Artificial aquifer recharge experiments in the Portuguese Campina de Faro Case-study area

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Abstract
This paper presents the preliminary results of the experimental work developed in Portugal in the framework of the 6th Framework Programme GABARDINE Project, *Groundwater artificial recharge based on alternative sources of water: Advanced integrated technologies and management*, as well as in the framework of a PhD Thesis under development at LNEC. The case study area is located in the Southern Portuguese Algarve region, more precisely in Campina de Faro, near the city of Faro. The case study area is approximately 9 km^2 large, being located in a section of the aquifer system of Campina de Faro. This aquifer system was declared as a vulnerable zone concerning the EU nitrates Directive. So, the aquifer needs groundwater rehabilitation, to fulfil the *Water Framework Directive* goals. The artificial recharge experiments intend to facilitate the accomplishment of those goals. Therefore, one of the main objectives of the research is the optimisation of groundwater rehabilitation based on artificial recharge aiming the minimization of diffuse pollution effects caused by typical local agricultural practices.

Keywords: Artificial recharge (AR), Campina de Faro, Gabardine Project.

1. Introduction

This paper presents some of the experimental work and results obtained, during the first half of Gabardine three years research (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. 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 those goals. This task will be achieved considering too climate variability challenges, and selecting a vulnerable area in the aquifer system of Campina de Faro for real case study technology experiments. 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 (Fig. 1):

(a) 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 floods. Three monitoring wells for quality and quantity monitoring were drilled;

(b) 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 monitoring wells were drilled for quality and quantity monitoring;
(c) 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;
(d) One 0.5 m medium diameter well intended to allow artificially recharge, in places where typical "*noras*" are not available;

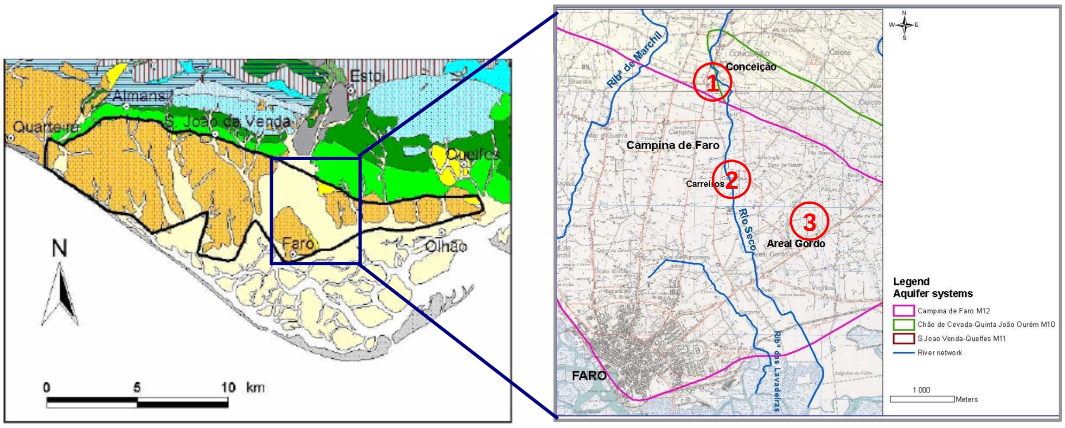

Fig. 1 - Portuguese case study areas in the Campina de Faro aquifer system.

This paper presents some of the experimental work and results obtained for the Portuguese case-study area. 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 modeling 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 is being developed during 2007 as part of the expected goals of Gabardine Project.

2. Artificial recharge experiments in Areal Gordo

2.1 Areal Gordo infiltration basins

Infiltration rates in three different types of sandy layers have been evaluated using *in situ* and laboratory AR tests. The first one was performed in a large infiltration pond with depth to the first layer (2 meters depth, corresponding to the red clayed sands of the Quaternary age outcropping in Areal Gordo), in a basin already available at Areal Gordo test site. The second one was performed in an 82 m^2 infiltration basin excavated to the second layer of brown sands (6 meters depth) and the third one was performed in a 60 m^2 infiltration basin excavated to the third layer of yellow sands (8 meters depth). This last basin included also a tracer experiment for unsaturated zone assessment.

