

Assessment of future climate change impacts on the hydrological regime of selected Greek areas with different climate conditions

Spyridon Paparrizos and Andreas Matzarakis

ABSTRACT

Assessment of future variations of streamflow is essential for research regarding climate and climate change. This study is focused on three agricultural areas widespread in Greece and aims to assess the future response of annual and seasonal streamflow and its impacts on the hydrological regime, in combination with other fundamental aspects of the hydrological cycle in areas with different climate classification. ArcSWAT ArcGIS extension was used to simulate the future responses of streamflow. Future meteorological data were obtained from various regional climate models, and analysed for the periods 2021–2050 and 2071–2100. In all the examined areas, streamflow is expected to be reduced. Areas characterized by continental climate will face minor reductions by the mid-century that will become very intense by the end and thus these areas will become more resistant to future changes. Autumn season will face the strongest reductions. Areas characterized by Mediterranean conditions will be very vulnerable in terms of future climate change and winter runoff will face the most significant decreases. Reduced precipitation is the main reason for decreased streamflow. High values of actual evapotranspiration by the end of the century will act as an inhibitor towards reduced runoff and partly counterbalance the water losses.

Key words | ArcSWAT, climate change, Greece, hydrological modelling, IPCC scenarios, streamflow

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INTRODUCTION

Water, along with air and land, are the main sources that contribute to the conservation of human life. Water is not only a basic element for our planet's life and environment, but also a regulating factor for economic, technological, social and cultural development (Mimikou 2005). Nevertheless, according to previous publications from the Intergovernmental Panel on Climate Change (IPCC), uncertainties in climate change impacts on water resources, droughts and floods arise for various reasons such as different scenarios of economic development, greenhouse emissions, climate and hydrological modeling (IPCC 2007). By the middle of the 21st century, annual average river runoff and water availability are projected to increase as a result of climate change at high latitudes and in some wet

tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics. Many semi-arid areas (e.g. the Mediterranean basin, etc.) are particularly exposed to the impacts of climate change and are projected to suffer a decrease of water resources due to climate change (Bates *et al.* 2008). The latest IPCC reports mask the importance of the regional changes and refer that these regional to global-scale projections of future runoff remain relatively uncertain compared to other aspects of the water cycle (IPCC 2014).

Numerous researchers have assessed the future changes and responses of the streamflow and the hydrological cycle in similar climates in the Mediterranean region. Indicatively, Arnell (1999) studied the future changes on hydrological

regimes in Europe with a continental perspective and concluded that in continental climates, the snowfall will become less important due to higher temperatures, and therefore winter runoff will be slightly increased, while spring runoff will be decreased. [Mimikou *et al.* \(2000\)](#) performed a simulation in an agricultural catchment in Central Greece and they showed that seasonal as well as annual runoff will be reduced, while the most significant reduction expected in mean summer runoff values (May–October). [Bürger *et al.* \(2007\)](#) used artificial neural networks and A2 emission scenario to study the future responses of rainfall-runoff in the Pyrenees in Spain, while [Fujihara *et al.* \(2008\)](#) explored the potential seasonal and annual impacts of climate change on the hydrology of a waterbasin in Turkey and found more than a 50% decrease in future runoff. [Sanchez-Gomez *et al.* \(2009\)](#) studied the future changes in the Mediterranean water budget by an ensemble of regional climate model (RCMs) and concluded that already significant changes will start to occur for the period 2030–2050 where the runoff is expected to be decreased by almost 25% and that will reach almost 45% by the end of the 21st century. The connection between runoff and sediment transport during the snowmelt period in a Mediterranean catchment in Central Spanish Pyrenees was studied by [Lana-Renault *et al.* \(2011\)](#) who demonstrated the key role of snow accumulation and melting process in controlling the hydrological dynamics and patterns. [Voudouris *et al.* \(2012\)](#) performed an assessment of runoff in future climate conditions in an agricultural area in Crete Island in Greece using the output simulations of the RCM REMO and establishing a rainfall-runoff model, and resulted drastic mean runoff reductions by 30%. [Kalogeropoulos & Chalkias \(2013\)](#) simulated the future runoff using the Soil and Water Assessment Tool (SWAT) model in Andros Island that faces purely Mediterranean conditions and concluded that the future decrease in rainfall will impact and will cause a significant decrease in mean annual surface runoff. The future global runoff change using several general circulation models (GCMs) was assessed by [Sperna Weiland *et al.* \(2012\)](#). [Molina-Navaro *et al.* \(2014\)](#) studied the change in land use under different climate scenarios, while [Zhang *et al.* \(2014\)](#) assessed the sensitivity of runoff to global mean temperature change.

Additionally, a large number of studies have examined potential trends in measures of river discharge during the

21st century, at scales from river basin to global. Some have detected significant trends in some indicators of flow, while others have demonstrated statistically significant links with trends in temperature or precipitation ([Milly *et al.* 2005](#)). Moreover, the majority of these studies attempt to approach this target by scenario-based analyses, which indicate possible trends of future climate evolution based on the assumed (scenarios) trends on forcings ([Cayan *et al.* 2001](#); [Giorgi *et al.* 2001](#); [Georgakakos 2003](#); [Dettinger *et al.* 2004](#)). On the other hand, few studies have also provided quantitative measures of uncertainty ([Koutsoyiannis *et al.* 2007](#)). [Milano *et al.* \(2013\)](#) performed a comprehensive study regarding the future seasonal runoff responses and trends in the Mediterranean and concluded south-eastern rims are experiencing high to severe water stress and a sustainable development of strategies is needed to cope with the future climatic and anthropogenic changes. Regarding the future variation of runoff in relation with irrigation, [Garrote *et al.* \(2015\)](#) assessed the climate change vulnerability of irrigation demands in Mediterranean Europe and the results indicated significant regional disparities with the Iberian Peninsula and some basins in Italy and Greece to face the strongest threats.

In summary, according to previous studies, runoff will face strong decreases and downward trends in the upcoming years and decreased land precipitation along with increases in the mean surface temperature will be responsible for these reductions.

Nevertheless, due to the complexity of the hydrological processes and the different basin characteristics, a large amount of input data is needed every time in order to assess the future responses of runoff; as well as complex computational techniques that they are able to spatially interpenetrate the water movement of a certain study area with high accuracy. Additionally, some studies that are performed in the macroscale (e.g. country or continental scale) present limitations as they do not really take into account all the topographic and physical characteristics that describe the natural environment of a study area or a water basin, but only a part of them.

