



Simulating Future Groundwater Recharge in Coastal and Inland Catchments

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Abstract

Groundwater is a primary source of drinking water in the Mediterranean, however, climate variability in conjunction with mismanagement renders it vulnerable to depletion. Spatiotemporal studies of groundwater recharge are the basis to develop strategies against this phenomenon. In this study, groundwater recharge was spatiotemporally quantified using the Soil and Water Assessment Tool (SWAT) in one coastal and one inland hydrological basin in Greece. A double calibration/validation (CV) procedure using streamflow data and MODIS ET was conducted for the inland basin of Mouriki, whereas only ET values were used in the coastal basin of Anthemountas. Calibration and simulation recharge were accurate in both sites according to statistical indicators and previous studies. In **Mouriki basin**, mean recharge and runoff were estimated as 16% and 9%, respectively. In **Anthemountas basin** recharge to the shallow aquifer and surface runoff were estimated as 12% and 16%, respectively. According to the predicted RCP 4.5 and 8.5 scenarios, significant variations in groundwater recharge are predicted in the coastal zone for the period 2020–2040 with average annual recharges decreasing by 30% (RCP 4.5) and 25% (RCP 8.5). Variations in groundwater recharge in the inland catchment of Mouriki were insignificant for the simulated period. Anthemountas basin was characterized by higher runoff rates. Groundwater management in coastal aquifers should include detailed monitoring of hydrological parameters, reinforced groundwater recharge during winter and reduced groundwater abstraction during summer depending on the spatiotemporal distribution of groundwater recharge.

Keywords SWAT · Data scarcity · Climate model projections · MODIS · Water Resource Management

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1 Introduction

The phenomenon of water scarcity in conjunction with the continuous depletion of groundwater resources could seriously threaten the sustainability of natural ecosystems and, consequently, human health and activities (Aeschbach-Hertig and Gleeson 2012). In the last decades, surface waters and groundwater resources have become highly vulnerable due to increased water demands arising from: i) population growth, ii) expanding industrialization, iii) increased food production, iv) anthropogenic pollution, and v) climate variability and land-use change (McDonald et al. 2014).

Consequently, an effective water resource management plan requires the assessment of all relevant hydrological processes, including streamflow, recharge and evapotranspiration. This allows aquifer recharge to be spatiotemporally quantified and suitable zones for sustainable groundwater exploitation be identified at basin scale. Several studies have pointed out the necessity of reliable groundwater recharge estimates to optimize groundwater and surface water exploitation (Nyeko 2014). The evaluation of recharge is essential in regions with significant climatic variations which can impact watershed hydrology and potentially lead to seasonal reduction of fresh water availability (Carvalho-Santos et al. 2017). However, recharge rate is characterized by discrepancies in space and time due to differences in local geomorphology, climate and vegetation (Scanlon et al. 2002). The Mediterranean region is one of the most vulnerable zones worldwide due to the magnitude of predicted changes to its temperature and rainfall patterns (Giorgi & Lionello 2008). Such variabilities could influence the hydrogeological regime and cause significant variations in the quantity and quality of groundwater resources (Donnelly et al. 2017).

Several methodologies have been developed and tested to estimate groundwater recharge and evaluate hydrological variation driven by climate and land use changes, such as: i) the paired catchments approach (Van Loon et al. 2019), ii) time series analysis (Hawtree et al. 2015), and iii) hydrological modeling. The latter can provide the most robust structure to analyze the complex relationships between climate, human activities and water resources as it accounts for the spatial variability of the specific factors influencing groundwater recharge (Awan et al. 2014). Physically based and distributed hydrological models have proved to be an important tool for water resource management (Li et al. 2009). Additionally, due to increasing availability of global and regional datasets, their applicability has been greatly enhanced (Abbaspour et al. 2019). The Soil and Water Assessment Tool (SWAT, Neitsch et al. 2000) is a watershed-scale, physically based, distributed hydrological model, that was created to evaluate and predict the impact of different agricultural management practices on hydrological processes and water quality status (Arnold et al. 1998). The SWAT model is considered a valuable tool to assess the effects of climate and land use changes on all basin hydrological processes such as: streamflow, soil erosion and recharge (Busico et al. 2020). Precise calibration, validation and uncertainty analysis is required to achieve the best model performance and reliability. Values of river/torrent streamflow are normally used for model calibration. Unfortunately, these parameters are not widely available thus making calibration problematic, especially in ungauged basins. To overcome this issue, many studies have demonstrated the potential of calibration using remotely sensed evapotranspiration (ET). Moderate Resolution Imaging Spectroradiometer (MODIS) ET products have proven to be reliable and useful tools for hydrological studies. These products are free downloadable datasets that are relatively simple to use (Miranda et al. 2017). Parajuli et al. (2018), assessed how a SWAT calibration with ET could adequately simulate streamflow data, while Odusanya et al. (2019),

highlighted the main advantages of a double SWAT calibration using streamflow and ET data. Accordingly, ET measurements become essential when calibrating a SWAT model, especially in an ungauged basin where a water resource management plan is necessary to ensure groundwater sustainability (Nyeko 2014). The SWAT model has been widely used in the Mediterranean, and especially in Greece (Venetsanou et al. 2020; Gemitzi et al. 2017). The SWAT model was selected to investigate spatiotemporal groundwater variation caused by climatic variations in two basins in northern Greece. Anthemountas basin is a coastal catchment where the water demands for human activities are met completely by local groundwater resources. Groundwater overexploitation in this coastal area has caused a significant lowering of the water table and groundwater salinization. In the inland basin of Mouriki, the aquifer is used mainly to meet the water demands for local domestic and agricultural use and has been subjected to increasing pressure in recent years.

