DROUGHT RISK AND CLIMATE CHANGE IMPACTS ON QUERENÇA-SILVES AQUIFER AND ODELOUCA WATERSHED (ALGARVE)

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Abstract

The evolution aquifer recharge and runoff in Querença-Silves aquifer and Odelouca watershed under three emissions scenarios (IS92a, SRES A2 e SRES B2), for year 2100, was calculated using BALSEQ daily water balance and a methodology developed by Oliveira et al. (2012) to generate the hydrological data required by this model. The results hint at a future drier climate regimes, with significant runoff reductions of 11 to 12% in Odelouca watershed and Querença-Silves aquifer while recharge decreases 17% in IS92a scenario; in SRES A2 (the most dry) recharge reductions in Querença-Silves are predicted to reach 54% and in Odelouca (dominated by low permeability formations) circa 63%; runoff reductions reach 67% (base runoff) in Odelouca and circa 50% in Querença-Silves.

Drought risk analysis performed for Querença-Silves for today's conditions, using precipitation data series for the past 30 years in São Bartolomeu de Messines, show that 10% of the years were very dry and 16.7% extremely dry, with extremely dry years having less than 394 mm/year precipitation.

Comparing values between drought risk analysis with average precipitation and direct recharge for Querença-Silves show that in A2 scenario, average direct recharge is 136 mm/year, which is almost half of today's and only slightly below today's recharge for dry years (143 mm/year); in scenario IS92a (less dry) recharge (186 mm/year) is circa 83% of today's. However, besides direct recharge and recharge due to irrigation losses, Querença-Silves also receives alochtonous recharge, which amounts to 16.7% of direct recharge.

Bearing in mind that the above results of recharge and runoff will be the future "average" conditions, this means that for A2 scenario alochtonous recharge will suffer reductions of 50%. In any case and scenario, it seems that a dryer climate might be our future and the ensuing reductions in recharge and runoff will generate significant reductions in water availability, be it surface (dams) or groundwater. A very careful integrated management strategy will be required to ensure water supply and ecosystem preservation.

Keywords: Climate change, drought risk, water management.

1. Introduction

Amongst the many impacts of climate change, some of the most expressive will occur upon water resources. The Mediterranean region is the most vulnerable area of the European Union (EEA, 2012; 2012a) and climate change will impact on already stressed to overexploited water resources. To understand such impacts on surface- and groundwater and upon groundwater dependent ecosystems (GDEs) a case-study was selected in Algarve, Portugal, encompassing the Querença-Silves aquifer and Odelouca watershed.

These impacts were assessed through the analysis of drought risk for Querença-Silves aquifer, runoff and recharge changes for scenarios HadRM2/IS92a, HadRM3/SRES A2 and HadRM3/SRES B2 for this aquifer and Odelouca watershed and quantity pressures evolution. Runoff changes in surrounding areas of Querença-Silves aquifer are important once a significant amount of runoff from the streams flowing from the hilly area of Serra Algarvia infiltrate into this aquifer; this means that Querença-Silves, due its extra "alochtonous recharge" given by these streams, is sensitive to both reductions in runoff and aquifer recharge.

As will be seen, quantity problems might arise not just by reduction of recharge and runoff but also by the expected increase in water demand, namely for agriculture (although tourism demand shall not be forgotten). Such quantity pressures might promote a decrease in water quality in some areas of the aquifer due to brackish water inflow from Arade estuary. Knowing the magnitude of such changes is paramount to the formulation of future water resources management policies and targets.

2. Case-study area

The case-study areas are presented in (Fig. 1); Odelouca is located on the permeability schist and graywakes of Serra Algarvia and Querença-Silves is a karst aquifer in Jurassic formations (Fig. 1). Due to its Mediterranean climate, these areas faces frequent droughts of which 2004/2005 was one of the most intense in recent years (Monteiro, 2006). Climate change predicts for Portugal longer and more intense drought periods (Santos & Miranda, 2006) and although Querença-Silves has been so far a reliable alternative water supply under drought events, things might be different under climate change. Once this aquifer receives recharge also from stream infiltrating along its riverbed, it important as well to know how climate change might affect flow regimes of streams and rivers coming from the northern hilly area of Serra Algarvia.

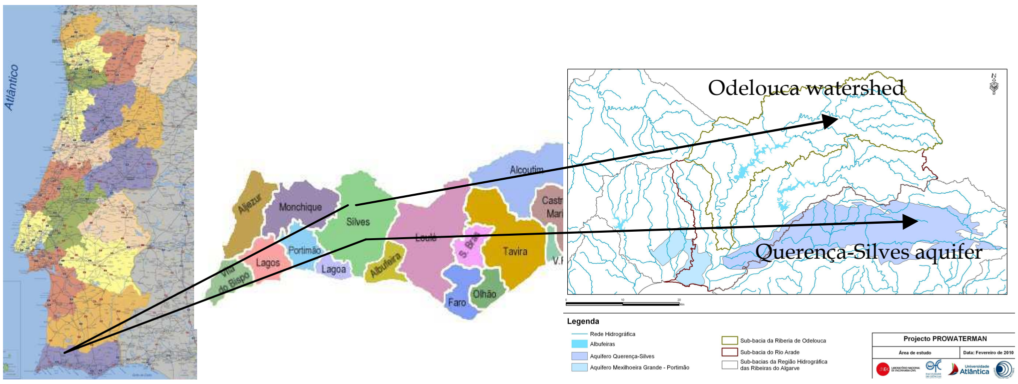

Figure 1. Case-study area's location.

