INTEGRATED MANAGEMENT OF WATERSHEDS AND AQUIFER SYSTEMS UNDER EXTREME DROUGHT SCENARIOS

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ABSTRACT

This paper addresses groundwater artificial recharge solutions for integrated management of watersheds and aquifer systems under extreme drought scenarios. Based on a lecture presented by Dr. JP Lobo Ferreira at UNESCO's International Year of Planet Earth (IYPE) Workshop held in Oslo, Norway, August 2009, the conceptual idea of Aquifer Storage and Recovery (ASR) is considered, in this paper, as one of the scientific based solutions towards scientific based mitigation measures to climate variability and change in many parts of the world.

In Portugal two European Union sponsored 6th Framework Programme for Research Projects have been addressing this topic, namely GABARDINE Project on "Groundwater artificial recharge based on alternative sources of water: Advanced integrated technologies and management" (*cf.* http://www.lnec.pt/organizacao/dha/organization/dha/nas/estudos_id/gabardine) and the Coordination Action ASEMWATERNet, a "Multi-Stakeholder Platform for ASEM S&T Cooperation on Sustainable Water Use" *(cf.* http://www.lnec.pt/organizacao/dha/nas/estudos_id/asemwaternet and http://www.asemwaternet.org.pt).

This paper addresses selected achievements of those Projects (*cf*. Lobo-Ferreira *et al*. (2006), Diamantino, (2007) and Oliveira (2007)).

Keywords: Drought; Artificial Recharge, Groundwater, Sustainability, GABA-IFI index.

1. INTRODUCTION

Pyne (1995) defined Artificial Storage and Recovery (ASR) as "the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed".

The Australian ASR and Artificial Storage, Transport and Recovery (ASTR) Guideline (Dillon *et al*., 2006 and CSIRO Webpage) advices nine guiding principles necessary to achieved best practices for ASR and ASTR. They are: Adopting a risk management approach, preventing irreparable damage, demonstrations and continuous learning, adopting a precautionary approach, establishing water quality requirements, rights of water bankers and recoverable volume, finite storage capacity of aquifers and interference effects between sites, highest valued use of resources and community and other stakeholder consultation.

Towards a sounder selection of the most appropriate method to build ARS facilities, several experiments have been carried out in the Portuguese Southern region of the Algarve. The values obtained for infiltration rates available on the multiple experimental facilities, depend not only on the hydraulic heads but also on the type of experiments and on the type of soils available regionally. The results gathered allowed the drawing of several original charts on infiltration rates that will be presented at the end of this paper.

In parallel a new method, called GABA-IFI, aiming preliminary identification of candidate areas for the installation of groundwater artificial recharge system was developed for ASEMWATERNet Coordination Action, at LNEC, based on based previous studies developed for five Portuguese Watershed Plans by Oliveira and Lobo-Ferreira (2002). This new method is described in http://www.asemwaternet.org.pt/pdf/events/GAB-IFI_eng.pdf. It was applied both to Campina de Faro aquifer and to Querença-Silves aquifer, in the Algarve.

2. TECHNIQUES FOR ARTIFICIAL RECHARGE

2.1. Infiltration basins

There are several techniques to artificially recharge of aquifers. The choice of the adequate technique depends of several factors such as natural characteristics of the aquifer, proximity to the water source or the objective of the artificial recharge. Infiltration basins for artificial recharge consist, basically, in increasing natural infiltration to the aquifer. Technically there is a change in the ground above the aquifer (to a more permeable soil) in a way that the recharge water percolates easily from the surface, through the unsaturated zone to the water table level, therefore recharging the aquifer system. This is the easiest and oldest technique of artificial recharge. The infiltration basins are the preferential techniques when large open areas are available.

2.2. Injection wells – Aquifer Storage and Recovery

When the area available is an obstacle or the water table is really deep the alternative is to inject directly water into the aquifer using wells.

Aquifer Storage and Recovery (ASR) (*cf.* Figure 1) is a technique with a double purpose, injecting water in a well when surplus of water is available and withdrawing it, from the same well, when the water is needed. The advantage of using the same well is economic. The fact is that no extra wells, facilities or treatment plants (*i.e.* the same water treatment plant can be used to treat the water that is going to be injected and to threat the one that is pumped back) need to be constructed and therefore purchase (Pyne, 1995).

An alternative is the Aquifer Storage Transfer and Recovery (ASTR, *cf.* Figure 1) plants where the injection and withdraw wells are not the same, adding a travel distance parameter to the recovery.

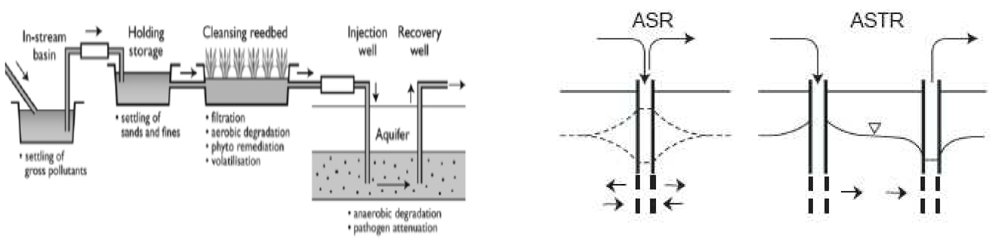

Figure 1 - Aquifer Storage and Recovery scheme and Aquifer Storage Transfer and Recovery

3. WHY DO WE NEED TO CONSIDER DROUGHTS AND ASR FACILITIES IN PORTUGAL

A drought is a natural phenomenon in the Mediterranean region. It is not a fatality rather a recurrent situation requiring solutions and mitigation measures (Santos, 1981).

