finite element models, Portugal – Algarve

II. GENERAL OVERVIEW OF CHANGES IN WATER USE DURING THE SECOND HALF OF XX CENTURY

Until the first half of the XX century water use in the Algarve region was entirely supported by groundwater wells. The Bravura and Arade dams, build in the decade of 50, were the first man made structures supporting the use of surface waters with expression at the regional scale. Water use in these dams, settled in the occidental area of the region, was initially related with their perimeters of irrigation in the western area of the Algarve with an area of 1747 ha and 2300 ha, respectively. The location and some characteristics of the large dams in the Algarve are shown in Figure 1 and listed in Table 1.

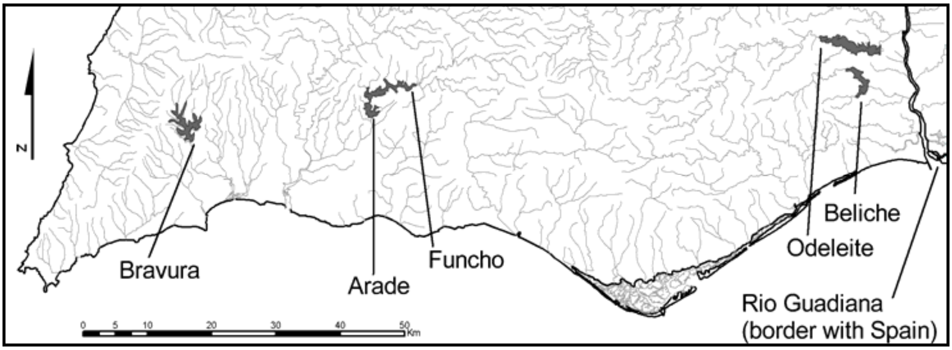

Fig. 1 : Large dams in the Algarve region.

At the time of the constructions of the Arade and Bravura dams, groundwater exploitation were based in the use of hand-dug wells with large diameter with a maximum depth usually inferior to 30 meters. At the start of the decade of 60, the introduction of drilling technology allowed the support of the explosive increase in water demand with basis in the construction of thousands of drilled boreholes in the region. These boreholes, often with more than 200m, where implanted without the support of regional planning that could be defined with basis in the existing knowledge regarding the hydrogeology of the region. Until the second half of the decade of 90 the supply of urban areas was locally and independently dimensioned by each of the 16 municipalities in Algarve, using a small part of these boreholes.

Despite the efforts of the local office of the National Environment and Planning Agency (Direcção Regional do Ambiente e Ordenamento do Território-DRAOT) the inventory of the existing boreholes still far from being exhaustive. The database actually available contains information related with more than 4000 mapped boreholes (see Figure 2).

Table. 1 : Some characteristics of the large dams in the Algarve region.

Dam	Year	Height (m)	Watershed (km^2)	Type	Max. Storage ($10^6 m^3$)
Arade	1956	46	224	embankment	27
Bravura	1958	41	75	concrete	32
Beliche	1986	54	99	embankment	48
Funcho	1993	49	211	concrete	43
Odeleite	1996	65	352	embankment	117

The intensive augmentation of groundwater use during this period was certainly one of the reasons contributing for the large number of scientific works related with the characterisation of groundwater resources in the Algarve Region. However, due to the lack of technical capacity of the municipalities, which were entirely responsible by the management of water supply during this period (from the wells to the taps), the existence of these studies was not in the origin of visible improvements in the efficiency of the regional water management.

