Reg Environ Change
DOI 10.1007/s10113-012-0377-3

ORIGINAL ARTICLE

Comparative assessment of climate change and its impacts on three coastal aquifers in the Mediterranean

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Received: 14 February 2012 / Accepted: 10 November 2012

Abstract A comparative study on climate change and its impacts on coastal aquifers is performed for three Mediterranean areas. Common climate scenarios are developed for these areas using the ENSEMBLES projections that consider the A1b scenario. Temperature and precipitation data of three climate models are bias corrected with two different methods for a historic reference period, after which scenarios are created for 2020–2050 and 2069–2099 and used to calculate aquifer recharge for these periods based on two soil water budget methods. These multiple combinations of models and methods allow incorporating a level of uncertainty into the results. Groundwater flow models are developed for the three sites and then used to integrate future scenarios for three different parameters: (1) recharge, (2) crop water demand, and (3) sea level rise. Short-term predictions are marked by large ranges of predicted changes in recharge, only showing a consistent decrease at the Spanish site (mean 23 %), particularly due to a reduction in autumn rainfall. The latter is also expected to occur at the Portuguese site, resulting in a longer dry period. More frequent droughts are predicted at the Portuguese and Moroccan sites, but cannot be proven for the Spanish site. Toward the end of the century, results indicate a significant decrease (mean >25 %) in recharge in all areas, though most pronounced at the Portuguese site in absolute terms (mean 134 mm/year) and the Moroccan site in relative terms (mean 47 %). The models further predict a steady increase in crop water demand, causing 15–20 % additional evapotranspiration until 2100. Scenario modeling of groundwater flow shows its response to the predicted decreases in recharge and increases in pumping rates, with strongly reduced outflow into the coastal wetlands, whereas changes due to sea level rise are negligible.

Keywords Mediterranean · Climate change · Aquifer recharge · Crop water demand · Sea level rise · Groundwater flow

Introduction

Groundwater resources are under increasing pressure due to large abstraction rates for various water-consuming

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Published online: 12 December 2012

activities, particularly irrigated agriculture, drinking water supply, and industry. Substantial aquifer exploitation threatens those wetlands that constitute groundwater-dependent ecosystems (GDEs) and in coastal areas can lead to seawater intrusion, a serious problem worldwide, including the Mediterranean countries. Climate change may particularly aggravate this problem in the Mediterranean region (e.g., Giorgi 2006), due to the combined effect of rising sea levels and reduced recharge of aquifers associated with the expected decrease in precipitation and average temperature increase. An increased frequency of long-lasting droughts can pose serious challenges for water resource management and create or increase tension between stakeholders (e.g., UN-Water 2006). The integration of climate models in the assessment of future water resource availability therefore deserves major attention.

Climate modeling incorporates a large number of uncertainties, such as the considered CO_2 emission scenarios, linked to socioeconomic scenarios (IPCC 2000), the circulation models used, as well as the downscaling and bias correction methods applied (Jackson et al. 2011; Prudhomme and Davies 2008; Serrat-Capdevila et al. 2007; Younger et al. 2002). Representative studies on the impact of climate change need to incorporate such uncertainty into their results. The different methods that exist for transforming climate data into runoff and recharge in a catchment, based on different scientific or empirical relations, provide additional uncertainty which needs to be accounted for. Moreover, the importance of climate change for groundwater has not received as much attention as compared to surface water resources (Bates et al. 2008). This may be due to a lack of knowledge on aquifer behavior (Bates et al. 2008) or because aquifers are considered more resilient to changes in climate or socioeconomic development, due to the buffering effect of groundwater storage (e.g., Jackson et al. 2011). Notwithstanding, aquifers are expected to be affected by climate change, particularly in arid and semi-arid regions where decreases in recharge can become very significant in the following decades (e.g. Giorgi 2006; Santos et al. 2002). The pressure on groundwater will further rise as surface water resources become scarcer and crop water demand increases due to global warming (e.g., Eheart and Tornil 1999; Goderniaux et al. 2009). A correct implementation of future adaptation measures requires a much more detailed insight into the way climate change affects aquifer recharge and discharge patterns, as also referred by Dragoni and Sukhija (2008).

Since 2005 there has been a growing number of publications on groundwater and climate change, a detailed overview of which is provided by Green et al. (2011). Most papers focus on one of the several climate change impacts that exist for groundwater, with the large majority focusing on recharge (e.g., Brouyère et al. 2004; Serrat-Capdevila et al. 2007; Dragoni and Sukhija 2008; Candela et al. 2009; Jackson et al. 2011), and others assessing the impact from sea level rise (e.g., Melloul and Collin 2006; Chang et al. 2011; Loáiciga et al. 2012). The current paper aims to address both aspects, i.e., changes in recharge and sea level rise, and study a third potential impact, namely the increase in crop water demand due to global warming. Where groundwater is the only source for irrigation, there will consequently be a need for increased pumping rates to satisfy crop water demand, which as far as we know has not been considered in climate change impact studies for groundwater.

The mentioned impacts on groundwater are assessed here in a comparative study for three sites with Mediterranean conditions (in Portugal, Spain and Morocco), where climate change-related studies on groundwater thus far have been scarce (e.g., Candela et al. 2009). Following a description of the study sites, the following sections describe the selection of climate scenarios using three climate models, the bias correction based on two methods, the estimation of aquifer recharge, pumping rates and future scenarios using two methods, and finally, the integration of these scenarios, as well as sea level rise, into numerical groundwater flow simulation models for the three sites. The presentation and discussion of the results is then performed for each of the study sites, but also in a comparative manner and within the scope of existing studies, further addressing the uncertainty that derives from the multiple combinations of used models and methods.

Methods

Study sites

The three study sites are located in the Central Algarve in the south of Portugal, the Ebre Delta in the northeast of Spain, and the Atlantic Sahel at the central western coast of Morocco. All areas are characterized by a Mediterranean climate, with dry and warm summers and cool wet winters. The climate normals (i.e., 30 years arithmetic means) for temperature and rainfall for 1980–2010 are, respectively, 17.5 °C and 739 mm in the Central Algarve, 17.2 °C and 609 mm in the Ebre Delta, and 18.6 °C and 411 mm in the Atlantic Sahel, which has the warmest and driest climate. Most of the rainfall in the Ebre Delta occurs in autumn and spring, rather than in winter, contrary to the other two areas. Its dry summer season is shorter than that of a typical Mediterranean climate.

In the Central Algarve, stream flow is highly ephemeral, except when located over the large karstified carbonate rock aquifer known as Querença-Silves, where it is highly influenced by base flow in effluent reaches. Covering an irregularly E-W elongated area of 324 km^2 (Fig. 1), the aquifer constitutes the most important groundwater reservoir in South Portugal, due to its large area and significant recharge. The main outlets of the aquifer are springs, of which the Estômbar springs at the western boundary are the most important. Here, the aquifer borders the Arade river, which forms an estuary. Important and sensitive surface/groundwater ecotones exist at the location of the springs, many of them classified as protected areas. Land use is dominated by irrigated citrus culture in the western sector overlying the aquifer, whereas extensive dry farming (olive, carob, almond and fig trees) occupies the eastern sector. Of the mean annual recharge (100 hm^3), currently 30 % is exploited for irrigation and 10 % for urban water supply (Stigter et al. 2009).