In Portugal the characterization of droughts is made since 1942 using precipitation data. Using the SPI-12 index (*cf.* Palmer, 1965) it is possible to say that since the agricultural year (September to August) of 1943/1944 there have been five years considered as drought in most of the country, being two years extreme droughts (*cf.* Domingos, 2006). An example of such characterizations can be seen in Figure 2. In this figure rows correspond to years (1969-2005) and columns correspond to districts from Northern Portuguese districts (on the left side) to Southern districts (in the right side). One may easily see in this SPI-12 index table, computed for all Portuguese mainland districts (*i.e.* not for the Portuguese Azores and Madeira archipelagos) a sequence of blue lines (wet years) flowed by a frightening sequence of red lines (dry years), that seems to become more solid as time proceeds, and also more compact along the districts from North to South. Something has to be done on adaptation measures to this reality. It is time now to proceed with scientific based appropriate methodologies to avoid recurrent scarcity.

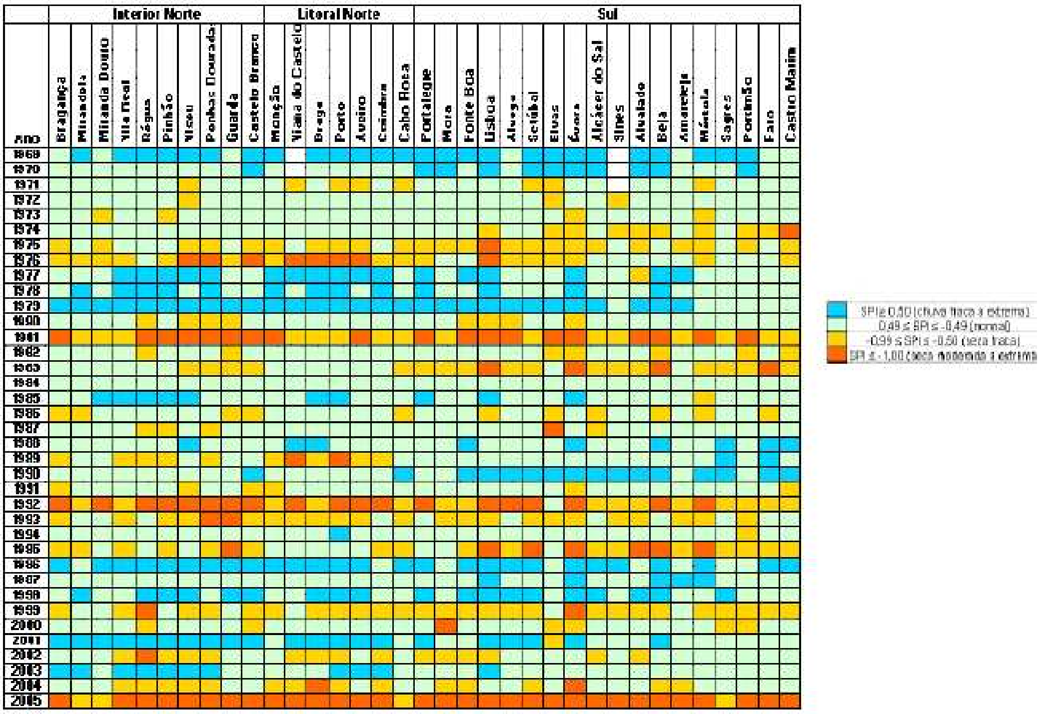

Figure 2 - SPI-12 values computed for selected municipalities (columns) from 1969-2005 for the Northern coastal zone and interior regions of Portugal as well as for the Southern region

The southern region of Portugal is the Algarve with an area of 4.995,2 km^2 and a permanent population of 405 380 inhabitants. Beautiful beaches, warm temperature in winter and hot summers, great touristic condition (*e.g.* excellent golf courses) makes Algarve one of the most attractive vacation places in the world.

Geographically is a low altitude zone, with the highest mountain being 906 m (Monchique ridge of mountains). This characteristic makes difficult the construction of large dams. On the contrary the region is rich in aquifer systems (17 systems identified). These two reasons explain why up to a decade ago almost all water in Algarve was supplied from groundwater.

The average precipitation in the Algarve is around 500 mm (*cf. Instituto de Desenvolvimento Rural e Hidráulica-Ministério da Agricultura, Desenvolvimento Rural e Pescas* Webpage), the highest zones having an annual average precipitation higher than 1200 mm and the littoral zones having values around 400 mm.

The variability of the total population over the year is the most evident social characteristic. While in the winter time the population is, more or less, 400 000 inhabitants, in the summer thanks to the tourists and visitants (around 6 000 000 persons do visit the Algarve per year) there is a huge increase of population.

4. APPLICABILITY OF THE ARTIFICIAL RECHARGE TO THE QUERENÇA-SILVES CASE-STUDY AREA

4.1. Introduction

The Querença-Silves Aquifer System (M5) is a 318 km^2 aquifer system, the largest of the Algarve, located in the municipalities of Silves, Loulé, Lagoa and Albufeira (Central Algarve) (*cf.* Figure 3).

The aquifer is mainly composed by karstified Lower Jurassic (Lias-Dogger) dolomites structure. The structure from the Jurassic is formed by confined to unconfined aquifer system. The aquifer system is limited by two less-permeable structures: in the North, the "*Grés de Silves*" and in the South, the marl-limestone and marls of the Calovian-Oxfordian-Kimeridgian (Almeida *et al.*, 2000).

