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ORIGINAL ARTICLE

# Impacts of surface and groundwater variability response to future climate change scenarios in a large Mediterranean watershed

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**Abstract** The objective of this research was to better understand the dynamics of surface–groundwater interactions in a large Mediterranean watershed (Evrotas River Basin) and to improve the seasonal forecasting of a potential hydrological drought under future climate change scenarios. This is achieved by integrating the quasi-distributed watershed Soil and Water Assessment Tool (SWAT) model with the three-dimensional groundwater flow Princeton Transport Code (PTC) model. The combined models are applied to the alluvial plain of Evrotas watershed in Greece by considering the interaction between the stream network and the aquifer to better spatially represent feedback fluxes within the surface and groundwater domains. Model simulation (2007–2011) was in good agreement with field observations demonstrating that this integrated modeling approach provides a more realistic representation of the water exchanges between surface and subsurface domains and constrains more the calibration with the use of both surface and subsurface observed data. Finally, the integrated SWAT-PTC model was used to study the impact of future climate change on surface and groundwater resources of the area under three different climate change scenarios. The results indicate that the study area is very sensitive to potential future climate changes. Upstream reaches display a loss of surface water to underlying groundwater systems whereas downstream the main river receives recharge from groundwater as the water table approached the surface topography. The low flow characterization for the current situation shows that a large part of the stream network will be too dry to accommodate the development of a viable aquatic ecological community throughout the years. In dry periods, the amount of water that is supplied to the aquifer is 40.9% less than the amount of water that is supplied under current climate conditions highlighting the need for new management strategies that must be implemented in order to avoid setbacks in the allocation of water resources in the future.

## Introduction

Understanding the complex behavior of the integrated surface and groundwater system is very important to the regional water resources management and necessitates an integrated modeling approach. In the Mediterranean basin, precipitation can be subject to high inter-annual and seasonal variability, with long and intense dry periods, or extreme rainfall and floods. Consequently, water is relatively scarce throughout most of the year, whereas high flows threaten lives and property. Under such conditions, the rising demand for water is met by building increasingly expensive and complex infrastructures necessary to store seasonal or annual water surpluses, transferring the water from storage to areas of demand, and to utilize groundwater reserves (García-Ruiz et al. 2011).

Various modeling approaches have been widely used for integrated investigation of surface water and groundwater. First efforts were undertaken in the 1980s to develop more

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complex integrated models of surface–subsurface components of the hydrologic cycle, which sought to overcome deficiencies in system representation (Abbott et al. 1986; Bencala 1984). Since the 1990s research activities on surface water–groundwater (SW–GW) interactions have increased steadily in disciplines ranging from hydrology and hydrogeology to ecology, biogeochemistry and environmental management and law (Krause et al. 2009). More complex models of surface water flows have been linked to existing groundwater models, and an entirely new class of fully integrated models has been developed that can simulate coupled SW–GW system as a continuum (Jones et al. 2008; Kollet and Maxwell 2006; Panday and Huyakorn 2004). There is a number of integrated SW–GW models in the scientific literature such as SWATMOD (Sophocleous et al. 1999), MIKE SHE (Graham and Butts 2005), HydroGeoSphere (Brunner and Simmons 2012), Swatmf (Guzman et al. 2015) and GSFLOW (Tian et al. 2015). These models have been applied to address different water resources issues, including irrigation management, SW–GW interactions, land use and climate change, ecology and water quality. Hydrological models are usually designed to simulate average and high flows and have been shown to give good results in catchments around the world. Unfortunately, low flows are often not captured satisfactorily and thus the simulations do not reflect actual drought conditions.

The link between the river channel to the extended aquifer and the incorporation of geologic heterogeneities at different scales into SW–GW models remains a challenge for the hydrogeologic community. New regulations such as the EU Water Framework Directive (WFD) now call for a sustainable management of coupled ground- and surface water resources and linked ecosystems. Rivers are complex head boundaries for the groundwater models and the surface–groundwater flux is dependent on the stage height in the river and the groundwater level in the aquifer. However, these interactions still remain poorly understood in many catchments throughout the world especially in case of large, karstic watersheds for which determination of groundwater-surface water interactions is particularly difficult because of the complex hydraulic interconnections of fractures and solution openings in carbonate rocks. Combining spatially and temporally field and laboratory data with physically based numerical models to identify key dynamics and to improve process understanding is an area of active research.

Global climate change is expected to seriously affect hydrological processes and alter the supply of ecosystem services that are vital for human well-being. Among all European regions, the Mediterranean appears most vulnerable to global change, with multiple potential impacts related primarily to increased temperatures and reduced precipitation. The Mediterranean region has been identified as one of the main climate change hotspots (i.e., affected by climate change) due to water scarcity, concentration of economic activities in coastal areas, and reliance on climate-sensitive agriculture. As Mediterranean countries are already facing important issues of water stress and extreme climate events (such as floods and droughts), climate change will most probably exacerbate issues, resulting in significant human and economic losses. According to the IPCC, a temperature rise of 2–3 °C is expected in the Mediterranean region by 2050, and a rise of 3–5 °C is expected by 2100 (IPCC 2001, 2007, 2013). Management of Mediterranean river basins is a challenge, because there is little information on periods with low discharges.

The sustainability of human populations and irrigated agriculture in arid and semiarid regions, with highly variable climate and surface water flows, is dependent on well-planned management of water resources, which in turn requires a thorough understanding of the physical processes that govern water movement. In river models, these interactions are generally treated simply as a loss term while in groundwater models, the river is generally just modeled simplistically as a boundary condition. Physical process and operational management alternatives can be evaluated using hydrologic system models, and in regions where surface water and groundwater interaction is significant, it is important to be able to adequately represent the exchange between the two regimes. In this study the seasonal variability of groundwater–surface water exchange fluxes and its spatially and temporally variable impact on the water balance and river discharge are investigated.

The objective of this research was to better understand the dynamics of SW–GW interactions and to improve the seasonal forecasting of hydrologic drought under future climate change scenarios which are necessary conditions for adequate operational water management in a large Mediterranean watershed. A comprehensive modeling framework was developed by integrating a hydrologic (SWAT) and a groundwater (PTC) model.