The evaluation of future trends and spatiotemporal variations of groundwater recharge rates is of outmost importance in the Mediterranean region for sustainable groundwater resources management. Nevertheless, the lack of relevant data requires examining different approaches to calibrate and verify modelling processes. Such approaches should consider different hydrogeological environments, such as those examined in the present work (one coastal and one inland aquifer). However, despite the importance of this issue, few studies have focused on the spatiotemporal variation of groundwater recharge. Sutanudjaja et al. (2018), proposed a spatial distribution of recharge on continental and regional scale by sacrificing spatial resolution. Several studies have applied the SWAT model for local assessment, focusing only on spatial (Awan and Ismael 2014) or temporal recharge (Gemitzi et al. 2017).

In this study, we aim to estimate the spatiotemporal variation of groundwater recharge at basin scale. To ensure result robustness different calibration approaches were used in two basins with different hydrogeological regimes. The innovative results of this study could be used as a fundamental framework to estimate spatiotemporal variation of groundwater recharge in areas with limited hydrological data.

2 Study Areas

2.1 Mouriki Basin

The Mouriki basin is located in the north part of Kozani Prefecture in northern central Greece (Fig. 1). It is an inland basin with a surface area of 110 km². The mean altitude of the study area is 874.5 m a.s.l. with a mean slope inclination of 26.1%. The climate is semi-arid Mediterranean with moderate rainfall during summer. The average annual air temperature and precipitation values are 11.2°C and 636 mm, respectively (Patrikaki 2012). The geological setting of the study area is presented in the Supplementary Material (Fig. S1a).

The main aquifer system is hosted in alluvial deposits with a mean thickness of 70 m covering an area of 30.5 km². The groundwater flow follows the local morphology moving towards the lowlands in an SSW to NNE direction. Livestock and agriculture are the main activities in the area and the main cultivations are corn, cereal crops, fruit trees, vegetables and legumes. The mountainous part of the basin is covered with mixed, coniferous forest vegetation.

