COASTAL LAGOONS AND THEIR WATERSHEDS AS GROUNDWATER DEPENDENT ECOSYSTEMS: A CASE STUDY IN THE SW COAST OF PORTUGAL

António Chambel[1**], Paula Chainho[2], Pedro M. Félix[2], Mª João Correia[2], Carla M. Fernandes[2], José Lino Costa[2,3], Mª Luísa Chaves[2], Tibor Stigter[4,11], Rui Hugman[4,7], Núria Salvador[4,7], Luís Costa[7], Isabel Domingos[2,10], Vera Lopes[2], João Castro[2,5], Teresa Cruz[2,5], André Costa[5], José P. Monteiro[4,7], Luís Nunes[4,7], Ana Silva[4], José Rosa Pinto[6], Ana M. Vidal[8], Isabel Pinheiro[9], Maria José Costa[2], Henrique N. Cabral[2,10], Luís Tavares Ribeiro[4], Luís Cancela da Fonseca[7,12]

1 Geophysics Centre of Évora, University of Évora, Geosciences Department, Rua Romão Ramalho, 59, 7000-671 Évora, Portugal, achambel@uevora.pt
2 Centre of Oceanography, Faculty of Sciences, University of Lisbon, Campo Grande, 1749-016 Lisboa, Portugal
3 University Lusófona of Humanities and Technologies, Campo Grande 376, 1749-024 Lisboa, Portugal
4 Instituto Superior Técnico, Centre of Geo-Systems/CVRM, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
5 CIEMAR and Laboratory of Sea Sciences, University of Évora, Apartado 190, 7520-903 Sines, Portugal
6 Department of Biologic Sciences and Bioengineering, Faculty of Sciences and Technology, University of Algarve, C. Gambelas, 8005-139 Faro, Portugal
7 Centre of Sciences and Water Technologies, University of Algarve, Campus de Gambelas, 8005-139 Faro, Portugal
8 Natural Reserve of the Santo André and Sancha Lagoons, Pavilhão A- Galiza, 7500-022 Vila Nova de Santo André, Portugal
9 Environmental Portuguese Agency/Administration of Hydrographic Region – Alentejo, Rua Eng. Arantes e Oliveira, 193, 7004-514 Évora, Portugal
10 Department of Animal Biology, Faculty of Sciences of the University of Lisbon, Campo Grande, 1749-016 Lisboa, Portugal
11 Water Science and Engineering Department, Hydrology and Water Resources Chair Group, UNESCO-IHE, Westvest 7, 2611 AX Delft, The Netherlands
12 Marine Laboratory of Guia/Centre of Oceanography (FCUL), Av. Na. Sra. do Cabo, 939, 2750-374 Cascais, Portugal
** - Corresponding author

ABSTRACT

The study of groundwater dependent ecosystems opened the opportunity to involve specialists of different areas of knowledge in order to obtain answers for complex interrelations between groundwater and the associated ecosystems. The actual study, carried out in two coastal lagoons of the Portuguese SW coast, showed the high dependency of the marine life and vegetation of the lagoons and associated streams discharging in the lagoons on the fresh water supply of these two lagoons and the high contribution they receive from groundwater in the dry period, which corresponds to more than half of each hydrologic year. Every year, the lagoons are artificially opened to the ocean for a few days to a few weeks, which dramatically changes the inside salinity. The sensitivity of these ecological niches is demonstrated by the strong dependence that some species that are more sensitive to high salinity waters show in relation to the entrance of freshwater resultant from the discharge of the phreatic aquifer of Sines sedimentary Basin. The great biodiversity of these lagoons and its precarious balance is only possible to preserve if the aquifer continue to act as a regulatory factor of the lagoon's salinity. The equilibrium can be changed in the event of overexploitation of the phreatic aquifer, which is not at risk in the near future. In a scenario of climate change the lagoons will benefit from a slow increase in groundwater contribution, due to the rise of sea level, which will be accompanied by a rise in groundwater levels in the aquifer near the sea.

