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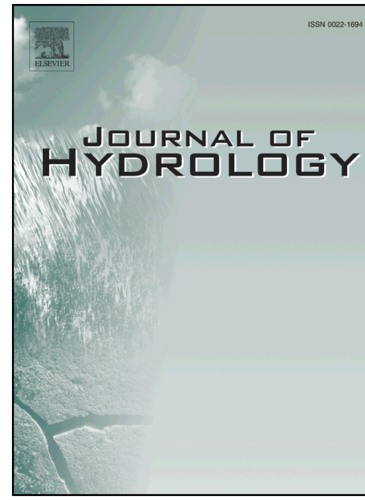

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Assessment of climate change impacts on soil water balance and aquifer recharge in a semiarid region in south east Spain

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Abstract

Climate change forecasts in a semiarid region are of much interest to academics, managers and governments. A significant decrease in annual precipitation and an increase in mean annual air temperature are expected; consequently, changes in the soil water balance and groundwater recharge to aquifers are expected as a response to climate change forecasts. In this context, our study aimed to assess the impact of climate changes on the soil water balance and natural groundwater recharge in a semiarid area (Ventós-Castellar aquifer, SE, Spain). To this end, we selected Global Climate Model HadCM3 after comparing it with two other models (ECHAM4 and CGCM2). The HadCM3 model climate data (air temperature and precipitation in two emission scenarios: A2-high and B2-low; 2011-2099) were coupled to a HYDROBAL hydrological model to determine the soil water balance. The HYDROBAL model results showed that climate change will have a significant impact on the soil water balance in the study area, especially on groundwater recharge during the latter period. In both the A2-high and B2-low scenarios, the selected years to run the HYDROBAL model showed a decrease in water balance components (Precipitation, actual evapotranspiration, aquifer recharge and runoff) in relation to the baseline period (1961-1990). Over the projected period (2011-2099), we expect fewer rainfall events (>15 mm), which promote aquifer recharge, longer dry summer seasons and, consequently, reduced average annual recharge that ranged from 3-17%; 10-49 mm, if compared to the baseline period. The methodology developed in the present study can be beneficial for assessing the impact of predicted climate change on groundwater recharge, and can help managers and planners to devise strategies for the efficient use and conservation of freshwater resources.

Keywords: Climate change, soil water balance, aquifer recharge, HYDROBAL model, semiarid region

1. Introduction

Global climate change will have a strong impact on the hydrological cycle and, therefore, on water resources in many regions of the world, which is the general agreement reached by academics and governments (Kundzewick, and Somlyódy, 1997; Allen and Ingram, 2002; Huntington, 2006; Wilby et al., 2006; IPCC, 2007, 2013). Groundwater is an essential component of the hydrological cycle that could be seriously affected. Variability in annual precipitation is expected to have direct consequences on groundwater resources (Green et al., 2011; Jyrkama and Sykesa, 2007; Dragoni and Sukhija, 2008; Kundzewicz and Döll, 2009). However, it is hard to establish global potential effects because the relation between climate compounds and groundwater is a rather complex one. For this reason, advancing further in our understanding of the impact of climate change is necessary because, on a global scale, one third of the world population depends on groundwater, especially in semiarid areas. Therefore, groundwater resources may be relatively robust in response to changes in driving climate variables under climate change if compared with surface water given the buffering effect of groundwater storage. Hence the role of groundwater in water resources management is particularly beneficial because it can be used to support public water supply projects and to study ecosystem services during the drought periods expected in future climate change scenarios. Groundwater resources will depend on changes in the volume and distribution (spatial and temporal) of natural recharge.

The latest Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC, 2007, 2013) state that the mean air temperature on the global surface has increased by 0.6±0.2ºC since 1861, and predicts an increase of 2-4ºC in the next 100 years. More frequent intense and extreme weather events (including drought and flooding) are also expected. Based on the IPCC (2007, 2013) predictions, annual air temperatures will show a warming rate of between 0.1 and 0.4°C per decade, but this impact could be particularly severe in south European countries like Spain (Giorgi et al., 2004; Alcamo et al., 2007). The warming pattern shows a strong south-to-north gradient, especially in summer, which indicates a warming rate across southern regions of between 0.2 and 0.6°C per decade. For annual precipitation, trends in Europe for the 1900-2000 period have shown a contrasting picture between northern Europe (10-40% wetter) and southern Europe (up to 20% drier). In most European countries, these changes are more marked in winter. Annual precipitation predictions in northern Europe indicate an increase from 1-2% per decade, with a decrease of up to 1% per decade (and even up to 5% in summer) in southern Europe. The frequency and duration of very wet periods have significantly decreased in many regions in recent decades (Hiscock et al., 2012). These general simulations have been specified for Spain, where an increase in the mean annual temperature of 2.5ºC and a decrease in annual rainfall ranging from 2% in northern basins to 17% in southern basins are expected. These predictions of climate change in south Europe, particularly in SE Spain, will have a considerable impact on agriculture and water resources, especially on the natural groundwater recharge of aquifers (Ayala-Carcedo and Iglesias, 2000; CEDEX, 2012).

Quantifying the impact of climate change on groundwater resources requires both reliable climate change forecasting and accurate groundwater recharge estimations (Maxwell and Kollet, 2008). Hydrological models can be combined with climate scenarios generated from downscaling Global Climate Models (GCMs) to produce potential scenarios of climate change effects on groundwater resources on the local scale. The IPCC gives a set of GCMs (e.g., HadCM3 from the UK, ECHAM 4 from Germany, and CGCM2 from Canada) with a well standardised group of scenarios (e.g., A1B, A2, B1, B2, etc.) for climate impact studies.

In the last decade, a growing number of case studies has been generated in an attempt to quantify the likely direct impacts on groundwater (Scanlon et al., 2006; Hendricks Franssen, 2009; Green et al., 2011; Herrera-Pantoja and Hiscock, 2008; Viviroli et al., 2011; Stoll et al., 2011; Thampi and Raneesh, 2012; Ali et al., 2012). Thus many of these studies have predicted decrease in recharge values over the 21st century. However, other studies predict an increase in aquifer recharge under certain conditions and periods (Döll, 2009; Gurdak and Roe 2010). Mediterranean region shows a high vulnerability to changes on meteorological variables such as temperature or rainfall. Otherwise, projections indicate an increased likelihood of droughts (Iglesias et al, 2007). Many climate change studies have consistently predicted a reduction in groundwater recharge (Manzano et al., 1998; Younger et al., 2002; Bates et al., 2008; Döll, 2009; Aguilera and Murillo, 2009; Guardiola-Albert and Jackson, 2011; Hiscock et al., 2012; Pulido-Velazquez et al., 2014). However, more studies about these changes are needed, especially in arid and semiarid Mediterranean area, where water resource availability is very reduced.

Therefore, we carried out this study to assess the impact of climate change on the soil water balance and natural groundwater recharge in a small aquifer in a semiarid area (SE, Spain). This well known karstic aquifer can be considered as well representative of the kind of aquifers in this region. Temperature and precipitation data from a selected GCM, previously downscaled by AEMet (2009), were coupled to the HYDROBAL hydrological model, which has been previously tested in this semiarid area with good results (Bellot and Chirino, 2013; Touhami et al., 2013, 2014). Impact on groundwater recharge was assessed for two emission IPCC scenarios: A2-high and B2-low. This work attempts to make up for the lack of such studies in semiarid ecosystems.