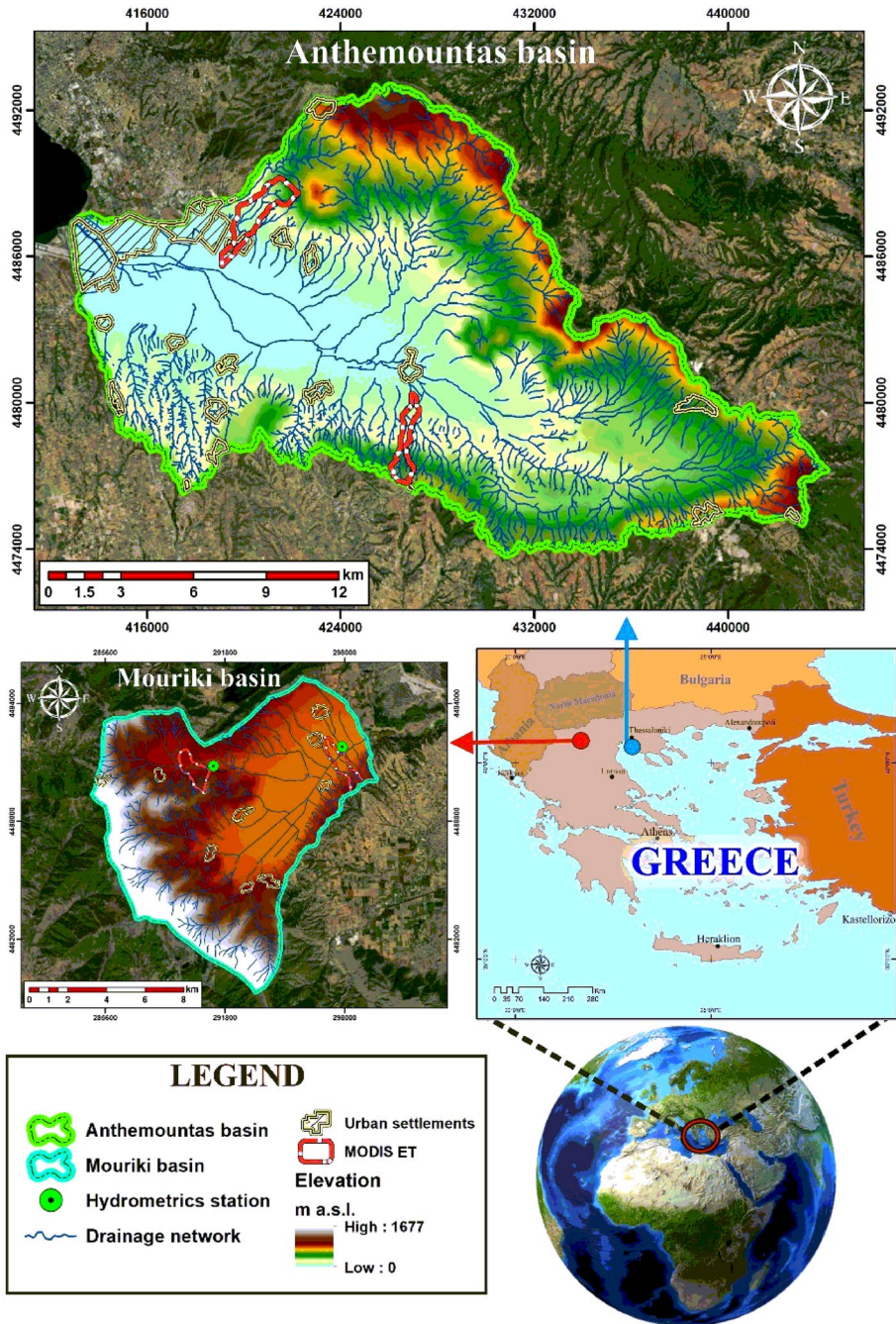


Fig. 1 Location of the study areas

2.2 Anthemountas Basin

Anthemountas basin is a coastal basin located in the eastern part of Thermaikos Gulf in northern Greece (Fig. 1b). The basin covers an area of 374 km², with altitudes ranging from 0 m (coastal zone) to 1201 m a.s.l (Mount Hortiatis). The mean slope inclination is 20% and ranges from 0.1 to 40%. The climate is characterized as a typical Mediterranean semi-arid climate with dry summers and wet winters. The mean annual temperature and precipitation values are 15.1 °C and 575 mm, respectively. The geological setting of Anthemountas basin is presented in the Supplementary Material (Fig. S1b).

The basin is characterized by a multiple aquifer system consisting of various aquifer types: i) a porous aquifer hosted in the Quaternary and Neogene sediments, ii) a karst aquifer located in the south-central part of the basin, and iii) fractured rock aquifers in the mountainous part of the basin. Agriculture is the primary economic activity of the area, although tourism has increased in recent years, mainly during the summer. The area's main crops include vegetables, olives, wine grapes, corn and cereals. The area's growing domestic and irrigation water requirements are met by numerous boreholes located in the porous aquifers. Due to overexploitation, groundwater depletion has been observed in the aquifer. There is limited surface runoff data for this study site.

3 Materials and Methods

The assessment of groundwater recharge variations and their relationship with other hydrological parameters requires various hydrological and hydrogeological data. The SWAT model was applied to both study areas. A brief resume of SWAT theory is available in the Supplementary Materials. A double calibration/validation (CV) procedure using streamflow data and MODIS ET was conducted for Mouriki basin, whereas only ET values were used in Anthemountas basin due to the complete lack of hydrometric data for this site. The assessment was performed using real (non-predicted) meteorological data for the period 2000–2019 and predicted data for the future (2019–2040) under two emission scenarios (RCP 4.5 and 8.5).

3.1 Data Collection

The data necessary to perform satisfactory hydrogeological evaluations of the two catchment basins was obtained and collected from online free-access sources, field measurements and relevant literature (Table S1). Specifically, i) a Digital Terrain Model (DTM) with a 10×10 m cell resolution was used to define the main watershed features, ii) soil information was obtained from the Digital Soil World Map (DSMW FAO 2007; scale 1:5 million) and amended with field measurements and default SWAT database values, iii) a preliminary land use classification was made using Corine Land Cover (CLC) classes for the year 2018 and then discretized using satellite images and relevant literature, and iv) meteorological data of minimum and maximum daily temperature and precipitation values for a 25-year period (1996–2020) were obtained from three meteorological stations and analyzed in the

R programming environment to complete any missing data. Data from two meteorological stations (Aristotelis and Kozani) were used for Mouriki basin and one station (Makedonia airport) for Anthemountas basin. Methods of elevation bands were used to reproduce the precipitation variability within the basins due to orographic effects. This methodology has been proved to greatly enhance model reliability even utilizing point observed precipitation (Tuo et al. 2016).

Data on daily river discharge and monthly ET values were used for the model calibration/validation (CV). Discharge data was obtained from two hydrometric monitoring stations (Galatia and Variko) located within [Mouriki basin](#) for the period November 2004 to September 2007 (Fig. 1). Monthly ET values for 2002–2010 for both Mouriki and Anthemountas basins were sourced from the MODIS dataset. The MOD16A2 Version 6 Total ET product (including potential and real ET) is an 8-day composite dataset produced at 500×500 m pixel resolution. The data was download using the AppEEARS (AppEEARS 2020) interface and the MYD16A3GF model (Running et al. 2019). Specifically, the algorithm used in the MOD16 products is based on the Penman–Monteith equation, which includes inputs of daily meteorological data along with MODIS remotely sensed data products such as vegetation property dynamics, albedo and land cover (Mu et al. 2011). The ET data was extracted using the average spatial values of two internal sub-basins within the two study areas (Fig. 1). The historical climate data and future projections for the entire period of 1976–2040 focused on simulations performed by the GCM/RCM combination, entitled MPI-M-MPI-ESM-LR/MPI-CSC-REMO2009, and here called REMO, made available by the World Climate Research Programme's CORDEX initiative (www.euro-cordex.net).

4 Modelling Framework

A detailed analysis of the SWAT calibration and performance evaluation procedure is presented in the Supplementary Material and includes equations, the monitoring stations (Fig. S2c), and the statistical methods applied to evaluate the modeling results.

