Journal of Hydrology 546 (2017) 1–13

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Developing empirical monthly groundwater recharge equations based on modeling and remote sensing data – Modeling future groundwater recharge to predict potential climate change impacts

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ARTICLE INFO

Article history:
Received 27 September 2016
Received in revised form 28 December 2016
Accepted 4 January 2017
Available online 5 January 2017
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Magdeline Laba, Associate Editor

Keywords:
Groundwater recharge
MODIS evapotranspiration data
SWAT model
Climate change effects on recharge

ABSTRACT

Groundwater recharge is one of main components of the water budget that is difficult to quantify due to complexity of recharge processes and limited observations. In the present work a simple regression equation for monthly groundwater recharge estimation is developed by relating simulated recharge from a calibrated Soil and Water Assessment tool (SWAT) model to effective precipitation. Monthly groundwater recharge and actual evapotranspiration (AET) were computed by applying a calibrated (SWAT) model for a ten year period (2005–2015) in Vosvozis river basin in NE Greece. SWAT actual evapotranspiration (AET) results were compared to remotely sensed AET values from the MODerate Resolution Imaging Spectroradiometer (MODIS), indicating the integrity of the modeling process. Water isotopes of ^{2}H and ^{18}O, originally presented herein, were used to infer recharge resources in the basin and provided additional evidence of the applicability of the developed formula. Results showed that the developed recharge estimation method can be effectively applied using MODIS evapotranspiration data, without having to adhere to numerical modeling which is many times constrained by the lack of available data especially in poorly gauged basins. Future trends of groundwater recharge up to 2100 using an ensemble of five downscaled climate change projections indicated that annual recharge will increase up to the middle of the present century and gradually decrease thereafter. However, the predicted magnitude is highly variable depending on the Global Climate Model (GCM) used. While winter recharge will likely increase in the future, summer recharge is expected to decrease as a result of temperature rise in the future.

1. Introduction

Future changes in groundwater recharge due to climate variability and change are uncertain because of the complex nature of recharge processes and lack of observational data (Green et al., 2011). Climate variability and change have impacted magnitudes of precipitation and its seasonal distribution (Easterling et al., 2000). The Mediterranean region in particular has been identified as one of the main "hot-spots" of climate change projections (Giorgi, 2006). Global climate model projections for this region predict decreases in annual precipitation especially during the warm season and increases in winter precipitation in the northern parts (Giorgi and Lionello, 2008). However, it is not clear how changes in precipitation impact recharge rates in this region.

Groundwater recharge is the amount of water that infiltrates through various mechanisms to the subsurface and reaches groundwater. Those mechanisms include rainfall infiltration through both diffuse and preferential pathways as well as irrigation return flows and leaking pipes in urban areas (Crosbie et al., 2010). Direct measurement of groundwater recharge is almost impossible due to the nature of the quantity itself as well as the complexity and heterogeneity of hydrogeological settings (Kinzelbach et al., 2002). Hydrologic modeling is a reliable indirect method for groundwater recharge estimations (Jayakody et al., 2014) and assessing the impact of climate variability on recharge. Crosbie et al. (2011) applied various hydrological models for future recharge predictions and found that uncertainty in estimations

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http://dx.doi.org/10.1016/j.jhydrol.2017.01.005
0022-1694/

mainly stems from the choice of the Global Climate Model (GCM) and the downscaling method, and to a lower extent to the choice of a hydrological model. Taylor et al. (2012) indicate that future groundwater recharge is closely related to projected changes in precipitation, and uncertainty of recharge predictions is attributed to an inherited uncertainty of estimating a physical quantity that cannot be directly measured (Taylor et al., 2009). Crosbie et al. (2013), predicted both increases and decreases in recharge rates even greater than 50% of the current recharge in the High Plains Aquifer, USA, and showed that the magnitude and direction of future changes in recharge rates are highly uncertain and vary greatly between future dry and wet climate scenarios. Döll (2009) conducted global scale groundwater recharge modeling and found that by 2050 under A2 and B2 emissions scenarios there will be decreases exceeding 70% of potential groundwater recharge in northeast Brazil, southwest Africa and in the southern edge of Mediterranean Sea. In the same study, increases of potential recharge of more than 30% in the Sahel, Middle East, northern China, Siberia and the western United States were determined. Regional recharge studies in Australia based on the ensemble medians of 16 GCMs predict that, recharge will decrease in the west, central and south Australia while there will be an increase in the north (Crosbie et al., 2013). Application of four GCMs in Europe showed a reduction in groundwater recharge in southern Europe and an increase in northern Europe (Hiscock et al., 2011). As pointed out by Taylor et al. (2012), groundwater recharge seems to follow the spatial and temporal distribution of precipitation. More precipitation, however, does not necessarily produce more groundwater recharge, especially when increased temperature transforms the excess precipitation to evapotranspiration. In all cases, predictions of groundwater recharge are highly variable both in terms of magnitude as well as in direction, depending on latitude and GCMs used.

As it can be seen, future changes in recharge rates are highly uncertain. On the other hand, sustainable water resources management requires reliable groundwater recharge estimates to determine renewable groundwater quantities and provide a threshold for human consumption. Therefore, there is a need to provide reliable recharge estimates particularly in data sparse regions by taking the advantage of hydrologic models, and the variety of remotely sensed products available at a global scale. While empirical relationships have been developed to relate annual precipitation to groundwater recharge, especially in the U.S. and India (Maxey and Eakin, 1949; Sehgal, 1973; Hearne and Dewey, 1988; Anderson et al., 1992; Waltemeyer, 2001; Kambhammettu et al., 2011), their application is often limited to the specific geographical area where they are developed for, and there is no unique universal formula applicable at the global scale. This is due to the fact that local climate, vegetation type and hydrogeological conditions are key controlling factors of groundwater recharge.

In our work, Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Arnold and Fohrer, 2005; Arnold et al., 1993; Neitsch et al., 2009) was used to estimate monthly groundwater recharge. SWAT is a basin scale physically based, semi-distributed hydrologic model developed to predict the impact of land management practices over long periods of time on water and sediment. Numerous applications of SWAT model include runoff, actual evapotranspiration, sediment yield, nutrient loading and recharge estimation at a catchment scale (Awan and Ismaeel, 2014; Izady et al., 2014; Pisinaras et al., 2014; Vigiak et al., 2015). Dakhlalla et al. (2016) used SWAT model to evaluate crop rotation impact on groundwater storage and recharge in the Big Sunflower River Watershed in Mississippi. It should also be noted that due to the scarcity of direct recharge rate measurements, hydrologic models cannot be calibrated and verified using recharge rates. Instead, runoff measurements or groundwater levels are used for calibration and verification of hydrological models (Dakhlalla et al., 2016). However, in many basins where continuous long term measurements of groundwater levels or stream flow are not available, research has been focused on the application of remotely sensed data (Lakshmi, 2013; Mohanty et al., 2013). The role of remote sensing in modeling and prediction of ungauged basins is thoroughly analyzed by Lakshmi (2004), focusing on the need to use readily available images of many hydrologic variables (soil moisture, soil surface temperature, evapotranspiration, vegetation) along with remotely sensed precipitation. Syed et al. (2004), used a combination of remotely sensed data and ground observations and found that the hydrologic cycle in the continental United States is mostly influenced by precipitation and potential evaporation. Lakshmi and Susskind (2000) concluded that remotely sensed data can form a realistic alternative for use in hydrological modeling. Nevertheless, those data have coarse resolution, making them suitable for use in medium to large basins, preferably larger than 100 km^2 (Lakshmi, 2004).