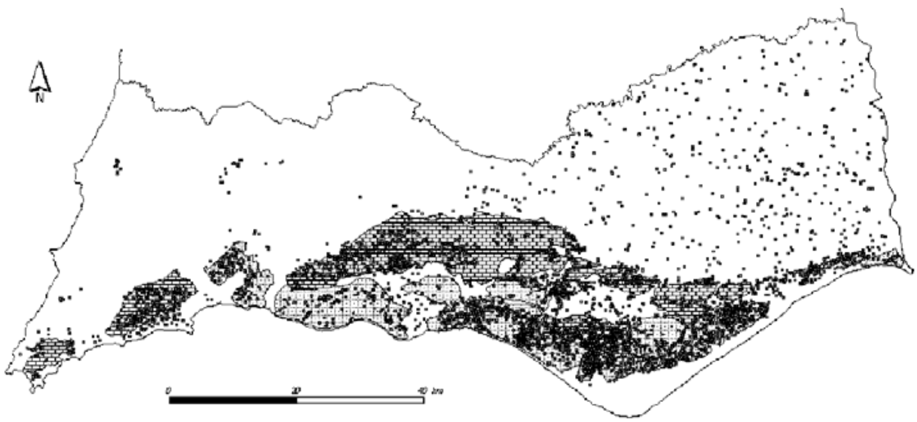

Fig. 2 : Location of dug wells and boreholes in the Algarve region and geometry of the 17 aquifer systems with regional expression in the Algarve (adapted from the DRAOT database).

The lack of regional planning, making the connection between the local solutions (defined by each city council) and the regional hydrogeologic potential and vulnerabilities, was in the origin of quantitative and qualitative problems. These problems were detected locally, in research projects or in the regular quality control of water supply. Research pursued in relation with the identification of the origin of quality problems showed that agriculture in irrigated areas (STIGTER et al., 1998) and displacement of the fresh water-salt water interface in some sectors of the coastal aquifers (CARREIRA, 1991) are the main origins of degradation of groundwater quality.
These situations, together with the continuous increase in water demand, conduced to the actual water policy defined by the Portuguese central administration, which is based in the development of public water supply schemes entirely based in the use of dam waters. The efforts to abandon groundwater as a source for public supply started in 1999, after a large investment in infrastructures related with the exploitation of the Funcho, Odeleite, Beliche dams, additionally to the previous investments related with

the Bravura and Arade dams already mentioned (and the Odelouca dam, which is not yet in operation).

In practice, and in addition to the support of the new scheme defined for the urban supply, the Beliche and Odeleite dams (Table 1) allowed the creation of a new perimeter of irrigation in the Eastern area of the Algarve with 8100 ha in the decade of 90. This new perimeter of irrigation, together with the aforementioned area irrigated by the Bravura and Arade dams, allowed a total of about 121km^2 being irrigated with surface waters. Taking into account the actual irrigated area in the region (about 200 km^2 (INE, 2001)), it is estimated that the total area irrigated by groundwater is about 79 km^2. The amount of water used for irrigation for agricultural land in the climatic conditions prevailing in the region is about 900mm·yr^{-1}. Therefore, a calculation of the water volume used for irrigation, based in these numbers, allows a rough estimation of 180×10^6 m^3 (60% based in the use of dams and 40% based in groundwater).

At a first glance, the immediate benefits associated with the construction of the Algarve dams seem evident. By the environmental point of view it was often claimed that the diminution of the exploitation of the coastal aquifers, associated with the abandon of many boreholes used for public supply in urban areas, would lead to the attenuation of the effects of saltwater intrusion. However, as water use for urban supply constitutes only 20% of the total water use, this is not necessarily true, because the effects of these phenomena is strictly conditioned by the pumping schedules at the scale of the aquifer sectors where boreholes were in use. On the other hand, there are real improvements in the current water management related with the use of dam waters for public supply. By the administrative point of view, the substitution of the water wells directly managed by the municipalities (without adequate technical structures to accomplish that task) by dam waters, managed by a multi-municipal company, brought evident benefits to the quality of water supply in the last years. In fact, for example, the control of water quality is, by far, easiest in few dams than in a large number of wells.

Dam waters are also treated by quality problems. Therefore, it is evident that the dependency of a single source of supply is more vulnerable than an integrated management scheme allowing the switch to one source to another when needed. For example, studies related with the actual microbiological quality control of dam waters showed that the lack of standardization on the methods used for the detection cyanobacteria in Portuguese dams is responsible by deficient control of situations potentially dangerous for public wealth. The occurrence of toxic cyanobacteria blooms are eventually reported by the occurrence of large amount of algae at the surface of pounds, associated with severe environmental impacts revealed by the death of a large number of fishes (MARGARIDO, 2001). The conclusions of this study showed that most water treatment plants haven't

included on their treatment lines suitable processes for the removal of cyanotoxins present in water due to these blooms. On the other hand, operational problems were detected in the plants where these processes have been installed. Therefore the effectiveness of these removal processes is low.
Other factors contributing for the predictable benefits associated with the definition of public supply schemes, based in conjunctive use, are reported in research works, related with the optimisation of technologies in treatment plants, used to produce drinkable water from the water exploited in dams. CAMPINAS et al. (2002) showed that the mixture of different proportions of groundwater originated in the Querença-Silves aquifer system (a Lias-Dogger karstic system, which constitutes the major water reserve in the Algarve Region), with water obtained from the Funcho dam, contributes for the improvement of the water quality obtained at the water treatment plant of Alcantarilha with a capacity of 253000m^3 /day.