The regimes of recharge, streamflow and evapotranspiration for the two analyzed catchments areas were obtained by following four main steps (Fig. 2): i) the physical characteristics of morphology, land cover and soil were collected and used as main inputs for the SWAT set-up, ii) the real (non-predicted) meteorological data were used to run the model for a 10-year period from 2000 to 2010, iii) the model was then calibrated and validated for Mouriki basin using observed streamflow and evapotranspiration data and using evapotranspiration for Anthemountas basin, and iv) the SWAT model used the selected RCM to simulate the past time period of 2000–2020 and the future period of 2020–2040 under two different emission pathways (RCP 4.5 and 8.5). The results were then analyzed to obtain annual values of recharge, streamflow and evapotranspiration using a time series chart. To obtain a spatial/temporal representation of aquifer recharge in both areas, the average yearly recharge (mm) over a 20-year period (2020–2040) was estimated at basin scale and compared with the 5-year sub-basin recharge for the shorter periods 2021–2025, 2026–2030, 2031–2035, and 2036–2040. This elaboration was performed considering only the 4.5 scenario since it is considered the most reliable of the two.

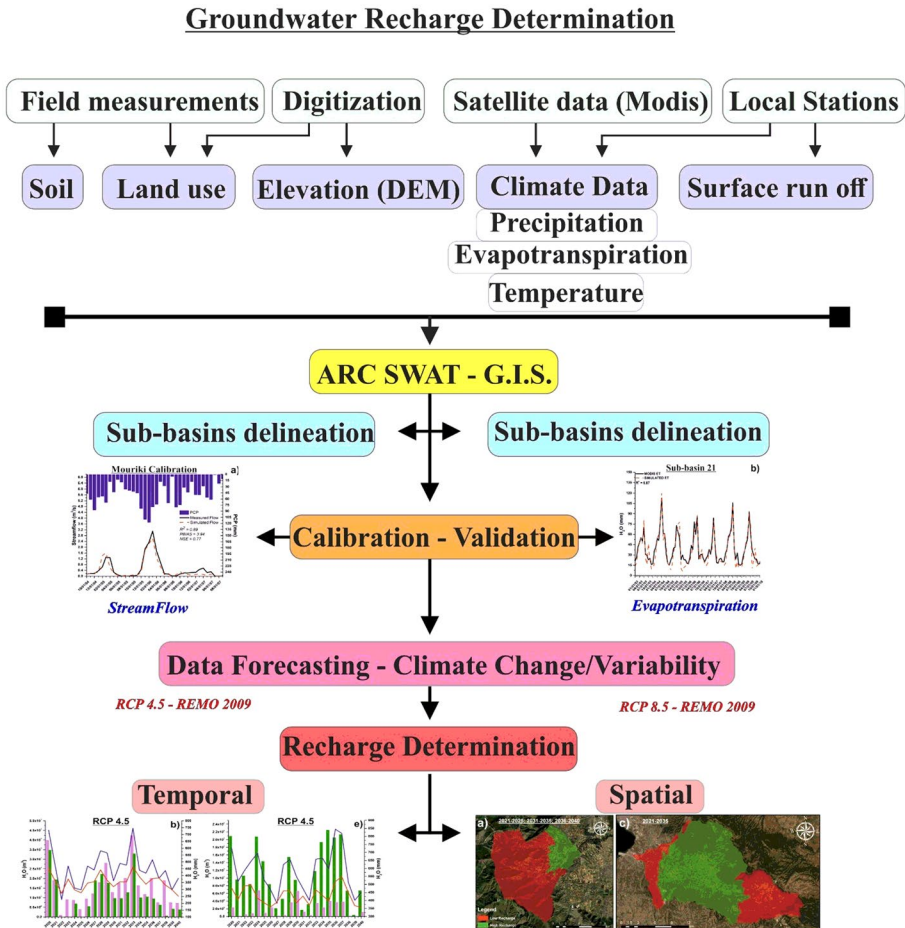


Fig. 2 Flowchart of the process followed to estimate spatiotemporal groundwater recharge

5 Results

5.1 SWAT Application

The application of SWAT in Mouriki and Anthemountas basins was done using ArcSWAT 2012 in an ArcGIS 10.5 environment. Mouriki basin was divided into 149 sub-basins and a total of 500 HRU. The area is mainly agricultural (Fig. S2a), dominated by wheat and vegetable crops (mainly tomatoes and potatoes) that cover 70% of the territory. Urban settlements account for less than 2% of the site’s surface and the remaining areas are covered by dense pine and oak forests. According to the DSWM, the entire basin is characterized by Chromic Luvisols with a clay-loam texture and a hydraulic conductivity (K_s) of 7.68 mm/h (Fig. S2b). The Anthemountas basin was divided into 233 sub-basins retaining a maximum of 500 HRU (Fig. S3c). The maximum of 500 HRU was set to reduce the model’s spatial requirements and computational time in accordance with Busico et al. (2020). The

analysis showed that land use of Anthemountas basin was mainly agricultural. Over 50% of the basin is cultivated with crops including wheat, corn, olives and vegetables (mainly lettuce and carrot), while urban settlements account for 6% of the basin's surface area and are mainly located along the coast (Fig. S3a). The remaining territory is characterized by Mediterranean shrubland and oak forests interspersed with pasture. In both catchments, multiple land uses were established by using the HRU refinements tool to reproduce high crop heterogeneity (Figs. S2a and S3a) and reflect the different forest densities in both study areas.