In addition to previous studies, the current research is aimed at the variation of future runoff in comparison with other fundamental aspects of the hydrological cycle, under the prism of agricultural production in areas that present

different climate characteristics. It constitutes an attempt to further explore the future responses of runoff in relation with future variation of precipitation and evapotranspiration.

In that concept, ArcSWAT ArcGIS extension is used based on the SWAT model (Arnold *et al.* 1993, 1998; Arnold & Allen 1996; Gassman *et al.* 2007). ArcSWAT is a powerful tool for the assessment of the water balance under the GIS spectrum and has been applied worldwide for watershed modelling (Eckhardt & Ulbrich 2003; Easton *et al.* 2008, 2010; Sheshukov *et al.* 2011), as well as for land-use and climate change assessment studies (Zhang *et al.* 2007; Wang *et al.* 2008; Ficklin *et al.* 2009; Ghaffari *et al.* 2010). The fundamental strengths of the model include flexibility in combining upland and channel processes and simulation of land management. Additionally, it can operate in almost every water basin scale, the estimated time in order for the model to complete its simulations and runs is very low, and although it uses a very large number of input data, the application procedure is facile. Moreover, as in recent years the rapid growth of technology has led to the development of complex models that require a significant amount of time in order to complete their procedures, the insignificant amount of time along with the great variety and manipulation (on behalf of the program) of the input data have established ArcSWAT as one of the most credible models while simulating the procedures of the hydrological cycle (Winchell *et al.* 2013).

These procedures and variations of the hydrological cycle concern a variety of sectors of economy, environment and society (Chen *et al.* 2001; Bates *et al.* 2008; Wang *et al.* 2010; Arnell *et al.* 2011; Qi & Chang 2011; Fernandez *et al.* 2016; Gohar & Cashman 2016; Kalbus *et al.* 2012). The socio-economic impacts of environments may arise from the interaction between natural conditions and human factors such as changes in land use, land cover and the demand and use of water. Excessive withdrawals can exacerbate the impact of reduced water resources, especially in areas where the water constitutes a vital coefficient for agriculture (Paparrizos *et al.* 2016a).

Greece belongs to a part in the south-eastern Europe where the use of water resources is mandatory for agriculture (Dalezios *et al.* 2000; Tigkas *et al.* 2012). According to data from the Food and Agriculture Organization of the United Nations (FAO 2015), the agricultural water

withdrawal versus the total water withdrawal in Greece for the years 1988–2012 was 90.1%.

The areas under investigation in this study are the Ardas River basin in north-eastern Greece, the Sperchios River basin in central Greece and Geropotamos River basin in Crete Island in southern Greece. The reason for the selection of these specific study areas lies in the fact that agriculture is the main production and economic activity. A significant part of the local population is employed fully or partly in the primary sector (agriculture and livestock). Due to this fact, most of the local population use the water from the torrential streams for irrigation. Irrigation plays an important role, due to the reduced amount of water availability from rainfalls and the farmer's inability to 'buy' water. Farming and manufacturing activities based on the agricultural activity, as well as other activities of the primary and secondary sector production are a pressing need for a research that will provide adapting systems and information regarding the availability of water resources and their future variations (Paparrizos *et al.* 2016b). The results of the current study will inform the farmers, residents and various stakeholders about the future availability of the water resources prevailing in their area so they can obtain knowledge that will give them the opportunity to adjust their systems in order to come up with future conditions.

MATERIAL AND METHODS

Study areas

The study areas are located in Greece. The Ardas River basin (Paparrizos *et al.* 2016c) is located in the north-eastern part of Greece (a big part of the basin belongs to Bulgaria – mostly the mountainous area of the basin) with an area of 5681.3 km². The mean annual precipitation is 839.8 mm while the mean annual temperature (T_{mean}) is 10.5 °C. In the Ardas River basin various climate types exist, but the basin is mainly characterized by humid continental climate conditions according to the Köppen-Geiger (Peel *et al.* 2007). Sperchios River basin (Paparrizos *et al.* 2014) with an area of 1727.7 km² is located in central Greece and it faces Mediterranean conditions with some differentiations on the rivers' springs in the mountainous area where

milder conditions appear, with mean annual precipitation of 792.9 mm and mean annual temperature (T_{mean}) of 16.6 °C. The third area is Geropotamos River basin (Matzarakis & Nastos 2011; Bleta *et al.* 2014), located in southern Greece in Crete Island. It has an area of 651.6 km², and it is purely affected by the Mediterranean climate conditions with mean annual precipitation of 759.8 mm and T_{mean} of 17.2 °C. The different climates that exist in the study areas are rather indicative and characteristic of the climate complexity that exists in Greece due to the harsh topography. Table 1 presents the local population that is employed in the primary section or are related with agricultural activities, while Figure 1 shows the general location, the meteorological stations and the characteristics of the study areas.

Climate and topographical data

Since Greece is an area characterized by diverse climate conditions due to the harsh topography and geomorphology, as well as an insufficient meteorological network (a problem that the researcher is called to overcome), stations within or adjacent to the study areas were used as inputs in the current study. Daily values of precipitation, air temperature (T_{mean} , T_{max} , T_{min}), solar radiation (Rs), relative humidity (RH), wind speed and discharge were obtained, derived by the Hellenic Meteorological Service (HNMS) and OGI MET (www.ogimet.com) that can be seen in Figure 1, and Tables 2 and 3. As there were no available common hydrometeorological data series for all the study areas, a homogeneity test was performed (Dingman 1994, 2002) followed by a statistical correlation test, the *t*-test (Snedecor & Cochran 1989; Haan 2002) in order to correlate the existing values and

determine the reference periods that will be adopted in the current study. Through these statistical processes, the determined reference periods were the years 1981–2000 for the Sperchios and the Geropotamos River basins, and 1985–2000 for the Ardas River basin.

Future data were obtained by the output simulations of an ensemble of six RCMs, which were carried out within the European project ENSEMBLES (<http://ensemblesrt3.dmi.dk>). The characteristics of the RCMs and the driving GCMs can be found in Table 4. The commercial software package 2014a (MATLAB and Statistics Toolbox 2000) was used to access the data. The climate simulations concern the future periods 2021–2050 and 2071–2100 against the reference periods that were pre-selected for each study area, under the A1B and B1 IPCC emission scenarios. According to IPCC (2007), the A1 storyline scenario family describes a future world of very rapid growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1F1), non-fossil energy sources (A1T) or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies). On the other hand, the B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives (Giorgi & Mearns 1999; Hagemann *et al.* 2004; Christensen *et al.* 2007; Matzarakis *et al.* 2014).