The Ebre river and delta dominate the landscape at the Spanish study site, but local surface runoff is low, except during heavy rain events. The *La Plana de La Galera* multi-layer aquifer, with a total area of 368 km^2, consists of Quaternary conglomerates and limestone gravels at the top, which receive direct recharge from rainfall. Below this lie Mesozoic limestones that form a regional confined multilayer karst aquifer (Pisani et al. 2011), with recharge and discharge areas beyond the limits of the *La Plana de*

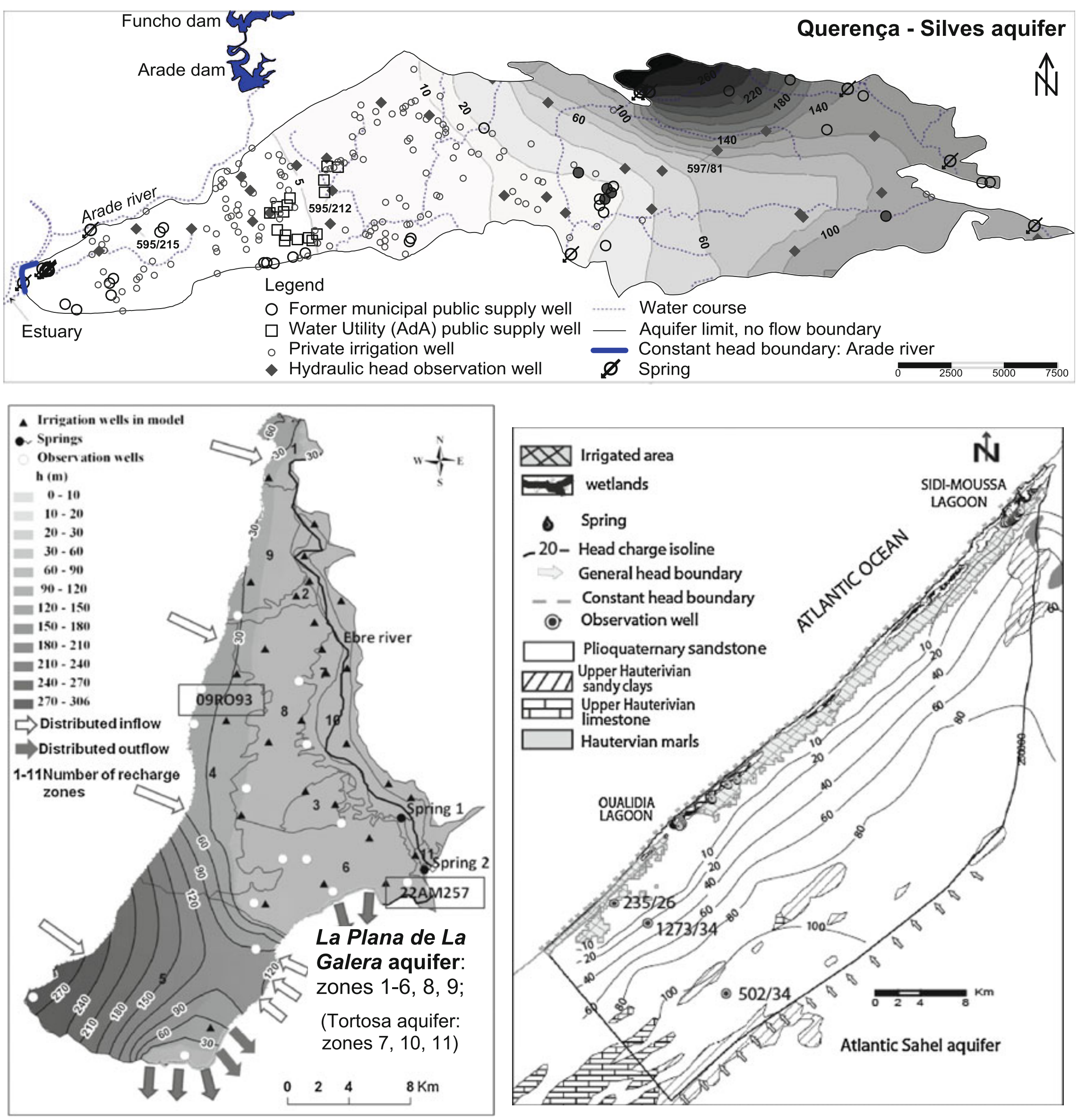

Fig. 1 Conceptual models of the Querença-Silves aquifer in the Central Algarve (*top*), the *La Plana de La Galera* and *Tortosa* alluvial aquifers (*bottom left*) and Atlantic Sahel aquifer (*bottom right*), indicating hydraulic head contour lines (in m above current mean sea level), boundary conditions (*no flow* where not indicated), location of wells and irrigation areas

La Galera. Discharge primarily occurs underground toward the Ebre river and the limestone aquifer in the East (CHE 1999), as well as a number of important springs, locally know as "ullals", which feed the only fresh water ecosystem in the Ebre Delta. The land is occupied by irrigated citrus and (mainly) rain-fed olive groves, as well as natural vegetation and urban and industrial zones (Bossard et al. 2000). The use of groundwater of the *La Plana de La Galera* aquifer is about 22.9 hm^3/year, 41 % of annual areal recharge (56 hm^3) (Pisani et al. 2011).

The geomorphology of the Atlantic Sahel study site, covering a total area of 713 km^2, is characterized by NE-SW Plioquaternary oriented dunes, parallel to the ocean. It is globally an endorheic basin, where the wetland of Oualidia-Sidi Moussa is the only perennial surface water body. The wetland is composed of saltmarshes and the two lagoons of Oualidia and Sidi Moussa. The latter are fed by ocean water and groundwater discharge from the Plioquaternary calcareous sandstone aquifer with high intergranular porosity, as well as the underlying Cretaceous limestone. Evidence of karstification processes within the coastal zone was provided by Fakir (2001) and Fakir and Razack (2003). In the absence of permanent surface runoff, groundwater is the single source of freshwater for all the socio-economic activities. Agriculture, mainly vegetable crops concentrated in the coastal belt, consumes the largest amount of groundwater, calculated to be about 30 % of mean annual recharge (estimated to be 70 hm^3). The aquifer also provides drinking water to the city of Oualidia and rural villages.

Development of climate scenarios

Following an analysis of available data, the available scenarios from the ENSEMBLES project were selected as a starting point (Van der Linden and Mitchell 2009). ENSEMBLES projections include results from 1950 up to 2100. Each scenario results from a combination between a Regional Climate Model (RCM) and a driving Global Circulation Model (GCM), applied to a study area including Europe and parts of North Africa with a 25 × 25 km resolution and a balanced CO_2 emission scenario: A1b. Three climate models cover the three study sites and the period up to 2100: CNRM-RM5.1, C4IRCA3, and ICTP-REGCM3. Data collection included downloading temperature (*T*) and precipitation (*P*) data from the ENSEMBLES site for selected reference periods, and two future climate normal periods: 2020–2050 and 2069–2099. The reference period, also referred to as control period, is the period for which historic data are available in order to perform the bias correction of the RCM results. For the Portuguese and Moroccan sites, this period was 1980–2010, while for Spain, it was 1960–1990. The choice of two different reference periods was related to data availability and has no direct effect on the bias correction of the absolute values for the future scenarios.

Bias correction was applied to the data, using two different approaches, in order to compare their applicability. The first method comprised the calculation of anomalies (as used by, e.g., Kilsby et al. 2007; Lenderink et al. 2007), where trends in *P* and *T* in modeled data are calculated as monthly deltas between the reference and future climate normal periods, and then applied to the observed values. The second method used monthly linear regressions between observed and modeled values to correct values of *P* and *T* both for the average and the extreme values (as in, e.g., Wood et al. 2002; Vidal and Wade 2008). For the Spanish site, limitation in time and resources resulted in using only the regression method and not the anomaly method. On the other hand, monthly values could be transformed into daily time-series using the GEN-BALAN software (Alvares et al. 2009), allowing a higher temporal resolution, which was not possible at the Moroccan and Portuguese sites. Possible limitations of using a monthly time step were accounted for during recharge calculations, as will be shown in the following section. An overview of the methods and models applied to each study site, showing the differences and similarities, is provided in Table 1.