## Methods and materials

### Study area description

The study area is the alluvial plain of Sparta in Laconia, Greece (Fig. 1), a largely relatively flat landform created by the deposition of sediment over a long period of time by Evrotas River originating from highland regions. Evrotas watershed has a drainage area of 1348 km$^2$ and is a complex hydrogeological system consisting of intermittent flow tributaries, high relief areas and springs which are the main
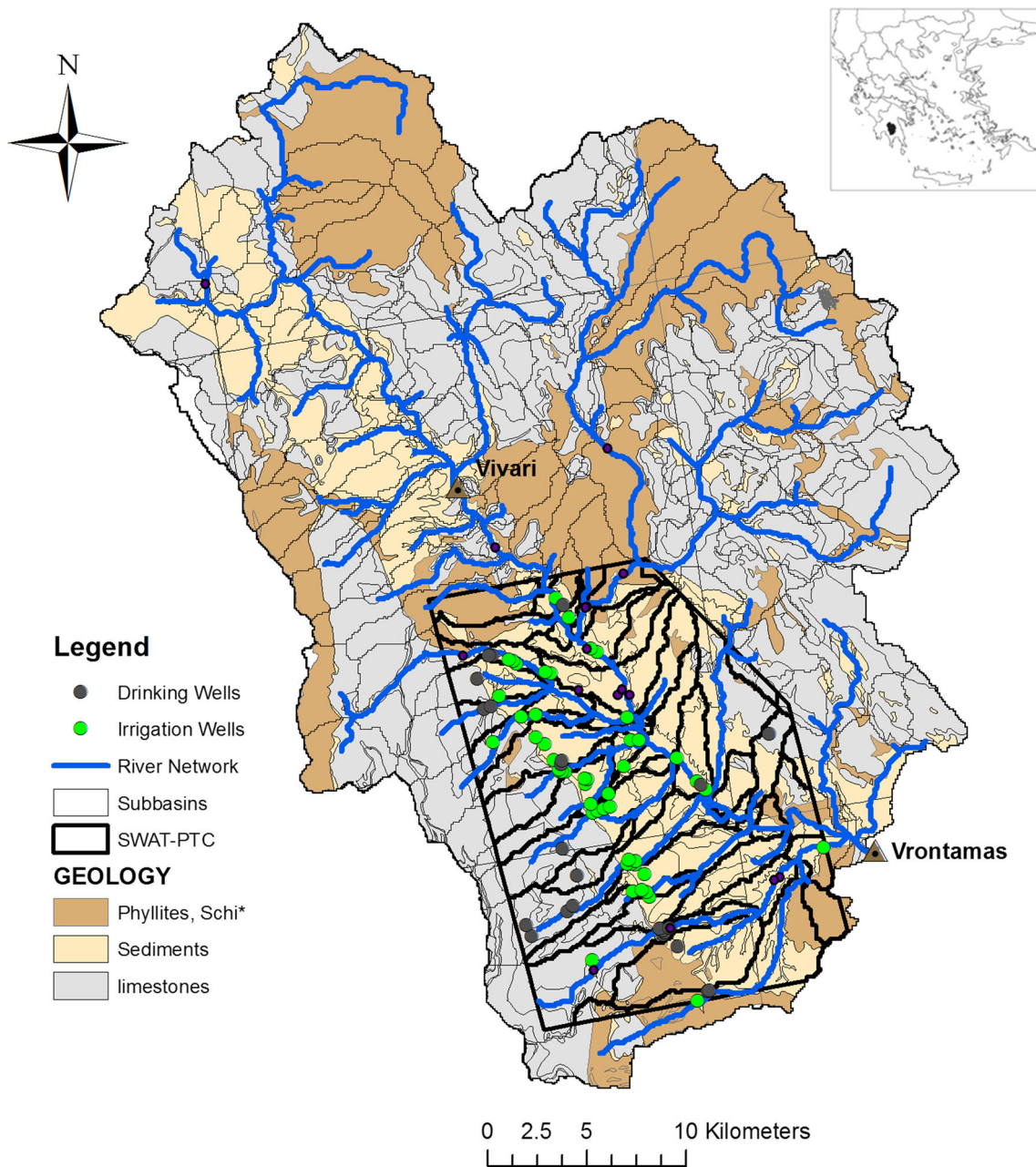
**Fig. 1** Evrotas River Basin location in Greece and the alluvial plain of Sparta study area

contributors to base flow. It is located in the southeast part of Peloponnesus, Greece and drains into Laconikos Gulf. The Evrotas River develops from north to south, between the Taygetos and Parnonas mountains.

The Evrotas basin has a mild Mediterranean climate influenced by orography with wet winters (November to March) and long dry summers (April to October). Monthly mean temperatures are typically 4–11 °C in the winter and 22–29 °C in the summer (Gamvroudis et al. 2015; Tzoraki et al. 2013). The main tributaries are Inountas, Xerias, Magoulitsa, Gerakaris, Kakaris and Rasina. Temporariness

in these rivers occurs not only because of specific climatic and geologic conditions but is also because of human actions. River flow may decrease because of direct abstraction or because of transmission losses induced by lowering of the groundwater level. Today the main problem remains the abstraction of water, by many methods, from the shallow aquifer. Water is directly removed by irrigation ditches, weirs, and pumping stations. Problems are encountered during the summer due to increased irrigation demands, which result to the dryness of Evrotas River network.

The geologic structure of the area includes almost all the geotectonic units of Peloponnesus (bottom to top: Plattenkalk or Mani Unit, Phyllite–Quartzite or Arna Unit, Tripolis Unit and Pindos Unit). Various types of post-alpine formations appear in the study area (Wilkinson and Pope 2003). The most common types are Pliocene and Pleistocene sediments, including massive alluvial fans. These deposits cover the lower areas of the region, have great thickness and consist of clays, sands, pebbles, conglomerates, marls and sandstones in alterations. Furthermore, there are more recent, Holocene deposits, which are separated in alluvial deposits and scree.

## Soil and Water Assessment Tool (SWAT) and Princeton Transport Code model (PTC) description

### Soil and Water Assessment Tool (SWAT)

The SWAT model requires GIS data layers, namely digital elevation model (DEM), soils, and land use data in addition to the weather data. Streamflow data are used to calibrate the model for hydrology. The model divides watersheds into sub-basins and further into hydrologic response units (HRUs) based on land use, soil, and slope information. The model requires several parameters to simulate hydrologic and water quality processes. These include weather, soils, groundwater, channel, plant water use, soil chemistry, and water quality parameters, as well as sub-basin and HRU characterization data. SWAT incorporates spatially distributed data on land use, soil, water bodies and digital elevation data into the hydrologic model. It also incorporates land management practices, as well as meteorological data into the model.

The SWAT modeling approach, calibration, verification and results to study the spatial distribution of runoff and sediment transport of Evrotas River Basin are extensively described by Gamvroudis et al. (2015). Model simulation of hydrology and sediment transport was in good agreement with field observations as indicated by a variety of statistical measures (PBIAS, NSE, RSR) used to evaluate the goodness of fit. The results suggest that the catchment has on average significant water surplus to cover drinking water and irrigation demands. On average, the catchment has water surplus to cover water needs; however, during the dry years, the majority of the reaches dried out and water demand is covered from groundwater abstractions (Gamvroudis et al. 2015).

The SWAT model has been successfully used in several other studies in Greece (Nikolaidis et al. 2013; Malagò et al. 2016; Nerantzaki et al. 2015).

### Princeton Transport Code model (PTC)

In order to describe the groundwater flow in the studied aquifer, the PTC (Princeton Transport Code) numerical simulation model was employed. PTC is a three-dimensional groundwater flow and contaminant transport simulator that uses a combination of finite element and finite difference methods to solve a system of partial differential equations that represents the groundwater flow, velocity and contaminant mass transport of the simulated physical system (Pinder and Gray 1977). PTC was used in combination with Argus ONE, a geographic information modeling (GIM) environment used for introducing the data into the simulator. Argus ONE GIS supports the largest number of groundwater models in the market such as MODFLOW, SUTRA, HST3D, NAPL, PTC. The model calibration requires data of geology, topography, hydraulic heads and pumping rates, as well as, infiltration and rainfall data. The PTC model is extensively presented and has been successfully used in several previous studies (Aivalioti and Karatzas 2006; Dokou and Pinder 2011; Karatzas and Dokou 2015).

## Experimental sampling design

Due to complex geological settings in the study area, a detailed description of the type, location and depth of the geological formations was a very important step in the development of an accurate SW–GW model. All available data (geological information from boreholes, groundwater levels, surface water discharges, climate data, etc.) pertinent to the surface and groundwater flow modeling of the area were organized into maps, using geographical information systems. Daily measured river discharge and water level elevation data from groundwater monitoring wells were used to estimate the initial conditions and to evaluate the groundwater levels simulated by the coupled model. The data were collected from various sources such as personal field campaigns and data taken from the Department of Environment and Hydrology, Region of Peloponnesus, Regional Unit of Lakonia. The available data also include detailed information regarding the weather, soil type, morphology and geology of the area of study. All this information was utilized for the determination of the geological stratification and representation of the physical system, including the determination of aquifer properties (e.g., porosity, hydraulic conductivity) using parameter ranges obtained from field studies and the literature. A potentiometric map was also created using hydraulic head data that correspond to the initial conditions of the model in 2007. In addition, the Department of Environment and Hydrology, Region of Peloponnesus, Regional Unit of Lakonia was monitoring the hydraulic heads of Evrotas

from 2007 to 2011 in seventeen locations twice per year (summer–winter period).

## Integrated SWAT-PTC model development

SWAT and PTC represent the physical world differently, and each is limited to its simulation domain, each having advantages and disadvantages when simulating biophysical processes and using computational resources. Therefore, an integrated SWAT and PTC model is essential to better spatially represent feedback fluxes within the surface and groundwater domains. Due to the differences in the spatial discretization between the two models (SWAT and PTC), there was a need to first geolocate the SWAT model derived results, and then to develop a linkage to the PTC spatial discretization.