Two soil categories were identified in Anthemountas basin following the DSMW classification: i) Chromic Luvisols in the central and eastern parts of the basin with the same characteristics as those of Mouriki basin, and ii) Calcaric Regosols with a clay-loam texture and a K_s of 4.2 mm/h that occur in the western part of the site and near the coastal zone. Morphologically, both catchments were divided into four slope classes with a 5% interval (Figs. S2b and S3b). Hargreaves method was applied to calculate ET calculation due to the lack of climatic data.

5.2 SWAT Calibration and Validation

The CV procedure was performed using real climatic data for the period 1996–2010 obtained from the local meteorological stations. A double parameter calibration was conducted for Mouriki basin using monthly streamflow data and MODIS monthly ET values via SWAT-CUP standalone software choosing the SUFI-2 algorithm. In Anthemountas basin the CV procedure was performed using only the MODIS values of ET and Mouriki's calibration results as a general guide, due to the complete absence of streamflow and runoff monitoring stations. The calibration parameters were chosen after an extensive review of the relevant literature. Following Chen et al. (2019), nine parameters were identified as those most relevant in affecting streamflow and ET simulation (Table S2). The NSE index was selected as optimization function for the SUFI-2 algorithm along with the statistical indices PBIAS and coefficient of determination (R^2) to check the model's performance. The boundary values of Moriasi et al. (2007) were considered to evaluate the reliability of the model's results. Due to the limited range of available streamflow data, data from the hydrometric station of Variko (basin outlet) were used for the calibration in the Mouriki analysis, while data from Galatia station (internal station) were checked for the validation procedure using the same time period. A total number of 1000 calibration runs divided into two interactions of 500 runs each were performed for the simulation. The first interaction set-up was applied using the initial boundaries (min. and max. columns in Table S2) as proposed by Abbaspour (2015). Figure S4 presents the results of the CV procedure applied for both study sites. According to the statistical indices values, the streamflow calibration showed excellent performance with R^2 0.89, PBIAS 3.94, and NSE 0.77 (Fig. S4a). Following the streamflow calibration, the SWAT-calculated ET values for sub-basin 21 were compared with the mean spatial ET values obtained from MODIS. The results of the comparison are shown in Fig. 4b and show a good match between SWAT and MODIS ET (R^2 0.87). The final parameter fitted values are shown in Table S2 along with the results of the sensitivity analysis (P-value). Galatia station (streamflow) and sub-basin 42 (ET) were checked for validation. In this case, the three indices also showed remarkable performance (R^2 0.83, PBIAS 25 and NSE 0.8 for streamflow, and R^2 0.87 for ET). In Anthemountas basin an alternative calibration was selected due to the complete lack of streamflow data. ET is the main parameter of the

hydrological cycle and can be used to estimate other components of the water balance, including surface runoff, lateral flow, base flow and aquifer recharge. The calibration parameters were the same as those applied in the case of Mouriki basin. Four parameters were detected as sensitive for ET simulation in **Anthemountas basin**: a) the fraction of recharge to the deeper aquifer (RCHRG_DP), b) the soil evaporation compensation factor (ESCO), c) the threshold depth of water in the shallow aquifer (GWQMN), and d) the revap coefficient (GW_REVAP). All final parameter values are presented in Table S4. Calibration with average ET values from MODIS for sub-basin 39 (Fig. S4e) showed an acceptable trend with an R^2 of 0.86, while validation for sub-basin 177 resulted in an R^2 of 0.83 (Fig. S4d).

5.2.1 Groundwater Balance

Following the CV procedure, conducted with the available real (non-predicted) climate data, the SWAT model was run for the period 1996–2040 (4-year warm-up) using the historical/projected climate dataset for the two catchments to evaluate variations of the main parameters of the hydrological cycle in the short-term period. For this purpose, a subset of climate models was selected considering the simulations made available by the World Climate Research Program's CORDEX initiative. Different criteria were considered including a wide range of possible future projections, a variety of driving global climate models (GCM), and several institutions providing regional climate models (RCMs). Nevertheless, to limit the necessary computational efforts for further processing using the SWAT model, the climate projections of this study focused on the simulations from a GCM/RCM combination entitled MPI-M-MPI-ESM-LR/MPI-CSC-REMO2009, and here called REMO. Jacob et al. (2012) state that REMO performs best for temperature over Europe, the Mediterranean and north America, whereas high skill scores for rainfall are produced in the regions of Africa, western Asia and the Mediterranean. The REMO model was also highlighted by Nerantzaki et al. (2019) for its accuracy when studying climate change impacts on the hydrological processes of the island of Crete. Regarding future climate scenarios, projections were based on two Representative Concentration Pathways: RCPs 4.5 and 8.5 (scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases, aerosols, and chemically active gases, as well as land use). While RCP 4.5 is an intermediate stabilization pathway in which radiative forcing is stabilized at approximately 4.5 W/m^2 , RCP 8.5 reaches greater than 8.5 W/m^2 by 2100 and continues to rise for some amount of time (Moss et al. 2008). Variations in the hydrological parameters over time, considering the actual data and the two predicted future scenarios are shown in Fig. 3. The results obtained for the long-term mean annual water balance are in good agreement with those of previous studies on Mouriki (Patrikaki 2010) and Anthemountas (Kazakis 2013) basins.