2.1.1 Artificial recharge tests in the first layer

The main purpose of the AR experiment was the assessment of the first layer infiltration rate in this type of cover soils, in a large basin already available at Areal Gordo test site (Fig. 2). The methodology was one *in situ* infiltration test and laboratory soil-infiltration test with column soil samples, collected at the bottom of the basin. In the bottom of the basin, with approximately 2 meters of depth, are the red clayed sands from the 1st layer. The equipment used was 1 meter rule to measure the water level at the basin. The method adopted was to measure the water level decrease in the rule for a period of 7 days.

Fig. 2 –Vertical profile of lithological materials in Areal Gordo (at right) and LNEC4 well lithological column and, infiltration basin in the first layer (at left)

From the infiltration field test and laboratory experiments it was concluded that the infiltration rate was negligible (ca. 4 cm/day), similar to evaporation losses in the pond.

2.1.2 Artificial recharge tests in the second layer

The main purpose of the second layer AR experiment was the assessment of the infiltration rate in the underling brown sandy formation. To accomplish this, one infiltration basin was constructed for one *in situ* infiltration test. Besides, laboratory soil-column tests were performed in soil samples collected at the bottom of the basin. This basin, called Areal Gordo AR Basin1, had an area of 82 m^2. The bottom was excavated up to the second layer depth of brown sandy soils, at approximately 6 meters depth (cf. Fig. 3). The source of water for this infiltration test comes from a nearby well opened in the deep confined aquifer. The objective of the *in situ* test was to maintain the water level in the basin (at approximately 1 meter of water depth) and to measure the inflow rate (with a flow meter) necessary to maintain the water level, for a period of 3 days. During the night, as there was no inflow to the pond, the infiltration rate was determined by dividing the basin area by the change in the water level registered during the night time interval. The piezometric level was continuously recorded in LNEC4 well. The monitoring equipment used for this tests was the following: 1) one multiparametric water sensor, named Troll9500 from *In-Situ Inc*. installed in LNEC4 well for continuous monitoring water levels, pH, temperature, electrical conductivity, ORP, nitrates and chlorides; 2) two meter rules, one monitoring water level diver and one multiparametric water sensor installed in the infiltration basin; 3) a flow meter installed at the outlet of the discharge well, for continuously recording the inflow discharge of water into the recharge basin.

Fig. 3 – Infiltration basin in the second layer and monitoring equipment used for the infiltration test.

Fig. 4 and Fig. 5 present the results of the AR tests in the second layer. In Fig. 4 one can see the water level variation in the infiltration basin from February, 13 to 16, 2007, and the time periods where inflow rate was set as to maintain a constant water level in the pond. The assessed infiltration rate during the periods without inflow into the basin give an average value of 6.4 cm/d. Fig. 5 shows the depth to the water table in the nearest well to the infiltration pond, LNEC4; from the plot two small decreases in the depth to the water table indicate the AR influence from the pond and also different time responses in the rates of infiltration during this recharge event.