The required topographical data (Digital Elevation Model-DEM with 20 m quantization and stream network of the study areas) were obtained through the digitization of maps 1:50.000 courtesy of the Greek Geographical Army Service. Land cover and vegetation was obtained

Table 1 | Local population related with the primary section

Study area	Region	Region population	People occupied in the primary section	Percentage (%)
Ardas River basin	Evros	149,354	37,560	25.1
Sperchios River basin	Ftiotida	169,542	52,426	30.9
Geropotamos River basin	Irakleion	304,270	116,251	38.2

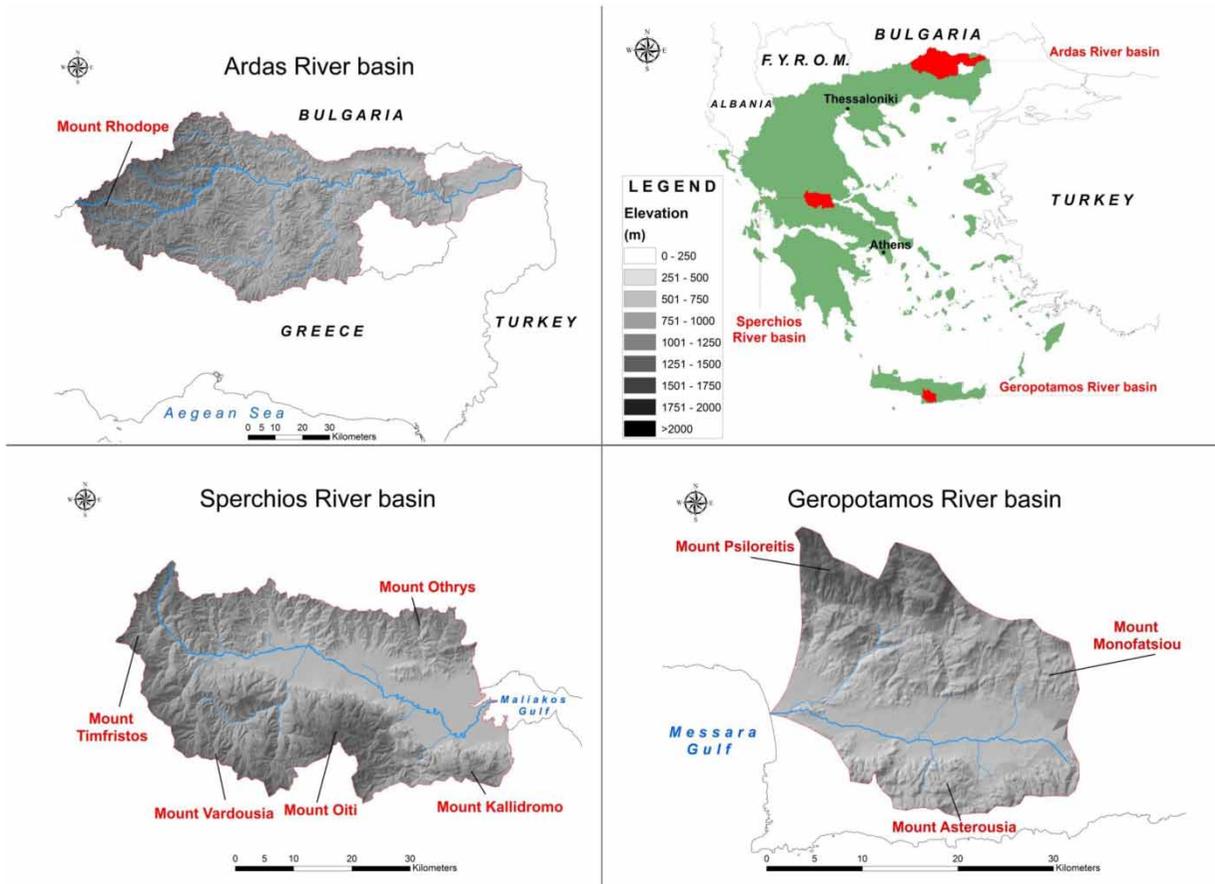


Figure 1 | Location and characteristics of the study areas in Greece.

Table 2 | Meteorological stations and their characteristics

Study area	Stations	Lat.	Long.	Elevation (m)	Years
Ardas River basin	Metaxades	41.41	26.23	129	1985–2000
	Orestiada	41.50	26.51	39	
	Edirne	41.66	26.56	50	
	Kurdjali	41.65	25.36	273	
Sperchios River basin	Karpenisi	38.90	21.78	819	1981–2000
	Lamia	38.91	22.43	144	
	Domokos	39.13	22.30	522	
Geropotamos River basin	Souda	35.54	24.10	106	1981–2000
	Irakleio	35.32	25.17	68	
	Ierapetra	35.01	25.72	24	
	Siteia	35.19	26.09	25	
	Rethimno	35.34	24.50	118	
	Tympaki	34.99	24.74	33	
	Palaioxora	35.23	23.68	25	
	Anogeia	35.28	24.95	823	
	Fourni	35.25	25.66	500	
Kastelli	35.12	25.20	350		
Zaros	35.13	24.90	322		

from the Corine Land Cover database (CLC 2000). Finally, soil data were obtained by the FAO database (FAO 2009).

Auto-regressive integrated moving average model for forecasting

In an effort to further assess the future hydrological regime and the variations of the future water resources in comparison with the undergoing simulations of the current study, yearly data regarding the irrigation water withdrawal in Greece were collected from the AQUASTAT main database, provided by the FAO (FAO 2015) for the years 1988–2012.

