



Observed and projected changes on aquifer recharge in a Mediterranean semi-arid area, SE Spain

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Abstract

Groundwater is the major water source in arid and semi-arid regions and its availability under future climatic scenarios is uncertain. In this context, the knowledge of the likely changes in aquifer recharge is very important for sustainable management of groundwater resources in these environments. This work assesses the effect of future potential changes in the climate variables on aquifer recharge in a Mediterranean semi-arid aquifer (Sierra de Las Aguilas (SAG), SE Spain). We used monthly piezometric data to validate the aquifer recharge simulated by HYDROBAL ecohydrological model over the period 2001–2016. This model was then used to simulate the aquifer recharge over the historical period 1971–2000 and over two projected periods (2039–2068 and 2069–2098) using 18 downscaled climate projections. The results show that the percentage of aquifer recharge to precipitation (PAR) decreased significantly over the historical period ($-0.3\% \text{ year}^{-1}$, $p < 0.05$). This decreasing tendency is expected to continue in the same direction with similar reduction rate ($-0.4\% \text{ year}^{-1}$, $p < 0.001$) under the moderate RCP4.5 climate scenario and with a higher rate ($-0.6\% \text{ year}^{-1}$, $p < 0.001$) under the high RCP8.5 scenario. These changes, due principally to the reduction of precipitations, will inverse the recuperation trend observed in the water level. Actually, the current water pumping from the SAG aquifer represents 10% of precipitation below the observed PAR (15.1%). However, in the future, the PAR is expected to decrease below the 10% threshold under the two RCP scenarios for the medium- and long-term periods.

Keywords Aquifer recharge · Climate change · Semi-arid area · SE Spain · HYDROBAL

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Introduction

In arid and semi-arid regions, groundwater resources are considered as the main source of freshwater. In some cases, even they can acquire the value of the strategic resource. There are many examples of arid and semi-arid regions

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around the world, and particularly in the Mediterranean area, that have improved their economies based on the use of groundwater (Ibañez et al. 2008; Siebert et al. 2010; Wada et al. 2012; Werner et al. 2013; Famiglietti 2014; Llamas et al. 2015; Rupérez-Moreno et al. 2017). However, in the context of climate change, the environmental sustainability of these socioeconomic systems was being questioned due to the pressure put on groundwater resources. According to the Intergovernmental Panel on Climate Change (IPCC), there is strong consistency in the projections regarding groundwater resources around the Mediterranean region showing a clear future reduction (Jiménez Cisneros et al. 2014).

Most of the global climate models (GCM) forecast a reduction in precipitation and an increase in temperature by the end of the 21st century for the Mediterranean region including the SE Spain (Milly et al. 2005; van der Linden and Mitchell 2009; Ferrer et al. 2012; IPCC 2014). Furthermore, the frequency and length of the wet periods have decreased in the last decades in the southern regions of Europe (Polemio and Casarano 2004; Schär et al. 2004; Good et al. 2006), and the drought period has increased by around 20% in the same regions (Hiscock et al. 2012). These conditions are altering the hydrological systems, affecting the availability of water resources in terms of quantity and quality but also in terms of sustainability and management (Andreu et al. 2008; Custodio et al. 2016).

During the last years, increasing efforts have been made to study the impact of the climate change on water resources with special focus on the impact on groundwater (Green et al. 2011; Kløve et al. 2014; Pulido-Velázquez et al. 2015). These studies are particularly relevant in areas, where water availability is a limiting factor and that are highly dependent on groundwater, as it is the case of the semi-arid areas of the extreme western Mediterranean. In these environments, carbonate aquifers water resources are crucial to meet the water demand peaks during the frequent drought periods of the Mediterranean region (Martos-Rosillo et al. 2015). Thanks to their relatively higher recharge rates, with a comparison to another type of aquifers, to its good water quality and their storage capacity, carbonate aquifers are considered as strategic reservoir systems (Martos-Rosillo et al. 2015; Hartmann et al. 2017).

Groundwater recharge is a complex process and it is considered as one of the water balance components most difficult to estimate. In arid and semi-arid regions, because of the limited recharge component, different variables have to be involved in the groundwater recharge estimation (Zagana et al. 2007). In these environments, aquifer recharge is significantly affected by climate variability and land use changes (Scanlon et al. 2006). In the literature, there are several methods to estimate the aquifer recharge. Soil water balance models provide a methodology to quantify the water that percolates through the soil to the water table and are

widely used methods (Touhami et al. 2014). Data requirements for this type of models are relatively simple and provide reasonable results under most hydrogeological conditions (Touhami et al. 2014). These models can make use of the downscaled climate scenarios data from different GCMs to evaluate potential climate change effects on groundwater resources on the local scale. Different kinds of biases in relation to the observed climate are comprised in the model outputs due to the limited ability of the GCMs to simulate Earth's climate system (Räty et al. 2014). Hence, the use of different climate model simulations should be considered to reduce the modelling uncertainty (Collados-Lara et al. 2018).

The aim of this work is to assess the effects of future potential climate change scenarios on aquifer recharge in a Mediterranean semi-arid area in the SE Spain. To this end, we used daily precipitation and temperature data over the period 1971–2017, to simulate the aquifer recharge using the HYDROBAL ecohydrological model. Monthly water level time series were used to validate the estimated aquifer recharge. Projected data based on 18 downscaled climate projections over the period 2017–2099 from nine Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models and two climate scenarios were used to analyze the future trends.

Study area

The Sierra de Las Aguilas (SAG) aquifer is located in the central part of Alicante province in the south of Spain (Fig. 1). This small carbonate aquifer with an area of 5 km² includes two reliefs or blocks: San Pascual (250 m a.s.l.) and Aguilas (550 m a.s.l.), both unified by small low area. The piezometric differences between eastern and western parts of the aquifer show that there is a clear hydraulic disconnection between both (Andreu et al. 2019). For this reason and for the availability of good piezometric data in the sector of Aguilas, we focus our work on this sector, which cover an area of 2.5 km². The climate of the region is semi-arid Mediterranean, where precipitation is below 300 mm and average temperatures of 17.3 °C. Pine forests, shrubland, and alpha grass represent the natural vegetation on the surface of this area.