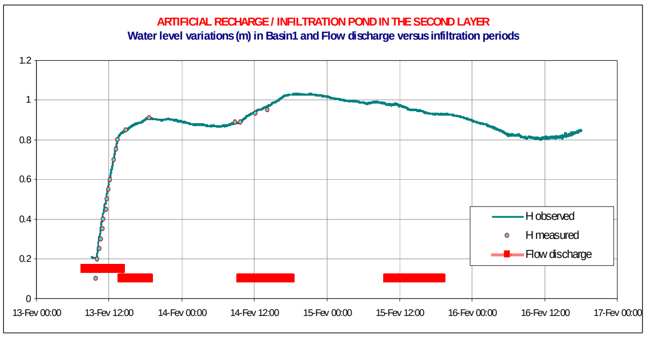

Fig. 4 - Water level variation in the infiltration basin in the second layer

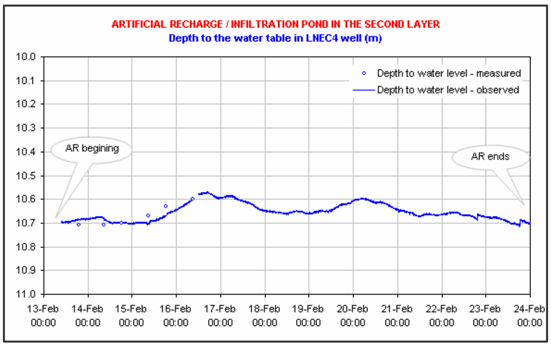

Fig. 5 -Depth to the water table in LNEC4, the nearest well to the infiltration basin in the second layer.

2.1.3 Artificial recharge tests in the third layer and tracer test

The objective of the AR in the third layer was the assessment of infiltration rates, this time 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 Basin 2* was 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 in LNEC4 well. The monitoring equipment used for the infiltration test was the same used in the previous infiltration basin. For the tracer test experience, 6 *teflon* cups were installed at the depths of 20, 60 and 100 cm. Maintaining the water level in the basin, an injection of NaCl tracer was done in 2007/02/28 (at 14h:55). The amount of salt was calculated to make the tracer 10 x the background level of 160 mg/l (100 kg/61 m^3). The tracer arrival to the *teflon* cups was done for the 3 depths. The tracer arrival at LNEC4 well, 6.5 m away was also recorded. Fig. 7 shows the infiltration rate calculations for a three days experience in the third layer infiltration basin. An average value of 1.52 m/d and median value of 1.59 m/d was obtained for the infiltration rate. Fig. 8 shows the electrical conductivity variations in the vadose zone underneath the basin, after the tracer test experience. Considering the time of arrival to 100 cm cup of 17h30 (at 08:30 of 07/03/01) the seepage velocity

(V_S) was calculated as 1.37 m/d and the permeability (K) as 0.53 m/d, using this expression: $K = (V_S \times n)/i$, where n is the soil porosity and i the hydraulic gradient. Considering this value for the velocity, the arrival time to the 20 cm and 60 cm cups should have been: 20 cm = 3h30 (18:30 of 2007/02/28) and 60 cm = 10h31 (1:31 of 2007/03/01), although these measurements were not confirmed since the water samples were not taken in small intervals during the night. Fig. 9 shows the chloride concentration recorded in LNEC4 well. The arrival to this well was 70 hours. This allowed to estimate 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).

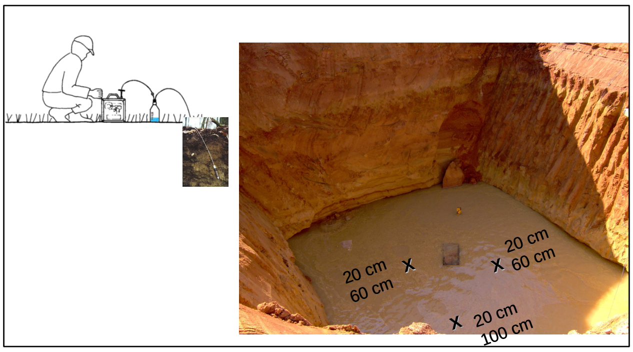

Fig. 6 – Infiltration basin in the third layer and monitoring equipment used for the vadose zone tracer test

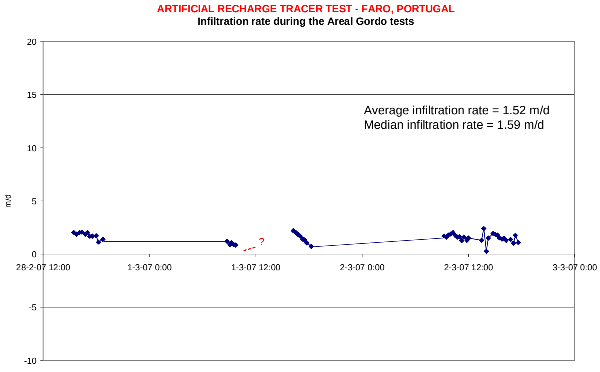

Fig. 7 – Infiltration rate in the third layer infiltration basin during a 3 days AR experience

