Impact of climate change on groundwater and its management in three coastal Mediterranean aquifers

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I. INTRODUCTION

Groundwater resources are under increasing pressure due to large abstraction rates for various consuming activities, particularly agriculture (irrigation), public water supply (consumption) and industry. In coastal areas intensive aquifer exploitation 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. Research performed in the scope of the CLIMWAT project, one of eight transnational research projects funded under the CIRCLE-MED network (http://www.circle-med.net/), aimed to assess the impact of climate change on coastal groundwater resources and dependent ecosystems in three Mediterranean areas (Stigter et al., *submitted*). Here we focus on the consequences for groundwater and its management.

II. STUDY AREAS

The three study sites are located in the Central Algarve in the south of Portugal, the *La Plana de La Galera* near the Ebre Delta of northeastern Spain and the Atlantic Sahel at the central western coast of Morocco. Their location is indicated in Figure 1. All areas are characterized by a Mediterranean climate, with dry and warm summers and cool wet winters. Mean annual temperature and rainfall for the 1980-2010 climate normal are respectively 17.5 ºC and 739 mm in the Central Algarve, 17.2 ºC and 609 mm in La Plana de La Galera and 18.6 ºC and 411 mm in the Atlantic Sahel, which has the warmest and driest climate. Most of the rainfall in La Plana de La Galera occurs in autumn and spring. Its dry summer season is shorter than that of a typical Mediterranean climate.

In the Central Algarve, the large karstified carbonate rock aquifer known as Querença-Silves, 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 located at the aquifer boundaries, particularly in the west, where the aquifer borders an estuary. Land use is dominated by irrigated citrus culture in the western sector, whereas extensive dry farming occupies the eastern sector. Currently 30% of mean annual recharge (approximately 100 hm^3) 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. The La Plana de La Galera multi-layer aquifer sits on a graben filled with Mesozoic, Tertiary and Quaternary materials (CHE, 1999). Conglomerates and limestone gravels form the Quaternary aquifer, and below this Mesozoic limestones form a regional confined multilayer karst aquifer (Pisani et al, 2011). The Quaternary aquifer receives recharge over the entire area of the outcrop. Lateral inputs from the western aquifers also occur. Discharge primarily occurs underground towards 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 ecosystems in the Ebre Delta and therefore have great ecological value. The land is occupied by irrigated citrus and (mainly) rain-fed olive groves, as well as natural vegetation and urban and industrial zones. Groundwater use is about 40% of annual areal recharge (the latter estimated at 55 hm^3).

The Atlantic Sahel geomorphology is characterised by NE-SW Plioquaternary oriented dunes, parallel to the ocean. The wetland of Oualidia-Sidi Moussa is composed of saltmarshes and the two lagoons of Oualidia and Sidi Moussa, fed by ocean water and groundwater discharge from the Plioquaternary calcareous sandstone aquifer, as well as the underlying Hauterivian limestone aquifer. 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. Currently, of the estimated 70 hm^3 of mean annual recharge, about 30% is exploited, mainly for irrigation of vegetable crops, but also providing drinking water to the city of Oualidia and rural villages.

Figure 1. Location of the three study areas. Base map © Google

III. METHODS

Regarding the climate scenarios, the available scenarios from the ENSEMBLES project were selected (Van der Linden and Mitchell 2009), including results from 1950 up to 2100, resulting from different combinations of a Regional Climate Model (RCM) and a driving Global Circulation Model (GCM), including Europe and parts of North Africa, with a 25x25 km resolution and the A1b CO_2 emission scenario (IPCC, 2000). 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 normals: 2020-2050 and 2069-2099. 1980-2010 was chosen as the reference or control period, i.e. the period for which bias correction of the RCM results is performed. For Spain the period was 1960-1990. Bias correction was applied to the data, using two different approaches, in order to compare their applicability (Stigter, et al., submitted).

The downscaled data were used to develop scenarios of groundwater recharge, using a variety of approaches: i) for the Portuguese and Moroccan sites, water budget calculations based on two methods: Thornthwaite-Mather and Penman-Grindley, to obtain a measure of involved uncertainty; ii) advanced hydrological modeling for the Spanish site (Stigter, et al., submitted). Besides the elaboration of recharge scenarios, the impacts of global warming on crop water demand and consequently groundwater extraction for irrigation were also assessed by analyzing the evolution of PET. Finally, the results were combined to develop multiple recharge scenarios, each consisting of a particular combination between RCM and, in the Portuguese and Moroccan sites, also the methods used for downscaling and recharge estimation.