Elaboration of recharge scenarios

The bias-corrected data were used to develop scenarios of total groundwater recharge and net groundwater recharge,

Table 1 Overview of similarities and differences of the methods used at each study site

	Central Algarve	La Plana de La Galera	Atlantic Sahel
Regional climate model	CNRM, C4IRCA, ICTP	CNRM, C4IRCA, ICTP	CNRM, C4IRCA, ICTP
CO_2 emission scenario	A1b	A1b	A1b
Bias correction	Anomalies, regression	Regression	Anomalies, regression
Recharge estimation	T-M, P-G	P-G (model)	T-M, P-G
Recharge time step	Monthly (adjusted)	Daily	Monthly (adjusted)
Groundwater model	FEN, FEFLOW	$CORE^{2D}$	MODFLOW

Full names of RCMs: CNRM-RM5.1, C4IRCA3, ICTP-REGCM3

T–M Thornthwaite–Mather, *P–G* Penman–Grindley defined as total recharge minus water extractions from the aquifer for irrigation (i.e., to fulfill crop water demand). The scenarios were developed using a variety of approaches: 1) for the Portuguese and Moroccan sites, water budget calculations based on two methods, Thornthwaite-Mather (TM; Thornthwaite and Mather 1957) and Penman-Grindley (PG; Grindley 1970), to obtain a measure of uncertainty involved in these soil water balance methods; 2) for the Spanish site hydrological modeling incorporating the PG method, using GIS-BALAN (Samper et al. 2007). Land use maps were obtained from satellite image and aerial photograph interpretation (Reis 2009, Fakir et al. 2011).

Both the TM and the PG water balance methods estimate excess rainfall (surface runoff or recharge) from rainfall and potential evapotranspiration (PET), using available water capacity of the soil (in the case of TM) and soil water deficit associated with a root constant (for PG) to determine effective evapotranspiration (EET). For the Portuguese and Moroccan sites, PET was calculated from mean, maximum and minimum air T data using the Hargreaves method applied following Neitsch et al. (2005). This method was selected due to the limitations in meteorological data available for Morocco and the constraints associated with correctly downscaling climate change scenarios for meteorological variables other than temperature. Nevertheless, the part of the equation dealing with extraterrestrial solar radiation should be correct for any given latitude and therefore for the study sites. PET estimated by the Hargreaves and Penman methods were compared for the Portuguese site (not shown); both had a good relationship at the monthly scale ($r^2 = 0.987$), and while Hargreaves tended to underestimate PET in the summer months by up to 20 %, this was not considered to be a relevant problem given that EET at this time is normally limited by available water.

The TM and PG methods were applied sequentially for each month. Since the use of a monthly time step can underestimate recharge by as much as 25 % (e.g., Dripps and Bradbury 2007), concentrated runoff/recharge caused by extreme rainfall events was accounted for by allotting 20 % of rainfall as direct groundwater recharge (i.e., without recharging soil water deficits) before performing the remaining balance calculations. The 20 % value was selected after a comparison of recharge calculations made using daily and monthly meteorological data for Portugal; since the available data for the Moroccan site was not sufficient for a similar comparison, a similar factor was assumed based on the similarity of meteorological patterns (recharge concentrated during the high rainfall months of winter), which is a potential limitation of this application. The methods were calibrated using EET data based on remote sensing for the Moroccan site (Fakir et al. 2011) and previous calculations of recharge (see overview in Stigter et al. 2009) at the Portuguese site, including the FAO dual crop coefficient method (Allen et al. 1998), recently applied by Oliveira et al. (2008).

The PG method was also used to calculate EET in the daily water balance model of the Spanish site, developed using the program GIS-BALAN (Samper et al. 2007). The program computes the daily water balance in the soil, unsaturated zone, and aquifer. For PET, the Blanney-Criddle and Thornthwaite methods were applied in irrigated and non-irrigated areas, respectively. The modeled area was sub-divided into 11 zones, each of which considered to have uniform climate and soil properties. Hence, it is a semi-distributed approach. The model was calibrated to fit observed piezometric oscillations in the aquifer during the control period (1960–1990).

The future recharge scenarios were created by integrating the previously developed climate scenarios into the hydrological model. For the other Portuguese and Moroccan sites, both the TM and PG methods were applied to the bias-corrected climate data based on anomalies, and TM was also applied to the bias-corrected data using regression.

The estimated evolution of net recharge further considered the impacts of global warming on crop water demand and consequently groundwater withdrawals for irrigation. These were analyzed by performing calculations on the evolution of PET: present and future groundwater irrigation needs (and hence net recharge values) were simulated using the ET deficit (EET–PET). We thereby assumed that there is no change in crop type, growth cycle, irrigated area, and irrigation efficiency and that groundwater is the only available source. For this reason, the calculations were not performed for the Spanish site, where surface water is currently and locally available as an alternative source for irrigation to compensate any increase in crop water demand that may occur.

The multiple combinations of RCMs, bias correction, and recharge estimation methods resulted in the following recharge scenarios:

- Nine recharge scenarios for the Portuguese and Moroccan sites, due to the use of three RCMs, each bias corrected using two methods for TM and one for PG;
- Three recharge scenarios for the Spanish site, due to the use of three RCMs with a single bias correction and recharge calculation method.

Groundwater flow simulation models

Numerical simulation models for groundwater flow were developed in horizontal and vertical 2D domains, using different software, namely FEN, a derived code from the original FEM301 (Kiraly 1985), FEFLOW (Koskinen et al. 1996), MODFLOW (Harbaugh et al. 2000), and CORE^{2D}

V4 (Samper et al. 2009). For the representation of the flow domain of karst systems, single continuum equivalent porous models were used, which is valid when modeling hydraulic heads and flow volumetrics on a regional scale (Scanlon et al. 2003). The models were calibrated and validated with existing data from national monitoring networks and newly obtained data from project-specific monitoring surveys. Total recharge was used in the models, and pumping wells were activated in the irrigated areas, with abstractions for irrigation summing up to calculated "total minus net recharge", calculated with the methods described in the previous section. Additional abstractions for public supply were included where they exist.

For the Querença-Silves aquifer in the Central Algarve, the boundary conditions for the model were defined as constant head along the Arade estuary in the west and no flow for the remaining part (Fig. 1). Boundary conditions for the tidal influence in the estuary as well as several small springs in the central and eastern sector were not included, as they were found to have relatively insignificant effects on the regional flow pattern and water balance (Monteiro et al. 2006; Stigter et al. 2009; Hugman et al. 2012). Transmissivity (*T*) was optimized through inverse calibration, whereas the storage coefficient (*S*) was calibrated by trial-and-error using available piezometric data (Hugman et al. 2012). For the transient model, the spatially distributed recharge percentages, calculated by Oliveira et al. (2008) as fractions of mean annual rainfall, were applied to daily rainfall data available for the period of model calibration (2002–2006) and validation (2006–2009). Besides abstractions for irrigation, applied to 150 private wells known to be located within the irrigated areas, known abstractions for public supply were also included. A more detailed description of these procedures can be found in Stigter et al. (2009) and Hugman et al. (2012).

The simulation model at the Spanish site accounts for groundwater flow through *La Plana de La Galera* and *Tortosa* alluvial aquifers (Fig. 1). The model domain was divided into five material zones based on the geology of the study area. *T* and *S* of these zones were calibrated by using available hydraulic head data. Groundwater recharge from rainfall and irrigation return flow was calculated with the daily hydrological water balance model described in the previous section. Groundwater extractions were evenly distributed among 28 wells located within the irrigated areas (Fig. 1). A Cauchy boundary condition (where flow depends on hydraulic head) was used at the stream beds, with a prescribed head equal to the elevation of the ground surface. A prescribed flux (Neumann) condition was considered at other model boundaries (Fig. 1). Groundwater flows into the aquifer across the west boundary, with a mean annual rate of 27 hm^3/year (CHE 1999). This inflow was assumed to be evenly distributed along the boundary line. There are inflows and outflows across the southeastern boundary, mean values of which were calibrated to be 29.8 and 36.7 hm^3/year, respectively, based on hydraulic head data from 16 wells.