Through coupling of models and obtaining better estimates of water flows and water abstractions, the estimation of the hydrologic mass balance will be improved.

The development of the coupled model involved the following steps:Conceptual model development;

- Development of a SWAT model;
- Calibration of the SWAT surface water model to observed discharges;
- Sensitivity analysis of the calibrated model to determine what are the key assumptions which have a significant impact on the model;
- Development of a PTC groundwater flow model using all the available data and in addition the results of the SWAT model (quantities of water through the streams fed and water lost from tributary channels via transmission through the bed);
- Calibration of the coupled SWAT-PTC model to the available observed groundwater hydraulic heads.
- Evaluate the effects of projected climate and irrigation scenarios.

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The scheme of the integrated SWAT-PTC modeling is illustrated in Fig. 2.

The study area was treated as an unconfined aquifer composed of two layers. Then the thickness of each layer was defined, which for layer 1 is fixed (50 m) based on geological observations, while layer 2 represents the topography of the study area. A potentiometric map was created using hydraulic head data that correspond to the initial conditions of the model in 2007. The groundwater discharge (Fig. 3), the total amount of water entering shallow and deep aquifers, from the SWAT surface water calibrated model is inserted in the PTC model as rain percolation.

The parameterization of hydraulic conductivity (K) on the study area varied depending on the different geological formations encountered in the area (Fig. 4). The hydraulic

conductivity values for the same geologic formation varied also from area to area, to account for the existence of small lenses inside the formation as well as interchanging layers of formations vertically inside the same model layer. This was necessary due to the geological complexity of the area.

For the simulation of the SWAT-PTC model, the domain was discretized using a triangular mesh with 2367 nodes and 4614 elements (Fig. 5). The area studied is approximately 300 km$^2$. The mesh was denser at locations where pumping wells exist, allowing for higher accuracy when the flow equations are solved.

Specifying the appropriate boundary conditions is one of the most critical tasks in groundwater modeling. The modeling of stream recharge from the river channel occurs through the setting of river cells in the groundwater model. This can be problematic, where streams are either naturally ephemeral or have become intermittent in flow due to excessive diversion and groundwater extraction. In modeling such phenomena, it is important to introduce a mechanism by which the boundary condition can be changed accordingly to allow recharge of the aquifer only when they flow.

As boundary conditions are so critical, they should be derived from a comprehensive understanding of the hydrogeological setting of the modeled aquifer. The flow boundary conditions (bc) chosen during the calibration were second-type boundary conditions (Neumann boundary conditions), applied at the well locations, the eastern, western and north study area borders and the river system. Pumping drinking wells in the area of interest were also defined as second-type boundary conditions, and their screens were set at various depths depending on the information on their boring logs. Some of the pumping rates were held constant during the simulation and some varied with time, depending on field conditions and the available data. As far as the river boundary conditions data were inserted from the SWAT calibrated model as quantities of water through the streams fed (GW_Q-Groundwater contribution to streamflow) and water lost from tributary channels via transmission through the bed (TLOSS-Transmission losses).

The calibrated coupled SWAT-PTC model was also used to simulate the climate change scenarios for the 2011–2060 period. As initial hydraulic heads, the hydraulic heads of the calibrated SWAT-PTC model in September 2011 were used. Quantities of water through the streams fed (GW_Q-Groundwater contribution to stream flow) and water loss from tributary channels via transmission through the bed (TLOSS-Transmission losses) we used as boundary conditions for the three climate change scenarios (2011–2060 period). In addition a 10% progressive decrease on boundary conditions due to the expected precipitation decrease by 2050 and a 20% progressive increase on the pumping rates on all wells was assumed (FAO 2011).
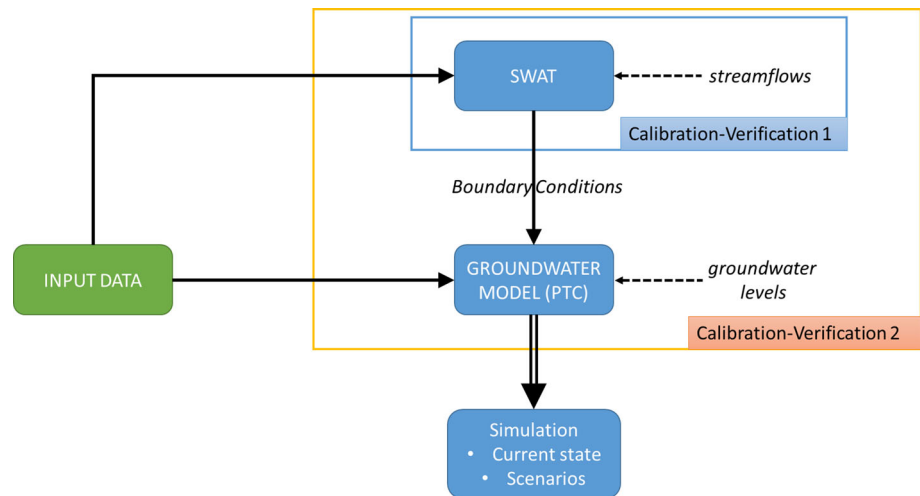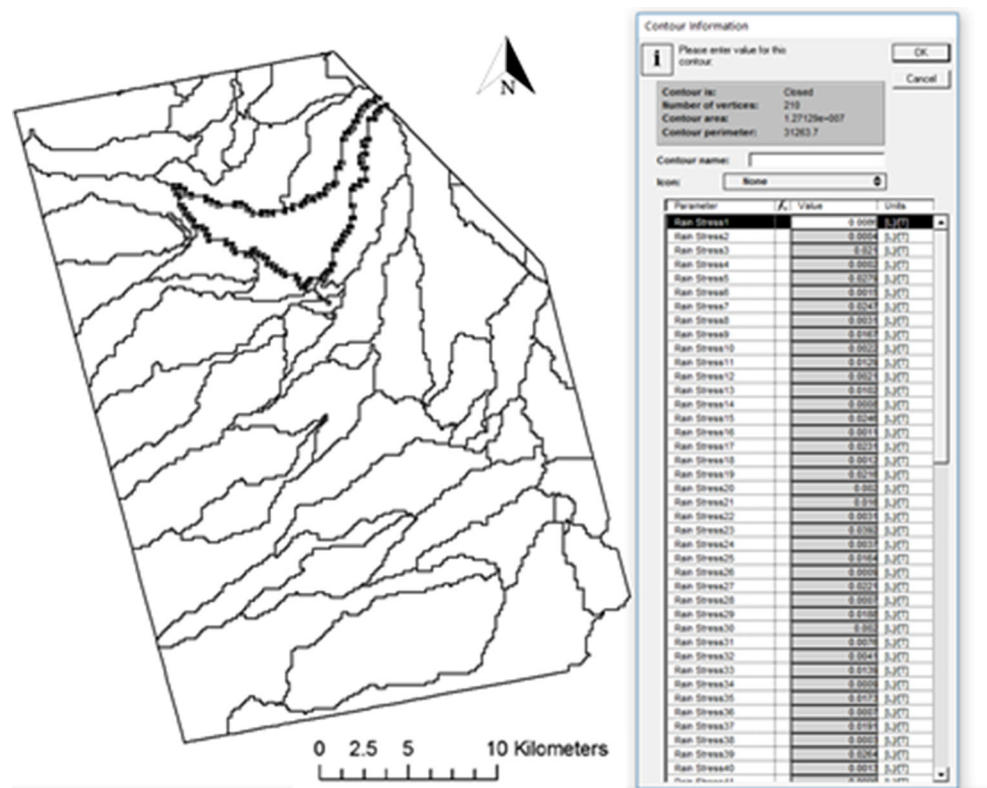
**Fig. 2** Scheme of the SWAT-PTC modeling



**Fig. 3** Groundwater discharge (water entering aquifer) for each sub-basin



## Calibration

The calibration of the model was performed for the years 2007–2011 matching the hydraulic heads predicted by the simulation with the hydraulic heads measured at seventeen head monitoring locations (Table 1).

