DOI 10.7343/AS-080-14-0106

Demonstrating managed aquifer recharge as a solution for climate change adaptation: results from Gabardine project and ASEMWaterNet coordination action in the Algarve region (Portugal)

La dimostrazione della ricarica degli acquiferi in condizioni controllate come una soluzione per l'adattamento al cambiamento climatico: i risultati del progetto Gabardine e le azioni di coordinamento di ASENWaterNet nella regione dell'Algarve (Portogallo)

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Riassunto: Nella regione dell' Algarve, Portogallo meridionale, le attività di ricerca sulla ricarica degli acquiferi in condizioni controllate sono state sviluppate per fornire non solo un surplus di acqua immagazzinata negli acquiferi negli anni piovosi, come nel caso della falda acquifera Querença-Silves (FP6 ASEMWATERNet Coordination Action), ma anche per rendere di qualità migliore le acque sotterranee dell'acquifero di Campina de Faro (progetto FP6 Gabardine). Seguendo le potenzialità della ricerca sulla ricarica delle falde nel sud del Portogallo, il presente contributo descrive gli obiettivi, la dimostrazione concettuale, il background e le funzionalità di uno dei siti pilota circum-mediterranei selezionati (in Portogallo) che sarà oggetto di studio nel nuovo progetto FP7-ENV-2013-WATER-INNO-DEMO MARSOL, che ha avuto inizio il 1 dicembre, 2013 nel sito pilota dell'Algarve, diverse aree studio saranno situate nell'acquifero di Querença-Silves e di Campina de Faro.

Abstract: *In the Algarve southern Portugal region, Managed Aquifer Recharge (MAR) research activities have been developed to provide not only water surplus storage in aquifers during wet years, focusing in the Querença-Silves aquifer (FP6 ASEMWATERNet Coordination Action), but also groundwater quality rehabilitation in the Campina de Faro aquifer (FP6 Gabardine Project). Following MAR research potentialities in southern Portugal, this paper describes the objectives, conceptual demonstration, background and capabilities of one of the selected Circum-Mediterranean pilot sites (in Portugal) that will be researched in the new FP7-ENV-2013-WATER-INNO-DEMO MARSOL project, which started Dec. 1st, 2013. In the Algarve pilot site, several case-study areas will be located in the Querença-Silves aquifer and in the Campina de Faro aquifer.*

Parole chiave: Ricarica degli acquiferi in condizioni controllate, adattamento al cambiamento climatico, esperimenti di infiltrazione attraverso letti di corsi d'acqua, indagini geofisiche, Acquifero di Campina de Faro.

Keywords: *Managed aquifer recharge, Climate change adaptation, River bed infiltration experiments, Geophysical assessment, Campina de Faro aquifer.*

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Ricevuto: 28 aprile 2014 / Accettato: 08 maggio 2014
Pubblicato online: 30 settembre 2014

Introduction

GABARDINE project (http://www.lnec.pt/organization/dha/nre/estudos_id/gabardine, 2005-2008; Lobo-Ferreira et al., 2006; Diamantino et. al., 2007 and 2008 and Diamantino, 2007) had the following major objectives: (1) explore the viability of supplementing existing water resources in semi-arid areas with alternative sources of water that could be exploited in the context of an integrated water resources management approach; (2) investigate the feasibility of using aquifers as the primal facility for the large scale storage of these alternative water sources and investigate techniques for their managed aquifer recharge and injection of the produced alternative water, including a monitoring of water quality and purification by natural attenuation and filtration processes; and (3) evaluate and quantify the potential impact of degrading factors, such as climate change, changes in the quality of water, salt water, etc. on the global quality and usability of the resource, by developing tools for risk mapping, for modelling and for monitoring, and to propose measures for preventing or minimizing, and mitigating their impact. The alternative water sources were surface water surpluses generated during rainy seasons, treated effluent, surpluses of desalinated water and exploitation of saline water bodies that could be used for adequate agricultural practices or used as raw material for low-cost desalination.

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Four test sites have been selected for GABARDINE project in the Circum-Mediterranean area, each representing a different aspect of the problem: (1) the aquifer of Thessaloniki area, in which MAR is being considered for controlling seawater intrusion and storage of treated effluent (Greece); (2) the Lower valley of the Llobregat river, where the objective is to mitigate the aquifer from seawater intrusion by means of MAR of effluent and or runoff water (Barcelona-Spain); (3) the Campina de Faro aquifer, in Algarve region where the objective is achieving groundwater quality improvement by injecting surface-water (Portugal, which will be detailed hereinafter); (4) the Coastal aquifer shared by Israel and Palestine (Gaza). In Israel most of the recharge technologies are implemented but the quality and mixing aspects need to be investigated and quantified.