Further to numerical modeling, environmental isotopes of hydrogen and oxygen were applied in the present work in order to acquire an assessment of groundwater recharge. Environmental isotopes are particularly useful and can be considered as an indirect method for estimating groundwater recharge. Previous investigations have used environmental isotopes for recharge estimation, study of mixing processes, determination of groundwater origin, and investigation of sources of groundwater salinity (Gemitzi et al., 2014; Subyani, 2004; Girard et al., 1997). Girard et al. (1997) used stable isotopes of oxygen and hydrogen, i.e. ^{2}H, ^{18}O as well as the radioactive Tritium (^{3}H) to explain recharge to Sahelian aquifers in Niger. Dassi (2011) used a multi-tracer approach including environmental isotopes to elucidate the origin and movement of groundwater within a multi-layer aquifer. ^{2}H and ^{18}O were used to estimate sources of river and lake water and the origin of groundwater in the Okanagan valley in Canada (Wassenaar et al., 2011) as well as for distinguishing sources of groundwater recharge (Blasch and Bryson, 2007).

The aim of the present work is to provide a simple empirical equation for monthly recharge computation and to examine whether it can be considered as an alternative to hydrological modeling for future monthly recharge estimation. This could offer a challenging alternative for other Mediterranean basins of analogous climate and hydrological setting, especially ungauged ones, where hydrologic modeling cannot be applied for recharge estimation. To achieve this objective, we examine the accuracy of recharge estimates of the SWAT model applied at a typical Mediterranean basin, using remotely sensed evapotranspiration data and stable isotopes recharge estimates, and compare the impacts of climate changes on groundwater recharge using empirical and numerical modeling approaches.

2. Methods and materials

2.1. Study area description

The study catchment is the Vosvozis river basin (Fig. 1) in NE Greece which extends from the Thracean Sea up to Greek - Bulgarian borders. It is a typical medium sized Mediterranean basin covering approx. 340 km^2. The average annual precipitation over the period 1960–2010 is 628 mm and the average annual temperature is 16.5 °C. Primary land use in the southern plain part of Vosvozis basin is agriculture, where groundwater is intensively used for irrigation and domestic use. Previous works, showed that water consumption for irrigation during summertime has caused groundwater level drawdown and a subsequent aquifer deteriora-

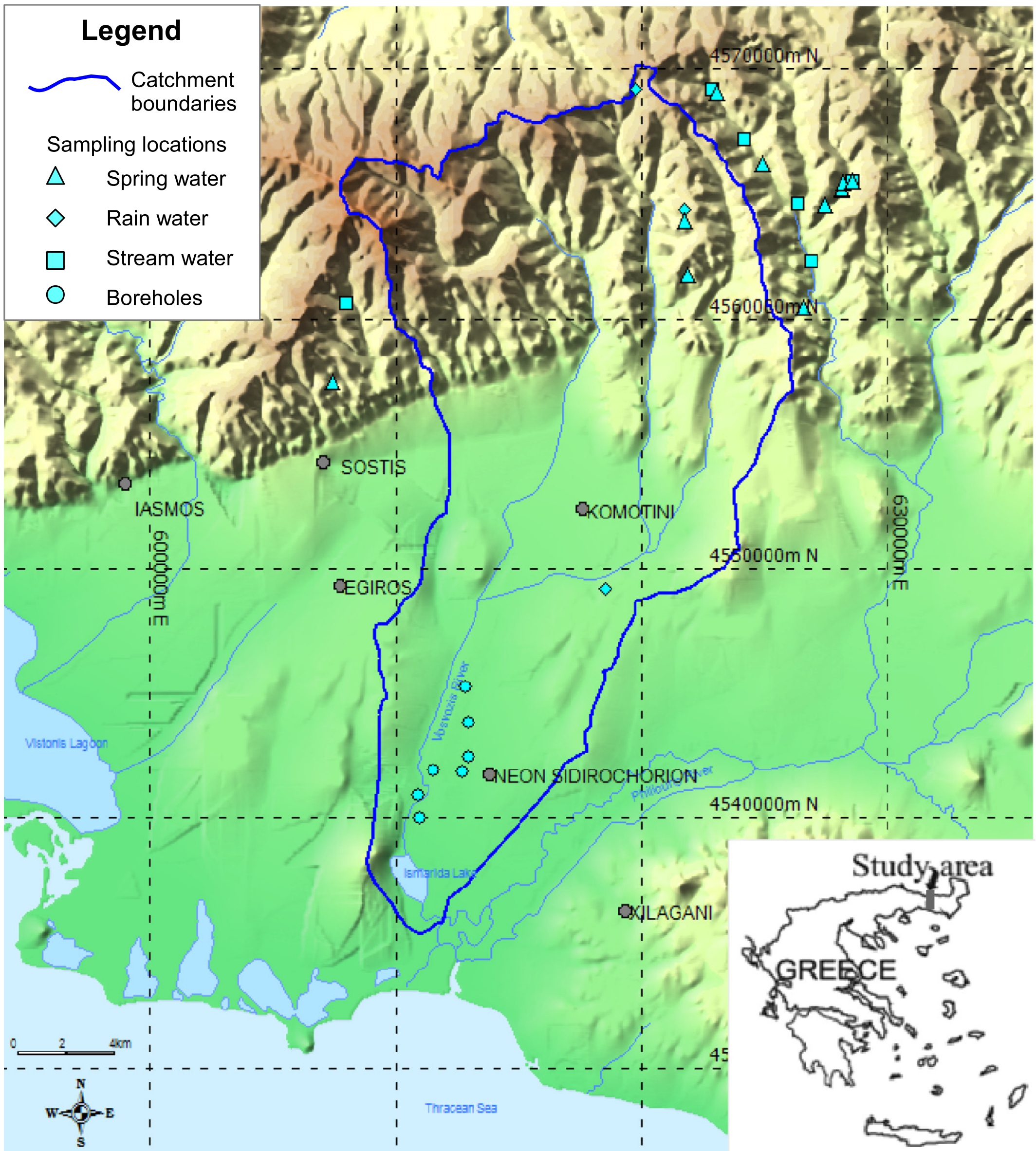

Fig. 1. Location map of the Vosvozis river basin showing sampling locations.

tion (Gemitzi and Stefanopoulos, 2011). The northern part is a pristine mountainous area covered by forest.

From the hydrogeological point of view the northern mountainous terrain of the study basin consists of Paleozoic metamorphic rock formations, mainly gneisses, schists, marbles and amphibolites (Kilias et al., 1999). Within this area, fractured aquifers are found and numerous springs are formed connected to those aquifers. The southern part of the basin is flat and it is formed by Pliocene and Quaternary alluvial deposits, where porous aquifers are found. Water coming from the mountainous area both in the form of subsurface or surface flow, provides recharge to those aquifers (Gemitzi, 2012).

Meteorological data for years 2005–2015, i.e. precipitation, minimum and maximum temperature values, relative humidity, solar radiation, wind speed, on a daily time step were provided from one meteorological station located in the centre of the Vosvozis river basin very close to Komotini town (Fig. 1). Mean monthly values of precipitation and temperature show a typical annual pattern with highest precipitation in cold months and maximum temperature in July and August (Fig. 2).

2.2. Recharge modeling using SWAT

In order to establish a simple monthly recharge computation formula, the calibrated SWAT model developed for the Vosvozis river basin (Pisinaras et al., 2014) was used. Pisinaras et al. (2014) developed a SWAT model of the Vosvozis study basin to predict land use change effects on major hydrologic budget components. The model was calibrated for the 2008–2010 period using stream flow observations. The period 2010–2012 was used for the verification period. During calibration several model parameters were adjusted within a predefined range until maximum agreement to stream flow measurements is reached. Calibration parameters included Curve Number (CN), Soil Evaporation Compensation factor (ESCO), Plant uptake Compensation factor (EPCO), Soil Available Water Capacity (SOL_AWC), Groundwater "Revap" coefficient (GW_REVAP), threshold Depth of water in shallow aquifer for percolation to occur (GWQMIN), deep aquifer percolation fraction (RCHRG_DP), and Manning's n for channel roughness (N) (see Supplementary material). CORINE land cover data, crop type and irrigation data were acquired from the Greek Ministry