III. A BI-DIMENSIONAL NUMERICAL REPRESENTATION OF THE ALGARVE AQUIFER SYSTEMS

The aspects discussed in the last sections show that there are evident benefits in the incorporation of the actual knowledge about groundwater resources in the scheme of regional water management. The use of numerical flow models can play a central role in the resolution of technical problems related with groundwater management and, additionally, in the establishment of platforms of compatibility and communication with hydrological specific tools used for the management of surface waters.
The actual knowledge available for the Almádena-Odeáxere, Querença-Silves, Ferragudo-Albufeira, Albufeira-Ribeira de Quarteira, Quarteira and Luz de Tavira aquifer systems regarding: (1) geometry; (2) boundary conditions; (3) recharge and discharge rates; (4) spatial distribution and temporal evolution of state variables and (5) hydraulic parameters, was applied for the implementation of finite element flow models. The methodology applied for the incorporation of the available data in these models is based in the use of a platform of compatibility between the model and a geographical information system, developed with the aim to perform automatic pre and post-processing modelling tasks (MONTEIRO et al., 2002a). A short description of some of these models and two examples of their possible role in the framework of the regional water management are presented in the next sections.

III.1 Short description of the used modelling techniques

The differential 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 and transport phenomena in flow domains with complex geometry. The physical principles simulated by the presented models are described by a differential equation, describing groundwater flow of constant density through saturated porous media, in the form (DE MARSILY,1986):

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

Where T (transmissivity) is the bi-dimensional conductive parameter [L^2T^{-1}], h is hydraulic head [L], Q (source term) is a volumetric flux per unit volume [$L^3T^{-1}L^{-3}$], divergence (*div*) is an operation performed in a vector that produces a scalar quantity and the gradient operator (*grad*) performed on a scalar produces a vector. Using this equation the overall water balance equals zero. Therefore, the hydraulic behaviour of the flow domain is simulated in a steady state, representing the long-term water balance.

III.2 Retrospective of conceptual models and implemented numerical models

The first hydrogeological characterisation of the Algarve at the regional scale was presented in Trac (1981). A division of the region in 10 aquifer systems was proposed in this work, according to the analysis of the geological units of the region. One Paleozoic hydrogeologic unit constituted by metamorphic rocks occupying an area of about 3700km^2 in the northern area of the region, and 9 aquifer systems corresponding mainly to Jurassic, Miocene and more recent formations, occupying 1700 km^2 in the coastal strip. A detailed water balance is presented in this work, considering the separate estimation of the surface and groundwater components. The average annual precipitation calculated for the period 1941/42-1973/74 is of 653mm. For the same period average temperatures are between 15ºC and 17ºC. According to the available climatic data sets, the calculated mass balance pointed to a range between 170×10^6m^3.yr^{-1} and 340×10^6 m^3.yr^{-1} for annual average recharge, entering the aquifers present in the 1700km^2 Mesocenozoic coastal strip. The large uncertainty revealed by these numbers is related with the assumed lack of knowledge regarding the volume of transferences between the stream network and the regional aquifer systems.