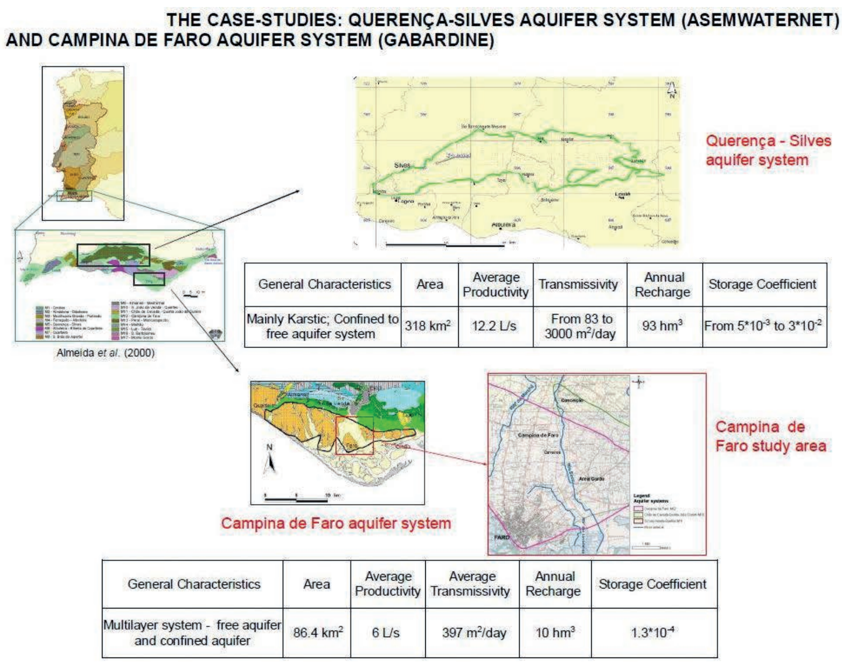
In Portugal two infiltration basins were constructed in the Rio Seco river bed and filled in with clean gravels for MAR tests. The source of water is the river water during runoff flow. The main objective was to investigate this type of MAR structures for surface water infiltration in terms of groundwater quality and quantity assessment in confined and unconfined aquifers. Also tracer tests for infiltration rate assessment and geophysical assessment have been developed during May, 2007. During the second and third year of the GABARDINE project two periods have been researched regarding the river bed infiltration basins: the summer time (irrigation period) from April, 1st to September, 31th 2007 and the winter time (no irrigation period) from October, 1st 2007 to June, 30th 2008.

Location and geological setting

The area of Campina de Faro aquifer system, in the Algarve, Portugal, is around 86.4 km^2, and is limited, in the North, by the less permeable deposits of Cretaceous, in the East, by the city of Olhão, in the West, by the Quarteira aquifer system, with a probable hydraulic connection between them, and in the South, by the sea. Figure 1 shows the identification of the aquifer systems in the Algarve coastal zone by Almeida et al. (2000), including the aquifer system of Campina de Faro (studied in GABARDINE project) and the Querença-Silves aquifer system, studied in ASEMWATERNet Coordination Action (http://www.asemwaternet.org.pt/; Lobo-Ferreira and Oliveira,2008).

The GABARDINE test site in Portugal is a section of the aquifer system of Campina de Faro, located in the Southern Algarve region. This section is located in the central part of Campina de Faro and encompasses an area of approximately 9 km^2. It is bordered by the estuary of Ria Formosa in the South, two aquifer systems in the North, the river Ribeira de Marchil in the West and 2 km to East from the river (rio in Portuguese) Seco (located in the centre of Figure 2). Figure 2 presents the geological map of Campina de Faro aquifer (adapted from Almeida et al., 2000).

Precipitation increases from the South (along the coastal zone) to the North (in the mountain areas). For the average annual precipitation in the Rio Seco basin (Lobo-Ferreira et al., 2006) calculated a value of 745 mm, using the Thiessen poligon method, and a value of 655 mm using the isohyets method. In the case of temperature, the annual medium values calculated were 17.3ºC in Faro and 16.8ºC in Quarteira.



General Characteristics	Area	Average Productivity	Transmissivity	Annual Recharge	Storage Coefficient
Mainly Karstic; Confined to free aquifer system	318 km^2	12.2 L/s	From 83 to 3000 m^2/day	93 hm^3	From $5*10^{-3}$ to $3*10^{-2}$

General Characteristics	Area	Average Productivity	Average Transmissivity	Annual Recharge	Storage Coefficient
Multilayer system - free aquifer and confined aquifer	86.4 km^2	6 L/s	397 m^2/day	10 hm^3	$1.3*10^{-4}$

Fig. 1 - The case-studies: Querença-Silves aquifer system (ASEMWATERNET) and Campina de Faro aquifer system (GABARDINE).

Fig. 1 - I casi di studio: il sistema acquifero di Querença-Silves (ASEMWATERNET) e quello di Campina de Faro.