The data were further forecasted using the autoregressive integrated moving average (ARIMA) model method within Mathworks 2014a environment up to year 2100. The ARIMA model (Box & Jenkins 1976) is one of the

Table 3 | Discharge stations and their characteristics

Study area	Stations	Lat.	Long.	Elevation (m)	Years
Ardas	Ivaylovgrad	41.58	26.1	120.5	1985–2000
Sperchios	Kastri	38.94	22.2	100	1981–2000
	Kompotades	38.86	22.36	20	
	Komma	38.84	22.43	12	
Geropotamos	Faistos	35.04	24.79	95.7	1981–2000

Table 4 | Driving GCMs, Institutes, RCMs, and relevant references of the used ENSEMBLES simulations

Driving GCM	Institute	RCM	References
BCCR-BCM2	Norwegian Meteorological Institute	METNO_HIRHAM	Christensen <i>et al.</i> (1996)
CNRM-CM3	Centre National de Recherches Meteorologiques	CNRM-RM4.5	Gibelin & Deque (2003)
ECHAM/MPI-OM1	Danish Meteorological Institute	HIRHAM5	Jungclaus <i>et al.</i> (2006), Roeckner <i>et al.</i> (2006)
METO-HC-HadCM3C	Met Office Hadley Centre, UK	HADCM3C	Johns (2009a)
METO-HC-HadGEM2	Met Office Hadley Centre, UK	HADGEM2	Johns (2009b)
HadCMeq0 (normal sensitivity)	Swiss Federal Institute of Technology	ETHZ-CLM	Jaeger <i>et al.</i> (2008)

most widely used time series models (Han *et al.* 2010). The popularity of the ARIMA model in many areas is due to its flexibility and the systematic searching at each stage (identification, estimation and diagnostic check) for an appropriate model (Zhang 2003). The ARIMA model approach has several advantages over others, such as moving average, exponential smoothing, neural network, and in particular, its forecasting capability and its richer information on time-related changes (Yurekli *et al.* 2005).

In order to identify the appropriate ARIMA model, the Box-Jenkins method was used. Since the current research deals with climate data that follow a non-seasonal cycle, the non-seasonal ARIMA (p,d,q) was used (Hosking 1981). A non-seasonal ARIMA model is classified as an 'ARIMA (p,d,q)' model, where p is the number of autoregressive terms; d is the number of non-seasonal differences needed for stationarity; and q is the number of lagged forecast errors in the prediction equation.

In the identification step data transformation is often required to make the time series stationary. Stationarity is a necessary condition in building an ARIMA model used for forecasting. The original time series is non-stationary

and they are all differenced at lag $d = 1$. The rest of the model's parameters determined by the autocorrelation function (ACF) and the partial autocorrelation function (PACF) plots and the fitting models are evaluated by examining the residuals with ACF, the Ljung-Box test (Ljung & Box 1978), and comparing the Akaike Information Criteria (AIC) values of each model. Following the above-mentioned steps, the appropriate ARIMA model was determined to be ARIMA (1,1,1). A sample was used for validation by holding out 30% of the data set (8 years) to check the validity of the afore-mentioned model ARIMA (1,1,1). Additionally, relative mean square error (RMSE) was estimated in order to quantify the performance of the model.

Modeling with ArcSWAT – brief theory and calibration performance

The ArcSWAT ArcGIS extension is a graphical user interface for the SWAT model (Arnold *et al.* 1998). SWAT is a river basin, or watershed, scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex

watersheds with varying soils, land use, and management conditions over long periods of time. The model is physically based and computationally efficient, uses readily available inputs and enables users to study long-term impacts (Winchell *et al.* 2013).

The calibration of the ArcSWAT model includes the choice of parameters which each time play a key role in the natural process of converting rainfall into runoff. In the current study a manual calibration was performed, following a general trial and error procedure.

Initially, the Digital Elevation Model raster, as well as the water basin boundaries, the hydrological network, the land cover and the soil shapefiles were given as inputs.

Pre-defining the stream network and the watershed boundaries, as well as adding a table with the observed discharge point data (giving the opportunity to the model to 'read' the observed points) allowed for a manual calibration in the desired outlet points of each basin (stations depicted in Table 3) which constitutes one of the most optimal procedures regarding model calibration (Paparrizos & Maris 2016). Specifically, the stations of Table 3 were given as intermediate outlet points and ArcSWAT simulated the discharge in these certain points for the reference period. Following that, their validity was checked using the coefficient of efficiency in order to create a well developed model.

The hydrological response units (HRUs) were dominated by land use, soil and slope having each time as threshold of the percentage of the land use or the geology class (according to ArcSWAT *HRU definition* function).

Regarding the Land Use, the Crop type parameters were set according the ArcSWAT database to default, while for the hydrological parameters, the Manning's N coefficient (roughness) and the SCS Runoff Curve Numbers were received values for every different type of land use throughout the literature (Chow 1959; Maris *et al.* 2014).

Regarding the soil data, for every soil type several parameters were tested for their sensitivity, i.e. saturated hydraulic conductivity, maximum rooting depth in soil profile, soil water content at saturated conditions, soil water content at field capacity, USLE's erodibility factor (K), etc., while for the groundwater parameters of the waterbasin, the initial depth of water in the shallow and deep aquifer, the initial groundwater height, the threshold depth of water in the shallow aquifer for return flow to occur, etc. were tested for their sensitivity.

Following that, the point stations were given as a shapefile and their daily values (precipitation, evapotranspiration, solar radiation, temperature and relative humidity) as plain text, in order for the model to 'read' and calculate the mean annual values, and include them in the simulation procedure. The future data were extracted from the ENSEMBLES simulations and were given as inputs in ArcSWAT by using the existing point stations after substituting their records with the ENSEMBLES simulations.

The *Manual Calibration Helper* function that is included in the model gives the user the opportunity to select various parameters (in this particular study the examined calibrated parameters were Manning's coefficient N and SCS Runoff Curve Numbers) and modify them. This simple function provides a method for making adjustments to parameters across a used defined group of HRUs during the manual calibration process. Every time after the parameters were adjusted, a simulation was performed for a wide range of values producing simulated runoff values.

Afterwards, these values were correlated with the observed values using the coefficient of efficiency (EF) or otherwise known as the Nash-Sutcliffe coefficient (Nash & Sutcliffe 1970; Henriksen *et al.* 2003). After several simulations in each of which several soil, land use and other characteristics were tested using various values, and when the EF was unable to further improve (and the simulated values were able to describe with high accuracy the observed values), the calibrated parameters were stored, and the simulations for the future periods were performed using these new parameters. The calibration procedure was unique for every study area.