In the Atlantic Sahel aquifer, a constant head boundary was defined along the shoreline and the lagoons (Fig. 1). A general head boundary was defined in the east where the piezometry becomes flat, marking the transition between the study area and the upstream part of the basin. A no-flow boundary follows a groundwater divide in the north and a flow line in the south. Recharge is provided by rainfall and its calculation was described in the previous section. Abstraction for irrigation was applied to wells located in the coastal belt. The simulation period of the transient model extends from 1993 to 2009, subdivided into 192 monthly stress periods. *T* and *S* were calibrated by trial-and-error using available piezometric records and water balance data.

Following calibration and validation, the developed recharge scenarios were integrated into the models, to study expected changes in the near and distant future in groundwater levels, discharge into GDEs and the risk of groundwater deterioration due to seawater intrusion. For the sake of comparison, the same climate scenario model run was chosen for the three study sites, ICTP-REGCM3. For the Querença-Silves aquifer in Portugal, all the climate scenarios were run in the groundwater model to analyze the sensitivity of aquifer response and related uncertainty. At the Spanish site, water inflows and outflows along boundaries having Neumann boundary conditions were assumed to change at the same rate as that of the predicted areal recharge. Additional scenarios considered increasing groundwater extractions for irrigation in time for the Querença-Silves and Atlantic Sahel aquifers (calculations based on TM), as well as a sea level rise of 1 m at all three study sites, applied to the appropriate boundary conditions.

Results and discussion

Climate and recharge scenarios

For analysis purposes, the results from the different climate and recharge scenarios have been summarized as an ensemble (see, e.g., Phillips 2006); ensembles have been used to handle climate change scenario uncertainty in previous studies (e.g., Wetherald and Manabe 2002; Nohara et al. 2006). Table 2 summarizes the mean annual results of future scenarios of climate (rainfall and temperature) and the total and net recharge for all study sites. The results indicate strong increases in temperature (*T*) for all study sites (+0.7 to +2.5 °C in 2020–2050, +2.4 to +5.4 °C in 2069–2099), which point to higher evaporative demands (PET) as well. As for rainfall, the results point to a strong decrease in the Central Algarve and Atlantic Sahel sites, and a relatively modest decrease in the Ebre Delta in 2069–2099 only; rainfall is expected to change by −7, −18, and −2 % in 2020–2050, and by −29, −40, and −6 % in 2069–2099, respectively, in Central Algarve, Atlantic Sahel, and Ebre Delta. For both temperature and rainfall, changes are stronger for the 2069–2099 scenarios. This indicates an increase in climatic aridity in all sites, but stronger in the Central Algarve and Atlantic Sahel. There is, however, a strong variability between future climate scenarios, particularly in respect to rainfall, for example, for 2020–2050, one scenario points toward a 9 % increase in rainfall for Central Algarve (and 4 % for the Ebre Delta). These differences result from differences between the ENSEMBLES RCM predictions and are therefore present in the three study sites.

These changes are not evenly distributed throughout the year, as illustrated by Fig. 2 for rainfall. In the Central Algarve, rainfall is predicted to decrease mostly during fall for 2020–2050; the potential rainfall increase noted earlier would happen in winter. For 2069–2099, rainfall decreases are expected in all the wet season but mostly in autumn and spring. In the Ebre Delta, the scenarios point to a small decrease for 2020–2050 localized in autumn, and a decrease in 2069–2099 localized in spring. For the Atlantic Sahel, rainfall decreases are expected from autumn to spring, i.e., throughout the wet season, but the greatest uncertainty lies in the late autumn–early winter period which could see moderate rainfall increases in 2020–2050.

Table 2 Mean annual results for climate and net recharge for the reference period and climate change scenarios; climate change results show the average of all scenarios, and the range between the lowest and highest scenario

Parameter	Study site	Reference period	2020–2050		2069–2099	
			Absolute value	Change	Absolute value	Change
Temperature (°C)	Central Algarve	17.5	18.8	1.3	20.9	3.4
			(18.3 to 19.2)	(0.8 to 1.7)	(20.2 to 22.0)	(2.7 to 4.5)
	La Plana de La Galera	17.2	19.1	1.9	21.3	4.1
			(18.4 to 19.7)	(1.2 to 2.5)	(20.3 to 22.6)	(3.1 to 5.4)
	Atlantic Sahel	18.6	19.8	1.2	21.6	3
			(19.3 to 20.2)	(0.7 to 1.6)	(21.0 to 22.7)	(2.4 to 4.1)
Rainfall (mm/year)	Central Algarve	739	685	−7 %	526	−29 %
			(581 to 806)	(−21 to 9 %)	(471 to 612)	(−36 to −17 %)
	La Plana de La Galera	636	626	−2 %	598	−6 %
			(573 to 658)	(−10 to 3 %)	(562 to 641)	(−12 to 1 %)
	Atlantic Sahel	411	338	−18 %	247	−40 %
			(265 to 379)	(−36 to −8 %)	(194 to 287)	(−55 to −30 %)
Total recharge (mm/year)	Querença-Silves	340	323	−5 %	206	−39 %
			(248 to 418)	(−27 to 23 %)	(177 to 267)	(−48 to −21 %)
	La Plana de La Galera	149	114	−23 %	109	−27 %
			(100 to 123)	(−33 to −17 %)	(101 to 117)	(−32 to −21 %)
	Atlantic Sahel	101	90	−11 %	54	−47 %
			(59 to 147)	(−42 to 46 %)	(42 to 78)	(−58 to −23 %)
Net recharge (mm/year)	Querença-Silves	246	216	−12 %	82	−67 %
			(137 to 324)	(−44 to 32 %)	(53 to 146)	(−78 % to −41 %)
	La Plana de La Galera	100	65	−35 %	60	−40 %
			(51 to 74)	(−49 % to −26 %)	(52 to 68)	(−48 % to −32 %)
	Atlantic Sahel	73	59	−19 %	19	−74 %
			(26 to 114)	(−64 to 56 %)	(2 to 42)	(−97 % to −42 %)
Crop Groundwater Demand (mm/year)	Querença-Silves	94	107	14 %	124	32 %
			(94 to 123)	(0 to 31 %)	(111 to 133)	(18 to 42 %)
	La Plana de La Galera	49	49	–	49	–
	Atlantic Sahel	28	31	13 %	35	26 %
			(28 to 34)	(2 to 22 %)	(30 to 40)	(10 to 43 %)