Numerical simulation models for groundwater flow were then developed in horizontal and vertical 2D domains, using different softwares (Stigter, et al., submitted). The models were calibrated and validated with existing data from national monitoring networks and newly obtained data from project-specific monitoring surveys (Stigter, et al., submitted). 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 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. In addition to recharge, the scenarios considered increasing groundwater extractions for irrigation in time for the Querença-Silves and Atlantic Sahel aquifers, as well as sea level rise at all three study sites.

IV. RESULTS AND DISCUSSION

The results indicate strong increases in temperature (T) for all study sites, 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, particularly for 2069-2099, and a relatively modest decrease in the Ebre Delta in 2069-2099 only. For 2020-2050 rainfall in the Central Algarve is predicted to decrease mostly during fall and increase in winter, whereas the Atlantic Sahel could see moderate rainfall increases in the late autumn-early winter period. There is however a strong variability in rainfall predictions between future climate scenarios, which result mostly from differences between the ENSEMBLES RCM predictions, and are therefore present in the three study sites.

These expected changes in climate result in a trend for decreasing recharge in all study sites, both due to the higher PET due to higher T (which also lead to higher irrigation requirements) and lesser available rainfall, with stronger decreases in 2069-2099 for the Querença-Silves and the Atlantic Sahel aquifers. At the *La Plana de La Galera* site the largest decrease in recharge is expected to occur in 2020-2050 due to the combined effect of a reduction in rainfall and an increase in T during autumn, the main recharge season. Net recharge rates are also expected to suffer different changes throughout the year; monthly changes are expected to follow rainfall changes, but the PET increase may also lead to higher soil moisture depletion during the dry season. For the Querença-Silves and Atlantic Sahel aquifers, in 2069-2099 decreases in groundwater recharge are expected in the entire wet season, whereas they will be most pronounced in autumn and spring at the *La Plana de La Galera* site. The interannual variability, which due to methodological aspects could only be analysed for Querença-Silves and the Atlantic Sahel (Stigter et al., submitted), shows an increase in the frequency of drought years already for 2020-2050. For the Querença-Silves aquifer, the higher 90% percentile value in 2020-2050 further indicates the occurrence of more extremely wet years. In 2069-2099, results indicate that the groundwater demand for irrigation will be higher than recharge at least once in every four years, if current land use is note modified. 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.
Figure 2 shows the predicted evolution of groundwater heads in representative boreholes of each of the three studied aquifers. The scenarios are based on recharge calculations for the ICTP-REGCM3 climate model run, and consider an increase in crop water demand for the Atlantic Sahel and Querença-Silves aquifers, maintaining the current spatial distribution of land use. Results seem most dramatic for these two aquifers. In the Atlantic Sahel, hydraulic heads in the recharge zone drop 10 m in 2020-2050, slightly stabilizing towards the end of that period and an additional 10 m towards the end of the century. In the

discharge area near the coast, the hydraulic head, nowadays just above 0 m above current mean sea level (+cmsl), shows a slightly increasing trend with regard to cmsl, driven by sea level rise, indicated by the dashed line. Heads drop below future msl, initially only at the end of summer, towards the end of the century throughout the entire year, indicating the occurrence of seawater intrusion. The negative heads are not expected to extend inland beyond the irrigated areas. The drastic lowering of recharge and increase in crop water demand are the main factors causing the negative effects in the Atlantic Sahel aquifer.