Trend analysis

The trends of the future discharge were investigated by performing the Mann-Kendall test for the years 2000–2100. The Mann-Kendall test (Kendall 1938; Mann 1945; Kendall & Stuart 1969) is a statistical control method, suitable for cases where the trend may be assumed to be monotonic and thus no seasonal or other cycle is present in the data. The existence of a statistically significant trend is evaluated using the Z-value. A positive (negative) value of Z indicates an upward (downward) trend. The statistical Z-value has a normal distribution (Salmi *et al.* 2002).

RESULTS

All the necessary data were used as inputs into the model and several simulations were run, for the reference, 2021–2050, 2071–2100 periods, and for A1B & B1 scenarios in every study area. Table 5 presents the results of the simulations for the study areas as well as the coefficient of efficiency (EF) values. The major contributors – apart from runoff – of the hydrological cycle i.e. actual evapotranspiration (AET), resulted as output through the model simulation, while mean annual precipitation (PREC) values for the same reference as well as future periods were given as inputs from the results of previous research (Paparrizos *et al.* 2016d) regarding the same study areas. In order to depict the complete concept of the procedures taking place in the hydrological cycle, Table 5 was enriched with information regarding the water that it is stored in the soil (SW) as well as ΔS which represents the change in storage which

means a change in the water volume in any number of ‘buckets’ in ArcSWAT namely: shallow aquifer, deep aquifer, soil moisture, and impoundments where they exist (reservoirs, ponds, wetlands, and potholes). The volume in these ‘buckets’ can go up or down depending on input versus output, which changes over the model runs. Moreover, regarding the ΔS as it resulted as an output from the model, it is referred to as the amount of water (mm) that occurred by the interactions amongst the ‘buckets’ by the end of a specific analysis period. Table 6 depicts the seasonal analysis of future responses of runoff. Figure 2 gives a schematic representation between the observed and the simulated discharge for the calibrated (reference) period for the study areas, respectively, while Table 7 presents the average irrigation water withdrawals and the agricultural water withdrawals vs total water withdrawals for Greece during 1988–2012 as well as the forecasted outputs from the ARIMA model for the periods 2021–2050 and

Table 5 | ArcSWAT simulation annual results (values in brackets present the difference between the reference period and the future period values in terms of percentage)

	Discharge Q (Observed) (m ³ /s)	Discharge Q (Simulated)		PREC (mm)	AET (mm) (mm)	SW (mm) (mm)	ΔS (mm) (mm)
		(m ³ /s)	(mm)				
Ardas River basin							
Reference period	54.7	51.3	223.5	839.8	420.1	166.8	29.5
2021–2050 A1B		48.0	162.6 (–6.4%)	499.1 (–40.6%)	190.3 (–54.7%)	122.8 (–26.4%)	–23.1
B1		50.4	175.7 (–1.8%)	555.3 (–33.9%)	193.6 (–53.9%)	130.2 (–21.9%)	12.0
2071–2100 A1B		40.3	120.4 (–21.5%)	450.8 (–46.3%)	194.5 (–53.7%)	110.7 (–33.6%)	–29.8
B1		42.6	133.0 (–16.9%)	468.6 (–44.2%)	197.5 (–53.0%)	106.9 (–35.9%)	–21.4
EF = 0.93							
Sperchios River basin							
Reference period	15.5	17.6	250.1	792.9	424.5	127.4	–9.1
2021–2050 A1B		14.3	203.2 (–18.6%)	550.5 (–30.6%)	251.5 (–40.8%)	91.3 (–28.3%)	4.5
B1		15.0	213.1 (–14.7%)	582.3 (–26.6%)	260.1 (–38.7%)	102.5 (–19.5%)	6.6
2071–2100 A1B		12.0	170.5 (–32.0%)	475.6 (–40.0%)	250.7 (–40.9%)	74.2 (–41.8%)	–19.8
B1		13.8	196.1 (–21.4%)	538.5 (–32.1%)	268.9 (–36.7%)	90.7 (–28.8%)	–17.2
EF = 0.91							
Geropotamos River basin							
Reference period	10.6	12.9	176.7	759.8	421.6	136.6	24.9
2021–2050 A1B		12.0	164.3 (–7.1%)	418.6 (–44.9%)	191.0 (–54.7%)	77.9 (–43.0%)	–14.6
B1		11.2	153.4 (–11.2%)	427.2 (–43.8%)	190.8 (–54.8%)	84.5 (–38.1%)	–1.5
2071–2100 A1B		10.6	145.2 (–18.3%)	372.8 (–50.9%)	196.5 (–53.4%)	67.5 (–50.6%)	–36.4
B1		11.0	150.7 (–14.5%)	391.5 (–48.5%)	195.5 (–53.6%)	69.8 (–48.9%)	–24.5
EF = 0.64							

PREC, precipitation (mm); AET, actual evapotranspiration (mm); SW, amount of water stored in soil profile in watershed (mm); ΔS , change in storage (mm).

Table 6 | ArcSWAT simulation seasonal results (values in the brackets present the difference between the reference period and the future period values in terms of percentage)

		Ardas River basin – Discharge (m ³ /s)				Sperchios River basin – Discharge (m ³ /s)				Geropotamos River basin – Discharge (m ³ /s)			
Current	Scenario/ Period	Reference		Future		Reference		Future		Reference		Future	
		A1B m ³ /s	B1 %	A1B %	B1 %	A1B m ³ /s	B1 %	A1B %	B1 %	A1B m ³ /s	B1 %	A1B %	B1 %
Current	Winter	91.0				31.7				13.5			
	Spring	62.2				13.1				12.7			
	Summer	26.2				5.9				6.5			
	Autumn	39.3				11.2				9.4			
2021–2050	Winter	65.1	62.5 (–28.5%)	(–31.3%)		17.9	17.9 (–43.6%)	(–43.4%)		13.2	12.5 (–2.4%)	(–7.8%)	
	Spring	65.7	76.4 (5.7%)	(22.9%)		17.7	19.8 (35.0%)	(51.3%)		13.1	12.3 (3.2%)	(–3.2%)	
	Summer	31.9	34.0 (21.9%)	(30.0%)		10.5	11.2 (79.7%)	(90.6%)		10.1	9.7 (55.4%)	(48.6%)	
	Autumn	29.6	28.5 (–24.8%)	(–27.6%)		11.0	11.2 (–1.9%)	(–0.7%)		11.3	10.1 (20.1%)	(7.4%)	
2071–2100	Winter	49.2	54.3 (–46.0%)	(–40.4%)		13.1	17.6 (–58.5%)	(–44.6%)		11.1	12.1 (–17.9%)	(–10.7%)	
	Spring	56.5	59.4 (–9.2%)	(–4.4%)		14.0	16.6 (6.7%)	(26.7%)		11.0	11.9 (–13.6%)	(–6.6%)	
	Summer	28.2	28.9 (7.8%)	(10.4%)		10.4	10.7 (76.6%)	(83.0%)		10.0	10.1 (53.9%)	(54.9%)	
	Autumn	27.3	27.6 (–30.5%)	(–29.8%)		10.4	10.1 (–7.6%)	(–10.2%)		10.1	10.2 (7.0%)	(7.5%)	

2071–2100. Table 8 and Figure 3 depict the trend analysis results for the years 2000–2100 divided into 10-year periods that also display maximum and minimum values for better representation and understanding of the results.