INTRODUCTION

Following a series of previous studies related with biology, geology and water resources, including contamination and prospecting of groundwater resources in the area of a number of lagoons (3) located in the Basin of Sines, a sedimentary basin containing Mesozoic and Cenozoic deposits overlying Paleozoic hard rocks, a project was developed to study (2010-2013) the interactions between surface water, sea water and groundwater and its importance for aquatic ecosystems in lagoon coastal systems. To develop this project an extensive multidisciplinary team of biologists and water specialists were assembled in order to give answers to the behavior of species according to the relations between waters of different origins inside the lagoons.

The main objective of this project was to identify the relations between saltwater, surface water and groundwater in two of the coastal lagoons (Santo André and Melides, Figure 1 and Figure 2) and to evaluate the ecologic responses of the groundwater dependent ecosystems in face of a possible reduction on groundwater recharge in a scenario of climate change or aquifer overexploitation.

In order accomplish with the objectives, the following questions were addressed:

- Does the water balance of the aquifer (recharge/uses) affect the water balance in the lagoons?
- Will the biodiversity of the little river systems and of the discharge zone in the lagoons be affected by the different level of dependency of the rivers in relation to groundwater?
- Will changes in the biodiversity at the interface of groundwater with surface water occur at the same temporal and spatial scale as the ones in the rivers and lagoons?

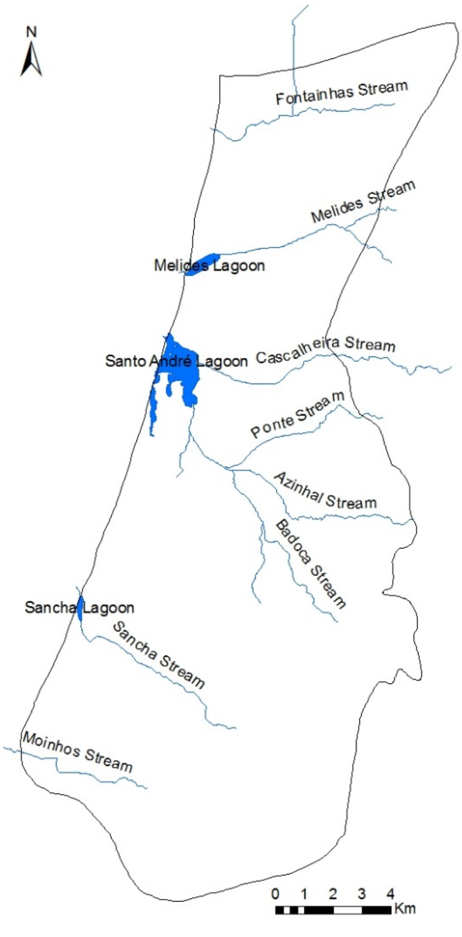

Figure 1. Position of the Santo André and Melides Lagoons in the sedimentary Basin of Sines, including the river network draining to these two lagoons.

Some results of this project can be seen in Correia et al. (2012), Chaínho et al. (2013) or Félix et al. (2013).

THE COMPLEXITY OF WATER INTERACTION IN THE LAGOONS

The system of coastal lagoons in the eastern coast of South Portugal is highly diverse and complex. The Sines sedimentary basin is a complex geologic structure formed since the opening of the Atlantic Ocean, containing formations from Triassic and Jurassic, but lacking the Cretacian in land. Cretacian was detected offshore, which means it was only deposited in the inner part of the basin or, more probably, it was eroded before the deposition of the more recent Miocene and Plio-Pleistocene sediments that overlay the Mesozoic formations.

The evolution of the coast, in a bay environment, had created conditions suitable for the creation of lagoons, which will tend to close in a short time. These lagoons have a maximum deep of a little bit more than 2 m and are very important in the context of the natural areas in Portugal, for flora, birds nesting and feeding and for reproduction of fish on the Portuguese western coast, which happens anytime the lagoons are artificially open to the sea. The evidences show that in the last decades the impact of sedimentation has been incremented, due to deforestation and agricultural use of the lands in the watersheds, creating conditions for a more rapid filling of these lagoons.