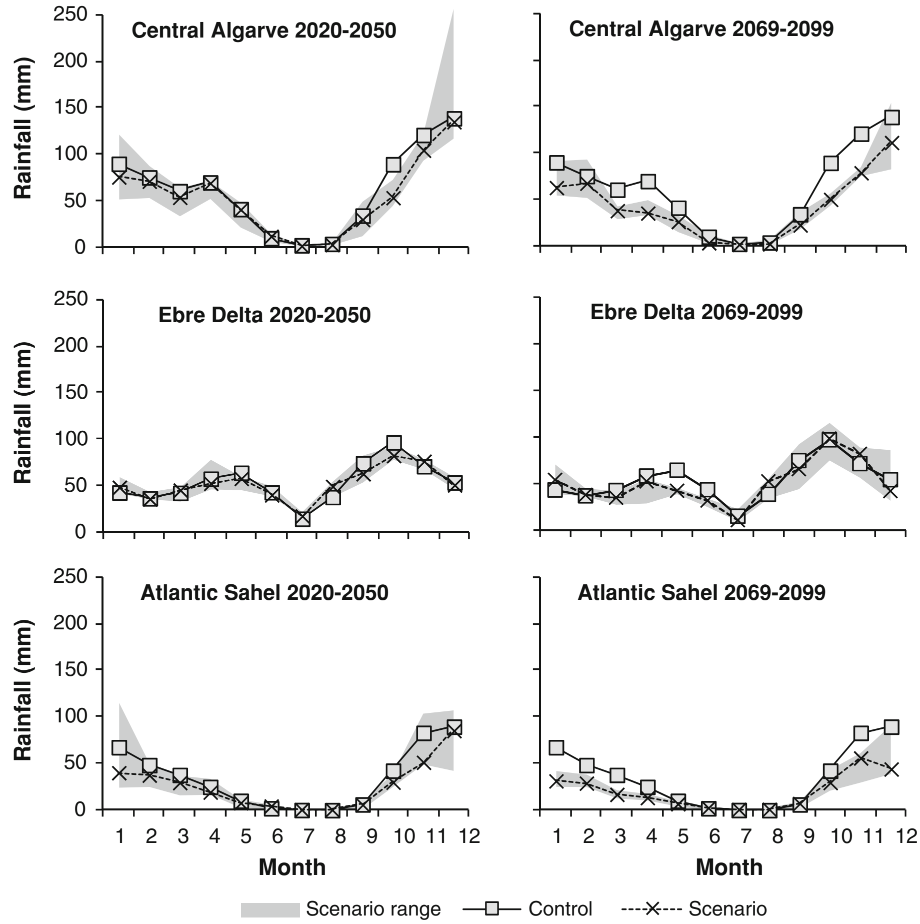

Fig. 2 Median monthly results for rainfall for the climate change scenarios, including the range of values obtained from the entire set of scenarios, as well as the values for the reference (control) period

These changes in climate are expected to have an impact on total and net recharge, both by the higher PET due to higher *T* (which also lead to higher irrigation requirements) and by lesser available rainfall, particularly in the Central Algarve and the Atlantic Sahel. The results in Table 2 indeed show a trend for decreasing total and net recharge in all study sites and for both scenarios, with stronger decreases in 2069–2099 for the Querença-Silves and the Atlantic Sahel aquifers (respectively −39 and −47 % for total recharge; −67 and −74 % for net recharge). For the *La Plana de La Galera* aquifer, the largest decrease in recharge is expected to occur in 2020–2050 (−23 % total recharge and −35 % net recharge) due to the combined effect of a reduction in rainfall and an increase in *T* during autumn, the main recharge season. It should be noted that the higher relative decreases in net recharge are largely a consequence of the lower initial value; for the Spanish site, absolute changes in net and total recharge are identical, as no increase in crop groundwater demand was considered. The latter values are also indicated in Table 2. For the Portuguese and Moroccan sites, crop groundwater demand is expected to increase 32 and 26 %, respectively.

The results have a strong variability between future scenarios, especially for the Querença-Silves and the Atlantic Sahel aquifers, mostly following the variability in rainfall predictions, highlighting the consequences of uncertainty in climate scenarios for recharge estimations. In 2020–2050, some scenarios predict increased recharge rates for these sites, mostly due to higher winter rainfall rates which increase net recharge even if total annual rainfall is lower. This is visible by the gray band indicating the scenario range in Figs. 2 and 3. Other authors (e.g., Serrat-Capdevila et al. 2007; Jackson et al. 2011) also find a small number of simulations to provide results that are contrary to the general trend. For the Querença-Silves and the Atlantic Sahel aquifers, the changes in net recharge are higher than the changes in total recharge, due to the increase of irrigation extractions caused by a higher PET. The quantification of the combined effect of a decrease in recharge and increase in crop water demand on groundwater resources is an interesting aspect that to our knowledge has not been considered in many studies so far. Brouyère et al. (2004) suggested it as one of the further steps in the examination of climate change impact on groundwater resources.

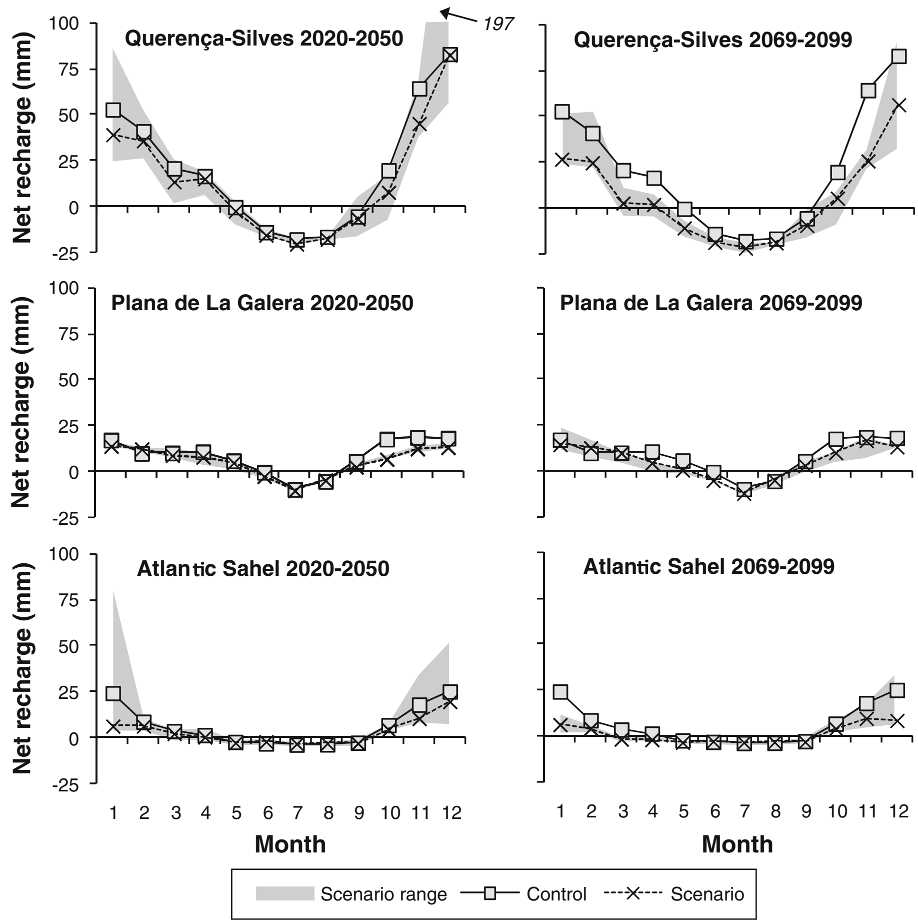

Fig. 3 Median monthly results for net recharge for the climate change scenarios, including the range of values obtained from the entire set of scenarios, as well as the values for the reference (control) period

Net recharge rates are also expected to suffer different changes throughout the year, as illustrated by Fig. 3. Monthly changes are expected to follow rainfall changes, but the PET increase may also lead to higher soil moisture depletion during the dry season, increasing the soil recharge needs during autumn and consequentially decreasing net recharge during this period. This can be seen in the net recharge scenarios (also by comparison with Fig. 2). In the Querença-Silves aquifer, the changes follow mostly those for rainfall. The most significant changes in 2020–2050 are a decrease in autumn, and the highest variability is in winter, with one scenario predicting more than double net recharge in December; in 2069–2099, decreases are expected in all the wet season, with the highest scenario variability in winter. The net recharge in the *La Plana de La Galera* aquifer will decrease in autumn in the period 2020–2050 due to an increase in PET and a decrease in rainfall. In the period 2069–2099, groundwater recharge will decrease both in autumn and spring. Winter rainfall is apparently hardly affected. In the Atlantic Sahel aquifer, decreases are expected for the entire wet season, with variability following the one reported for rainfall.

Model predictions show changes in the interannual variability of net recharge as well, as shown in Fig. 4. For the *La Plana de La Galera* aquifer, it should be noted that the predicted reduction of the variance of the monthly recharge values is directly related to the reduction of the variance of the monthly rainfall values. The latter is caused by the statistical regression method used to bias-correct the RCM monthly precipitations to the basin-scale measured precipitations. This regression method is known to lead to a reduction in the variance of the predictions which depends on the R^2 of the regression equation. The reduction of the variance decreases when R^2 tends to 1. This is not expected for the rainfall predictions for the Central Algarve and Atlantic Sahel: the anomalies method preserves the relative difference between the median and extreme rainfall years observed in the present-day period, and the regression method used at these sites also calculates values for the inter-annual variability of the RCM results. Therefore, the interannual variability results allow an analysis of changes to net recharge distribution for Querença-Silves and the Atlantic Sahel aquifers, but not for the *La Plana de La Galera* aquifer. It should be noted, for the anomalies method, that while the present-day variance in climate is preserved, the same is not necessarily true for recharge due to its nonlinear relationship with climate variables.