3. Methodology

Climate changes impacts upon Odelouca watershed and Querença-Silves aquifer were assessed through the evaluation of changes on recharge and runoff for the 3 climate/emissions scenarios IS92a, SRES A2 and SRES B2, the evaluation of the drought risk for such areas and comparing today's drought and moist years with the precipitation averages for these three scenarios.

3.1. Drought risk analysis

Drought risk analysis is performed for today climate and the climate change scenarios, taking into account: 1) probability of drought occurrence in the case-study area, 2) impact of drought onto the aquifer's water budgets, which demands the knowledge of the aquifer long term water-budget. The following assumptions are adopted: a) aquifer direct recharge as a straightforward relationship with precipitation, b) precipitation reduction entails an increase in water abstraction, once crops – the major consumer – require higher irrigation supply, sometimes much higher than the usual volumes if drought is a concomitant event with heat waves or hot summer days. The methodology comprises these steps (Oliveira et al., 2012):

Step 1 – Classification of the hydrologic reference period by the Deciles Method (Gibbs e Maher, 1967) with the following classification for each year of the analysed series:

- **Extremely dry** – year's precipitation stays below 90% of the yearly precipitation values observed in the analysed series.
- **Very dry** – year's precipitation stays below 80% of the yearly precipitation values observed.
- **Dry** – year's precipitation stays below 70% of the yearly precipitation values observed.
- **Wet** – year's precipitation stays above 70% of the yearly precipitation values observed.
- **Very wet** – year's precipitation stays above 80% of the yearly precipitation values observed.
- **Extremely wet** – year's precipitation stays above 90% of the yearly precipitation values observed in the series.

Step 2 – Establishment of the relationship precipitation/recharge, being aquifer's recharge calculated by BALSEQ_MOD (Oliveira et al., 2008).

Step 3 – Evaluation of the weight of the crops on water consumption abstracted from the aquifer, its monthly water requirements, water irrigation allocation per crop and the monthly and yearly irrigation volumes abstracted. Water irrigation allocation is determined by evaluating the difference between water requirements per crop and precipitation; water stored in the soil was disregarded because what was to be evaluated was the worst case scenario for the resilience of the karst system, in the areas dominated by fast infiltration and high transmissivity. Yearly water irrigation demand was determined using the area occupied by each crop.

Step 4 – Evaluation along the reference series of the relationship between total water abstraction in Querença-Silves aquifer and precipitation observed.

Step 5 – Establishment, on this observation series, of the 90%, 70% and 50% recharge thresholds versus precipitation for today's conditions. The relationships water abstraction/precipitation, 90%, 70% and 50% recharge thresholds/precipitation and water availability in the aquifer as a function of precipitation and its change were determined.

Step 6 – Impact evaluation due to land cover changes, based upon the socioeconomic projections of Lourenço et al. (2011) and the methodology developed by Novo et al. (2013), for the horizon of 2030. With the new crop areas expected by the socioeconomic projections, and calculating the new water irrigation demand as stated in Step 3, the impact of such changes can be ascertained for recharge, water irrigation demands and water abstraction from the aquifer.

Step 7 – For the impact evaluation of climate change, recharge and runoff changes are calculated by the methodology explained in the following section, assuming constant land cover until 2100. Then, using the method presented in Step 3, the new water demands per crop due to changes in precipitation and the ensuing changes in water volumes abstracted are calculated. From the new recharge values and water volumes abstracted due to climate changes, the new exploitation rates are determined and compared with today's values.

3.2. Recharge and runoff changes under climate change scenarios

This methodology was developed based upon previous studies of climate change impacts on groundwater water resources (Novo et al., 2013).

The daily budget model BALSEQ_MOD (Oliveira et al., 2011) was used to determine the changes in recharge and runoff under climate changes scenarios IS92a, SRES A2 and SRES B2 using the climatologic variables required by the model, as given by SIAM study (Santos e Miranda, 2006). The base-line series to calculate the 2070-2100 input data series for BALSEQ_MOD was the 1979-2009 hydrological data series, from Praia da Rocha meteorological station and precipitations from udometric stations of: a) São Bartolomeu de Messines (30H/03UG), for Querença-Silves aquifer; b) Alferes (30G/01UG) for Odelouca watershed.

3.2.1. Precipitation series transformation

The transformation of precipitation series was performed by season, using the average changes predicted for 2070-2100 in scenarios HadRM2/IS92a, HadRM3SRES A2 and HadRM3/SRES B2 as stated in Siam study (Santos & Miranda, 2006). The seasonal daily data of the reference series used (1979-2009) were changed according with the average change predicted for the season in question (e.g. in Summer, daily data for the scenario A2, precipitation values for each day were reduced by 65%; cf. Table 1). Seasons encompass the following months: (1) Winter – December, January, February; (2) Spring – Mars, April, May; (3) Summer – June, July, August; (4) Fall – September, October, November.

Table 1. Precipitation average change by season for Portuguese territory, predicted by tree climate change scenarios

Season	Scenario IS92a	Scenario SRES A2	Scenario SRES B2
Winter	+ 40%	- 30% to - 40%	- 20% to - 30%
Spring	- 20% to - 30%	- 50%	- 20% to - 30%
Summer	- 70% to - 85%	- 65%	- 30% to - 40%
Fall	- 50% to - 60%	- 40%	- 20% to - 30%

Adapted from Santos & Miranda, 2006

3.2.2. Temperature series transformation

Temperature is not an input parameter for BALSEQ_MOD, however temperature is required to estimate evapotranspiration, which is an input parameter of the model. This demands that temperature series be transformed in accordance with the projections of climate scenarios for 2070-2100. Temperature is changed by adding to monthly average temperature the changes predicted for each respective season of the year, as stated in Table 2. The seasonal daily data used were those belonging to the 1979-2009 reference series.

