Combined use of geophysical methods and water information to assess human activities impacts on karst groundwater quality

Teresa E. LEITÃO(1), Rogério MOTA(2), Maria Emília NOVO(3) & João Paulo LOBO-FERREIRA(4)

(1) PhD in Hydrogeology, Senior Research Officer with Habilitation, Groundwater Division of National Laboratory for Civil Engineering (LNEC), tleitao@lnec.pt

(2) PhD in Geophysics, Research Officer, Engineering Geology and Environmental Geotechnics Division of LNEC, rmota@lnec.pt

(3) PhD in Environmental Engineering, Research Officer, Groundwater Division of LNEC, enovo@lnec.pt

(4) Dr.-Ing. Habil in Civil Engineering, Principal Researcher and Head of LNEC Groundwater Division, lferreira@lnec.pt

Abstract: The presence of high vulnerable karstic systems in areas of intense human activities often results in the degradation of existing groundwater quality status. The water quality (WQ) protection and improvement, as required by the WFD (Water Framework Directive), depends on a correct prioritisation of the most relevant impact pollution sources to be identified within complex multi-stressor conditions. This paper presents a methodology that combines the use of hydrogeology, WQ and quantity data, and geophysical methods to access the human activities' impacts upon the water cycle, focusing on the WQ of a karstic system.

The procedure was applied to a section of the Portuguese karstic Querença-Silves aquifer, under FCT PROWATERMAN project PTDC/AAC-AMB/105061/2008 (http://www.lnec.pt/organizacao/dha/organizacao/dha/nas/estudos_id/PROWATERMAN). During this study an interpretation of the possible interconnections between pollutant sources, their pathways and local surface-groundwater connections was analysed, based on data obtained from field campaigns.

As a result of this study, the most relevant recharge areas and the identification of influent sites of the local stream to the aquifer were acknowledged. The areal distribution of the diffuse pollution sources was verified in the monitoring points, especially those located in the near downstream of the larger farming plots. Pollution in this karst aquifer results from seepage through agricultural areas and infiltration in the influent points of the stream. This aspect of stream influence upon the aquifer means that pollution sources located upstream the area of the aquifer (e.g. WWTP (Wastewater Treatment Plant)) can contribute to the aquifer pollution.

Key words: groundwater quality, impacts, human activities, geophysical methods and water information.

1. INTRODUCTION

In contrast to sedimentary terrains where groundwater occurs in the pores of horizontal strata of rocks like sandstone or in the interstitial spaces of deposits, in hard-rock terrains groundwater occurs in fractures, fissures, crushed zones and joints. In karstic formations, like that present in the Ribeiro Meirinho (RM) case-study, water pathways carved within the rock formation play an important role in the circulation of groundwater.

The use of geophysical methods, namely the electrical methods, as a non-intrusive method is a common procedure to complement discrete field data information concerning water quantity and quality data. Among them, the resistivity method is one of the most suitable for groundwater studies. Electricity is conducted electrolytically by the interstitial fluid, so it is controlled by porosity, water content, WQ, and dissolved salts than by the resistivity of the rock matrix (Yazicigil and Sendlein, 1982; Nielsen, 1991; Meju, 2002). Determination of the water table's position by the resistivity method is based on the fact that the saturated materials will have lower resistivity than the unsaturated materials.

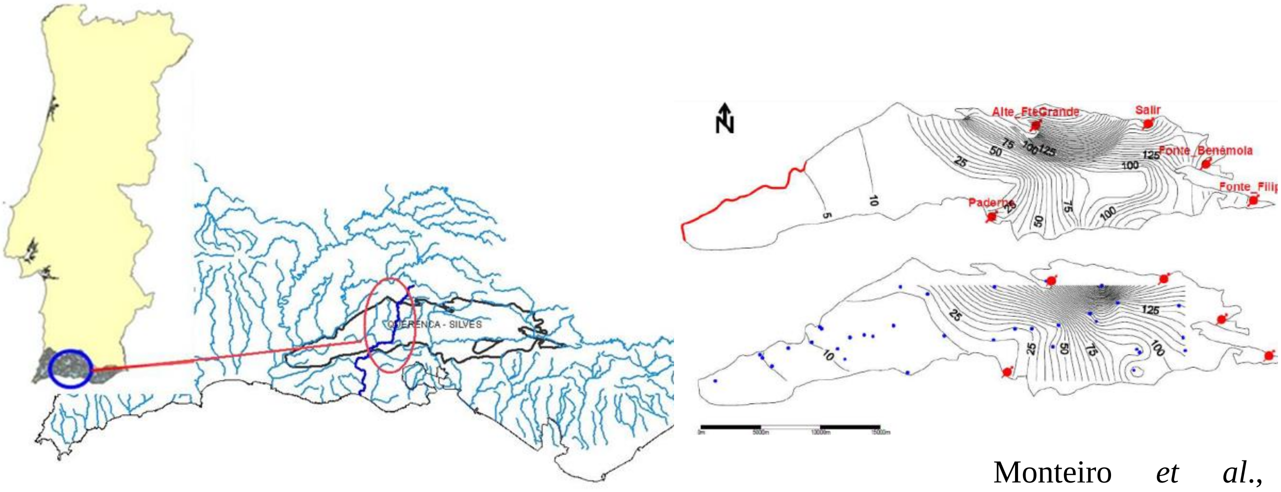
With geophysical surveys one wanted to assess the subsurface on locations where aquifer recharge is likely favourable and simultaneously needs protection measures in order to guarantee groundwater's quality.

