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PILOT DESCRIPTION AND ASSESSMENT

Campina de Faro Aquifer System (Portugal)

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LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
CF	Campina de Faro Aquifer System
FW	Freshwater
SW	Seawater
SWI	Seawater intrusion

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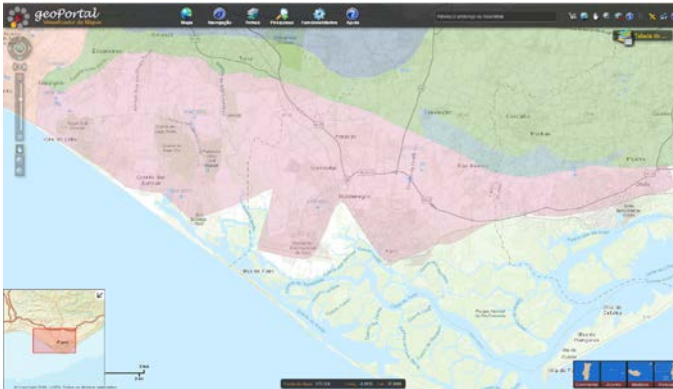
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1 EXECUTIVE SUMMARY

Pilot name	CAMPINA DE FARO AQUIFER SYSTEM (Code M12)	
Country	Portugal	
EU-region	Mediterranean region/Atlantic Ocean	
Area (km ²)	86.4 km ²	
Aquifer geology and type classification	Sands and gravels of Quaternary deposits cover biocalcarenites from Miocene. Porous and karstified Aquifer System.	
Primary water usage	Irrigation, industry, drinking water (few people).	
Main climate change issues	Abstraction for the tourism sector has intensified over the last years with the irrigation of golf courses located in Vale de Lobo and Quinta do Lago (sector W of the aquifer system). Long-term piezometric time series show that water levels have been persistently declining since 2010, accompanied by a constant increase of chlorides, which may indicate an ongoing saline intrusion process. The decrease of annual precipitation, river flow and recharge will lead to the need to implement mitigation measures such as the intensification of natural recharge and reuse of treated wastewater for irrigation of golf courses.	
Models and methods used	Chemical indicators, time series analysis, statistical analysis, lumped indices, integrated hydrological model (although without reliable recharge).	

Key stakeholders	Portugal Environment Agency (APA), Portuguese Environmental Ministry, Algarve University.
Contact person	Judite Fernandes, LNEG Portuguese Geological Survey, judite.fernandes@lneg.pt

The Campina de Faro Aquifer System (M12) is a coastal aquifer along the Algarve coast (south coast of Portugal), with an area of 86.4 km² selected as a pilot area for the Tactic project. The aquifer system is used for agricultural supply. However, over the last years, the extraction for the tourism sector has intensified with the irrigation of golf courses located in Vale de Lobo and Quinta do Lago (in the western (W) sector of the aquifer system), causing declining groundwater levels. Sands and gravels of the Plio-Quaternary deposits (30 - 60 m thick) form a shallow phreatic aquifer, which covers a confined multi-layered aquifer comprised of Miocene sandy limestones (300 m thick). Evaporites are injected into faults at 90 to 120 m depth. In the past, there was evidence of artesian water levels in some areas, showing the hydraulic independence of the two aquifers. Nowadays, poor drilling practices caused hydraulic connection between them, increasing the vulnerability to contamination of the deeper aquifer. Natural flow goes from north to south towards the sea, locally changing due to the extractions. The shallow aquifer receives direct recharge from precipitation, while the Miocene aquifer receives indirect recharge through the aquitard that separates both aquifers, from the Jurassic-Cretaceous limestones located up to north and also from influent streams/rivers along faults. Downstream, the rivers and streams have an effluent behaviour and maintain sensitive ecosystems dependent on groundwater discharge. In the W sector of the aquifer system, time series show that water levels have been persistently lower than sea level since 1995. Since 2010, this trend has been followed by a constant increase of chlorides, which may indicate an ongoing seawater intrusion process. Climate models predict a virtually systematic decline in water table recharge and river flow, due to temperature rise and decrease in effective rainfall. Significant sea water (SW) encroachment would be expected under climate change and groundwater water use conditions, making abstraction for agriculture and golf course irrigation unfeasible and completely reducing the freshwater discharge in streams and into the Ria Formosa lagoon.

Chemical indicators were helpful to get an update overview of seawater intrusion status allowing the definition of an area of 4.6 km² currently impacted by sea water intrusion (SWI). Ratios of rCl / rHCO₃ and rSO₄ / rHCO₃ discretized groundwaters affected by seawater intrusion from those affected by evaporites dissolution + fertilizers input. The vulnerability of the aquifer system to SWI was assessed by applying the GALDIT method. There is a good agreement between highly vulnerable areas and SWI impacted area. A density-dependent flow and transport model was able to simulate future SWI impacts considering 3 different scenarios of recharge reduction (5%, 10% and 20%) according to climate change predictions in this region. Simulations show that the Miocene deep aquifer is more affected by SWI than the Plio-Quaternary phreatic aquifer, an expected result since the deep aquifer is affected by a higher



rate of abstraction. This becomes more evident in the western sector of the aquifer (Vale do Lobo sector), which is subject to higher and more concentrated water abstraction, hence being more vulnerable to seawater intrusion processes.

Adequate management measures and changes in water use practices are needed to counteract SWI such as intensification of natural recharge and reuse of treated wastewater for irrigation of golf courses, among others. Although further work is still needed to improve the understanding of the system and provide reliable predictions of the impact of changes to water use and climate, results provided here already show that groundwater management needs to be adapted to avoid serious problems in the future.

2 INTRODUCTION

Climate change (CC) has already resulted in widespread and significant impacts in Europe, which are expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, have established the project “Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies – TACTIC”. By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infrastructure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

The Campina de Faro (CF) Aquifer System (M12) is a coastal aquifer along the Algarve coast (south coast of Portugal) selected due to its unbalanced water budget. Groundwater removed from the aquifer system for human use is almost equal to total estimated recharge, placing the system at risk of seawater intrusion. The evidence of SWI in the western sector where a few boreholes are already salinized confirms that CF is currently overexploited in an unsustainable way. Groundwater dependent ecosystems are seriously threatened, especially those dependent of effluent streams.

Assessment of seawater intrusion status, aquifer vulnerability to seawater intrusion and scenarios of seawater intrusion impacts due recharge reduction are the main goals of the work here presented.

3 PILOT AREA

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The pilot area is the Campina de Faro Aquifer System, a coastal aquifer along Algarve coast (southern of Portugal), with an area of 86.4 km².

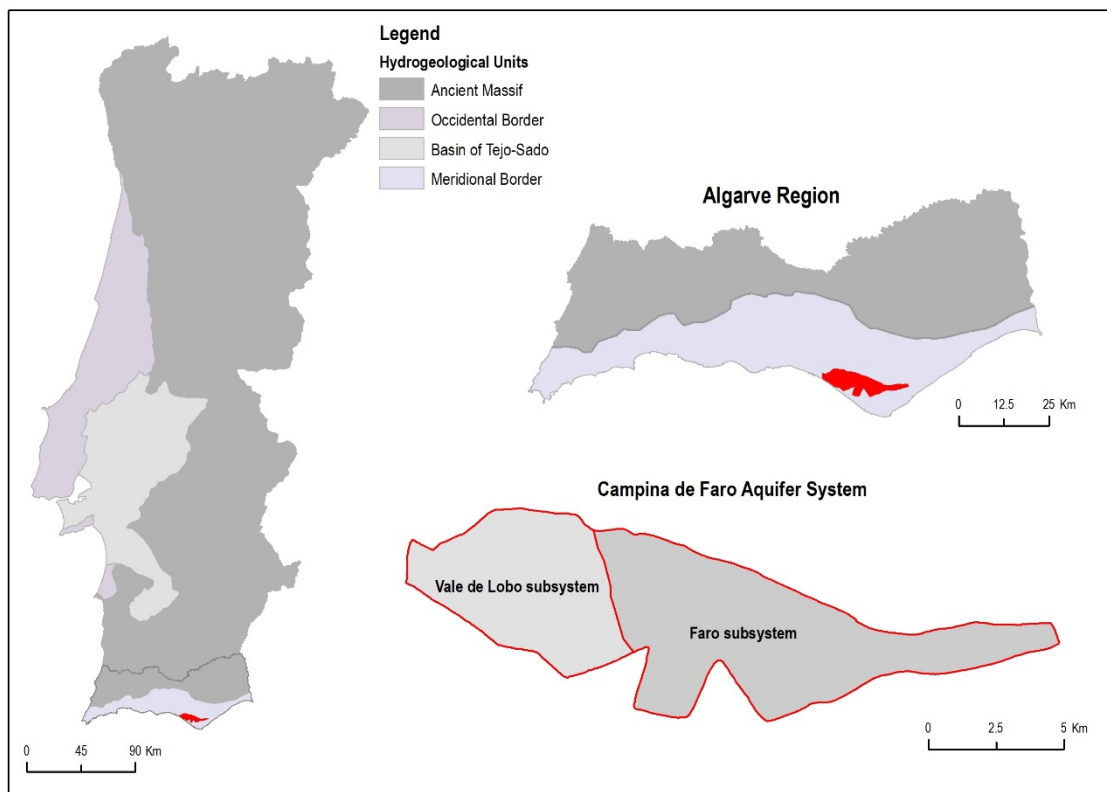


Figure 1. Location and extension of the Campina de Faro Aquifer System

The aquifer system of Campina de Faro is divided into two subsystems: Faro and Vale do Lobo. Both have several spatial discontinuities from the potentiometric and hydrogeochemical point of view, and a certain independence between them can be seen.

Our focus will be mainly on Vale do Lobo subsystem, which occupies the western part of CF with an area of about 32 km².



3.1.2 *Geology /aquifer system main characteristics*

The aquifer system of Campina de Faro consists of two aquifers:

At the surface, the detrital sediments (clayey sandstones with intercalations of pebbles and gravels, sands and alluvial deposits of Quaternary age) support an upper phreatic aquifer, of porous type with variable thickness, reaching in some places 65 m depth (Quinta do Lago), representing the preferential recharge area of this groundwater body.

Beneath the phreatic aquifer there is a deeper aquifer associated with fossiliferous limestones, biocalcarenes, and carbonate sandstones from Miocene. This porous/karstic aquifer type has a confined/semi-confined behaviour and its thickness can reach 300 m (Almeida et al., 2000).

Cretaceous formations are the substrate on which the above-mentioned aquifer formations are based (Silva, 1988). A sequence of marls, limestones and dolostones constitute the C 1-2 formation followed by clay, sandstones, limestones and dolostones of the C 1 formation.

The shallow aquifer and the deep aquifer are separated by a clayey confining layer, that makes the lower part of the aquifer system independent from the upper part. However, in some places, there may be a hydraulic connection between both, due to the absence of the confining layer (Almeida et al., 2000).

The vertical and lateral variability of lithologic facies of this groundwater body is thus reflected in the formation of a multi-aquifer system, subdivided into a phreatic shallow aquifer at the top, and an underlying multi-layered semi-confined/confined aquifer.

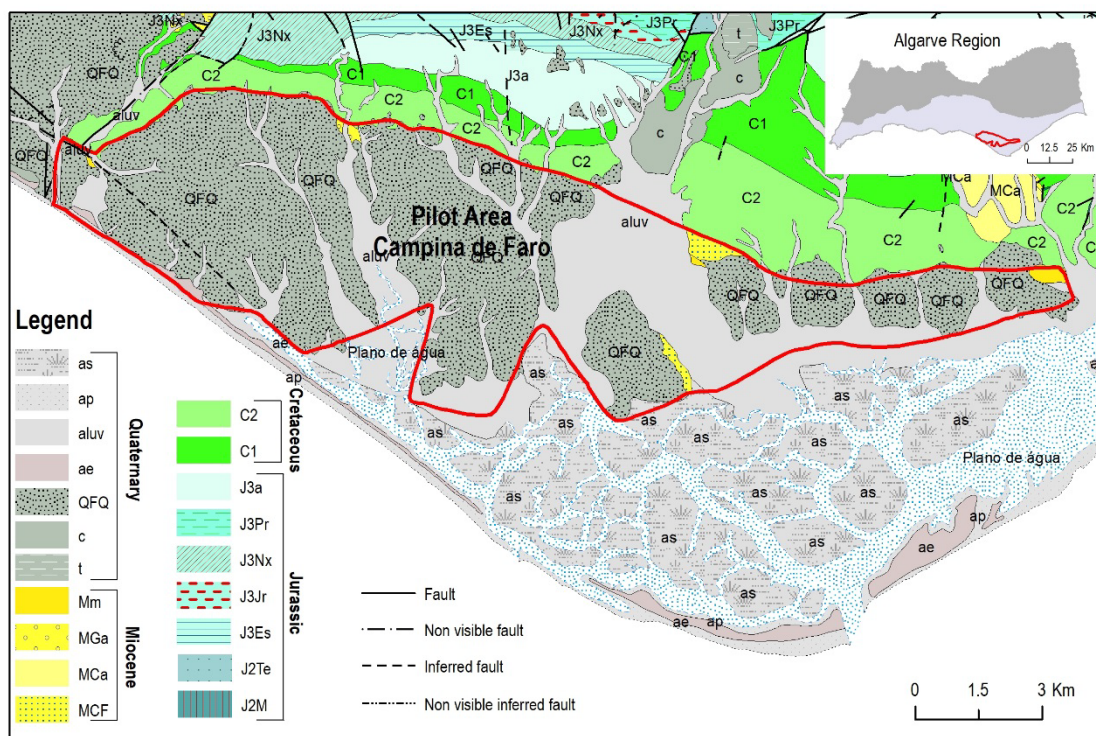


Figure 2. Geological formations of the Campina de Faro Aquifer System.

The geological structure corresponds to a monocline with a smooth slope (20°) towards south. The Miocene formations were deposited in a basin, graben type, controlled by faults, whose directions reflect the alignments of the main watercourses. Another aspect to be taken into account is the presence of diapiric structures which outcrops in Faro city, also recognized in geophysical studies (gravimetry) and confirmed by drill cores between depths of 91 (Quinta da Penha) and 120 m (Pontes de Marchil) at N of Faro (Silva, 1988).

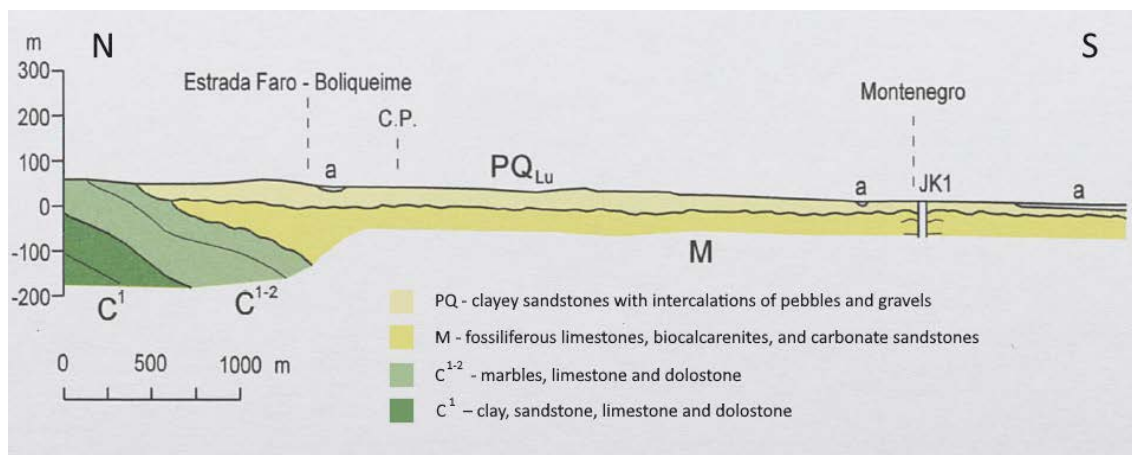


Figure 3. Geologic North-South Cross-section of the Campina de Faro Aquifer System, extracted from Manuppella, 2017.

The shallow aquifer receives direct recharge from precipitation, while the Miocene aquifer receives indirect recharge from the Cretaceous and Jurassic limestones located at North, and this is the most important recharge source. However, in the absence of the confining layer there is also recharge from upper aquifer and from the streams located along faults that cross the aquifer system, namely the streams of Rio Seco and Ribeira da Biogal (Faro subsystem) and of S. Lourenço and Corgo da Gondra (Vale do Lobo subsystem).

From the geological point of view, the existence of NW-SE and N-S faults cause compartmentalization of the aquifer into several blocks. These faults play an important role in the groundwater flow, with N-S faults functioning as preferential groundwater flow directions, whereas NW-SE faults act as a barrier (Stigter et al., 1998).

According to piezometric data, the regional groundwater flow pattern in natural conditions shows fluxes from north to south-SW, towards the sea.

Discharge occurs along the end part of streams into the Ria Formosa coastal lagoon and into the Atlantic Ocean.

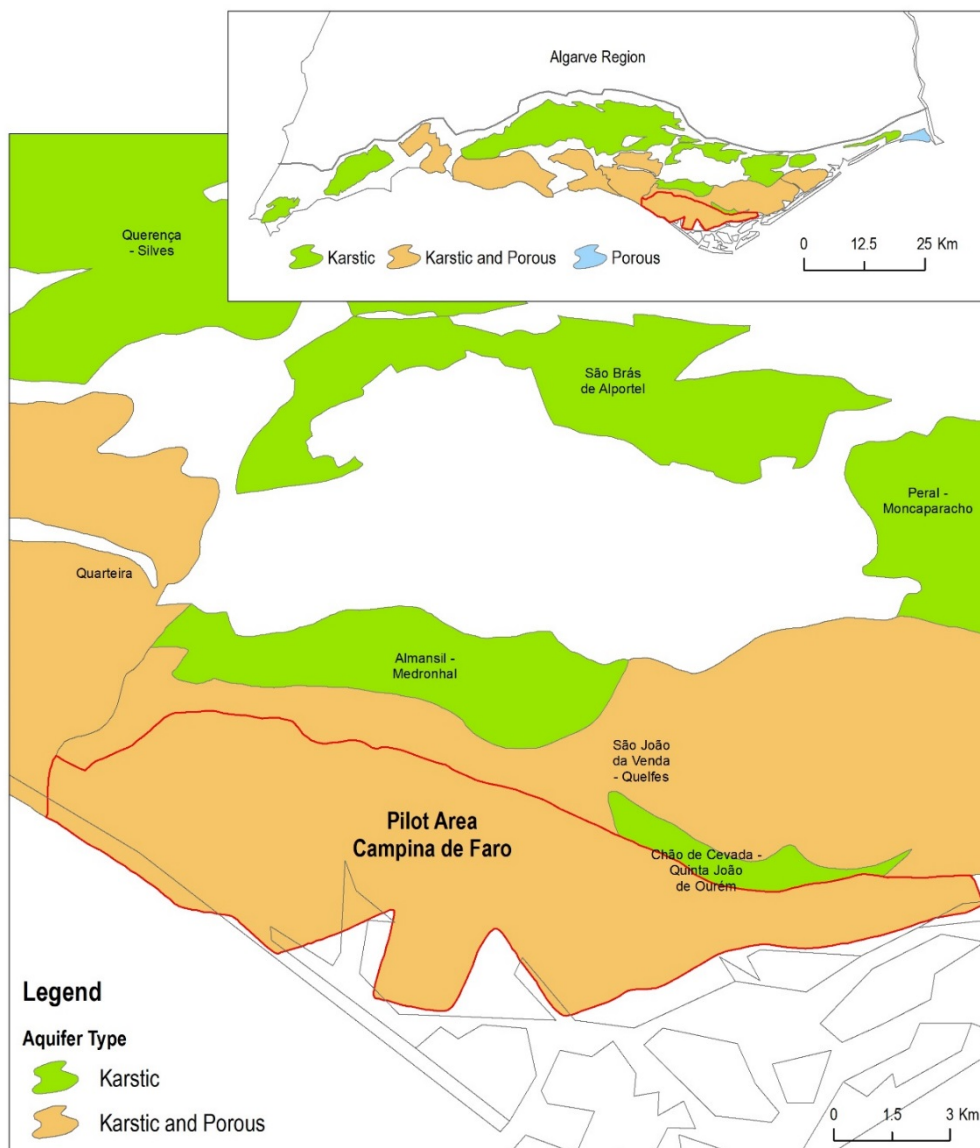


Figure 4. Aquifer Type of the Campina de Faro Aquifer System.