Geological and hydrogeological setting

From the geological point of view, the area in which is located this aquifer belongs to the Prebetic domain of the External Zone of the Betic Cordillera. The Sierra de Las Aguilas relief is formed mainly by a series of Cretaceous and tertiary terrains (Fig. 1). Synthetically, the series

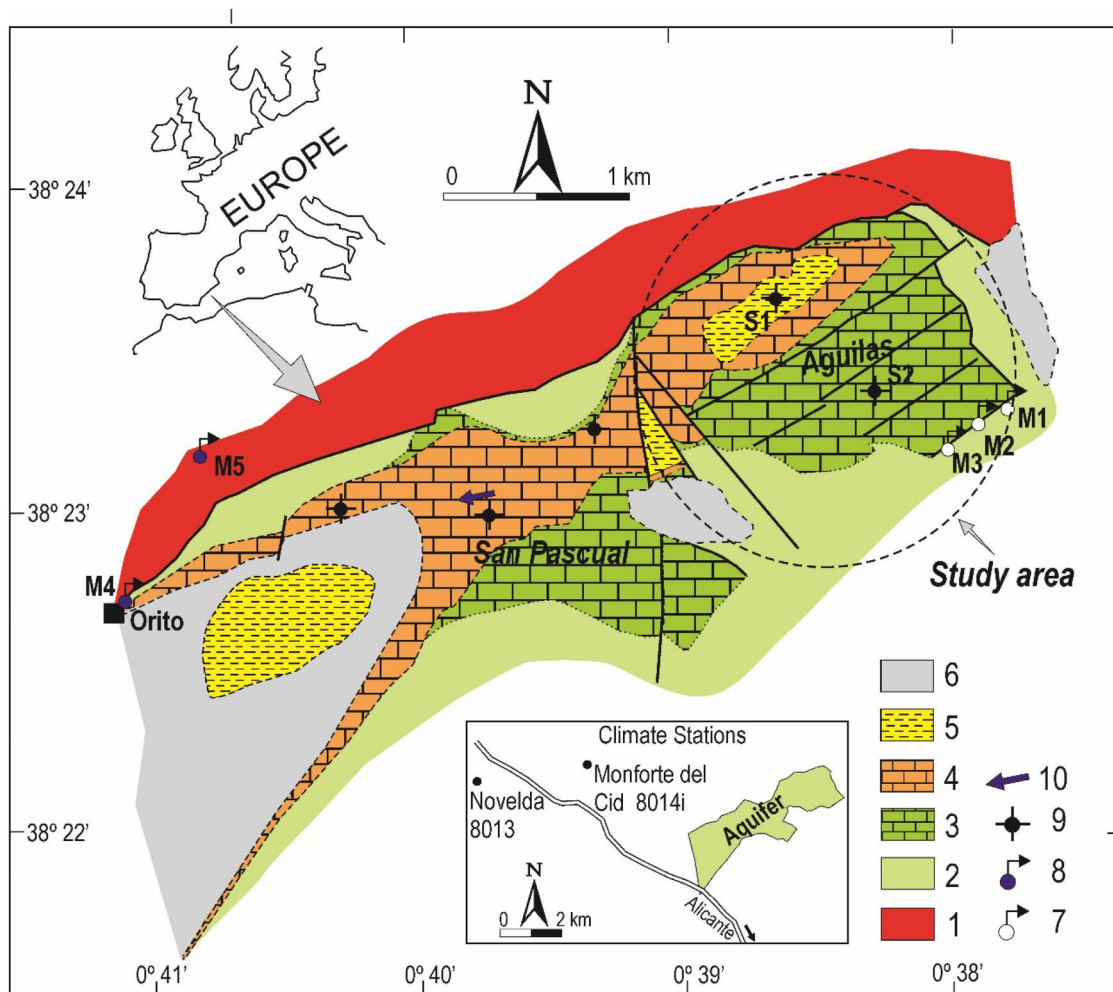


Fig. 1 Geographical and hydrogeological setting of Las Aguilas aquifer. (1) Clay and gypsum (Triassic). (2) Marls (Lower Cretaceous); (3) limestones and marly limestones (Albian-Cenomanian); (4) bioclastic calcarenites to conglomerate (Miocene). (5) Marls (Miocene);

(6) recent terrains; (7) dried springs; (8) springs; (9) wells; (10) flow direction. S1 and S2 are the two observation wells used in this work. Novelda and Monforte del Cid are the used meteorological stations

begin with marls from Lower Cretaceous followed by a set of 250 m thick of limestone and marly limestone (Albian-Cenomanian). These lithological formations are outcropping in most parts of the relief. Above these deposits lie discordant 50 m of a sequence of bioclastic calcarenites with lateral changes to conglomerate from the Miocene. The series continues with a sequence of white marls from Miocene, which only outcrops in the most depressed parts of the relief. Sierra de Las Aguilas is bordered by marls from Lower Cretaceous and Triassic clays and gypsum.

The general structure of the area corresponds to a syncline running approximately SW–NE whose axis sunk towards the SW. This syncline is more open toward the southeast than the northwest. The effects of intense tectonic activity also have provoked numerous fractures. These fractures cutting across the relief and divide it into distinct blocks. Some of these faults have been responsible

for leaving to lower altitude the central part of the Sierra de Las Aguilas.

Of the formations present within the study area Cretaceous limestones, Miocene calcarenites and conglomerates behave as an aquifer and between them constitute the SAG aquifer. The impervious bottom is constituted by a thickness series of Albian marls. These deposits and Triassic terrains located in the north of the area define the geometry and isolate the aquifer from others of this region. This aquifer was defined as a unity, where the principal recharge comes from direct infiltration of the precipitation over permeable rocks. Its discharge took place mainly by different springs located in the southern slopes of the Aguilas relief and others situated nearby the Orito town.

It was between the end of the 70s and the beginning of the 80s when the aquifer began to be exploited intensively, which caused declines of more than 100 m in some points,

causing the depletion of springs in the sector of the Aguilas. Over time, this situation of overexploitation also caused the abandonment of most of the pumping wells. In the current situation, only a few active points remain. The annual average withdrawals do not exceed 50,000 m³/year (Fig. S1). This has caused an increase in water level of about 30 m during the period 2001–2016 in the western part of the aquifer (Fig. 2).

Data and methods

Climate data

Daily maximum and minimum air temperatures and rainfall data from two nearest meteorological stations (Novelda: 38.37° N; 0.72° W and Monforte Del Cid: 38.38° N; 0.77° W), provided by the Spanish Meteorological Agency, (AEMET), were used. The reconstruction and homogenization of this climate the time series were performed in a previous work over the period 1953–2012 (Moutahir 2016) and they were completed until 2017 for this work.

For the future analysis, we used 18 projected climate data sets. Climate simulations from nine models of Coupled Model Intercomparison Project Phase 5 (CMIP5; Table S1) downscaled to the two used meteorological observatories for the period 2010–2099 under two future climate projections corresponding to the Representative Concentration Pathways RCP4.5 (stable scenario) and RCP8.5 (more increasing scenario) (Table S2). The projected climate data were downscaled by the Foundation for Climate Research (FIC) as described in Ribalaygua et al. (2013) and in Monjo et al. (2016). The downscaling was performed using a two-step analogue/regression statistical method (Ribalaygua et al.