2. Study area

The study area (Figure 1) is a small aquifer called Ventós-Castellar located in the Municipality of Agost in the province of Alicante in SE Spain (38º 28'N, 0º 37'W). Altitude ranges from 300 to 840 m a.s.l. Slopes vary between 25-30% and are mainly south-facing. The Ventós-Castellar aquifer consists chiefly of 80-120-metre-thick fractured Cenomanian limestones, bound at the base by Albiense marls, while there are Upper Cretaceous limestones and marls at the top. The geological structure is characterised by a synclinal with its main axis tilted to the southwest. On the southern and eastern aquifer borders, Albiense marls outcrop, while faults come into contact with impermeable (Cretaceous and Tertiary) marls on its north and western borders. The aquifer is completely isolated from other aquifer formations. Aquifer recharge takes place through the direct infiltration of rainwater, while natural discharges are produced mainly through the Agost spring located on the southern border of the carbonate outcrops. Nowadays this spring is dry and is solely exploited for urban supply to the town of Agost. Despite pumping not being excess (< 189.000 $m^3 yr^{-1}$), the hydrological balance of the system has been severely altered; consequently, the water table has dropped more than 70 m over the last three decades. Short-term changes in groundwater levels suggest that aquifer replenishment responds only to significant rainfall episodes. Thus, automated piezometric records reveal that rises in the water table are observed for a few hours after each storm (Andreu et al., 2010, 2011). The Ventós-Castellar aquifer is optimal for the purpose of this paper for several reasons: it has been under direct observation for the last 30 years; it presents an automatic weather station that takes continuous recordings, and nowadays, it is equipped with two continuous-log piezometers. Hence, long-term climatic data records (daily rainfall, air temperature, atmospheric pressure, wind speed and direction) and water table elevations are readily available. Its small size also allows better monitoring, and it shows a quick response to rainfall events (>15 mm), which provides a better understanding of this aquifer.

According to the Agost Meteorological Station database (1976-2010 period), this area has a semiarid Mediterranean climate characterised by highly variable rainfall pulses. The mean annual rainfall is 275 mm and the mean annual temperature is 18.5ºC. The interannual variability of precipitation is very high. However, the temporal distribution is the main abiotic factor that affects the regeneration of the vegetation cover in the semiarid area. Vegetation cover is sparse. *Stipa tenacissima* L. is the dominant species, followed by *Globularia alypum* L., *Brachypodium retusum* (Pers.), and scattered patches of *Quercus coccifera* L., mixed with reforested *Aleppo* pine (*Pinus halepensis* Miller). Soils are shallow, thinner than 15 cm on average, which have developed over marl and calcareous bedrock, and are classified as Lithic Leptosol (FAO-ISRIC-IUSS, 1998). It has a silt-loam texture (17.7% clay, 50.9% silt, 8.4% fine sand and 23.0% coarse sand), an average bulk density of 1.3 g cm^{-3} and porosity of 58% (Chirino, 2003).

3. Methodology

3.1. Climatic data source

The climatic data (from 1961 to 2099) were obtained by the Spanish National Meteorological Agency (AEMET) from the meteorological stations closest to the study area. Two weather stations were selected to model the climatic conditions at Ventós-Castellar aquifer, and they hold the longest climate records available for this area. The daily precipitation data from 1961 to 2099 were collected from the Agost-Escuela weather station (376 m a.s.l., 38º 26'N; 0º 38'W) which is about 1 km southwest of the aquifer. The maximum and minimum temperatures data were obtained from the Novelda weather station (241 m a.s.l., 38º 23´N; 0º 46´W). This weather station is located 15 km southwest of the aquifer. By considering the different altitudes above sea level of the Novelda and the Agost-Escuela weather stations, the maximum and minimum temperatures values were corrected. The corrected factor was 0.50ºC/100 m a.s.l. for the minimum temperature, and 0.75ºC/100 m a.s.l. for the maximum temperature. The temperature and precipitation data during the 1991-2010 period were not considered in this study, because the climate database during this period is not available to the HadCM3 model.

3.2. Analysis of climate change forecasts on temporal dynamic of precipitation and air temperature toward the end of the 21st century

Firstly, in order to select the most representative Global Climate Model (GCM) of the climatic conditions (historical and future data) at the study site, we selected the three most widely used GCMs in the European region from the IPCC Data Distribution Centre: (1) The CGCM2 model represents the second generation coupled Canadian global model (Flato et al., 2000); (2) The HadCM3 model represents the third version of the coupled atmosphere-ocean model presented by Gordon et al. (2000); (3) The ECHAM4 model is based on the prevision model of the European Centre for Medium Range Weather Forecast (ECMWF; Roeckner et al. 1996). For this purpose, we used the AEMet data downscaled within the PRUDENCE and ENSEMBLES projects (AEMet, 2009).

For the purpose of comparing the performance of the three GCMs (HadCM3, ECHAM4 and CGCM2), we attempted to answer two questions: (1) Are there differences between the data observed at the study site and in databases of the three GCMs? For this purpose, we analysed the database (precipitation, minimum and maximum air temperature) corresponding to the periods 1976-1990 and 1980-1990 respectively. A statistical analysis was done using the multiple pair-wise comparisons of the Kruskal-Wallis non-parametric test (XLSTAT©, 2014). (2) Do the forecasts of the three GCMs differ very much for the emission scenarios during the future period? For this analysis, we compared the database (precipitation, minimum and maximum air temperature) from the 2011-2099 period of the three GCMs for two emission scenarios: Scenario A2-high projects, high population growth and slow economic and technological development; Scenario B2-low estimates, slower population growth, rapid economic development and places more emphasis on environmental protection. Scenario B2-low shows more concern for environmental and social sustainability if compared to Scenario A2-high. These two selected scenarios cover a wide range of variation, which have been considered sufficiently representative of the set of scenarios. The climate series data of emission Scenarios A2-high and B2-low were analysed for three future time series (2011-2040, 2041-2070 and 2071-2099), which are commonly used in scenario constructions (IPCC, 2007).

Secondly, in order to analyse the temporal variation of the climatic variables of this model (precipitation, minimum and maximum air temperature) throughout the study period (from 1961-1990 and 2011-2099), a General Linear Model univariate analysis was performed. Data were analysed by two-way ANOVA using two factors: (1) the period's factor (1961-1990, 2011-2040, 2041-2070 and 2071-2099) and (2) the emission scenarios factor (A2-high and B2-low). Annual precipitation (Figure 2) and mean annual air temperature (maximum and minimum; Figure 3) were used as the dependent variables. This statistical analysis was performed using the SPSS v.18 package (SPSS Inc., Chicago, IL, USA).

3.3. HYDROBAL model description

Hydrological simulations were performed with the HYDROBAL model (Bellot et al., 1999, 2001; Bellot and Chirino, 2013). HYDROBAL is a model that integrates meteorological conditions, vegetation characteristics and soil processes to simulate water balances in ecosystems dominated by different vegetation types. The model estimates water flows across vegetation canopy and soil water balance using a simple mass balance equation calculated by a daily time step. This equation estimates the groundwater recharge (R) by considering precipitation (P) to be input, less output by rainfall interception, actual evapotranspiration (Et_a), runoff (R_{off}) and change in soil water storage (θ). A brief description of the model is presented herein, but a more detailed description and discussion of it can be found in Bellot and Chirino (2013) and in Touhami et al. (2013). The input data are: (1) soil data (depth of soil, total porosity, field capacity, wilting point and initial soil moisture); (2) climate data (rainfall, air temperature, relative humidity and global radiation); (3) vegetation data (plant cover, vegetation structure and species composition). Reference evapotranspiration (Et_o) was computed from the climate variables by the Hargreaves-Samani method (Hargreaves and Samani, 1982). Actual evapotranspiration (Et_a) was estimated using a negative exponential approach according to the k factor and Et_o. The k factor is an empirical parameter that integrates the structural and ecophysiological characteristics of vegetation cover types. The model's outputs variables (expressed in L m^{-2} day^{-1}) were: interception, net precipitation, surface runoff, soil water reserves, actual evapotranspiration, direct percolation, infiltration and potential recharge. A multivariate sensitivity analysis of the HYDROBAL model was performed. The model was calibrated during 1997/98 and 1998/99 on the basis of soil moisture by the Time Domain Reflectometry System (Reflectometer Tektronic 1502C, Metallic TDR cable Tester, Tektronix, Beaverton, OR, USA) from 0 to 30 cm (maximum soil depth) by employing 12 probes installed in the experimental plots (Chirino, 2003; Bellot and Chirino, 2013). The HYDROBAL model has been validated using water table records from 2002 to 2008 (Touhami et al., 2013). Over the last decade, the HYDROBAL model has been successfully applied under semiarid conditions to analyse the soil water balance on different vegetation cover types and to assess its effects on runoff, evapotranspiration and soil moisture (Bellot et al., 1999; Chirino, 2003). It has also been used to assess the effect of different land-use scenarios on water resources and aquifer recharge (Bellot et al., 2001; Touhami et al., 2013, 2014).