3.1.3 Topography and soil types

The area occupied by the aquifer system corresponds to an extensive flattening coastal plain, with heights ranging between 30 and 40 m. It is practically occupied by the sands and gravels of

Faro-Quarteira of Quaternary age and recent alluvium. This area is crossed by several streams, on its terminal section, slightly embedded, which flow into the Ria Formosa coastal lagoon.

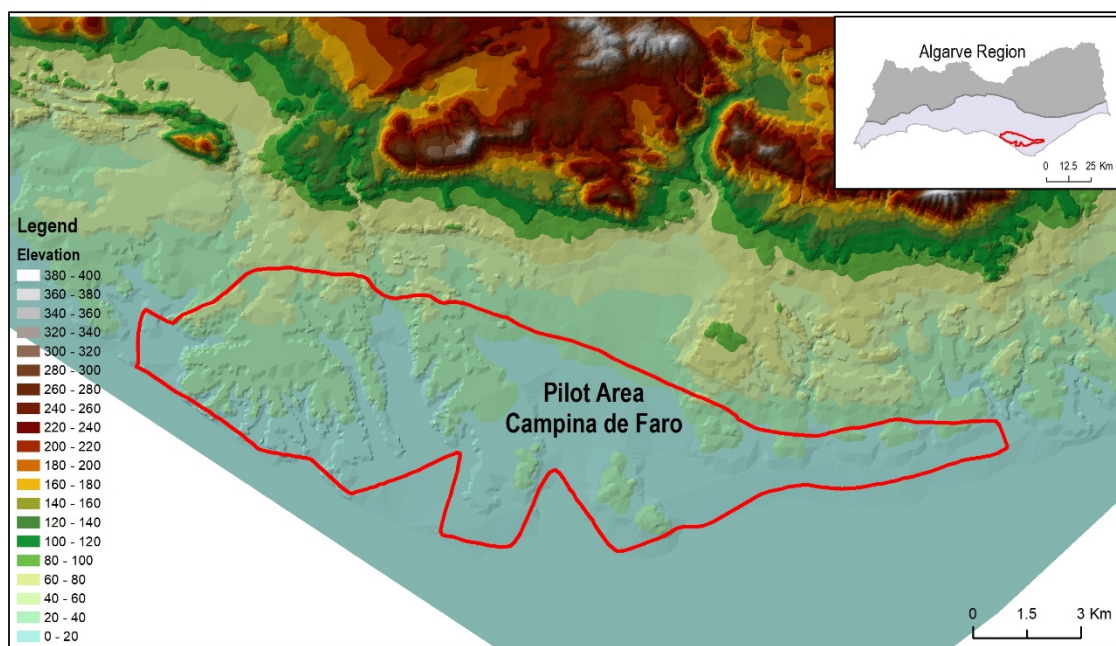


Figure 5. Digital Terrain Model of the Campina de Faro Aquifer System.

The soils lie on a sandy substrate with smooth slopes, predominantly lower than 3% (Management Plan for the Hydrographic Region of the Ribeiras do Algarve, 2016). The most abundant soils are the Mediterranean Soils, red or yellow, from compact limestone or dolomite (Vcd). Other soils, also important in the area under analysis, are: i) Calcareous soils from Climatic Xeric Regime, developed on non-compacted limestone (Pc); ii) Lithosoils, no humus, slightly insaturated, developed on coarse sandstones (Vt); and iii) Red calcareous soils, from Climatic Xeric Regime, of limestones (Vc). It can be said that only Lithosoils are originated from Areias e Cascalheiras of Faro-Quarteira Formation (Management Plan for the Hydrographic Region of the Ribeiras do Algarve, 2016).

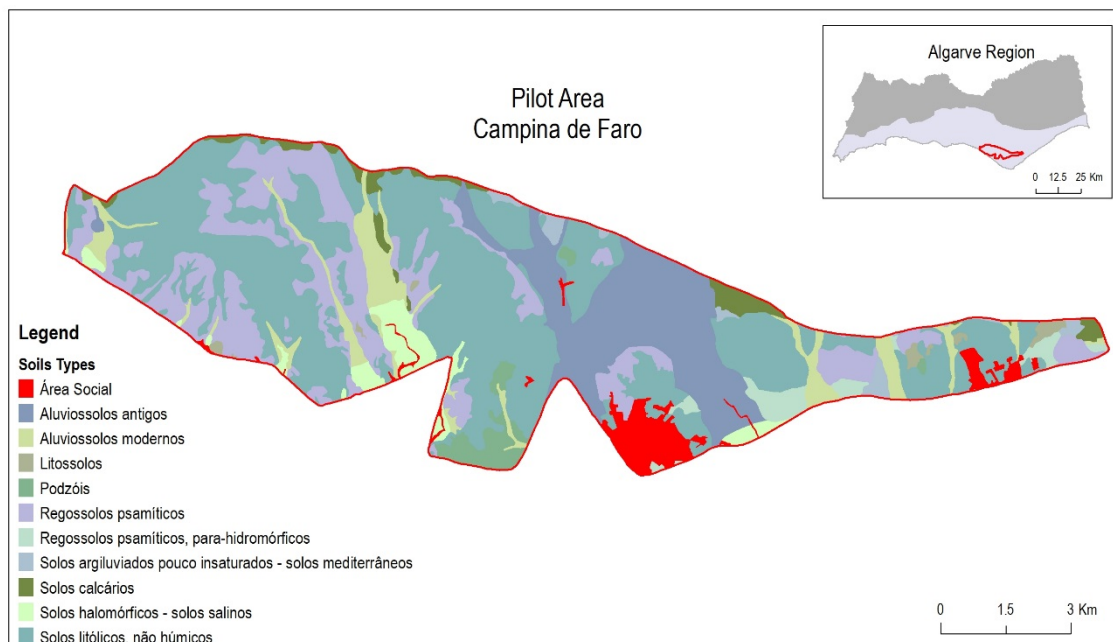


Figure 6. Soils Types of the Campina de Faro Aquifer System (Portuguese Classification).

3.1.4 Surface water bodies

The surface water bodies within the area covered by the aquifer system of Campina de Faro are: the Carcavaí and S. Lourenço streams in the Vale do Lobo subsystem area and the Biogal, Rio Seco and Bela Mandil streams in the subsystem of Faro.

With an approximate direction N – S all these waterlines are tributaries of the Ria Formosa coastal lagoon, belonging to the drainage basin of Ria Formosa barrier islands and coastal lagoon system. The streams have a temporary regime, being dry during much of the dry season and their flow regime presents a high interannual and seasonal variability. They also present an important interaction with groundwater, being influent upstream and effluent downstream already within the Ria Formosa lagoon system.



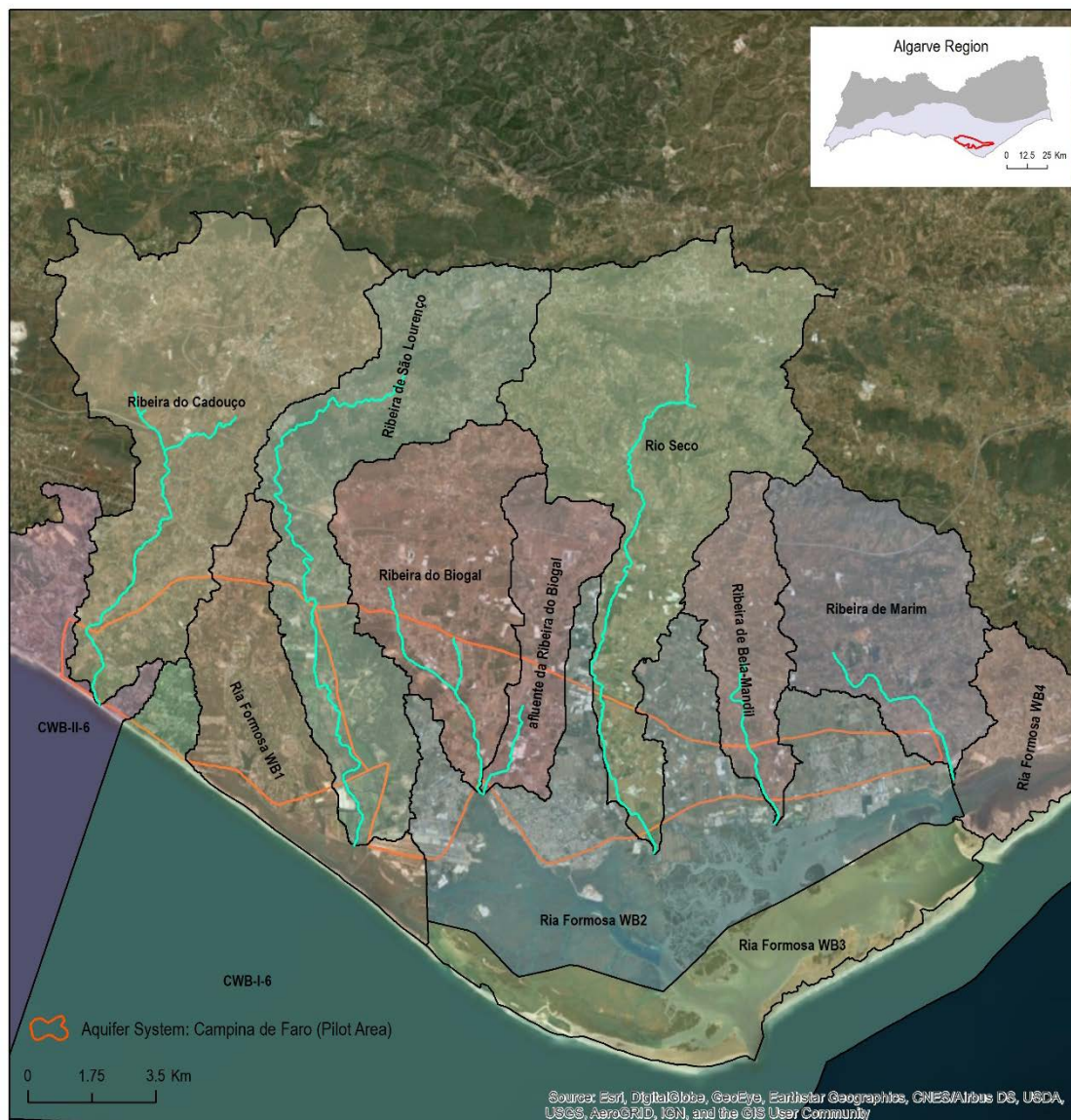


Figure 7. Surficial water bodies, Hydrographic basins and main streams (Management Plan for the Hydrographic Region of the Ribeiras do Algarve, 2016).

3.1.5 Hydraulic Head evolution and Hydrochemical aspects

Monitoring of piezometric levels in the study area began in the early 1980s. The piezometric network has 20 piezometers which have been monitored on a monthly basis for approximately 30 years. Monitoring was carried out continuously in some points and during certain periods of



time in other points. The groundwater quality monitoring network has 23 points, where electrical conductivity, pH and temperature have been measured twice a year since 1995. Laboratory physical-chemical analysis have been also carried out twice a year.

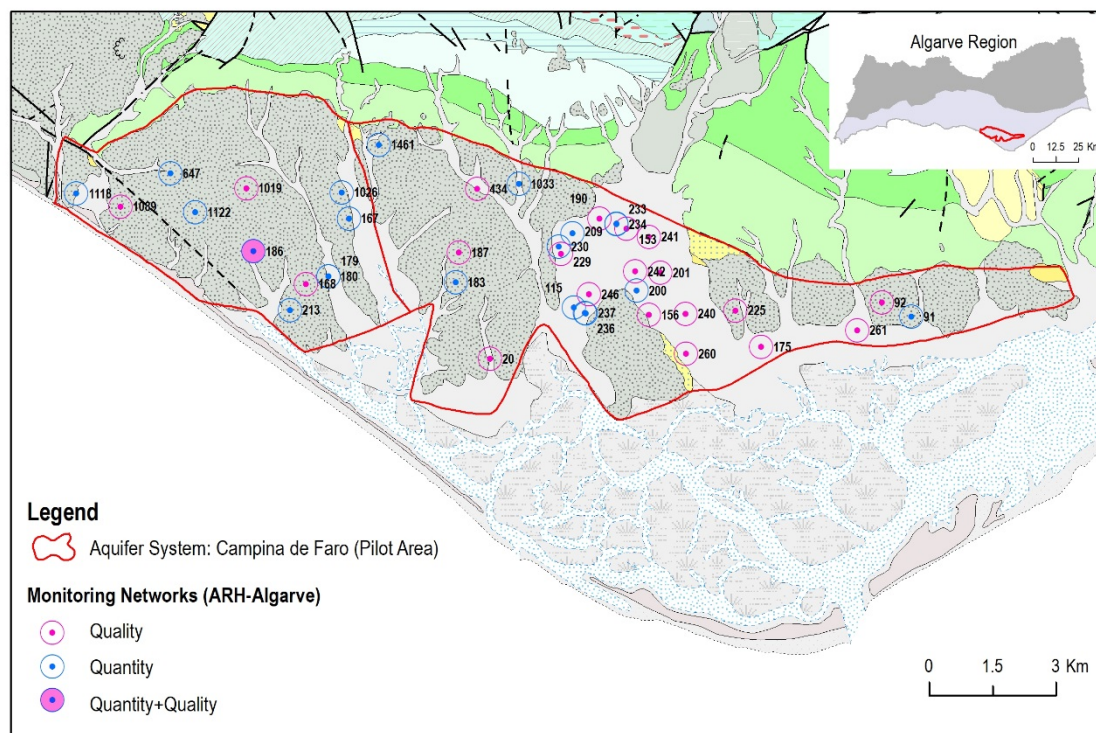


Figure 8. Monitoring quality and quantity networks (APA - ARH Algarve).

Both subsystems of the aquifer system have somewhat different hydrogeochemical and piezometric characteristics.

Figure 9 shows the piezometric surface from April 1984 and Figures 10 and 11 present recent piezometric surfaces for May 2018 (end of the rainy season) and October 2017 (end of the dry season), respectively.

A comparison of piezometric surfaces shows that the eastern sector of the Campina de Faro has recovered to positive water levels whilst levels within the western sector of Vale do Lobo have fallen, with negative values indicating groundwater levels are generally below sea level in this sector.



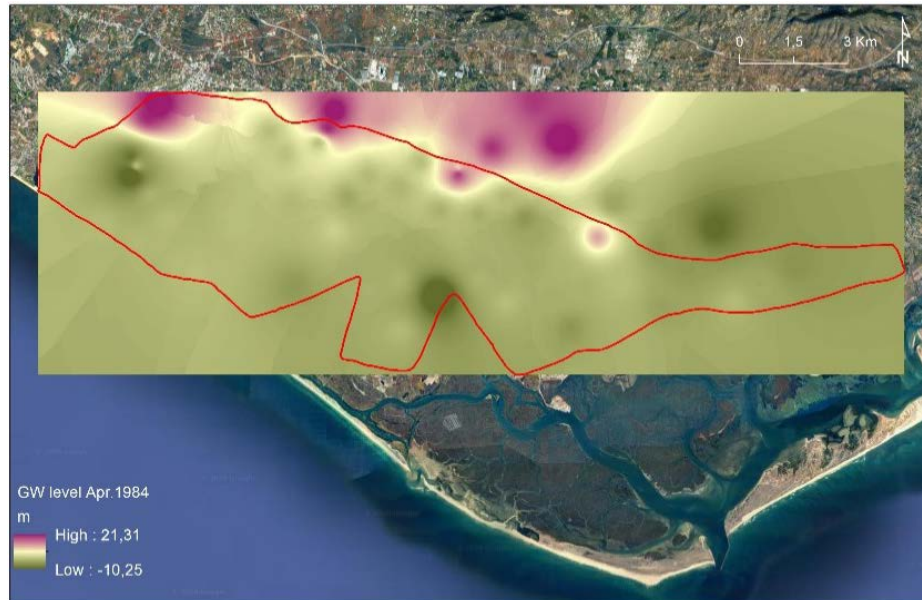


Figure 9. Piezometric surface for April 1984 (end of the rainy season).

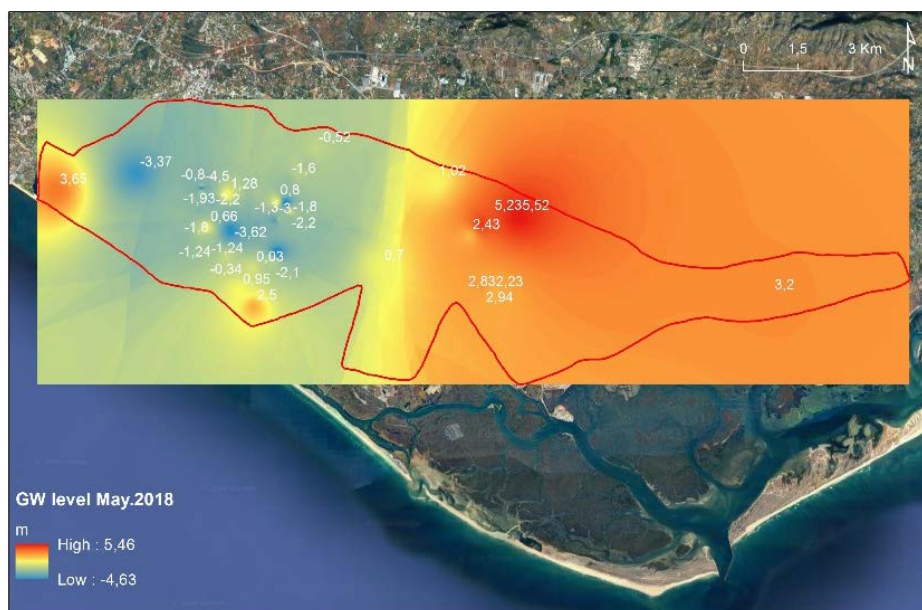


Figure 10. Piezometric surface for May 2018 (end of the rainy season).