The ecological importance of these lagoons had led to the creation of the Natural Reserve of Santo André and Sancha Lagoons (the last one south of Santo André Lagoon and almost filled with sediments nowadays).

The two lagoons defined as targets for this project (Melides and Santo André, Figure 2) were chosen due to their dependence on groundwater, received through little streams which are dependent of the water of the top phreatic aquifer of Sines. Both lagoons are isolated from the sea by sand barriers except for short periods during early spring when the connection to the sea is artificially made by the opening of an inlet in the sand barrier. The reason for this opening is to emulate the natural opening of the lagoons to the sea, which happened naturally in the past (still in the beginning of the twenty century) and also to avoid the eutrophication or contamination of the waters of the lagoons, which can happen through discharges of water from agriculture (rice fields mainly) along the streams that drain into the lagoons. During the period of time that the Lagoons are opened to the ocean, the sea water mixes with brackish water inside the lagoon, influencing the spatial and temporal salinity regime. The inlet provides the main exchange between the lagoons and the sea (discharge of retained materials and recruitment of marine species), and the opening persists for a variable period (ranging from a few days to a few weeks) until the they are sealed off by the sea waves and currents (Cancela da Fonseca et al., 1989; Costa et al., 2003). In 2011 Melides lagoon was opened for 3 days in April and Santo André for 56 days, from March to May (Félix et al. 2013).

Figure 2. Lagoons of Melides (A) and Santo André (B); the sand bar that separates the lagoons from the sea are on the background of both photos.

THE AQUIFER SYSTEM OF SINES

The Basin of Sines contains at least two main aquifers, the top one a phreatic aquifer on marine Miocene and Plio-Pleistocene formations, and the second one an artesian karstic aquifer based in carbonate Jurassic formations. They are separated by the top non-fractured layers of the Jurassic limestones and sometimes also by clay formations of the more recent Miocene sediments. The phreatic aquifer is sometimes defined as multilayered; in many parts drilling has shown clay layers up to 20 m thick. However, it is clear that none of these clay layers are continuous and the location is highly variable along the aquifer, corresponding clearly to lenses in different stratigraphic positions. This is the main reason why the upper aquifer is normally considered, for practical reasons, as a unit, once there is hydraulic connectivity between these water points.

The two aquifers are only separated by the impermeable layer(s) in the aquifer's north-western part (white area on the left map in Figure 3). In the eastern and south part (grey area) the karstic and the porous upper aquifer are linked. The division is clearly marked in Figure 3 by the main fault F-F defined on the map and in both geological and hydrogeological cuts A-B. The general flux on both aquifers occurs from the eastern limit of the aquifer system to the western part (ocean), as it can also be seen in the hydrogeological profile of Figure 3. The recharge area of the confined aquifer is clearly the northern part of the grey area of Figure 3.