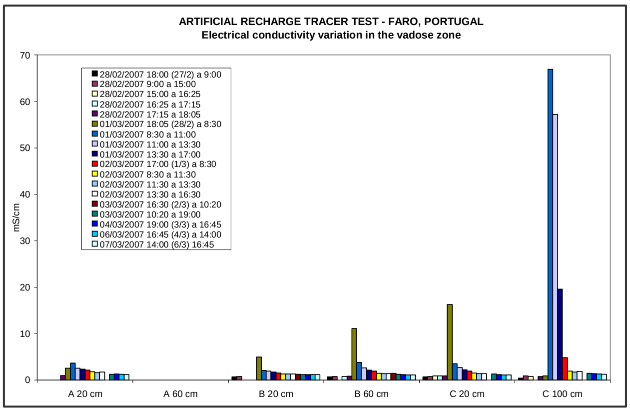

Fig. 8 – Electrical conductivity variation in the vadose zone underneath the third infiltration pond, after the tracer test experience

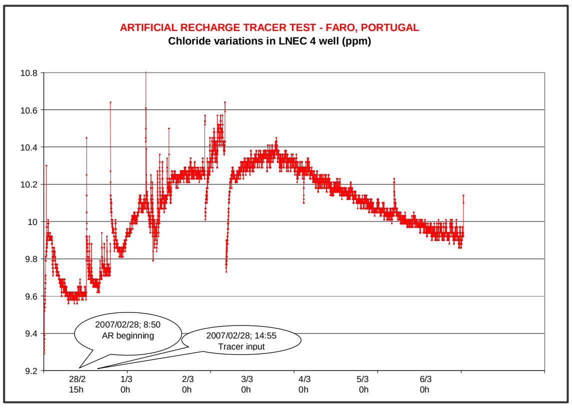

Fig. 9 - Chloride concentration variations obtained in LNEC4 well during the tracer test experience

2.2 Areal Gordo injection tests in wells

2.2.1 Artificial recharge using a large diameter well (5.0 meters)

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*" (Fig. 10). 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 infrastructures 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^2; 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: the 1st one, in March 5, for a period of 4 hours, the 2nd one, in March 7 for the period of 7 hours, and the last one, in March 14 for the period of 50 hours. The water discharge into the well was set to a constant value of 20 m^3/h. Infiltration rates were calculated based on the water level decrease during the non injection periods. 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 (Fig. 11). As expected, it was concluded that increments in the infiltration rate are strongly connected to the increase in the water column inside the well. Fig. 12 shows the water level and NO_3^- concentrations recorded in the nearest well (LNEC5), 15 m away from the large diameter well, during the last injection test. From the beginning of the injection test one could observe from the plot that the water level and NO_3^- concentrations are gradually increasing, possibly indicating in the case of NO_3^- a gradual dilution between two different compositions of groundwater, the one existing in the well and the other from the injection source. As the time is passing this is specially noted in the NO_3^- concentrations, which visibly increase, and appear to follow water level variations. The precise time of the recharge water arrival to LNEC5 well is difficulty to precise, but it could be estimated approximately as 34 hours after the injection test started. Based on this assumption the permeability of the sandy layer can be estimated as 10.6 m/d, considering the distance of 15 meters between the "*nora*" and LNEC5 well.