The flow calibration results show a good agreement between measured and modeled values (Fig. 6). The coupled SWAT-PTC model calculated heads were close to the ones observed ($R^2 = 0.9996$). Flow calibration was performed by varying a) the hydraulic conductivity values of the model within pre-specified ranges for each geologic formation obtained from the literature and b) the lateral inflow boundary conditions.

## Results and discussion

The observed gradients of groundwater heads, which respond very dynamically to changes in river stage, were simulated with the SWAT-PTC model. The groundwater velocities for the model area are presented in Fig. 7. The

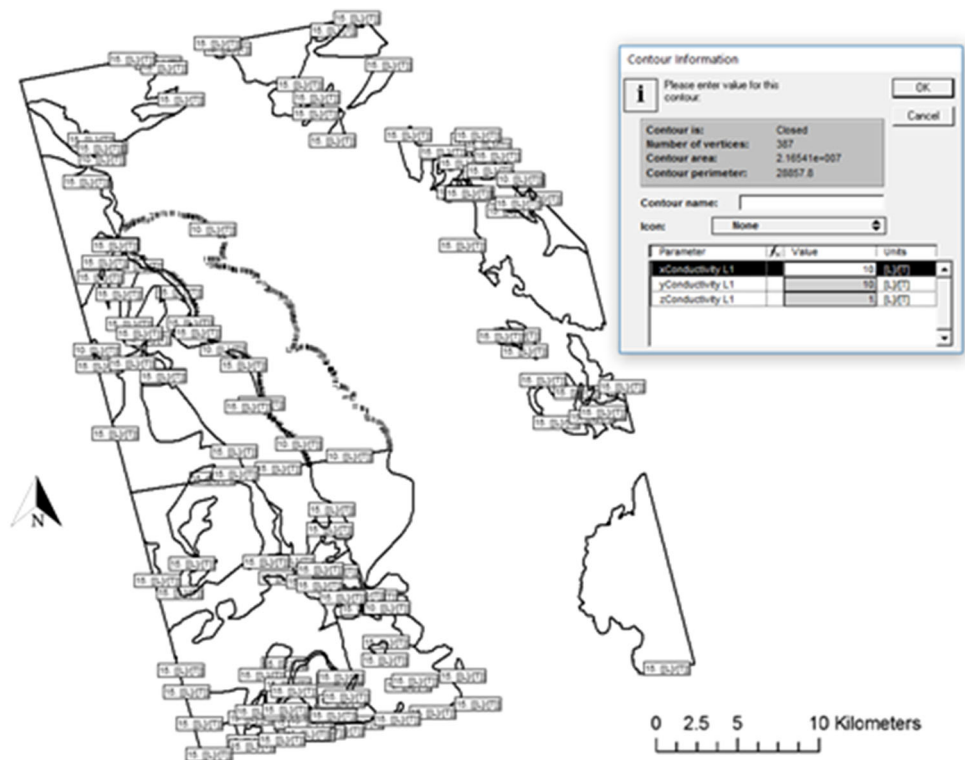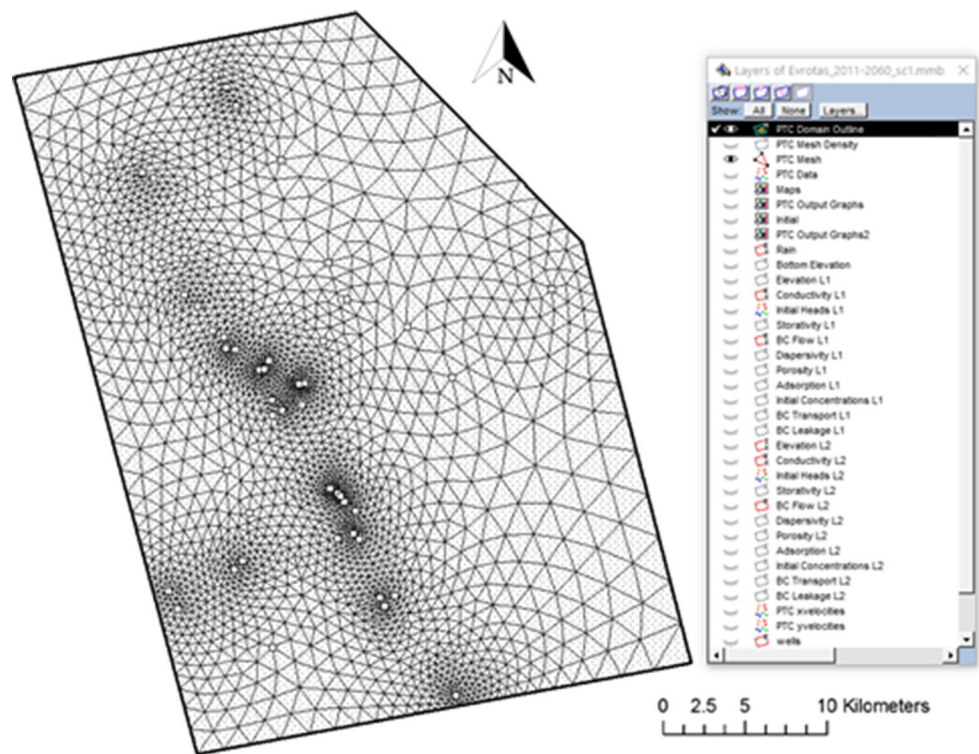**Fig. 4** Hydraulic conductivity for each geological formation



**Fig. 5** Discretization of study area using a triangular mesh



results indicate that during the 2007–2011 simulation, the northwestern part of the study area does not present significant variation in the values of hydraulic heads. The northwestern section of the basin is part of mountain Taygetos which has high rainfall and snow during the year and provides a continuous replenishment to the Sparta aquifer. Streams flowing from mountainous terrain commonly flow across alluvial fans at the edge of the valleys.

**Table 1** Observed (equilibrium) and simulated (SWAT-PTC) hydraulic heads (m)

|   | Well | Pumping rate m³/h | Hydraulic head (m) September 2011 observed | Hydraulic head (m) September 2011 SWAT-PTC |
|---|------|-------------------|----------------------|----------------------|
| 1 | N1 | 70 | 198.1 | 197.9 |
| 2 | AM3 | 50 | 201.1 | 200.7 |
| 3 | AM5 | 50 | 201.5 | 201.0 |
| 4 | P1 | 50 | 247.5 | 246.7 |
| 5 | P2 | 45 | 245.3 | 245.6 |
| 6 | P3 | 50 | 251.4 | 252.1 |
| 7 | P4 | 90 | 252.1 | 251.5 |
| 8 | AM1 | 40 | 208.0 | 208.1 |
| 9 | AM2 | 100 | 206.1 | 206.7 |
| 10 | AM6 | 50 | 207.0 | 206.9 |
| 11 | AM7 | 50 | 204.0 | 204.3 |
| 12 | NG2 | 100 | 250.4 | 250.9 |
| 13 | Borehole 1 | – | 260.8 | 260.3 |
| 14 | Borehole 2 | – | 210.3 | 209.6 |
| 15 | Borehole 3 | – | 200.5 | 199.4 |
| 16 | Borehole 4 | – | 230.3 | 230.1 |
| 17 | Borehole 5 | – | 133.4 | 133.4 |