Table 2. Maximum and minimum temperature average changes by season for Portuguese territory, predicted by tree climate change scenarios.

Season		Scenario IS92a	Scenario SRES A2	Scenario SRES B2
Winter	Maximum	+ 4.25 ºC	+ 3 ºC	+ 2 ºC
	Minimum	+ 4.75 ºC	+ 3.5 ºC	+ 2 ºC
Spring	Maximum	+ 4.75 ºC	+ 3.5 ºC	+ 2.5 ºC
	Minimum	+ 4.5 ºC	+ 3 ºC	+ 2 ºC
Summer	Maximum	+ 5.75 ºC	+ 3.75 ºC	+ 3ºC
	Minimum	+ 5.25 ºC	+ 3 ºC	+ 2.5 ºC
Fall	Maximum	+ 5.5 ºC	+ 4 ºC	+ 3 ºC
	Minimum	+ 5.25 ºC	+ 3 ºC	+ 2 ºC

Adapted from Santos & Miranda, 2006

3.2.3. Reference evapotranspiration series transformation

Reference evapotranspiration for 1979-2009 was determined by Penman-Monteith method (Allen et al., 1998), using data from Portuguese Institute of Meteorology, of monthly maximum average (T_{max}), monthly minimum average temperature (T_{min}), average monthly relative moisture (HR_{med}), average monthly wind speed (u) and monthly insolation (ins) as explained in Oliveira et al. (2011) and Oliveira et al. (2012). Using the transformed maximum and minimum temperature series in Penman-Monteith formula, the new reference evapotranspiration series is determined for each climate change scenario. But first, the new relative moisture must be determined; for this it was assumed that the insolation and average wind speed in 2070-2100 will remain similar as today's, because there was no data in the study area to allow an estimation of these parameters. The new relative moisture and evapotranspiration was calculated through the following methodology (Oliveira, 2006):

Step 1 – The determination of the new water vapour pressure and average moisture is preformed starting by the evaluation of water vapour (e_a), which is done through the expression:

$$e_a = HR_{med} * e_z$$

were HR_{med} = average relative moisture measured in the climatological stations for the reference period (1979-2009); e_z = average water vapour saturation, being e_z determined by the expression:

$$e_z = \frac{e^0 \times (T_{max}) + e^0 \times (T_{min})}{2}$$

where $e^o(T)$ = saturation vapour pressure (kPa) at temperature T (ºC), being $e^o(T)$ determined by:

$$e^0(T) = 0.6108 \times \exp\left(\frac{17.27 \times T}{T + 237.3}\right)$$

Step 2 – Assuming that water vapour pressure remains constant, maximum and minimum relative moisture is calculated by:

$$HR_{máx} = \frac{e_0}{e^0 \times (T_{min})} \text{ and } HR_{min} = \frac{e_0}{e^0 \times (T_{mmax})}$$

Step 3 – with these maximum and minimum relative moisture values, the new average relative moisture (HR_{med*}) is then calculated. Once the average moisture is not exactly equal to the new HR_{med*} above calculated, because relative moisture and temperature does not follow a linear relationship, a correction factor (corrHR) is determined through the relationship HR_{med*}/HR_{med}.

Step 4 – Assuming that for each climate change scenarios (IS92a, SRES A2, SRES B2) water vapour pressure remains similar to today's, and replacing in the last 2 equations the maximum and minimum temperatures for each scenario as determined previously (cf. 3.2.1), and today's water vapour pressure, the relative maximum and minimum moistures are determined.

Step 5 – Average relative moisture (HR_{med}) is determined using the maximum and minimum relative moistures calculated in the previous step. Once this average relative moisture is obtained for each climate change scenario in 2070-2100, its correction is performed using correction factor (corrHR) to rectify the non-linearity effect between relative moisture variation and temperature.

Step 6 – With the relative moisture values determined in Step 5, the minimum relative moisture for each climate scenario is determined. This minimum relative moisture is one of the input parameters for BALSEQ_MOD model. Now, combining the 2 first and the 2 last above equations relative to HR_{min}, the expression to determine minimum relative moisture becomes:

$$HR_{min} = \frac{\frac{e^0 \times (T_{máx}) + e^0 \times (T_{min})}{2}}{e^0\, x(T_{máx})} \times HR_{méd}$$

Step 7 – Computation of the evapotranspiration series: once the new temperatures and minimum relative moisture are evaluated for each climate change scenario, and setting the remaining parameters of Penman-Monteith 's equation constant, the new evapotranspiration reference series for 2070-2100 for each climate change scenario (IS92a, SRES A2 and SRES B2) are obtained.

3.2.4. Evaluation of recharge and runoff changes

Recharge and runoff evaluation for the horizon 2070-2100 and each climate change scenario adopted in this study, was performed through BALSQ_MOD using the climate parameters (precipitation, evapotranspiration, etc.) transformed as explained in the previous section.

3.3. Socioeconomic scenarios and associated exploitation rates and pollution loads' trends

To elaborate projections concerning quantity and quality pressures upon the water resources under climate change scenarios, it is required to evaluate, for each climate change scenario, the following changes in: (1) runoff, (2) recharge, (3) human, animal and plant water demands, (4) exploitation ratios taking into account these changes, (5) pollution loads due to changes in economic activities and demography.

4. Results

4.1. Drought conditions' classification by the deciles index

For reference period 1930/1931 – 2008/2009 precipitation series observed in São Bartolomeu de Messines meteorological station drought conditions classification per year are presented in Table 3, being the classes for dry years in these last 30 years), the following:

• **Dry year** – precipitation between 500 mm/year and 557 mm/year (3.3% of the series).