3.4. Soil water balance and aquifer recharge calculation

The daily data (precipitation and air temperature) predicted with the HadCM3 model were used in the HYDROBAL hydrological model to assess the impact of climate changes on the soil water balance and natural groundwater recharge in the Ventós-Castellar aquifer. One representative year per decade during the different analysed periods was selected; the baseline and future periods (emission scenarios A2-high and B2-low). The selected year had to meet two conditions: (1) the year whose annual precipitation came close to the mean precipitation of the decade; (2) showing a similar distribution of monthly precipitation to the mean monthly observed in the study area. According to the two conditions, the selected years per analysed period were: during the baseline period (1961-1990), the years 1970, 1971, 1990; in the future time series for scenarios A2-high; period (2011-2040), the years 2020, 2023, 2031; period (2041-2070), the years 2047, 2058, 2066; and the period (2071-2099), the years 2078, 2084 and 2096. For scenario B2-low; period (2011-2040), the years 2017, 2021, 2033; period (2041-2070), the years 2050, 2060, 2068; period (2071-2099), the years 2077, 2087 and 2098.

The HYDROBAL model was used to estimate the soil water balance and aquifer recharge in the main representative vegetation cover types of the study area. The considered vegetation types were: (*1*) open *Stipa tenacissima* steppes with lesser dwarf shrubland cover (52% of the total surface cover); (*2*) degraded open land or bare soil (0.5%); (*3*) afforested pine and dry grassland (10%); (*4*) dry grassland (18%); (*5*) afforested pine and thorn shrubland (13.5%); and (*6*) scattered thorn and sclerophyllous shrublands (6%). In order to determine the soil water balance on the aquifer scale, the model's variable output values were weighted according to the percentage of vegetation cover types on the aquifer surface. A further explanation is presented in Touhami et al. (2013, 2014).

Finally using the HYDROBAL model output variables (precipitation, actual evapotranspiration, groundwater recharge, runoff, and soil moisture), a General Linear Model univariate analysis was performed to analyse the water balance results. Data were analysed by a two-way ANOVA using two factors: (1) period factor, by considering the average during each period, and the mean of the three selected years per period (1961-1990, 2011-2040, 2041-2070 and 2071-2099); (2) the emission scenarios factor: A2-high and B2-low. Given our aim to know the temporal evolution tendency towards the end of the 21st century, several regression analyses were also performed. A polynomial equation ($y = a + bx + cx^2$) showed the best fit. This statistical analysis was performed using the SPSS v.18 package (SPSS Inc., Chicago, IL, USA).

4. Results

4.1. *Global Climate Models selection*

The first analysis results indicated that during the baseline period, the HadCM3 model presented the most similar database (precipitation and air temperature) to the data observed (1976-1990) if compared with the three analysed GCMs ($p < 0.001$, Table 1). The ECHAM4 database showed slight differences, while the CGCM2 database presented the largest differences ($p < 0.001$, Table 1). In the second analysis, when we compared the forecast of the three GCMs for emission scenarios A2-high and B2-low during the 2011-2099 period, we observed that the databases of the HadCM3 model and ECHAM4 models presented similar precipitation and minimum air temperature values ($p < 0.001$, Table 2) in both emission scenarios (A2-high and B2-low). For maximum air temperature, we found significant differences ($p < 0.001$, Table 2). In this case, the CGCM2 database also showed the largest differences ($p < 0.001$, Table 2) if compared to the other GCMs; therefore we considered not using this CGM for the water balance study. In summary, the HadCM3 model database gave the best fit according to the observed data (1976-1990) and showed similar climatic forecast in emission scenarios A2-high and B2-low during the 2011-2099 period if compared to ECHAM4 model. For this reason, we selected the HadCM3 database as it was the most suitable model to assess the impact of climate change forecasts on the soil water balance and natural groundwater recharge in our study area. This model is extensively described in Gordon et al. (2000), Pope et al. (2000), and has been widely used in climate change studies in Mediterranean region (Rodríguez et al., 2007; Candela et al., 2009).

4.2. Climate change impact on precipitation and air temperature

The results indicate a significant decreasing of annual precipitation from the baseline period (1961-1990) to the future period (2071-2099; Table 3). The modelling predictions suggest that mean precipitation will decrease by 1% during (2011-2040); 6% during (2041-2070) and 12% during the latter period (2071-2099) if compared to the baseline period (1961-1990). This will be the equivalent to a reduction in average annual precipitation of up to 1.1% per decade. Neither differences between emission scenarios (A2-high and B2-low) nor interactions between the assessed factors ($p < 0.05$, Table 3) were found. The report of the Centre for Studies and Experimentation of Public Works, Spain (CEDEX, 2012), obtained a similar results, which generally predicted that the mean precipitation in Spain will lower by 5% during the first period (2011-2040); 8% during the middle period (2041-2070) and 13% during the last period (2071-2099).

As a result of climate change forecasts for the selected years (a representative distribution years for the study condition), there will be more days without precipitation (P = 0 mm). Although a mean of 325 days yr^{-1} without rainfall was found during the baseline period (1961-1990), this will increase to 344 days yr^{-1} during the last period (2071-2099). Another consequence of climate change is that the duration of dry summer periods will prolong. In the summers during the baseline period, a mean of 117 consecutive days without significant rainfall (< 5 mm) was observed. However by the end of the 21st century (2071-2099), summer dry periods are expected to last 173 days (5.7 months) in the A2-high scenario and 148 days (4.9 months) in the B2-low scenario. Consequently, the duration of dry seasons will increase from 26.5% to 47.8% depending on the scenario emissions. This increase in drought events will become commoner in southern European regions (Hiscock et al. 2012).

Previous hydrogeological studies carried out in the Ventós-Castellar aquifer have indicated that rain events of < 15 mm are predominant (Chirino et al., 2006) and that these events hardly ever increase the water table level (Andreu et al., 2002; Touhami et al., 2013). So their contribution to aquifer recharge is considered negligible. We also considered the rainfall events of >15 mm during the baseline period (120 events), and found a decrease of almost 19% and 27% at the end of this century (23-32 rain events) in the A-high scenario and the B2-low scenario, respectively.

The maximum air temperature will increase by 1.4ºC during 2011-2040, 2.7ºC during 2041-2070 and 4.4ºC during 2071-2099 in comparison to the baseline period. The same pattern was also observed for minimum temperature (an increase of 1.3ºC during 2011-2040, 2.5ºC during 2041-2070 and 4.0ºC during 2071-2099). These will be the equivalent to an increase in the maximum and minimum temperatures of up to 0.4ºC per decade. A significant increase in air temperature was also found towards the end of this century ($p < 0.001$, Table 3). The scenarios factor affected air temperature. The A2-high scenario showed a higher air temperature (maximum and minimum) than B2-low ($p < 0.01$, Table 3), and some interactions between both emission scenarios were also seen.

The frequency distribution of analysing the annual precipitation for the baseline and the future periods provided some evidence for climate change. During the baseline period (1961-1990), 53% of the years showed annual precipitation to be 200-350 mm (Figure 4), classified as a semiarid climate according to the climatic classification of Rivas-Martínez (1983). The predominance of years with annual precipitation falling within the semiarid climate range (200-350 mm) was maintained during periods 2011-2040 and 2041-2070. However at end of the 21st century, the years with precipitation below 200 mm yr^{-1} will predominate (>62% in both scenarios; Figure 4), which corresponds to an arid climate. These results, along with the expected increase in air temperature, are indicators of climate aridification in the study area at end of the 21st century, which is expected to affect the soil water balance.

4.3. Water balance results for climate change scenarios

Changes in meteorological variables alter the water balance and the partitioning of precipitation between evapotranspiration, surface runoff, and groundwater recharge. In order to establish the effect on water budget a soil water balance has been applied to the future meteorological variables. After applying the HYDROBAL model's water balance (Table 4) to the Ventós-Castellar aquifer, the results show a decreasing in the annual average of all the output water balance variables at the different periods projected, especially with the A2-high scenario. The average recharge during the last period, 2071-2099, will decrease by up 3% during (2011-2040), 8% during (2041-2070) and 17% during the last period (2071-2099) if compared to the baseline period (1961-1990).