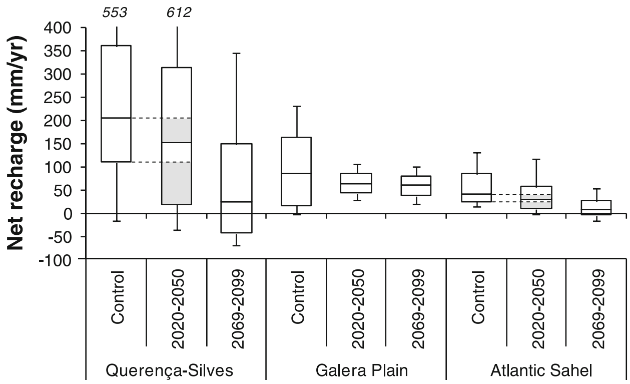

Fig. 4 *Box-plot* showing the 1st quartile, median and 3rd quartile (*boxes*) and the 10th and 90th percentiles (*bars*) for annual net recharge for the reference (control) period and climate change scenarios; climate change results are calculated using an ensemble of all annual predictions from all scenarios; *dashed line* and *shaded* areas show differences in median values and in 1st quartiles between 2020 and 2050 and the reference period

The results in Fig. 4 illustrate that one important change for 2020–2050 in the Querença-Silves and the Atlantic Sahel aquifers can be an increase in the frequency of drought years, since in both cases the 1st quartile decreases more than the median net annual recharge; this means that the decrease in average recharge is driven, in this scenario, more by the higher frequency of low recharge years than by recharge in a typical year. This is not the case in 2069–2099, where the median and quartile of annual recharges decrease by a similar amount, i.e., the decrease in average recharge is also due to a decrease of recharge in a typical year. Also in 2069–2099, results indicate that the 10th percentile and the 1st quartile will have negative net recharge (i.e., groundwater extraction for irrigation higher than recharge), which means that this will occur with a frequency higher than one in every 4 years. This could lead to irrigation water shortages during these periods, even more so when considering the fact that if necessary, public water supply will have priority over agriculture. For the Querença-Silves aquifer, the higher 90 % percentile value in 2020–2050 further indicates the occurrence of more extremely wet years.

It should be noted, however, that these results are complex and derive from multiple factors. The selected downscaling methods should influence inter-annual variability, as previously described for climate; however, in the Querença-Silves and Atlantic Sahel aquifers, they showed similar trends (not shown) and so their influence appears to be limited. This presents a level of uncertainty which is difficult to quantify, and which should be added to that associated with recharge and groundwater extraction calculations and their underlying assumptions, e.g. no changes to cultivated crops or areas, or the correction factor (direct recharge fraction) applied for monthly recharge corrections. In any case, and despite the nonlinear relation of both recharge and groundwater extractions with climate scenarios, it should be noted that the evolution of extractions for irrigation was responsible for less than 20 % of the changes to net recharge in the majority of scenarios.

Aquifer response to climate change

Figure 5 shows the predicted evolution of groundwater heads in representative boreholes of each of the three studied aquifers (for location see Fig. 1), until the end of this century, whereas Fig. 6 shows the evolution of discharge from these aquifers into the surface water bodies. The scenarios are based on recharge calculations for the ICTP-REGCM3 climate model run, and also in addition to the constant irrigation scenarios for all three sites, include a scenario that considers increasing groundwater abstractions for irrigation to satisfy crop water demand for the Atlantic Sahel and Querença-Silves aquifers, maintaining the current spatial distribution of land use. When analyzing the median values for rainfall and recharge for the simulated climate normal periods, it was observed that the ICTP_REGCM3 scenario considers the largest impacts of climate change on aquifer recharge, particularly predicting the most significant reductions in recharge in 2020–2050. The idea of focusing on one specific RCM rather than an ensemble scenario was to avoid the additional uncertainty that might arise from differences that occur between RCMs within each of the three study areas. In other words, here we focus on the differences in recharge values and aquifer response considering the same RCM for each study site.

In the *La Plana de La Galera* aquifer, significant lowering of hydraulic heads is expected (Fig. 5), up to 20 m for 2069–2099 at well 09RO93 located in the recharge area. Near the Ebre delta, heads show an increasing trend driven by sea level rise, which causes an identical rise in the Ebre's final stretch. After the correction for sea level rise, one can see that the hydraulic heads in fact decline. From the model and from field observations, it is known that groundwater input into the freshwater wetlands through springs is only a small component of total groundwater discharge. Notwithstanding, Fig. 6 shows that until the end of the century, a reduction of 20 % in spring discharge into these wetlands is expected. Both the head and discharge time series reveal gradual and continuous lowering, which does not correspond entirely to the average recharge scenarios for this aquifer (Table 2) that indicate that the strongest decrease occurs in 2020–2050. The reason is that the ICTP-REGCM3 scenario shows a different behavior for calculated recharge than the average trend.

In the Atlantic Sahel, simulated hydraulic heads in the recharge zone (well 502/34) drop 10 m in 2020–2050,