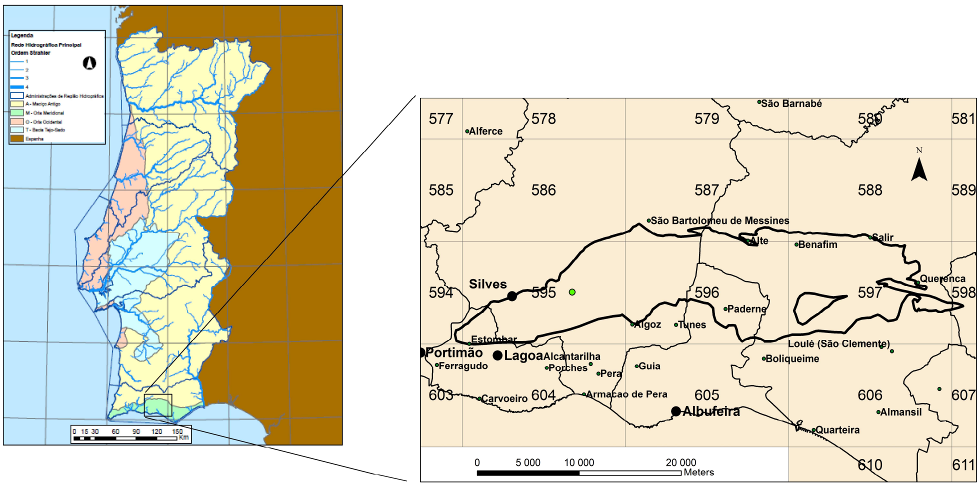

Figure 3 - Querença-Silves Aquifer System and it localization in Portugal

4.2. Water availability

The most recent drought was in the hydrological year of 2004/2005 (Lopes *et al.,* 2005). This drought affected the volume of water in Algarve dams, some of them registering levels below the minimum exploration level. The solution to this problem was, as in the past, groundwater resources.

During that hydrological year new well fields in Vale da Vila with abstraction around 500 l/s have been excavated in the Querença-Silves aquifer. The decision for this area was especially based on its proximity to the water treatment plant of Alcantarilha. Monteiro *et al.* (2006) estimated a water extraction volume higher than 50.29 hm^3/year during that period of drought. The value calculated is the sum of water user, 47.31% for agriculture (23.79*10^6 m^3), 28.34% for the urban supply of the Águas do Algarve regional system of Algarve (14.25*10^6 m^3), 24.36% for the urban supply of the local municipalities (12.25*10^6 m^3) and a percentage not calculated of private users.

Figure 4 shows the quality level in the hydrological year of 2004/2005 in the Querença-Silves aquifer system according to the Portuguese Decree-Law 236/98.

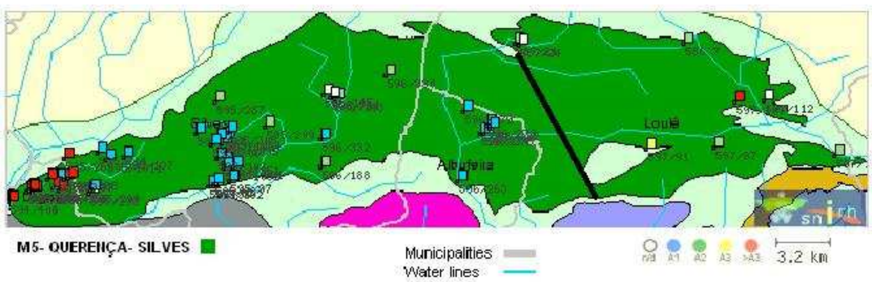

Figure 4 - Quality levels in monitoring points in the Querença-Silves - 2004/2005 (http://snirh.pt)

The red spots in Figure 4 correspond to quality values below Portuguese legislation A3 level in the West (Fontes de Estômbar) where due to the excess of electrical conductivity, *i.e*. an indication of saline intrusion.

Previous years to this extreme drought have been normal from the hydrological view point. Table 1 presents the average (1940-1990) annual precipitation of three odometers and the values of each in the hydrological years of 2000/2001 to 2003/2004.

As can be seen in Table 1 the five previous hydrological years to the drought year were almost normal (compared to the average 1940-1990). What is important to analyse is that the Arade dam odometer had two years with annual precipitation higher than the average, *i.e.* in five hydrological years there was one drought and two years with values above the average precipitation.

Table 1 - Values of precipitation in three odometers (from http://snirh.pt)

	BARRAGEM DO ARADE (30G/03C)	**SÃO BARTOLOMEU DE MESSINES (30H/03UG)**	**PADERNE (30H/05UG)**
	Precipitation (mm/year)	**Precipitation (mm/year)**	**Precipitation (mm/year)**
Average	603.5	699.3	671.6
2000/2001	814.8	898.4	702.8
2001/2002	678.0	642.1	-
2002/2003	492.3	636.4	-
2003/2004	524.6	-	440.8
2004/2005	273.8	248.0	248.5

It is normal to conclude that in the year of 2000/2001 there was discharge in the Arade's river dams. Table 2 presents the peak discharges of the Arade dam in the year of 2000/2001.

Table 2 - Peak discharge of the Arade dam in the hydrological year of 2000/2001

Dam	**Depth discharge (*10^3 m^3)**	**Surface discharge (10^3 m^3)**	**Total discharge (*10^3 m^3)**
ARADE	37 499.20	19 256.70	56 755.90

Arade dam is the downstream dam of the Arade River, therefore more than 50 hm^3 of water went to the sea.

4.3. Preliminary identification of possible areas for artificial recharge

To discuss the applicability of artificial recharge to this case-study area we have to reflect on different factors. In this paper the parameters analysed are the identification of the area for artificial recharge according to Lobo-Ferreira *et al.* (2007), the horizontal travel time (time of residence) of the water in the aquifer and others (legal, institutional and environmental issues).

Oliveira and Lobo Ferreira (2002) developed an Infiltration Index (IFI) that basically analyse the natural ability of the non-saturated zone of an aquifer to infiltration. This index was further developed to GABA-IFI a "methodology to a preliminary identification of candidate areas for artificial recharge" (Oliveira *et al*., 2008).