It is predicted that the available water volume for groundwater recharge will decrease over the entire 21st century. In the later years of this century, we will observe lower annual precipitation if compared to the baseline period in both scenarios and, consequently, groundwater recharge will diminish (Table 4). By averaging the three selected years per period, the temporal variation analysis of the HYDROBAL model's output variables indicated a significant decrease in water balance components (recharge, actual evapotranspiration, runoff and soil moisture; $p < 0.01$; Table 5) with different amplitudes. We did not find significant differences between scenarios ($p > 0.05$; Table 5). In both scenarios (A2-high and B2-low), a second-grade polynomial equation with a significant fit ($p > 0.05$) showed a temporal decrease in the HYDROBAL model's output variables from the baseline period to the end of this century (Figure 5).

Soil water content and annual rainfall distribution play a key role in the aquifer recharge volume. In the A2 scenario, the year 2058, with less annual precipitation (220 mm), will produce a higher aquifer recharge (47 mm) than the year 2066 (P = 249 mm; R = 36 mm; Figure 6). This result is due to a higher rain event concentration in the spring of 2058 (Figure 6), which will bring about a sustained increase in soil water content and, consequently, in aquifer recharge. However, in 2066, we will observe more separate rain events. Although an increase in soil water content will take place, the increase in aquifer recharge was not observed (Figure 6). We observed a similar result in the B2-low scenario. The year 2098, with 23 mm less of annual precipitation, will produce 10 mm more of aquifer recharge than the year 2033 (Figure 6). The explanation is the same as that indicated for the A2-high scenario.

5. Discussion

The results of the predicted scenarios for precipitation (a decrease in annual precipitation of up to 1.1% per decade) and air temperature (an increase in the mean air temperature of up to 0.4ºC per decade) agree with the Assessment Reports of the Intergovernmental Panel on Climate Change in southern Europe (IPCC, 2007, 2013). Similar results have been confirmed in the Alicante region, SE Spain, where Aguilera and Murillo (2009) estimated a decrease in annual precipitation of up to 1% and an increase in the mean air temperature of up to 0.45ºC per decade for the future 100-year series when compared to the baseline period (1961-1990). Christensen et al. (2007) compared the results of eight Regional Climate Models (RCMs) in basins in south Spanish basins for the same climatic scenarios, A2-high and the B2-low, with the baseline period (1961-1990). In this previous work, the future climate simulated with the HadCM3 model reported similar results, with increases of 0.5ºC in air temperature and slightly higher results for annual precipitation (2% per decade) during the 21st century.

As expected, the results predicted for semiarid regions, which is our case, will be slightly higher than the results predicted for wetter regions. On the Island of Majorca, Candela et al. (2009) used the same GCM, HadCM3, and estimated a less marked decrease in annual precipitation of up to 0.1% per decade, and an increase in the mean air temperature of up to 0.2ºC if compared to the control period 1970-2000. Larger differences were observed if compared to studies done in northern Spain. The estimated data results from the work of Raposo et al. (2013) on the Galicia Coast, NW Spain, used different RCMs to predict a decrease in annual precipitation by up to 0.2% per decade, and an increase in the mean air temperature of up to 0.1ºC during the future 2071-2100 period if compared to the control period of 1961-1990. The works of Candela et al. (2009) and Christensen et al. (2007) found significant differences between scenarios A2-high and B2-low for variable precipitation, but no significant differences in air temperature.

The study area has a high potential vulnerability to climate changes. The changes projected in the precipitation and air temperature regime will significantly influence the average annual recharge of the Ventós-Castellar aquifer. Despite uncertainties we will observe that the change in the percentage of aquifer recharge *vs.* the baseline period (1961-1990) will decrease by up 3% (10 mm) during the period 2011-2040; 8% (24 mm) during the period 2041-2070 and by up 17% (49 mm) during the last period (Table 5). Several previous studies have reported results that came close to the values observed in our study. On the Island of Majorca (Spain), Younger et al. (2002) also estimated the same decrease in mean aquifer recharge of up to 16% during the future 100-year series if compared to the pre-1995 values. By using the HadCM3 projections between 2071-2099 *vs.* the 1961-1990 baseline period in the Almonte-Marismas aquifer (Doñana wetland, SW Spain), Guardiola-Albert and Jackson (2011) indicated that the mean annual recharge rates will decrease by 14%. The same reduction value for scenario A2-high (14%) has been reported by Pulido-Velazquez et al. (2014) in the Serral-Salinas aquifer in Altiplano (Murcia, SE Spain) after applying different RCMs. Other studies carried out in the Iberian Peninsula have shown lower recharge. Candela et al. (2009) investigated the impacts of climate change on groundwater recharge in the Inca-Sa Pobla coastal aquifer (Majorca Island, Spain) for the year 2025. They indicated a 12.5% decrease in natural recharge if compared to 1980-2005, which could be due to differences in the compared periods. On the Galicia Coast, N Spain, Raposo et al. (2013) estimated lower decrease in recharge of up to 9% for the 2071-2100 period if compared to the 1961-1990 one, which is in accordance with the wetter climatic conditions in north Spain. While studying the effect of climate change on the natural groundwater recharge in other karstic aquifers similar to Ventos-Castellar aquifer (Jumilla-Villena, Solana, Serral-Salinas and Peñarrubia) in the province of Alicante, SE Spain, Aguilera and Murillo (2009) applied the ERAS model and observed that the mean annual groundwater recharge values for 1900-2000 decrease significantly of up to 50%. This major difference in the change in the recharge percentage might be due to the fact that these authors adopted a different methodological approach and a distinct baseline period to those used in our study.

These reductions in recharge could affect dependent groundwater supplies. In Alicante province many small towns like Agost only use groundwater resources. Therefore the forecasts of changes in vegetation cover (species distribution and composition), according to Thuiller et al. (2005) and Bakkenes et al. (2006), will give rise to further changes in the soil water balance and aquifer recharge forecasts. It is necessary to devise specific water resources management policies in accordance with future forecasts. Therefore, adaptation measures to climate change in the water resources field for the Ventós-Castellar aquifer are necessary. Planning water resources projects using the principles of precaution, organisation and efficiency will prove most profitable in the future.

The results showed in this study have been obtained from climate data forecasts indicated by the Global Climate Model HadCM3. Although the IPCC have used several methods and models (simple models, multi-models) in order to get solid data on climate change forecasts, still there are uncertainties, and the sources are diverse. At present, some methods are explicitly responsible for major sources of uncertainty such as climate feedbacks, ocean heat uptake, radiative forcing and the carbon cycle (IPCC, 2007). Using disturbances in the atmosphere feedbacks, land carbon cycle, ocean physics and aerosol sulphur cycle processes, Booth et al. (2012) show several studies about variations in the climate change forecasts due to uncertainty in the global climate model HadCM3. The authors indicated that a small minority of simulations resulting from combinations of strong atmospheric feedbacks and carbon cycle responses show temperature increases in excess of 9 degrees. Davy and Esau (2014) indicated the need for a better description of the stably-stratified atmospheric boundary layer in global climate models in order to constrain the current uncertainty in climate variability and projections of climate change in the surface layer. They show that the uncertainties in the depth of the atmospheric boundary layer can explain up to 60% of the difference between the simulated and observed surface air temperature trends and 50% of the difference in temperature variability for the Climate Model Intercomparison Project Phase 5 (CMIP5) ensemble mean. The aerosol indirect effects continue to be a major source of uncertainty in modelling the climate of Earth. Ban-Weiss et al. (2014) indicated that the used sensitivity in some GCMs could be subject to misinterpretation due to the confounding influence of meteorology on both aerosols and clouds. Other uncertainties can be due to climate scenarios; for this, some works had been focused to get consistent climate scenarios, enabling project teams, researchers and academics a best understanding of the climate change forecast (Ricketts et al., 2013). On the other hand, we must also consider the own uncertainties of the hydrological models (McMahon et al., 2015) from database of precipitation and temperature of the GCMs.