The numerical models presented in this paper are based in conceptual flow models proposed in several scientific contributions produced in the last two decades. The actual state of development of the Algarve hydrogeology allows the definition of 17 aquifer systems with regional importance, occupying 1074 km^2 of the total $1700km^2$ Mesocenozoic strip in the coastal area. The definition of these 17 aquifer systems was proposed by ALMEIDA et al. (2000). The sum of the recharge values, estimated separately for each of these aquifers is between 169×10^6 $m^3.yr^{-1}$ and 215×10^6 $m^3.yr^{-1}$. The large amount of productive water wells outside the limits of these aquifer systems (Figure 2) shows that the area without a "well established hydrogeologic identity" is certainly important to obtain a more accurate value for the total groundwater flow.
Figure 3 shows the finite element meshes generated for the Querença-Silves, Ferragudo-Albufeira, Albufeira-Ribeira de Quarteira and Quarteira aquifer systems. Figure 4 is self explanatory and shows a simulation performed with these models. Boundary conditions correspond to hydraulic heads imposed where the coast line constitutes the regional discharge area of the aquifers, in rivers hydraulically connected with aquifers and in springs draining some sectors of the Querença-Silves system.

III.3 Examples of possible contributions of models to support water management

The actual state of development of the implemented numerical flow models allows the analysis of coherence between the established conceptual flow models and the "observed" regional flow patterns. This is accomplished by the analysis of available data regarding the spatial distribution and temporal evolution of state variables, together with the regional water balance established by each aquifer system. The analysis of the simulations shows that the available conceptual flow models supporting the numerical models are detailed enough to obtain a consistent representation of the general flow patterns at the regional scale. Therefore, even in their actual preliminary form, these finite element models can be useful in terms of the analysis of problems related with water management as shown in the next two examples.
The first example consists in a contribution for the refinement of the water balance estimated for the 17 Algarve aquifers identified in ALMEIDA et al. (2000). These authors presented an individual water balance for each aquifers system, calculated by taking into account the fractions of infiltration of precipitation (defined in function of the outcrops of different lithologies). These values can be as low as 10% of the precipitation (for some quaternary deposits) and as high as 50% (for some outcrops of carbonate rocks). The maps of spatial distribution of precipitation, needed to make the recharge calculations by this method, were obtained by classical methods with low spatial resolution (as the

isohyetal and Thiessen methods). However, Actually there are much more detailed precipitation maps, obtained by robust geostatistic methods, using auxiliary variables as altitude that is known to have a strong effect in the spatially distribution of precipitation. The models available for the Algarve where therefore applied to recalculate water balance for some of the Algarve aquifers. A precipitation map with a resolution of 1000m×1000m, for discrete values of precipitation recently presented by NICOLAU (2002) was used according to a methodology proposed by VIEIRA and MONTEIRO (2003), to recalculate recharge values. As the spatial distribution of precipitation and the definition of infiltration classes are easily simulated with this kind of models, the augmentation in accuracy, allowed by the new precipitation data sets, can be readily incorporated in order to increase the accuracy of recharge estimates. For each of the aquifer systems where this methodology was applied, the new calculated values for annual recharge differ from 8% to 33% of the pre-existent values proposed in the literature (see Table 2).

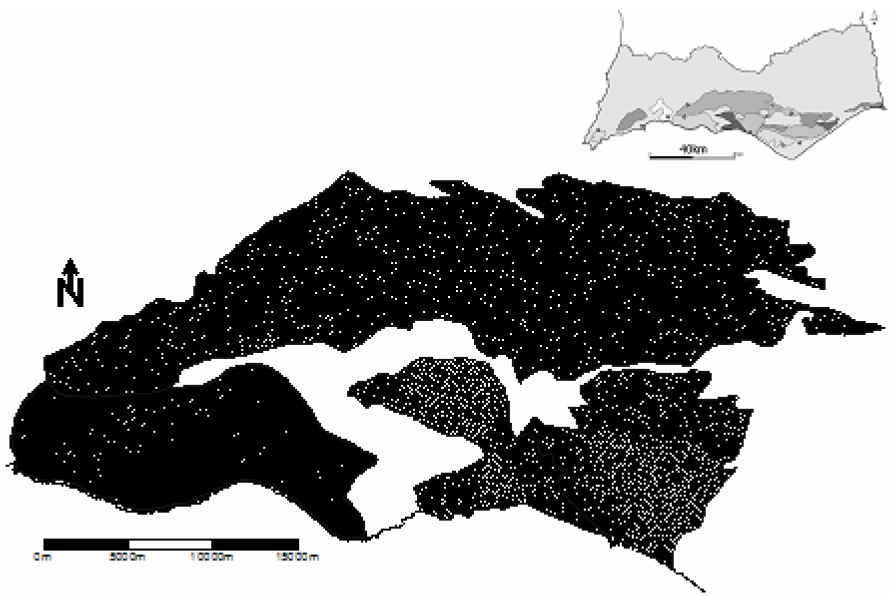

Fig. 3 : Finite element meshes built for the of Querença-Silves, Ferragudo-Albufeira, Albufeira-Ribeira de Quarteira and Quarteira aquifer systems. The position of these aquifers is showed in the map above, adapted from ALMEIDA et al. (2000).