Fig. 10 – Injection test developed in the "*nora*": water levels at the beginning and at the end of the test

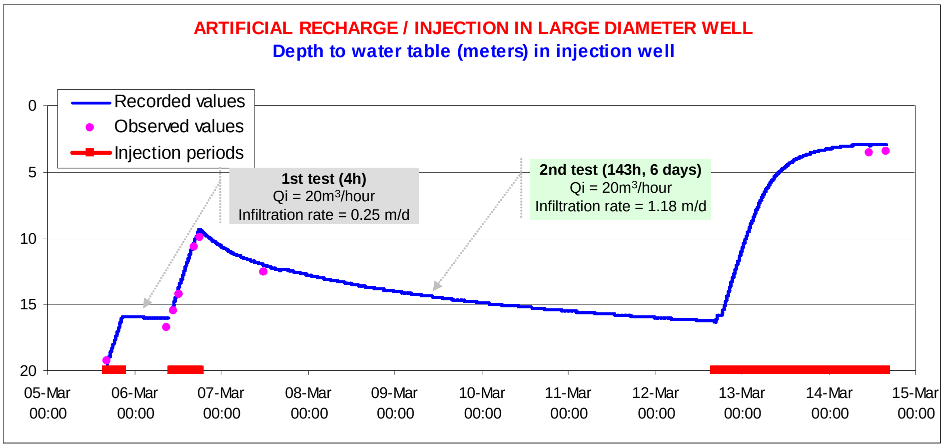

Fig. 11 – Depth to the water table automatically recorded and manually measured during the injection tests performed in the "*nora*"

2.2.2 Artificial recharge using a medium diameter well (0.5 meters)

A one day injection test was performed in an experimental medium diameter well of 0.5 m, located in Areal Gordo, and called LNEC6. 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=20m^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 Fig. 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).

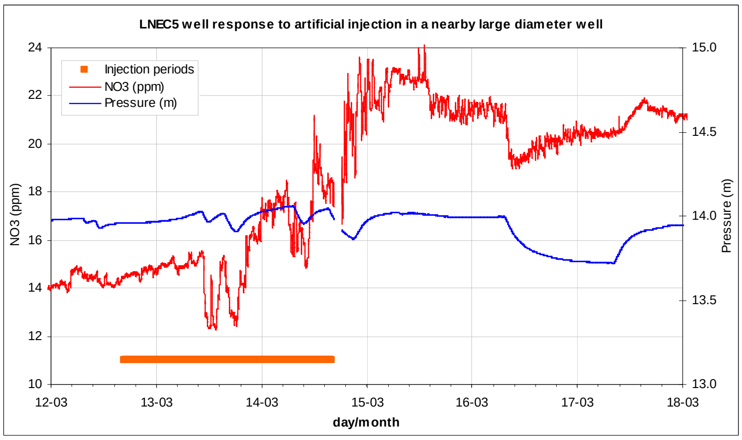

Fig. 12 – Depth to water table and NO_3^- variations recorded in the nearest well (LNEC5), at 15 m distance from the large diameter well, during the last injection test

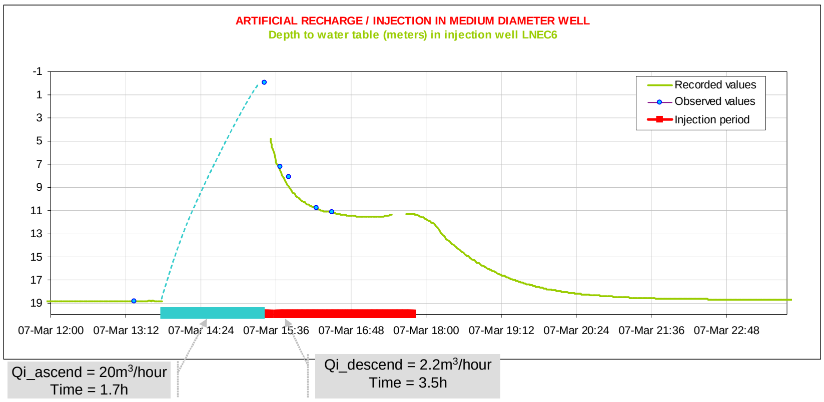

Fig. 13 – Depth to the water table automatically recorded and manually measured in LNEC6 (medium diameter well) during the injection test