GABA-IFI methodology has besides the IFI basic parameters, *i.e.* soil type, water available for evapotranspiration (AGUT parameter), topography and geology, also other parameters as vertical hydraulic conductivity in saturated conditions (K), depth to the water table (D), excavation depth (E), distance to the water source (O), land use (L) and vertical time of travel in saturated conditions, given by the relation D/K (tt). Higher values of GABA-IFI do correspond to more favourable areas for artificial recharge. Since the area around Fonte de Louzeiros is a karst formation, the local value corresponds to the maximum value 30 (Figure 5). We have considered this area as the most favourable to artificial recharge in the Western part of Querença-Silves aquifer.

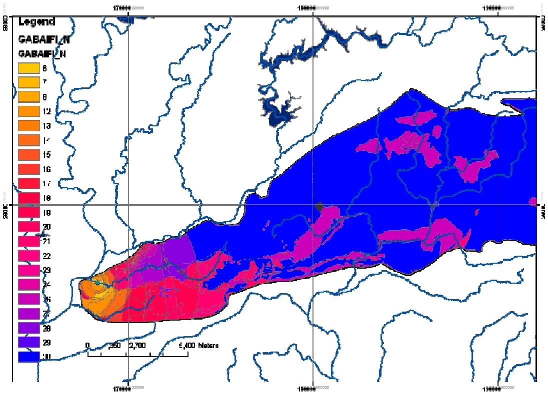

Figure 5 – Application of GABA-IFI index to the Western part of Querença-Silves aquifer

A field visit confirmed the availability of several locations as possible candidate areas to artificial recharge. After a deeper analysis an open space location near Fonte de Louzeiros (*cf.* Figure 6), between São Bartolomeu de Messines and Silves, was selected as appropriate. Besides, land use is appropriate as abandoned agricultural areas seem to be available.

Figure 6 - Location of the study area of Fonte de Louzeiros (google earth image)

Other advantages of the area are the proximity to the water source (Arade dam, about 7 km by road, and or Odelouca dam and tunnel to the Arade watershed, recently (2011) complementing the water supply to Alcantarinha Water Treatment Plant).

The depth to the water table is expected to be higher than 40-50 m, and so parameter D value is advantageous as available unsaturated zone will allow for extra recharge water to be incorporated into the aquifer reserves. Also the fact that the zone is a karst one allow a quicker vertical travel time (tt). Algarve has a large amount of traditional large diameter wells (in Portuguese “noras”) for water withdraws. Nowadays these traditional wells are almost in disuse and many are abandoned. Another aim of the study was to use these existing wells to inject water and recharge the aquifer, avoiding the problem of the vertical travel time and the need to excavate or construct wells (*cf.* session 5.4).

4.4. Water available to recharge and time of residence in the aquifer system

Other two relevant parameters to be assessed are the amount of water available for artificial recharge and the time of residence of water within the aquifer before arriving to a spring or river.

As analysed before, in the year of 2000/2001 more than 56 hm^3 (that by coincidence is a similar volume to the pumping from Querença-Silves in 2004/2005) was discharged from the Arade dam to the Arade River and consequently to the sea. Similar situation happened in the past, *e.g.* before the drought of 1998/99 the dam of Arade had a total peak discharge of 246 hm^3, from 1995/96 to 1997/98. This “*not used or lost*” water together with similar volumes of water from the future Odelouca dam is more than enough for the artificial recharge of

Querença-Silves aquifer. After this conclusion we have to address the question: *How long will the injected water stay in the aquifer?*

Technically on how to inject the water in the aquifer will be answered in section 5.

On the groundwater travel time before the injected water reaches a spring or a river bed, a simple way of assessing it is by using a groundwater flow mathematical model based on Darcy law (*cf.* Ribeiro (2006), Figure 7).

There is some discussion on the conceptual model of this aquifer system but almost all authors agree that in the Western part of the Querença-Silves aquifer the direction of the flow is E-W (*cf.* Monteiro (2005).

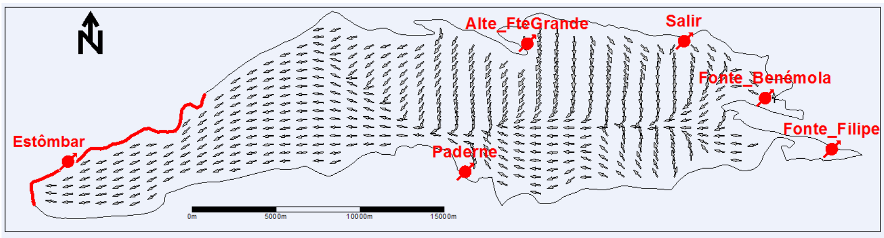

Figure 7 – Direction of groundwater flow in Querença-Silves aquifer

The analysis of the hydraulic gradient in this area gives the information that for 5000 m the piezometric level decrease (from East to West) around 5 m. So a very low slope of $1*10^{-3}$ is obtained. As a result, a first approximation to the horizontal travel velocity, using 50 m/day for the hydraulic conductivity, is 5 cm/day, *i.e.* if the aquifer was recharged in Fonte de Louzeiros and the pumping back was made 100 m to the West the time of residence of the water would be 2000 days, more than 5 years.

Even if we considered that with the artificial recharge the hydraulic gradient increases, *e.g.* a decrease of 10 m per 5 km, the horizontal travel velocity is 10 cm/day, *i.e.* a time of residence of 1000 days (almost 3 years) per 100 m.

An important problem could be the occurrence of faults in the Western region of Querença-Silves aquifer that could increase locally the regional groundwater flow velocity supplying ways for passing the normal Darcy law porous media velocity concept.