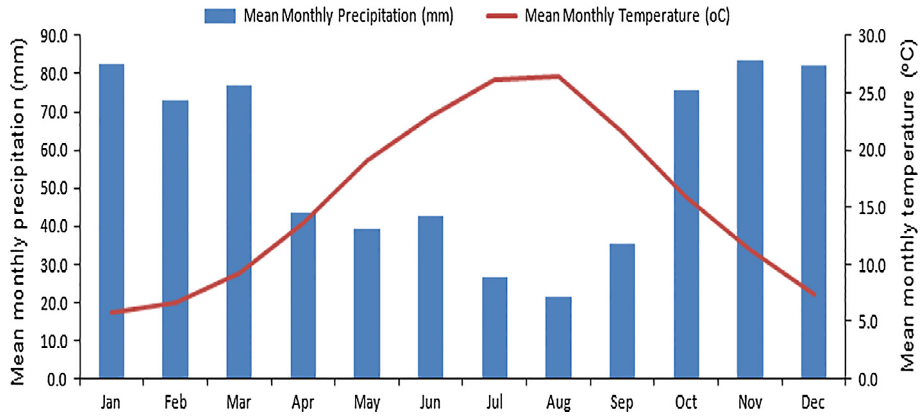

Fig. 2. Means of historical monthly precipitation and temperature for 2005–2015.

of Agriculture. Those land cover types were reclassified to SWAT land cover codes for input to the model. Soil data were obtained from the soil map of Eastern Macedonia and Thrace (Misopolinos, 2009) and were incorporated into the SWAT database. A Digital Elevation Model (DEM) with a 50 × 50 m resolution was used to delineate 211 sub-basins and 265 Hydrologic Response Units (HRUs). While there is only one meteorological station available in the study basin, SWAT incorporates up to 10 elevation bands in each sub-basin to adjust for orographic effects. In SWAT, precipitation and minimum and maximum temperature are calculated for each band as a function of the difference between the elevation of the gage station and the elevation band. More details on the SWAT model application, calibration and verification are provided in Pisinaras et al. (2014).

In order to calculate recharge rates, the calibrated SWAT model was applied for the time period 2005–2015 in this study. Within the SWAT model, recharge is the amount of water that enters and flows through the vadose zone and moves out of the bottom of the soil profile through percolation or bypass flow, to reach the underlying aquifers. Temporal variability of vadose zone soil moisture is controlled by precipitation and water table fluctuations. Recharge is routed to two types of aquifers in SWAT; the shallow aquifer and the deep aquifer. The shallow aquifer contributes base flow to the main channel of the sub-basin whereas the deep aquifer does not. Recharge to the deep aquifer is not considered in future water budget calculations and is regarded as loss from the system. Within the present work, recharge is the total amount of water entering the groundwater system, either shallow or deep aquifer system. As no recharge measurements are available for the basin, validity of the developed model is further assessed by comparing modeled monthly AET from SWAT with remotely sensed monthly AET product retrieved from the MODerate Resolution Imaging Spectroradiometer (MODIS) satellite from January 2005 to December 2014. This evaluation provides an additional evidence for the integrity of the SWAT computations and the reliability of the calibrated SWAT model for estimating groundwater recharge rates. MODIS AET dataset comprised of 8-day AET values from January 2005 to December 2014 (no AET values yet available for 2015), with a spatial resolution of 1 km (Mu et al., 2011). 8-day AET values from 1 km grid cells across the whole basin were aggregated to get the monthly values. Evapotranspiration (ET) can be calculated using remotely sensed data either by statistical methods that link measured ET to remotely sensed vegetation indices or by applying physical models that calculate ET using remotely derived vegetation data. Mu et al. (2007), developed an algorithm that calculates ET using the Penman - Monteith formula (Monteith, 1964) and MODIS land cover, albedo, leaf area index (LAI), and Enhanced Vegetation Index (EVI) together with daily meteorological reanalysis data. The initial algorithm was further improved to incorporate nighttime ET components (Mu et al., 2011). Within this latter work, AET is the sum of evaporation from the wet canopy surface, the transpiration from the dry canopy surface and the evaporation from the soil surface. This methodology was implemented for the computations of MODIS AET product that was used in the present work. Those products have been used extensively in global and regional hydrological research and they are recognized as a reliable source of information for impact studies.

2.3. Groundwater recharge estimates using stable isotopes

The stable oxygen and hydrogen isotopic composition of water can offer a valuable tool for determining possible sources of recharge, recharge areas and mixing processes (Schmidt et al., 2011). Within the present work ^{2}H and ^{18}O were used to compute recharge rates in the study area. Water samples were collected in the broader area, from spring water, river water, precipitation and boreholes during summer 2013 (Fig. 1). Borehole water was used to estimate isotopic signature of groundwater, as it corresponds to water that has remained a sufficient period of time within the aquifer. River water was used to calculate surface water isotopic signature. The isotopic composition of water from springs was used to estimate recharge rates in the study area, assuming that water from springs is a mixture of pre-existing groundwater, surface water contribution and precipitation recharge.

Sampling took place during summer 2013 in locations shown in Fig. 1. Samples were collected in 100 ml clean polyethylene bottles, which were tightly capped in order to avoid any evaporation before the analysis. Stable isotope ratios (^{2}H/H and ^{18}O/^{16}O) were determined by isotope mass spectrometry following the procedure described in Gemitzi et al. (2014) and the results were reported in the delta notation (δ^2H, δ^{18}O) in per mil (‰) relative to Vienna Standard Mean Ocean Water (VSMOW). Isotopic analyses were conducted at the Department of Isotope Biogeochemistry within Helmholtz Centre for Environmental Research in Leipzig.

In general, n + 1 different sources that contribute proportionally to a mixture can be uniquely quantified using n different isotope tracers (e.g. δ^2H, δ^{18}O) by linear mixing models and mass balance equations. Phillips and Gregg (2003), developed a computer software namely IsoSource, that calculates possible combinations of each source contribution, even when the number of potential sources exceeds n + 1, using an iterative procedure. The program iteratively creates each possible combination of source proportions (that sum to 100%) by an increment of 1% and then the predicted isotopic signatures for the mixture are computed for each combination and they are compared to the observed ones. A tolerance of 0.1% is allowed for a certain combination to be regarded as a feasible solution. In the present work IsoSource together with the isotopic signatures of three end members corresponding to each water source i.e., groundwater, surface water, rain water, were used to calculate their proportional contributions to the mixture.

2.4. Establishing a groundwater recharge to effective precipitation relationship

Recharge is a fraction of precipitation after evapotranspiration losses. Therefore, it was thought reasonable to develop a regression equation to relate monthly effective precipitation (EP) (precipitation minus actual evapotranspiration) to modeled monthly groundwater recharge using monthly aggregates of SWAT simulated daily AET and groundwater recharge respectively. SWAT first calculates potential evapotranspiration (PET) using one of the three incorporated PET estimation methods, i.e., Priestley - Taylor (Priestley and Taylor, 1972), Penman - Monteith (Monteith, 1964), or the Hargreaves (Hargreaves and Samani, 1982). The Hargreaves method was selected in the presented work. Once PET is determined, AET is calculated by evaporating any rainfall intercepted by the plant canopy and then by providing transpiration and soil evaporation losses (Neitsch et al., 2011).

Furthermore, we replaced SWAT AET values by the remotely sensed MODIS AET values (ORNL DAAC, 2008) to develop the regression equation. As a result, the final formula for monthly recharge estimation does not rely on modeled AET values. Monthly recharge can be simply computed by acquiring monthly precipitation and remotely sensed AET values.

3. Results and discussion

In order to measure agreement of MODIS AET values to SWAT calculated monthly AET, the Index of Agreement (IoA) was used as it is an efficient way of cross comparison across models (Willmott, 1982):

$$d = 1 - \left[\sum_{i=1}^{N}(P_i - O_i)^2 \Big/ \sum_{i=1}^{N}(|P'_i| + |O'_i|)^2\right] \quad 0 \leqslant d \leqslant 1 \tag{1}$$

where $P'_i = P_i - O_i$ and $O'_i = O_i - \bar{O}$. P_i and O_i correspond to predicted and observed values respectively. $\bar{O}$ is the mean value of observed values. In our case observed values (O_i) are taken to be catchment averaged monthly MODIS AET values and predictions (P_i) are monthly AET modeled with SWAT model during January 2005 to December 2014. d = 0 indicates no agreement between the two data sets, whereas d = 1 refers to a perfect agreement. IoA for the two predefined data sets is 0.90 and R-squared coefficient is 0.89, implying that SWAT modeling processes managed to capture sufficiently well the hydrological processes in the study basin. Comparison graph of the MODIS and SWAT monthly AET can be seen in Fig. 3.