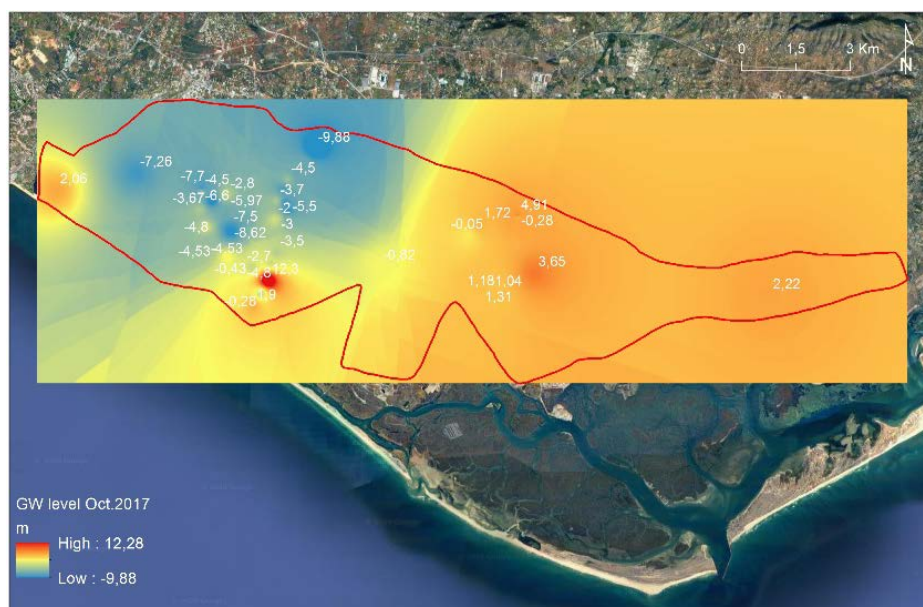


Figure 11. Piezometric surface for October 2017 (end of the dry season).

In the Vale do Lobo subsystem, the observation of about 30 years of piezometric levels indicates a downward trend especially from 2010 onwards, which is more pronounced in the eastern part of this sector, due the combined effect of the decrease of the precipitation and, consequently, of the recharge and the increase of water withdrawals.

From the mid-1990s onwards, in points that have been exploiting the upper aquifer, piezometric levels have been negative most of the time (APA-ARH Algarve).

The maximum amplitude of oscillation of the water levels in the Miocene aquifer is about 15 m and the inter-annual oscillations vary between 5 to 6 m (APA-ARH Algarve).

In the Faro Subsystem, this situation does not occur, as water levels are always higher than mean average sea level and no downward trend is observed.

These differences have been previously attributed mainly to the geological context which controls the recharge at depth (Management Plan of the Hydrographic Region of the Ribeiras do Algarve, 2016), whilst high levels of water abstraction for irrigation purposes has led to depression of the piezometric surface, particularly during summers and intensified during drought years, must be also considered.

Seawater intrusion is ongoing in the SE of Vale do Lobo subsystem causing groundwater deterioration (Figure 12). In the Faro Subsystem, groundwater quality problems are related with nitrates concentrations resulting mainly from poor agricultural practices for several years. Throughout the aquifer system, there are problems of evaporites leaching that are injected along the faults leading to high concentrations of sulphate and chloride.



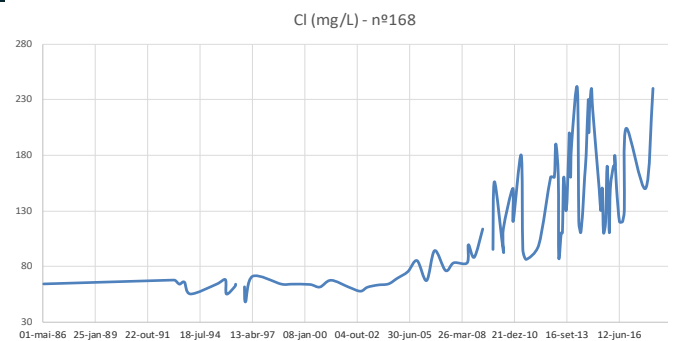
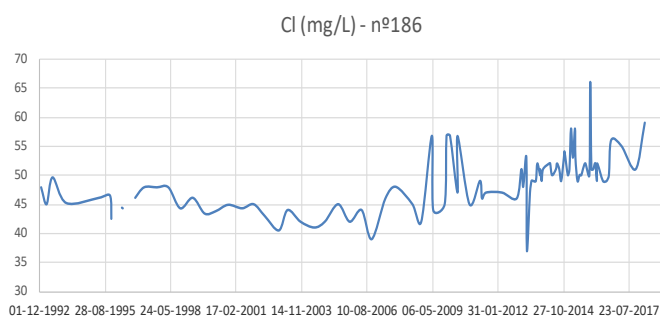
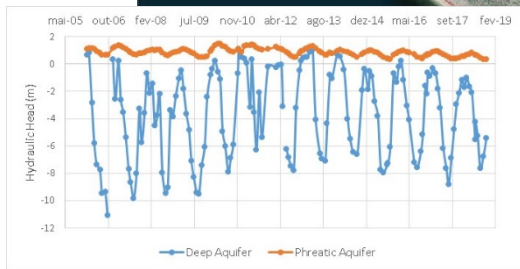
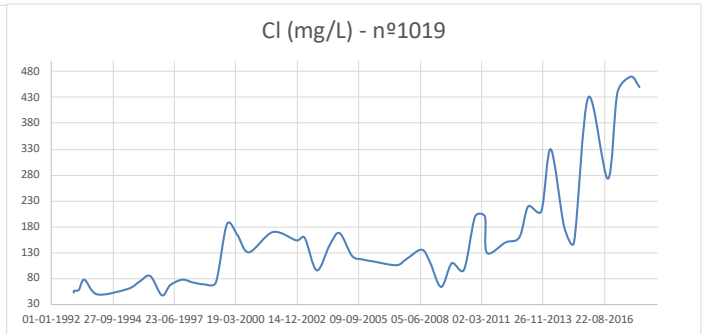
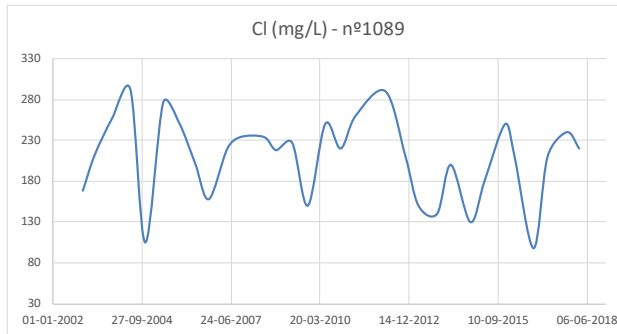


Figure 12. Cl time series in Vale de Lobo subsystem (W sector) and hydraulic head of both aquifers (APA - ARH Algarve), where can be seen positive hydraulic head for shallow aquifer and negative height for deep confined aquifer followed by a rising trend of chlorides concentration (mg/L).

From the hydrogeochemical point of view, the groundwater is of sodium chloride (Na-Cl) and calcium bicarbonate (Ca-HCO_3) *facies*. Although two sources for increasing Cl must be considered, one from seawater and other from evaporites, the recent increase in Cl is more likely to be related with the advance of seawater intrusion.

3.1.6 Hydraulic parameters

Pumping tests provide some values for hydraulic parameters. Silva (1988) obtained a transmissivity value of $300 \text{ m}^2/\text{day}$ from a recovery test in a borehole located in Quinta do Lago that pumps from the lower aquifer.

A pumping test on deep aquifer conducted by DRAH in Gambelas gave the following results:

Transmissivity $T = 397 \text{ m}^2/\text{day}$ and Storage coefficient $S = 1.3 \times 10^{-4}$

In the Campina sector, another pumping test provided transmissivity values ranging from 140 to $284 \text{ m}^2/\text{day}$ for the deep aquifer (Silva, 1988).

For the upper aquifer no data are available on hydraulic properties, except for some values of hydraulic conductivity determined by Silva (1988). These indicated a very low permeable medium. However, given the evident heterogeneity of the upper detrital unit, probably there are some areas characterized by significantly higher values of that parameter.

Based on 470 flow rate measurements Almeida et al., 2000, calculates Q1-Q3 ranging from 4.2 to 8 L/s with the maximum flow rate of 44 L/s .

3.1.7 Climate

The Algarve coast, where the study area is located, has a Mediterranean climate, with two seasons, a warm and dry season and a wet season. Temperatures in the summer months are attenuated by the effect of the ocean. The mountains located at north have a protective effect in the winter months, preventing the advance of the continental polar air masses over the region, also called “nortadas” (Nemus, 2002).

According with data recorded at the Patação station (Direção Regional de Agricultura e Pescas do Algarve (DRAPALG)), located inside the area covered by the Campina de Faro subsystem, the average annual rainfall is around 600 mm . The months of heaviest rainfall are from October to March and those of lower rainfall from June to August. The average annual temperature is



17.3°C. The warmest months are July and August with average monthly temperatures of around 24°C and the coldest months are January and February, at around 11°C. Potential evapotranspiration has an average value of about 876 mm/year (Faria et al., 1981, in Stigter, 2005), which largely exceeds precipitation. The actual evapotranspiration was estimated between 75 to 88% of the precipitation, depending on the method of determination (Silva, 1984; Silva, 1988; Stigter et al., 1998; De Bruin, 1999 in Stigter, 2005).

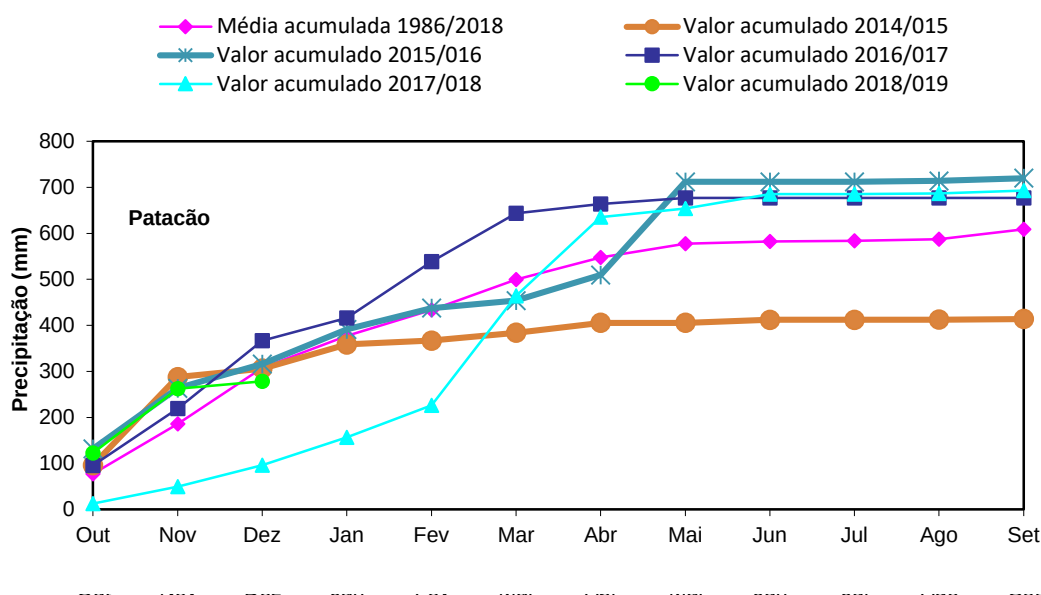


Figure 13. Cumulative annual rainfall (mm, 1986 – 2018). Source: DRAPALG.

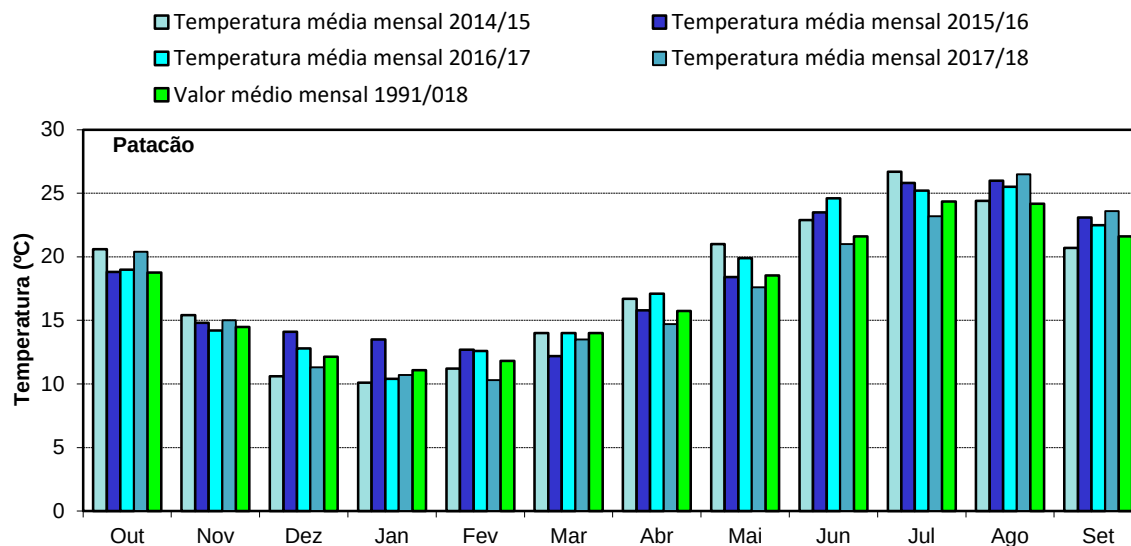


Figure 14. Average seasonal temperature (°C, 1991 – 2018). Source: DRAPALG.

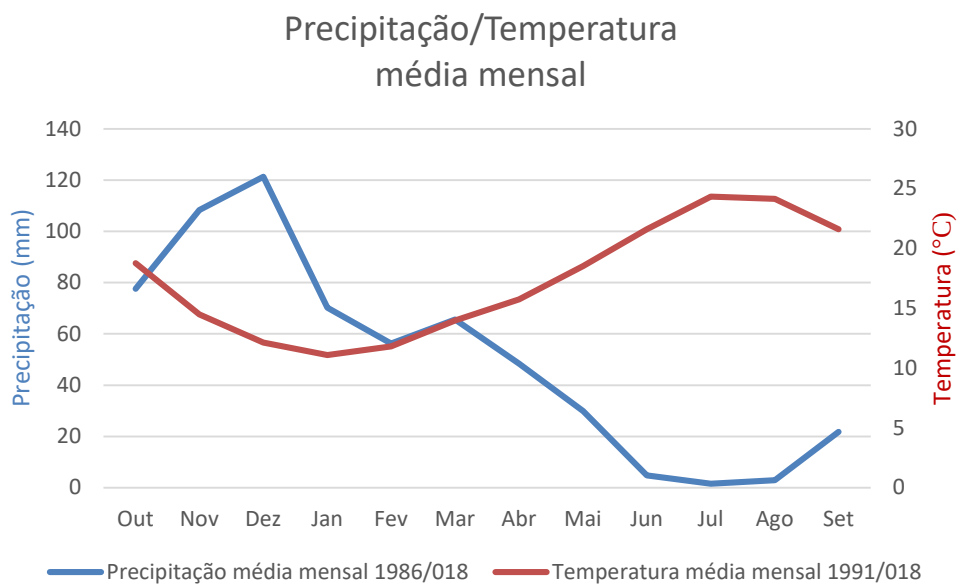


Figure 15. Average monthly rainfall and temperature (mm 1986/°C 1991 – 2018). Source: DRAPALG.

3.1.8 Land Use

In the current land use classification, agricultural use predominates (mainly citrus groves and watercress production), tourism (golf courses and urbanizations with large garden areas) and pinewoods.

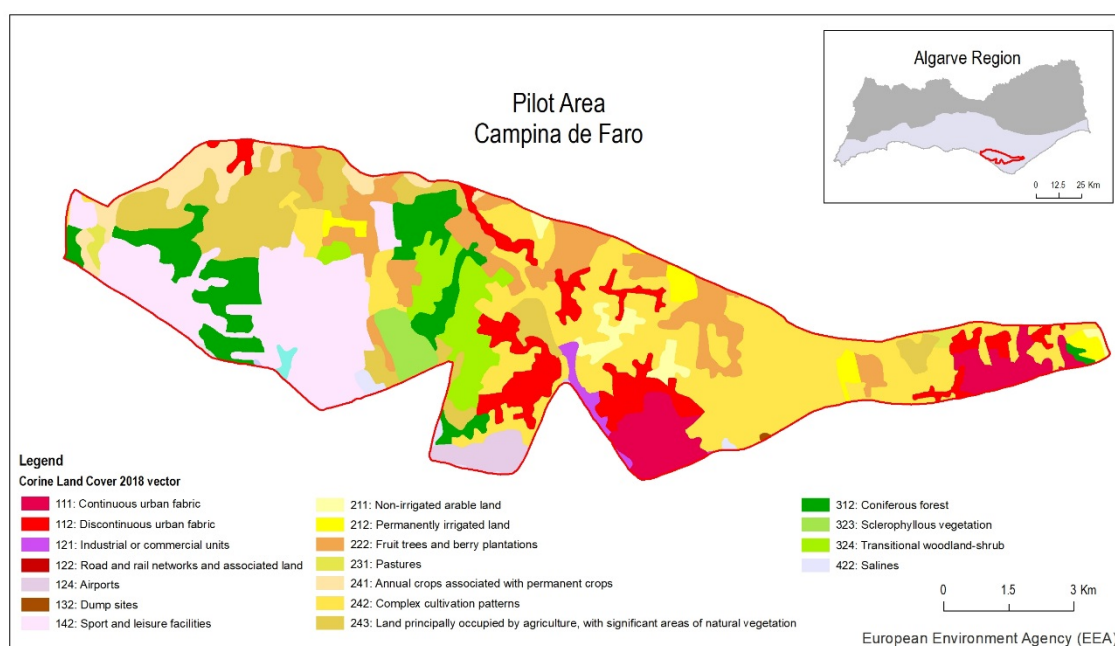


Figure 16. Corine Land Cover 2018. <https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=mapview>

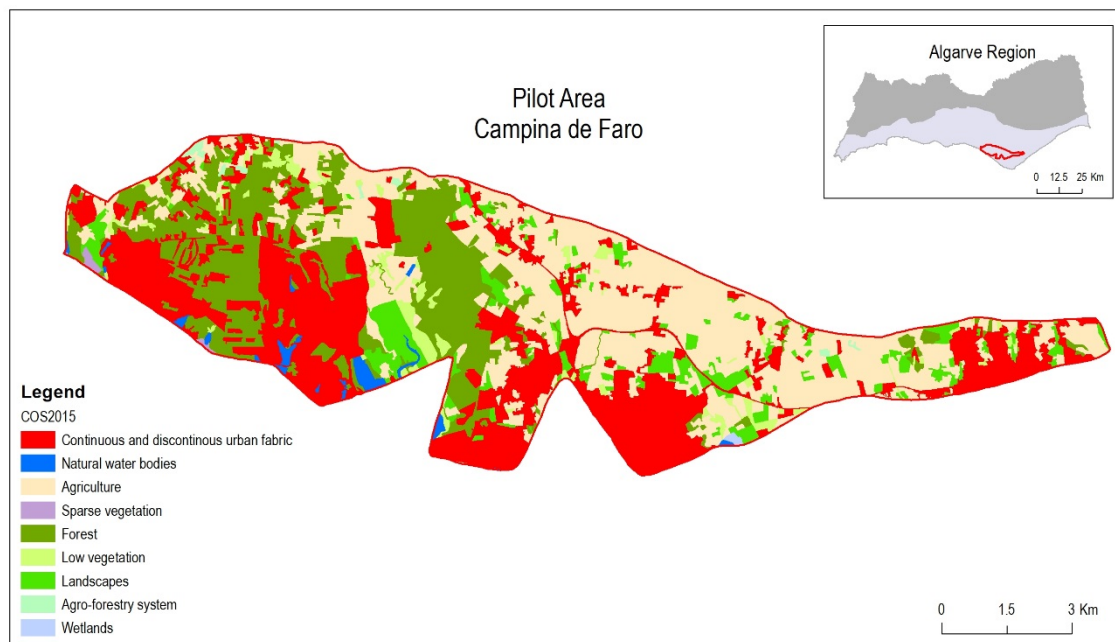


Figure 17. Land Use Mapping 2015.