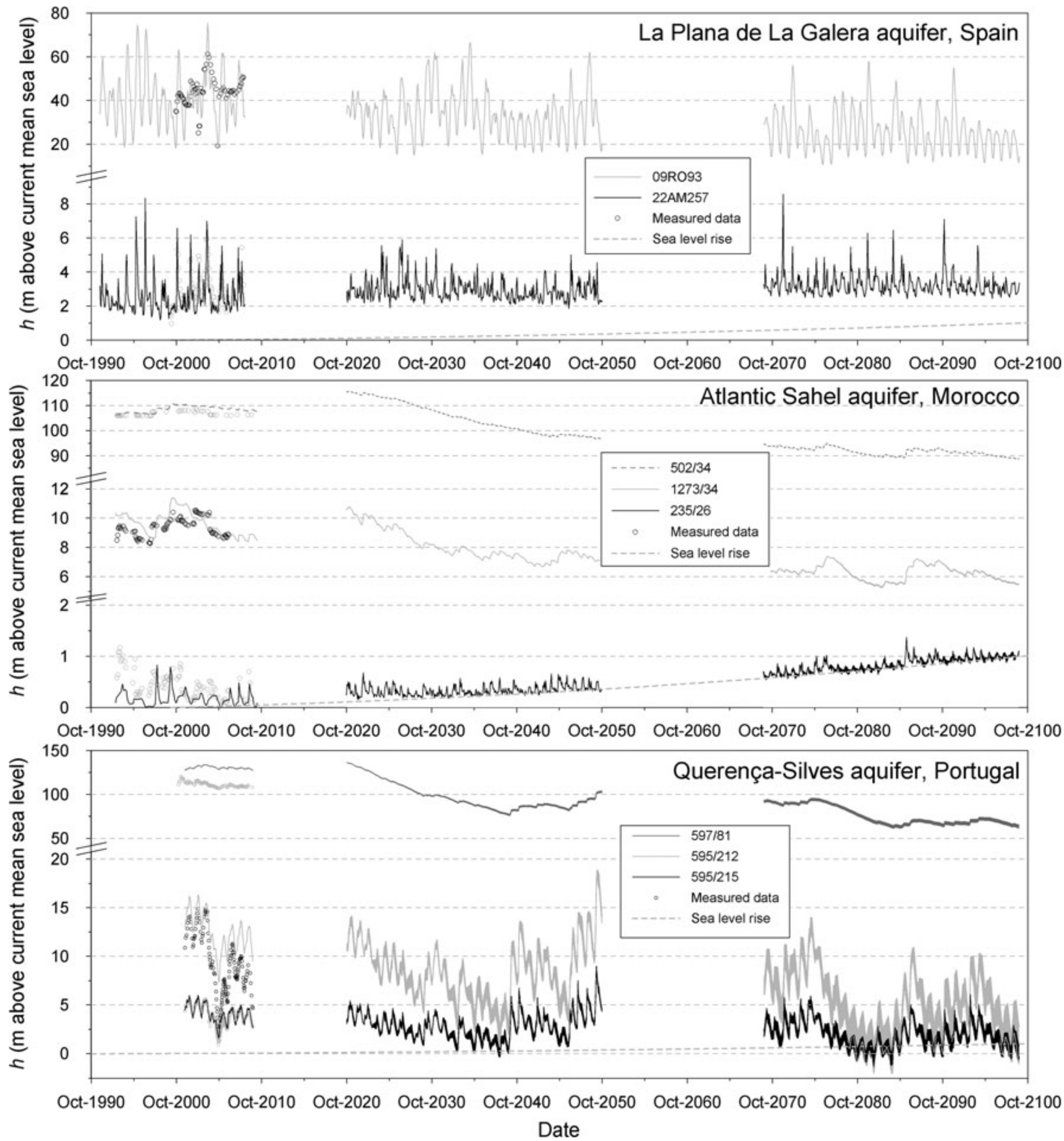

Fig. 5 Time series of groundwater heads in representative boreholes of each of the three studied aquifers (location indicated on the maps of Fig. 1), showing the evolution until 2100, based on integration of the recharge scenarios calculated for the ICTP-REGCM3 model run; where *lines* are substituted by bands, these represent the range between the scenario with constant and increasing groundwater abstractions for irrigation, also shown are the observed data used for model calibration. Note the breaks and different scale in the y-axes for each aquifer

slightly stabilizing toward the end of that period and an additional 10 m toward the end of the century. In the discharge area near the coast (well 235/26), the hydraulic head, nowadays just above 0 m above current mean sea level (+cmsl) with a seasonal amplitude of 0.5 m, shows an increasing trend with regard to cmsl, driven by sea level rise (represented by the dashed line), as well as a decrease in amplitude. The level in well 235/26 drops below this line, in rare occasions in 2020–2050, but more frequently in 2069–2099, particularly in the scenario of increased groundwater pumping to satisfy the increase in crop water demand. The latter effect is visible by the thickening of the line, which transforms into a band, the upper and lower limits representing constant and increased irrigation scenarios, respectively. These bands are particularly visible in the dry seasons of 2069–2099. The increased occurrence of seawater intrusion is reflected by the negative discharge values in Fig. 6. These only occur in 2070–2099 and only in the increased irrigation scenario. It should be noted, however, that the curve reflects a regional behavior, i.e.,

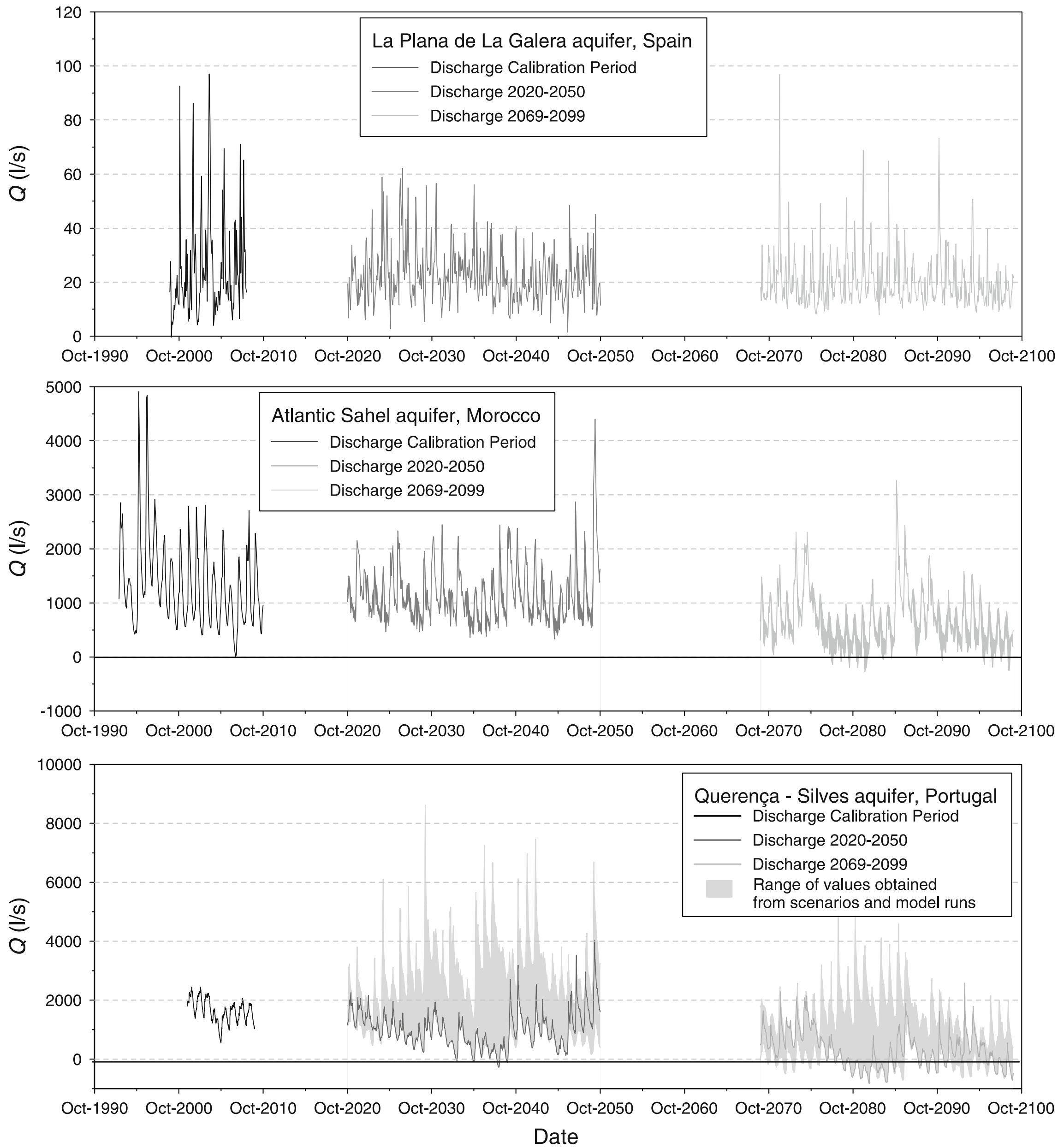

Fig. 6 Time series of discharge from the *La Plana de La Galera* aquifer into the freshwater wetland (*top*), the Atlantic Sahel aquifer into the Oualidia/Sidi Moussa lagoons (*center*) and the Querença-Silves aquifer into the Arade estuary (*bottom*), for the calibrated period and predicted climate scenarios, for the ICTP-REGCM3 model run. For Atlantic Sahel, bands represent the range between the scenario with constant and increasing groundwater abstractions for irrigation

along the outflow boundary defined in the model. Well 235/26 is located near an irrigated area and therefore more affected by groundwater pumping and seawater intrusion in the absence of recharge. The piezometric level time series of well 1273/34 indicates that the negative heads are not expected to extend inland beyond the irrigated areas, despite a significant decline in hydraulic head (>5 m) at this location as well. The lowering of recharge and increase in crop water demand, to a lesser extent, are the main factors causing the negative effects in the Atlantic Sahel aquifer.