Applying a regression analysis as described in Section 2.4 resulted in the determination of two simple monthly recharge estimation formulas. Eq. (2) uses SWAT AET values, whereas Eq. (3) is based on the monthly MODIS AET:

$$\mathrm{GR} = 0.4999(\mathrm{P} - \mathrm{AET_{SWAT}}) + 0.041 \tag{2}$$

$$\mathrm{GR} = 0.5174(\mathrm{P} - \mathrm{AET_{MODIS}}) + 0.2145 \tag{3}$$

GR corresponds to monthly groundwater recharge (mm), P is monthly precipitation (mm) and AET_{SWAT} and AET_{MODIS} are monthly actual evapotranspiration values (mm). As can be seen in Fig. 4a and 4b, both equations have high R-squared coefficients of 0.82 and 0.72 respectively. While lower R^2 value is obtained using MODIS AET data in Eq. (3), the use of readily available meteorological and remotely sensed data without having to set up a hydrological model seems a reasonable compromise.

The fact that intercept in both Eqs. (2) and (3) is not zero can be explained by taking into account that small amounts of recharge can be observed in SWAT results even in dry months. This is due to the physical subsurface processes that delay water in the unsaturated zone from instantaneously reaching the groundwater table. Thus, precipitation from previous months may result in recharge during future months.

Comparison of the computed seasonal recharge with values acquired using stable isotopes of oxygen and hydrogen, provided an additional justification of the results obtained by SWAT and Eqs. (2) and (3). It should be noted that isotopic data were available only for summer 2013 (see Supplementary material). Therefore they can be regarded only as an indication that the methodology is sound. Fig. 5 shows scatter plots of $\delta^{18}O$ and $\delta^{2}H$ values for various water bodies in the study area during summer 2013. On the same graph the Local Meteoric Water Line (LMWL) is plotted. The Greek LMWL is defined to be equal to $\delta^{2}H = 8.7\delta^{18}O + 19.5$ (Dotsika et al., 2010). Plotting of the majority of water samples below the LMWL indicates the evaporation effect during the summer period, as the period of sampling corresponds to the period of highest evaporation impacting all water bodies in the study area. According to the results presented in Tables 1 and 2, precipitation recharge ranges from 10.7% to 31.9% with median value of 14.5% using stable isotopes. Solution for 5 samples could not be reached as the oxygen or hydrogen values or both were out of the range of the isotopic signatures of the three end members. The corresponding recharge value for summer 2013 (May to August) with SWAT model is equal to 11%, while for Eqs. (2) and (3) are 10.8% and 11.5% respectively. It should be noted herein, that isotopes provided a quite high range of recharge rates attributed to the specific characteristics of each individual spring. Within this context, these results provide some additional indication that SWAT recharge is within expected range obtained from isotope data.

4. Climate change effects

Groundwater recharge corresponds to the quantity of water that enters the aquifer system and it would be thus of particular importance to be able to predict its future trend for groundwater management planning and sustainable use. To predict future recharge, downscaled precipitation and temperature data up to 2100 were provided from the Rossby Centre of Swedish Meteorological and Hydrological Institute (SMHI) within the frames of the recently completed FP7 project Groundwater and Dependent Ecosystems: New Scientific and Technological Basis for Assessing Climate Change and Land-use Impacts on Groundwater (GENESIS, Contract No: 226536). These data are based on the A1B scenario of the following five GCMs: (a) CCMS3, (b) CNRM, (c) ECHAM5-r3, (d) HADCM3-Q0 and (e) IPSL described in Pisinaras et al. (2014). The A1B Intergovernmental Panel on Climate Change (IPCC) scenario indicates a very rapid economic growth, introduction of new and more efficient technologies and a balanced use of energy sources (IPCC, 2000). These five predefined GCMs were dynamically downscaled using the RCA3 regional climate model (RCM) with a spatial resolution of 50 km. Distribution Based Scaling (DBS) was used to correct systematic bias in GCM/RCM outputs (Olsson et al., 2013), with reference observation data from five meteorological stations in the broader region of Eastern Macedonia and Thrace for the time period 1960–2010.

Time series plots of annual precipitation and temperature according to the ensemble of the five climate models are shown in Fig. 6. Trend lines (blue lines) and their 95% confidence intervals

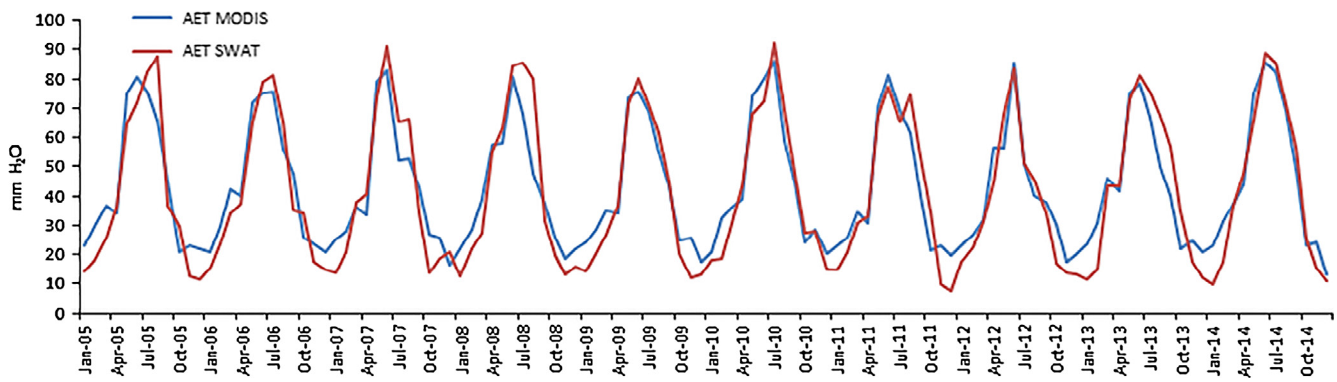

Fig. 3. Comparison of catchment averaged MODIS derived monthly AET to SWAT modeled AET.

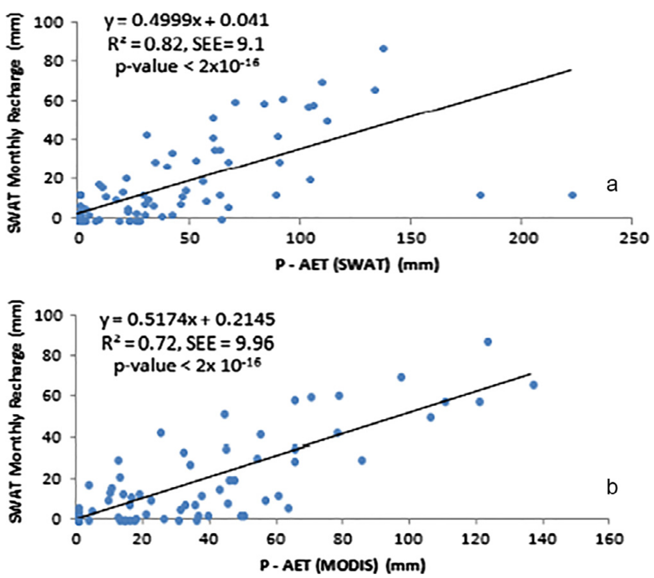

Fig. 4. Regression equations for monthly groundwater recharge estimation, (a) using SWAT computed AET, (b) using MODIS estimates for AET.

are also shown on those plots, together with the p-values of statistical significance of the trends. Compared to the long term historic mean (1960–2010) (black lines), annual precipitation (Fig. 6a) shows a decreasing trend. However only annual precipitation from the CNRM demonstrated an almost statistically significant trend at 5% level (p-value = 0.05), whereas p-values of the rest of models where higher than 0.06 indicative of not statistically significant trend. High precipitation variability is the major characteristic of projected annual precipitation across the five examined scenarios. Therefore, this variability seems to be the main reason that results in no statistically significant trend in four out of the five examined climate scenarios. Nevertheless, future precipitation is predicted to decrease in the Mediterranean region as shown in other studies (Giorgi, 2006; Giorgi and Lionello, 2008), where a substantial drying of the specified region, especially in the warm season (precipitation decrease exceeding −25–30%) is determined.