**Fig. 6** Observed (equilibrium) versus simulated (SWAT-PTC) hydraulic heads H (m)
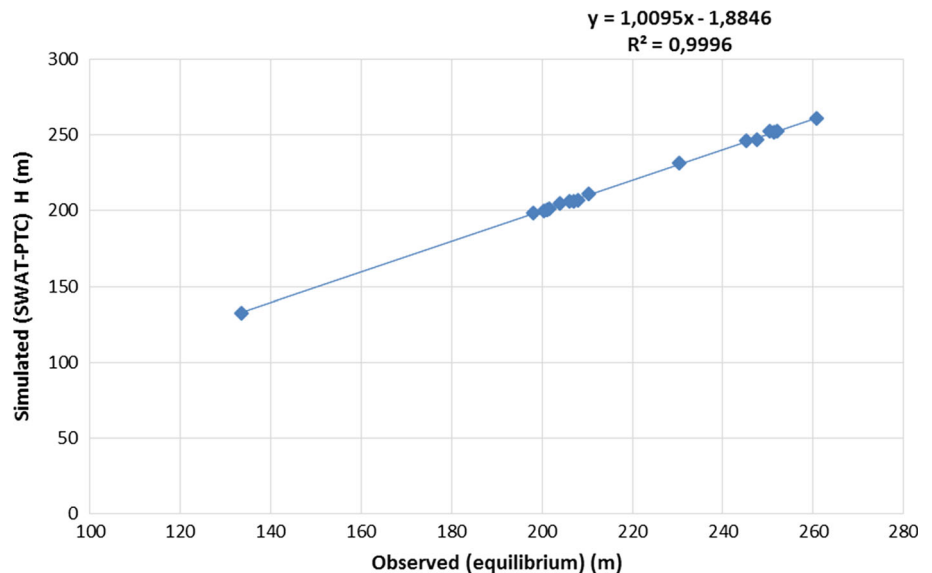
In arid and semiarid regions, seepage of water from the stream can be the principal source of aquifer recharge. In addition, the areas near the pumping wells show local variations in the values of their hydraulic heads. Groundwater velocities calculated by the model are relatively small, suggesting generally slow transport processes. In general, their values do not exceed 0.5 m/d and their maximum values are encountered at areas where pumping is applied (reaching 1.78 m/d locally).

Driven by human population growth and declining summer streamflows, the potential for increases in groundwater pumping as an indirect response to climate change could have large consequences for state groundwater storage conditions in the study area. The indirect impact of pumping would likely far outweigh the direct consequences of climate-driven meteorological changes.

The modeling results indicate that the upstream reaches displayed a loss of surface water to underlying groundwater systems (movement largely follows changes in topography), whereas downstream the main river received recharge from groundwater as the water table approached surface topography. The downstream reaches carry water
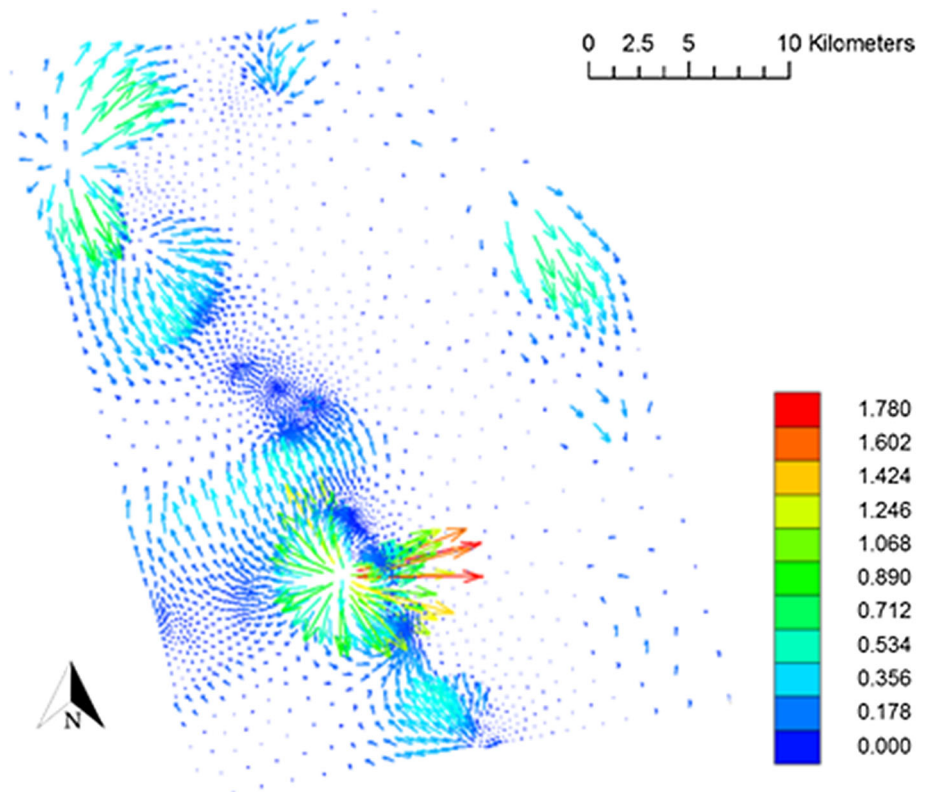
**Fig. 7** Flow velocities—
September 2011
(SWAT + PTC)



**Table 2** Flow occurrence (Mf) and the Seasonal predictability (Sd6)—KNMI-RACMO-ECHAM5

| Location | 2000–2060 | | | | | |
|---|---|---|---|---|---|---|
| | KNMI-RACMO-ECHAM5 | | MPI-REMO-ECHAM5 | | SMHI-RCA-ECHAM5 | |
| | Mf | $Sd_6$ | Mf | $Sd_6$ | Mf | $Sd_6$ |
| Vrontamas | 0.718 | 0.83 | 0.69 | 0.82 | 0.74 | 0.85 |
| Vivari | 0.72 | 0.92 | 0.73 | 0.93 | 0.76 | 0.94 |
| Magoulitsa Ag. Irini | 0.48 | 0.80 | 0.49 | 0.81 | 0.52 | 0.85 |
| Kelefina Kladas | 0.70 | 0.91 | 0.72 | 0.91 | 0.71 | 0.91 |
| Kelefina Vassaras | 0.87 | 0.97 | 0.89 | 0.94 | 0.89 | 0.98 |
| Rasina Airport | 0.86 | 0.94 | 0.83 | 0.92 | 0.92 | 0.96 |
| Rasina Koumousta | 0.88 | 0.94 | 0.83 | 0.92 | 0.92 | 0.96 |

most of the time and have gentle slopes. Generally the water table is not far below the land surface in alluvial valleys but in Sparta alluvial plain human-induced groundwater extraction influences the temporal phenomena of surface and groundwater interaction. Heavy extraction of groundwater results in the lowering of the water table to a level below that of stream stage (Table 2).

**Irrigation/pumping and climate change scenarios**

*No irrigation and no pumping scenario*

As irrigation dominates current groundwater use and depletion, the effects of future climate variability and change on groundwater may be greatest through indirect effects on irrigation-water demand. In the Study area, current irrigation practices consume water at a rate twice the recommended, placing a major burden on water resources. Problems in water demand are encountered during the summer when numerous private wells in use lower the water table. A no irrigation/pumping scenario was examined to facilitate a better understanding of the situation during the dry months. To create this scenario, we assumed that the irrigation and pumping efficiency is zero for the 2007–2011 period.

The results indicate that the total groundwater system in the study area is not significantly influenced by the zero pumping conditions. Compared with the conditions of the

water hydraulic heads in 2011, where the pumping quantities were exceeding the needs, there is an average increase in the water table by 0.5 m corresponding in 44 M m$^3$ additional groundwater resources. In the western part of the basin, the hydraulic heads are affected differently by the zero pumping conditions where this increase reaches 1 m in areas near the pumping wells.

### ERB climate change simulation: climate change scenario simulations for Evrotas watershed

Under climate change, significant variability in precipitation and evapotranspiration would dramatically affect the catchment water balance. Monthly simulated precipitation and temperature data from a regional climate model at 25 km resolution were obtained from the EU Ensembles project (http://www.ensembles-eu.org). The 50-year period climatic data (2010–2060) based on the three climate change scenarios were used as input into the calibrated version of SWAT-PTC model. The three climate change scenarios are: KNMI-RACMO-ECHAM5 (van Meijgaard

et al. 2008), MPI-REMO-ECHAM5 (Jacob 2001) and SMHI-RCA-ECHAM5 (Kjellström et al. 2005). For the purposes of this study the Standardized Precipitation Index (SPI) (McKee et al. 1993) was used to define and monitor the drought effect on the study area under the three climate change scenarios (Fig. 8). The SPI is spatially and temporally normalized and is therefore applicable to both wet and dry climatic conditions. In addition, it can be applied regardless of location (Cancelliere et al. 2007) and has been extensively applied in Greece (Livada and Assimakopoulos 2007; Loukas et al. 2007; Vasiliades et al. 2009).