5.2.2 Mouriki basin

The total average annual ET in **Mouriki basin** was calculated as accounting for 75% of the hydrological balance, while recharge and runoff account for 16% and 9%, respectively. Mean annual recharge for the period 2000–2019 was calculated to be $12.4 \times 10^6 \text{ m}^3$ while runoff was much lower with an average value of $3.00 \times 10^6 \text{ m}^3$ per year. A high inverse correlation between recharge and ET was estimated. The simulation for 2020–2040 under the

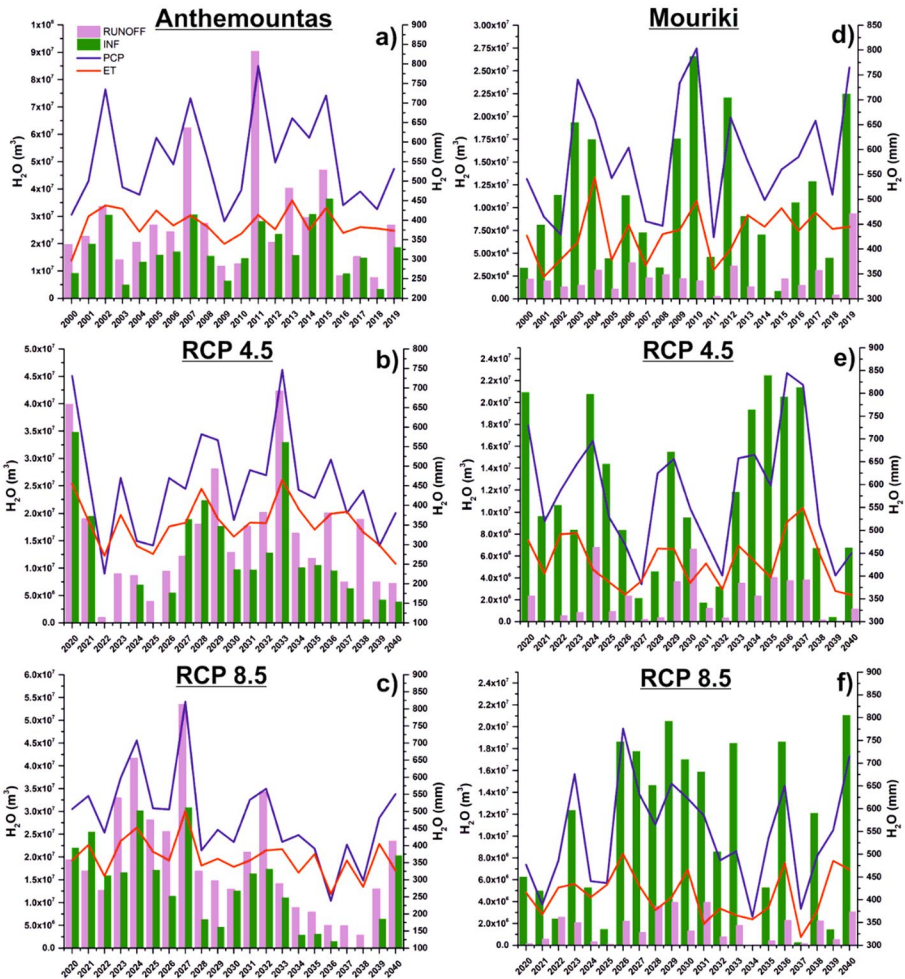


Fig. 3 Water balance representation for the two study areas considering the actual scenario and the two predicted future scenarios

RCP 4.5 and 8.5 scenarios (Fig. 3b, c) did not predict significant differences in the average percentages of the examined parameters. Indeed, a 25% decrease in runoff was predicted for the RCP 8.5 scenario. The relation between recharge and ET remained constant in both predicted RCP scenarios. The total amount of infiltration is not predicted to decrease significantly but is predicted to experience annual variations in the future.

5.2.3 Anthemountas Basin

For the period 2000–2019, total ET was estimated to account for 72% of the entire hydrological balance in **Anthemountas basin**, while recharge to the shallow aquifer and surface runoff RF accounted for 12% and 16%, respectively (Fig. 3d). Mean annual recharge to the shallow aquifer was calculated as $17.9 \times 10^6 \text{ m}^3$, while runoff was $28.1 \times 10^6 \text{ m}^3$. The runoff/recharge ratio appears stable for 2000–2019 thus confirming the strong relationship


between the two parameters. According to the predicted RCP 4.5 and 8.5 scenarios, greater variation will characterize the years 2020–2040 and the average annual recharge will decrease by 30% (RCP 4.5) and 25% (RCP 8.5). Both climate scenarios predict severe drought conditions due to low precipitation and high ET rates which will negatively affect both recharge and runoff values. Runoff values are predicted to reduce by 30% and 25% for the RCP 4.5 and 8.5 scenarios, respectively, but remain consistently higher than recharge values.