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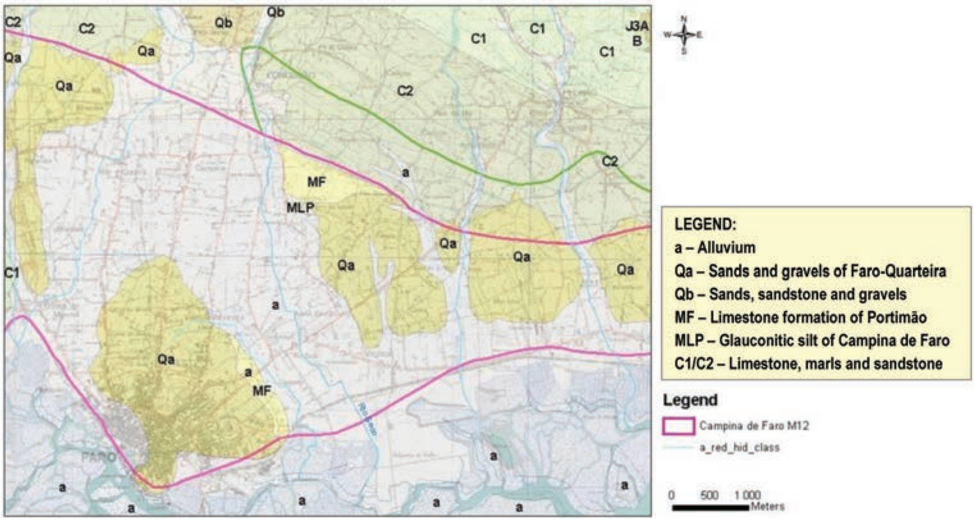

Fig. 2 - Geological map of Campina de Faro aquifer (adapted from Almeida et al., 2000).

Fig. 2 - Carta geologica dell'acquifero di Campina de Faro (adattata da Almeida et al., 2000).

Methodology

During November 2006, two infiltration basins in the riverbed, filled with clean gravels, and three monitoring wells (LNEC1, LNEC2 and LNEC3) for groundwater quality and piezometric levels assessment have been constructed (Figure 3 and Figure 4). Each well was equipped with multiparametric sensors for quality and water level continuous recording. Each basin surface area is 100 m^2 (20m x 5m) and has approximately 7 meters depth. 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.

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.

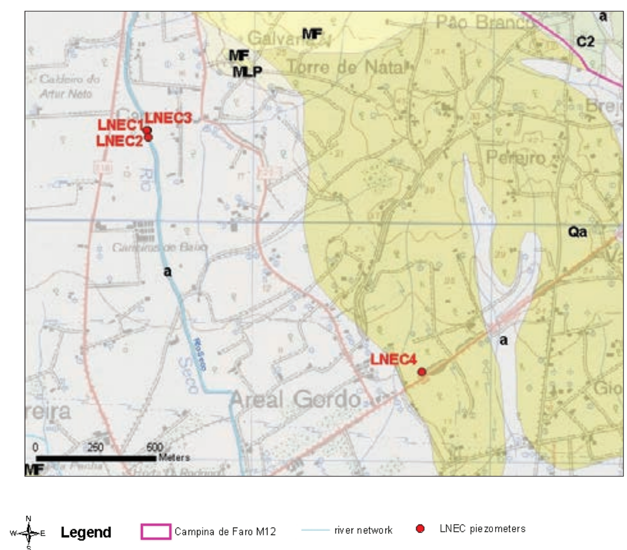

Fig. 3 - Location of LNEC piezometers (LNEC 1, 2 and 3, drilled in rio Seco at Carreiros and, LNEC 4 and 5, drilled in Areal Gordo)

Fig. 3 - Ubicazione dei piezometri LNEC (LNEC 1, 2 e 3, nel Rio Seco a Carreiros e, LNEC 4 e 5, nell' Area di Gordo).

A tracer test experiment was performed in May 2007 during 4 days, in the South infiltration basin, with a NaCl tracer spread uniformly in the basin surface with a constant water discharge (500 kg of NaCl and 100 m^3 of water). Before the tracer experiment a previous 3 days MAR experiment was performed for a preliminary infiltration rate assessment. The source of water for those experiments was extracted from the confined aquifer (LNEC3). Piezometric levels, electric conductivity, Cl and NO_3^- concentrations were measured every minute in the monitoring probes installed in the monitoring wells LNEC1 and LNEC2.

Results

The first results, during winter time, of the groundwater quality and quantity assessment recorded in the monitoring wells are presented in Figure 5 – the first plot shows the piezometric variation recorded in the 3 monitoring wells (LNEC1, 2 and 3) and the second one shows the NO_3^- concentrations results obtained from the groundwater samples.