All three scenarios gave consistent results, predicting significant decreases in annual precipitation, actual ET and runoff after 2030. The results suggest a 10% decrease in precipitation, 4% decrease in ET and 19% decrease in flow in 2030–2050 compared to 2010–2020. Climate change will exacerbate the problem of water scarcity in the region which is expected to be pronounced in the summer months. Figure 9 presents the wet and dry period occurrence (%)
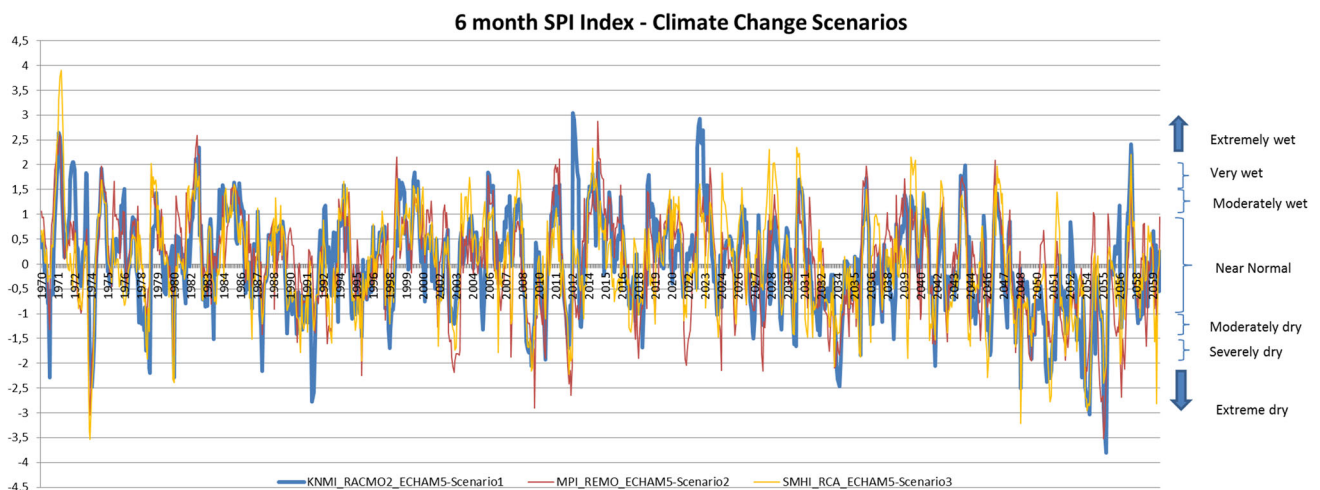


**Fig. 8** SPI values with a 6 month time scale in the study area for climate change scenarios
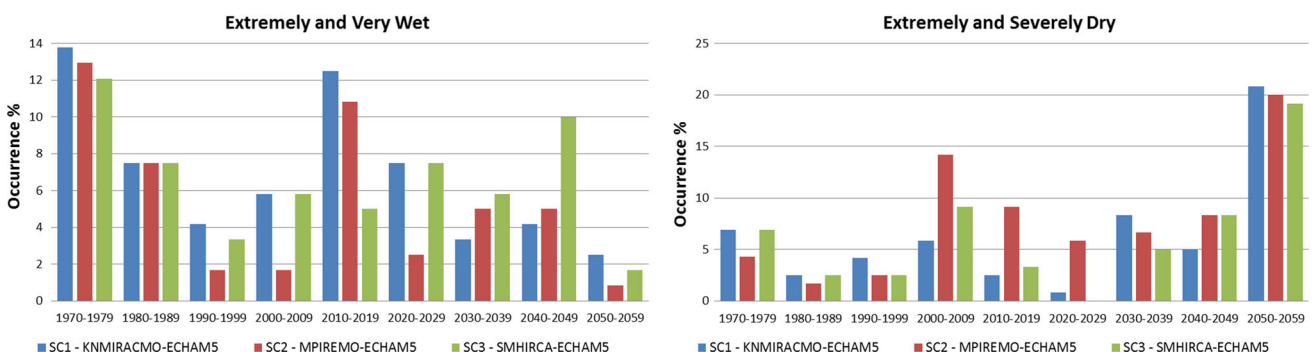


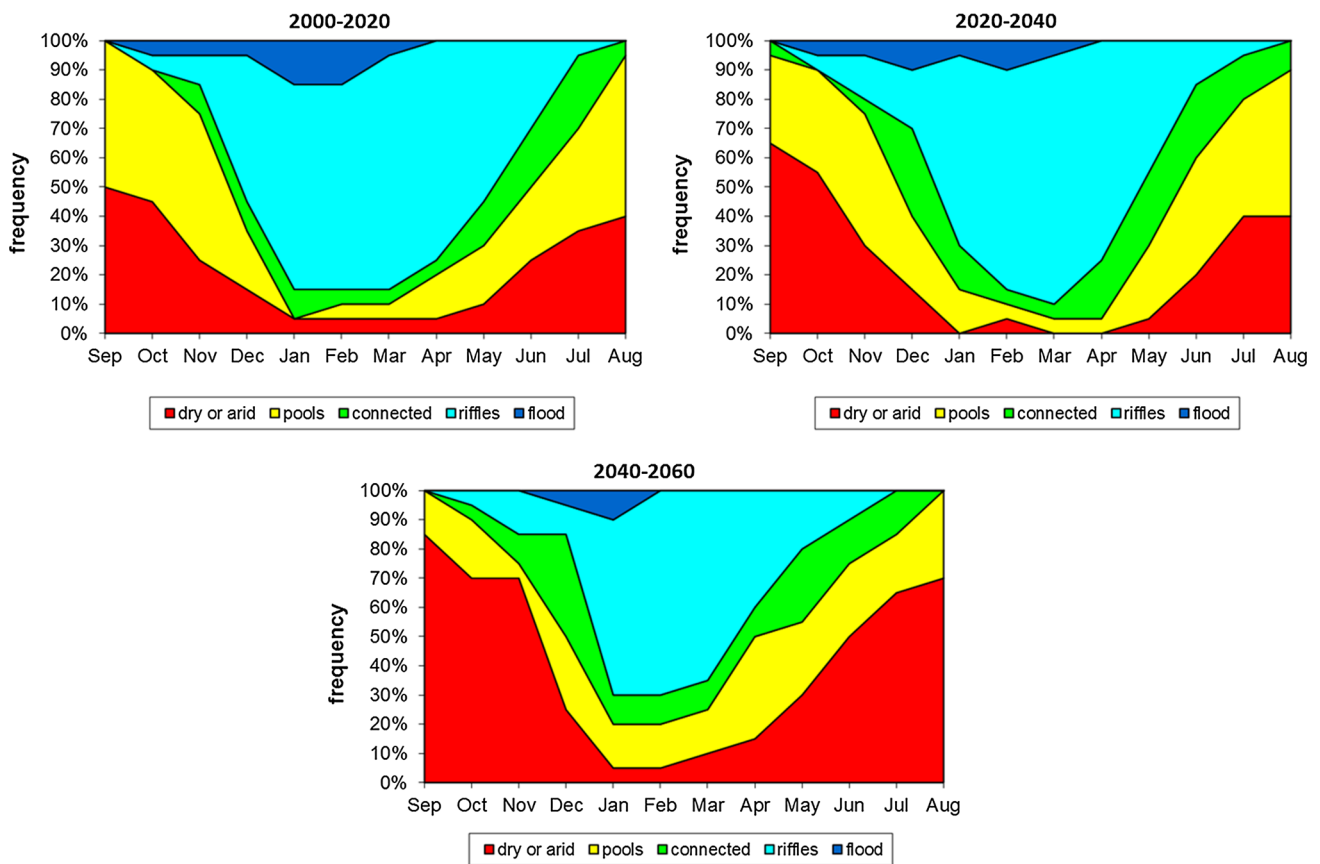**Fig. 9** Wet and dry period occurrence (%) since 1970

**Fig. 10** Aquatic states frequency graph at Vrontamas reach—KNMI-RACMO-ECHAM5

for the three climate change scenarios on a decade time scale since 1970.