3. Artificial recharge experiments in Rio Seco river bed infiltration basins

During November 2006, in Rio Seco river bed, at Carreiros, two 100 m^2 (20m(H)x5m(W)x5m(D)) infiltration basins were constructed and filled in with clean gravels for AR tests. Three monitoring wells (LNEC1, LNEC2 and LNEC3) for groundwater quality and piezometric levels assessment have been constructed. Each well was equipped with multiparametric sensors for quality and water level continuously recording. LNEC1 is opened in the unconfined sandy aquifer with 13 meters depth, LNEC2 is opened (possibly) in the confining aquitard at 20 meters depth and LNEC3 is opened in the sandstone confined aquifer, at 40 meters depth. For the AR experiment, water from the deep aquifer was used from LNEC 3 well. In normal use the source of recharge water, instead, will be that of the river runoff flow. 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 (Fig. 14).

Results of the groundwater quality and quantity assessment recorded in the monitoring wells are presented in Fig. 15 – the first plot shows the piezometric variation recorded in the 3 monitoring wells (LNEC1, LNEC2 and LNEC3) and the second one shows the NO_3^- concentrations obtained from the groundwater samples. Also the daily precipitation recorded in the nearest station (São Brás de Alportel) is presented in the plot to give, as a first approach to the periods surface runoff in the river was available. The river water NO_3^- concentration could also be determined in two samples plotted with a red cross. From these results one can observe that piezometric levels tend to increase during the rainy months of November and December 2006, when surface runoff infiltrates in basins. NO_3^- concentrations strongly decreased in the same period and tend to get closer to the NO_3^- quality value of the river water. This is a remarkable fact, and of paramount relevance regarding the achievements of Gabardine objectives on the rehabilitation of the polluted unconfined aquifer, confirmed for LNEC1 well.

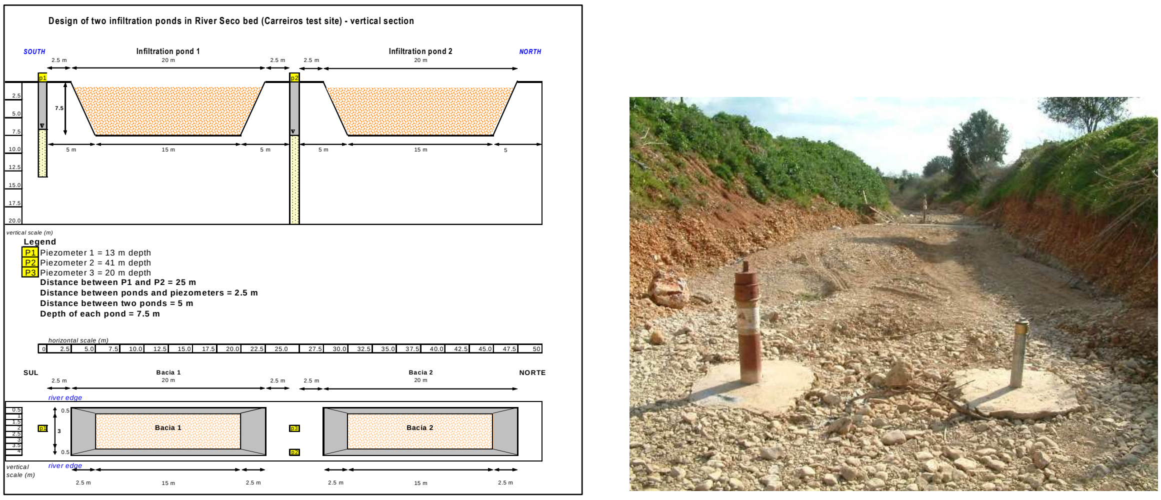

Fig. 14 - Design configuration of the two infiltration basins in the river bed of rio Seco (Carreiros)