Also the daily precipitation recorded in the nearest climatological station (São Brás de Alportel, located 12.5 km North of LNEC1, 2 and 3 monitoring wells) is presented in the plot to give an idea of the time periods of eventual surface runoff in the river. The river water NO_3^- concentration could also be determined in two samples plotted with a red cross. It can be observed from this results that piezometric levels tends to increase during the rainy months of November and December - during those months the surface runoff was also infiltrating in the tested basins. NO_3^- concentrations strongly decreased in the same period and tend to be close to the surface water NO_3^- value, especially in the unconfined aquifer wells. This is a relevant result regarding the achievements of GABARDINE objectives on the rehabilitation of the polluted unconfined aquifer of Campina de Faro. The results recorded in LNEC1 during the summer period, concerning NO_3^- and Cl^- concentration and electrical conductivity values are presented in Figure 6 and Figure 7. They show an improvement

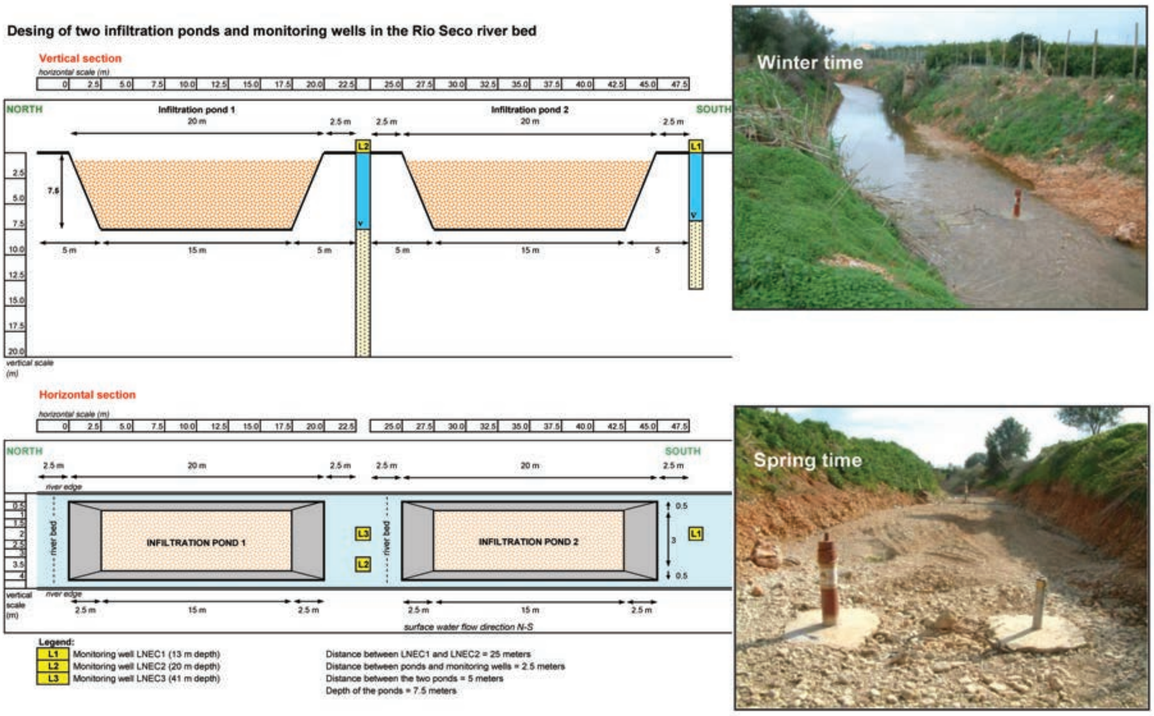

Fig. 4 - Design configuration of the two infiltration basins in the river bed of Rio Seco (at Carreiros), winter time and spring time photos.

Fig. 4 - Schema dei due bacini di infiltrazione nel letto del Rio Seco (a Carreiros), nelle foto il periodo invernale e primaverile.

in terms of groundwater quality caused by surface water infiltration during the first flash flood taking place at the end of the summer period. These results are verified by the increase in the depth to the water table recorded in the same period.

Results of the tracer test experiments (Figure 8) showed the Cl^- concentration breakthrough curve and the arrival time at LNEC1. An infiltration rate of about 120 m^3/day (i.e. 5 m^3/h) was measured at the southern basin that has an area of about 100 m^2. Per m^2 the infiltration is about 1.2 m/day. A small monitoring well for water levels and electric conductivity recording installed inside the basin allows obtaining similar values.

The real groundwater velocity was estimated after the NaCl tracer experiment (May, 18^{th} to August, 20^{th}, 2007) at the Rio Seco river bed as follows: arrival at LNEC1 – 27/06 10:30h=39d´24h=936h; Vint=6.4 cm/d; K=V´ne/I=6.4´0.35/0.088=25 cm/d=0.25 m/d (arrival at LNEC1 is presented in Figure 8).