Regarding temperature projections, all GCMs show increases in annual temperature which are statistically significant trend (p-values < 10^{-13}) (Fig. 6b). Compared to the long term historic mean (1960–2010) (black dotted line), annual temperature is expected to rise from 3 °C (CCMS3) to 5.5 °C (HADCM3-Q0). This is also in agreement with works from Giorgi (2006) and Giorgi and Lionello (2008), which predicted warming of the Mediterranean region to exceed 4–5 °C.

The calibrated SWAT model was run for the period 2015–2100, using precipitation and temperature input from the above mentioned climate models. No land use changes were incorporated in the model. Monthly recharge was estimated using both SWAT model and Eq. (2). As no future AET products were available from remotely sensed sources (e.g. MODIS PET and AET products) the following approach was implemented to estimate AET in Eq. (2). PET was first estimated using the Hargreaves method (Hargreaves and Samani, 1982) and AET was calculated from PET using the following regression formula:

$$AET = 0.62\ PET - 2.313 \tag{4}$$

The above formula was extracted from monthly Hargreaves PET values and SWAT monthly AET modeled values from January 2005 to July 2015. The R-squared value as seen in Fig. 7 is 0.92.

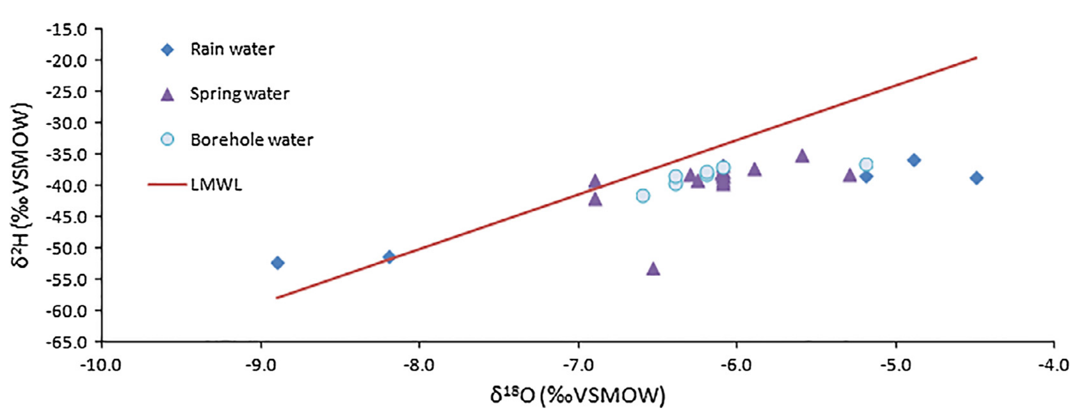

Fig. 5. Scatter plot between δ2H and δ18O in various water bodies of the study area during summer 2013.

Table 1
Calculated mixing ratios using isotope data for spring waters in the study area during summer 2013.

Sample name	Sampling date	δ18O (‰ SMOW)	δ2H (‰ SMOW)	Precipitation contribution to spring water (%)	Pre-existing groundwater contribution to spring water (%)	Surface water contribution to spring water (%)
S1	21–06–13	−6.1	−37.5	13.5	84.5	2.0
S2	21–06–13	−6.9	−41.8	n/a[1]	n/a[1]	n/a[1]
S3	21–06–13	−5.3	−38.0	n/a[1]	n/a[1]	n/a[1]
S4	21–06–13	−6.1	−39.4	20.5	79.5	0.0
S5	21–06–13	−5.9	−37.2	22.7	74.3	3.0
S6	21–06–13	−6.1	−38.2	14.5	84.4	1.1
S7	21–06–13	−6.1	−37.7	10.7	87.7	1.5
S8	21–06–13	−6.3	−38.1	31.8	65.8	2.5
S9	21–06–13	−6.1	−37.8	12.7	85.7	1.5
S10	21–06–13	−6.5	−53.0	n/a[1]	n/a[1]	n/a[1]
S11	21–06–13	−6.3	−39.0	31.9	66.8	1.3
S12	21–06–13	−6.1	−38.3	13.3	85.7	0.9
S13	21–06–13	−6.1	−39.1	17.6	82.2	0.2
S14	29–06–13	−6.1	−36.7	13.0	84.0	3.0
S15	29–06–13	−6.9	−39.0	n/a[1]	n/a1	n/a[1]
S16	29–06–13	−5.6	−35.1	n/a[1]	n/a[1]	n/a[1]

N/A corresponds to not available values as the required accuracy of computations could not be reached.

Table 2
Isotopic signatures of various water sources.

End member	δ18O (‰ SMOW)	δ18O (‰ SMOW)
Groundwater	−6.2	−38.3
RainWater	−6.3	−43.1
SurfaceWater	−6.20	−38.1

Future annual recharge projections are shown in Fig. 8 and Table 3. Fig. 8 shows decadal (except of the period 2095–2100) means of annual recharge estimates using SWAT model and Eq. (2) predictions based on the inputs from the five GCMs. The reference period (2005–2015) in Fig. 8 presents the SWAT estimated groundwater recharge with observed climate data. Both SWAT and Eq. (2) provide very similar recharge estimates. The mean annual recharge based on the precipitation estimates from ensemble of five GCMs (black line in Fig. 8) demonstrates a significant increase in recharge for 2015–2025 period which is a result of higher precipitation estimates in the first prediction decade, 2015–2025 than the 2005–2015 period. As all 5 GCMs project increases in precipitation for 2015–2025 period, it is likely that the 2015–2025 decade will be wetter than the previous decade with observed mean annual precipitation of 610 mm which is below the historical mean of 628 mm. Increase of recharge is observed up to 2035–2045 decade and a gradual decline thereafter, which agrees with the predicted precipitation pattern (R2 of recharge to precipitation for all models > 0.85). Fig. 9 shows monthly mean recharge estimates using precipitation and temperature data from 5 GCMs in Eq. (2). As can be seen in Fig. 9, projected spring and summer months recharge are lower than the historical mean recharge (2005–2015) (black dotted lines in Fig. 9). The exception is recharge in September which is higher than historical mean monthly recharge up to the middle of the century and then decreases afterwards demonstrating a statistically significant declining trend. While recharge during October and November months are higher than the historical mean, a statistically significant declining trend is also observed in these cases. Predicted recharge in December is also higher than the historic mean; however, no significant trend was detected. While recharge in January is below the historic mean, an increasing trend in future January recharge is observed which is not statistically significant. An apparent decrease of recharge during May is perhaps the most alarming evidence regarding monthly groundwater recharge. Recharge in May is constantly below the historical period throughout the century with a statistically significant sharp decreasing trend. This finding and the fact that all summer months show recharge values lower than those of historical period, imply that groundwater will lose much of its replenishment during the period of peak demand and it is possible to pose stress to the local aquifer systems. Additionally, recharge decline during May, September and October combined with anticipated temperature increase, might result in longer growing season, as farming period in Mediterranean areas typically corresponds to warm and dry period of summer.