• **Very dry year** – precipitation between 394 mm/year and 500 mm/year (10% of the series).

• **Extremely dry year** – precipitation bellow 394 mm/year (16.7% of the series).

In this precipitation series, only one 2-year event with precipitation below normal did occur and the driest year was 200/2005, with precipitation = 249 mm while the average annual precipitation = 643 mm/year. The longer dry period had 5 years (1990/1991 to 1994/1995).

Table 3. Drought classification for the last 30 hydrologic years in São Bartolomeu de Messines (Deciles method).

Hydrologic year	Classification	Hydrologic year	Classification
1979/1980	Normal	1995/1996	Extremely wet
1980/1981	Extremely dry	1996/1997	Normal
1981/1982	Normal	1997/1998	Extremely wet
1982/1983	Very dry	1998/1999	Extremely dry
1983/1984	Normal	1999/2000	Normal
1984/1985	Normal	2000/2001	Very wet
1985/1986	Normal	2001/2002	Normal
1986/1987	Dry	2002/2003	Normal
1987/1988	Very wet	1992/1993	Very dry
1988/1989	Wet	1993/1994	Normal
1989/1990	Extremely wet	2003/2004	Normal
1990/1991	Normal	2004/2005	Extremely dry
1991/1992	Extremely dry	2005/2006	Normal
1992/1993	Very dry	2006/2007	Normal
1993/1994	Normal	2007/2008	Normal
1994/1995	Extremely dry	2008/2009	Very dry

4.2. Evaluation of the relationship precipitation/direct natural recharge

Recharge was evaluated by BALSEQ_MOD (Oliveira et al., 2008) from 10/1979 to 9/2009 for Arade (includes Odelouca) watershed; for Querença-Silves aquifer it was from 10/1941 – 9/1991 and from 10/1979 – 9/2009 for (cf. Oliveira et al., 2008; Oliveira et al., 2011), as seen in Table 4 and Figs. 2 and 3. Crossing the recharge values for each year of the reference series (1979/2009) with precipitation of the same years, the relationship precipitation/recharge is shown in Fig. 4. For this period the maximum recharge was 694 mm (precipitation = 1244 mm, year 1995/1996); minimum recharge was reached during the extreme drought spell of 2004/2005, with values of 79 mm (precipitation = 249 mm).

Table 4. Average recharge (mm/year) for the total area of the aquifer and watershed.

Hydrologic period	Querença-Silves aquifer	Arade watershed
1941-1991	323	--
1979-2009	294.2 (> 450 for outcropping karst areas)	38.47

Source: Oliveira (2007); Oliveira et al. (2008)

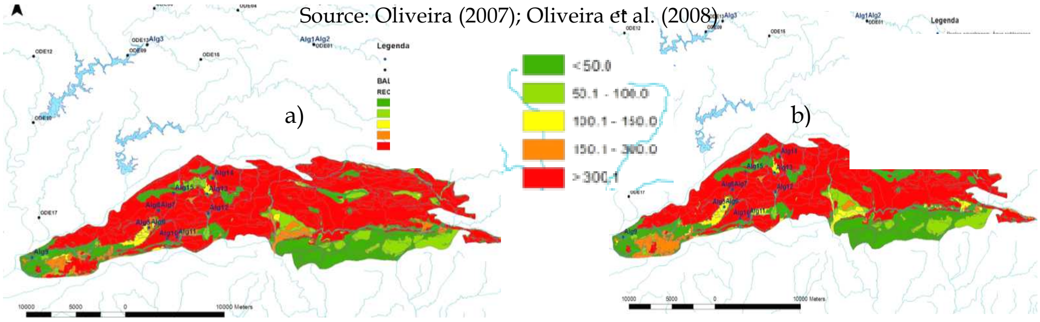

Figure 2. Average annual recharge in Querença-Silves: a) 1941-1991; b) 1979-2009.

Source: Oliveira et al. (2011)

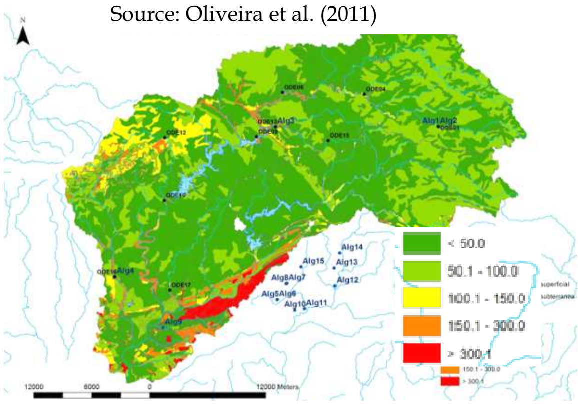

Figure 3. Average annual recharge in Arade (includes Odelouca) watershed (for 1979-2009).

From the values of annual drought condition classes and the relationship precipitation/recharge of Fig. 4, recharge classes for different drought conditions classes were established for Querença-Silves aquifer (Table 5). These recharge values exclude those due to losses by irrigation or from stream infiltration through riverbeds. Notice that recharge due to stream infiltration can be as high as 20.5% for the sector of Ponte Mesquita and more than more than 50% for Purgatório were determined by Oliveira & Oliveira (2012).