5.2.4 Groundwater Recharge Discretization

Following the RCP 4.5 scenario, the 20-year average recharge values for 2020–2040 were predicted as being 87 mm and 40 mm for Mouriki and Anthemountas basins, respectively. To identify the most sensitive sub-basins in both study areas, a 5-year average recharge value was calculated for each sub-basin for four stress periods (2021–2025, 2026–2030, 2031–2035, 2036–2040). The sub-basins were then classified as “Low recharge” or “High recharge” when the mean recharge value of each stress period was lower or higher than the mean recharge value of the total time period. In this way, spatial mapping of future recharge trends was achieved (Fig. 4). The higher recharge areas of Mouriki basin are concentrated near the basin’s outlet where the morphology is flat. Consequently, all the mountainous areas characterized by steeper reliefs and higher runoff, showed a 5-year average recharge of under 87 mm. No significant changes over time were identified during the four stress periods. However, one exception is predicted to occur in the years 2026–2030 where a 10% increase is observed in the areas of “High recharge”. These areas were previously classified as “Low Recharge”. A different situation is observed in the Anthemountas catchment basin. The first three stress periods showed stable classification, with the central part of the basin classified as “High recharge”. For the last stress period of 2026–2030, the entire basin is predicted to show an average recharge of under 40 mm.

6 Discussion

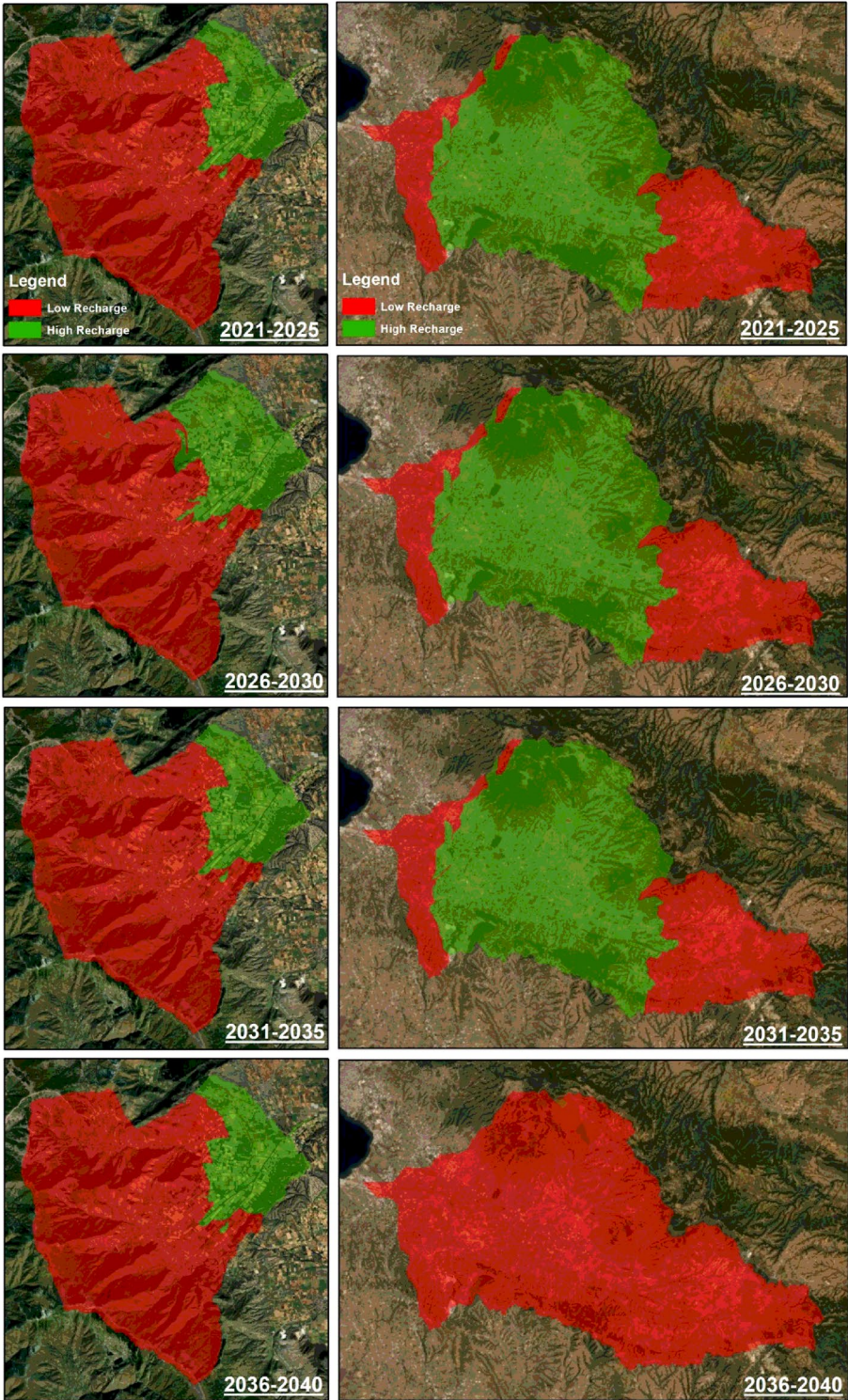
Climate projections for the Mediterranean region predict an estimated annual increase in temperature of between 1.5 and 2.0 °C, especially during the summer period (Giorgi and Lionello 2008; Bucchignani et al. 2016). In contrast, a slight decrease in precipitation is predicted with a marked seasonal regime (Mastrocicco et al. 2019) together with increased frequency of extreme events (Busico et al. 2019). In the present study the SWAT model was successfully calibrated using streamflow and ET to forecast surface runoff and groundwater recharge in two Mediterranean basins. The robustness of the SWAT model was verified using the existing groundwater balance, which highlights the importance of the basic hydrogeological research that must be supported by a detailed monitoring plan of the various hydrological components. The two hydrological basins showed different situations and very different predicted responses to climatic change. Despite showing a similar ET percentage and comparable mean annual precipitation values for the simulation period, they greatly differ in runoff and groundwater recharge. These differences were observed inside the catchments and can be attributed to two main characteristics: i) basin land cover, and ii) rain distribution throughout the year. Regarding land cover, Mouriki basin has a higher percentage of high-altitude dense pine forests than