To investigate sensitivity of recharge to changes in future precipitation, a scatter plot of changes of decadal means of annual precipitation versus changes in decadal means of annual recharge compared to reference decade (2005–2015) is produced for the five climate scenarios (Fig. 10a). The slope of the regression lines reflect sensitivity of recharge to precipitation changes, whereas the intercept represents recharge sensitivity to variables other than changes in precipitation (e.g. temperature changes, changes in precipitation intensity, land use changes, etc.) (Crosbie et al., 2013b). The slopes of regression lines of Fig. 10a range from 0.6 to 1.2, indicating that for every 1% change in decadal precipitation there is a 0.6–1.2% change in decadal recharge. The intercept of regression lines range from 13.1 to 16, indicating that changes in decadal recharge are expected even if no precipitation changes occur. Those changes are attributed to changes in factors other than precipitation, including changes in precipitation intensity and frequency, changes in precipitation and temperature seasonality as well as changes in PET that influence AET in the various GCMs.

Sensitivity of recharge to changes in future temperature is presented on the scatter plot of Fig. 10b. Changes of decadal means of annual temperature versus changes in decadal means of annual recharge compared to reference period (2005–2015) are plotted for the five climate scenarios (Fig. 10b). The slopes of regression lines are all negative, ranging from −2.9 to 10.8. Thus for every 1 °C increase in decadal temperature a decrease in decadal mean of annual recharge of 2.9–10.8% is expected. The y-intercepts are all positive and range from 16.9 to 48.5, indicating that if no temperature changes occur, a significant increase in recharge is expected attributed to other factors except temperature. These factors are changes in precipitation intensity and frequency, seasonal differences in precipitation and temperature and PET changes in the various GCM.s

Comparing the percentage of change of recharge for precipitation and temperature over the range of the various GCM scenarios in Fig. 10a and b, an increase of 11–32% of recharge is observed related to precipitation and a reduction of recharge of 5–31% is

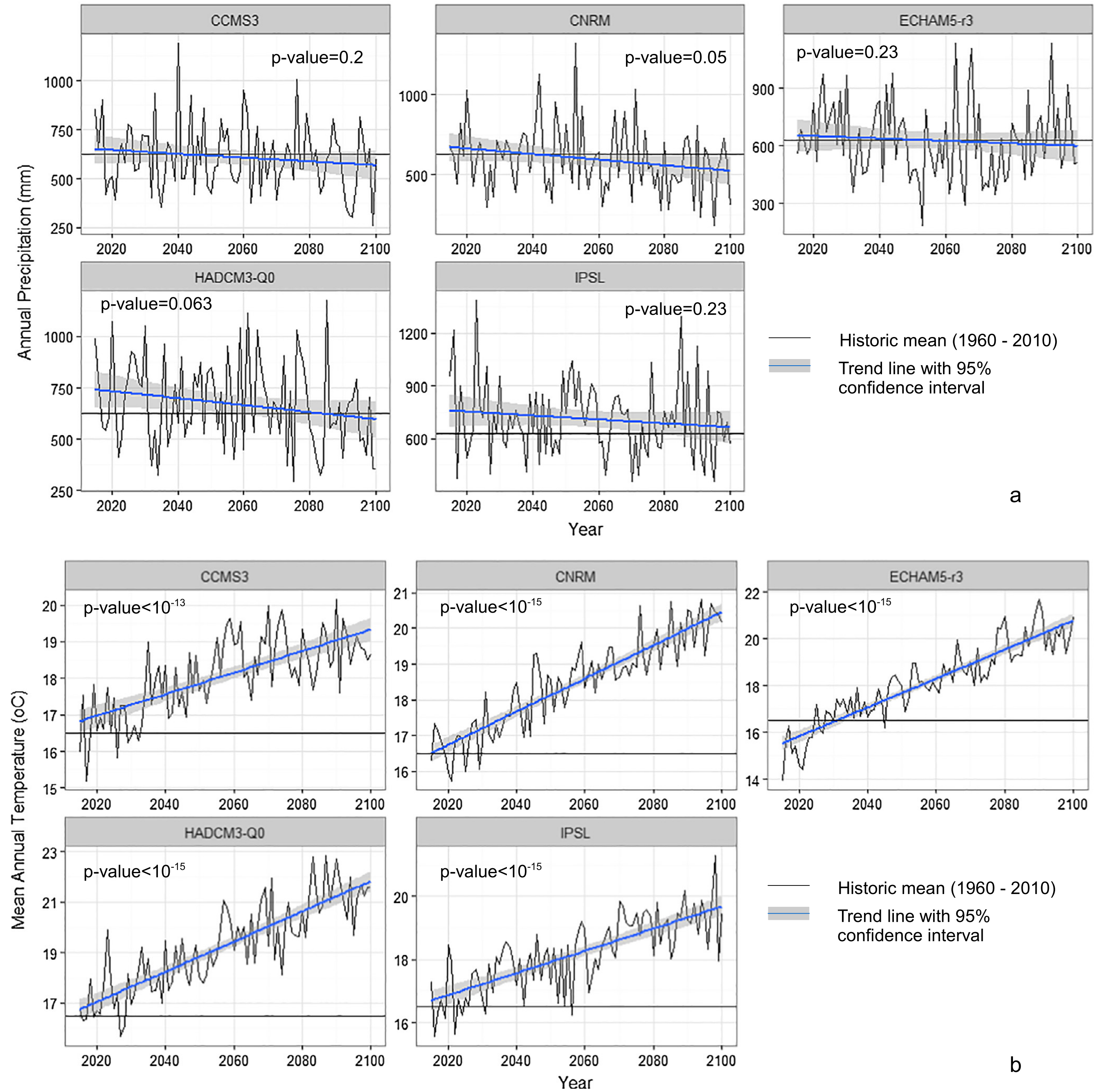

Fig. 6. Time series plots of (a) annual precipitation and (b) mean annual temperature according to the ensemble of the five climate projections using the A1B scenario for the prediction period 2015–2100. p-values correspond to statistical significance of the trends.

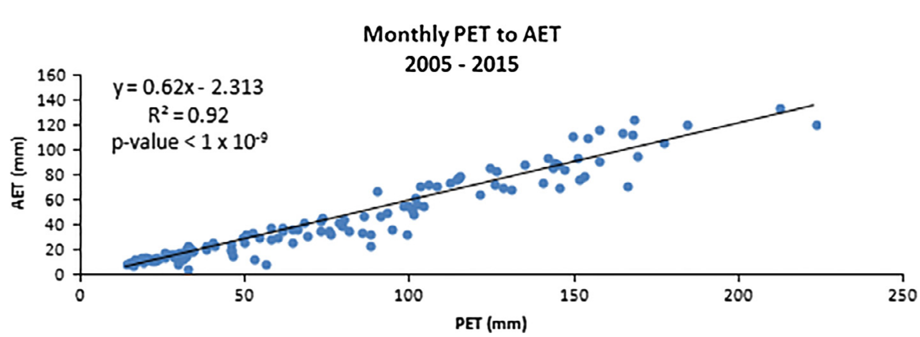

Fig. 7. A regression equation for predicting SWAT monthly AET using Hargreaves's PET values.

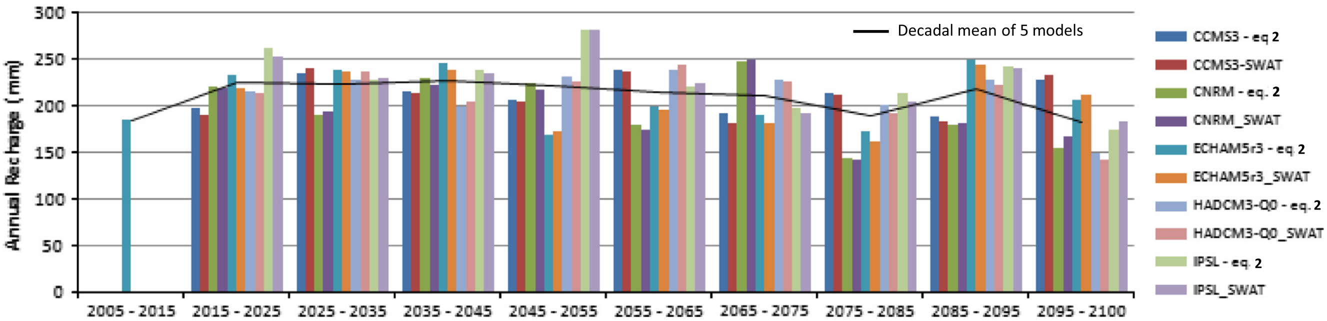

Fig. 8. Decadal means of annual recharge projections for 2015–2100 period using SWAT and empirical Eq. (2). Mean of annual recharge for 2005–2015 is shown as a reference for historic condition.