2013). In the first step, the *n* most similar days to the problem day are selected using an analogue stratification (Zorita and Von Storch 1999). Large-scale wind fields (speed and direction of the geostrophic wind at 1000 hPa and 500 hPa) were used as predictors to measure the similarity between the 2 days using a weighted Euclidean distance. In the second step, a nonlinear transfer function is applied between the analogous rainfalls and the rainfall of each problem day according to probability distribution of each problem month (Ribalaygua et al. 2013; Monjo et al. 2016).

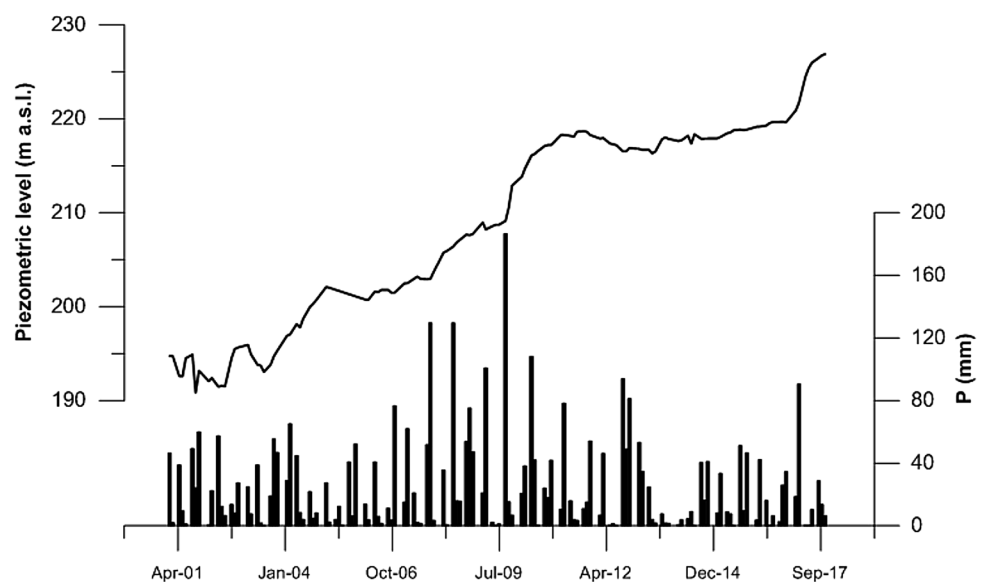
A monthly adiabatic lapse rate estimated in a previous work (Moutahir 2016) and the mean altitude of the study area were used to correct the air temperature time series. This corrected air temperature time series and solar radiation were then used to calculate the potential evapotranspiration (PET) according to Hargreaves and Samani (1982) method.

Vegetation structure and soil parameters

An update of the cartography of land cover in the aquifer recharge area was elaborated using the Land Cover and Use Information System of Spain (SIOSE 2011) maps. Based on photo interpretation and using 2 ha as a minimum surface unit for forest and natural areas, the SIOSE divides the territory in a set of closed homogeneous polygons well described associating one or more covers and attributes to each polygon. The aquifer recharge area is mainly covered by natural vegetation that we grouped in three main types: shrubland (32%) which a mixture of different shrubs species, pine (10%) represented by Aleppo pine (*Pinus halepensis* Miller) and steppes (58%) mainly dominated by alpha grass.

The spatial and vertical structure of vegetation inside each type of vegetation is very important because of its role on rainfall partitioning. An inventory of all plant

Fig. 2 Evolution of the piezometric and precipitation records in the SAG aquifer over the study period



species and their covers was carried out in three 100 m² subplots inside the shrubland (Ruiz-Yanetti 2017) and three subplots in the pine (Manrique-Alba et al. 2017) types. This inventory served to establish the spatial and vertical structure of vegetation (Table 1). The structure of the steppes has been assumed to be similar to the steppes Sierra del Ventós (Ramírez 2006) located 10 km away from the study area. Within the different types, different combinations representing the vertical structure of vegetation in the study area have been established (Table 1). Physical properties of the soil for each vegetation type in the study area were determined from previous works (Manrique-Alba et al. 2017; Ruiz-Yanetti 2017; Touhami et al. 2013). At each subplot, continuous measuring with eight soil moisture sensors per subplot was used to monitor soil water content (SWC) (cm³ cm⁻³) from 0 to 30 cm of soil depth using during three hydrological years from 2012 to 2015 (Manrique-Alba et al. 2017; Ruiz-Yanetti, 2017).

Piezometric and groundwater pumping data

Monthly piezometric and groundwater pumping data recorded over the period 2001–2016 in two observational points located in Las Aguilas block is used (Fig. 1). In the period 2001–2011, water level was measured manually once or twice a month. Since 2012, thanks to the installation of automated piezometers, daily data are available. These data were used: (a) to assess the evolution of the water level in the aquifer over the study period and (b) to calibrate and validate the HYDROBAL model used in this study. The water pumping data were provided by “*Aguas Municipalizadas de Alicante*” which manages and supplies water in the region of Alicante and controls the pumping wells in the SAG aquifer. The water extracted from SAG aquifer is mainly used for water supply.

Table 1 Different combinations representing the vertical structure of vegetation in the study area and its covers (%)

	Pine	Shrubland	Steppes
Pine	11.9	–	–
Pine + shrubs	3.3	–	–
Pine + shrubs + grass	6.7	–	–
Pine + steppe	2.9	–	–
Pine + grass	35.7	–	–
Shrubs	5.7	23.3	15.0
Shrubs + grass	5.2	23.3	–
Steppe	0.5	–	57.6
Grass	17.1	22.4	1.8
Bare soil	11.0	31.0	25.6

HYDROBAL model

HYDROBAL is an ecohydrological model that integrates meteorological conditions (precipitation, temperature, and potential evapotranspiration), vegetation characteristics (spatial distribution and vertical structure) and soil properties (porosity, soil depth, field capacity, and wilting point) to simulate a daily soil–water balance at plot level in ecosystems dominated by different vegetation types (Bellot et al. 2001; Bellot and Chirino 2013). HYDROBAL simulates the daily dynamic of the main water flows involved in the water balance including the aquifer recharge. This last one is estimated as the sum of the direct percolation of some infiltration water percolating downwards before the field capacity is reached (Samper 1997) and the slow infiltration that occurs when soil moisture exceeds the field capacity. A detailed description of HYDROBAL can be found in Bellot and Chirino (2013) and Moutahir (2016). Good results were obtained when applying HYDROBAL in different studies to simulate the effect of vegetation types, rainfall distribution and climate changes on the soil water balance and aquifer recharge (Bellot et al. 2001; Bellot and Chirino 2013; Touhami et al. 2013, 2014, 2015; Moutahir 2016).