6. Conclusions

Process of forecasting climate change and groundwater recharge is highly complex, especially in semiarid region where recharge is reduced and associated to few events per year. In order to continue the advance in this research topic, this study presents a methodological approach for assessing climate change impacts on soil water balance and aquifer recharge. Coupling projected climates based on circulation models and a HYDROBAL hydrologic model, recharge has been estimated on a small karstic aquifer in southern Spain. Three global change models were tested, but HadCM3 model was selected as the most suitable model to assess the impact of climate forecast on the region on A2-high and B2-low scenarios. Mean annual precipitation will decrease in annual precipitation of up to 1.1% per decade. Drought periods will be more frequents along the time for both scenarios (A2-high and B2-low). The analysed data suggest a transition from the semiarid condition during the baseline period (1961-1990; 53% of the years with annual precipitation between 200-350 m) to the arid condition at end of the century (2071-2099; 62% of the years with annual precipitation <200 mm).

Results reveal that during the different periods climate change will have variables impacts on groundwater recharge. Despite uncertainties recharge will be affected (2011-2040 up to 3% and 2041-2070 up to 8%). In the last period (2071-2099), climate change seems have a strong impact and recharge could be seriously reduced if it is compared to the baseline period (1961-1990). This may be attributed to the decrease in mean annual precipitation and the increase in mean air temperature observed during the last period. The results obtained in this work are subjected mainly to uncertainties and the level of confidence in the regional projections.

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FIGURE CAPTIONS

Figure 1. Geographical location and geological setting of the Ventós-Castellar aquifer.

Figure 2. Annual precipitation during the baseline period (1961-1990) and the future period (2011-2099). The HadCM3 model output data for the A2-high (grey bar) and B2-low (black bar) scenarios.

Figure 3. Mean annual (maximum and minimum) temperatures during the baseline period (1961-1990) and the future period (2011-2099). The HadCM3 model output data for the A2-high (grey line) and B2-low (black line) scenarios.

Figure 4. Frequency distribution of annual precipitation for both the baseline period (1961-1990) and the future period (2011-2040, 2041-2070 and 2071-2099) if compared to the A2-high and B2-low scenarios from the HadCM3 model. The climatic classification based on the works of Rivas-Martínez (1983) determines three bioclimatic belts for this region, which range from dry (350-600mm), semiarid (200-350mm) to an arid climate (<200mm).

Figure 5. The temporal evolution tendency of the HYDROBAL model output variables for the future period in both emission scenarios: A2-high (white circle and polynomial regression as a dashed line); B2-low (black circle and polynomial regression as a solid line). The data of the HYDROBAL model output variables in each selected year. Quadratic Polynomial Equation ($y = a+b*x+c*x^2$) and determination coefficient (significant level* $p<0.05$; ** $p<0.01$; *** $p<0.001$).

Figure 6. Temporal variation of daily precipitation, soil moisture and aquifer recharge using the HYDROBAL model for the years analysed, 2047 and 2058 for A2-high and 2060 and 2098 for B2-low (P: precipitation, black bar, R: recharge, dash-dot line and θ: soil moisture, grey solid line).

TABLE

Table 1. Comparison between the observed data from the Agost-Escuela and Novelda meteorological station and the databases for the baseline period for the GCMs. Results of the non-parametric test, multiple pair-wise comparisons of the Kruskal-Wallis test and the *post hoc* Wilcoxon pairs comparison. Mean±standard error. For each climatic variable, the values followed by the same letter are not significantly different at $p < 0.05$.

Table 2. A comparison results of the GCMs for the study period (2011-2099; N=90). Statistical analyses were performed using the Kruskal-Wallis test (XLSTAT©, 2014). Mean±standard error. For each climatic variable, the values followed by the same letter are not significantly different at $p < 0.05$.

Table 3. Precipitation and air temperatures for the study period of the HadCM3 model. General Linear Model univariate results using two factors: periods (1961-1990, 2011-2040, 2041-2070 and 2071-2099) and emission scenarios (A2-high and B2-low). Mean ± standard error; $N_{period} = 30$, $N_{scenario} = 30$; Tukey's HSD *post hoc* test.

Table 4. The water balance results for climate change in the A2-high and B2-low scenarios from HadCM3 between the baseline period and future years.

Table 5. The water balance results. General Linear Model univariate results using two factors: (1) period: considering one average year per decade (3 years/period/scenario) during each periods (1961-1990, 2011-2040, 2041-2070 and 2071-2099) and (2) scenarios (A2-high and B2-low). Mean ± standard error; N=3; Tukey's HSD *post hoc* test.

Table 1. Comparison between the observed data from the Agost-Escuela and Novelda meteorological station and the databases for the baseline period for the GCMs. Results of the non-parametric test, multiple pair-wise comparisons of the Kruskal-Wallis test and the *post hoc* Wilcoxon pairs comparison. Mean±standard error. For each climatic variable, the values followed by the same letter are not significantly different at $p < 0.05$.

Variables	Observed data	Global Climate Models (GCMs)			p-values
		HadCM3	ECHAM4	CGCM2	
P (mm)	302.6 ± 32.3a	303.7 ± 26.5a	236.7 ± 20.3ab	165.9 ± 11.9b	<0.001
max Tª (ºC)	23.06 ± 0.33a	23.45 ± 0.17a	24.05 ± 0.14b	22.14 ± 0.17c	<0.001
min Tª (ºC)	11.44 ± 0.40a	11.73 ± 0.18a	11.98 ± 0.10a	10.54 ± 0.14b	<0.001

[P] Precipitation between the years 1976-1990 (N=15).
[max Tª] maximum temperature between 1980-1990 (N=11).
[min Tª] minimum temperature between 1980-1990 (N=11).

Table 2. A comparison results of the GCMs for the study period (2011-2099; N=90). Statistical analyses were performed using the Kruskal-Wallis test (XLSTAT©, 2014). Mean±standard error. For each climatic variable, the values followed by the same letter are not significantly different at $p < 0.05$.

Variables	Global Climate Models (GCMs)			p-values
	HadCM3	ECHAM4	CGCM2	
A2-high scenario				
P (mm)	246.40 ± 9.17[a]	231.17±5.77[a]	180.55±3.88[b]	<0.001
max T[a] (ºC)	25.35 ± 0.18[b]	26.02±0.16[a]	24.11±0.15[c]	<0.001
min T[a] (ºC)	13.53 ± 0.18[a]	13.67±0.13[a]	12.17±0.12[b]	<0.001
B2-low scenario				
P (mm)	246.94 ± 10.51[a]	227.08 ± 6.39[a]	166.59±4.12[b]	<0.001
max T[a] (ºC)	25.05 ± 0.13[b]	25.79 ± 0.13[a]	23.73±0.11[c]	<0.001
min T[a] (ºC)	13.24 ± 0.13[a]	13.51 ± 0.11[a]	11.82±0.09[b]	<0.001

[P] Precipitation.
[max Tª] maximum temperature.
[min Tª] minimum temperature.

Table 3. Precipitation and air temperatures for the study period of the HadCM3 model. General Linear Model univariate results using two factors: periods (1961-1990, 2011-2040, 2041-2070 and 2071-2099) and emission scenarios (A2-high and B2-low). Mean ± standard error; $N_{period} = 30$, $N_{scenario} = 30$; Tukey's HSD *post hoc* test.

	Period factor				Scenario factor		Main effects and interactions		
	1961-1990	2011-2040	2041-2070	2071-2099	A2-high	B2-low	Period	Scenario	Period x scenario
P (mm)	273.58 ± 5.82a	270.81 ± 6.90a	258.10 ± 6.64ab	240.26 ± 7.54b	261.21 ± 4.67	260.51 ± 4.95	0.002**	0.912 ns	0.940 ns
max Tª (ºC)	21.39 ± 0.11d	22.74 ± 0.11c	24.04 ± 0.11b	25.79 ± 0.12a	23.63 ± 0.13	23.31 ± 0.10	<0.001***	0.002**	<0.001***
min Tª (ºC)	10.25 ± 0.12d	11.59 ± 0.11c	12.71 ± 0.12b	14.23 ± 0.13a	12.33 ± 0.12	12.03 ± 0.10	<0.001***	0.009**	<0.001***

[P] Precipitation.
[max Tª] maximum temperature.
[min Tª] minimum temperature.
[a-d] Values followed by the same letter are not significantly different at $p < 0.05$.
[***] $p < 0.001$
[**] $p < 0.01$
[ns] not significant.

Table 4. The water balance results for climate change in the A2-high and B2-low scenarios from HadCM3 between the baseline period and future years.