For the Querença-Silves aquifer, the results of integration of the ICTP-REGCM3 scenario also point toward a strong decline of hydraulic heads in the recharge area, up to 40 m in 2020–2050 and 70 m in 2069–2099, for observation well 597/81. The inversely calibrated heads are not optimal for this well, with the model systematically producing higher heads. Notwithstanding, the results for the scenarios are compared to the simulated results in the control period and are therefore valid. Moreover, the modeled seasonal dynamics do closely follow the observed variations, except for the first 2 years. In the discharge sector of the aquifer, groundwater levels are expected to decrease and then recover again toward the end of 2050, caused by the occurrence of several exceptionally wet years in this scenario. Droughts are also more frequent, but hydraulic gradient inversion and subsequent seawater intrusion only very rarely occur in 2020–2050. In contrast, half of the summers of 2069–2099 show negative heads in the discharge zone, resulting in seawater intrusion, when considering the impact of increased pumping rates due to an increase in crop water demand. This impact, represented by the thickness of the time series band, is clearly noticeable in the discharge sector of the aquifer, where the main irrigated areas are located, and in addition to the evident seasonal effect (higher water demands in summer), increases toward the end of the century due to the expected increase in crop EET.

The discharge time series plot (Fig. 6) provides an overview of the full range of results for aquifer discharge into the Arade Estuary provided by all recharge scenarios. Three important aspects should be retained: first of all, it can be observed that the uncertainty involved in the discharge simulations is relatively large, particularly in 2020–2050. This is similar to results found in the studies of, for example, Brouyère et al. (2004) and Jackson et al. (2011), though under different (more humid) climate conditions. Second, the ICTP-REGCM3 scenario is among the most pessimistic for large periods of time, as previously discussed. Finally, and notwithstanding the previous arguments, all scenarios tend to converge toward the end of the century, which is unlikely to be a consequence of the groundwater model internal dynamics, as the convergence is not systematic. A similar observation was made by Goderniaux et al. (2011) in their study including six RCMs and 30 equiprobable scenarios. Their results show that despite consistently large confidence intervals around projected groundwater levels, the climate change signal becomes stronger than that of natural climate variability by 2085. The decrease in uncertainty of predictions for the Portuguese site is further confirmed by the box plots of recharge calculations in Fig. 4.

In comparative terms, all three areas show clearly decreasing trends in groundwater levels, most pronounced in the recharge zone, which can clearly be attributed to a reduction in recharge and results in a lowering of the regional hydraulic gradient in all areas. Negative changes in recharge and resulting impacts have been predicted under similar conditions in other areas: Serrat-Capdevila et al. (2007), for instance, show that in the semi-arid basin of Arizona and Sonora, the multi-model GCM average projected 26 % reduction in recharge until 2100 will lead to a significant lowering of the water table, affecting riparian vegetation that constitutes a GDE in the region. For the Mediterranean region of Mallorca, Candela et al. (2009) present a predicted decrease in recharge under the A2 scenario (close to the A1B scenario in terms of CO_2 emission) leading to a significant drop in spring discharge, which can only be balanced by a reduction of 20 % of irrigated land. Neither of the two cited studies considers the increase of vegetation/crop EET due to temperature increase, which in our study was seen to have an additional contribution of 15–20 % on a mean annual basis (Table 2). On the contrary, the impact of sea level rise is very modest: the main observation is a lifting of the groundwater levels near the coastal border, whereas predicted changes in groundwater discharge due to sea level rise are negligible. The process of lifting due to sea level rise was studied in detail by Chang et al. (2011), who consider it to occur over the entire aquifer. This is not observed in the three aquifers studied here, which can be explained in part by the fact that they all possess high regional hydraulic gradients. Sea level rise is expected to be most pronounced in unconfined aquifers of low-lying areas with flat topography (e.g., Melloul and Collin 2006). Under many circumstances, intensive pumping near the coast is a more important trigger of seawater intrusion than sea level rise itself, as also demonstrated by Loáiciga et al. (2012) for a study site in California, with Mediterranean climate conditions. Indeed, the same can be said for the Portuguese and Moroccan sites, where seawater intrusion is predicted to occur largely as a consequence of increased pumping rates and lower recharge.

Similar to the way Serrat-Capdevila et al. (2007) observed negative consequences for a riparian GDE in their case study, the large reductions of groundwater outflow at the three study sites (Fig. 6) can have important consequences for the local GDEs that exist. Such consequences were studied by the CLIMWAT project team for the macroinvertebrate community at the Portuguese site, at a branching channel of the Arade estuary (Fig. 1), which receives significant groundwater input from springs. It was shown that there is a clear qualitative and quantitative response of the macroinvertebrate community to the salinity gradient inherent to the sampling locations in the channel: those which tolerate low salinity are the most abundant at the location of groundwater input (Silva et al. 2012). The macroinvertebrate community structure was also seen to respond to the seasonal differences in salinity between summer and winter, with a higher impact from groundwater discharge into the channel during winter. It was therefore possible to conclude that changes in macroinvertebrate communities potentially constitute early warnings of reductions of aquifer discharge, which is particularly useful where monitoring of groundwater discharge is difficult, as is the case with submarine groundwater discharge.

Final considerations

The present paper aimed to show the combined effect of changes in recharge, crop water demand and sea level rise on groundwater levels and flow into coastal wetlands of three Mediterranean areas. The multiple combinations of climate models, bias correction, and recharge calculation methods allowed incorporating a level of uncertainty into the results. It should be emphasized that the combined study of the different types of climate change impact on groundwater resources is essential, as these impacts can be interrelated. Both the decrease in recharge and increase in crop water demand will boost groundwater pumping rates, and together they will have a more pronounced effect on the decline in groundwater levels, which on its turn may enhance the impact of sea level rise. In the three study sites, the effect of sea level rise is insignificant when compared to the decrease in recharge and increase in crop water demand, the latter increasing EET rates by 15–20 % until 2100. Certain (non-permanent) crops may undergo changes in growth cycles that can affect water demand, which was not taken into account in this study. Other sources of uncertainty in the results stem from i) global, regional, and local socio-economic development and related CO_2 emission scenarios; ii) the accuracy of GCMs, as well as downscaling and bias correction methods; iii) recharge estimation methods; and iv) aquifer parameterization. Such levels of uncertainty may stand in the way of transferring obtained results to stakeholders [see Faysse et al. (in press) in the current issue] who are concerned with what may happen in the following three to four decades. Notwithstanding, the climate scenarios, and recharge and groundwater flow scenarios derived from them, provide valuable information, even on a short-term basis, particularly regarding a predicted shift in precipitation and recharge regimes in all areas, and more frequent occurrence of extremely dry and wet years and an increase in crop water demands for the Portuguese and Moroccan sites. In the long term, water availability in the three regions is predicted to decrease substantially and, together with increasing water demands, may seriously affect the well-being of humans and ecosystems that depend on groundwater for their subsistence. This shows that despite the higher resilience of groundwater when compared with surface water resources, adaptation measures are needed to cope with the potential negative impacts of climate change. These can either target supply, for instance by enhancing groundwater (artificial) recharge and promoting the use of alternative water sources such as reclaimed wastewater for irrigation, or they can aim at demand, by increasing water use efficiency in agriculture, public supply and domestic use. The determination of sustainable yields for aquifer exploitation and continuous monitoring of groundwater levels and quality, particularly in coastal aquifers, will thereby constitute essential tasks.

Acknowledgments The research that supports this paper was performed within the scope of the CLIMWAT project funded under the CIRCLE-MED network of the CIRCLE-2 ERA-Net. The authors wish to acknowledge the Portuguese funding institution FCT—*Fundação para a Ciência e a Tecnologia* for supporting this network. They also wish to thank all the people that collaborated in the project and contributed to its success. Funding for the research of the Spanish group was provided by *Xunta de Galicia* (Ref. 08MDS016118PR). Thanks are given to Carlos Loaso (*Agència Catalana de l'Aigua*) and Emilio Custodio (*Universitat Politècnica de Catalunya*). The first author holds a research position under the Ciência 2007 program financed by the FCT.

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