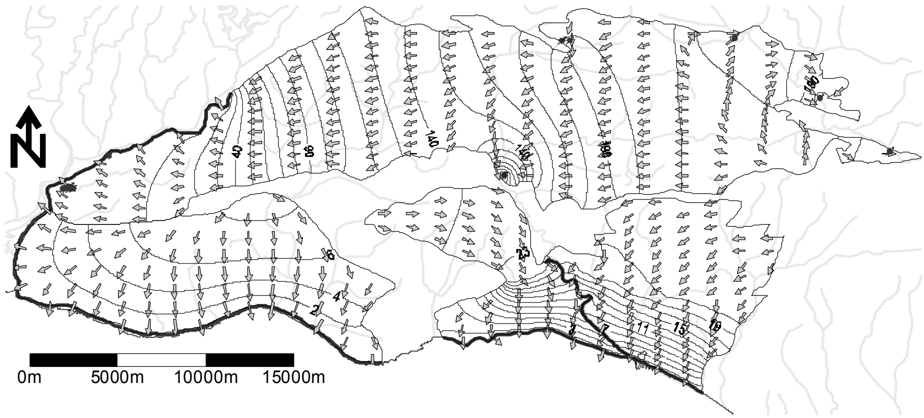

Fig. 4 : Example of finite element simulations performed for a variant of the models implemented for the Querença-Silves, Ferragudo-Albufeira, Albufeira-Ribeira de Quarteira and Quarteira aquifer systems. Boundary conditions correspond to imposed hydraulic heads (represented by bold lines) in the limits of the aquifers (coast line and rivers in hydraulic connection with aquifers). There are also imposed heads in springs controlling the regional flow pattern in the Querença-Silves system. The equipotentials and gradient vectors show the direction of groundwater flow. The stream network is also represented in order to illustrate the coincidence of the predominant patterns of groundwater and surface water flows.

The second example of application of modelling techniques to support water management is based in the fact that a very large number of boreholes used few years ago are nowadays inactive. Therefore a very interesting opportunity is open to make a consistent management of these wells. Figure 5 shows an example of two simulations presented in (MONTEIRO et al. 2002b), putting in evidence the impact of some wells used in the recent past for public supply in the regional flow pattern. The future use of these wells in a framework of conjunctive use can be done after the selection of wells taking into account water quality criteria, together with the definition of more adequate pumping schedules in order to avoid undesirable effects as salt intrusion.

Fig. 5 : Equipotentials (meter) generated from a simulation taking into account only the recharge-discharge balance of the aquifer in natural conditions (top left), and from a simulation where the withdrawals of the pumping wells used for urban supply is superimposed to the natural conditions (top right). At the bottom a residual maps shows the difference between these two simulations.

Table. 2 : Recharge values proposed in ALMEIDA et. al (2000) and computed with the implemented models.

Aquifer System	Area (km2)	Recharge (m3/yr) Referenced values	Recharge (m3/yr) Models	Difference (%)
Querença-Silves	324.24	7.00E+07	9.33E+07	133.26
Almádena-Odiáxere	63.49	2.00E+07	1.67E+07	83.41
Luz de Tavira	27.90	4.00E+06	4.77E+06	119.36
Ferragudo-Albufeira	118.26	8.00E+06	1.00E+07	124.98
Albufeira e Rib. Quart.	140.97	2.37E+07	2.56E+07	108.05

IV. FINAL CONSIDERATIONS

After a brief description of the hydrological setting and evolution of water use in the Algarve region during the last decades, some examples were presented in relation with the possible role of groundwater flow models to improve water management. It is predicted that the actual policy, defined by the Portuguese central administration, based in the definition of urban supply schemes entirely supported by dam waters, corresponds to a transitory phase, before the adoption of solutions better adapted to the hydrologic potential of the region in an integrated way. As stated by WANIELIST et al. 1997, the advantage of using two sources of supply is that the variations in the quantity and quality of surface water do not usually coincide with those of groundwater. Thus, a more economical and reliable supply can be maintained by switching from on source to the other when needed.