	Baseline period			A2-high scenario								
	1970	1971	1990	2020	2023	2031	2047	2058	2066	2078	2084	2096
P (mm)	279	297	303	323	274	200	273	220	249	246	167	141
Et_a(mm)	178	212	201	190	170	172	165	197	175.7	193.6	151	127
R (mm)	73	72	76	97	73	41	78	47	36	37	22	11
R_{off} (mm)	4.0	5.2	5.0	5.3	4.6	3.8	3.7	4.6	4.0	4.0	3.3	2.2
θ (%)	13.8	14.5	13.6	14.2	14	13.9	13.3	14.2	13.5	13.5	13	12.4
	Baseline period			**B2-low scenario**								
	1970	1971	1990	2017	2021	2033	2050	2060	2068	2077	2087	2098
P (mm)	279	297	303	285	269	201	222	259	216	193	167	178
Et_a(mm)	178	212	201	160	181	152	172	167	141	159	134	131
R (mm)	73	72	76	83	61	26	38	59	40	25	20	36
R_{off} (mm)	4.0	5.2	5.0	4.2	4.1	3.2	3.6	4.1	2.8	3.2	2.5	2.9
θ (%)	13.8	14.5	13.6	13.8	14.1	13.4	13.6	13.6	12.6	13.3	12.9	12.8

^{P} precipitation.
^{Roff} runoff.
^{Eta} actual evapotranspiration.
^{R} groundwater recharge.
$^{\theta}$ Soil moisture.

Table 5. The water balance results. General Linear Model univariate results using two factors: (1) period: considering one average year per decade (3 years/period/scenario) during each periods (1961-1990, 2011-2040, 2041-2070 and 2071-2099) and (2) scenarios (A2-high and B2-low). Mean ± standard error; N=3; Tukey's HSD *post hoc* test.

	Period factor				Scenario factor		Main effects and interactions		
	1961-1990	2011-2040	2041-2070	2071-2099	A2-high	B2-low	Period	Scenario	Period x Scenario
P (mm)	293.00 ± 4.56a	258.66 ± 19.95a	239.83 ± 9.71ab	182.00 ± 14.56b	247.66 ±16.15	239.08 ±13.97	<0.001	0.571	0.981
Et_a (mm)	197.14 ± 6.49a	170.72 ± 5.49ab	169.73 ± 7.40ab	149.26 ± 10.23b	177.68 ± 6.79	165.75 ± 7.25	<0.002	0.149	0.754
R (mm)	73.42 ± 0.83a	63.76 ± 10.90a	49.54 ± 6.64ab	24.93 ± 3.98b	55.11 ± 7.65	50.71 ± 6.48	<0.005	0.144	0.829
R_{off} (mm)	4.75 ± 0.24a	4.20 ± 0.29a	3.80 ± 0.25ab	3.01 ± 0.26b	4.14 ± 0.26	3.74 ± 0.25	<0.001	0.550	0.826
θ (%)	13.94 ± 0.17a	13.91± 0.11a	13.47 ± 0.21ab	12.98 ± 0.16b	13.66 ± 0.17	13.49 ± 0.15	<0.005	0.366	0.789

[P] precipitation.
[Roff] runoff.
[Eta] actual evapotranspiration.
[R] groundwater recharge.
[θ] Soil moisture.
[a-b] the values followed by the same letters within rows do not differ significantly at p = 0.05.

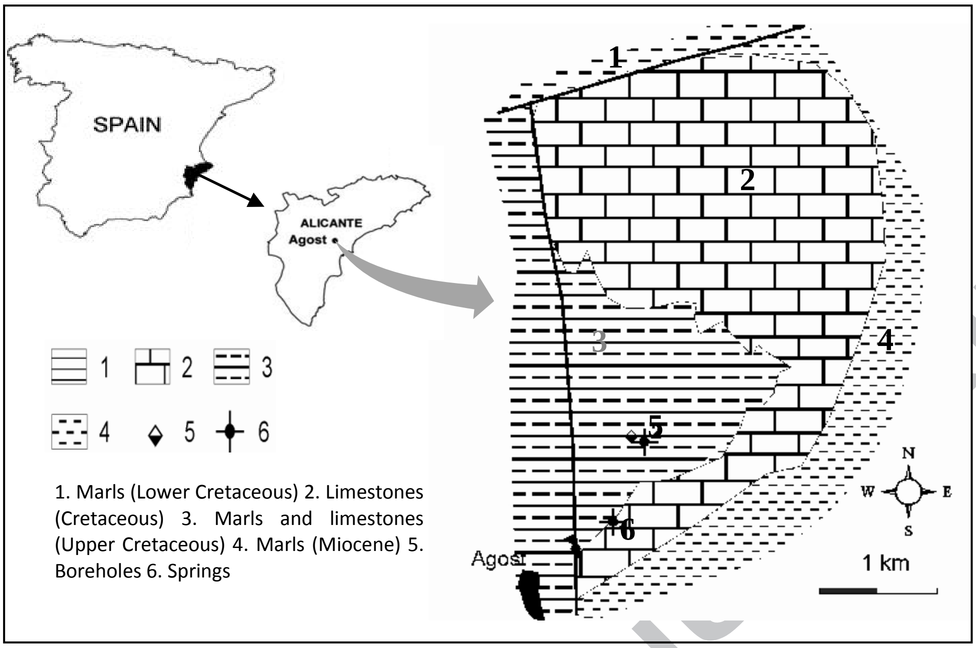

Fig. 1. Geographical location and geological setting of the Ventós-Castellar aquifer.

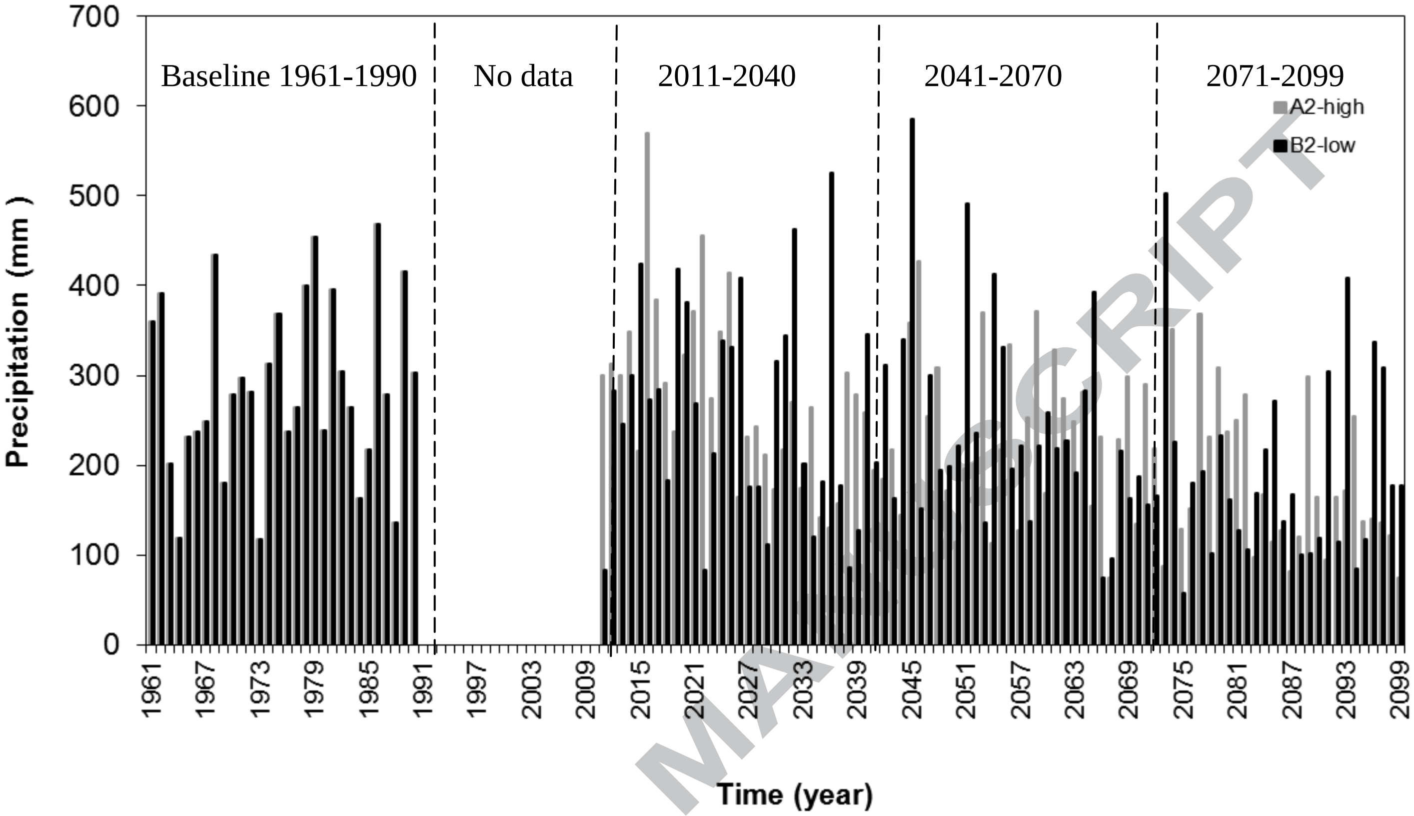

Fig. 2. Annual precipitation during the baseline period (1961-1990) and the future period (2011-2099). The HadCM3 model output data for the A2-high (grey bar) and B2-low (black bar) scenarios.