<https://snig.dgterritorio.gov.pt/rndg/srv/por/catalog.search#/search?anysnig=COS2015&fast=index>

3.1.9 Abstractions/irrigation

3.1.9.1 Vale do Lobo subsystem

According to Reis (2014), in the Vale do Lobo subsystem 625 abstractions of groundwater (boreholes and wells) are currently included in the inventory.

The abstraction is mainly for irrigation of golf courses and agriculture, namely citrus fruits. The irrigation of private gardens also demand significant groundwater volumes. Private human consumption and swimming pools are uses that consume smaller volumes. Table 1 shows the volumes of private abstractions for uses referred above, according to the volumes authorized in use permits of groundwater resources. Total volume of abstractions from the Vale do Lobo subsystem, giving the above data, is 4.3 hm³/year.



Table 1 - Volumes of groundwater withdrawals according to the volumes authorized in the use permits of water resources, Reis (2014).

Use	Consumption (hm ³ /year)
Garden watering	0.48
Agricultural irrigation	1.32
Golf	2.26
Human consumption	0.18
Swimming pools	0.005
Total	4.25

As the volumes authorized in the use permits may not often coincide with the volumes actually abstracted, another method was applied to calculate the consumption for agriculture and garden irrigation, based on land use of the orthophoto maps of 2007. After determining the irrigated area, an irrigation volume was attributed, according to the existing crop, for a critical year. Data on human consumption and golfing were obtained from data submitted by the owners. Total volume of water abstractions of the Ludo - Vale do Lobo water body by the referred method is 5.4 hm³/year.

Table 2 - Volumes of groundwater abstraction according to land use and owner's data, Reis (2014)

Use	Consumption (hm ³ /year)
Garden watering	0.25
Agricultural irrigation	1.87
Golf	3.25
Human consumption	0.024
Total	5.39

3.1.9.2 Faro subsystem

According to Reis (2014), in the Faro subsystem 563 abstractions of groundwater are presently inventoried. Currently, there is no exploitation for public supply.

The private consumption is mainly used for agriculture irrigation, namely horticulture and citrus. Giving the authorized volumes in use permits of groundwater resources, abstractions for irrigation are around 1.7 hm³/year.

Another method applied to calculate irrigation consumption was based on land use, using the orthophoto maps of 2007. After the determination of the irrigated area, an irrigation volume was attributed, according to the existing crop, for a critical year. The abstractions obtained for irrigation purposes of Faro sub-system are 5.4 hm³ / year.

The difference among the two calculation methods is significant, being probably the value achieved by the second method closer to reality. The withdrawal obtained by the second method represents about 87% of the average annual recharge in the long term. However, the recharge of this groundwater body is underestimated due the lack of knowledge of depth groundwater transfers from the water bodies at the north. It should be noted that the present-day piezometric levels are high when compared to the time series and show no downward trend.

3.1.10 Water Balance

Evaluation of water inputs for the Vale do Lobo subsystem has been carried out through the contribution of the various sources of recharge. The shallow aquifer receives direct recharge from the precipitation, while the Miocene aquifer has the most important source of recharge as indirect recharge from the Jurassic-Cretaceous limestones located to the North.

Average annual rainfall in this groundwater body is around 600 mm. Using the recharge rate of 16% (Stigter et al., 2009), a natural recharge value of 3.1 hm³/year is reached (96 mm/year) for the entire area of the Vale do Lobo subsystem (32 km²).

This subsystem is crossed by streams that contribute to the recharge. The most important is the S. Lourenço stream, where a hydrometric station is located upstream of this groundwater body. The existing data series have a very short sampling period and adequate data treatment has not been carried out yet. However, it is estimated that the average recharge of the aquifer from this stream will be about 1.5 hm³/year, so it was considered that the annual average long-term recharge is about 4.6 hm³/year.

In addition to the aforementioned sources of recharge, there is also the deep recharge from the water infiltration in the northern limestones, for which there is no data that allow estimation. Therefore, the average annual recharge value will be higher than the above-referred value.

Campina de Faro subsystem presents the same behaviour of the Vale do Lobo subsystem. In addition to recharge from rainfall ($5.2 \text{ hm}^3/\text{year}$), the Rio Seco stream is an important source of recharge. Of the Jurassic-Cretaceous limestones in the North, a deep recharge reaches the sandy limestone aquifer mainly through faults and fractures.

Regarding the water outputs from the whole system, in addition to the abstractions mentioned in the previous subchapter, there are also natural discharges, which sustain groundwater dependent ecosystems, such as the Ria Formosa lagoon and the end sectors of the S. Lourenço, Biogal, Rio Seco and Bela-Mandil streams. There is no data to estimate the volumes of these discharges.

Considering the inputs and outputs of the groundwater body, the water balance is then presented in tables 3 and 4.

Table 3 - Water balance for the Vale do Lobo subsystem (hm^3/year), Reis (2014)

Vale do Lobo (subsystem)		
Input		
Natural recharge(hm^3/year)		3.1
Influent recharge from surficial water (hm^3/year)		1.5
Annual average long-term recharge (hm^3/year)		>4.6
Output		
Discharge to aquatic and terrestrial ecosystems (hm^3/year)		?
Abstractions (hm^3/year)	Known (permits)	4.3
	Estimated (land use)	5.4
Water Balance (hm^3/year)	Known (permits)	0.3
	Estimated (land use)	-0.8

Table 4 - Water balance for the Faro subsystem (hm³/year), Reis (2014)

Campina de Faro (subsystem)		
Input		
Natural recharge(hm ³ /year)		5.2
Influent recharge from surficial water (hm ³ /year)		1
Annual average long-term recharge (hm ³ /year)		>6.2
Output		
Discharge to aquatic and terrestrial ecosystems (hm ³ /year)		?
Abstractions (hm ³ /year)	Known (permits)	1.7
	Estimated (land use)	5.4
Water Balance (hm ³ /year)	Known (permits)	4.5
	Estimated (land use)	1.7

3.2 Climate change challenge

Climate change will not affect the water resources in the whole of Europe in the same way, depending on various factors, which are mostly related to climate, geology, pedology and land use (Figure 18).

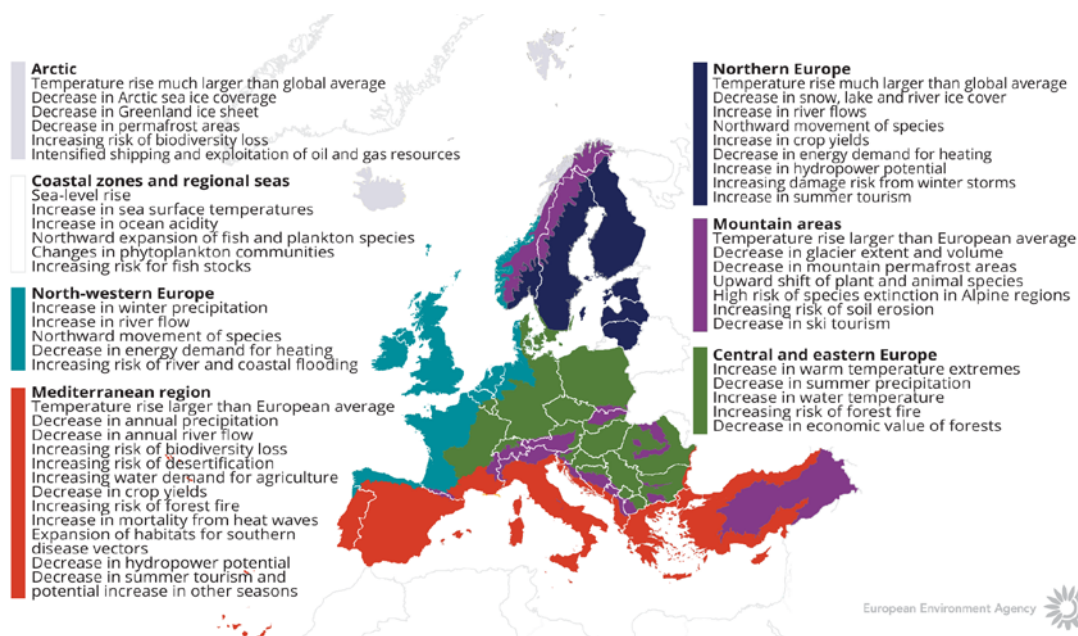


Figure 18. Observed and projected climate change and impacts for the main biogeographical regions in Europe (European Environmental Agency).

3.2.1 How is the climate expected to change in the area?

In the SIAM, SIAM_II and CLIMAAT_II projects, climate change scenarios for Portugal were analysed using simulations of different climate models. The simulation control of the model with the higher spatial resolution was compared with the observed values, indicating a high level of adherence in the variables mean temperature and precipitation. Together with the results of other models analysed in the referred projects, the following climatic scenario is suggested for the period 2080-2100:

- All models in all scenarios predict a significant increase in mean temperature in all regions of Portugal by the end of the 21st century;
- An increase in summer maximum temperature on the continent, between 3°C in the coastal zone and 7°C in the inland, together with an increase in the frequency and intensity of heat waves;
- All weather indexes related to temperature also show changes in the climate scenario. The increases are large in the number of warm days (maximum over 35°C) and tropical

nights (minimums over 20°C), while reductions in cold weather indexes are expected (eg, frost days or days with minimum temperatures lower than 0°C);

Regarding rainfall, the uncertainty of the future climate is substantially greater. However, almost all the models analysed foresee a reduction of precipitation in continental Portugal during spring, summer and autumn. One of the climate models foresees reductions in the amount of precipitation in the continent, that can reach values corresponding to 20% to 40% of the annual precipitation (due to a reduction in the duration of the rainy season), with the largest losses occurring in the southern regions. The regional model, with greater regional disaggregation, points to an increase in precipitation during the winter, due to increases in the number of days of strong precipitation (above 10 mm/day).

In the scope of the climate portal project (<http://portaldoclima.pt/>) meteorological/climatological data from the IPMA stations (Instituto Português do Mar e da Atmosfera), installed in the District capitals, with records for the study period from 1970 to 2016, were processed to forecast scenarios until the end of the 21st century.

The model data were obtained using the same methodology adopted in all the processes, and for this validation process, the average value of the 4 points of the matrix around the meteorological/climatological station location was used. The statistics corresponding to the models (modelling history and projections) are calculated from average values of each of the models according to the indicated period (annual, monthly or seasonal).

Data is available for 4 series:

- hist-obs: historical observed (1971-2016)
- hist-mod: historical modeling (1971-2005)
- proj-mod: future projections (2006-2100, divided into two scenarios (RCP 4.5 and RCP 8.5))

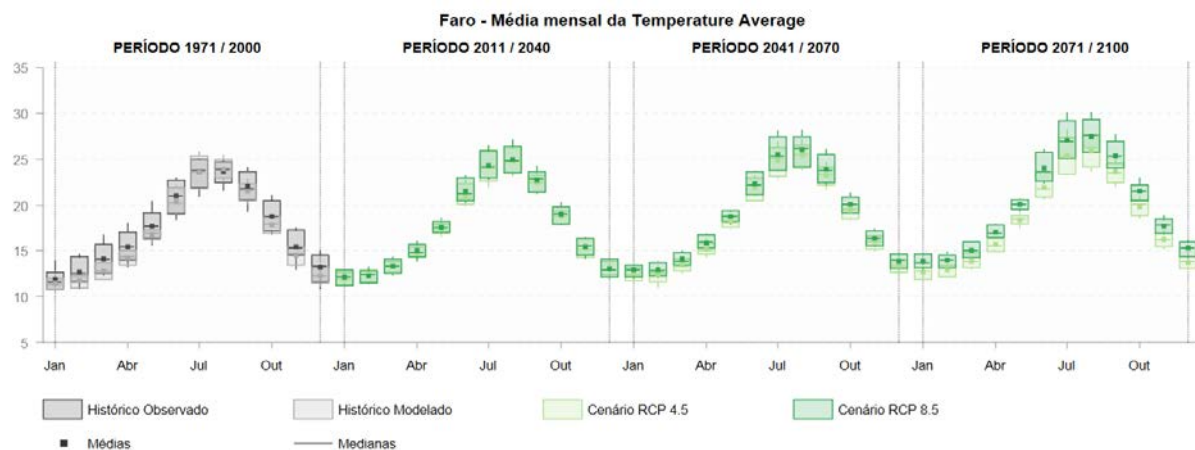
Ongoing climate change in Portugal based on IPMA time series data (30 years) and SIAM, SIAM_II and CLIMAAT_II Project Reports, can be summarized as follows:

- 1) A significant increase in an average of the maximum and minimum temperatures with reduction of thermal amplitude;
- 2) Increase in the number of "summer days" and "tropical nights", as well as in the annual rate of heat waves;
- 3) Decrease of cold days and nights and in the number of cold waves;
- 4) Great irregularity in precipitation but no significant trends (increase or decrease) in the annual average value;
- 5) An important reduction in the precipitation on the month of March in the whole territory;

6) Smaller but significant reduction in precipitation in February.

The results for the Faro station located in the study area are presented below.

Monthly analysis



Annual analysis

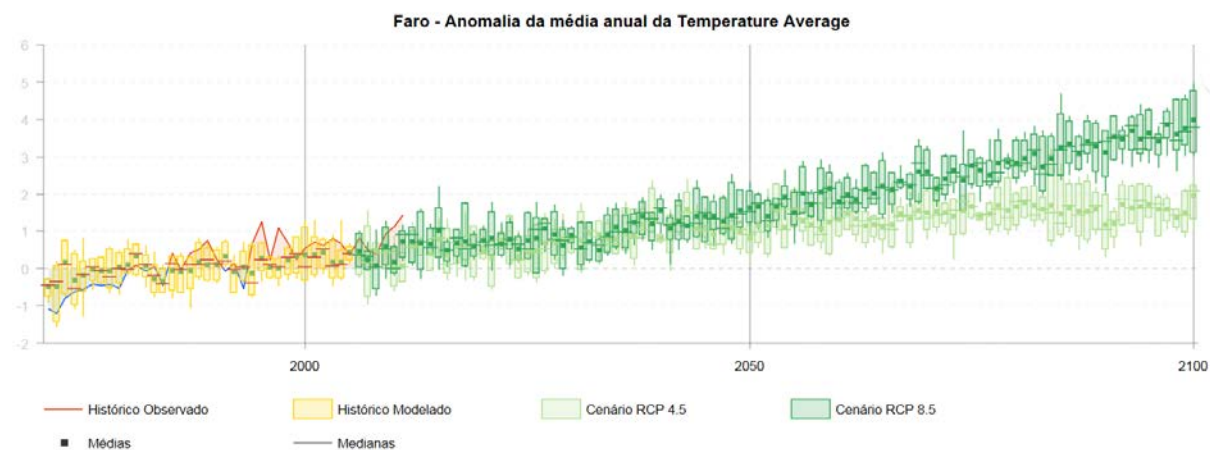
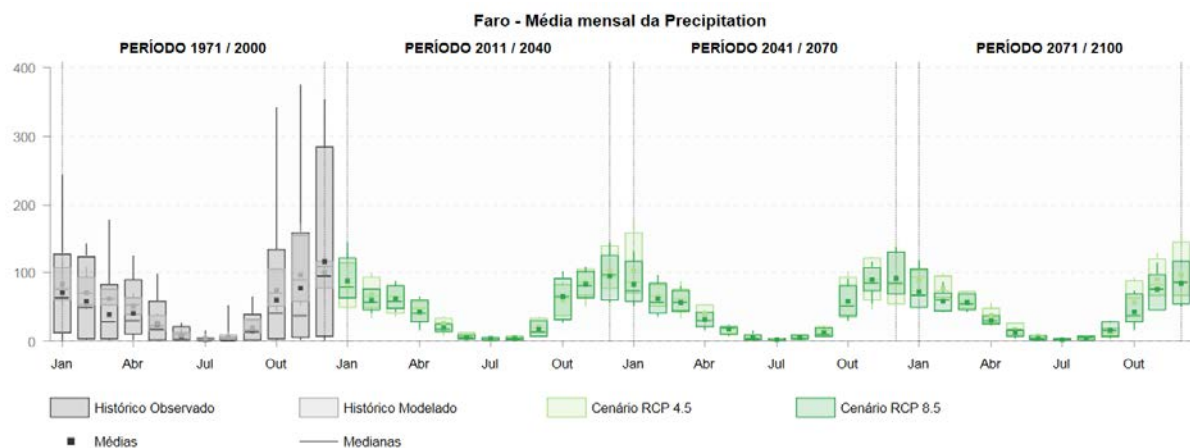


Figure 19. Temperature Predictions up to 2100 for Faro Station. <http://portaldoclima.pt/>



Monthly analysis



Annual analysis

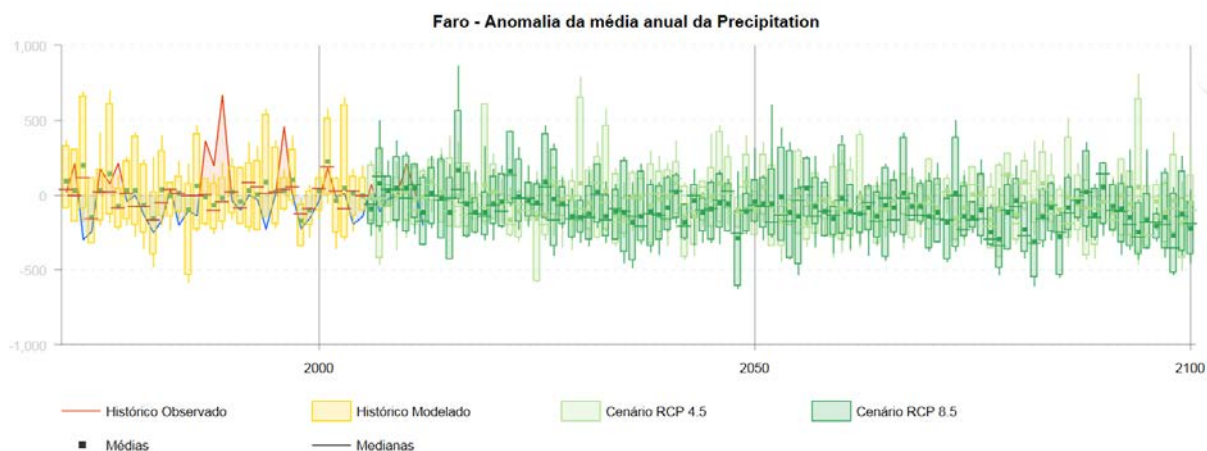


Figure 20. Precipitation Predictions up to 2100 for Faro Station. <http://portaldoclima.pt/>

3.2.2 What are the challenges related to the expected climate change?

As shown above, the rise of temperature and, consequently, the rise of the potential evapotranspiration (ET_p) together with the decrease in annual precipitation will lead to dry soils, and a decline in average river flow and water table recharge, as well as potential loss of groundwater resources.



Under these circumstances, the risk of events with potential significant impact will rise, such as the increase of the frequency and intensity of droughts and heat waves, rainstorms (especially in winter) and floods.