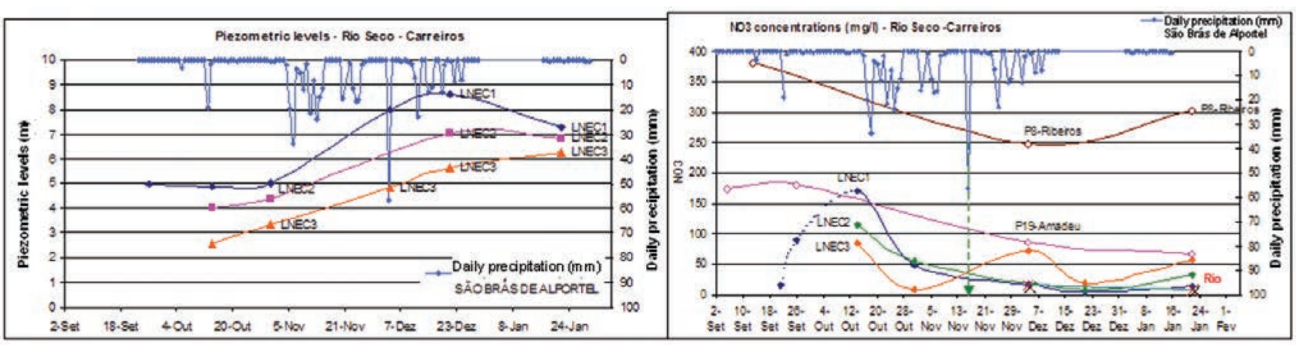

Fig. 5 - Piezometric levels variation and NO_3^- concentrations recorded between October, 2006 and January, 2007 at Carreiros test site (winter time results).

Fig. 5 - Variazione dei livelli piezometrici e della concentrazione di NO_3^- registrati tra ottobre 2006 e gennaio 2007 nel sito test di Carreiros (risultati del periodo invernale).

DOI 10.7343/AS-080-14-0106

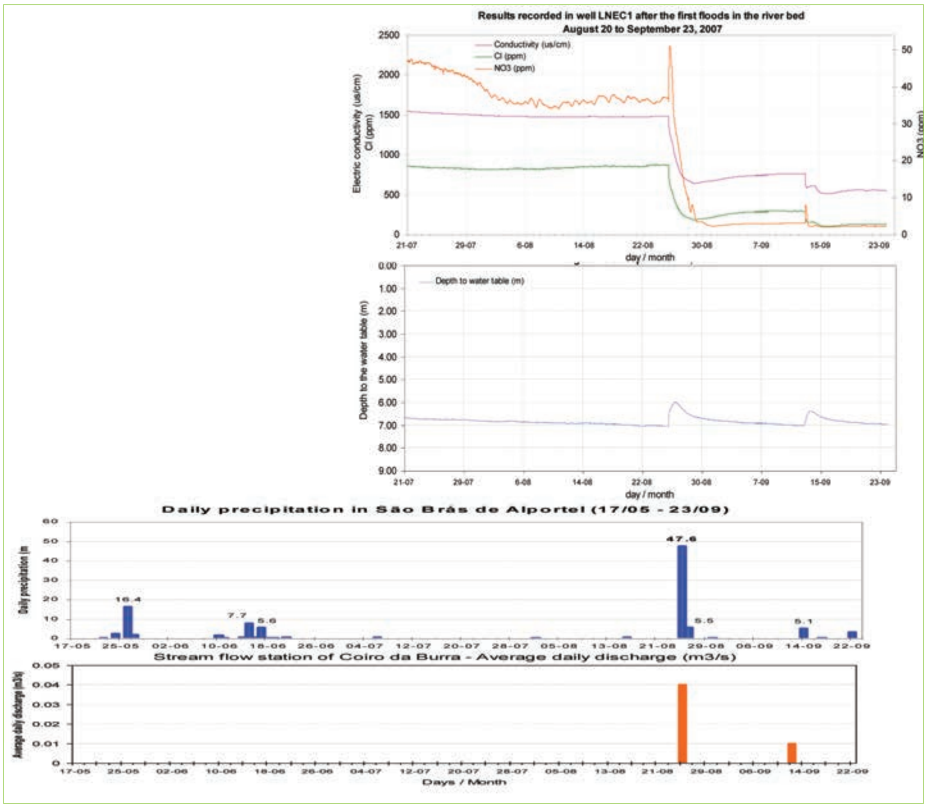

Fig. 6 - Quality results and depth to water table recorded in LNEC1 after the first flood in the river bed. Results comparison with daily precipitation values recorded in São Brás de Alportel climatological station and with average daily discharge recorded in Coiro da Burra stream flow station, in the same period

Fig. 6 - Risultati registrati nel LNEC1 dopo la prima inondazione del letto del fiume. Comparazione dei risultati con i valori delle precipitazioni giornaliere registrate nella stazione climatologica di São Brás de Alportel e con il deflusso medio giornaliero registrato nella stazione idrometrica di Coiro da Burra, nello stesso periodo.