Fig. 4 Spatial distribution of “High” and “Low” recharge areas in the two catchment basins 

Anthemountas basin in which pine forests represent just 2% of the total forested land. Moreover, the main forest vegetation of the Anthemountas catchment is sclerophyllous (oak) and Mediterranean shrub-land usually interspersed with pastureland of low tree density that can benefit runoff formation (Zhang et al. 2020). Agricultural land covers a much higher percentage in Anthemountas than Mouriki basin. This explains the higher runoff values observed in this site compared to the recharge values. These results are in accordance with studies that suggest susceptibility to runoff in agricultural and sparsely forested areas is generally higher than in densely forested areas where runoff is reduced to the benefit of evapotranspiration and infiltration (Ferreira et al. 2012). The runoff regime might be higher due to increased land cover with low permeability potential (Eshtawi et al. 2014). Moreover, analysis of the meteorological data showed that Anthemountas basin has 30% less rain days than Mouriki, despite the mean annual precipitation for the studied period being almost the same for both sites, thus indicating higher precipitation density in Mouriki basin (Table S3).

The spatial distribution of groundwater recharge indicated that a severe water crisis may occur in Anthemountas basin in the years 2036–2040. A decrease in precipitation along with an increase in ET (Fig. 4e) may be the main causes of this crisis, while groundwater scarcity may be higher if the 8.5 scenario is confirmed. In contrast, the predictions for Mouriki basin indicate a more stable groundwater recharge regime for the next 20 years. The decrease in recharge predicted by the climate scenario simulation for Anthemountas basin agrees with the conclusions of Tylor et al. (2013) who predicted a substantial reduction in potential groundwater recharge in the future for all southern Europe. On the other hand, the results of that study confirmed that RCH can be slightly subjective to spatial variability (Jyrkama and Sykes 2007). The future recharge projection for Anthemountas basin predicts a serious threat on water availability in both RCP 4.5 and 8.5 emission scenarios. For this reason, an extensive monitoring system should be set up inside the basin, including groundwater level monitoring, surface run off measurements, and climatological stations. Some countermeasures such as the construction of reservoirs to collect runoff water or land use management that targets higher infiltration could be also considered for inclusion in future water resources planning. In coastal aquifers where groundwater constitutes the main water supply source any management plans should be adopted based on the simulation results. Groundwater depletion and water table decline intensifies due to increasing water demands. Initially, the phenomenon should be stabilized by reinforcing groundwater recharge and limiting groundwater abstraction. Additionally, small dams could be transformed into small power plants and excess water collected in winter used to manage aquifer recharge.

Future research should aim to apply this SWAT simulation methodology to other catchment basins in the Mediterranean, and compare the results and limitations of this technique. Specifically, combining surface/groundwater modelling will allow the more accurate simulation of all water cycle components and help to account for different climatic and management scenarios such as: i) droughts, ii) extreme rainfall events, and iii) groundwater overexploitation. At present, the main limitations of this study include data scarcity due to the lack of monitoring stations. Nevertheless, despite the absence of hydrological monitoring, data can be partly obtained by advanced technological innovation (e.g., satellite data), although ground stations and monitoring remain



an essential factor for effective water resource management and reliable predictions. Adaptive strategies and multi-data elaboration are required to overcome past decades of groundwater mismanagement.

7 Conclusions

The hydrological physical-based model SWAT was applied in two catchment basins of northern Greece, Mouriki and Anthemountas, to forecast groundwater recharge under climate-driven changes. Due to the absence of hydrometric stations in [Anthemountas basin](#), the calibration was successfully obtained by using ET values from MODIS. The two study areas differ widely regarding recharge and runoff predictions. Mouriki is characterized by a high recharge rate and low runoff production that will probably not undergo significant changes in the future, both in temporal and spatial distributions. The recharge of this site is highly dependent on ET and driven by the local dense forest vegetation. In [Anthemountas basin](#), runoff was calculated as being significantly higher than recharge. This difference is attributed to land cover regime and precipitation levels. In the coastal basin of Anthemountas, the predicted reduction in precipitation and increased air temperatures may lead to years with severe drought conditions in the future. This is in accordance with predicted decrease in groundwater recharge which may lead to groundwater scarcity in the coming years, especially for the period 2036–2040. Small eco-friendly energy recharge dams may be a solution to partly overcome future groundwater scarcity in [Anthemountas basin](#).

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11269-021-02907-2>.

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Data Availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval The authors declare that the submitted manuscript is original and unpublished elsewhere, and that this manuscript complies with the Ethical Rules applicable for this journal.

Conflicts of Interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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