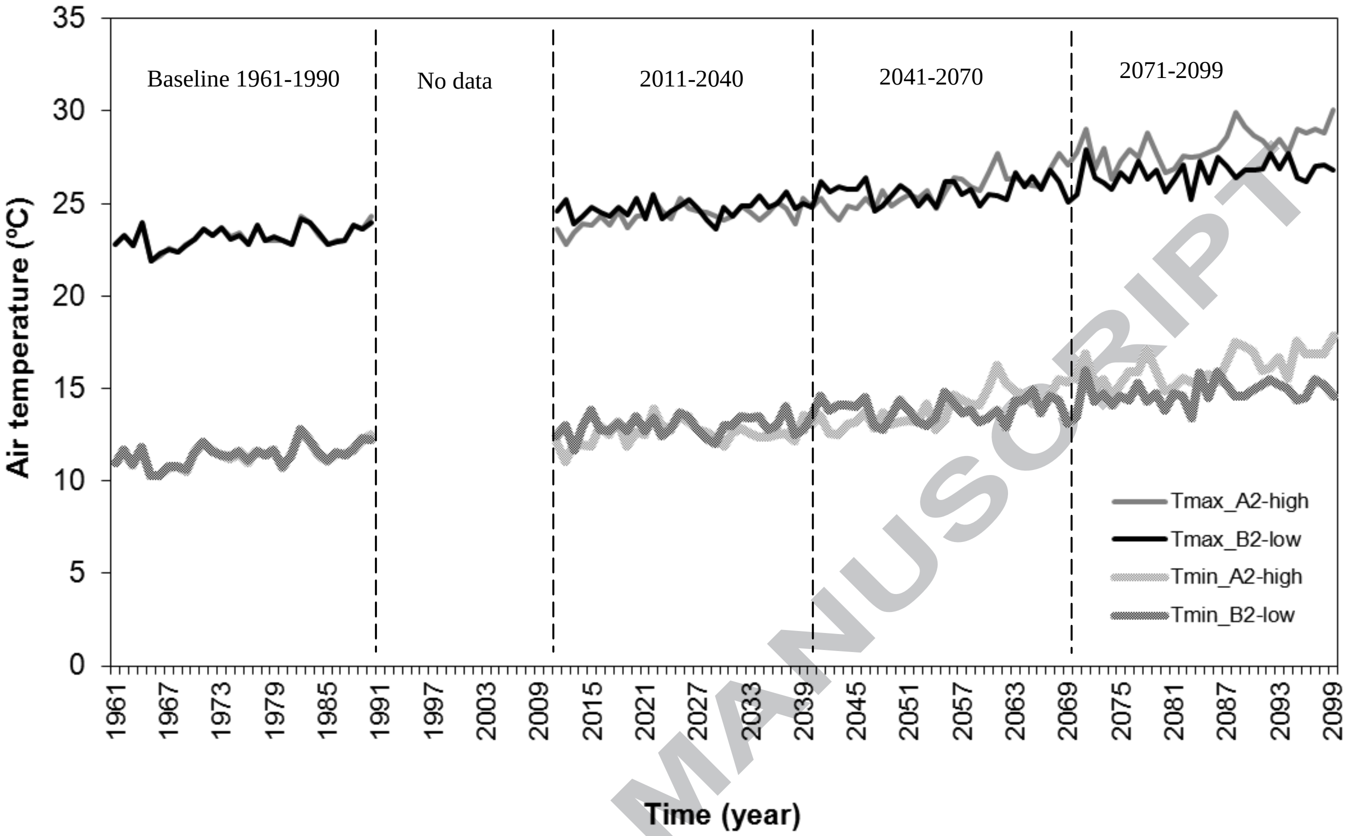

Fig. 3. Mean annual (maximum and minimum) temperatures during the baseline period (1961-1990) and the future period (2011-2099). The HadCM3 model output data for the A2-high (grey line) and B2-low (black line) scenarios.

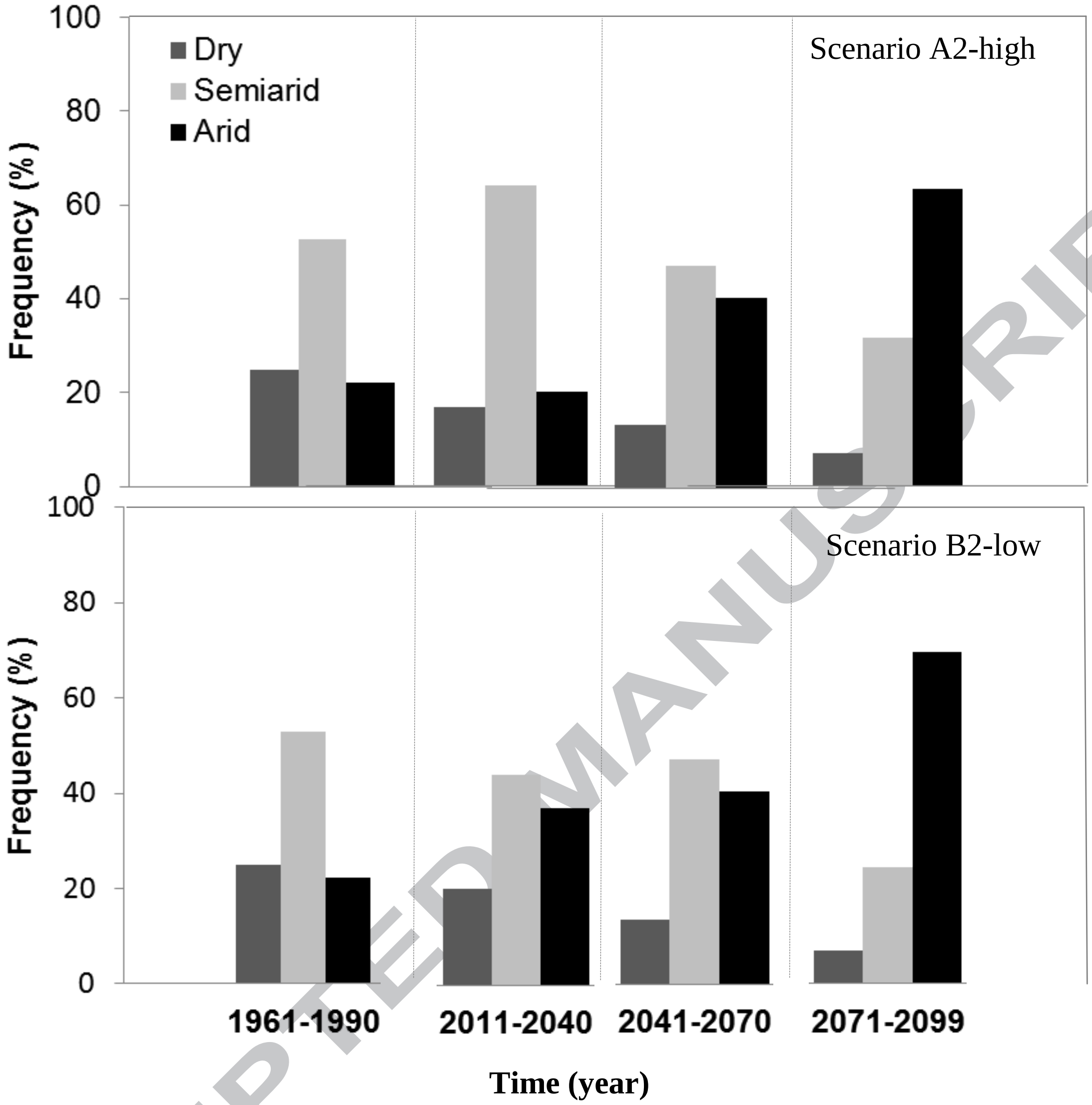

Fig. 4. Frequency distribution of annual precipitation for both the baseline period (1961-1990) and the future period (2011-2040, 2041-2070 and 2071-2099) if compared to the A2-high and B2-low scenarios from the HadCM3 model. The climatic classification based on the works of Rivas-Martínez (1983) determines three bioclimatic belts for this region, which range from dry (350-600mm), semiarid (200-350mm) to an arid climate (<200mm).