DISCUSSION

During the calibration process of the model, special emphasis was placed on the successful representation of the annual discharge. The main initial objective of the calibration procedure was the reproduction of realistic and acceptable values of the observed streamflow data series. As a first remark, the EF coefficient shows great effectiveness for the study areas and especially for the Ardas and the Sperchios River basins. These values were very close to the optimal value of 1.0, and imply that the model was able to simulate the streamflow almost with the same efficiency as the observed values. Figure 2 depicts the observed and the simulated streamflow (m³/s) for the study areas. ArcSWAT was able to simulate with great efficiency (EF=0.93) the streamflow procedure in the Ardas River basin, while in the Sperchios River basin EF was equal to 0.91, and 0.64 in the Geropotamos River basin.

Once the model was calibrated, future meteorological data series were given as inputs and the streamflow was calculated for each area, chronological period and scenario. During the simulation of the reference periods' data, the Ardas River basin was the only basin where the model

slightly underestimated the results, compared with the observed data series. In the Sperchios and the Geropotamos River basins, the model output values of the streamflow were higher than the observed values.

Regarding the streamflow, for the simulated period of 2021–2050, it is expected to be reduced in every study area for both applied scenarios. The greatest reduction will be observed in the Sperchios River basin, followed by the Geropotamos and the Ardas River basins, accordingly. For the period of 2071–2100, streamflow is expected to further reduce and in the Sperchios River basin this reduction will reach up to 32% of the initial simulated values for the A1B scenario. During the second simulation period of 2071–2100, the Ardas River basin also appeared to have critical reductions that will reach up to –21.5%, while the Geropotamos River streamflow will be reduced by more than 18%. That practically means that the Sperchios River basin will lose more than 1/3 of its streamflow by the end of the century, while the Ardas and the Geropotamos River basins will lose almost one-fifth.

Concerning the AET that was also exported from the simulations, for the first period of 2021–2050, it is expected to decrease in all the study areas, compared with the reference period analysis. Nevertheless, during the years 2071–2100, the AET is expected to increase for both scenarios following the increase of mean air temperature in the Mediterranean that has been reported by the IPCC (2007) reports and various similar studies (Hertig & Jacobeit 2008; Nastos *et al.* 2013).

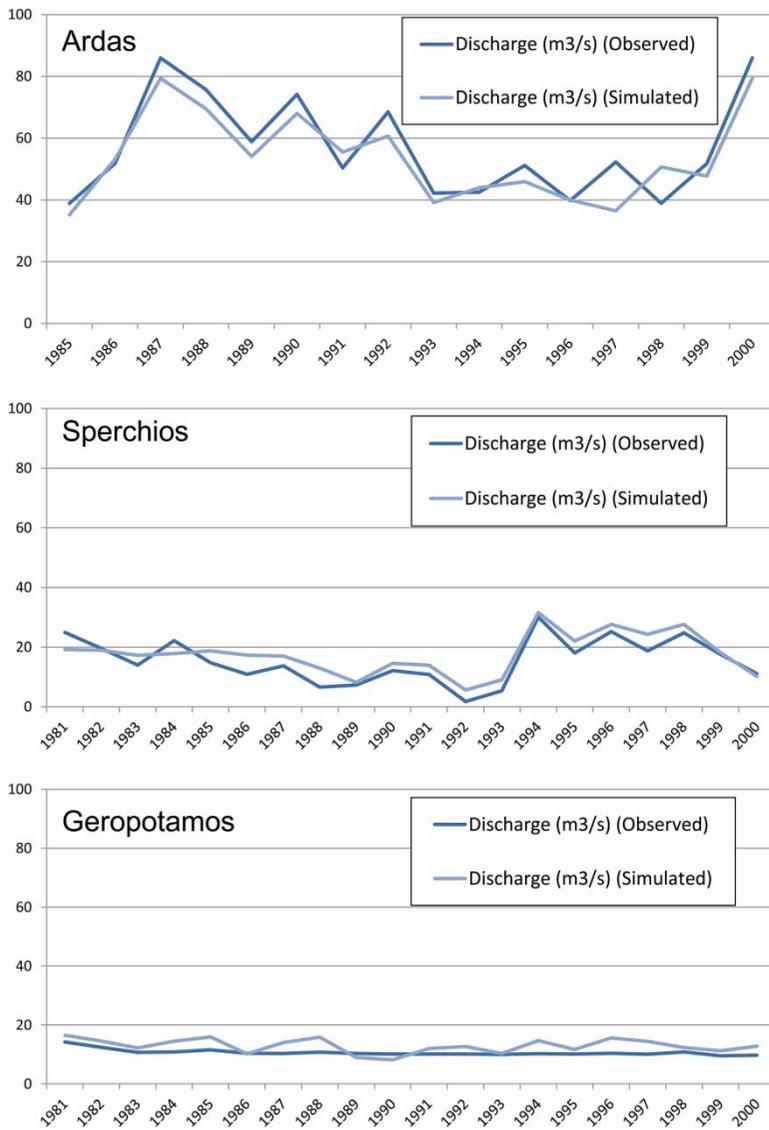


Figure 2 | Observed and simulated discharge (m³/s) for the study areas.