HYDROBAL calibration and validation

HYDROBAL uses an evaporative coefficient (k factor) to express the transpiration rate capacity characteristic of each vegetation type (Bellot and Chirino 2013). A daily k factor value is calculated as a function of the soil water availability and takes values between a minimum and a maximum value (k_{\min} and k_{\max}). The calibration of the model lies in searching k_{\min} and k_{\max} values for each vegetation type. To do this, a randomly set of k_{\min} and k_{\max} values is selected to run HYDROBAL multiple times by means of Monte-carlo simulations. The objective function to minimize is the root mean square error (RMSE) between the simulated and observed soil water content (SWC). HYDROBAL was calibrated in previous works for the study area (Moutahir 2016; Manrique-Alba et al. 2017) using measured SWC of two hydrological years between 2012 and 2014. SWC data from a third hydrological years 2014–2015 were used to validate the model which performance was evaluated using the Nash–Sutcliffe model efficiency (NSE) coefficient (Nash and Sutcliffe 1970).

Aquifer recharge validation

To validate the estimated aquifer recharge and to evaluate the HYDROBAL model performance, we compared the observed piezometric level with the simulated one over the periods 2001–2016. However, HYDROBAL does not deal directly with the water table. Therefore, we first needed to

convert the deep drainage in water-level fluctuations. The relationship between water-level fluctuations and water volume is described by

$$\Delta h = V/A, \quad (1)$$

where Δh is the water-level fluctuation, V is the water volume of the deep drainage and A is the effective area. Considering the aquifer as a tank, the effective area is described as the effective area of the tank and is physically equivalent to the product of the average specific yield and surface area of the tank (Barrett and Charbeneau 1997) which changes with the elevation.

From the observed data, we get the total water level fluctuation (Δh_o) over the study period 2001–2016 (the water level h_o in the last year minus h_o in the first year). Considering this Δh_o and the total water input (V_o) to the aquifer and using the Eq. (1), we can estimate the average effective area \bar{A} as the following equation:

$$\bar{A} = V_o/\Delta h_o. \quad (2)$$

The total water input (V_o) to the aquifer is estimated as the total aquifer recharge from precipitation (P) minus the total pumped water over the period 2001–2016. The total aquifer recharge can be estimated as a ratio to the total precipitation (R_{ratio}) over the study period. Therefore, the average effective area can be estimated according to the following equation:

$$\bar{A} = R_{\text{ratio}} \times P/\Delta h_o. \quad (3)$$

The selection of the average ratio of aquifer recharge to precipitation (R_{ratio}) is supported by a sensitivity analysis in which this ratio was varied from 0.1 to 0.25 by increments of 0.005. Each R_{ratio} allows us to calculate an average effective area, which was used to estimate the annual water-level fluctuations using the annual precipitation and pumping data. These estimated annual level fluctuations were compared to the annual observed fluctuations. The objective function to minimize in this analysis is the mean-squared error (MSE) between observed and estimated annual water-level fluctuations.

The best \bar{A} corresponding to the best R_{ratio} , that minimizes the MSE between observed and estimated annual water-level fluctuations, was used to convert the deep drainage simulated by HYDROBAL to water fluctuations. The simulated water fluctuations were compared to the measured fluctuations using the Nash–Sutcliffe model efficiency (NSE) coefficient.

Data analysis

We analyzed the trends and changes in the mean to assess the likely effects of climate change on aquifer recharge in our study area. We first start by analyzing the observed changes over the study period 2001–2016. Then, we compared this

period to the historical 30-year period 1971–2000. This historical period is used as a reference period for the evaluation of the potential changes over two projected periods: medium-term period 2039–2068 and the long-term period 2069–2098. To derive the magnitude of the trends, we used the least squares regression method, while we used the non-parametric Mann–Kendall (MK) test (Mann 1945; Kendall 1975) to determine their statistical significance. MK test is widely used in detecting monotonic trends hydrometeorological time series (Yue and Pilon 2004). Finally, we used t test method to analyze the changes in the mean with respect to the reference period. All these analyses were performed using R Statistical Software (R Core Team 2017).

To reduce the noise introduced by the delayed water level responses to the precipitations of the last month of the previous year, we used the hydrological year from September to August, given that precipitations in August are scarce in our region. This was used only for validation of the aquifer recharge simulated by HYDROBAL. For the rest of the analysis, we used the hydrological year from October to September.

Results and discussion

Validation of the aquifer recharge: HYDROBAL performance

According to the sensitivity analysis, the minimum MSE between the observed and the estimated annual water-level fluctuations, using the estimated average effective area \bar{A} and Eq. (3), were obtained with R_{ratios} ranging from 0.135 to 0.155 (MSE = 1.3, Fig. 3a). This step of the analysis is done independently of the use of HYDROBAL. Here, we only used the measured data to estimate an average effective area \bar{A} .

We used the average effective area estimated using the best R_{ratios} and Eq. (3) to convert the annual deep drainage simulated by HYDROBAL to water-level fluctuations. These simulated annual water fluctuations were accumulated to the water level observed in September 2001, considered as the base point, to be compared to the observed water-level evolution over the period 2001–2016. All R_{ratios} in the range 0.135–0.155 gave good results; however, the best fit was obtained with the average effective area estimated using R_{ratio} equal to 0.155 (NSE = 0.78, Fig. 3b). This R_{ratio} is comparable to the simulated one by HYDROBAL. Indeed, the ratio of aquifer recharge to the precipitation simulated by HYDROBAL during the period 2001–2016 ranged between 0 and 0.23 with an average value of 0.151.