This issue is being further analysed in the on-going PROWATERMAN project, a Portuguese sponsored project (*cf.* http://www.lnec.pt/organizacao/dha/organizacao/dha/nas/estudos_id/PROWATERMAN) by Fundação para a Ciência e a Tecnologia (FCT).

4.5. Environmental analysis

Different aspects may be considered in the environmental analysis: the vulnerability of the aquifer, the possibility of creation of an artificial wet area due to excess of recharge, protected areas, saline intrusion and the quality of the water that is used for artificial recharge.

The fact that the area considered for the artificial recharge has a large depth to the water table situates the aquifer not in such vulnerability conditions to pollution (even been in a highly karstified zone). The vulnerability analysis was made using the DRASTIC method and the values computed weren't as high as expected. This characteristic also ensures the natural capabilities of the aquifer for its protection against pollution.

Protected areas are also not a problem in this case-study since the closer areas considered protected are the "Rocha da Pena", north of Benafim, the "Fonte de Benémola" and the "Ria Formosa" in Faro.

The potential problem of saline intrusion with water from the Arade River estuary due to over-exploitation and low recharge of the aquifer (a normal situation in drought conditions) could be solved with the reuse (for injection) of treated waste water in the East of Silves creating a barrier to the brackish water intrusion.

4.6. Legal issues

The required quality of the water for artificial recharge is a legal issue, requiring further analysis.

Gabardine project research (*cf.* Lobo-Ferreira *et al.* (2006 and 2007) and Dimantino *et al*. (2007)) quantified infiltration rates in the order of 150 m^3/day in infiltration basins, with areas 100 m^2 large, and, up to 480 m^3/day in the traditional large wells or "noras" (infiltration area of 20 m^3). It is possible to consider that in the Querença-Silves the values are higher since it is a karstified aquifer. Using values of infiltration 40% higher regarding Querença-Silves aquifer we obtain 210 m^3/day per infiltration basin and 670 m^3/day per "nora".

As an institutional problem we may say that this proposal may eventually collide with interests of different institutions involved in water management issues in the Algarve region. We do hope that the recently created Regional Administrations for Water Resources in Portugal (ARHs) may help decreasing the possibility of conflicts.

Considering other legal issues, focus should be made on the new Portuguese Water Law (Decreto-Lei nº 58/2005 of 29 December 2005) where it is mentioned that "*controls, including a requirement for prior authorization of artificial recharge or augmentation of groundwater bodies. The water used may be derived from any surface water or groundwater, provided that the use of the source does not compromise the achievement of the environmental objectives established for the source or the recharged or augmented body of groundwater*".

5. ARTIFICIAL AQUIFER RECHARGE EXPERIMENTS IN CAMPINA DE FARO AQUIFER

5.1. Objectives of GABARDINE project

This part of the paper presents some of the experimental work and results obtained, during the three research years of Gabardine project (Nov. 2005 – Oct. 2008), for the Portuguese case-study area. The case study area is located in the Southern Portuguese Algarve region, more precisely in Campina de Faro, near the city of Faro (Figure 8). The case study area is approximately 9 km^2 large, located in a selected area of the aquifer system of Campina de Faro. It is bordered by Ria Formosa lagoon in the south, two aquifer systems in the North, the Ribeira de Marchil in the west and the Rio Seco, 2 km to the east. This aquifer needs groundwater rehabilitation to fulfil the Water Framework Directive goals of achieving good water quality status by 2015.

The artificial recharge experiments intend to facilitate the accomplishment of the Water Framework Directive goals, also considering climate variability challenges.

The main purpose of the artificial recharge (AR) experimental plan is to use surplus of surface water for subsequent groundwater recharge in the river bed, contributing therefore to the improvement of groundwater quality (decreasing the nitrates level) by recharging the aquifer with water of a better quality. AR systems require a good understanding of the site specific conditions. The type of AR system to be developed at Campina de Faro aquifer system does depend to a large degree on the geologic/hydrogeologic and hydrologic conditions.

From the beginning of the Project a selection of interesting areas for the development of AR experiments in Campina de Faro was performed. The first area selected was Conceição but the geological and geophysical investigations revealed important lithologic constrains, that forced the abandon of this area. Two other areas, Carreiros and Areal Gordo, were selected for the development of the AR experiments using different technologies and water sources. Four AR systems/experiments were developed in Campina de Faro area. They are the following (Figure 8):

- Two infiltration ponds located in Rio Seco river bed, at Carreiros test site, filled with clean gravels. The source of water for recharge is surface water from the river, during winter time. Three piezometers for quality and quantity monitoring were drilled;
- Two infiltration ponds, excavated to different local sandy layers depth, at the Areal Gordo test site. The water for recharge was extracted from the regional confined aquifer. Two piezometers were drilled for quality and quantity monitoring;
- One typical 5 m large diameter well (in Portuguese "*nora*") intended to increase artificial recharge rates, as the recharge water flows directly into the water table;
- One 0.5 m medium diameter well intended to allow artificially recharge, in places where typical "*noras*" are not available.