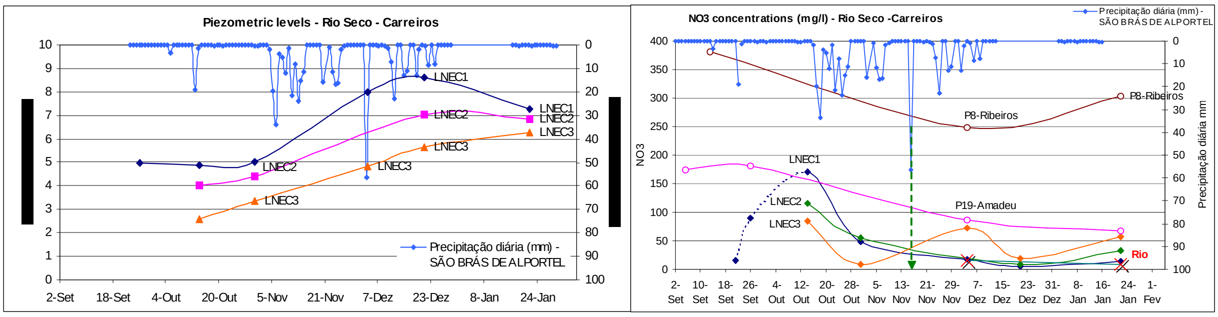

Fig. 15 - Piezometric levels variation and NO_3^- concentrations recorded between October, 2006 and January, 2007 at Carreiros test site

4. Rio Seco river bed geophysical assessment

During the end of January, 2007 a geophysical campaign was made. Fig. 16 shows the results of electrical resistivity profiles, one longitudinal and four transversal profiles performed at the river bed, intersecting the two infiltration basins. These results are essential for assessing the background values of resistivity prior the tracer test experience developed during May 2007.

5. Laboratory tests and results

Soils samples were collected before the AR experiences in Areal Gordo for laboratory soil-columns tests, hydrodynamic soil parameters characterization and grain size analysis. In the bottom of the infiltration basins undisturbed soils columns were collected. During monitoring wells construction disturbed soils samples were also recovered. For the intact soil-columns (30cm×5.9cm - filled 28.5cm) constant flow rate during 15 hours tests were done for soils bulk density, porosity and permeability determinations. Permeability was determined using the Darcy equation: $K=(V\times L)/A\times T\times(h_1-h_2)$, where V=drained water volume for a time interval; L=soil column height; A=test column area; T=time interval; (h_1-h_2)=hydraulic gradient.