Table 7 | Average irrigation water withdrawal in Greece and agricultural water withdrawal vs total water withdrawal

	Irrigation water withdrawal (10 ⁹ m ³ /year)	Agricultural water withdrawal vs total water withdrawal (%)
1988–2012	8.0	90.1
2021–2050	8.8	73.9
2071–2100	10.0	50.1

Future decreases in runoff are reflected and confirmed by the decrease in precipitation amount, as shown in a previous study of Paparrizos *et al.* (2016d). According to this

Table 8 | Trend analysis results

Study area Scenario	Ardas		Sperchios		Geropotamos	
	A1B	B1	A1B	B1	A1B	B1
Z-value	-1.68	-1.61	-1.15	-0.98	-0.65	-0.61

study, precipitation will be greatly decreased in every case and for every chronological period and scenario. The greatest reductions are expected in the Geropotamos River basin that faces purely Mediterranean conditions.

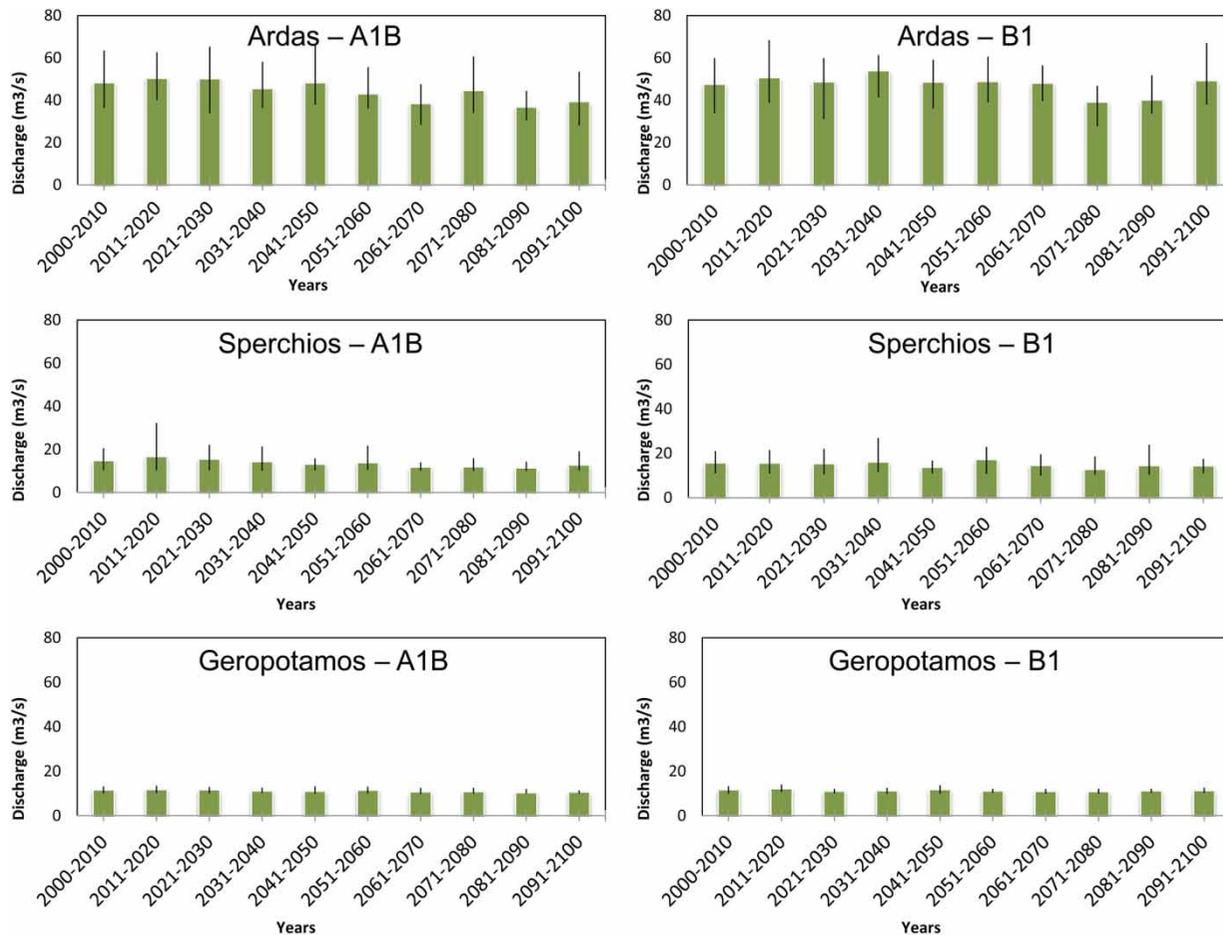


Figure 3 | Schematic representation of trend analysis results.

The amount of water that is stored in the soil profile (SW) will also face strong decreases due to the overall decrease of the water balance amount, but these decreases will be stronger in the Geropotamos River basin.

Seasonal analysis of future responses of runoff indicated that, according to Table 6, during the summer period runoff is expected to increase in every case. Nevertheless, although the percentages particularly for the Sperchios and Geropotamos River basins are quite high, the actual increase in values not that significant: e.g. Sperchios – B1 2021–2050 shows an increase of 90% but in real values runoff will be increased from 6 to 11 m³/s. On the other hand, the seasonal analysis indicated that winter runoff is expected to be critically decreased in every case. Spring and autumn seasons displayed differentiations in both future periods but by the end of the century, their values tend to decrease.

Specifically, in the Ardass River basin during the spring and especially summer season runoff is expected to increase for both future periods. Nevertheless, by the end of the century, although the estimated runoff indicated an increase compared with the reference period values, it will decline, compared with the first future period of 2021–2050. Winter runoff will be significantly decreased, but the strongest reductions are depicted during autumn runoff, which constitutes the main reason for future decreased runoff. In the Sperchios and Geropotamos River basins, reduced winter runoff is the main reason that the area will face strong reductions in terms of future responses of runoff in the upcoming years.

Trend analysis indicated that the Ardass River basin will face the strongest downward trend, followed by the Sperchios and the Geropotamos basins, respectively. Moreover, the Ardass River basin is shown to have the greatest variations which are very abrupt in many cases for both scenarios,

while the variations in the Geropotamos and the Sperchios River basins will be smoother in the upcoming years, as was depicted in Figure 3.

Another noteworthy fact is that for both chronological periods, A1B scenario appeared more pessimistic than the B1 scenario where the results tend to be more moderate.

In order to further understand how these variations of the aspects of the hydrological cycle and specifically streamflow will impact in the following years on the sustainable development of the environment, as well as society, data regarding the irrigated water withdrawal were collected by FAO for the period 1988–2012 and using the ARIMA (p,d,q) model were forecasted up to 2100. Initially, the RMSE was estimated for the irrigation water withdrawal (iww) and the agricultural water withdrawal (aww). The $RMSE_{iww} = 0.68$, while the $RMSE_{aww} = 13.05$, which indicates that for the years that the validation was performed, the model was able to perform a satisfactory prediction regarding the comparison of observed and simulated values.