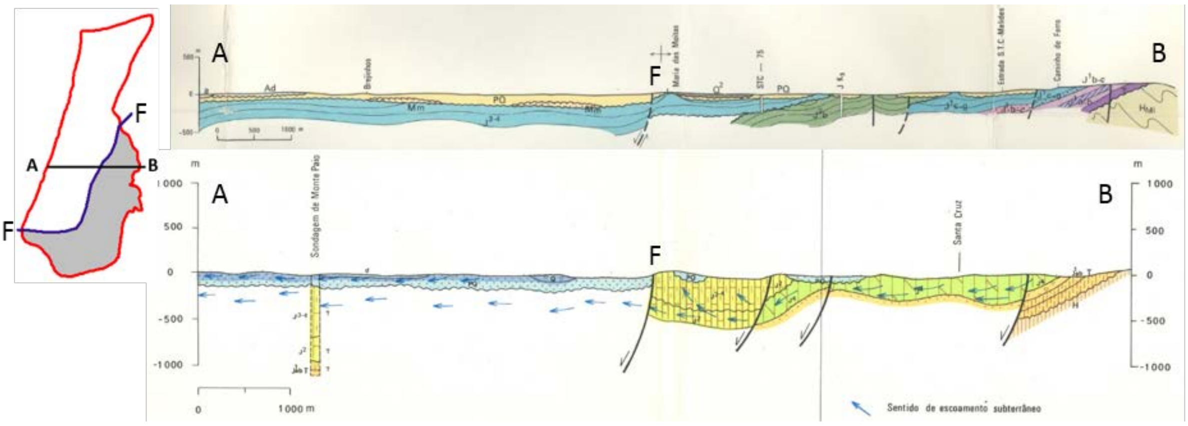

Figure 3. Left: the two areas of the aquifer system of Sines, separated by the fault F-F; in the white area there are two aquifers, the sedimentary porous phreatic aquifer on top and the confined karstic aquifer on the bottom; in the grey area both the karstic and the sedimentary aquifer are linked.
Top profile: Geologic profile of Sines Basin (Oliveira 1984). At right (east) the Paleozoic Formations, over imposed by the Terciary (violet) and Jurassic (blue and green) Formations. On top the sedimentary layers of Miocene and Plio-Pleistocene (yellow).
Bottom profile: Hydrogeologic profile of Sines Basin (Esteves Costa 1994). At right (east) of the fault F both sedimentary (where it exists) and karstic aquifers are linked; at left (west) of the fault, the two aquifers are separated by an impermeable layer and the confined aquifer is between 60 and greater than 100 m deep.

ECOLOGICAL STATUS OF THE LAGOONS

In order to recognize the influence groundwater has in the functioning of the lagoons, the ecological state of both lagoons was analyzed. Principal Components Analysis (PCAs) based on metrics were used for the evaluation of the ecological state, considering benthonic macroinvertebrates, environmental variables and a ratio of non-insects/insects.

The results of this investigation showed:

- That the lotic habitats with finer sediments were associated with a worst ecologic state
- That the better ecologic classifications were associated with a good habitat structure, but also to a minor quality of the existent riparian vegetation.
- A higher taxonomic diversity was associated with the Melides Basin, which seems to depend on a more diverse structure of habitats.
- That the lentic zones have less diversity and dominance of tolerant species, representing less quality.

Inside the lagoons, the study was organized in order to get information near their eastern part, where the influence of streams discharge are more important (at 50 m from the margin) and at 200 m from the eastern margin, where the influence of the streams are less important (Figure 4). Two more points were considered (7, 8) in the Lagoon of Santo André, in this case closer to the sand bar and ocean, but where some influence from the aquifer is noted (Caniços outflow); the same was considered in Melides Lagoon with points 3 and 4.