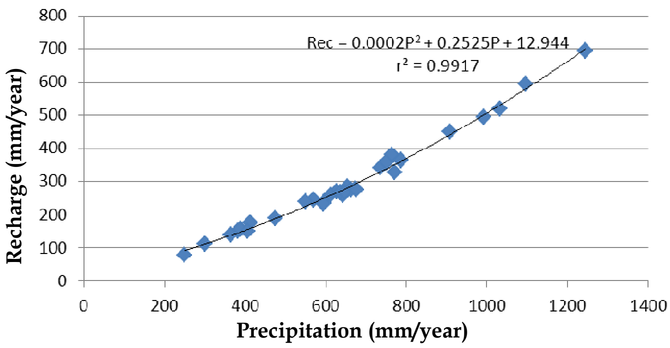

Figure 4. Relationship between annual precipitation and annual natural recharge.

Table 5. Upper limits of precipitation and recharge classes as function of drought classes for Querença-Silves aquifer.

Year drought class	Precipitation (mm/year)	Recharge (mm/year)
Extremely dry	394	143
Very dry	500	189
Dry	557	216

Source: Oliveira et al. (2012)

4.3. Recharge and runoff for 2100 under climate change scenarios

4.3.1. Querença-Silves Aquifer

Recharge and runoff are obtained through BALSEQ_MOD, for the new precipitation, (Fig. 5), relative moisture and evapotranspiration for the series 2070-2100, obtained by the methodology above described. The results are in Table 6 and Fig. 6a), b) and c) and point to important recharge and runoff reductions in the future. Such changes will for almost sure promote significant piezometric drawdowns and expected reductions in spring discharge in Arade area, facilitating conditions for possible saline water intrusion from Arade River.

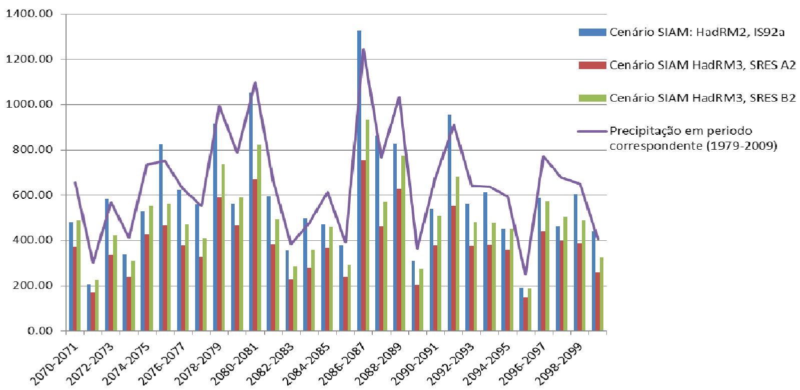

Figure 5. Precipitation (mm/year) in São Bartolomeu de Messines (30H/03UG) udometric station.

Table 6. Direct recharge and direct runoff in Querença-Silves aquifer.

		Runoff (mm/year)	Recharge (mm/year)	% of today's value	
				Runoff	Recharge
	Today's conditions	*115*	*294*	*100%*	*100%*
Scenarios	HadRM2/IS92a	100	245	87.6	83.4
	HadRM3/SRES A2	59	136	51.4	46.2
	HadRM3/SRES B2	79	186	68.9	63.3

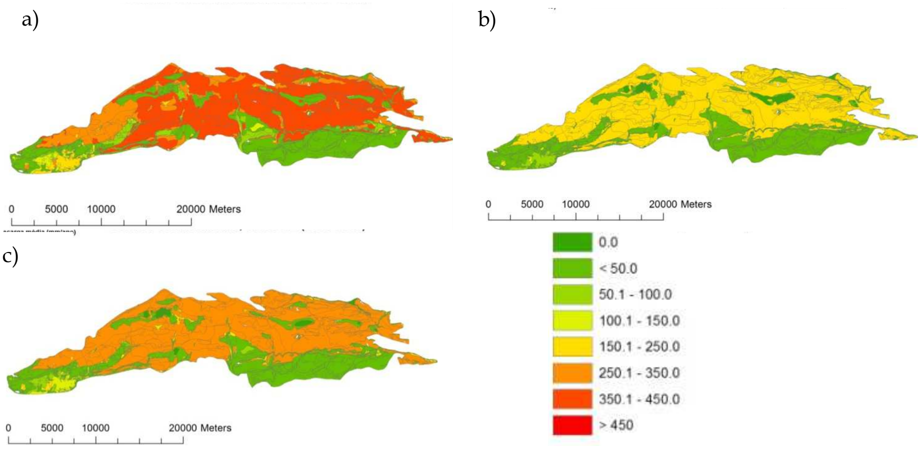

Figure 6. Average recharge (mm/year) in Querença-Silves aquifer for 2070-2100 in scenarios: a) HadRM2/IS92a, b) HadRM3/SRES A2; c) HadRM3/SRES B2.

4.3.2. Odelouca watershed

Due to the strongly impervious nature of its terrains, climate change impacts will be felt most strongly upon runoff in Odelouca watershed, which nowadays has a recharge of 60 mm/year and runoff of 520 mm/year (Oliveira et al., 2011). Under climate change scenarios its runoff and recharge are given in Table 7 and in Fig. 7a) b) and c). The worst case scenario is again SRES A2 with the largest predicted runoff and recharges reductions; base runoff is the most reduced. This shows how climate change can have a very adverse impact on this region and maybe compromise flow regimes and fluvial aquatic environments. Base runoff was determined by the expression (Oliveira, 2006):

$$Eb = 0.1185 \times P - 39.641$$

Where:
Eb – Base runoff (in mm)
P – Precipitation in the watershed (in mm)

Table 7 – Recharge, direct, base and total runoff under climate change scenarios for Odelouca watershed