Due to the incidence of these events, other impacts are expected, namely:

- 1) Forest fires, biodiversity loss and desertification, changes in land use and soil capacities, decrease in crop yields;
- 2) High risk to the functioning of groundwater dependent ecosystems, increase in water demand for public supply, industry, and agriculture, and a decrease in hydropower production;
- 3) Related with sea-level rise, the rise of waves overtopping on coastal areas, coastal erosion, saline intrusion due to the loss of groundwater resources;
- 4) Expansion of habitats for southern disease vectors, dehydration and breathing problems for the elderly and children.

These will lead to the need for implementation of control and mitigation measures, for instance:

- 1) Reforestation with native species adapted to dry climates, change of practices in agriculture without destruction of the organic matter layer to retain more water in the soil, development of new underground irrigation technologies that avoid evapotranspiration;
- 2) Increase the water monitoring surveillance, promote rainfall collection, intensification of natural recharge, reuse other sources of water like treated wastewater for irrigation of golf courses, promote water use efficiency, installation of hydraulic barriers against seawater intrusion progression with the injection of treated wastewater close to the coast;
- 3) Creation of infrastructures to control flooding and promote infiltration, removal of human settlements in the flood beds and areas subject to flooding;
- 4) Rethink the planning of land use in the coastal area, shifting the population and agriculture with greater demand for water from the coast;
- 5) Energy production from other renewable sources;
- 6) Health education for climate change.

4 METHODOLOGY

Chemical indicators were applied to provide an overview of seawater intrusion status and to define the area/volume impacted by SWI. Aquifer system vulnerability was assessed applying GALDIT method. A density-dependent flow and transport model was able to simulate future impacts of SWI on the aquifer system considering 3 different recharge reduction scenarios according to climate change predictions in this region.

4.1 Assessment of seawater intrusion status through chemical indicators

In order to get an updated overview of seawater intrusion status, field work was carried out in the end of the dry season of 2019 and of 2020, collecting 38 groundwater samples each year for physicochemical analysis (major cations and anions and trace elements).

Some chemical parameters and relationships between them quickly provide an insight on seawater intrusion status within the aquifer. The concentration and spatial distribution of Cl, Br and Sr, strongly related to seawater, allow us to make a first assessment.

Secondly, ratios like $rCl/rBr \sim 655$ for seawater, $rCl/rHCO_3 = 1-5$ for inland waters and 20-50 for seawater, $rMg/rCa = 5$ for seawater (Custodio and Llamas, 1983), have been proved to be useful grouping groundwater samples affected by seawater intrusion. High concentrations of Cl may be the result of dissolution of evaporites in addition to seawater intrusion. To distinguish waters affected by each process, the ratios $rCl/rHCO_3$ and $rSO_4/rHCO_3$ were applied.

Thirdly, in the piper diagram the relative proportions of the major ions indicates which process is occurring for each groundwater sample. Their spatial distribution allows us to define the affected area and calculate the affected aquifer volume.

4.2 GALDIT (PT) - Assessment of aquifer vulnerability to seawater intrusion in coastal aquifers

The GALDIT index (CHACHADI and LOBOFERREIRA, 2001, 2005) was developed on the assumption that the vulnerability of groundwater to seawater intrusion can be defined as “the sensitivity of groundwater quality to an imposed groundwater extraction rate or sea level rise or both in the coastal belt, which is determined by the intrinsic characteristics of the aquifer”. To apply the method the base of the aquifer(s) must lie below the mean sea level.

The most important mappable factors that control the seawater intrusion were found to be:

- Groundwater occurrence (aquifer type; unconfined, confined and leaky confined).
- Aquifer hydraulic conductivity.
- Height of groundwater Level above sea level.

- Distance from the shore (distance inland perpendicular from shoreline).
- Impact of existing status of seawater intrusion in the area.
- Thickness of the aquifer, which is being mapped.

$$\text{GALDIT Index} = (1 \cdot G + 3 \cdot A + 4 \cdot L + 4 \cdot D + 1 \cdot I + 2 \cdot T) / 15$$

The vulnerability of the area to seawater intrusion is assessed based on the magnitude of the GALDIT Index. In a general way, lower the index less vulnerable to seawater intrusion.

Table 5 – GALDIT Index Range and Vulnerability Classes

Sr. no.	GALDIT-Index Range	VULNERABILITY CLASSES
1	≥ 7.5	Highly vulnerability
2	5 to 7.5	Moderately vulnerability
3	< 5	Low Vulnerability

The height of groundwater level above sea level and the impact of existing status of seawater intrusion in the area are 2 out of a total of 6 parameters that might vary over time. Thus, GALDIT's vulnerability mapping remains more or less constant if no significant changes in land use and water abstractions occur.

4.3 Flow and transport model

4.3.1 Model description

A three-dimensional density-coupled flow and transport model for the aquifer system was developed by Hugman (2016), to provide an insight into local SWI processes. Long-term changes in land use within Vale do Lobo subsystem are unlikely to occur as tourism is well established with several golf courses, resorts and villas. The greatest pressure on the system will be the maintenance of the current abstractions alongside with the reduction of the recharge due to climate change. Based on the forecast of climate change in this area (section 3.2.1), three scenarios of 5%, 10% and 20% of recharge reduction have been simulated to predict the progress of the SWI.

4.3.2 Model set-up

A detailed description of the model set-up can be seen in Hugman (2016). A summary of the main aspects is presented as follows.

A three-dimensional (3D) geological representation of the three layers (sandy phreatic aquifer, clay aquitard and sandy limestone aquifer) of the CF was created, based on a digital elevation model (DEM), data collected from borehole logs and results from previous geophysical studies. Onshore, the outer limits were extended to include the coastal lagoon and a 500 m offshore extent where the CF connects directly with the Atlantic Ocean. Elevation of the sea-floor was based on detailed bathymetry data.

Mesh generation took into account the location of the geological units, fault-lines, main streams and channels of the lagoon.

Recharge from rainfall was assigned to the top layer, with a uniform value of 17.5% of average annual rainfall. Monthly rainfall data was used to determine recharge for transient simulations. Estimated abstraction rates for the several golf courses active within the aquifer limits were assigned to boreholes inventoried within their respective areas of operation. Abstraction for agriculture was arbitrarily distributed with 25% in the phreatic and the remaining 75% in the semi-confined aquifer. Transient simulations considered constant abstraction for irrigation concentrated from mid-May to mid-September.

Porosity affects the rate of contaminant movement. Therefore, minimum values were assumed, as they represent the worst-case scenario where SWI occurs faster.

Table 6 –Hydrogeological parameter ranges in Hugman (2016)

Layer	Porosity	Specific Yield (S_y)	Hydraulic Conductivity (K) ($m.d^{-1}$)
Phreatic (sand)	0.22-0.38 *	0.20-0.35 *	0.0167-46.32 *
Aquitard (clay)	0.35-0.60 **	0.00-0.05 *	0.005 *
Semi-Confined	0.05-0.40 **	0.001 ***	0.19-3.97 ***

*(Roseiro, 2009); **(Fitts, 2002); *** (Silva, 1988)

To determine the potential amount of lateral recharge to the CF, the average annual groundwater budget of the area to the north was estimated (Hugman, 2016). The average water budget from 1983 to 1999, assuming constant irrigation and public water supply demands, results in a excess water budget of $1.0 \times 10^6 m^3.yr^{-1}$. With the decrease in abstraction for public water supply from 1999 to 2008, average groundwater available for lateral recharge was estimated at $4.2 \times 10^6 m^3.yr^{-1}$.

4.3.3 Model calibration

A detailed description of the model calibration can be seen in Hugman (2016). A brief summary of the main aspects is presented as follows.

K and b were calibrated by trial-and-error for the period between 2000-2007. This period was chosen for the large amount of continuous time-series. Subsequently storage parameters (Sy Specific Yield and Ss Specific Storage) were calibrated by trial-and-error using transient data for the period between 1990 to 1999. Simulated variation in hydraulic head was compared to measured values from the official monitoring network. Results were validated by extending the simulation to 2007.

4.3.3.1 Observation/Simulated data

Simulated temporal variation in hydraulic head for the 1990-2007 period was compared with observed values for selected piezometers in Figures 21 and 22.

Best fit for simulated hydraulic head was obtained with K values of 5.62 m.d⁻¹ (phreatic), 0.0045 m.d⁻¹ (aquitard) and 0.95 m.d⁻¹ (semi- confined) and with an S_y of 0.05 (phreatic), 0.01 (aquitard) and 0.2 (semi- confined) (Hugman, 2016).

Both phreatic and aquitard layers were not sensitive to S_s, and the default 0.0001 m⁻¹ was maintained, whilst the best fit for the semi-confined layer was obtained with a value of 0.0003m⁻¹ (Hugman, 2016).

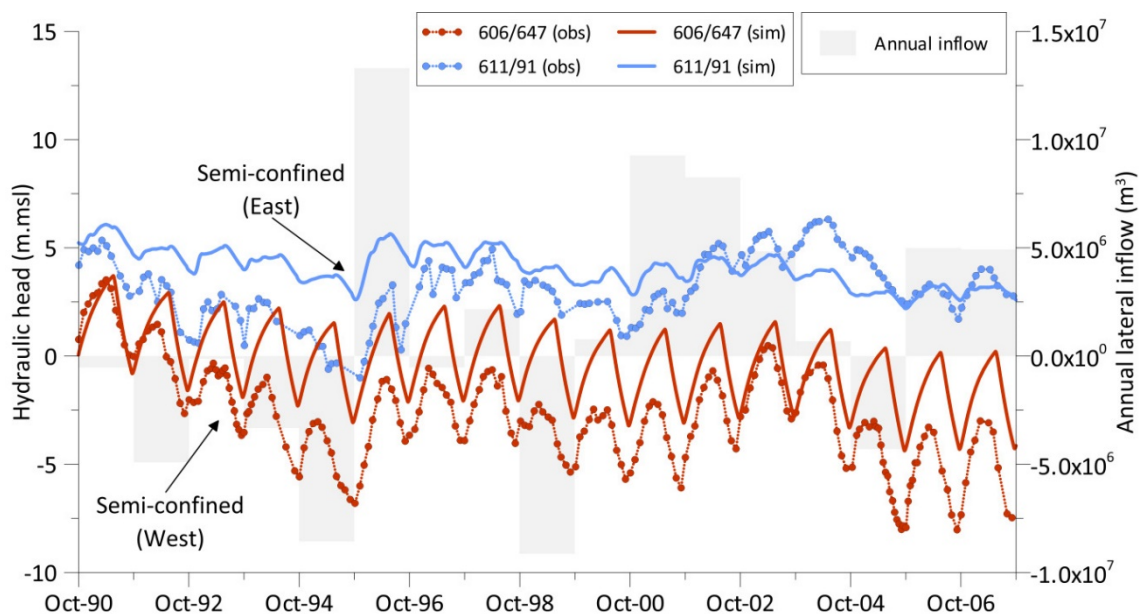


Figure 21. Time-series of simulated and observed hydraulic head between 1990 and 2007 in the east and west sectors of the CF, extracted from Hugman (2016).

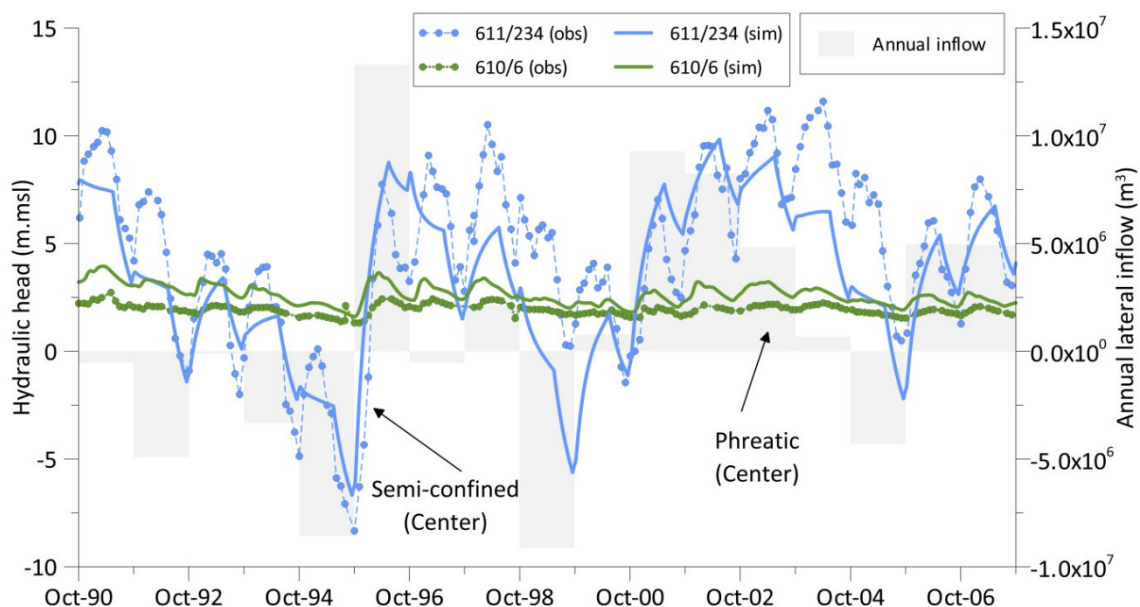


Figure 22. Time-series of simulated and observed hydraulic head between 1990 and 2007 in the central sector of the CF, extracted from Hugman (2016).

4.3.4 *Uncertainty*

The good fit between observed and simulated hydraulic heads, for an acceptable range of hydraulic parameters, corroborates the conceptual model of lateral inflow through fractures/faults contributing to groundwater budget of the system (Hugman, 2016). Lateral recharge to the CF is subject to a large amount of uncertainty and calls for further work to constrain the estimate of lateral inflow, as this is an important part of the CF water budget.

Discharge into aquatic and terrestrial ecosystems is also a source of uncertainty and does not allow greater accuracy in the water balance.

5 RESULTS AND CONCLUSIONS

5.1 Assessment of seawater intrusion status

High Cl, Na, Br, Sr concentrations clearly show the affected area in Figures 23, 24 and 25. Seawater intrusion is ongoing in the South of Vale do Lobo subsystem.

High concentrations of Cl and Br are also observed within the aquifer system, in aligned points, coinciding with trending faults W-E and NW-SE. In fact, there are evaporites injected into these faults at a depth of about one hundred meters which are responsible to these high concentrations accompanied by high concentrations of sulphate.



Figure 23. Spatial distribution of Cl concentration(mg/L) on October2019.



Figure 24. Spatial distribution of Sr concentration(mg/L) on October2019.



Figure 25. Spatial distribution of Br concentration(mg/L) on October2019.

Ratios such as rCl/rBr , $rCl/rHCO_3$ (Figure 26) and rMg/rCa allowed us to clarify which are the sampling points whose chemical composition results from mixing with seawater.

Additionally, the ratios $rCl / rHCO_3$ and $rSO_4 / rHCO_3$ were calculated and projected one against other on a scatter plot in order to discretized groundwaters affected by seawater intrusion from those affected by evaporites dissolution + fertilizers input (Figure 27). Two distinct groups of groundwaters are observed. There is a group of 4 samples showing a strong mixture with seawater, namely San Lorenzo - Green 10 (610/228), San Lorenzo - Hole 2 (610/195), Infraquinta (610/211) and JJW - Formosa Park Hotel (610/256) corresponding to the highest values of $rCl / rHCO_3$ (Figure 26). In the other group, the discretization of groundwater can be seen according to the concentration of sulphates from the dissolution of evaporites, sometimes masked with the input of fertilizers (Figure 27).

rCl / rBr ratio was not very conclusive, highlighting only the sampling point 610/195 of the group of 4 and pointing out also 606/1098 and 606/1019, both located inland, 1600m and 3000 m far from the coast.

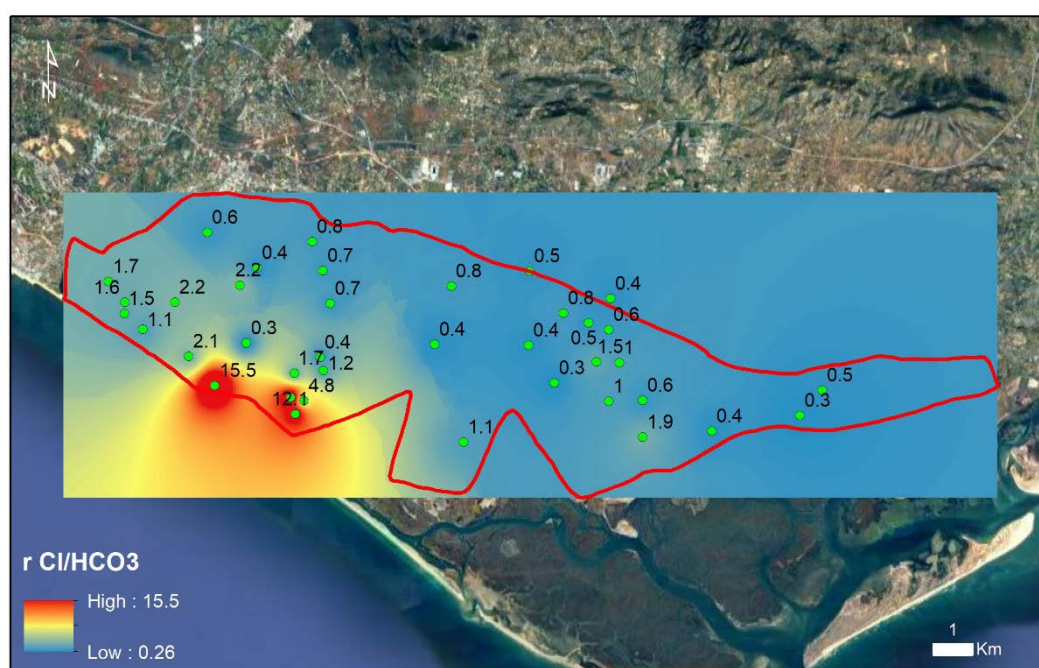


Figure 26. $rCl/rHCO_3$ mapping on October 2019. Values >5 indicate seawater intrusion.

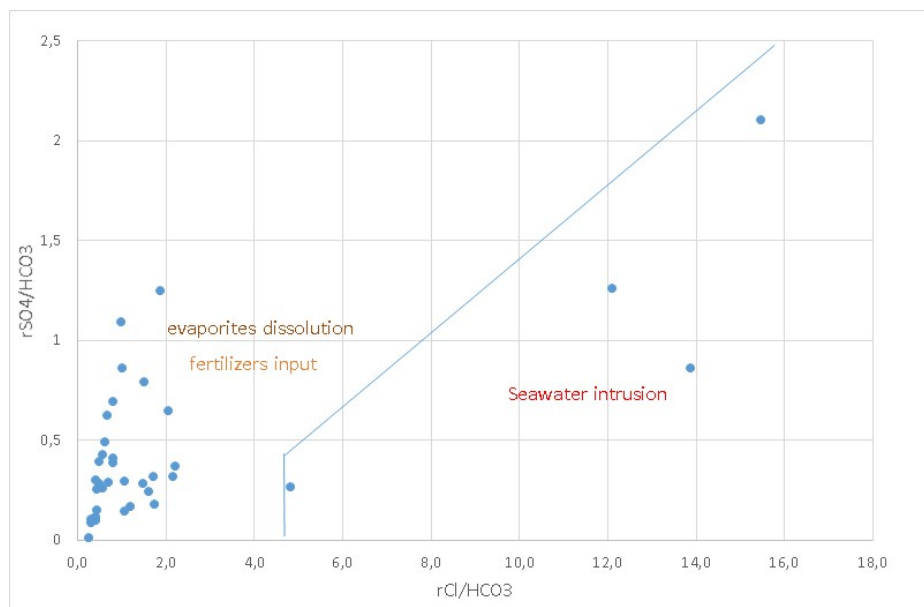


Figure 27. Scatter plot between $rCl/rHCO_3$ and $rSO_4/rHCO_3$ on October 2019. 2 distinct groups affected by seawater intrusion and evaporites dissolution can be observed.