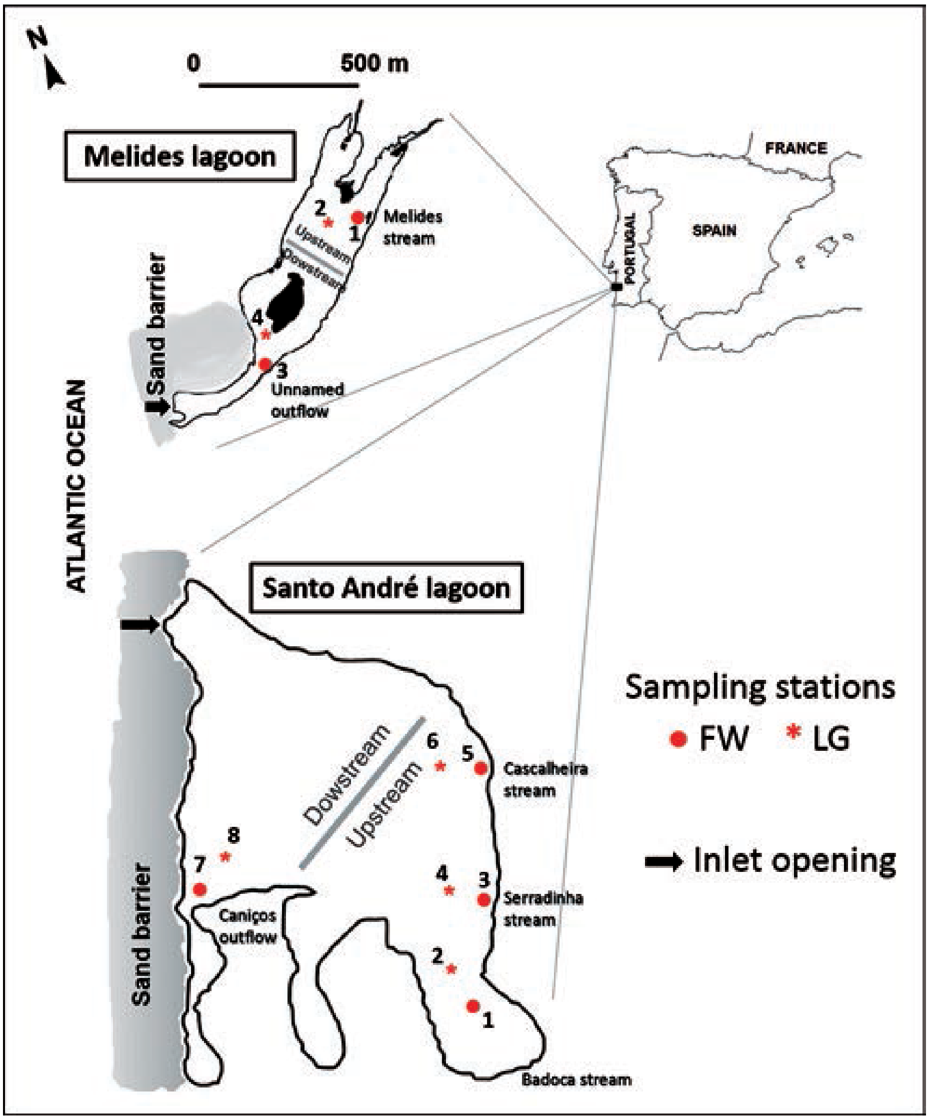

Figure 4. Study area with the location of the sampling stations, with indication of freshwater tributaries and groundwater outflows. FW – direct freshwater influence zone (50 m of discharge); LG – away from the direct freshwater influence (200 m of discharge) (Félix et al. 2013).

RELATIONS BETWEEN GROUNDWATER AND SURFACE WATER IN THE LAGOONS

The study also showed that the direct interaction between the groundwater of the phreatic aquifer and the water of the lagoons is probably null or near null. The lagoons in the past were much more extensive than today and its basins have suffered subsidence in the past. So, the bottom and actual margins of the lagoons are formed by fine sediments (muds) reaching more than 20 m deep, going up to 40 m in some cases. This geological environment does not permit an extensive direct contact between the water in the lagoons and the phreatic aquifer. However, as a previous study showed, the streams discharging in the lagoons are totally dependent on groundwater during most part of the year. Therefore, the lagoons receive groundwater indirectly through these streams (Chambel & Monteiro 2007; Monteiro et al. 2008), and the entrance of groundwater in the lagoons is not diffuse, but concentrated in the mouth of each stream in the eastern margin of both lagoons. Modelling of the phreatic aquifer (Figure 5) shows the flux simulation for this aquifer using two different transmissivity values, 90 and 1,000 m^2/day (Chambel & Monteiro 2007). These two transmissivities were used as there is limited data for the upper aquifer and due to the fact that the transmissivity values change a lot from place to place in addition to clay intercalations in the sedimentary porous sequence and strong lateral variation of the sedimentary facies. Modelling was performed using Feflow (Wasy 2002). The calibration of the model was done using a set of phreatic levels measured in wells in the upper aquifer. The stream beds were also used to refine the model, which permitted the final definition of the flow lines.

Only 6 piezometers have monitored the levels in the phreatic aquifer since 1983 (ARH Alentejo 2012). In a single campaign in 2010, 330 wells where identified in both aquifers (phreatic and confined), with records of the phreatic levels and field physical-chemical parameters (EC, pH and temperature) collected. From 2010 on, under the remit of the present project, the data was collected from around 100 shallow wells in the phreatic aquifer during the wet and dry seasons. The general phreatic gradient is E-W, following the topography, which attains more than 180 masl in the eastern part of the aquifer and is at sea level on the aquifer western part. Therefore, water discharges mainly at the ocean. However, locally, there are very different flow directions, mainly near the few streams crossing the area. Streams present influent and effluent sectors, depending on location and hydrologic period of the year. Stream reaches with an elevation lower than 20 masl tend to be permanent and feed the coastal lagoons throughout the year.