		Runoff (mm/year)			Recharge (mm/year)
		Direct (E_d)	**Base (E_b)**	**Total ($E_d + E_b$)**	
	Today's conditions	*520*	*61*	*581*	*59*
Scenarios	HadRM2/IS92a	467	52	519	44
	HadRM3/A2	278	19	298	22
	HadRM3/B2	367	36	403	32

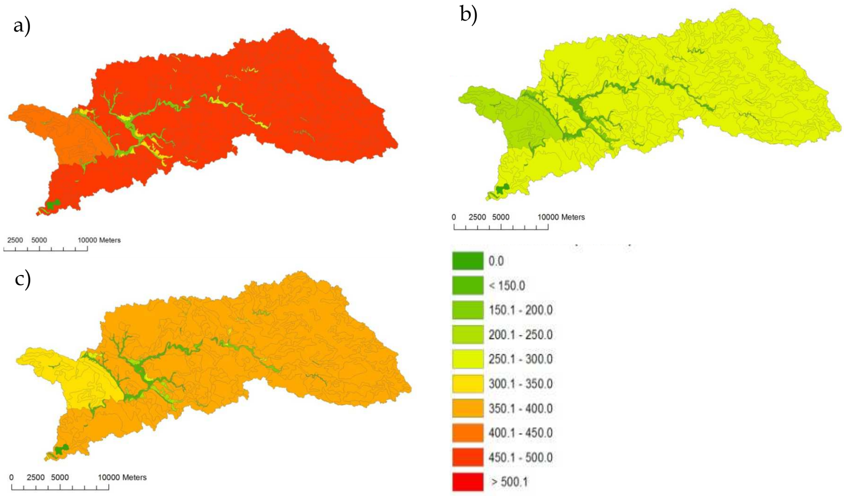

Figure 7. Average direct runoff (mm/year)in Odelouca watershed for 2070-2100 in scenarios: a) HadRM2/IS92a, b) HadRM3/SRES A2; c) HadRM3/SRES B2

4.4. Water allocation for crops under today's conditions for Querença-Silves aquifer

Land use in Querença-Silves aquifer is mainly farming plots, dominated by citrus orchards (2 920 ha ≈ 80% of farmed areas) and heterogeneous crop areas (Nunes et al., 2006), as presented in Table 10. Knowing the average monthly evapotranspiration conditions and the physiological characteristics of each crop, the monthly water requirements are determined (Table 8). Once precipitation and water requirements of plants are known for an average year, water irrigation allocation is determined per crop (Table 9). Total amount of irrigation water demand per crop (Table 10) is determined taking total crop area into account. Water stored in soil was assumed zero, a situation that happens after a protracted drought event.

Table 8. Water requirements (in mm) by crop types on Querença-Silves aquifer.

Crops	**Jan.**	**Feb.**	**Mar.**	**Abr.**	**Mai.**	**Jun.**	**Jul.**	**Ago.**	**Set.**	**Out.**	**Nov.**	**Dec.**	**Year**
Citrus	50.38	50.38	64.33	72.85	85.25	93.78	100.75	95.33	79.83	62.00	55.80	49.60	860.28
Spring	41.60	41.60	53.12	60.16	70.40	77.40	83.20	78.72	65.92	51.20	46.08	40.96	710.36
Summer	51.35	51.35	65.57	74.26	86.90	95.59	102.70	97.17	81.20	63.20	56.88	50.56	876.90

Table 9. Water irrigation allocation (in mm) in Querença-Silves, for an average year.

Crops	**Jan.**	**Feb.**	**Mar.**	**Abr.**	**Mai.**	**Jun.**	**Jul.**	**Ago.**	**Set.**	**Out.**	**Nov.**	**Dec.**	**Year**
Citrus	0.00	0.00	13.24	8.72	51.50	86.78	98.52	90.97	51.59	0.00	0.00	0.00	401.33
Spring	0.00	0.00	2.03	0.00	36.65	70.40	80.97	74.36	37.68	0.00	0.00	0.00	302.10
Summer	0.00	0.00	14.48	10.13	53.15	88.59	100.47	92.81	53.13	0.00	0.00	0.00	412.77

Table 10. Irrigation water demand (in mm) in Querença-Silves, for an average year.

Crops	**Irrigation (mm/year)**	**Area (ha)**	**Irrigation volumes (hm³/year)**
Citrus	401	2 920	11.72
Spring	302	170	0.51
Summer	412	560	2.31
Total	**--**	***3 650***	***14.54***

Besides the 14.54 hm³/year for farming needs, 14.28 hm³/year are abstracted to supply other activities than agriculture (NEMUS, 2011), which means that the total amount abstracted from Querença-Silves is at least 28.8 hm³/year, for an average year. For the same average year direct recharge fluctuates falls between 93.7 up to 139 hm³/year, even without adding up the recharge due to stream infiltration along the streambeds (more than 62 hm³/year, according with Oliveira & Oliveira, 2012); so, exploitation rates for this aquifer are largely below overexploitation and water withdrawal is sustainable under these conditions.

4.5. Relationship between precipitation, recharge and water withdrawal in Querença-Silves aquifer

An analysis year-by-year, based on drought classification classes and their respective recharge/ precipitation (cf. Table 5) for 1979/1980 to 2008/2009, coupled with data from water irrigation demands by crops for each year, allowed the correlation between precipitation, recharge and water abstracted from the aquifer (Fig. 8). The graphic was constructed with precipitation and recharge data year-by-year instead of averaged values, because it was a more sensitive approach to the analysis of protracted drought impacts on recharge, water abstraction and eventual periods of quantitative risk. Here recharge is the sum of direct recharge and recharge from streams (“alochtonous recharge”).