BIBLIOGRAPHICAL REFERENCES

ALMEIDA C., MENDONÇA J.L., JESUS M.R., GOMES A.J. (2000). Sistemas Aquíferos de Portugal Continental", Relatório. INAG, Lisboa. Documento electrónico em CD-ROM.

CAMPINAS M. LUCAS H., ROSA M.J. (2002). O Tratamento Conjunto de Águas Subterrâneas e Superfciais é Vantajoso para a ETA de Alcantarilha? Actas 6º Cong. Água. APRH. Porto. 2 pp e documento electrónico em CD-ROM 10pp.

CARREIRA P.M. (1991). Mecanismos de Salinização dos Aquíferos Costeiros do Algarve. Lab. Nac. Eng. Tecn. Industrial. Sacavém. 122 pp.

DE MARSILY G. (1986). Quantitative Hydrogeology. Academic press. San Diego. USA. 440 pp.

I.N.E. (2001). Os Números do Turismo em Portugal , Lisboa, Instituto Nacional de Estatística.

MARGARIDO A. (2001). Cianobactérias e Cianotoxinas em Águas para Consumo Humano. Caracterização da Situação em Portugal Continental no ano 2000. Relatório de Projecto Tecnológico. Lic. Eng. Ambiente. Universidade do Algarve. 74pp.

MONTEIRO J.P., MARTINS R.R., SANTOS I.J. (2002a). Implementação de Ferramentas de Pré e Pós processamento para um Modelo em Elemento Finitos Usando um SIG. Actas 6º Congresso da Água. APRH. Porto. pp315-316 e documento electrónico em CD-ROM 10pp.

MONTEIRO J.P., SANTOS J., MARTINS R.R. (2002b). Avaliação dos Impactes Associados a Alterações no Regime de Exploração de Sistemas Aquíferos do Algarve Central Usando Modelos Numéricos. Univ. Sevilha. III Congresso Ibérico sobre Gestão e Planificação da Água. pp717-724 e documento electrónico em CD-Rom 10pp.

MONTEIRO J.P., NUNES L., VIEIRA J., STIGTER T., MARTINS, R., SANTOS I.J., REIS M.E. (2003). "Sintese Bidimensional dos Modelos Conceptuais de Funcionamento Hidráulico de Seis Sistemas Aquíferos do Algarve". *in* Jornadas Luso-Espanholas Sobre as Águas Subterrâneas no Sul da Península Ibérica. APRH. Universidade do Algarve, Faro (Portugal). 10pp

NICOLAU R. (2002). - Modelação e Mapeamento da Distribuição Espacial da Precipitação- Uma Aplicação a Portugal Continental. Dissertação para a obtenção do grau de doutor, FCT, Universidade Nova de Lisboa, Lisboa (Portugal), 356p.

STIGTER T., VAN OOIJEN S., POST V., APPELO A., DILL A. (1998). "A Hydrogeological and Hydrochemical Explanation of the Groundwater Composition Under Irrigated Land in a Mediterranean Environment, Algarve, Portugal." Journal of Hydrology, 208, 1998, pp. 262 - 279.

TRAC N.Q. Coordinator (1981). Evaluation des Resources en Eaux des Systèmes Aquifères de L' Algarve – Technical report. UNESCO, PNUD, Portugal, 112pp.

VIEIRA J., MONTEIRO J.P. (2003). Atribuição de Propriedades a Redes não Estruturadas de Elementos Finitos Triangulares (Aplicação ao cálculo da recarga de sistemas aquíferos do Algarve). Actas das Jornadas Luso-Espanholas Sobre as Águas Subterrâneas no Sul da Península Ibérica. APRH, Universidade do Algarve, Faro (Portugal), 10p.

WANIELIST M., KERSTER R., EAGLIN R. (1997). Hydrology – Water Quantity and Quality Control. John Wiley and Sons. Second Edition.