Sites selection for the geophysical survey was based on 2011 water campaign and in the knowledge gathered from previous works in the region (Monteiro *et al.*, 2006; Reis *et al.*, 2007), namely the fact that due to its karstic nature there are locations where streams like RM can contribute to the aquifer recharge.

2. SITE DESCRIPTION

2.1 Location and characteristics

The RM case-study area is located northeast of Silves, Algarve region, Portugal (Figure 1). The hydrogeological setting is the Querença-Silves aquifer, a karstic formation with a complex compartmented structure; its western area has a well-developed karst, westwards flow direction, with the main discharge areas along the Arade river, with particular relevance to Estombar springs (west most point); its eastern area has more random flow directions and less regular piezometric surfaces (Figure 1). The tectonic activity of this region results in its subdivision, with more or less constrained and restricted hydraulic links (Mendonça and Almeida, 2003; Monteiro *et al*., 2006).



Monteiro *et al*., 2006

Figure 1 – Site location along RM stream and central-western area of Querença-Silves aquifer and its piezometry

RM stream is located in the central-western area of Querença-Silves aquifer and its upper reaches are located outside the aquifer, in Serra Algarvia. The latter are Palaeozoic terrains, composed mainly of schist and graywakes, essentially impervious lithologies, being therefore the main source of water for this stream until it reaches the Jurassic limestones and other calcareous formations composing the karst aquifer of Querença-Silves.

The water availability in the region is low and therefore the importance of its preservation is clear. Accordingly to Costa *et al.* (1985) the average annual rainfall of the Querença-Silves Aquifer System, ranges from about 550 mm/year on the southwesterner zone of the aquifer system, increasing to E and NE, with 800 mm/year of rainfall in its SE boundary, reaching values above 800 mm/year across the eastern sector. There is evidence of a trend for the occurrence of most intense droughts at around a 10 years period. The average annual recharge of Querença-Silves aquifer, for the period 1941-1991, was estimated as 314 mm/year, i.e. 100 hm^3/year (Oliveira *et al.* 2008). For the period 1979-2009 it was estimated an average annual recharge value of 294 mm/year (Oliveira *et al.* 2011), equivalent to 94 hm^3/year.

Due to its karstic properties, there is a strong relation between the aquifer and the streams with some influent sections that can significantly contribute to recharge it (Monteiro *et al*., 2006; Reis *et al*., 2007). This is the case of RM, which undergoes a sharp reduction of the flow rate when it reaches the carbonated formations, having several sinks in his bed. It is estimated that besides direct recharge, an extra amount of 62hm^3/year, originated from surface flow produced on the drainage area, infiltrates when the rivers crosses the aquifer system (Oliveira and Oliveira, 2012).

2.2 Main stressors

The study area is located in a rural region and the main WQ stressors are related to the agricultural activity. The other existing pollution sources are a WWTP, septic tanks and livestock production units. The agriculture pattern is dominated by citrus orchards, with a very marginal component of market gardens and vineyards (Figure 2). Pollution loads of N and P are given in Table 1 for each type of pollution source.