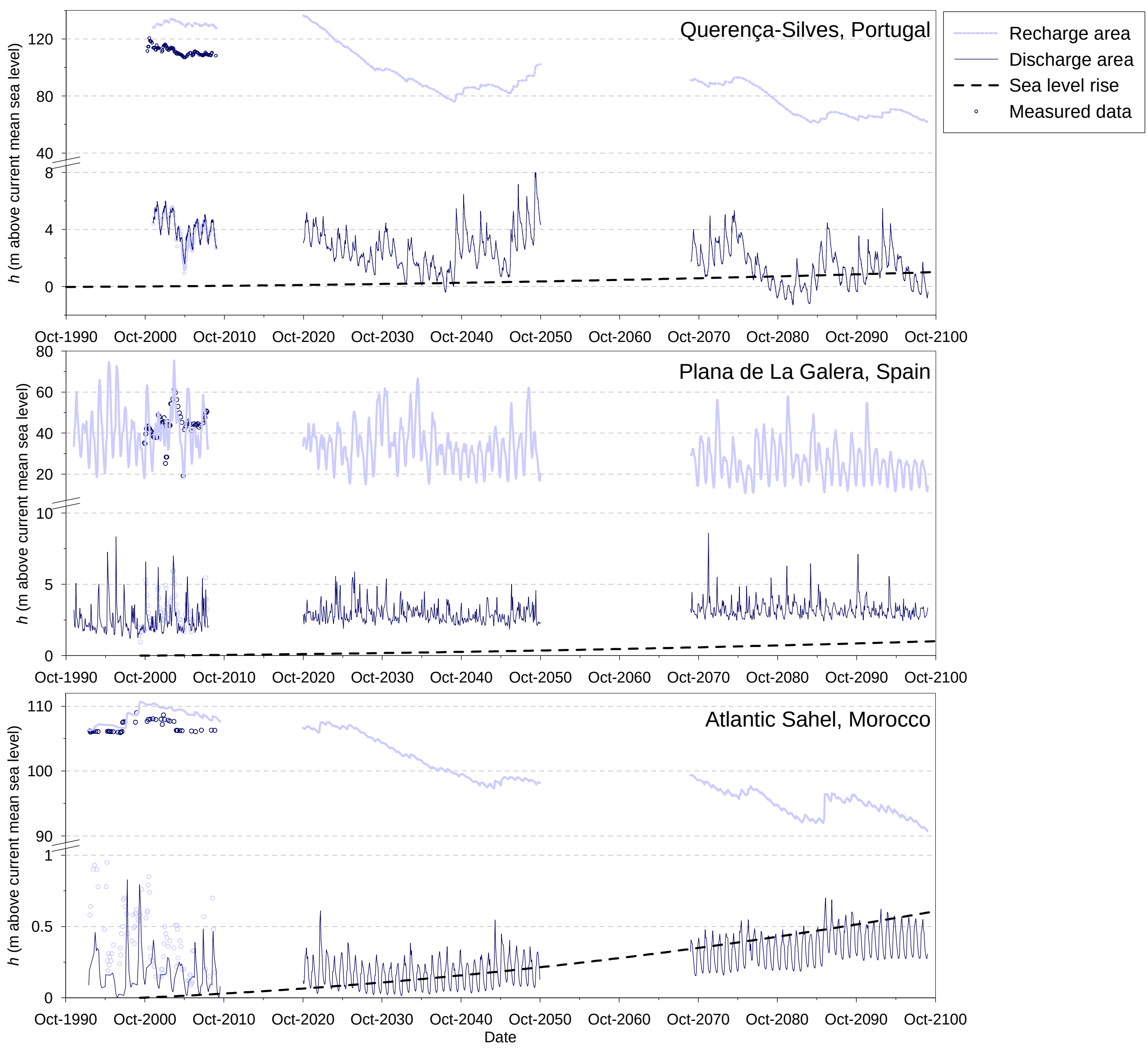

Figure 2. Time series of groundwater heads in representative boreholes located in the recharge and discharge areas of each of the three studied aquifers, showing the evolution until 2100; also shown are the observed data used for model calibration. Note the breaks and different scale in the y-axes.

The same is true in the Querença-Silves aquifer, where the results point towards a strong decline of hydraulic heads in the recharge area, up to 40 m in 2020-2050 and 70 m in 2069-2099. In the discharge sector of the aquifer groundwater levels are expected to decrease and then recover again towards 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. The latter is not the case for the La Plana de La Galera site in Spain, despite the significant lowering of hydraulic heads, up to 20 m for 2069-2099 in the recharge area. Similar to the other two aquifers, the piezometric levels near the Ebre river show an increasing trend driven by sea level rise. After the correction for sea level rise, one can see that the hydraulic heads in fact decline.

From the foregoing it is clear that climate change is expected to have a large impact on coastal groundwater resources. Though prudence is required, due to a high degree of uncertainty involved in the climate models, results seem to agree that in the short term, i.e up to 2050, extreme events such as very wet years and droughts will occur more frequently and crop-water demands will increase, whereas on a long-term basis, i.e. until the end of this century, groundwater recharge will drop significantly, resulting in reduced availability and increased risk of seawater intrusion in coastal areas. Groundwater management in coastal zones will have to cope with these expected changes, in addition to dealing with the present-day, sometimes already intensive and uncontrolled, groundwater pumping activities that can have a more immediate and possibly more severe impacts on the aquifers than climate change. The determination of sustainable yields for aquifer exploitation, such as proposed for arid zones by Hugman et al. (*in press*), is therefore an essential step towards the implementation of adaptation measures. Such measures can either target consumption, by increasing water use efficiency in agriculture, public supply and domestic use, or availability, by enhancing groundwater (artificial) recharge and storage, as well as promoting the use of alternative water sources such as reclaimed wastewater for irrigation.

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