The chosen aquifer recharge ratio to precipitation is much higher than those reported by Scanlon et al. (2006) in the global synthesis of groundwater recharge in semi-arid and

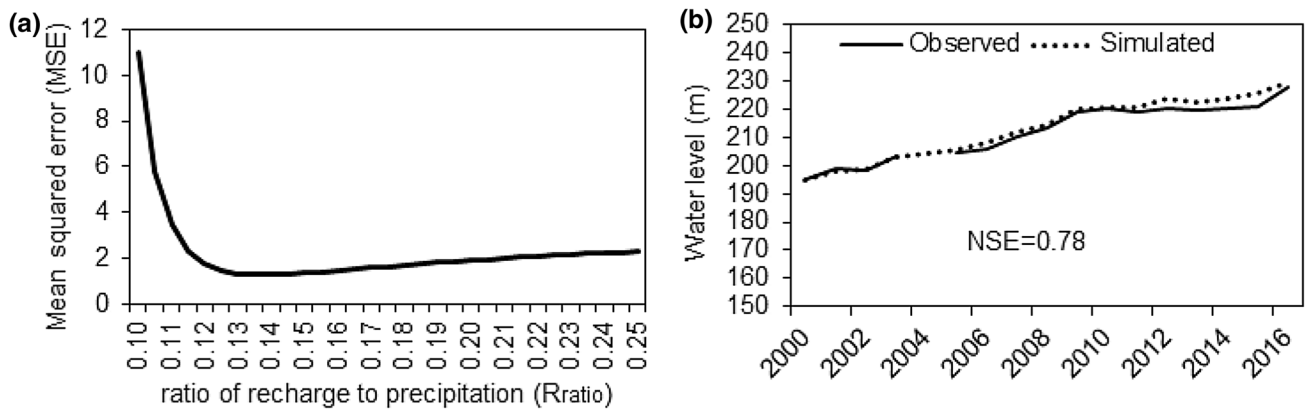


Fig. 3 **a** MSE between observed and estimated annual water-level fluctuations using an average effective area calculated from R_{ratios} ranging from 0.10 to 0.25 by an increment of 0.005. **b** Comparison

between the observed and the simulated water level by HYDROBAL using the selected average effective area

arid regions. In their work, the average recharge rates, estimated over 97 sites in the major continents, ranging from 0.1 to 5% of long-term average annual precipitation. However, in the SAG aquifer, the water level showed a rising tendency over the studied period, which means that the recharge rates are higher than pumping rates. This means that the aquifer recharge rate in our study area should be higher than 0.10, which is the average annual pumping rate to precipitation. Actually, the chosen recharge rate is similar to rates reported in our region. In the continental Spain, using the atmospheric chloride mass balance (CMB) method, the average diffuse recharge over average precipitation was estimated to vary from 0.03 to 0.6, with 90% ranging from 0.1 to 0.4 (Alcalá and Custodio 2015), and specifically in our area to vary between 0.1 and 0.14. In another study of Estrela et al. (1999), in a map of natural aquifer recharge in Spain, our area appears in a region with recharge ranging between 0 and 50 mm/years, which is approximately between 0 and 17% of the long-term average precipitation. Locally, in a study in a small aquifer near our area, Bellot and Chirino (2013) estimated that the ratio of aquifer recharge to precipitation

ranges between 0.05 and 0.43 depending on climate conditions and vegetation types, while Touhami et al. (2013) reported a value of 0.1 on average approximately for the same area.

Observed and projected trends on climate variables

During the studied period 2001–2016, the mean annual precipitation in the study area was about 294.1 mm. This value is 7.9% less than the historical mean precipitation, which was about 319.3 mm in the reference period 1971–2000 (Table 2). According to the nine CMIP5 climate models used in this study, the same tendency of reduction in precipitations is expected in the future. For the medium term (2039–2068), the precipitation is expected to decrease 5.4% and 8.7%, in an average of the nine CMIP5 models, with respect to the reference period under the moderate climate scenario RCP4.5 and the high scenario RCP8.5, respectively. For the long term (2069–2098), the rate of change with respect to the reference period is expected to be higher above all under the high scenario (–7.1% and –13.4% in

Table 2 Observed mean annual precipitation (Pr) and potential evapotranspiration (PET) and their standard deviations (Sd) and projected relative changes (%) with respect to the reference period (1971–2000)

	Observed		Projected			
	Mean (mm) and Sd		Relative change (%) to the reference period			
	1971–2000	2001–2016	2039–2068		2069–2098	
			RCP4.5	RCP8.5	RCP4.5	RCP8.5
Pr	319.3 ± 131.4	294.1 ± 107.8	–5.4**	–8.7***	–7.1***	–13.4***
PET	1185.9 ± 82.8	1229.2 ± 37.4	+7.5***	+10.3***	+9.4***	+18.0***

Projected data are average values of nine CMIP5 models and under two RCP emission scenarios over medium and long-term periods. The comparison of means was done by a *t* test and all differences are significant

*, **, ***Significant at 5, 1, and 0.1%, respectively

average of the nine CMIP5 models under the RCP4.5 and RCP8.5 scenarios, respectively). All these average projected changes are significant at 1% (Table 2). Although some models showed positive changes in the projected mean annual precipitations, the negative changes are the significant ones (Fig. S2).

The potential evapotranspiration (PET) showed a significant increase during the study period with respect to the reference period and is likely to continue increasing in the future as a result of the rise of temperatures. Indeed, the PET increased a 4% in the study period with respect to the reference period and is expected to increase 7.5% and 10.3%, in an average of the nine CMIP5 models, in the medium term under the two emission scenarios RCP4.5 and RCP8.5, respectively (Table 2). For the long term, the PET is likely to increase two times higher under the high scenario RCP8.5 (+18%) than under the moderate scenario RCP4.5 (Table 2). At the opposite of precipitations, the changes in the PET are positive and significant under the RCP scenarios and the nine CMIP5 models (Fig. S3).

The observed and projected changes in the mean are the result of long-term trends on precipitations and PET. Precipitations showed a negative non-significant trend over the study period 2001–2016 (Fig. 4a) which is part of a long-term negative tendency observed over the historical period 1971–2016 (Table 3, Fig. 4c). This tendency of reduction of precipitations is likely to continue in the future over the projected period 2039–2098 under the moderate scenario RCP4.5 with an average rate of change of -17.9 and -1.4 mm decade $^{-1}$, respectively. While a significant negative trend is expected under the high scenario RCP8.5 (-3.8 mm decade $^{-1}$, $p < 0.01$, Table 3, Fig. 5a). At the opposite, the PET showed a significant positive trend ($+19.4$ mm

Table 3 Observed and projected trends (mm/decade) on precipitation (Pr) and potential evapotranspiration (PET)

	Observed (1971–2016)	Projected (2039–2098)	
		RCP4.5	RCP8.5
Pr (mm/decade)	-17.9	-1.4	-3.8^{**}
PET (mm/decade)	$+19.4^{**}$	$+7.4^{***}$	$+31.0^{***}$

Projected trends are average values of nine CMIP5 models and under two RCP emission scenarios. Statistical significance is tested by Mann–Kendall test

*, **, ***Significant at 5, 1, and 0.1%, respectively

decade $^{-1}$, $p < 0.01$) over the observed and the historical periods (Table 3, Fig. 4b, d) and is likely to continue in the same direction of increase under the two moderate and high RCP scenarios ($+7.4$ and $+31.0$ mm decade $^{-1}$, respectively, $p < 0.001$, Table 3, Fig. 5b).