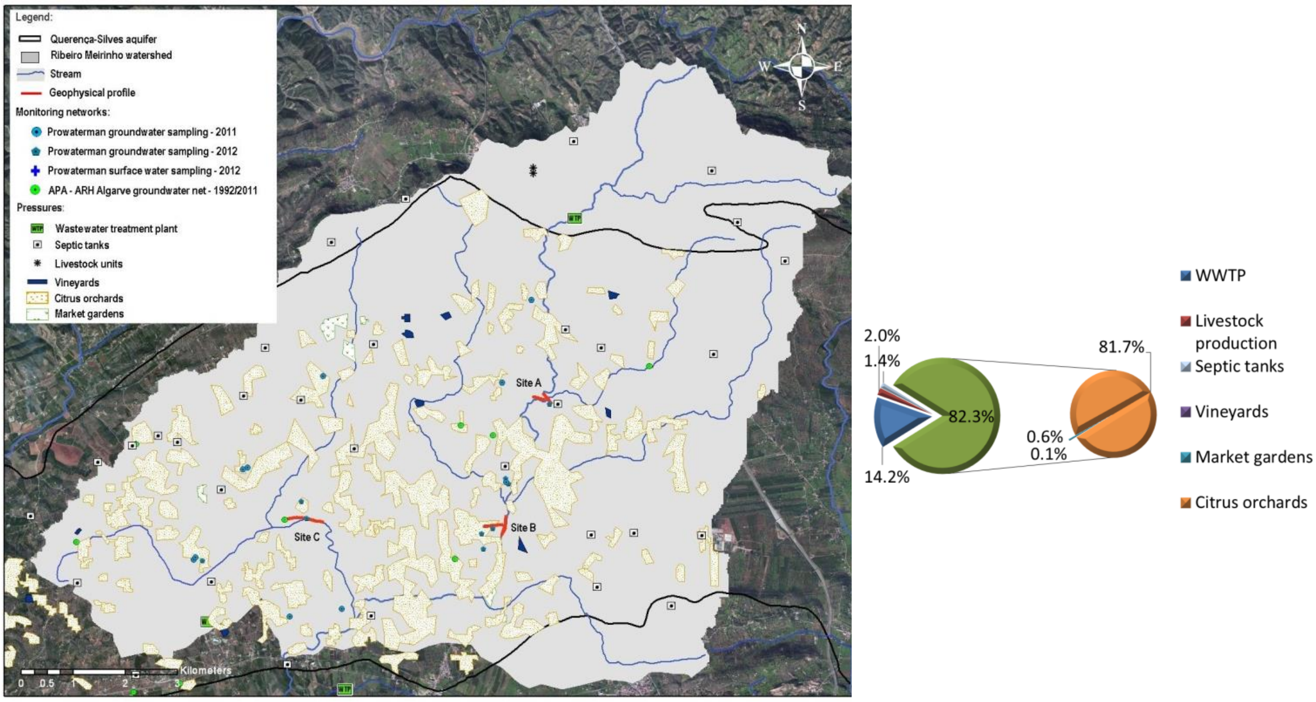


Figure 2 - Soil occupation, main stressors and monitoring sites

Table 1 – Pollution loads by type of source

Origin	**Flowrate (hm^3/y)/rejection area (ha)**		**Rejection/application**		**% losses**	**Loads (ton/y)**	
WWTP	0.262(a) to 0.32(a)	hm^3/y	157(b)	mgNO$_3^-$/L	100%	9.31 11.37	N
			5.5(b)	mgP/L		1.44 1.76	P
Agriculture							
Citrus orchards	1,358.530	ha	160	kgN/ha/y	30%	65.21	N
			80	kgP/ha/y		32.60	P
Vineyards	15.830		20	kgN/ha/y		0.095	N
			13.5	kgP/ha/y		0.064	P
Market gardens	30.570		48	kgN/ha/y		0.44	N
			21.6	kgP/ha/y		0.20	P
Septic tanks	Point source		5783.5	kgN/y	20%	1.16	N
			1499.8	kgP/y		0.30	P
Livestock production	Point source	n.º	1594.2	kgN/y	100%	1.59	N
			531.4	kgP/y		0.53	P

(a)http://www.google.pt/url?sa=t&rct=j&q=&esrc=s&source=web&cd=7&ved=0CGQQFjAG&url=http%3A%2F%2Finsaar.inag.pt%2Fbo%2Fcontents%2Fresultadostabelasdados%2F12681367577896.xls&ei=pwrTUMKeGYaXhQesvYGABg&usg=AFQjCNFTwsRf1bC1PHLXOQtdvoe5IvyxUQ&bvm=bv.1355534169,d.ZG

(b) Data from: http://www.aguasdoalgarve.pt/qualidadeefluente.php

Data from INSAAR shows WWTP effluent directly rejected in RM after a secondary treatment, with an average flow rate between 0.262 and 0.320 hm^3/year. The following parameters are measured on a monthly basis: pH, BOD5 (mgO_2/L), COD (mgO_2/L), P total (mgP/L), N total (mgN/L), Nitrates (mgNO_3/L), TSS (mg/l), Cl (mgCl/L), and Coli (ufc/100mL). Figure 3 shows the results of nitrates and coliforms concentrations in WWTP and in RM's surface water stream. The nitrates annual average concentration varies from 117-197 mgNO_3^-/L.

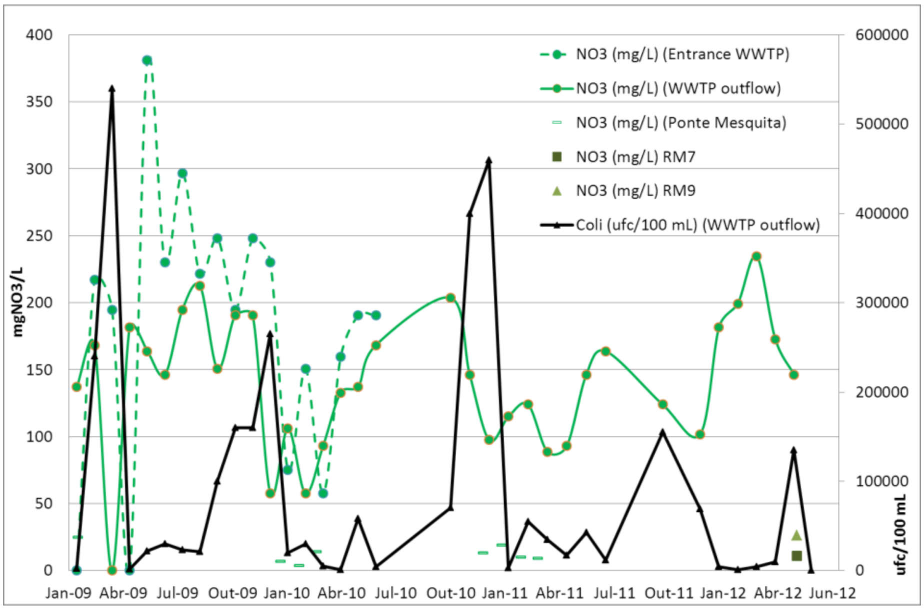


Figure 3 - Concentration in nitrates and coliforms in WWTP and in surface water stream (RM)

For the farming areas, the annual loads considered the amount of fertilizers traditionally used in the area for each specific culture. It was considered that 70% was subtracted by plant requirements and 30% are lost to the soil due to excess of fertilization.

For septic tanks the pollution load amount of N and P per unit was calculated by evaluating the average population in each human settlings (village) connected to such structures multiplied by the pollution load by person-equivalent. Due to the differences in population density, the average population by village will be different from one county to another, and this was accounted for in the calculations. The pollutant removal capacity of the septic tanks was also considered, assuming that they are running in perfect conditions, therefore having a removal capacity of around 80% of the pollution load produced. The remaining 20% are lost.

Livestock production units are pig production for meat, and are located outside the aquifer, in the upper reaches of RM. It was considered that their discharge into this stream is mainly as an entrance to the system since the soil outside the area is impervious until it reaches the aquifer terrains, where part of its flow is assumed to infiltrate. The livestock pollution loads/unit was calculated as the average of the total value considered to be point source discharged by the livestock units in the study area. The data were gathered from the recent watershed planning reports (Nemus, Hidromod and Agro.ges, 2012).