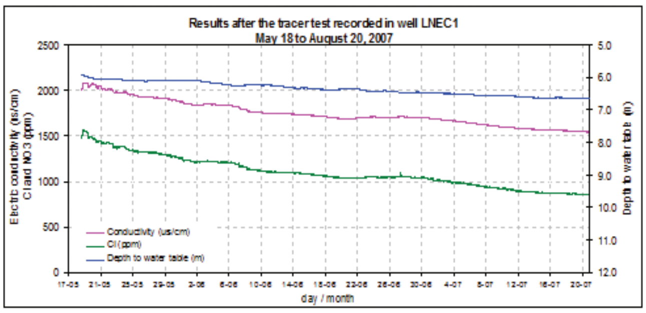

Fig. 7 - Results after the tracer test experiment recorded in LNEC1, concerning electrical conductivity, Cl^- concentrations and depth to water table variations (undisturbed groundwater flow).

Fig. 7 - Risultati dopo l'esperimento con tracciante effettuato al LNEC1, riguardante la conducibilità elettrica, la concentrazione di Cl e la variazione del livello piezometrico (in condizioni di deflusso sotterraneo naturale).

Rio Seco river bed geophysical assessment

During the end of January 2007, a geophysical campaign was made. Figure 9 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 experiment developed during May 2007. The new electrical resistivity profiles performed during the tracer experiment showed a very good correlation with the electrical conductivity values observed in the monitoring wells and allowed the detection of a saline plume migration during the recharge experiment.

The longitudinal profile resistivity values were measured twice a day during the infiltration and tracer test experiments, and also repeated a week after the test conclusion. Some transversal profiles were also measured during the tracer test. Figure 10 presents two examples of the electrical resistivity results obtained in the longitudinal profile before and during the saline injection. In LNEC Report named “Time-lapse resistivity tomography with a saline tracer for the Gabardine Project” (Mota, 2008) a more detailed description of this geophysical assessment is presented.

Complementarily, it was included a preliminary development of an optimization model that merges restrictions and parameters for the objective function. Its future application will allow selecting more adequate techniques considering the maximization of the improvement of water quality and total cost minimization.

Conclusions of the GABARDINE Campina de Faro case study

The main goal of GABARDINE project was to optimize groundwater rehabilitation through implementation of MAR, minimizing the effects of diffuse pollution caused by agricultural practices in Campina de Faro. Besides the development of infiltration tests, several tracer experiments have also conducted in (1) three infiltration basin, with different soil types; (2) two river bed infiltration basins; (3) one 5m diameter infiltration well (“nora”) and, (4) one 0,5m diameter infiltration well. The results gathered, depending on hydraulic heads and on soil types, eventually allow the extrapolation of infiltration rates to other case study areas, with similar

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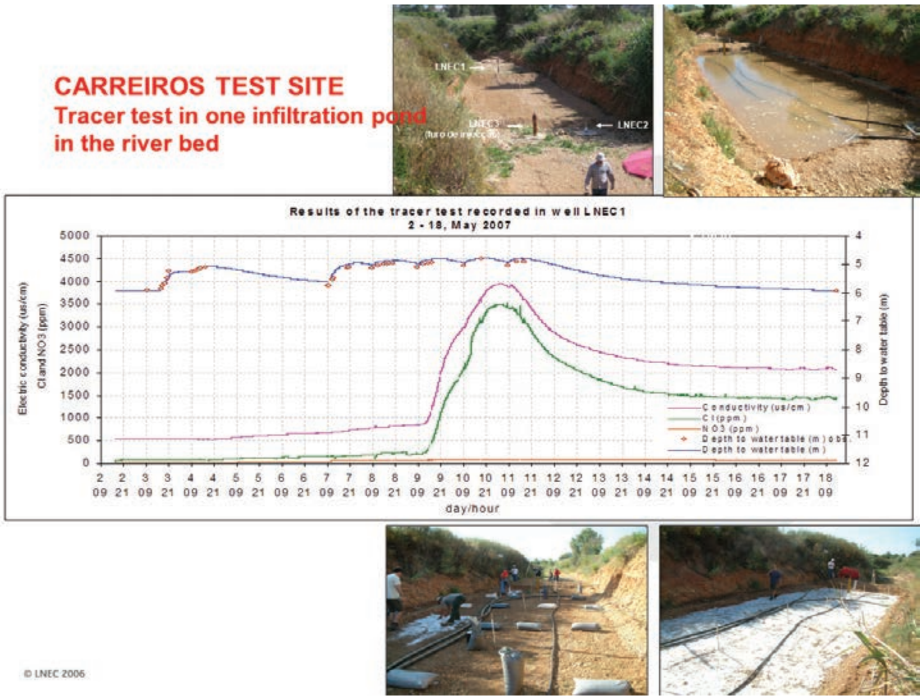

Fig. 8 - Results of the Rio Seco at Carreiros tracer test experiment recorded in LNEC1, concerning electrical conductivity, Cl⁻ concentrations and depth to water table variation.