The results indicate also the KNMI-RACMO-ECHAM5 scenario presents the highest percentage of drought occurrence (21.1%) during the 2050–2060 period while for the SMHI-RCA-ECHAM5 and MPI-REMO-ECHAM5 scenarios this is 20.0% and 19.0%, respectively.

## Impact of climate change scenarios on surface water-link with ecology

The analysis of complex temporal patterns of occurrence of dry periods is simplified by the introduction of the Aquatic States (Gallart et al. 2011). The aquatic states consist of a number of aquatic habitats available on a particular stretch of river in a certain time of year depending on the amount of flow. Such analyses can be done using daily discharges or monthly averages. The different aquatic states off a river segment are Flood, Riffles, Connected and Dry (Gallart et al. 2011). The Threshold values are needed as reference to construct the Aquatic States Frequency Graphs ("ASFG"). It is important, in establishing these thresholds, to ensure that the boundaries between the aquatic states are

well based. Thresholds in the discharge have been identified by the SWAT model 1970–2011 simulation results to perform a low flow characterization: flow status frequencies have been determined for every reach of the main stream network, to define the possible states, i.e., dry, pools, connected, riffles or flood. Aquatic states frequency graphs have been calculated for the main tributaries (Vrontamas, Vivari, Magoulitsa Ag. Irini, Kelefina Kladas, Kelefina Vassaras, Rasina Airport, Rasina Koumousta) in the river network for the 3 climate change scenarios. The ASFG for the Vrontamas reach which is located downstream of Sparta (Fig. 1) is presented in Figs. 10, 11 and 12 for each climate change scenario in 20-year time scale, respectively. This time scale gives an average image of the daily fluctuations in river discharge.

In the aquatic states frequency graphs it is visible that the river will be more affected by dry state periods. The low flow conditions are important also for the ecosystem due to species reproduction. For the viability of an aquatic ecosystem in an intermittent river, the periods a river falls dry each year are very important. In addition to the analysis with the ASFG, Gallart et al. (2011) propose two other indicators which can be used to assess the impacts on
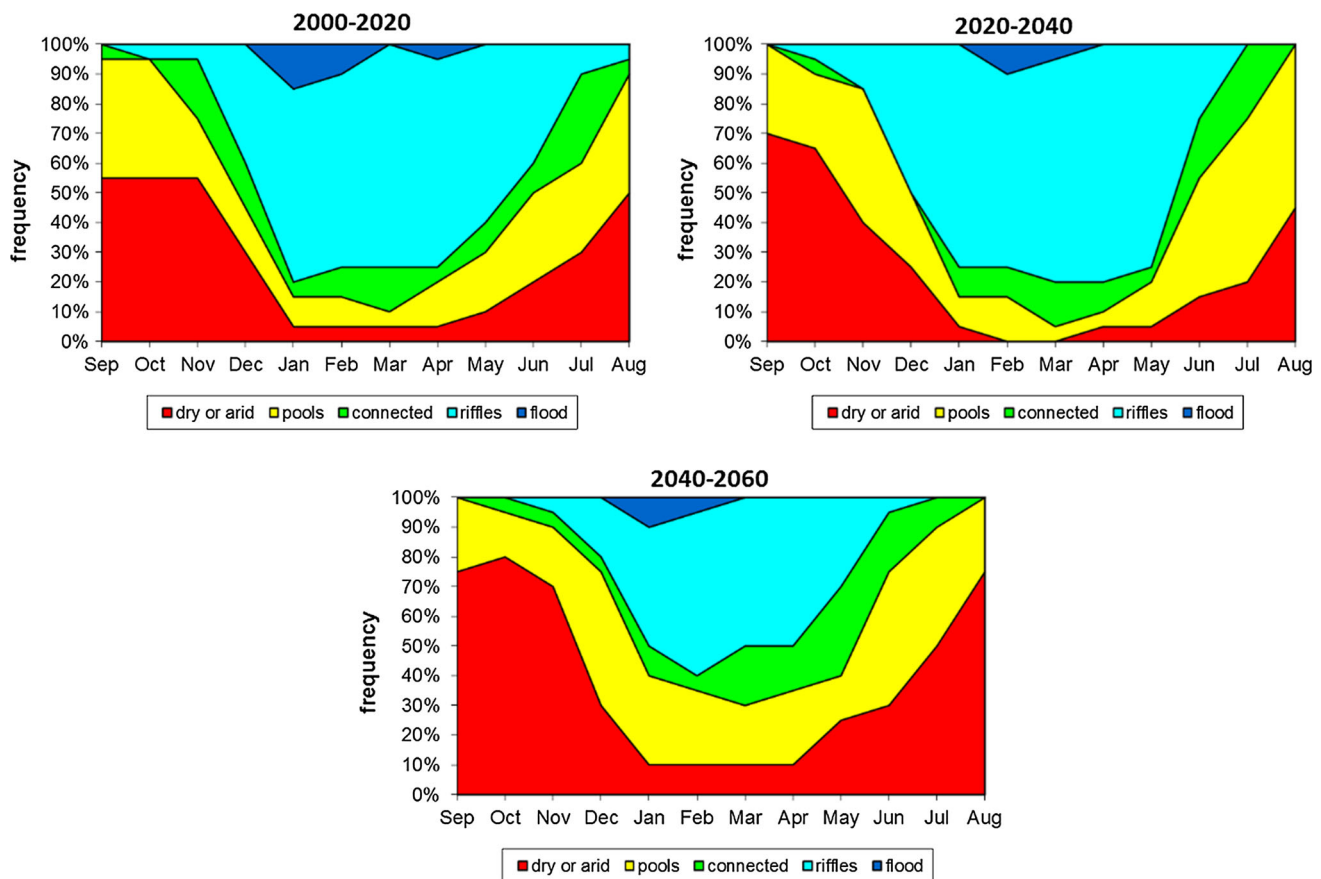
**Fig. 11** Aquatic states frequency graph at Vrontamas reach—MPI-REMO-ECHAM5

ecology. These are the Flow occurrence (Mf) and the Seasonal predictability (Sd6). The flow occurrence, Mf, is the method used to describe the degree of drying up. This is a measure for the flow permanence, presented as the average percentage per year there is flow. The seasonal predictability indicator, Sd6, is a measure developed by Gallart et al. (2011) to be able to give a characterization of the dry periods. This method uses the probability for the river to fall dry for each month and always divides the average of six months by the average of the following six months. This is performed for all combinations of the consecutive months: 1 through 6 divided by 7 through 12 followed by 2 through 7 divided by 8 through 1, and so on. The smallest value is chosen as the largest difference between the sets of six months. If there is always flow, the seasonal predictability Sd6 cannot be calculated. In these cases, the Sd6 is arbitrarily set to one, because the predictability of a non-dry period is obviously 100%.

The results indicate that the biggest problem of low and no flow conditions will occur during the years 2040–2060 and specifically at the Magoulitsa Ag. Irini reach where the Mf and Sd6 indexes have the lowest value while other

reaches such as Rasina (highland and lowland areas) showed somewhat higher flow permanence and a more regular seasonal pattern due to higher value in the Sd6. The low flow characterization for the current situation showed that a large part of the stream network is too dry to accommodate the development of a viable aquatic ecological community throughout the year.