Having in mind the annual recharge value (Oliveira e Oliveira, 2012) and the annual loads calculated, we can estimate that recharge water in the cultivated areas has an average concentration of 28.65 mgNO_3^-/L, which corresponds to 65.7 ton N (sum of agriculture in Table 1) converted to NO_3^- and divided by 19.25 hm^3 annual recharge value in the areas with cultivated outcrops.

3. MATERIALS AND METHODS

3.1 Water quality monitoring

Based on two main pressures in the watershed (Figure 2), a general assessment of the WQ was made, later on focused on a specific area known to be influent in some sections of the stream bed.

WQ was monitored for both surface- and groundwater. The first campaign was carried out in May 2011 (Figure 2) and aimed at a global characterization of the water status, identifying areas with poorer status. The following chemical parameters were analysed: Na^+, Ca^{2+}, K^+, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, NH_4^+, NO_2^-, PO_4^{3-}, Al, As, Be, Ba, Cd, Cr, Zn, Cu, Fe, S, Cu, Pb, Zn, organic matter, total hydrocarbons, detergents, and total coliforms. As a result of the data obtained, the case-study area was focused on RM stream and the surrounding groundwater, being the second monitoring period carried out in May 2012. In all campaigns, representative samples were taken, after the stabilization of electrical conductivity and pH or after a significant volume of water withdrawal.

The local water authority (APA-ARH Algarve) is also carrying out a monitoring program since 1992, with historical information.

3.2 Geophysical surveys

Electrical resistivity measurements are a function of the type of soil or rock, its porosity, and the conductivity of the fluids that fill the pore spaces. In a resistivity survey, a direct current of intensity I is passed into the ground through a pair of current electrodes and the resulting potential drop ΔV is measured across a pair of potential electrodes. The resistivity is given by

$$\rho = K \frac{\Delta V}{I} \qquad \text{(Eq.1)}$$

Where, K is a geometric factor depending upon the relative position of the four electrodes (electrodes array).

Modern geophysical equipment like that used in the present survey, the ABEM S4000 resistivimeter with a multielectrode cable system, are characterised by automatic switching electrodes equally spaced along the profiles. This allows a quick collection of large data sets, which permits the execution of 2D electrical resistivity tomographies (ERT).

Three sites were selected from 2011', water campaign results to perform ERT (Figure 2). Sites selection naturally ought to take into account the local geological environment and the available space for the electrodes array. The ERT were performed along six alignments with dipole-dipole array and different dipole distances (dd), in order to have a higher investigation depth or to adequate the spread to the available space: profiles Algoz1 and Algoz2, were performed with dd=6 m (total length=240m); Algoz3, Algoz4 and Algoz6, were performed with dd=10 m (total length=390m), and Algoz5 was executed with dd=8 m (total length=312m).

Collected apparent resistivity data were inverted with RES2DINV algorithm (Loke, 2012), with incorporation of topographic effects. Coordinates on the horizontal axis of each resistivity model are distances from the beginning of the profile, always considering observer's vision in the south-north direction. Resistivity's range is 35-6336 ohm.m for all sites, with lower values in blue.

4. RESULTS

4.1 Water quality

2011' results allowed the conclusion that groundwater has a bicarbonate calcic facies typical of karstic areas. Groundwater from Alg13 (large well) seems to have a direct input from surface water, showing higher chloride content (Figure 4). It was also possible to identify areas with strong influence from pollutant sources, namely by the higher concentrations of nitrates, boron, barium, and copper. These last three are probably related with the influence from the WWTP and the livestock discharges directly made in RM.