Figure 6A shows one of the places where groundwater discharge can be directly observed on the bottom of the stream bed. Figure 6B and C show a special situation in this drainage system: a well targeting the confined aquifer discharging its artesian flow of 30 L/s to one of the streams flowing to the Lagoon of Santo André for a number of years. Apart from the natural discharge of the phreatic aquifer, this is the only other source of water entering the system of this lagoon during the dry period.

DISCUSSION AND CONCLUSIONS

This project showed that the coastal lagoons of Melides and Santo André are strongly dependent on groundwater, except for the rainy period, where there are some contribution of surface runoff and direct precipitation over the lagoons and not through the bottom of the lagoons. But groundwater contribution is done mainly by the groundwater discharge on the streams flowing to the lagoons. The salinity of the lagoons is mainly due to the yearly opening of a link between the lagoon and the ocean and to some strong evaporation during summer times. The direct link between sea water and the water in the lagoons beneath the sand barrier separating the lagoons from the ocean doesn't seem possible as the water level in the lagoons is always higher than sea level, except during the short period of the artificial opening to the sea.

The study of the ecology of the lagoon systems showed that inside the lagoons there are (Chainho et al. 2013):

A – Marine species that do not tolerate very low salinities
B – Marine species that can withstand very low salinities
C – Freshwater species that withstand brackish environments
D – Freshwater species that tolerate only very low salinities