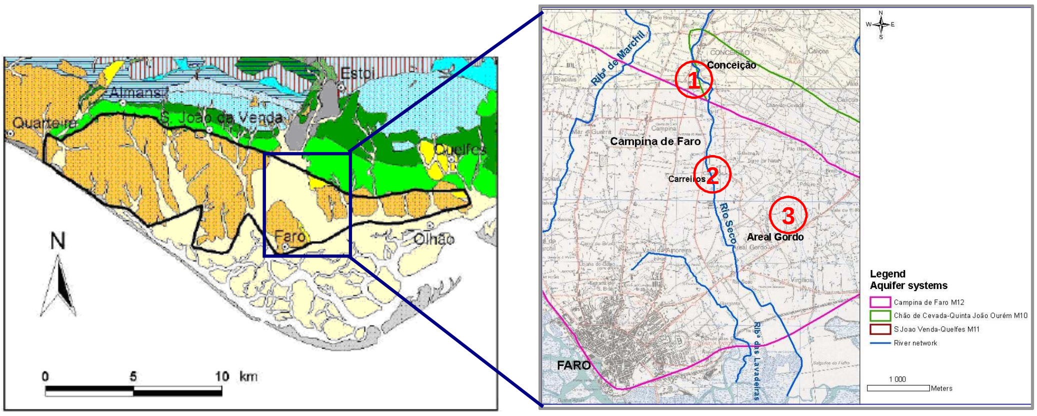

Figure 8 - Portuguese case study areas in the Campina de Faro aquifer system.

AR experiences in Campina de Faro test site were developed in the period November 1st, 2006 - April, 30, 2007. The experiments that have been concluded can be summarized as follows:

1 – Geophysical assessment at Carreiros test site (January, 2007);
2 – Groundwater infiltration rate assessment of Areal Gordo test site (February, 2007):
- Basin 1 (depth to 6 m): Infiltration test in the 2nd layer and LNEC4 well monitoring;

3 – Groundwater infiltration rate assessment of Areal Gordo test site (February, 2007):
- Basin 2 (depth to 8 m): Infiltration basin in 3rd layer and LNEC4 well monitoring;

4 – Vadose zone (3 depths levels) + saturated zone (LNEC4 well) tracer test for transport modelling parameter assessment in the 3rd layer of Areal Gordo test site (February, 2007);
5 – 5 m diameter injection well tests in Areal Gordo, LNEC5 well monitoring (March, 2007);
6 – 0.5 m diameter injection well tests in Areal Gordo, LNEC6 well monitoring (March, 2007);
7 – Groundwater quality and quantity assessment of unconfined + confined aquifer in Carreiros test site:
- Infiltration basins inside river bed, Winter time (*i.e.* no irrigation period), Dec. 2006 - Mar. 2007:
- LNEC1 well for the unconfined aquifer; LNEC2 well for aquitard confining layer; LNEC3 well for the confined aquifer.

The AR experiences results will be input parameters and/or restrictions for an optimization model aiming to maximize groundwater rehabilitation, *i.e.* minimizing today diffuse pollution effects caused by agricultural practices while minimizing the required costs. This achievement has developed as part of the expected goals of Gabardine Project (Rusteberg *et al*., 2011).

5.2. Artificial recharge tests in infiltration basins

The objective of the AR was the assessment of infiltration rates in the very permeable yellow sands and to assess the unsaturated zone, and saturate zone transport parameters with a tracer test. To accomplish this purpose Areal Gordo AR Basins 1, 2 and 3 (Figure 9 and Figure 10) have been constructed for *in situ* infiltration and tracer test experiences. Besides, laboratory soil-column tests were performed in soil samples collected at the bottom of the basin. Areal Gordo AR Basin 2 had an area of 61 m^2. The bottom was excavated up to the third layer of yellow sandy soils at approximately 8 meters depth. The source of water for this infiltration test comes from a nearby well opened in the confined aquifer. To fulfil the objective of measuring the infiltration rate capacity, the water level in the basin was maintained constant (with a water column of approximately 90 cm) for a period of 3 days, and the infiltration rate was calculated by dividing the volume of water added by the basin area. At that time, the piezometric level and the groundwater quality parameters have been continuously recorded at the 6 m far LNEC4 well. The arrival to this well was 70 hours. This allowed estimating the permeability of this sandy layer as 0.21 m/d, considering the distance of 8 meters between the bottom of the infiltration pond and the well (*i.e.* up to 1.5 m in the vadose zone + 6.5 m distance in the aquifer).

5.3. Artificial recharge using a large diameter well

In the case study area of Campina de Faro a large amount of 5.0 m diameter wells equipped with a waterwheel are common, the so called “noras” (Figure 11). Some of them are still used for agricultural irrigation or even domestic consumption. In Areal Gordo an injection test was performed in one of those wells with the objective of assessing if they could be effective infrastructured to be used, as already available facilities for AR. Also foreseen was the assessment of the infiltration rate vs. the recharging depth of water column, ranging from the surface to water table depth. Besides recording the level inside the large diameter well the effect of the recharge in the regional water level was monitored in the nearby LNEC5 monitoring well. This well allowed assessing a first approach to the groundwater hydraulic conductivity and some transport parameters. The input water discharge from a close deep well was controlled during the injection periods. The main characteristics of this large diameter well are presented hereinafter: area at the bottom of the “nora” with a diameter of 5 m = 19.625 m; depth to water table at the beginning of the first test=19 m; available storage volume at the “nora” for the test=373 m^3; total well depth=24 m. The monitoring equipment used was the following: multiparametric water sensors for continuous monitoring installed in the “nora” and LNEC5 well; from the discharge well a flow meter was installed for continuously record the discharge water volume.

Three injection tests were developed during March, 2007. A maximum value was assessed when the water level at the “nora” stabilized near the surface (at 1.5 m depth) allowing the recharge water input of 20 m^3/h to be incorporated in the aquifer. The values vary with the water level inside the “nora” ranging from 0.25 m/d - 1.18 m/d to a maximum value of 24.5 m/d, respectively for the 1st, 2nd and 3rd test (Figure 12).

As expected, it was concluded that increments in the infiltration rate are strongly connected to the increase in the water column inside the well.

5.4. Artificial recharge using a medium diameter well

A one day injection test was performed in an experimental medium diameter well of 0.5 m, located in Areal Gordo, and called LNEC6 (Figure 13).