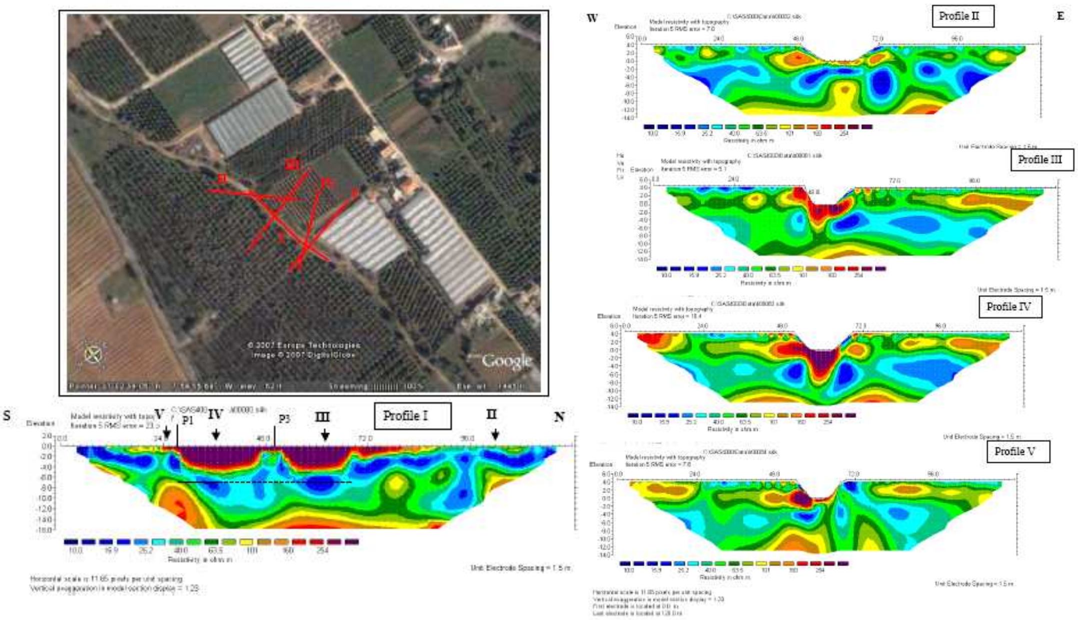

Fig. 16 - Geophysical assessment using electrical resistivity profiles intersecting the infiltration basins at the river bed (Carreiros)

In Table 1 one can observe the results of grain size analysis and the results of soil-column tests. Soil samples were collected at the bottom of the three infiltration basins at different sandy layers and depths. Samples were also collected in LNEC4 and LNEC5 monitoring wells, at the deepest layers of the well lithologic column. Grain size analysis was performed using sieving analysis for the coarse fraction (sand and gravel) and sedimentation method by laser diffractometry for the fine fraction (silt and clay). The measurements for both the coarse and fine fractions are presented in Fig. 17. A simply calculation of the permeability values from grain size curves can be done with the Hazen formula: K=C×d102, where K=hydraulic conductivity (cm/s); C=constant; d10=effective diameter or grain size at which 10% of the grains are finer (more details about laboratory procedures and results in Henriques, 2007).

6. Conclusions

Several in situ artificial recharge experiments and laboratory tests were performed in the framework of the Gabardine Project for a selected area of the Campina de Faro aquifer system. The comparison of different lithologic 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. The *in situ* experiences showed very favorable rates of infiltration in yellow sands, especially in the large diameter well (“nora”) experiment, 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 an optimization model. The model will incorporate as restrictions and parameters of the objective function that values evaluated in the experiments, described above. The application will allow the selection of most appropriate AR techniques aiming the maximization of groundwater quality improvement, while minimizing the cost. This research will be under development till Nov. 2008 both in the framework of the Gabardine Project and of first author PhD. Therefore, future thematic papers will be published.

Table 1 – Results from soil-column laboratory tests

Soil type and reference	**Porosity** (n)	**Soil bulk density** g/cm3	**Seepage velocity** (V_S) m/day	**Darcy velocity** (V_D) m/day
Red sands - Basin1 (depth 3m)	0.23	1.44	0.16	0.04
Brown sands - Basin 2 (depth 6m)	0.39	1.52	0.18	0.07
Yellow sands - Basin3 (depth 8m)	0.35	1.50	7.78	2.71
Yellow sands - LNEC4 (depth 21-24m)	0.39	1.30	-	-
Yellow sands - LNEC5 (depth 31-34m)	0.33	1.51	-	-

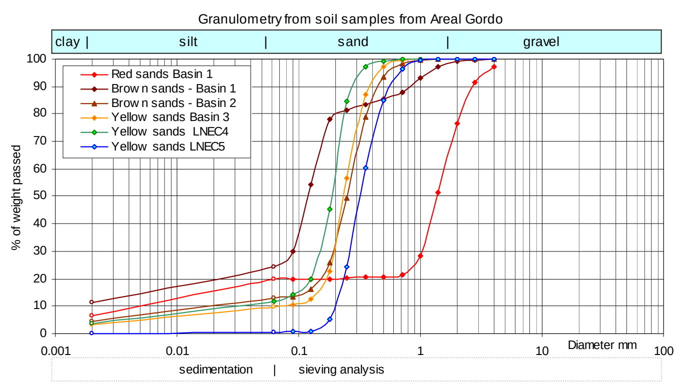

Fig. 17 – Grain size curves from soil samples collected at the bottom of infiltration basins and at LNEC4 and LNEC5 monitoring wells

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