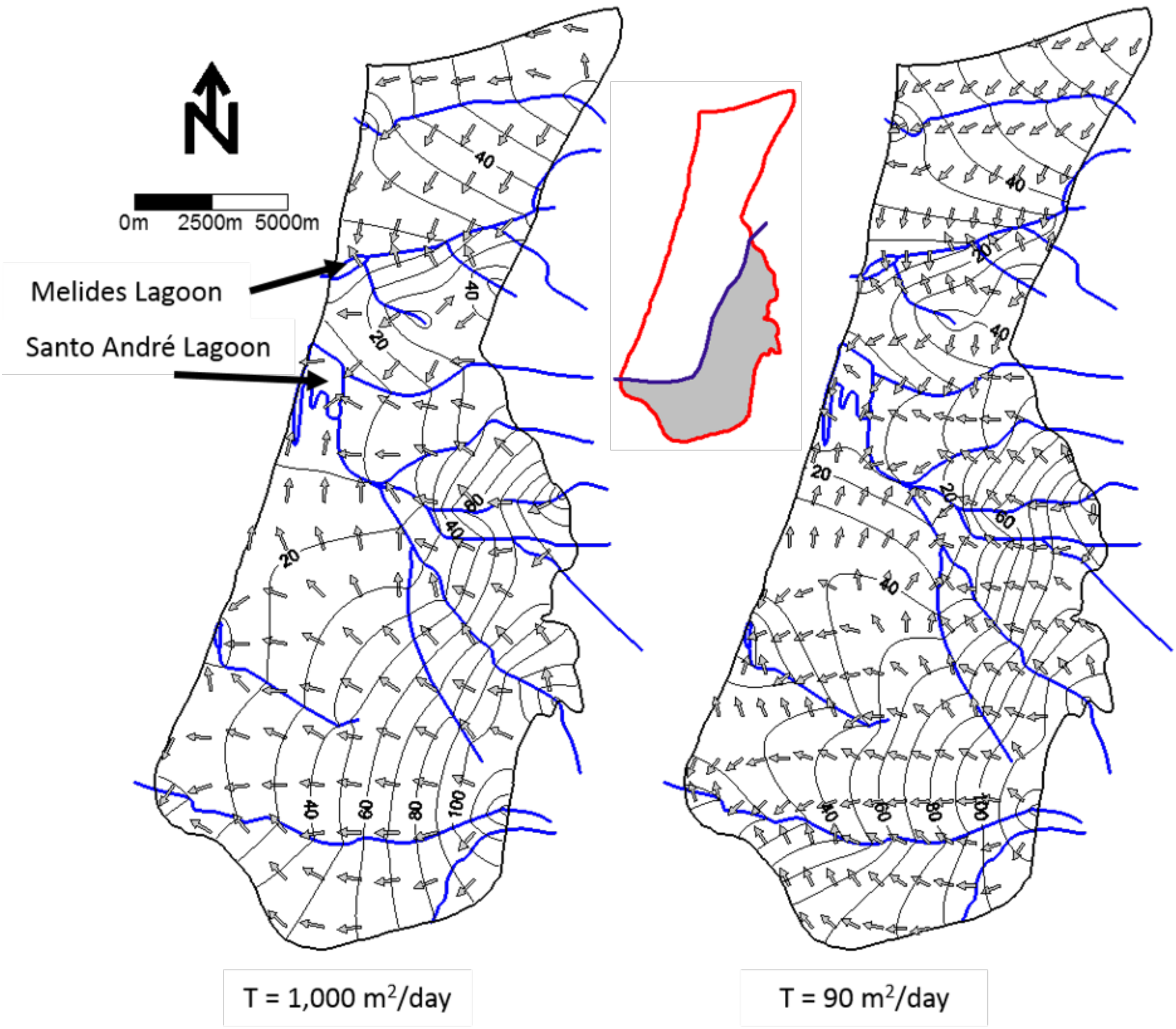

Figure 5. Analysis of the flow in the phreatic aquifer of Sines, assuming two different values of transmissivity (Chambel & Monteiro 2007). The results show that the flow is mainly to the ocean, but locally it flows to the little streams intersecting the territory, discharging part of groundwater indirectly to the lagoons. The central map shows the area where two separate aquifers exist (white area) and the area where there is hydraulic connection between them.

Figure 6. A: One of the points of groundwater discharge in the streams. B: The only artificial discharge to streams directly from the confined aquifer (30 L/s or natural discharge, during the year). C: The stream after receiving the recharge of the confined aquifer (image B).

During and following the opening of the lagoon to the sea, the freshwater species which cannot tolerate high salinities take refuge on the lower parts of the discharging streams, until the environmental conditions inside the lagoon permit their return, which happens slowly after the closing of the inlet between the lagoon and the ocean. In contrast, the marine species that are not so tolerant to very low salinities avoid the areas near the discharge of the streams and take refuge in the area near the dune ridge that separates the lagoon from the sea.

The system is so sensitive that if the abstraction of groundwater increases, there will be a shortage of fresh water into the lagoons, changing the natural spatial and temporal salinity inside. The ecology of the lagoon would change drastically, as all the species less tolerant to salinity would disappear if their freshwater refuge also disappeared. In that case, even if the reaction was to avoid the opening of the lagoon to sea water, the evaporation that occurs would tend to concentrate the internal salinity of the lagoon during the dry period and the pollutants would probably cause irreversible damage to all the life in the lagoon. The consequences could be a great reduction of biodiversity and the survival of only the most resistant species. However, for the moment the abstraction in this aquifer is clearly a reduced percentage of the infiltration that occurs, so in the near future there will be no risk of overexploitation.

In contrast, as the aquifer discharges to the ocean in the area of the lagoons, resulting in an increase in the sea level related with climate changes, the consequence will be an increase also in the groundwater level in the upper aquifer, which will permit an increment of the groundwater discharges to the lagoons in the future.

ACKNOWLEDGEMENTS

This work was developed in the aim of the projects GroundScene (PTDC/AAC-AMB/104639/2008) and PEstOE/MAR/UI0199/2011, financed by FCT – The Portuguese Foundation for the Science and Technology (FCT). So, we thank FCT for their support to this project.

The author also acknowledges the funding provided by the Évora Geophysics Centre, Portugal, under the contract with FCT (the Portuguese Science and Technology Foundation), PEst-OE/CTE/UI0078/2014.

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