Over the historical period, the precipitations showed negative trends. However, these trends are not significant due to the high temporal variability of precipitations in the area ($CV = 40\%$). This is similar to results obtained by Hidalgo et al. (2003) for the Valencian Community and Moreno (2005) for entire Spain indicating a downward trend in the south during the 20th century without a precise judgment because of the high temporal variability. At the opposite, the PET showed a very significant positive trend ($p < 0.01$) due to the observed significant trend of increase in temperatures (0.5 °C/decade over the period 1971–2016, $p < 0.001$). This is higher than two times the global trend on temperature reported by the IPCC (2018) in his last special report (0.2 °C/decade). The projected trends, on precipitations and temperatures, expected under the different climate scenarios

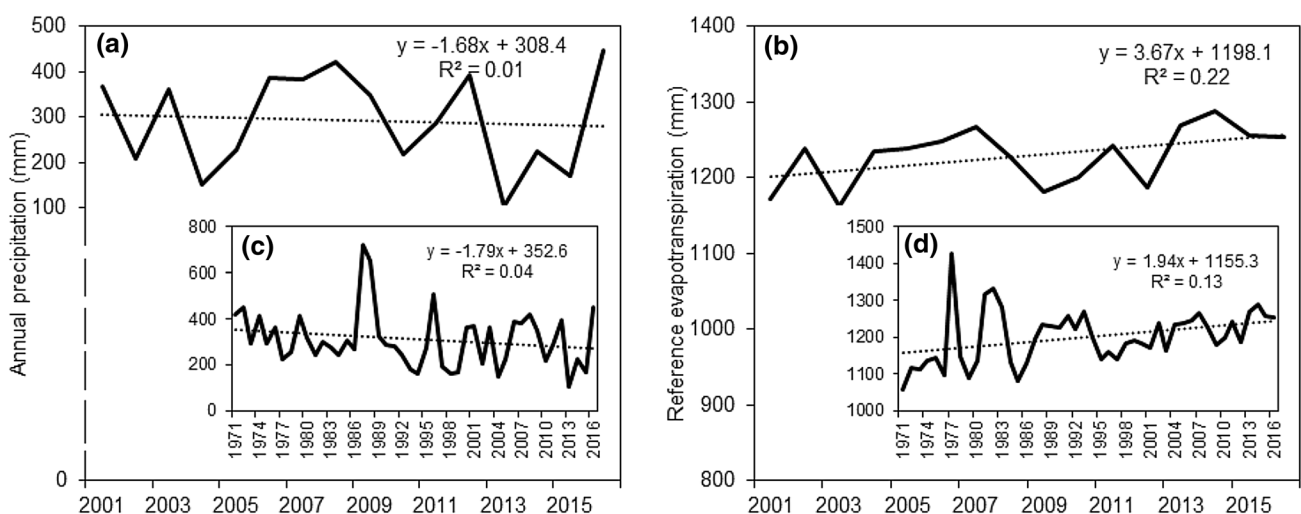


Fig. 4 Evolution of annual precipitation and potential evapotranspiration over the study period 2001–2016 (a and c, respectively) and over the historical period 1970–2016 (b and d, respectively)

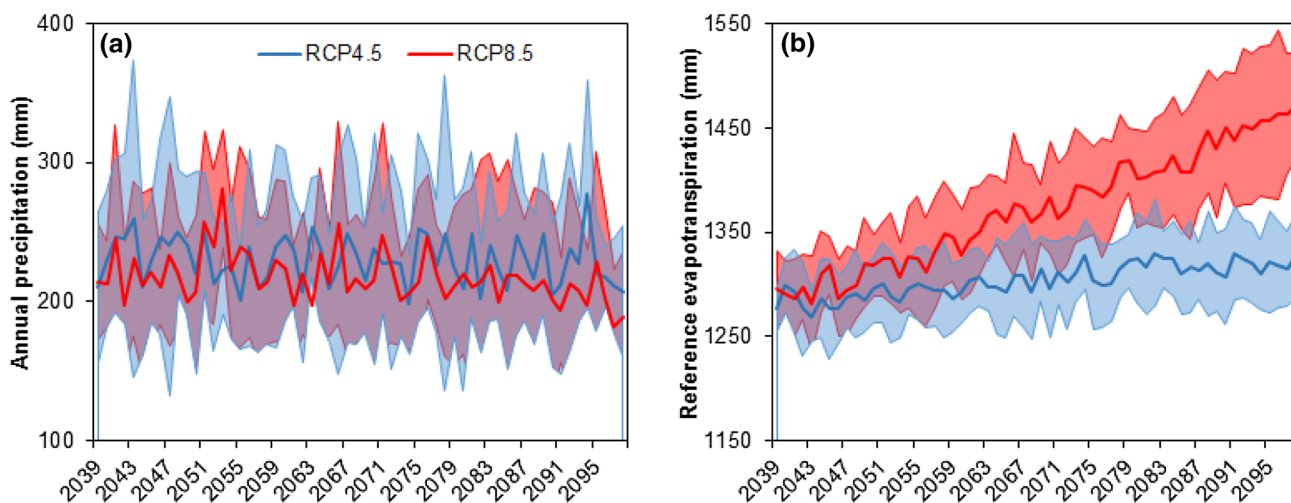


Fig. 5 Projected trends in **a** precipitation and **b** potential evapotranspiration over the projected period 2039–2098 under the moderate scenario RCP4.5 (blue line) and the high scenario RCP8.5 (red

line). Projected trends are average values of nine CMIP5 models and colored area shows the interval between the maximum and minimum