Table 3
Percent change between mean annual recharge at the mid and end of the century compared to the reference period (2005–2015) using 5 GCMs projections and two recharge estimation methods.

Climate models - recharge estimation method	Annual recharge change % at the 2035–2045 decade	Annual recharge change % at the end of the century
CCMS3 - Eq. (2)	16.8	23.8
CCMS3 - SWAT	15.9	24.6
CNRM - Eq. (2)	25.0*	−15.7*
CNRM - SWAT	24.7*	−16.2*
ECHAM5r3 - Eq. (2)	33.4 *	12.3*
ECHAM5r3 - SWAT	35.8*	13.4*
HADCM3-Q0 - Eq. (2)	8.1	−19.6
HADCM3-Q0 - SWAT	7.8	−18.7
IPSL - Eq. (2)	29.8	−5.6
IPSL - SWAT	30.5	−6.1

* Mean difference between historic and predicted values are statistically significant ($p < 0.05$).

found for temperature. Those ranges suggest that recharge appears to be almost equally sensitive to both precipitation and temperature. Nevertheless, most of recharge changes are explained by precipitation changes as indicated by the low y-intercepts (Fig. 10a), whereas the wide range of slopes and the high y-intercepts related to temperature (Fig. 10b) reduces the role of temperature in explaining recharge changes relative to precipitation.

The findings of the present study showed that future changes in recharge have different seasonal characteristics consistent with future precipitation patterns in the five examined GCMs. Recharge during winter months seems to be dependent on precipitation changes and therefore its fate is strongly related to future precipitation projections. Although the direction of change in winter recharge is positive across all the GCMs, the magnitude of change of annual recharge is highly uncertain. Thus, it seems that water managers have to deal with considerable uncertainty while making important decisions on water allocations. This is in accordance with the findings of other works. Crosbie et al. (2013a) estimated recharge in the U.S. High Plains region up to 2050 and found that results encompass both increases and decreases, ranging from 0.5 to 1.25 of the historical recharge, according to climate scenario examined, i.e. dry, medium, and wet. The same uncertainty in recharge projections is also described in Murray - Darling basin, Australia, where recharge in 2030 is predicted to increase up to 32% based on a wet scenario, whereas recharge could decrease up to 12% in the case of a dry GCM scenario (Crosbie et al., 2010). Crosbie et al. (2011) applied multiple GCMs under the SRES A2 scenario (a relatively high emissions scenario) in order to predict future recharge changes for 2046–2065 period with respect to reference period 1981–2000, in west, south and eastern Australia. Results showed a wide range of future recharge changes, i.e. −55% to +17%, −83% to +447% and −68% to +101% at the three sites respectively. They also found that uncertainty in recharge estimates is mostly attributed to climate models projections Döll (2009) conducted future recharge projections at the global scale using ECHAM4 A2 scenario. According to this study a 15% decrease of groundwater recharge is expected in north eastern Greece in 2050 compared to 1961–1990 period. In our work, a decrease of groundwater recharge is predicted at the end of the century. We should note the difference in the reference periods for historical recharge estimation between the two studies. Furthermore, concerning the direction and magnitudes of seasonal recharge due to projected changes in seasonal precipitation and increases in temperature, those were also found to be highly uncertain (Ajami et al., 2012; Jasechko et al., 2014). (Ajami et al., 2012), applied the Anderson's empirical equation (Anderson et al., 1992) to estimate annual recharge in the Upper San Pedro basin in southeast Arizona (an arid to semiarid region) up to 2099 under six climate change scenarios. Anderson's equation is a regression equation based on mean annual precipitation and it does not directly incorporate the impact of ET in recharge estimation as we did in this study. Results of Ajami et al. (2012) predicted changes in annual recharge up to the end of the century to range from −27% to +15% compared to the historical period (1950–2000). Despite the differences in basin characteristics and using different GCMs between these two studies, annual groundwater recharge at the end of the century in the present work range from −19.6% to +24.6%, and are close to the range of values reported in Ajami et al. (2012). On the other hand, recharge during May and all summer months shows a distinct decreasing trend, which is highly variable in terms of magnitude. This can be attributed to temperature increases which are expected to reach extreme high values during the present century, according to predictions of all examined GCMs. It should be noted that the main contributor to recharge in the Mediterranean region, is winter recharge (November to April) which accounts for approximately 75% of the annual recharge and therefore further research should focus towards highlighting the influence of other factors such as rainfall intensity or land use changes that might prove to be important in controlling recharge rates in the future.

5. Limitations of the methodology

Within the present work monthly groundwater recharge is estimated by means of SWAT model and a regression equation (Eq. (2)) which has been adapted to make use of remotely sensed AET values (Eq. (3)). Besides the simplicity of the developed methodology, it is true that such regression formulas demonstrate limitations to their use, as they are developed for particular geographical areas under specific climate and geological conditions. Their transferability to other areas without careful consideration of the