On the piper diagram, the relative proportions of the major ions indicates which process is occurring in each groundwater sample (Appelo and Postma, 1996, Figure 28).

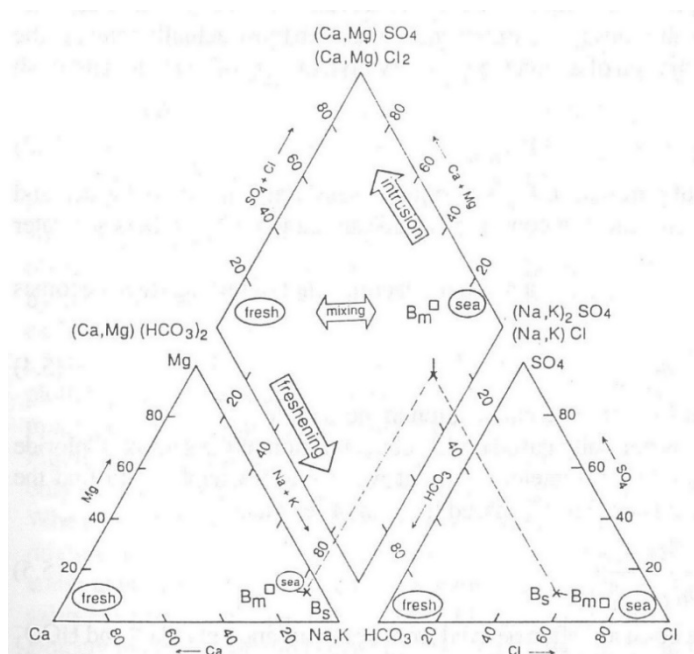


Figure 28. Processes that are taking place in groundwater can be identified with the Piper diagram (Appelo and Postma, 1996)

Plotting groundwater samples from Vale do Lobo subsector (Figure 29, right), it can be seen that the group of 4, mentioned above, are over the intrusion domain.

On Campina de Faro subsector, samples 611/201, 611/242 and 611/260 are aligned with a NW-SE fault and also present high concentrations of Cl, Br, SO₄ related with evaporites dissolution (Figure 29, left, orange highlighted).

On the E of the aquifer system, sample 611/261 is very different from the other samples (Figure 29, left, blue highlighted). In fact, this sample is from a borehole that has been without extraction and the groundwater was not renewed prior to sampling, having been collected with a sampler. This sample is not representative and should not be considered in the assessment.

Figure 30 shows how relative proportions of the major ions are spatial distributed on the aquifer system showing an agreement with previous results.



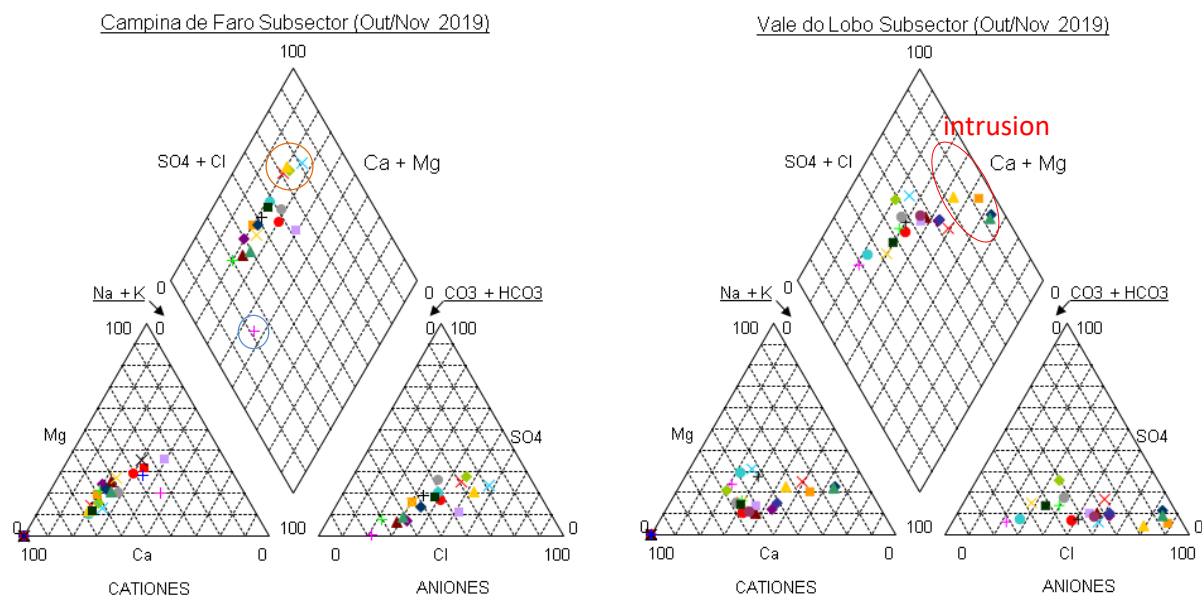


Figure 29. Processes that are taking place in groundwater from Campina de Faro and Vale do Lobo subsectors.



Figure 30. Relative proportions of major ions in the aquifer system.

The overlapping of various indicators allows the delimitation of an area of 4.6 km² impacted by seawater intrusion, which corresponds to 14.4% of Vale do Lobo subsystem. If we take into account 250 m of aquifer thickness, we can estimate that a volume of 1,150 x 10⁶m³ of the aquifer matrix is currently impacted.

5.2 Assessment of aquifer vulnerability to seawater intrusion

The application of the GALDIT method to Campina de Faro is shown below in figures 31 to 37.

G (Groundwater Occurrence (aquifer type; unconfined, confined and leaky confined))

Indicator	Weight	Indicator Variables	Importance Rating
Groundwater occurrence/Aquifer type	1	Confined Aquifer	10
		Unconfined Aquifer	7.5
		Leaky confined Aquifer	5
		Bounded Aquifer (recharge and/or impervious boundary aligned parallel to the coast)	2.5

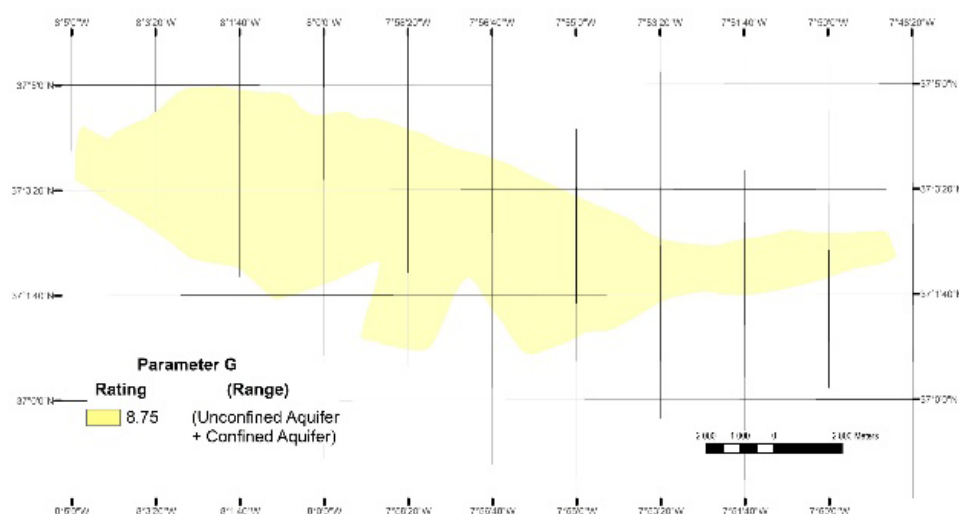


Figure 31. Parameter G - Groundwater occurrence/aquifer type.

A (Aquifer Hydraulic Conductivity)

Indicator	Weight	Indicator Variables		Importance Rating
		Class	Range	
Aquifer Hydraulic Conductivity (m/day)	3	High	>40	10
		Medium	10-40	7.5
		Low	5-10	5
		Very low	<5	2.5



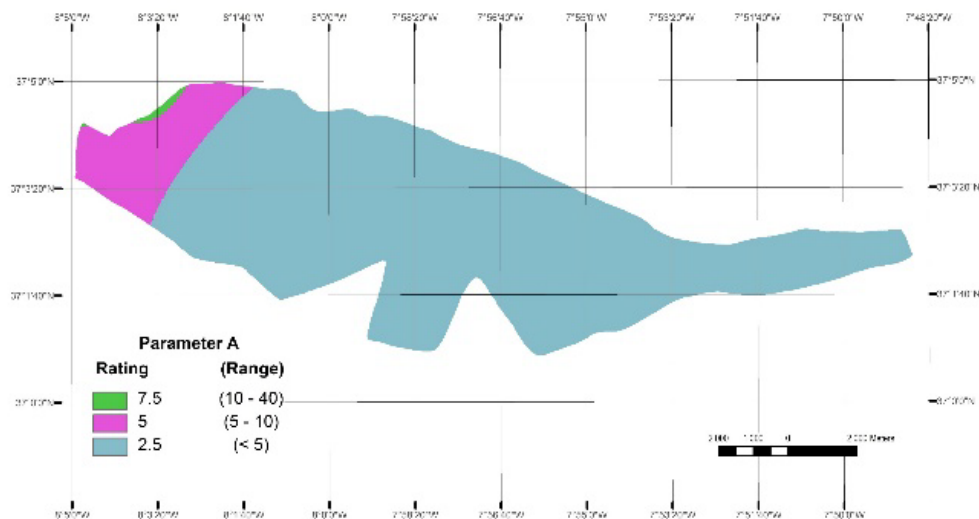


Figure 32. Parameter A - Aquifer Hydraulic Conductivity.

L (Height of Groundwater Level above Sea Level)

Indicator	Weight	Indicator Variables		Importance Rating
		Class	Range	
Height of ground water Level above msl (m)	4	High	<1.0	10
		Medium	1.0-1.5	7.5
		Low	1.5-2.0	5
		Very low	>2.0	2.5

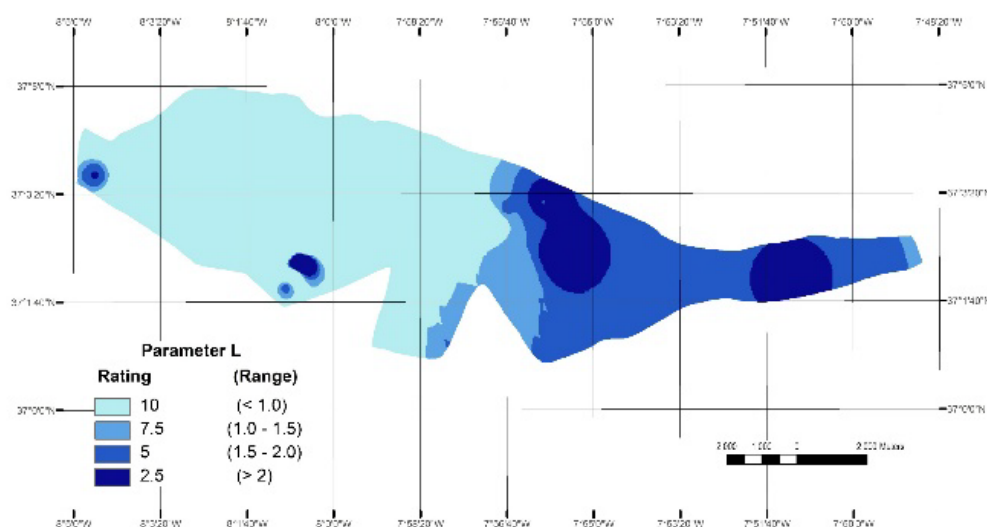


Figure 33. Parameter L - Height of Groundwater Level above Sea Level.



D (Distance from the Shore)

Indicator	Weight	Indicator Variables		Importance Rating
		Class	Range	
Distance from shore / High Tide (m)	4	Very small	<500	10
		Small	500-750	7.5
		Medium	750-1000	5
		Far	>1000	2.5

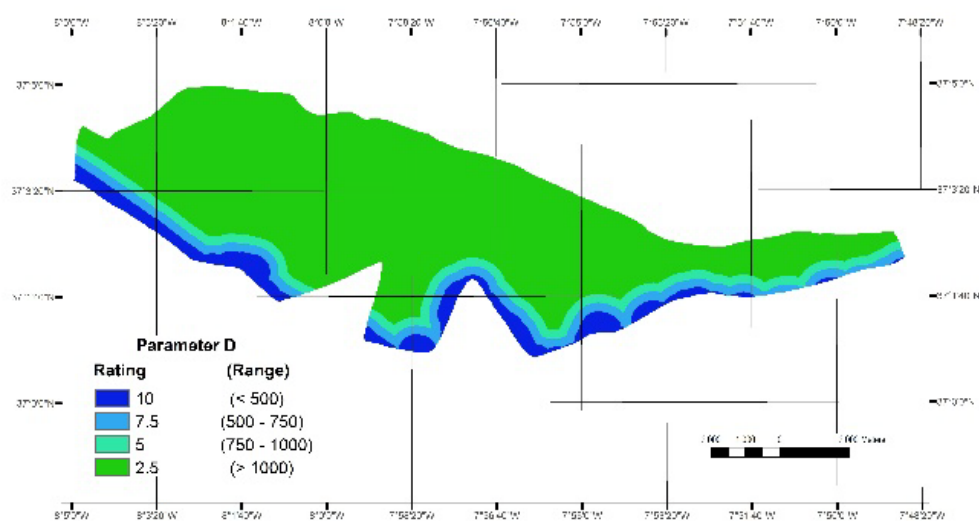


Figure 34. Parameter D - Distance from the Shore.

I (Impact of existing status of seawater intrusion in the area)

Indicator	Weight	Indicator Variables		Importance Rating based on $Cl^- / [HCO_3^{-1} + CO_3^{2-}]$, ratio of ground water
		Class	Range of $Cl^- / [HCO_3^{-1} + CO_3^{2-}]$, ratio in epm in ground water	
Impact status of existing seawater intrusion	1	High	>2	10
		Medium	1.5-2.0	7.5
		Low	1-1.5	5
		Very low	<1	2.5

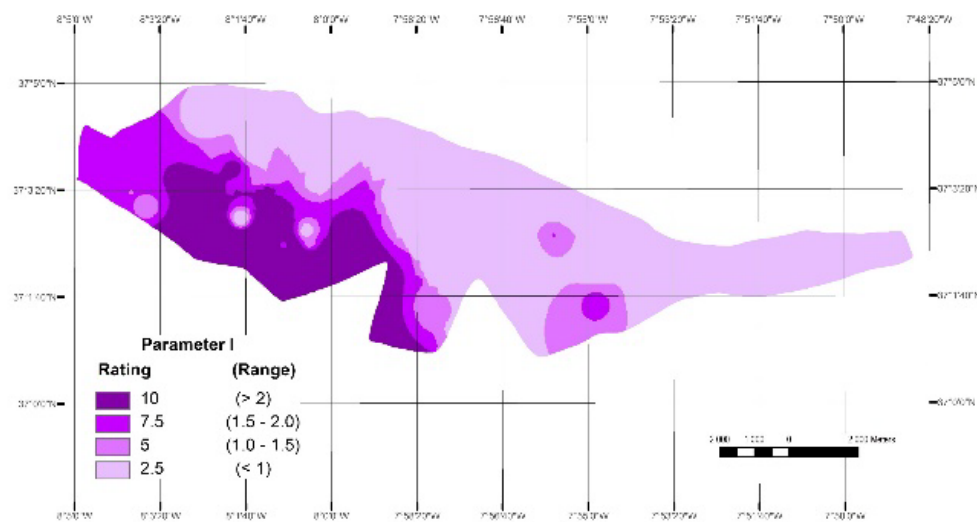


Figure 35. Parameter I - Impact of existing status of seawater intrusion in the area.

T (Thickness of the aquifer)

Indicator	Weight	Indicator Variables		Importance Rating based on the saturated aquifer thickness
		Class	Range	
Aquifer thickness (saturated) in metres	2	Large	>10	10
		Medium	7.5-10	7.5
		Small	5-7.5	5
		Very small	<5	2.5

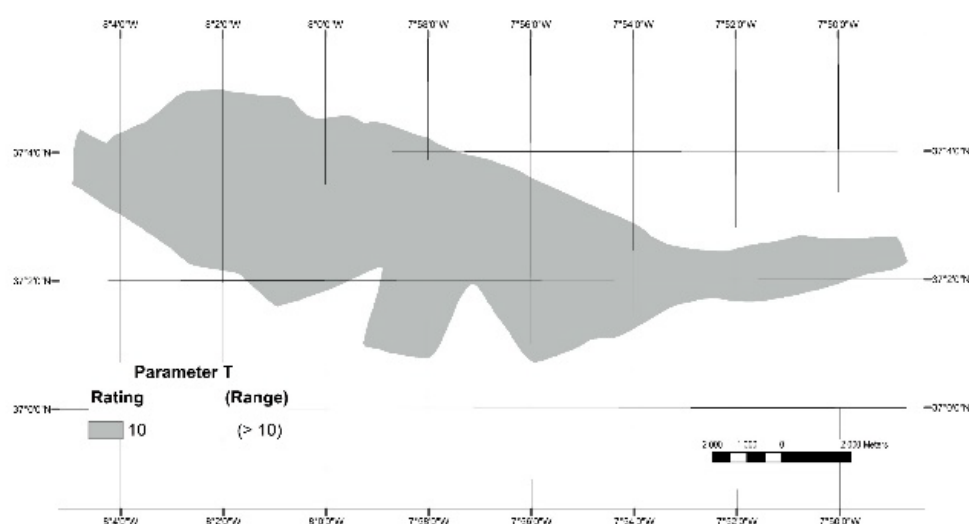


Figure 36. Parameter T - Thickness of the aquifer.



Figure 37. GALDIT index.

In figure 37 it can be seen that the results of GALDIT Index are very consistent with what is seen in the aquifer system.

The eastern sector of the Campina de Faro is less vulnerable than the western sector of Vale do Lobo. Within the highly vulnerability area of Vale do Lobo we can find the boreholes affected presently by seawater intrusion.

5.3 Scenarios of seawater intrusion impacts due recharge reduction

Due to predicted climate change for the region, reduced rainfall will affect the aquifer in two ways. On the one hand, direct recharge is automatically reduced and, on the other hand, surplus recharge from aquifers systems at the north will also be reduced decreasing the lateral recharge in CF. It is unexpected long-term changes in land use once tourism and agriculture are well established. So, the greatest challenge of the system will be maintaining currently demand alongside with recharge reduction and potential increase in the irrigation requirement.

Based on the forecast of climate change in this area (section 3.2.1), three scenarios of 5%, 10% and 20% of recharge reduction have been simulated to foresee SWI impact.

Results for the simulation of the density driven flow model are shown on Figure 38 to Figure 45.