Curves in Fig. 9 relate precipitation with recharge and for an average year (precipitation = 654 mm/year), water abstracted is way below the 90% recharge threshold for overexploitation. However, in years were recharge decreases to 50% of the average year, abstractions approaches the overexploitation threshold. In an extremely dry year (precipitation < 394 mm/year) water abstracted can rise above this threshold. Extremely dry years account for 16.7% of the last 30 years, which indicates a recurrent situation of drought. This could strain the aquifer if no other factors, namely its large water reserves and feeding from its less developed sectors, amongst other less known constraints, would provide a security cushion for water supply. In matter of fact, if a drought event is not too protracted (less than 2 years), groundwater can still supply the demand, as 2004/2005 drought, the driest in the last 30 years (precipitation = 249 mm/year; recharge = 25 hm³/year; water withdrawal > 50 hm³/year), show. However, if conditions become increasingly drier, as climate change scenarios predict (cf. Tables 6 and 7), this might pose some problems as groundwater, and surface water resources are concerned, as shall be analysed in section 4.7.

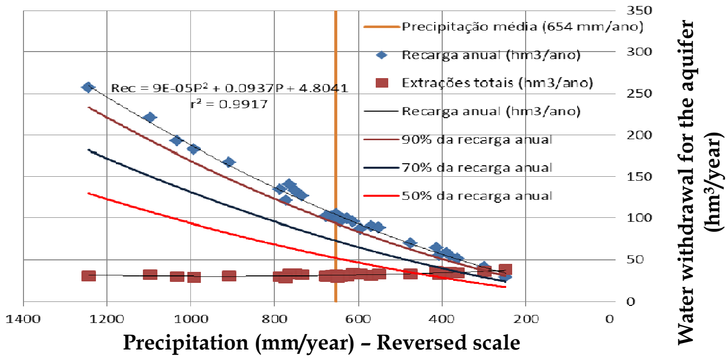

Figure 8. Relationship between precipitation, recharge and water withdrawal in Querença-Silves aquifer.

4.6. Drought risk under land cover change scenarios

To evaluate the changes due to land cover modification as result of socioeconomic evolution the methodology developed by Novo et al. (2013) was applied, using the socioeconomic scenarios developed for the case-study area by Lourenço et al. (2011). In the case-study area such scenarios predict an (1) increase of urban and road area, (2) reduction of seasonal crop areas, (3) expansion of permanent crop areas (citrus orchards), which is by far the most important permanent crop in the region. As such, increases are expected in water demand for commerce, domestic and industrial uses, a slight increase for citrus irrigation demands and a reduction in recharge areas (so reducing aquifer recharge) and irrigation demands for spring and summer crops. The new water requirements for agriculture on average year are determined from data of Table 8 and the new crop areas; the results show a slight decrease in water demand, due to reduction of spring + summer crops (= 205 ha), which compensates the expansion (= 160 ha) of citrus crop (Table 11). Assuming the same precipitation distribution along the year and the same water requirements for crops as today, the data of Tables 9 and 10 are used to calculate irrigation demand (Table 12); these results point to a slight reduction of agriculture exploitation rates. However, once socio-economic scenarios predict an increase in urban sprawling and tourist occupation, if domestic demands that are supplied by groundwater are accounted for, then today total exploitation rates of 28 rises 5%, which is still far from the overexploitation threshold.

Table 11. Water requirements per crop, in volume, today and in 2030.

Crops	**Today area (ha)**	**Área in 2030 (ha)**	**Water requirements**	
			Today	**In 2030**
Citrus	2 920	3 080	25.12	26.50
Spring	170	120	1.21	0.85
Summer	560	395	4.91	3.46
Total	***3 650***	***3 595***	***31.24***	***30.81***

Table 12. Irrigation demand (hm^3/year) per crop, today and in 2030.

Crops	**Today area (ha)**	**Área in 2030 (ha)**	**Today irrigation**	**Irrigation in 2030**
Citrus	2 920	3 080	11.72	12.35
Spring	170	120	0.51	0.38
Summer	560	395	2.31	1.63
Total	***3 650***	***3 595***	***14.54***	***14.36***

4.7. Drought risk under climate change

For this analysis the land cover was assumed equal to 2030 situation, which is a worst case scenario, once for the Mediterranean South environmental zone it is predicted a general decrease in crop areas that can go up to 30% (Rounsevell et al., 2006). From Table 6, direct recharge can be, in 2100, 51% inferior of today's 294 mm/year (scenario SRES A2) which is the driest of the three climate scenarios analysed; such values belong to today's Extremely Dry years (recharge in A2 = 136 mm/year and the upper recharge for extremely dry years = 143 mm/year) and even the less adverse scenario (IS92a) has average conditions (recharge = 245 mm/year) just slightly above those of today's Dry years (upper recharge limit = 216 mm/year). Alochtonous recharge (due to stream infiltration) is expected to change in accordance with Table 7, once such streams come from the same impervious terrains as Odelouca stream.

Assuming crop water requirements will remain the same, once there aren't enough data concerning water requirements changes of crops due to physiological reactions to climate change in the case study area, it was assumed a worst case scenario were water requirements equals irrigation demand, and this demand is 100% supplied by groundwater, a situation occurring today under protracted drought spells (today irrigation demands are 50% of crop's water requirements; cf. Tables 8 and 10), which are the average conditions for A2 scenario; exploitation rates under such circumstances are given in Tables 13 and 14. The 90% recharge threshold is only surpassed in A2 scenario and only if all water demands (agriculture + domestic + others) are supplied by groundwater, a not unlikely scenario if we bear in mind the 2004/2005 drought and the sharp reduction in runoff, and in consequence on dam reservoirs, predicted in Table 7.