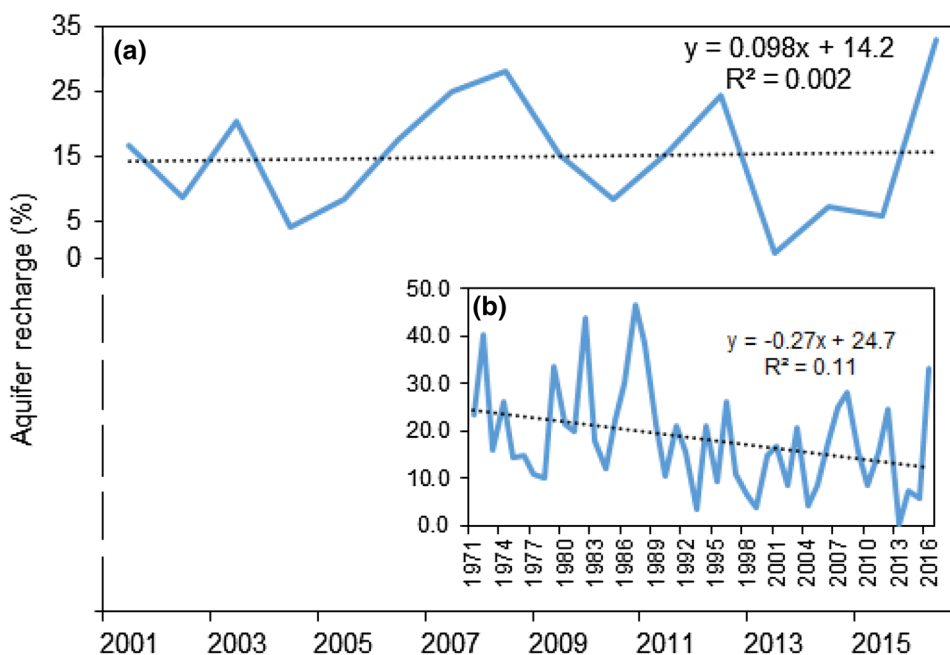
in the study area are similar to trends reported by the IPCC (2013) for the Mediterranean region. However, these tendencies of future climate resulting from the application of global climate models are affected by different sources of uncertainty (Moreno 2005).

Observed trends on aquifer recharge

The aquifer recharge, as the percentage of precipitation (PAR), simulated by HYDROBAL, showed a non-significant positive trend (+0.1% year⁻¹) over the study

period 2001–2016 (Fig. 6a). However, this positive trend is due to the high value of recharge in the last year thanks to the large number of heavy precipitation events (HPEs, > 20 mm day⁻¹), that occurred during the hydrological year of 2016, which are expected to produce appreciable aquifer recharge in this region (Moutahir et al. 2017). A total of 7 HPEs occurred which is significantly higher when compared to the mean annual number of 2.8 HPEs per year (2001–2016). Without considering this year, the aquifer recharge showed a negative trend (−0.4% year⁻¹) over the period 2001–2015. This negative tendency over the

Fig. 6 Evolution of the aquifer recharge as percentage of precipitation (%) over: **a** the study period (2001–2016) and **b** the historical period 1971–2000



last years is part of a long-term significant negative trend ($-0.3\% \text{ year}^{-1}$, $p < 0.05$) in aquifer recharge simulated by HYDROBAL over the historical period 1971–2016 (Fig. 6b). Similar decreasing trend in the percentage of groundwater recharge to the precipitation was observed in four karstic aquifers near our study area during the twentieth century (Aguilera and Murillo 2009).

Additional influences such as the land use changes, besides the climate change, can affect the aquifer recharge (Stoll et al. 2011) which make difficult the attribution of aquifer recharge changes to only climate changes (Jiménez Cisneros et al. 2014). However, the entire recharge area of SAG aquifer is covered only by natural vegetation that does not show any significant change over the last decades. Therefore, the observed reduction of aquifer recharge is a result, principally of the observed reduction of precipitations. The aquifer recharge showed a high correlation with precipitation ($R^2 = 0.85$) and no correlation with PET. Crosbie et al. (2013) reported that the sensitivity of groundwater recharge change to precipitation change was found to be highest for low groundwater recharge in the semi-arid High Plains aquifer. However, the changes in the mean annual precipitations are not the only ones expected to affect the groundwater recharge. Indeed, changes in the frequency and size of extreme precipitation events are also expected to significantly influence the groundwater recharge. In a previous work, Moutahir et al. (2017) showed that heavy precipitation events (HPEs; $> 20 \text{ mm day}^{-1}$) are the only ones expected to produce appreciable aquifer recharge in a semi-arid region including our study area. The aquifer recharge in SAG aquifer showed good correlation with the number of precipitation events higher than 20 mm day^{-1} ($R^2 = 0.87$) in contrast with the total number of precipitation days ($R^2 = 0.34$). A trend reduction in the number of this kind of heavy precipitation events were observed over the period 1953–2012 and the same tendency is expected in the future for this region (Moutahir et al. 2017).

Projected trends on aquifer recharge

According to the nine CMIP5 models used in this work, the same tendency of changes detected in aquifer recharge over the observed period (2001–2016) is expected under the two RCP scenarios over the last 60 years of the 21st century (Fig. S4). The reduction in the aquifer recharge is expected to be higher under the high RCP8.5 scenario than the reduction under the moderate RCP4.5 scenario with respect to the simulated reference period. Indeed, the PAR is expected to decrease 44.9% and 32.3% under the high and moderate scenarios, respectively, for the medium future term (2039–2068). For the long term (2069–2098), the aquifer recharge is likely to decrease 55.1% and 39.8% under the high and moderate scenario, respectively (Table 4). These

Table 4 Mean projected annual aquifer recharge as percentage of rainfall (%) and standard deviation using simulated inputs from nine CMIP5 models and under two RCP climate scenarios for the medium future term 2039–2068 and the long future term 2069–2098 and the relative change (%) compared to the simulated reference period 1971–2000

	Recharge as percentage of rainfall (%)		Relative change (%)	
	2039–2068	2069–2098	2039–2068	2069–2098
RCP4.5	9.0 ± 1.7	8.1 ± 2.3	-32.3 ± 16.7	-39.8 ± 15.9
RCP8.5	7.4 ± 1.9	6.0 ± 1.8	-44.9 ± 16.3	-55.1 ± 14.3

relative changes in the mean values of the PAR are results of very significant negative trends over the period 2017–2099 (-0.4 and -0.6% per decade under the RCP4.5 and RCP8.5, respectively, $p < 0.001$, Fig. 7a, b).