Four scenarios have been simulated according to: Scenario A – Business as Usual; Scenario B – reduction of 5% recharge; Scenario C – reduction of 10% recharge; Scenario D – reduction of 20% recharge

The spatial distribution of the seawater-freshwater (SW-FW) fraction for the different scenarios is shown in figures 38 to 41 respectively, for the following slices:

- Slice 1 – Top of Plio-Quaternary aquifer;
- Slice 4 – Bottom of Plio-Quaternary aquifer;
- Slice 6 – Top of Miocene aquifer;
- Slice 8 – Upper mid slice of Miocene aquifer;
- Slice 12 – Lower mid slice of Miocene aquifer;
- Slice 18 – Bottom of Miocene aquifer;

Most of the abstractions in the area occur within slices 8 and 12.

According to the spatial distribution of the SW-FW, it can be seen that scenario A (BAU) results in the scenario with lower extent of area affected by SWI, when compared with the remaining scenarios of recharge decrease. As expected, the area affected by SWI increases when the recharge decreases, which can be seen when comparing the same slice of different scenarios. It can also be observed that for all the scenarios, the mixing zone becomes wider with depth. A particular increase of the width of the mixing zone towards the interior of the aquifer appears to occur at slice 8, which could be due to the effect of the abstractions wells, since most abstractions wells fall within slices 8 and 12. Results obtained suggest that the western sector of this aquifer (Vale do Lobo sector) appears to be more vulnerable to seawater intrusion processes, as can be seen by the larger mixing zone in this sector, when compared to the easternmost sector.

Figure 38. Scenario A – Business as Usual; Fraction SW – FW (1 = fully seawater, 0 = fully freshwater)

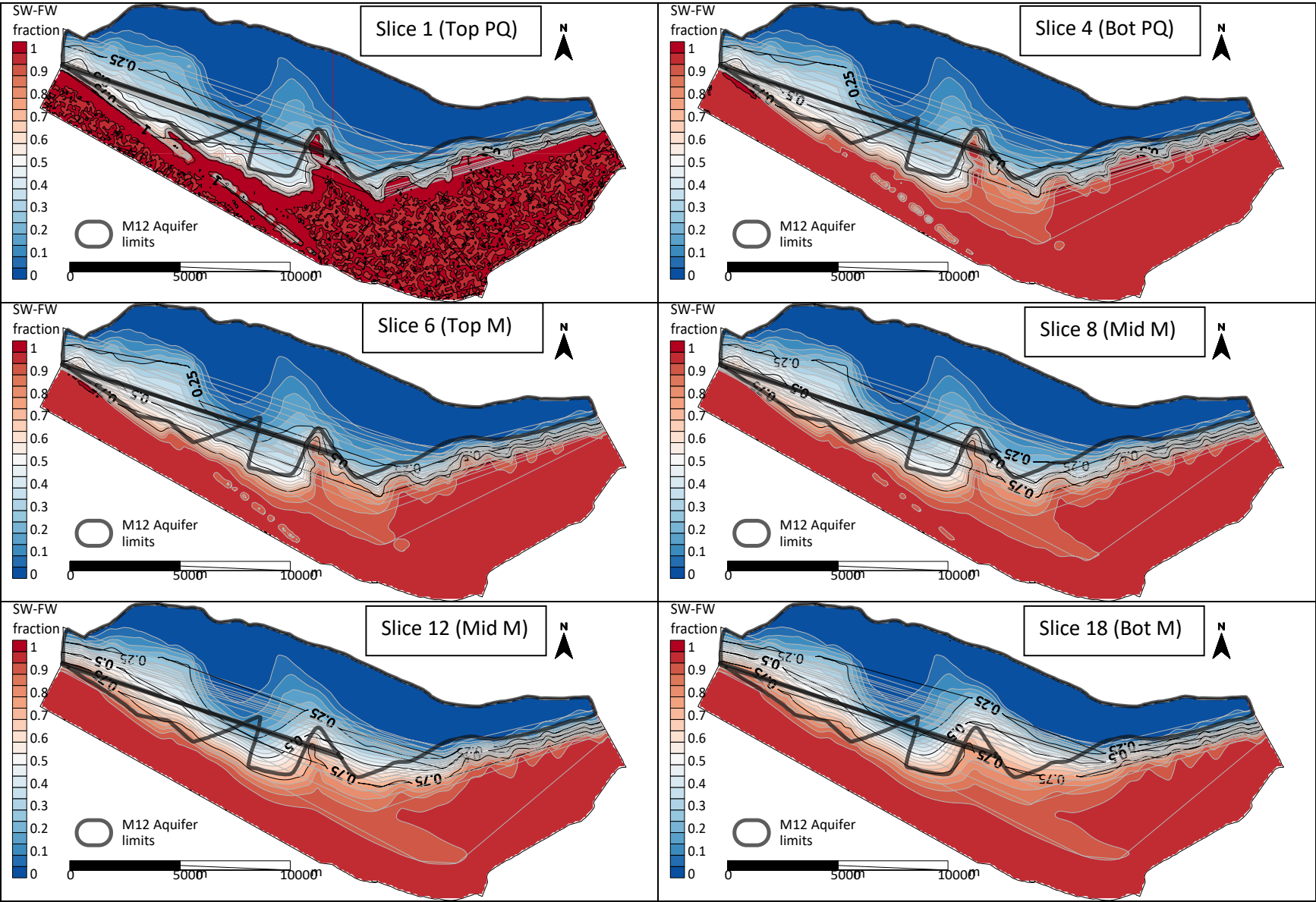


Figure 39. Scenario B – Recharge reduction – 5%; Fraction SW – FW (1 = fully seawater, 0 = fully freshwater)

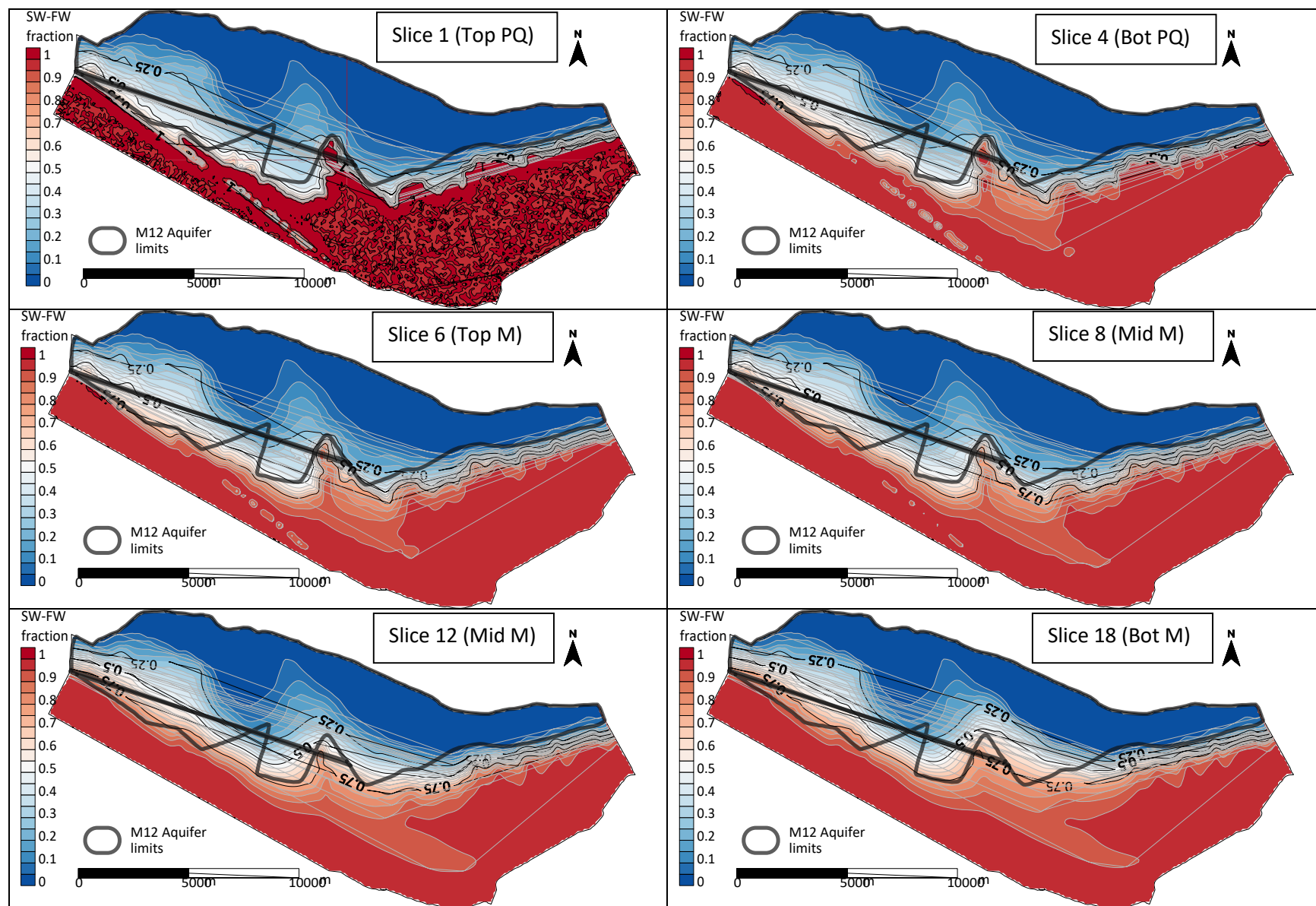


Figure 40. Scenario C – Recharge reduction – 10%; Fraction SW – FW (1 = fully seawater, 0 = fully freshwater)

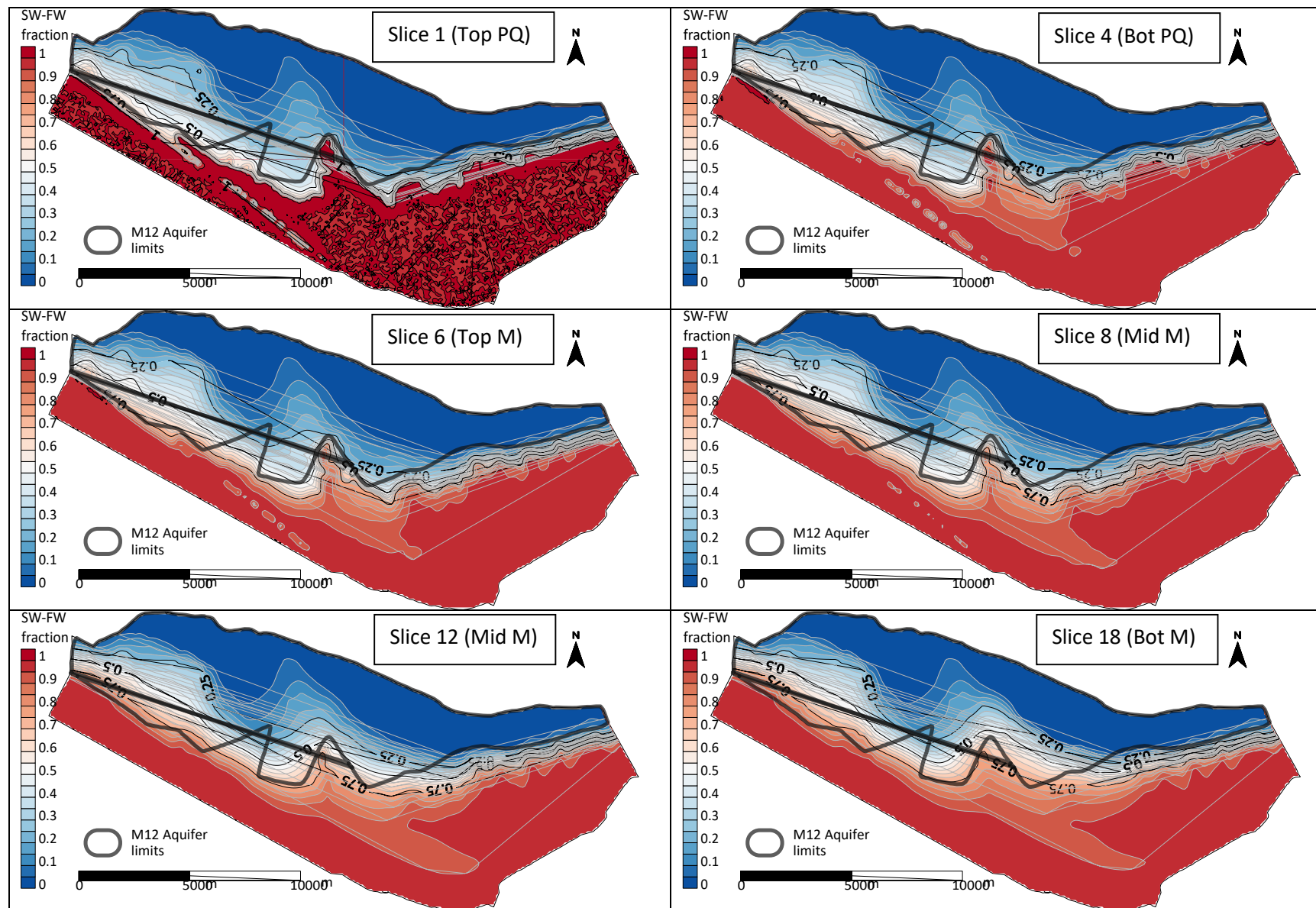
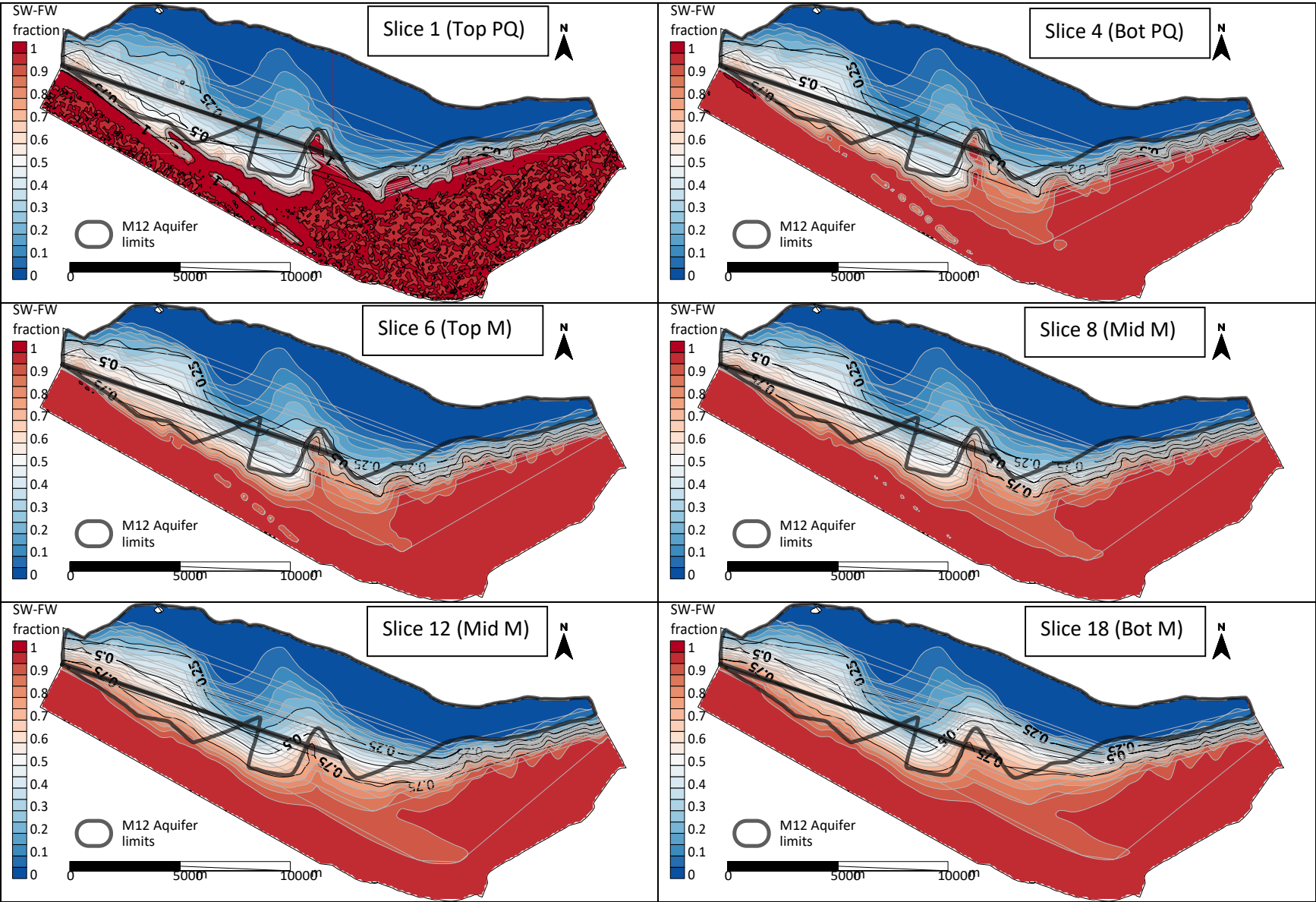


Figure 41. Scenario D – Recharge reduction – 20%; Fraction SW – FW (1 = fully seawater, 0 = fully freshwater)



Figures 43 to 44 show two N-S and NE-SW cross sections with the calculated SW-FW fraction in the aquifer system. Two cross sections have been analysed, namely, Vale do Lobo (VL), in the Western sector and Rio Seco (RS) in the Eastern sector of the aquifer system and the location of such cross sections is shown in figure 42. With the analysis of both cross-sections, it becomes clear that the semi-confined Miocene aquifer appears to be more affected by seawater intrusion than the upper Plio-Quaternary aquifer, since a higher extension of this system shows higher SW fraction. As previously mentioned upon the analysis of the SW-FW fraction spatial distribution, the cross sections also show that the Vale do Lobo sector have a higher extent of seawater fraction towards the inside of the aquifer system, in the Miocene aquifer.