Fig. 8 - Risultati del test con tracciante nel Rio Seco a Carreiros registrati nel LNEC1, riguardanti la conducibilità elettrica, la concentrazione di Cl^- e la variazione del livello piezometerico.

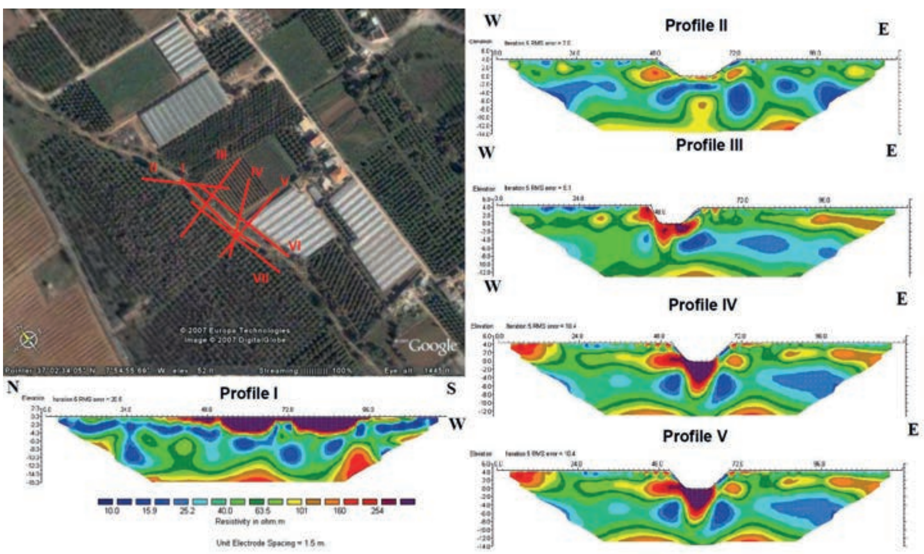

Fig. 9 - Geophysical assessment using electrical resistivity profiles intersecting the infiltration basins at the river bed (Rio Seco at Carreiros test site; Mota, 2008).

Fig. 9 - Analisi geofisica usando i profili di resistività elettrica attraversoi bacini di infiltrazione nel letto del fiume (Rio Seco nel sito test di Carreiros; Mota, 2008).

soil types, as shown in figure 11: (a) infiltration rates vs. type of technology used (infiltration basins in the field or in river bed and, large and medium diameter recharge wells); and, (b) infiltration rates vs. type of soil available in the Algarve at Campina de Faro and Rio Seco). This goal aimed the assessment in the Portuguese study area of problems resulting from the application of these practices. Today they are well documented in terms of groundwater quality. The study area was designated as a vulnerable area concerning nitrate concentration by the application in Portugal of the Nitrates Directive (http://ec.europa.eu/environment/water/water-nitrates/index_en.html). Together with the "good quality status" referred by the Water Framework Directive (Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy, http://ec.europa.eu/environment/water/water-framework/index_en.html), these are the main reasons for the implementation of infrastructures aiming at improving the groundwater quality in a section of this aquifer allowing, on the other hand, to increase groundwater availability with good quality in the Algarve region.

The Project improved scientific knowledge of several methodologies aimed not only to improve groundwater quality, but also allowing subterranean storage of water with good quality in wet year periods of major availability and during events of heavy rainfall.

Several MAR experiments were accomplished in the Portuguese case study area during the second year of the Project.

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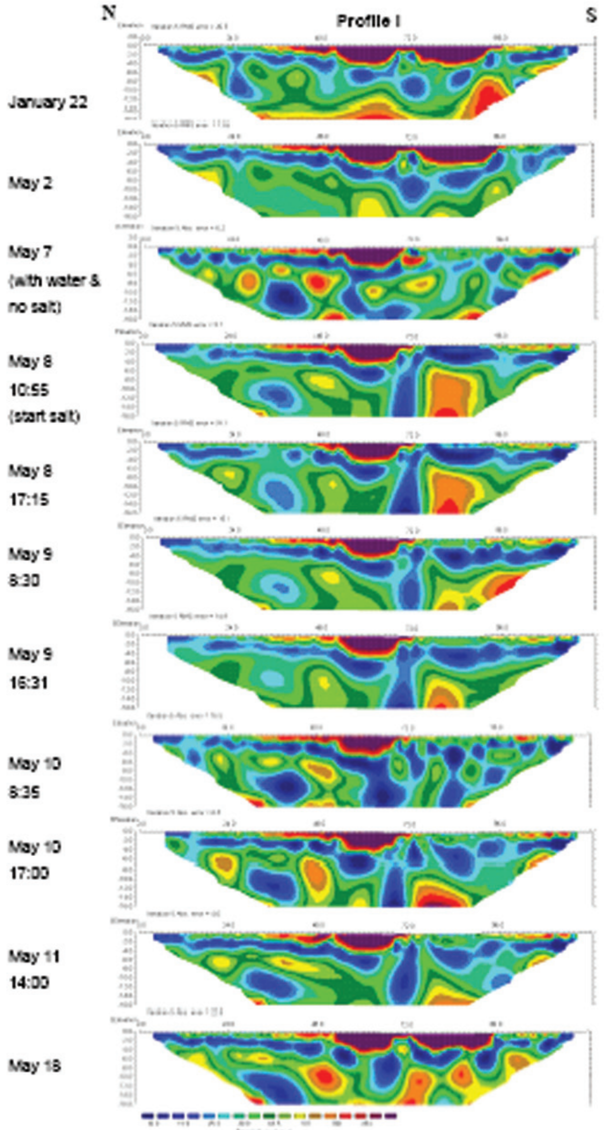