The results of the predicted scenarios for aquifer recharge in the SAG area (a decrease in the PAR of more than 38% and 47% for the medium and long terms, respectively) agree with results obtained by Portmann et al. (2013) in a study at a global scale. Using five CMIP5 models and four RCPs scenarios, Portmann et al. (2013) indicated that groundwater recharge decreases of more than 30% affect especially (semi) arid regions. Similar results were obtained in another study, indicating that groundwater recharge will decrease strongly by 30–70% or even more than 70%, in some currently semi-arid zones, including the Mediterranean (Döll 2009). At regional and local scales, other studies reported different rates of change but in the same direction. Pulido-Velázquez et al. (2018) indicated that global mean net aquifer recharge is expected to decrease by 12% on average over continental Spain with the largest reduction in the center and south-east of the Spanish territory, dropping 28% in some areas, including our study area. In a small karstic aquifer, which is only 10 km away from our area, Touhami et al. (2015) indicated that aquifer recharge will decrease by up to 17% for the long-term period under the A2-high scenario. Similar results were obtained in different aquifers in Spain; -16% in the Island of Majorca (Spain) by Younger et al. (2002), -14% in the Almonte-Marismas aquifer (Doñana wetland, SW Spain) by Guardiola-Albert and Jackson (2011) and in the Serral-Salinas aquifer Altiplano (Murcia, SE Spain) by Pulido-Velázquez et al. (2015). All of these last studies used GCMs previous to the CMIP5 models, which can explain part of the differences in the changes expected in the PAR.

Changes with respect to the study period: impacts on groundwater availability

The above-described projected changes on PAR are relative changes to the simulated reference period (1971–2000). In this section, we applied the relative changes between

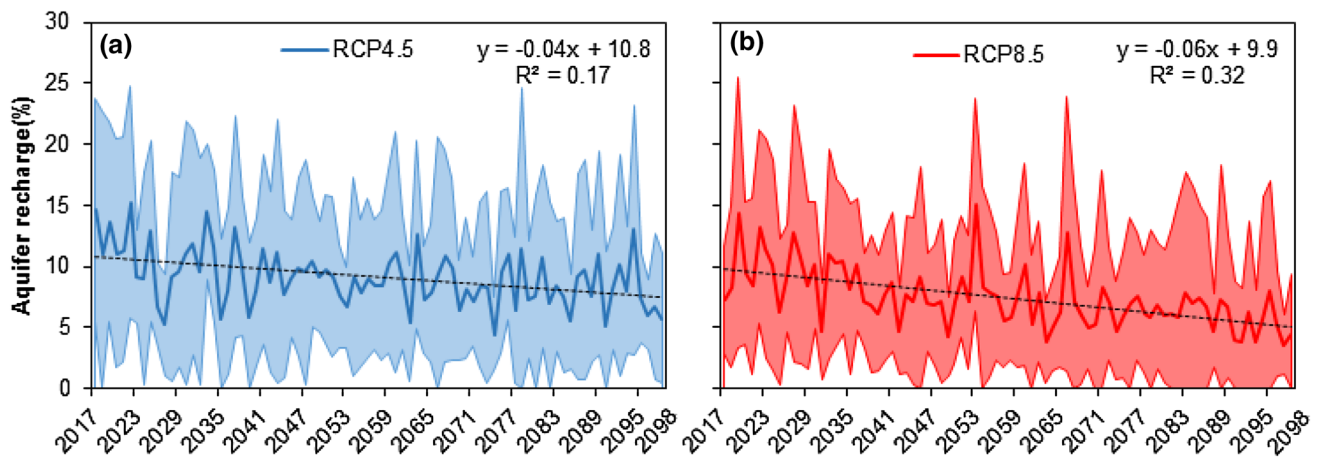


Fig. 7 Projected trends of aquifer recharge (%) as percentage of precipitation (PAR) over the projected period 2017–2098 under **a** moderate scenario RCP4.5 and **b** high scenario RCP8.5. Projected trends

are average values of nine CMIP5 models and colored area shows the interval between the maximum and minimum. Both trends are very significant ($p < 0.001$)

the projected period and the simulated reference period expected under the two climate scenarios, to the observed aquifer recharge in the period 2001–2016 (Table 5). The mean aquifer recharge during the period 2001–2016 was 53.4 mm, which represents 15.1% of precipitation, while the water extraction by pumping represents 10% on average. This misbalance favorable to the aquifer recharge allowed the recuperation of water level over the last years. Under the two climate scenarios RCP4.5 and RCP8.5, the PAR is expected to decrease to 10.2 and 9.1% for medium term, and 8.3 and 6.8% for the long term. This means that, if in the future the water pumping continues at the same rate (10% of precipitation), the aquifer of SAG will be at its limit of exploitation for the medium term and overexploited for the long term.

According to the different CMIP5 models, precipitations will decrease in the future. Therefore, the amount of water pumped currently will represent a higher percentage of the projected precipitation (> 10% pumped currently). Indeed, to continue pumping the current amount of water, the percentage of pumped water to precipitation should increase by 0.5% under the RCP4.5 and 1% under the RCP8.5. The water pumped out from SAG aquifer, which is mainly used for water supply in different municipalities of Alicante,

is considered as a strategic resource (IGME-DPA 2015). Indeed, the SAG aquifer plays a buffer role against droughts. The pumped water is at his highest during periods of time with reduced precipitations (Fig. S1). Therefore, this means that the availability of water will be affected, because the SAG aquifer will be overexploited under the two RCP scenarios for the medium and long-term term because of the projected precipitation reduction.

Conclusions

This work presents a methodological approach for validating the aquifer recharge simulated by HYDROBAL ecohydrological model using the registered water level fluctuations. This model showed good performance (NSE=0.78) and allowed the simulation of the aquifer recharge over the last decades since 1971 and over the projected periods in a Mediterranean semi-arid aquifer. The analysis of the aquifer recharge changes observed over the last decades and those expected under the climate change scenarios for the 21st century highlighted the vulnerability of groundwater resources to climate change. The results obtained in this work showed a significant negative trend in the percentage

Table 5 Expected changes in the aquifer recharge under the two RCP climate scenarios for the medium future term 2039–2068 and the long future term 2069–2098 compared to the observed study period 2001–2016

	Observed	RCP4.5		RCP8.5	
	2001–2016	2039–2068	2069–2098	2039–2068	2069–2098
Recharge (mm)	53.4	44.3	39.0	35.1	29.0
Recharge as percentage of precipitation (%)	15.1	10.2	9.1	8.3	6.8

of aquifer recharge to precipitation (PAR) over the last 5 decades (-0.3% year⁻¹, $p < 0.05$). According to different GCMs, this observed tendency is expected to continue in the same direction with similar reduction rate under the moderate climate scenario and higher rate under the high scenario (-0.4 and -0.6% under the RCP4.5 and RCP8.5, respectively). These changes are due principally to climate change, since the aquifer recharge area is covered entirely by natural vegetation, which did not show any significant change over the last decades. The high correlation between the aquifer recharge and the precipitation ($R^2 = 0.85$) suggests that the aquifer recharge decrease is due principally to the reduction of precipitations. Indeed, precipitation showed a decreasing trend over the observed period and will continue decreasing with a similar rate under the moderate climate scenario but with a higher reduction rate under the high scenario.

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