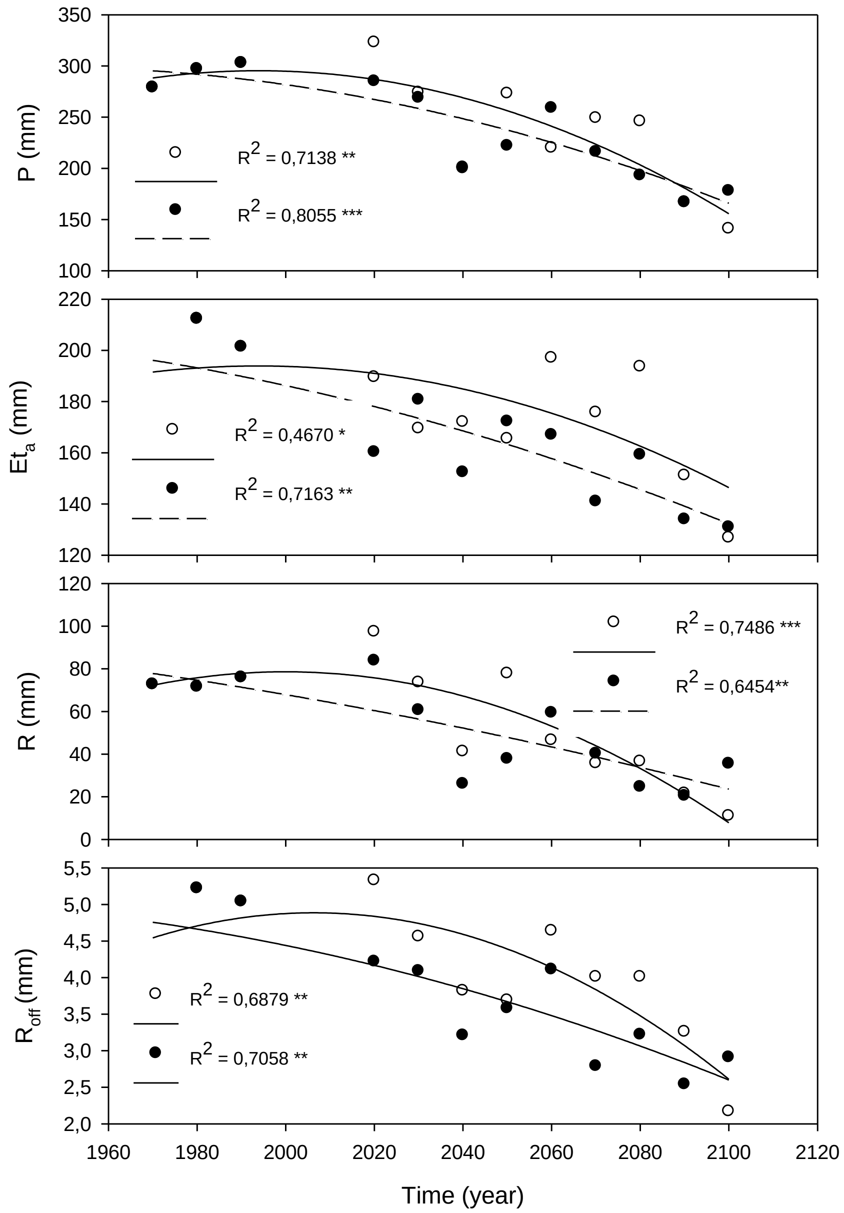

Fig. 5. The temporal evolution tendency of the HYDROBAL model output variables for the future period in both emission scenarios: A2-high (white circle and polynomial regression as a dashed line); B2-low (black circle and polynomial regression as a solid line). The data of the HYDROBAL model output variables in each selected year. Quadratic Polynomial Equation ($y = a+b*x+c*x^2$) and determination coefficient (significant level* $p<0.05$; ** $p<0.01$; *** $p<0.001$).

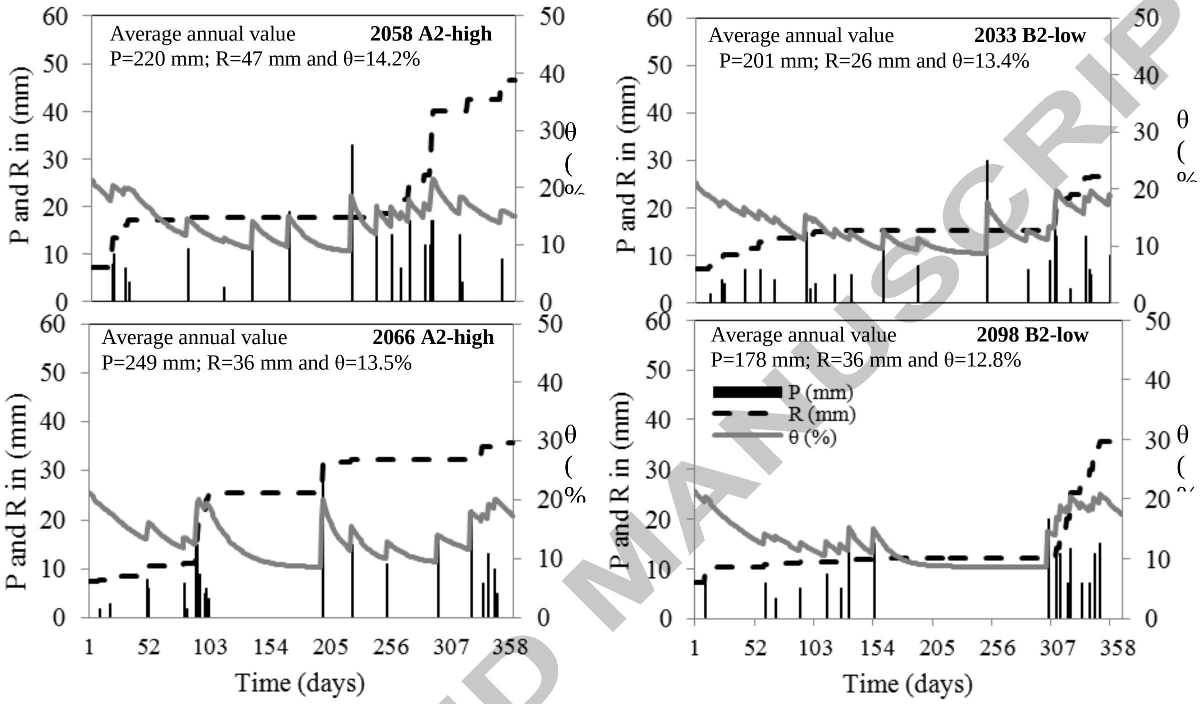

Fig. 6. Temporal variation of daily precipitation, soil moisture and aquifer recharge using the HYDROBAL model for the years analysed, 2047 and 2058 for A2-high and 2060 and 2098 for B2-low (P: precipitation, black bar, R: recharge, dash-dot line and θ: soil moisture, grey solid line).

Highlights

- Research analyses impact of climate change on the soil water balance and recharge
- Three GCM's were tested. HadCM3 model was selected as the most suitable model
- Change in precipitation and temperature will influence the average annual recharge
- HYDROBAL model showed that climate change have a significant impact on recharge