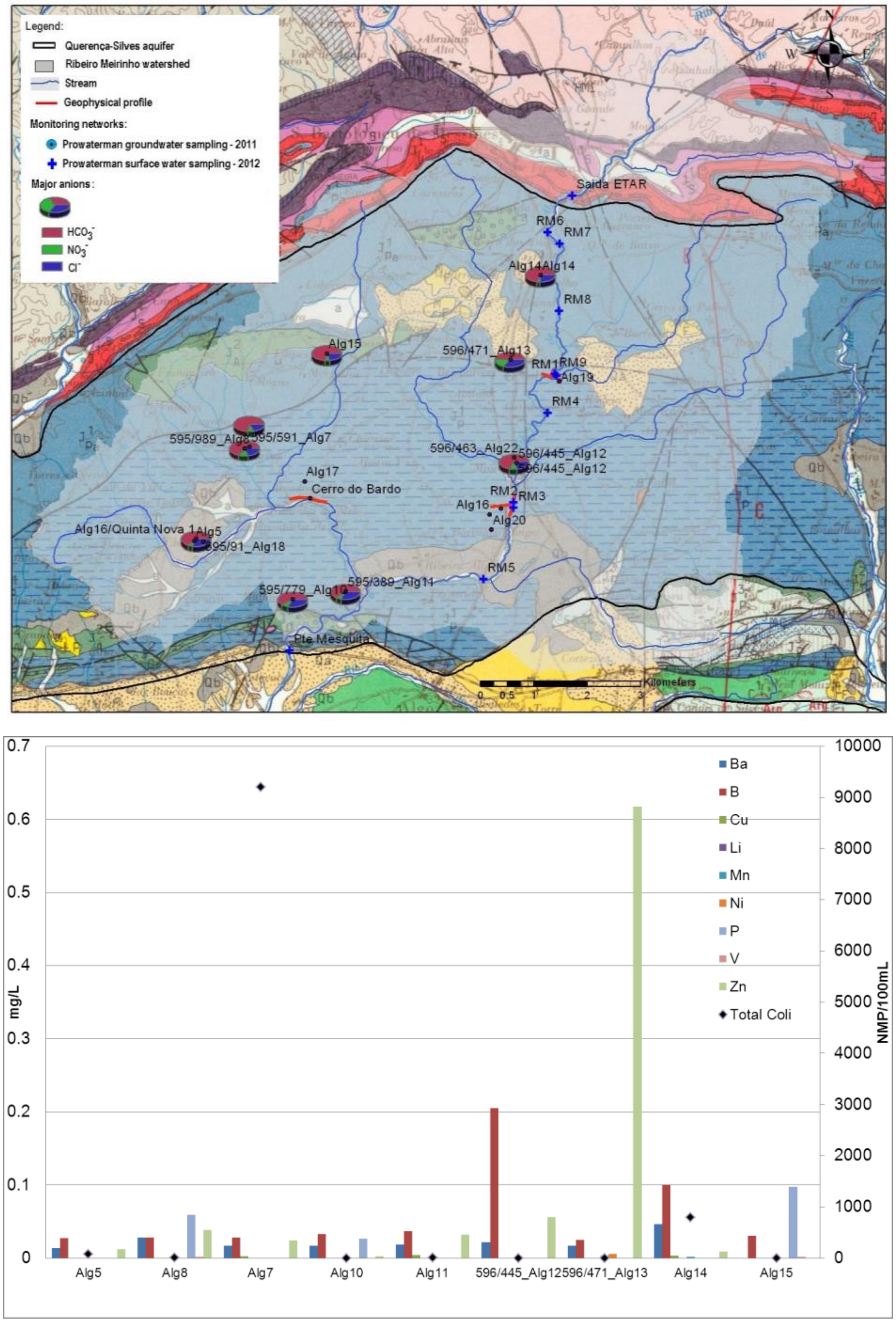


Figure 4 – Groundwater concentration (upper: major anions; bottom: minor elements)

Based on 2011 assessment of groundwater quality, a further campaign was done for surface- and groundwater with data gathered specifically for electrical conductivity (Figure 5) and nitrates (Figure 6), as two representatives of the impact caused by the existing pressures.

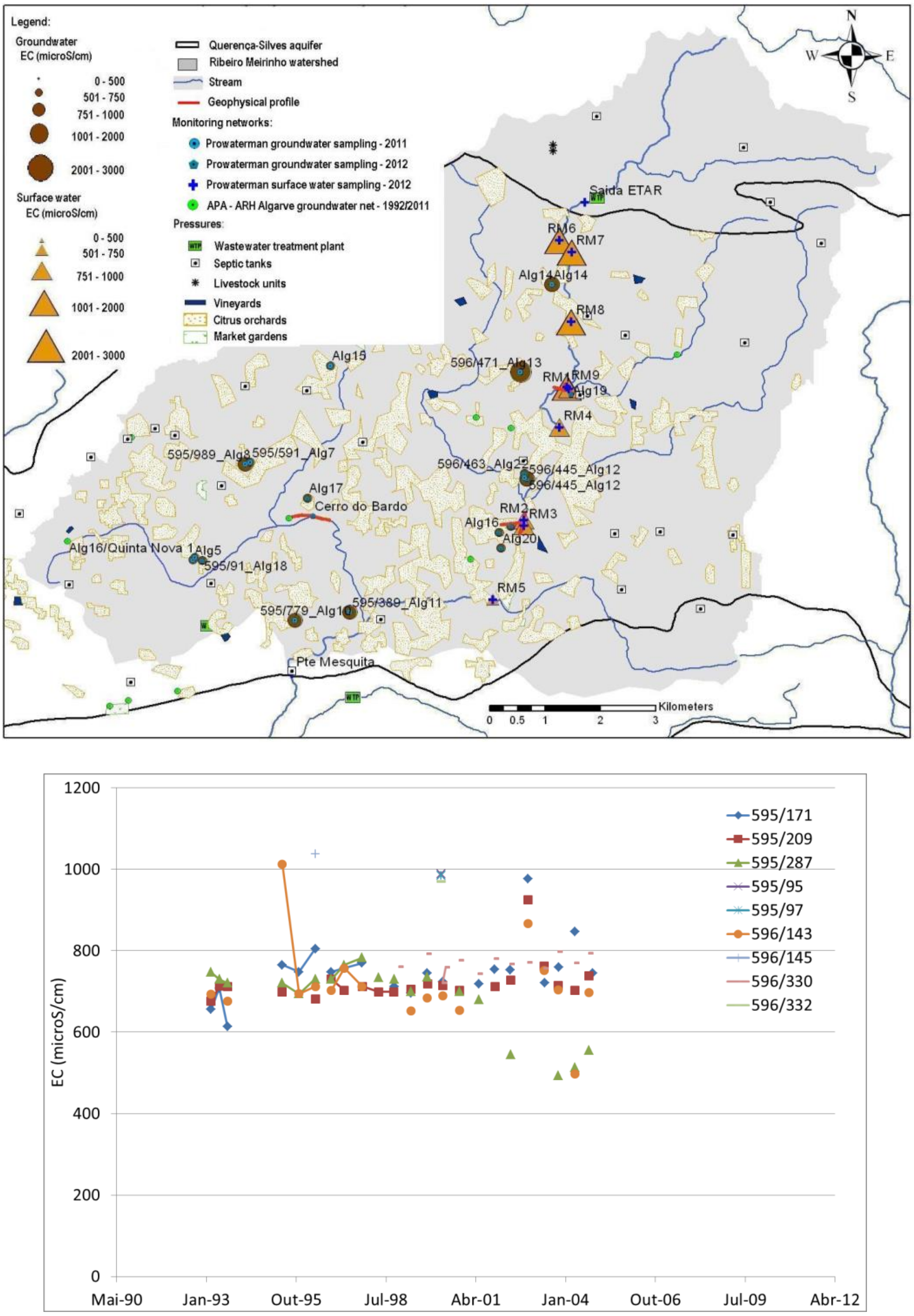


Figure 5 – Electrical conductivity values (upper: in surface- and groundwater; bottom: evolution in groundwater)