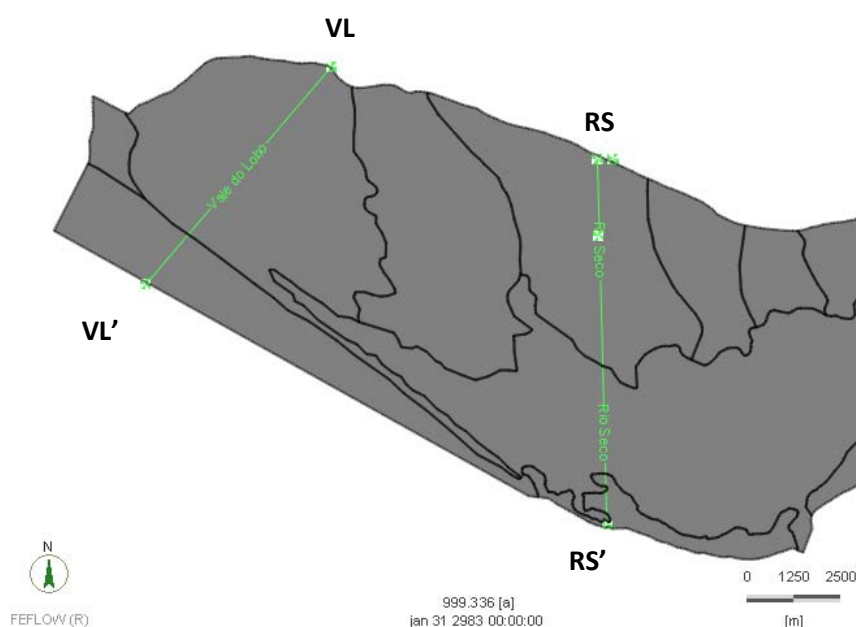
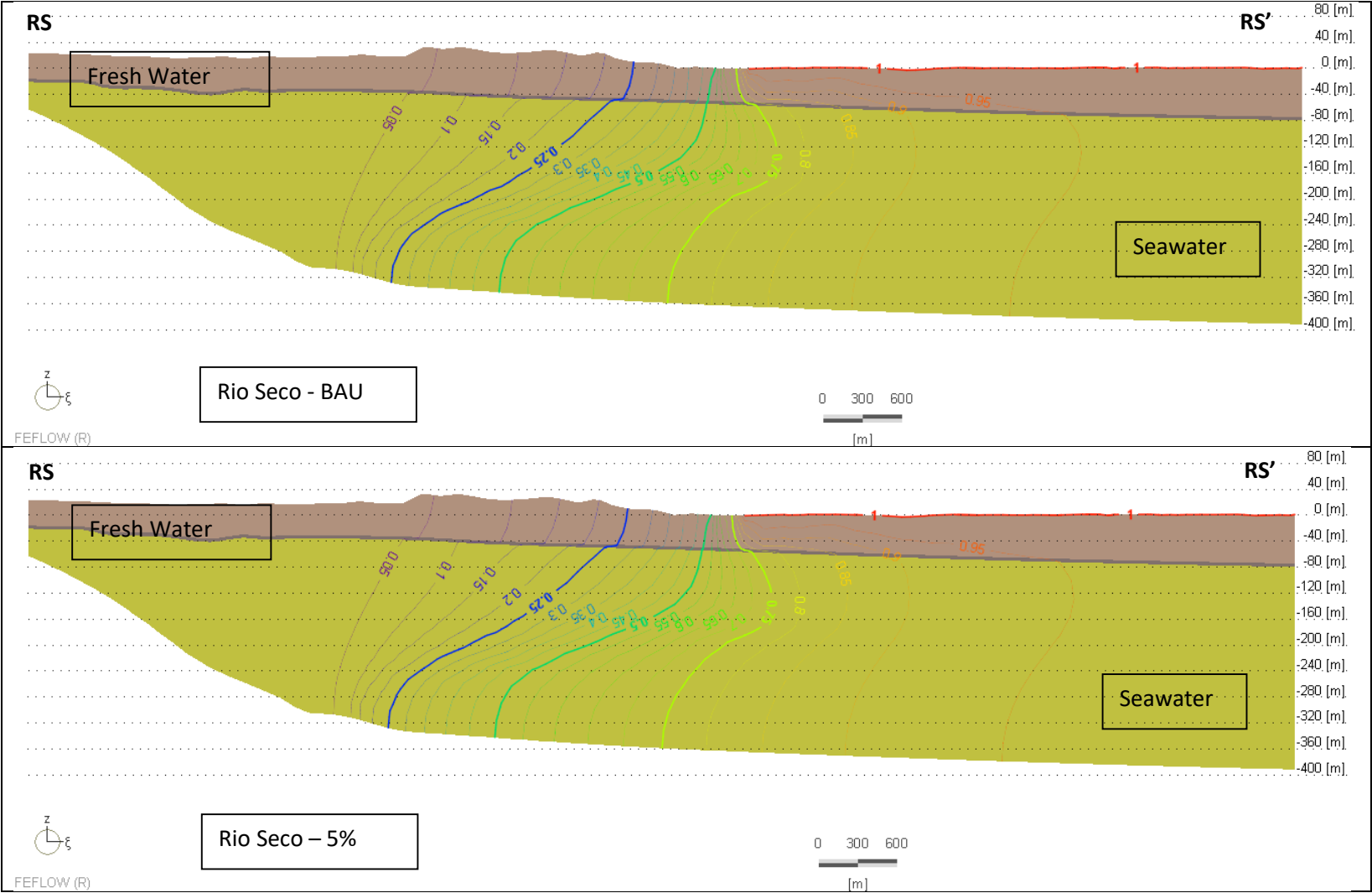


Figure 42. Cross Sections location: VL = Vale do Lobo cross section; RS = Rio Seco cross section.

In order to present a better representation of the differences of SW-FW fraction amongst the simulated scenarios, a residual map is presented in figure 45, showing the residual between scenario A (Business As Usual) and the worst case scenario D (decrease of 20% recharge). Within this figure, negative values, represented in red shades, indicate increase of SW fraction, when comparing scenario D to A, i.e., it indicates areas where scenario D shows higher fraction of seawater than scenario A. On the opposite, green shades indicate areas where scenario A shows higher fraction of SW comparing with scenario D.

Figure 43. Rio Seco Cross Section with SW-FW fraction



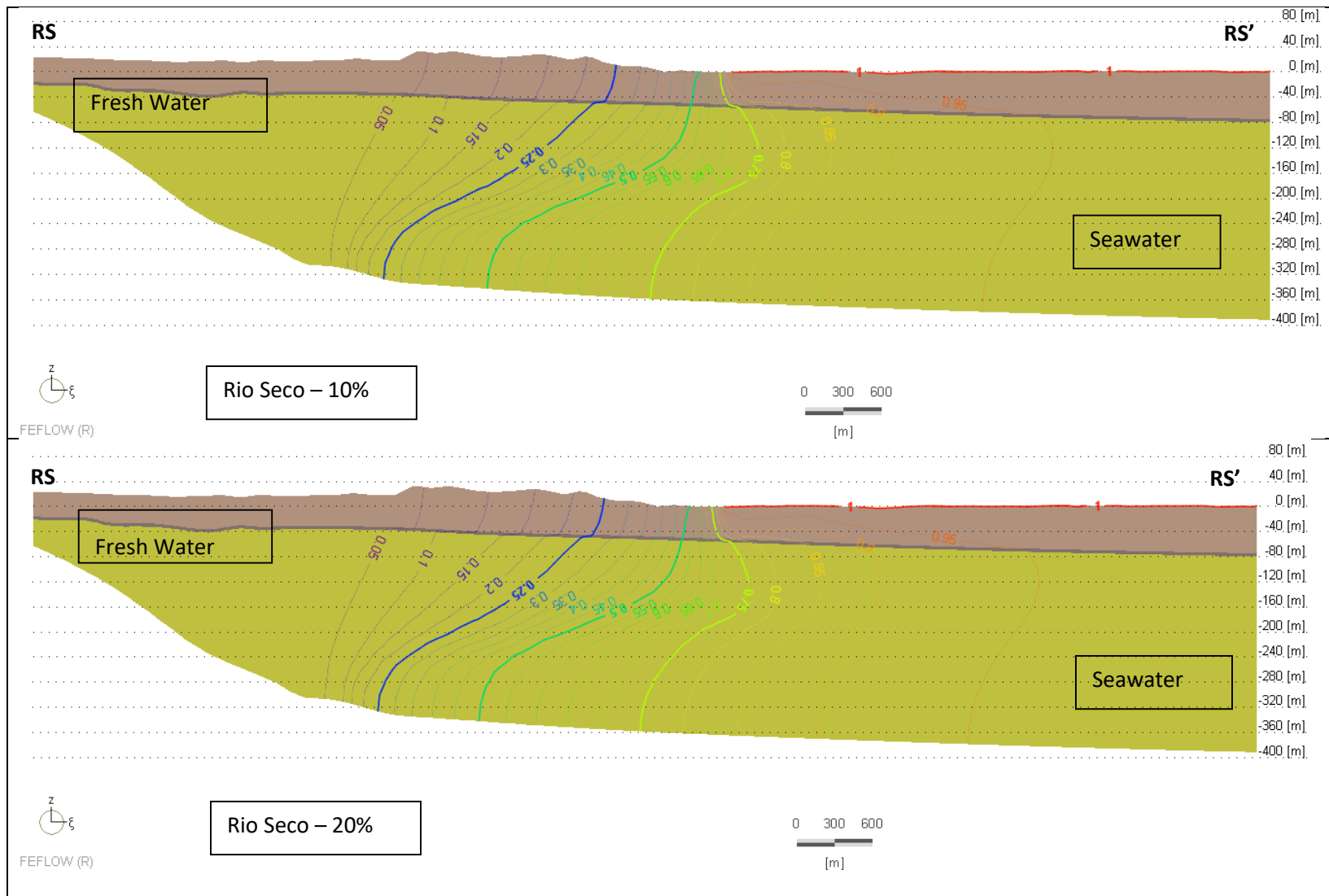


Figure 44. Vale do Lobo Cross Section with SW-FW fraction

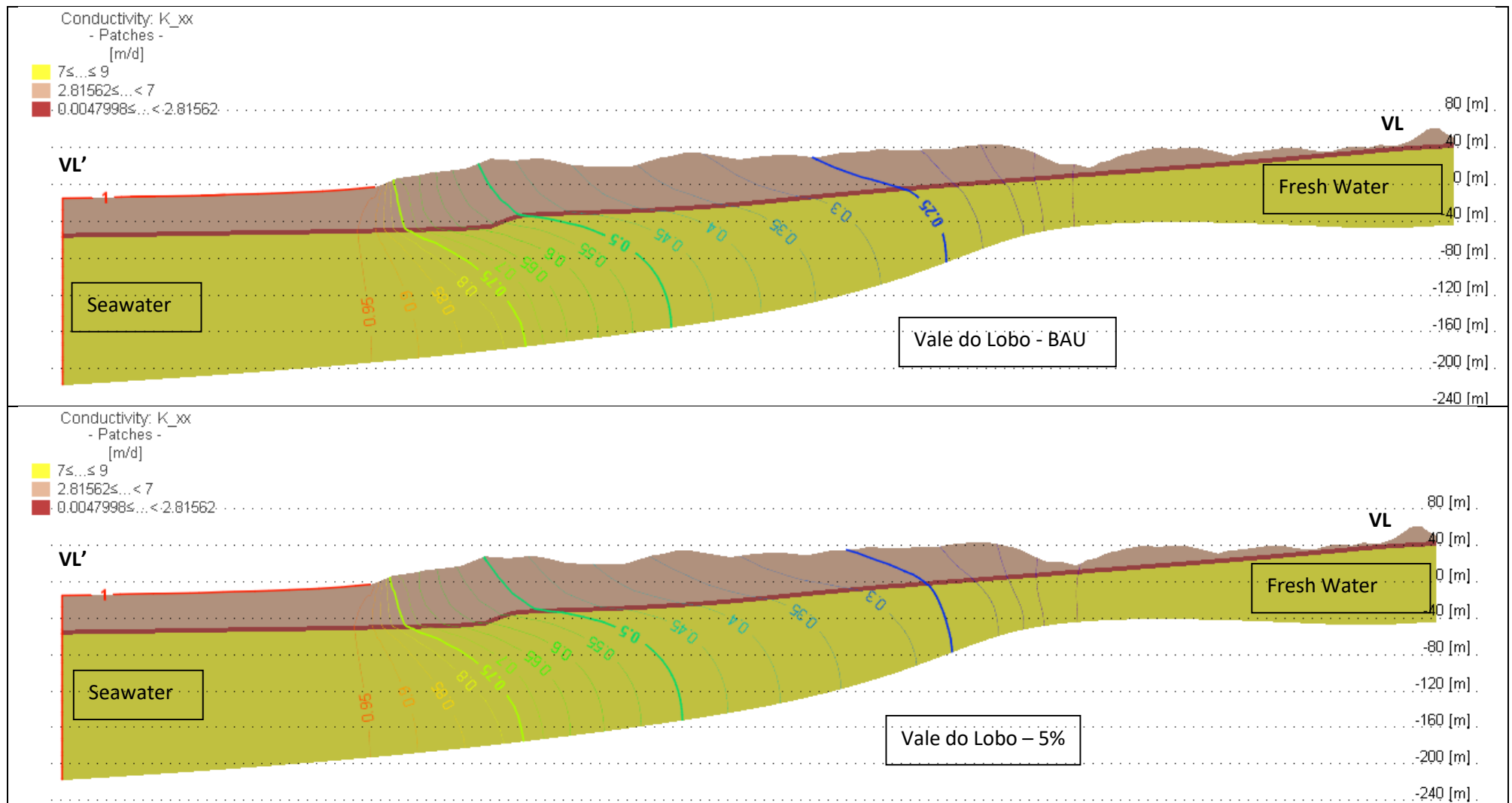
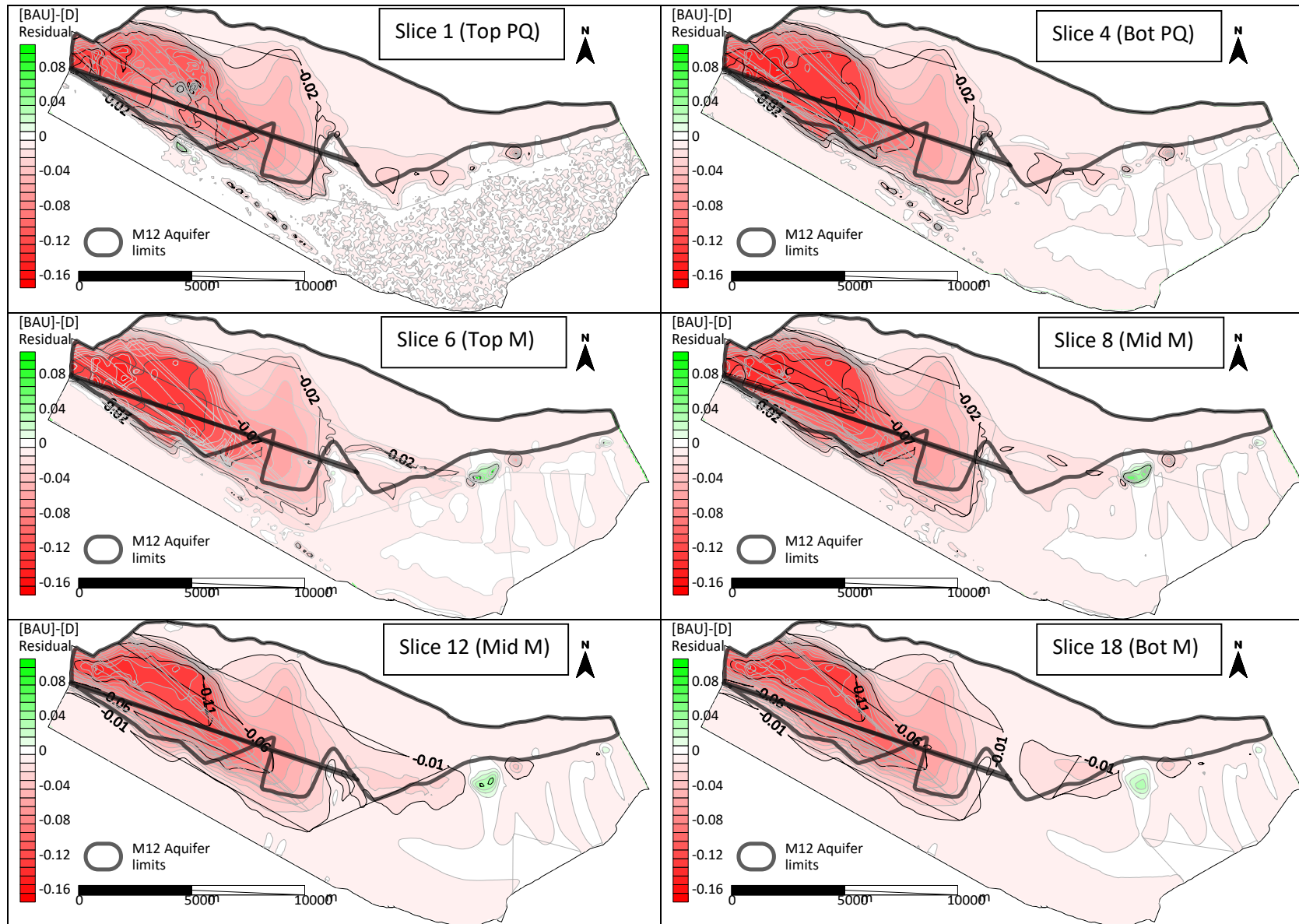


Figure 45. Residuals between Scenario BAU and Scenario D – Decrease of 20% recharge; Residual [BAU] – [D]



Modelled results show that for the entire aquifer limits, SW fraction affected areas are higher for scenario D. There are some areas in which the opposing is happening, i.e., scenario A shows higher fraction of SW, but those happen outside of the aquifer system limits, and could be due to numerical instability of the model. The residual map clearly shows the most affected areas by the decrease in recharge, which, as already suggested before, is in the western sector of Vale do Lobo, while the remaining sector of the aquifer is only mildly affected.

This pedagogical analysis shows in general that the Miocene aquifer of this aquifer system is more affected than the Plio-Quaternary aquifer. This is an expected result since the Miocene aquifer is affected by a higher rate of abstraction. This becomes more evident in the western sector of the aquifer, the Vale do Lobo sector, which is subject to a higher and more concentrated water abstraction, hence being more vulnerable to seawater intrusion processes.

5.4 Conclusions

Good agreement can be seen between the methods employed, including the major ions (Cl, Na, Br, Sr) spatial distribution, whose high concentrations has seawater as source, the rising trend in Cl time series, the ratio $rCl/rBr \sim 655$ and the ongoing processes as showed by piper diagram. As high concentrations of Cl may have evaporites dissolution in addition to seawater intrusion as sources, ratios $rCl / rHCO_3$ and $rSO_4 / rHCO_3$ were applied to distinguish waters affected by each process.

Time series of piezometric levels and chemical parameters showed that average piezometric surface of the western sector for deep aquifer has been below sea level since 1980's and with the Cl concentration starting to increase from 2005.

The combined analysis allows the delimitation of an area of 4.6 Km² currently impacted by seawater intrusion, which corresponds of about 14.4% of Vale do Lobo subsystem (Figure 46).

The highest vulnerability areas identified by the GALDIT method also contain the above impacted area.



Figure 46. Area currently affected by seawater intrusion in Vale de Lobo subsystem.

Although the water balance is uncertain, it can be seen that groundwater removed from the CF for human use is almost equal to total estimated recharge, placing all the system at risk of SWI. The evidence of SWI in the western sector confirms that is currently overexploited in an unsustainable way. Groundwater dependent ecosystems, especially those located at streams end section, are seriously threatened.

When recharge reductions due to climate change are simulated, the results show that the Miocene deep aquifer is more affected by SWI than the Plio-Quaternary phreatic aquifer, an expected result since the deep aquifer is affected by a higher rate of abstraction. This becomes more evident in the western sector of the aquifer (Vale do Lobo sector), which is subject to a higher and more concentrated water abstraction, hence being more vulnerable to seawater intrusion processes.

Adequate management measures and changes in water use practices are needed to counteract SWI. Among other measures to be evaluated, the following are suggested:

- 1) Reuse other sources of water like treated wastewater for irrigation of golf courses and installation of hydraulic barriers against seawater intrusion with the injection of treated wastewater close to the coast;
- 2) Intensification of natural recharge through private systems of rain water collection from the roofs and injection into boreholes or wells; replacement of waterproofed areas by



- wooden decks to promote water infiltration; Increase the water monitoring surveillance;
- 3) Reforestation with native species adapted to dry climates, change of practices in agriculture without destruction of the organic matter layer to retain more water in the soil, development of new underground irrigation technologies that avoid evapotranspiration;
 - 4) Rethink the planning of land use in the coastal area shifting agriculture with greater water demand from the coast;
 - 5) Education for climate change promoting water use efficiency.

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