The objective of this test was to determine the infiltration capacity and to compare it to the one assessed for the 5 m large diameter “nora”. The injection test was performed during 4 hours and the depth to water table was recorded during the test. The input water discharge from a close deep well was controlled during the injection periods. Two injection discharges were considered, one to fill up the well and the other necessary to stabilize the water level: Qi_ascend=20 m^3/h and Qi_descend=2.2 m^3/h. The main characteristics of LNEC6 well, opened in the unconfined sandy aquifer, are the following: section area (diameter 0.5 m)=0.196 m^2; depth to water table=18.9 m; available storage volume=3.7 m^3; total well depth=28 m. The monitoring equipment used was the same as in the previous injection test.

The depth to the water table recorded in LNEC6 is plotted in Figure 13 as well as the two injection periods (4 hours total time duration). The infiltration rate was calculated by the change in the water level after the stop of the injection and during the necessary time interval to achieve the initial head, before the injection test (*i.e.* 7.4 m of water level variation during 0.6 days = 11.5 m/day of infiltration rate).

5.5. Artificial recharge experiments in river bed infiltration basins

In Rio Seco river bed, two 100 m^2 (20m(H)x5m(W)x5m(D)) infiltration basins were constructed and filled in with clean gravels for AR tests (Figure 14).

The main objectives of the experiment were to assess the effectiveness of this type of AR structures for surface water infiltration, including the computation of groundwater recharges rates and evaluating groundwater mass transport parameters in unconfined aquifer via the monitoring of a breakthrough tracer curve.

Two concrete sections were constructed and two pneumatic gauges for river water levels control were installed, upstream and downstream of the infiltration basins, during January, 2007, in order to measure the river discharge upstream and downstream the AR infiltration basins.

Tracer tests have been performed during May, 2007 (Diamantino *et al.* (2008), Figure 15 and Figure 16).

Figure 9 –Vertical profile of lithological materials in Areal Gordo (at right) and LNEC4 well lithological column and, infiltration basin in the first layer (at left)

Figure 10 – Infiltration basin in the second layer and monitoring equipment used for the infiltration test

Figure 11 – Injection test developed in the "*nora*": water levels at the beginning and at the end of the test

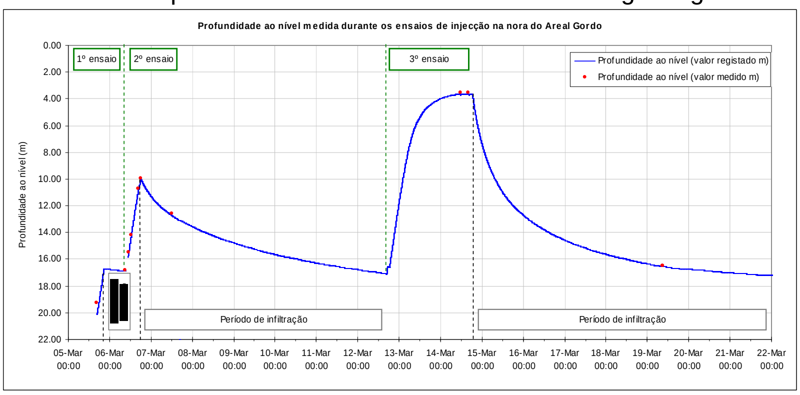

Figure 12 – Depth to the water table automatically recorded and manually measured during the injection tests performed in the "nora"

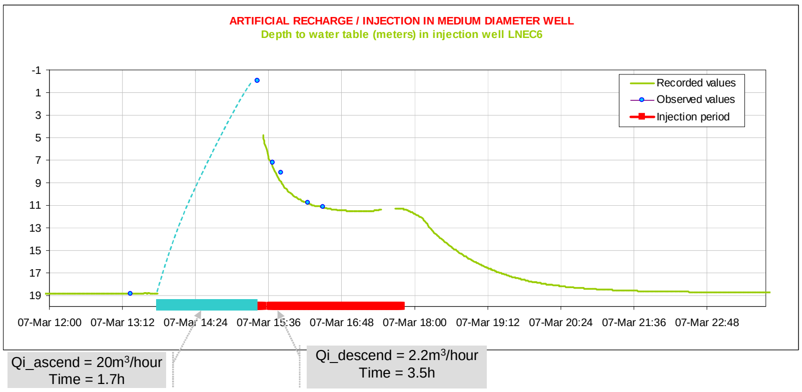

Figure 13 – Depth to the water table automatically recorded and manually measured in LNEC6 (medium diameter well) during the injection test

Results of the groundwater quality and quantity assessment recorded in the monitoring wells during the rainy months of November and December 2006, when surface runoff infiltrates in basins, show NO_3^- concentrations strongly decreasing the same period and tend to get closer to the NO_3^- quality value of the river water (Figure 17).

This is a remarkable fact, and of paramount relevance regarding the achievements of artificial recharge experiments towards the rehabilitation of the polluted unconfined aquifer, confirmed by LNEC 1 piezometer 2.5 m downstream of the infiltration basin.