From Figure 5 it is possible to see the negative influence of WWTP on surface WQ, as well as some contribution to groundwater in places near this stream. The EC values have been stable along the years, with a small upward trend and an increase of the variance.

For nitrates concentration, it is possible to see that the agriculture land use has a stronger impact than RM (Figure 6). In fact, as previously stated, agriculture practices contribute with loads around 6 times higher than those from WWTP (Table 1). In the long term values, a seasonal effect influence (due to fertilization input) is clear in most wells, being also higher its standard variation. This confirms the high recharge rates of this aquifer, which allow the input of cleaner water in periods of low fertilization, decreasing the nitrates concentrations, but also the effect of irrigation charged with excess of nitrates (Figure 6).

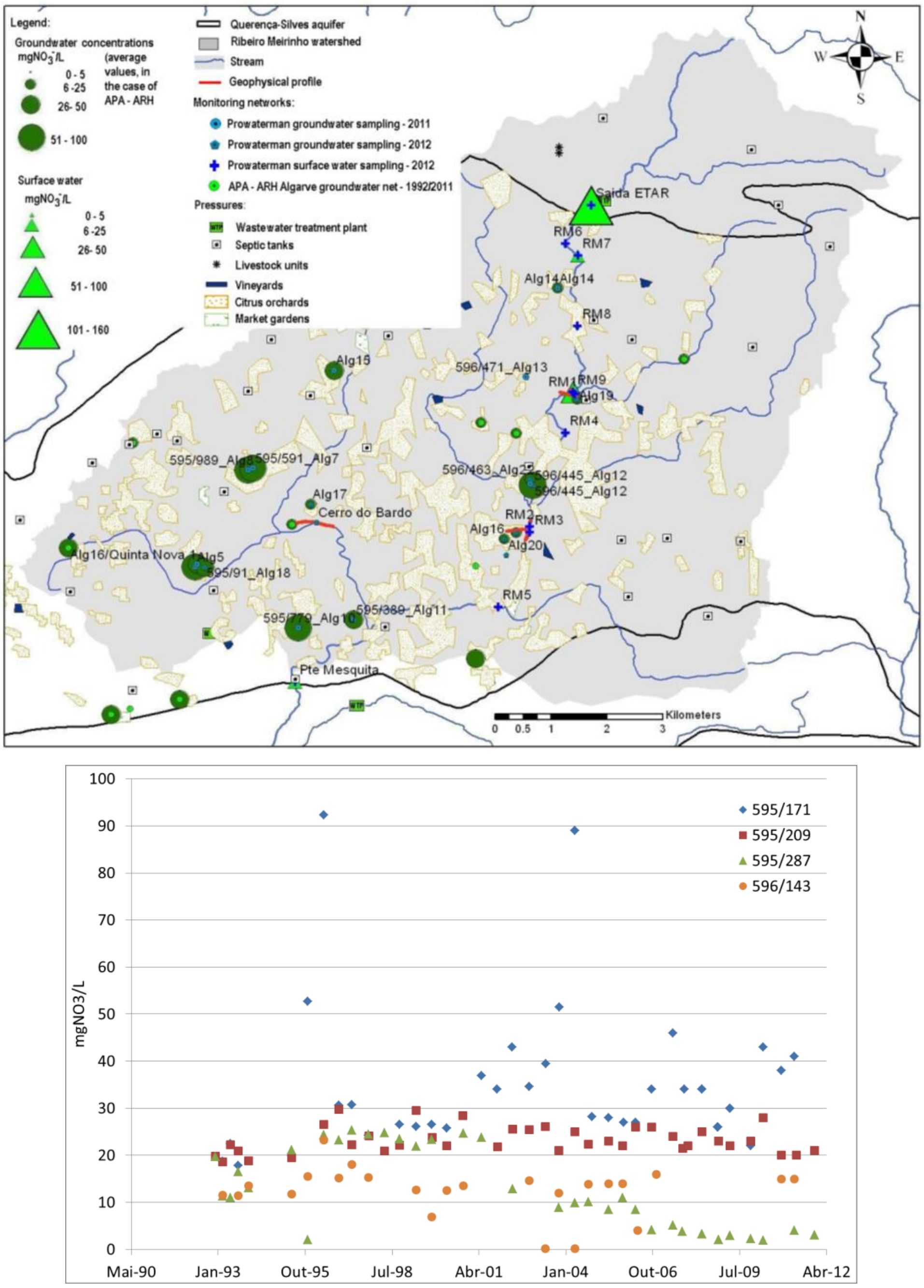


Figure 6 – Nitrate values (upper: in surface- and groundwater; bottom: evolution in groundwater)

4.2 Geophysics: interpretation

At **Site A**, ERT profiles were performed on a meander of RM (Figure 7), and its influence in depth is clearly identifiable by the low resistivity zone in Algoz1 (0-160m) and Algoz2 (100-240 m) (Figure 8). This points out that this place requires some attention concerning aquifer protection, since there is a clear capacity for surface water infiltration into the aquifer. The low resistivity values present in the top of Algoz1 (60-108 m) are due to the very clayey nature of the top soil, which showed a high degree of saturation at the time of the survey. The very low resistivity (<15 ohm.m) where the profile crosses RM and near to the well is indicative of the presence of water with high ionic content. The region of higher resistivity in Algoz1, located between the river and the well, coincides with the transition between the two topographic levels on site: one around the level 60 m- where the river flows, and another over level 70 m - where the well is located - and behaves as a barrier to the movement of groundwater, which enhances the recovery of the hydrostatic level of the well after water extraction, as reported by the owner of a neighbouring house.