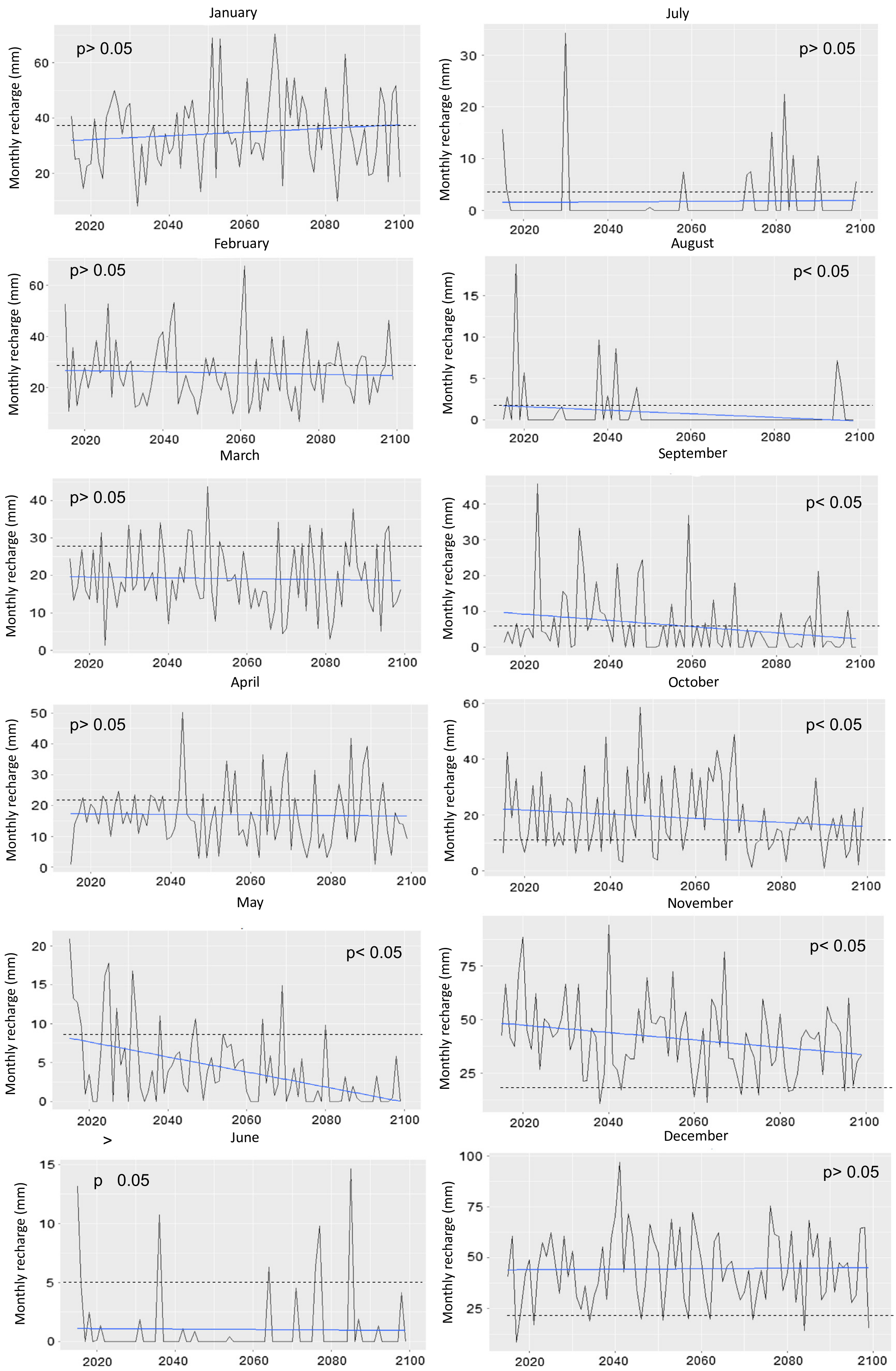

Fig. 9. Monthly recharge predictions as the mean of monthly recharge of the 5 GCMs for 2015–2100 period using empirical Eq. (2). Mean monthly recharge for 2005–2015 is shown with black dotted line as a reference for historic condition. Blue line corresponds to the trend of monthly recharge. p-values refer to statistical significance of the trends.

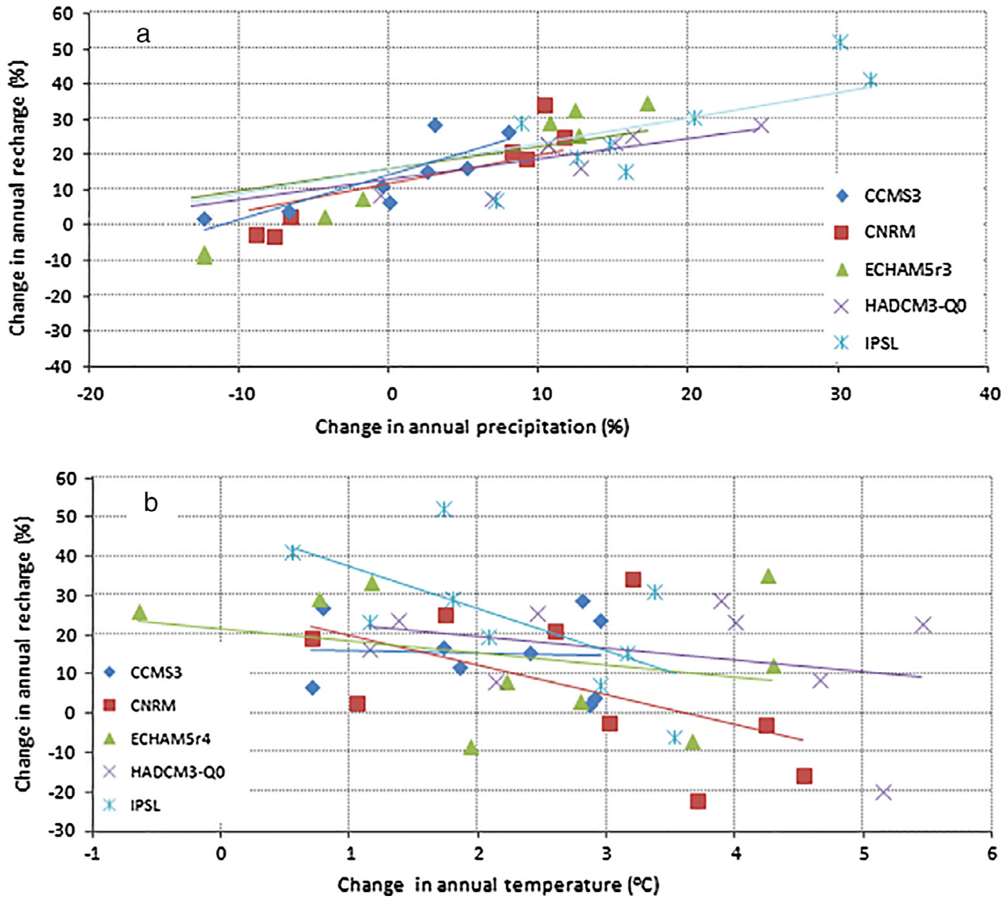

Fig. 10. Scatter plots of (a) changes in decadal means of precipitation and (b) changes in decadal means of annual temperature versus changes in decadal means of annual recharge for the five climate scenarios compared to reference decade (2005–2015).

hydrogeological setting and verification of results with alternative methods is not recommended. In our work, we examined and cross checked recharge results with modeled values and estimates from remotely sensed sources and stable isotopes application and found that the developed formula produces reasonably accurate results in Vosvozis catchment area. Due to the fact that our study basin has a typical Mediterranean climate with typical crops (cotton, corn, olive trees) cultivated in the Mediterranean region, the developed recharge equations are applicable to other poorly gauged Mediterranean basins of analogous hydrological setting and type of land uses (mainly rural agricultural) where groundwater recharge cannot be modeled. Concerning the spatial distribution of groundwater recharge, the presented herein methodology could be expanded to provide spatial recharge estimates provided there is a network of rain gauging stations operating within or close to the catchment area. It is regarded that distributed hydrological modeling is more suitable for spatial assessments, as such models take explicitly into account the soil and geological parameters of the study area but even in this case models cannot be calibrated for groundwater recharge, as usually no such measurements exist. Therefore, there is no direct way of verifying recharge computations and results are indirectly verified by the calculation of the water budget. On the other hand, our methodology focuses on the determination of groundwater recharge as a quantity at the catchment scale. Knowledge of this parameter enables sustainable groundwater use, as the long-term average of groundwater recharge is equivalent to renewable groundwater resources.

Future projections of annual recharge showed that overall annual recharge will increase up to the middle of the century and decrease thereafter, and summer recharge will decrease. However, our computations only incorporated future changes in precipitation and temperature, assuming that the present land use and irrigation patterns are not altered. The combined effects of temperature and precipitation changes together with other factors such as rain intensity and land use changes are difficult to predict, and complicate even more the prediction of magnitude and direction of expected recharge changes.

6. Conclusions

Within the present work, recharge estimates of a SWAT model calibrated based on streamflow were indirectly verified using MODIS AET and results found to be consistent. Using SWAT modeled monthly groundwater recharge values, two regression equations are developed to relate monthly recharge estimates to monthly effective precipitation. The first regression formula makes use of the Hargreaves PET and SWAT's AET values in order to compute monthly effective precipitation and monthly recharge. The second one, which is a modification of the first equation, uses remotely sensed AET values to estimate monthly recharge. Application of the SWAT model and empirical formulas for future recharge predictions using five climate projections up to the end of the present century, showed increases in future annual recharge rates ranging from 7.8% to 35.8% up to the middle of the present century compared to the reference period of 2005–2015. A decline of annual recharge ranging from 5.6% to 19.6% is predicted at the end of the century by 4 out of the 5 GCMs. A distinct reduction of monthly recharge from May to November is consistent between SWAT and empirical equation predictions. Taking into account the results and limitations presented herein, the present methodology can be used as an alternative to distributed hydrologic modeling, in order to define the monthly and annual groundwater recharge at the catchment scale in areas of similar climate and geological conditions where limited data exist. The results can be considered as the quantity corresponding to renewable groundwater and should be used as a limiting factor when water allocations for human consumption are made.

Acknowledgments

The first author acknowledges the Technical Chamber of Greece for its support through the project "Climate Changes and Dependent Ecosystems in Eastern Macedonia and Thrace" (Project ID: 81472 - Democritus University of Thrace). The first author also acknowledges Mr. Stylianos Kavour, brigadier general of the Greek Army, for providing essential help during the water sampling campaign in the mountainous Rhodope area.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2017.01.005.

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