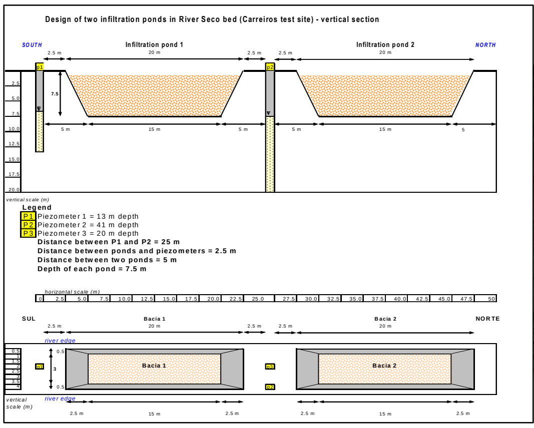

Figure 14 - Design configuration of the two infiltration basins in the river bed of rio Seco (Carreiros)

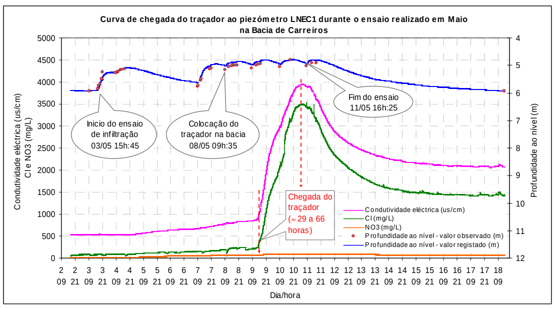

Figure 15 - Breakthrough tracer experiment curves at Rio Seco infiltration basin (Carreiros)

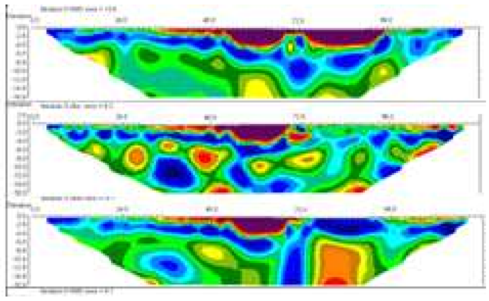

Figure 16 - Electric resistivity models obtained before, during and after the tracer test at the infiltration basin in Rio Seco, Carreiros (Mota *et al*., 2008)

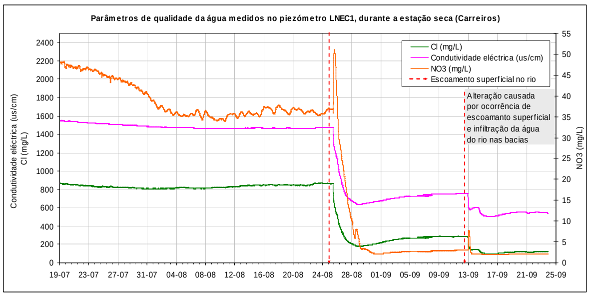

Figure 17 – Variation of the water quality in Campina de Faro unconfined aquifer, after runoff events in Rio Seco, monitored in LNEC 1 piezometer 2.5 m downstream of the infiltration basin

6. CONCLUSIONS

As main conclusion, we may state that artificial recharge may be seen as one good solution aiming a scientific based adaptation to climate change or climate variability conditions in the near future. This technology allows the use of surplus water in wet years so that extra supply water may be available later in drier years, as we have clearly shown as feasible in this paper for Querença-Silves aquifer.

Besides we have also clearly shown in this paper for Campina de Faro aquifer, that other uses of artificial recharge can be achieved, *e.g.* for cleaning polluted aquifer.

The solutions proposed are, in our opinion, worthy to be considered as measures to be included in integrated water resource management plans, being part of a variety of solutions to minimize water scarcity, for instance in the Algarve, during severe drought situation.

Several *in situ* artificial recharge experiments and laboratory tests were performed in Gabardine Project for a selected area of the Campina de Faro aquifer system.

The comparison of different lithological materials *in situ* and *in the lab*, and the assessment of artificial recharge efficiency allowed data gathering regarding performances (on rates of infiltrations) and the adequacies of the different techniques for different geological layers (Figure 18). The *in situ* experiences showed very favourable rates of infiltration in yellow sands, especially in the large diameter well ("nora") experiments, when infiltration rates were as high as 24 m/day. In the case of the "nora" a function of the infiltration rate *vs*. the water column depth in the "nora" was computed.

The aim of all these experiments was to improve the knowledge on real case studies application of different AR methodologies to assess the parameters needed to develop optimization models. The model may incorporate restrictions and parameters of the objective function that values evaluated in the experiments, described above. The results presented in this chapter allow the selection of most appropriate AR techniques aiming the maximization of groundwater quality improvement, while minimizing the cost (Rusteberg *et al*., 2011).

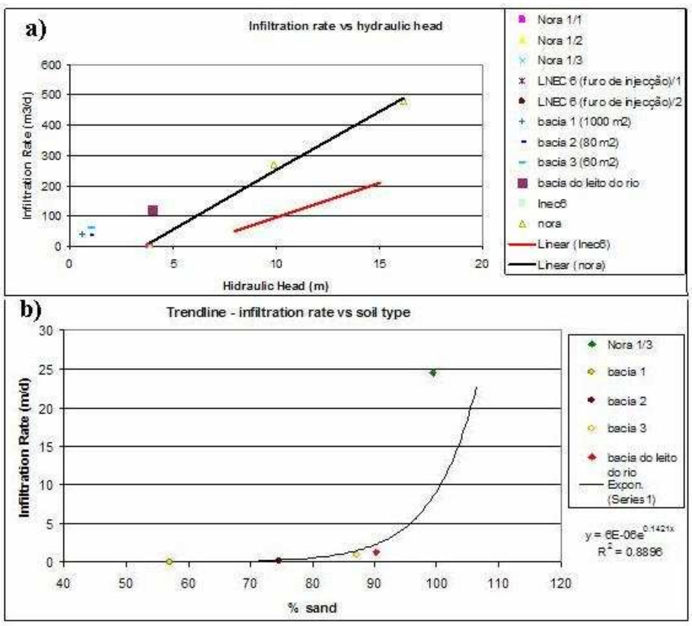

Figure 18 – a) Infiltration rates vs. the type of technology used (infiltration basins in the field or in river bed and, large and medium diameter recharge wells) ; b) Infiltration rates vs. the type of soil available in the Algarve at Campina de Faro and Rio Seco

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