Figure 7 – Location of profiles (from Google earth): top left – Site A (Algoz1 and Algoz2); top right – Site B (Algoz3 and Algoz4); bottom – Site C (Algoz5 and Algoz6). Blue circle depicts: the man-made water wells at sites A and C, and the water supply borehole at site B.

Site B – ERT Algoz3 (Figure 8) presents a top layer of relative low resistivity (<2240 ohm.m) which correlates with the joint presence of *terrarossa* (a clayey soil) and water with nitrates from orange trees watering. According to the farm owner, when drilling a water supply borehole situated in the vicinity of Algoz3 until 40 m depth the material was very heterogeneous ("crushed rock" in its description) and without water. This description fits well to the regions on Algoz3 and Algoz4 with resistivity greater than 4500 ohm.m (7-47 m depth on Algoz3 and at depth greater than 25 m on profile Algoz4 (0-220 m)). These zones are interpreted as resistive limestone. When well boring reached about 70 m in depth (0 m a.s.l.) the water level rose to 50 m. About the same ground level (0 m a.s.l.) resistivity drops to about 2000 ohm.m in both Algoz3 and Algoz4 (> 240 m), which is correlated to the saturated rock basement. Coincidentally, at this point of Algoz4, RM inflects to southwest, which could be due to the fact that the bedrock is far more compact in the north part of the profile until this point. So the south end of Algoz4 may well be an appropriate place for aquifer recharge.

Site C – resistivity model for ERT Algoz5 (Figure 8) shows a high resistivity value near the well at a higher topographic level. This allows the conclusion that the top soil at this location has a higher permeability than the surroundings since water is being drained into the well, where the hydrostatic level (h.l.) is about 25m deep. This means that the place is good for aquifer recharge, requiring its protection to prevent entry of polluted water into the aquifer. The dike was built for retaining river waters, given the large amount of water that is drained by several sinks existing along its banks and bed, some of which were identified in the course of this survey, on the right bank, between the well and the dike. From Algoz6 stands out the thicker top low resistivity layer upstream of the dike, showing the highest infiltration capacity of the upstream area. This may also be due to the presence of the dike, which holds water that may have circulated in the stream during the previous week. Basement rock has resistivity values in the same order of magnitude of those from Site B, showing the same characteristics at both sites.