Table 13. Exploitation rates under climate change scenarios, just for agriculture.

Scenarios	**Precipitation (mm/year)**	**Recharge (hm^3/year)**	**Withdrawal (hm^3/year)**	**Exploitation rates (%)**
HadRM2/IS92a	589	78.05	32.10	41.10
HadRM3/A2	388	43.27	32.93	76.10
HadRM3/B2	490	59.33	30.61	51.60

Table 14. Exploitation rates under climate change scenarios.

Scenarios	**Recharge (hm^3/year)**	**Total water demand[1] (hm^3/year)**	**Exploitation rates (%)**
HadRM2/IS92a	78.05	40.29	51.32
HadRM3/A2	43.27	40.89	94.49
HadRM3/B2	59.33	38.57	65.00

If the new climate will evolve as in A2 scenario, this means the possibility of overexploitation, if the aquifer will have to supply all the water demands in the region, once in that scenario the average conditions fall under today Extremely Dry class and in Extremely Dry years the aquifer is called to support almost all the demands. Fig. 8 shows that recharge reduction of 50% puts the system near thresholds; however for climate scenario A2, recharge is almost 5x lesser than actual values while for IS92a it is 2.7x inferior.

To compound the problem, alochtonous recharge will also suffer significant reductions once runoff is expected to decrease circa 50% (Tables 6 and 7) for A2 scenario in Querença-Silves and Odelouca watershed. If these extreme conditions will be the future average, then phreatic levels might lower significantly, which in turn shall promote changes in hydraulic connections between the aquifer and river network.

Such changes will have 2 effects: (1) expected reduction of aquifer's discharge periods and volumes, (2) larger capacity to receive stream water (although probably it will be less due to runoff decreases). Other impacts, such as the advance of saline intrusion from Arade River might occur, as it is suggested by mathematical modelling of 2004/2005 drought conditions expanded for a wider period (Lopes et al., 2005).

[1] Domestic demands assume population stabilises in 2030 and no-physiological changes in water needs *per capita* were assumed.

5. Discussion and conclusions

Results show that for the last 30 years 16.7% were extremely dry years, and 10% very dry ones, which account for almost 30% of the whole series, underlining the importance of drought events in the region. Average direct recharge for this time span is 294 mm/year, a quite low value once it is just 1.4x the upper recharge limit for dry years (216 mm/year); extremely dry years have upper recharge values of 143 mm/year and very dry ones 189 mm/year, for Querença-Silves aquifer. Alochtonous recharge is a large component of this aquifer water budget, accounting for more than 20% (> 62 hm^3/year) of total direct recharge. Water abstracted from the aquifer in an average year is 28.8 hm^3, of which 14.5 hm^3 are for irrigation (11.7 hm^3 allocated to citrus); this means that total exploitation rates = 30.6% and agriculture exploitation rates = 15.5% (citrus crops account for 12.5% exploitation rate). However, in an extremely dry year, where recharge is below 50% of average recharge, exploitation rate surpasses the 90% recharge threshold (overexploited aquifer) and only the large resilience and wide water reserves of the aquifer can cope with such situations if the drought event is not too long. Nevertheless extremely dry years account for almost 17% of the last 30 years and if climate change will impose very to extremely dry conditions, the aquifer might on the long run not be able to cope with the demand. Recharge under climate change scenarios suffers reductions from 17 (IS92a) to 54% (A2) in Querença-Silves while for Odelouca watershed – a mainly impervious area – such reductions go from 26% (IS92a) to 63% (A2); total runoff decreases range from 12 (IS92a) to 49% (A2) in Querença-Silves and Odelouca watershed and base runoff (associated with discharges in the streambeds) in Odelouca shows smaller reductions that recharge itself, with the exception of scenario A2 (67.7% base runoff reduction against a 63% recharge reduction). Querença-Silves recharge under A2 scenario is lower than the upper limit established for today extremely dry years (cf. Table 5 and 6) while the best case scenario (IS92a) has recharges of a today normal year but approaching those of the upper limit for dry years (*ibidem*), suggesting that dry to extremely dry conditions might become the future "average". Assuming that precipitation/recharge/water abstracted relationship remains similar as today, A2 recharge values are way below the threshold of 50% today's recharge (≈ 150 mm/year = conditions of a dry year almost reaching the upper recharge limit for an extremely dry year) and B2 recharge is not very far above such threshold; when recharge falls below this threshold, overexploitation of the aquifer can occur. If the aquifer is able to cope with such conditions remains to be evaluated once this will no longer be a short lived event, from which the aquifer has obvious capacity to rebound, but the average. Runoff reductions predicted for the 3 climate scenarios, both for Querença-Silves and Odelouca, compound even more the problem once recharge from runoff is an important component of aquifer's total recharge. The analysis of exploitation rates using water demand trends based on socioeconomic scenarios and departing from 2030 situation (were a 0.2% reduction of agriculture exploitation rates is compensated by the rise on domestic demands, setting future total exploitation rates near 35%, a rise of 5% from today's values) shows that under A2 scenario the agriculture exploitation rate rises to 76% and total exploitation rates reach 95% 8Tables 14 and 15). The reduction in recharge, runoff and the increase in exploitation rates, and an overall dryer climate suggest an evolution towards water level lowering, which will bring changes in aquifer discharge and hydraulic behaviour between aquifer and the river network, maybe even allowing for saltwater intrusion for Arade river, and so impacting aquatic ecosystems, with special emphasis on groundwater dependent ones.

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