Fig. 10 - Geophysical assessment in the longitudinal electrical resistivity profile before and during the tracer test at the river bed (Rio Seco at Carreiros test site; Mota, 2008).

Fig. 10 - Analisi Geofisica di resistività elettrica lungo il profilo longitudinale prima e durante il test con tracciante nel letto del fiume (Rio Seco nel sito test di Carreiros; Mota, 2008).

The purpose of the experiments was to assess and quantify the effectiveness and applicability of the different MAR methodologies, in a way that the achieved results can contribute to the development of the GABARDINE Decision Support System (GDSS).

Final Remarks

Storing water in aquifers during times of excess can help address water scarcity challenges experienced in many parts of the Mediterranean Basin. Moreover, water quality can be improved through aquifer transport and storage, due to chemical and biological reactions. (MAR), Soil-Aquifer-Treatment (SAT) systems and Aquifer Storage and Recovery (ASR) can be proved as key technologies to solve Mediterranean's

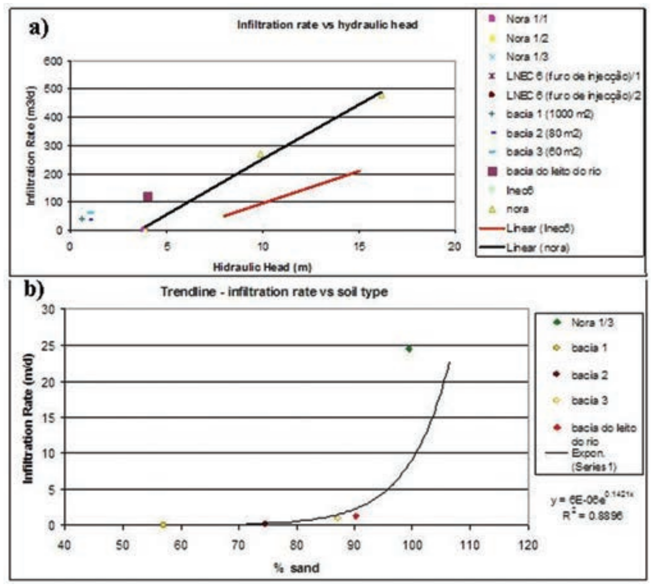

Fig. 11 - a) Infiltration rates vs. the type of technology used (infiltration basins in the field or in river bed and, large and medium diameter recharge wells); b) Infiltration rates vs. the type of soil available in the Algarve at Campina de Faro and Rio Seco.

Fig. 11 - a) Tassi di infiltrazione vs il tipo di tecnologia usata (bacini di infiltrazione in campo o nel letto del fiume, pozzi di ricarica a largo o medio diametro); b) Tassi di infiltrazione vs il tipo di suolo presente nell'Algarve a Campina de Faro e Rio Seco.

upcoming water crisis by linking water reclamation, water reuse and water resources management. The diversity and complexity of the water problems in the Circum-Mediterranean area call for a clear and focused research program in order to successfully meet the imminent challenges, as well as to direct the ongoing developments towards socioeconomic and ecological sustainability.

Following the fruitful achievements of GABARDINE project in Portugal and the i+R&D DINA-MAR project in Spain, the new FP7-ENV-2013-WATER-INNO-DEMO MARSOL project, which started Dec. 1st, 2013, will envisage advancing the use of MAR as a sound, safe and sustainable strategy for improving water security by demonstrating that MAR is a key solution to water scarcity not only in Portugal and Spain but also in all Circum-Mediterranean region.

Acknowledgements:
GABARDINE Project financial support from 6th Framework Programme for Research and from LNEC,
FP6 ASEMWATERNet Coordination Action financial support from 6th Framework Programme for Research and from LNEC,
WATER INNO-DEMO MARSOL project financial support from 7th Framework Programme for Research.

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