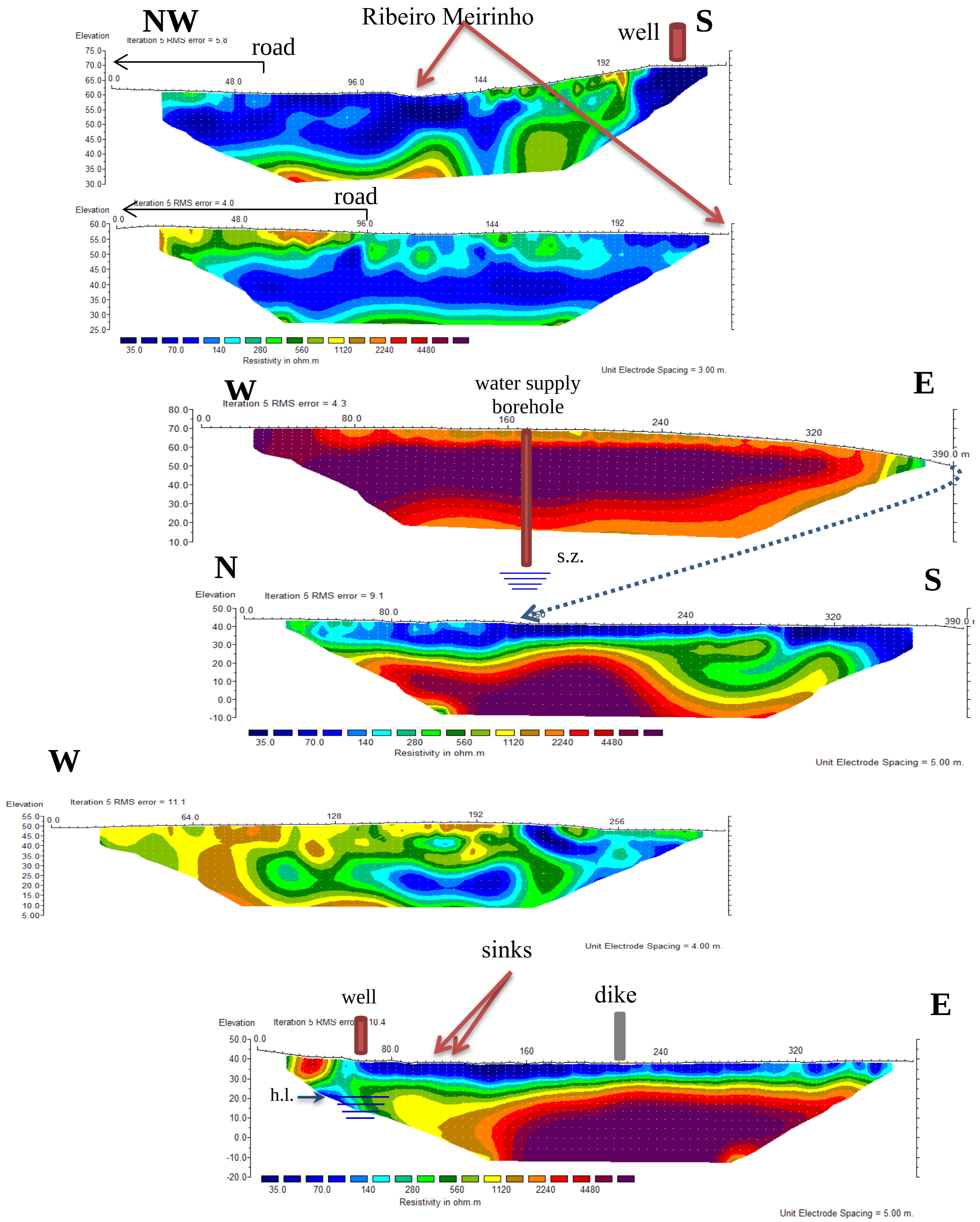


Figure 8 – Resistivity models profiles (upper: Algoz1 (top) and Algoz2 (bottom); middle: Algoz3 (top) and Algoz4 (bottom) (s.z. – top of saturated zone); bottom: Algoz5 (top) and Algoz6 (bottom))

It is worth notice the general increase of top layer resistivity from upstream to downstream, which may be due to the fact that RM stops running between sites A and B. However, this behaviour of the resistivity matches with the decline in the value of electrical conductivity (inverse of resistivity) measured in the samples of surface and groundwater collected in the campaigns of 2011 and 2012.

5. CONCLUSIONS

From the geophysical and water quality surveys it was possible to observe several sites favourable to aquifer recharge and, at the same time, for the entrance of pollutants into the aquifer.

Since the geologic environment is similar between sites A and B and the resistivity rises from A to B, resistivity models confirm the chemical results whereas groundwater quality in poorer in the north (site A) compared to south (site B). In several profiles, top soil seams to act like a filter retaining the contaminants from WWTP and from agriculture activities.

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REFERENCES

Costa, F.E., Brites, J.A., Pedrosa, M.Y., Silva, A.V., 1985 – "Carta Hidrogeológica da Orla Algarvia", Escala 1:100 000, Notícia Explicativa. Serviços Geológicos de Portugal, Lisboa.

Loke, M.H., 2012 – “Rapid 2-D Resistivity & IP inversion using the least-squares method”, Geotomo Software.

Meju, M. 2002 – “Environmental geophysics: Conceptual models, challenges, and the way forward”, The Leading Edge, May 2002, pp. 460-464

Mendonça, L., Almeida, C., 2003 – "A Exploração de Recursos Hídricos Subterrâneos: O Exemplo do Sistema Aquífero Querença-Silves". Revista Recursos Hídricos, APRH, Vol. 24, n.º 3, pp. 53-61, In: e-geo.ineti.pt/edicoes_online/obras/costa_almeida/tp067.pdf.

Monteiro, J.P., Guerreiro, P., Martins, J., Matos Silva, J., Reis, E., 2006 – "A Ribeira do Algibre e os Aquíferos do Algarve Central: Relações entre Águas Superficiais e Subterrâneas". Project POCI/AMB/57432/2004 Groundwater Flow Modelling and Optimisation of Groundwater Monitoring Networks at the Regional Scale in Coastal Aquifers: The Algarve Case-study. In:http://www.cvrm.ualg.pt/projectos/malgar/publ_archive/7_rel-sub-sup-V0_ok.pdf.

NEMUS, ECOSSISTEMA, AGRO.GES, 2011 – “Planos de Gestão das Bacias Hidrográficas Integradas nas Regiões Hidrográficas 6 e 7. Região Hidrográfica 6. Relatório Técnico para Efeitos de Participação Pública”, Lisboa, pp. 386.

Nielsen, D.M., 1991 – “Practical handbook of groundwater monitoring”, Lewis Publishers, pp. 717.

Oliveira, M.M., Oliveira, L., Lobo Ferreira, J.P., 2008 – "Estimativa da recarga natural no sistema aquífero de Querença-Silves (Algarve) pela aplicação do modelo BALSEQ_MOD". 9th Water Congress, Cascais, 15 pp.

Oliveira, M.M., 2011 – "Conceptualização do processo de recarga e do balanço hídrico de sistemas aquíferos no planeamento de recursos Hídricos por sub-bacias hidrográficas". 8º Seminário APRH sobre Águas Subterrâneas, Lisboa.

Oliveira, M.M., Oliveira, L.S., 2012 – “Água, Ecossistemas Aquáticos e Actividade Humana – Projecto PROWATERMAN. Quinto Relatório Temático - Estimativa da Recarga e do Escoamento Direto na Área de Drenagem do Sistema Aquífero Querença-Silves”. Relatório 180/2012-NAS. LNEC, pp. 108.

Reis, E., Gago, C., Borges, G., Matos, M., Cláudio, A., Mendes, E., Silva, A., Serafim, J., Rodrigues, A., Correia, S., 2007 – "Contribuição para o Cálculo do Balanço Hídrico dos Principais Sistemas Aquíferos do Algarve". Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional. CCDR, pp. 41.

Yazicigil, H., Sendlein, L.V.A., 1982 – “Surface geophysical techniques in groundwater monitoring - Part II, Groundwater Monitoring Revue, winter, pp 56-62.