According to the outputs of the ARIMA model presented in Table 7, irrigation water withdrawal is expected to increase in the upcoming years, which means that although the streamflow levels in all the examined areas that are characterized by different climate conditions will be reduced in the future, the needs regarding irrigated water will be increased. On the other hand, the agricultural water withdrawal versus the total water withdrawal will be critically decreased. The increase of the withdrawal water for irrigation is significant, but in the future the ratio regarding the agricultural vs total water withdrawal will follow a downward trend, mainly due to the eventual development of infrastructures, capable of serving, providing and acting as a regulator against the insufficient availability of water in the future.

Regarding the implications for the uncertainty associated with ARIMA forecasts in the current study, it is likely that the probable insufficiency of the model is due to the small sample in proportion to the prediction years which could lead to significant deviations from the actual values. Nevertheless, the qualitative characteristics of the model are the same (or nearly the same), which constitutes it as a very satisfactory solution to predict future time series.

In summary, in order to perform an informative comparison regarding the climate conditions prevailing in Greece and how these will affect the future variations of

the hydrological cycle, the three study areas were divided into *North* (that is represented by the Ardas River basin), *Central* (Sperchios River basin) and *South* (Geropotamos River basin) according to their geographical position.

North: Streamflow will face minor reductions by the mid 21st century that will become major by the end of the century. These areas will become more resistant to the future variations of the hydrological cycle, at least up to a certain period of time. AET will also face significant decrease in areas located in the North. These facts classify the study areas located in northern Greece as the least vulnerable to future change. Autumn season will face the strongest reductions, while summer runoff is expected to be slightly increased.

Central: Streamflow will face the greatest reductions in the upcoming years. Nevertheless, precipitation is expected to face strong, but compared to the other study areas, fewer reductions. This fact classifies the study areas located in central Greece as very vulnerable to future change. Reductions in winter runoff will be the most significant parameter for future reduced runoff.

South: Streamflow will face minor reductions in the first half of the century that will become more intense by the end of the century. Additionally, precipitation and AET will face the strongest reductions, classifying this study area the most vulnerable in terms of future climate changes regarding the water resources. Decreased winter runoff during the first future period and winter and spring runoff during the second future period will be the main reasons for a general decrease in future runoff responses.

In order to better understand the future variations of the aspects of the hydrological cycle, Table 9 was created, based on the percentage changes in Table 5, presenting the study areas, the variables of the hydrological cycle and their classification, regarding the severity of the future climate changes that will prevail amongst these study areas. The numbers represent the classification having 1 as the most severe, 2 as moderately severe, and 3 as the least severe regarding future change.

Table 9 | Classification regarding the severity of future climate change

Study area	Discharge	PREC	AET	SW	In total
Ardas (North)	3	2	2	3	3
Sperchios (Central)	1	3	3	2	2
Geropotamos (South)	2	1	1	1	1

Note: 1 = most severe; 2 = moderate severe; 3 = least severe.

From the results of Table 9 it is evident that areas located at lower altitudes will be more vulnerable to future climate change with regard to the variations of streamflow in comparison with the other aspects of the hydrological cycle than areas located at higher altitudes.

AET plays a very important role in the current study. It is mainly influenced by air temperature and solar radiation (Ampas & Baltas 2012). When hot conditions exist (especially in areas characterized by *Csa* and *Csb* climate classification), AET can reach very high levels and this will lead to a greater uprising of moist air, which will be lifted, cooled and the water vapour will condense to form clouds that will replenish the water bodies through precipitation.

As highlighted by the results, streamflow is expected to be decreased in the upcoming years in all the study areas, regardless of the climate conditions prevailing in each area. The reductions will be harsher during winter and autumn seasons, while during the summer a slight increase will be observed. For this reason, water resources management must take serious actions in order to avoid future water problems. The Directive 2000/60/EC of the European Parliament (European Parliament and Council 2000) clearly states the framework of how all the interested parties should act. Therefore, a strong and efficient cooperation is needed towards water resources management. Moreover, although the Sperchios River basin will be expected to face the greatest reductions regarding the streamflow, it is the only area without a large reservoir to act as a regulator, especially in periods when the streamflow is critically reduced (Dry period), but need is very high. Thus, the creation of a dam that will serve irrigation purposes is mandatory. Regarding the rest of the study areas, it is critical to examine if the existing water volume of the reservoirs is sufficient to meet the needs of agricultural production.

Additionally, the current research focused on the mean seasonal and annual comparison of the components of the hydrological cycle, and thus some percentage changes are relatively significant. Moreover, future research can focus on the soil and land use parameters, and perform a deeper analysis and a constructive comparison between the study areas, and how the baseline hydrologic characteristics could influence each catchment's behaviour under climate change. In every case, rational management is needed in the upcoming years.

CONCLUSIONS

In the current research, an estimation of future streamflow and its variation for the future periods of 2021–2050 and 2071–2100, under the A1B and B1 IPCC emission scenarios using the ArcSWAT model for three indicative areas widespread in Greece that face different climate conditions was conducted. Future meteorological data were obtained from the ENSEMBLES European project, topographical data as well as hydrological data for the calibration of the model and were obtained and used as inputs in the model in order to simulate the future response of runoff.

The results indicated that runoff is expected to be greatly reduced, especially during the winter season in areas where complex climate conditions exist and are mainly affected by the Mediterranean climate, while areas characterised by continental climate will be more resistant to future changes. These areas will face the strongest reductions during the autumn season with future decreased land precipitation one of the main contributing factors. On the other hand, due to future increased mean air temperature, AET values will not face strong variations and will partly offset this issue.

Nevertheless, since the climate in the Mediterranean is one of the most vulnerable in terms of climate change, great caution is needed when drawing conclusions. The climate uncertainties resulting from reduced runoff is one of the major threats in contemporary water resources management. The impacts of the upcoming changes concern not only the water planners and the farmers, but they also have diverse social, economic and environmental impacts.

In conclusion, the current research will be of assistance in order to understand the future response of streamflow in areas that face different climate conditions, and hence add to the planning, implementation and management of water resources and water availability that will lead to sustainable development of the agriculture and the water resources.

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