### Impact of climate change scenarios on groundwater

During the 2043–2055 period, the KNMI-RACMO2-ECHAM5 climate change scenario projected an average decrease in the hydraulic heads equal to 0.82 m is estimated in the study area. This decrease corresponds to a 72 M $m^3$ water loss during these 12 years. The average precipitation of the basin for this period was estimated to be 683 mm $year^{-1}$. The actual evapotranspiration was 45.9% (314 mm $year^{-1}$), and the total water yield was 27.9% (190.8 mm $year^{-1}$). The rest 178.2 mm $year^{-1}$ (26.2%) is the amount of water that supply the aquifer which will be 40.9% less than the amount of water that was supplied in the 2000–2011 period highlighting the need for
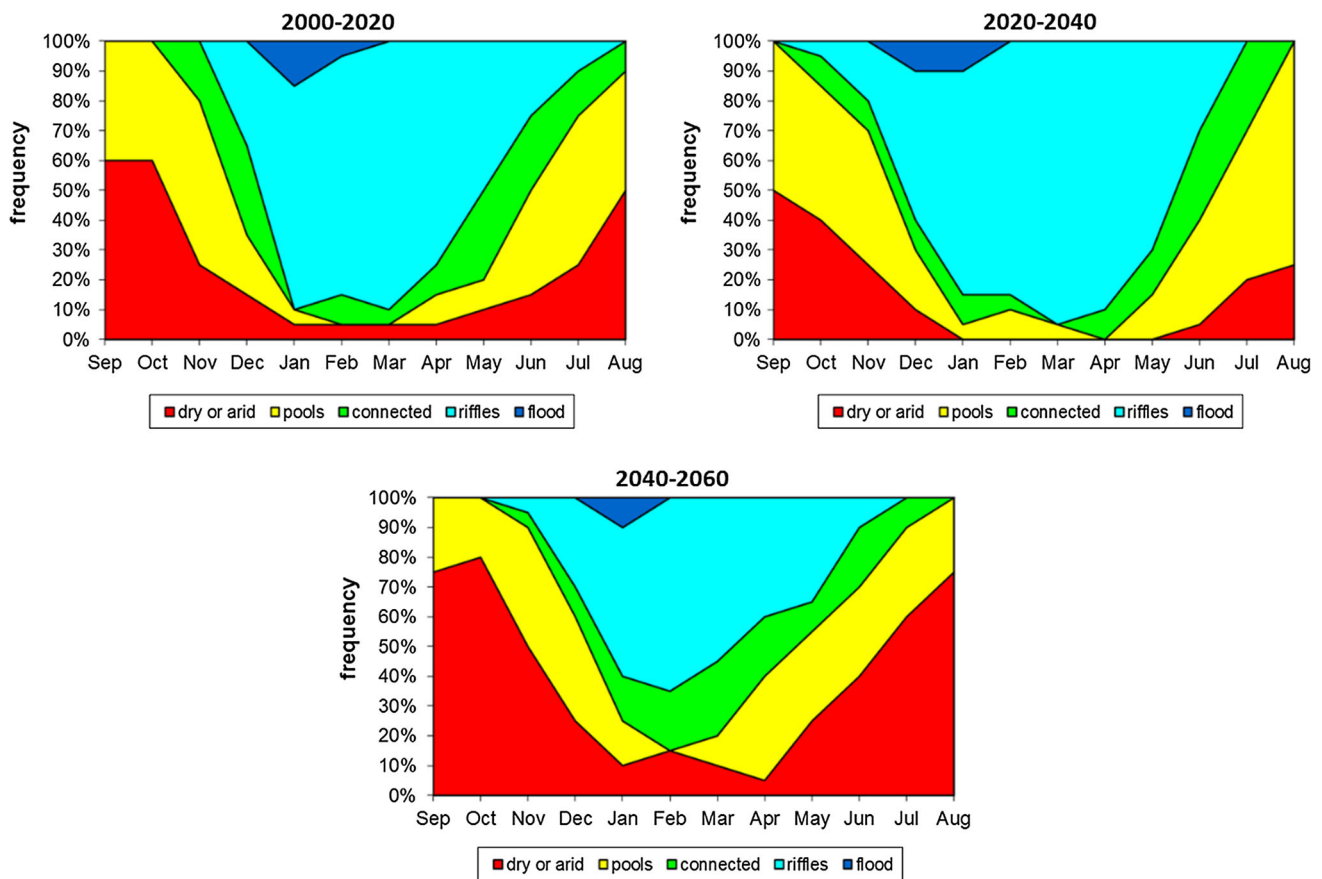
Fig. 12 Aquatic states frequency graph at Vrontamas reach—SMHI-RCA-ECHAM5

new management strategies that must be implemented in order to avoid setbacks in the allocation of water resources in the future.

On the other hand, when the SPI Index changes from dry to wet periods (2055–2057), an increase in the hydraulic heads equal to 0.16 m is estimated. For the MPI-REMO-ECHAM5 climate change scenario the average decrease for the 2043–2055 period equal to 0.47 m which corresponds to a 42.3 M $m^3$ water loss and for the SMHI-RCA-ECHAM5 scenario equal 0.87 m (78.3 M $m^3$), respectively. The results indicate that the Evrotas River Basin is very sensitive to potential future climate changes.

Figures 14, 15 and 16 present the response (hydraulic head change) in 10 model monitoring points (Fig. 13) that correspond to locations adjacent to the river reaches studied for the three climate change scenarios for the 2020–2060 period.

The reach with the most intense fluctuations on the hydraulic heads is the Magoulitsa Ag. Irini (SP3 και SP10) reach reaching 1.5 m decrease for all three climate change scenarios. These results are comparable with the results presented in the previous section in which Magoulitsa Ag. Irini will have the biggest problem of low to no flow (dry) conditions mostly by the 2040–2055

period providing additional evidence that the model can consistently depict low flow conditions in the basin. In general, all monitoring reaches return to their initial conditions by the year 2060.

Groundwater storage responses to direct climate-driven changes in precipitation and recharge rates are likely to be slower than surface water responses. Aquifers generally have comparatively greater temporal stability to changes in climate. Groundwater will be less directly and more slowly impacted by climate change, as compared to rivers. This is because rivers get replenished on a shorter time scale, and drought and floods are quickly reflected in river water levels. Groundwater, on the other hand, will be affected much slower. Only after prolonged droughts groundwater levels will show declining trends.

## Conclusions

Future scenarios for water resource management will be characterized by increasing water demand in the Mediterranean basin. Climate change will affect water resources in the future due the changes in hydro-meteorological variables at different scales. Adaptation is

**Fig. 13** Hydraulic head monitoring reaches (indicated by a cross)
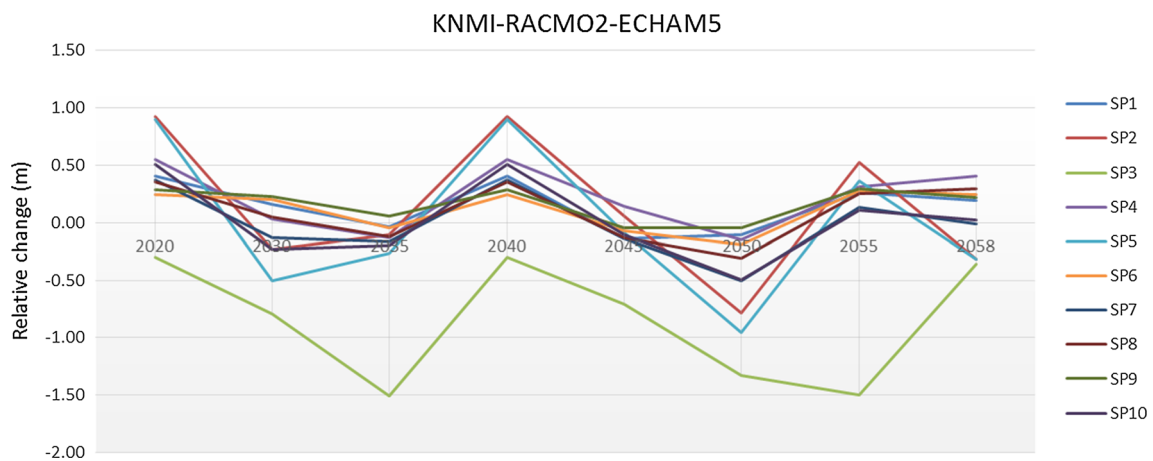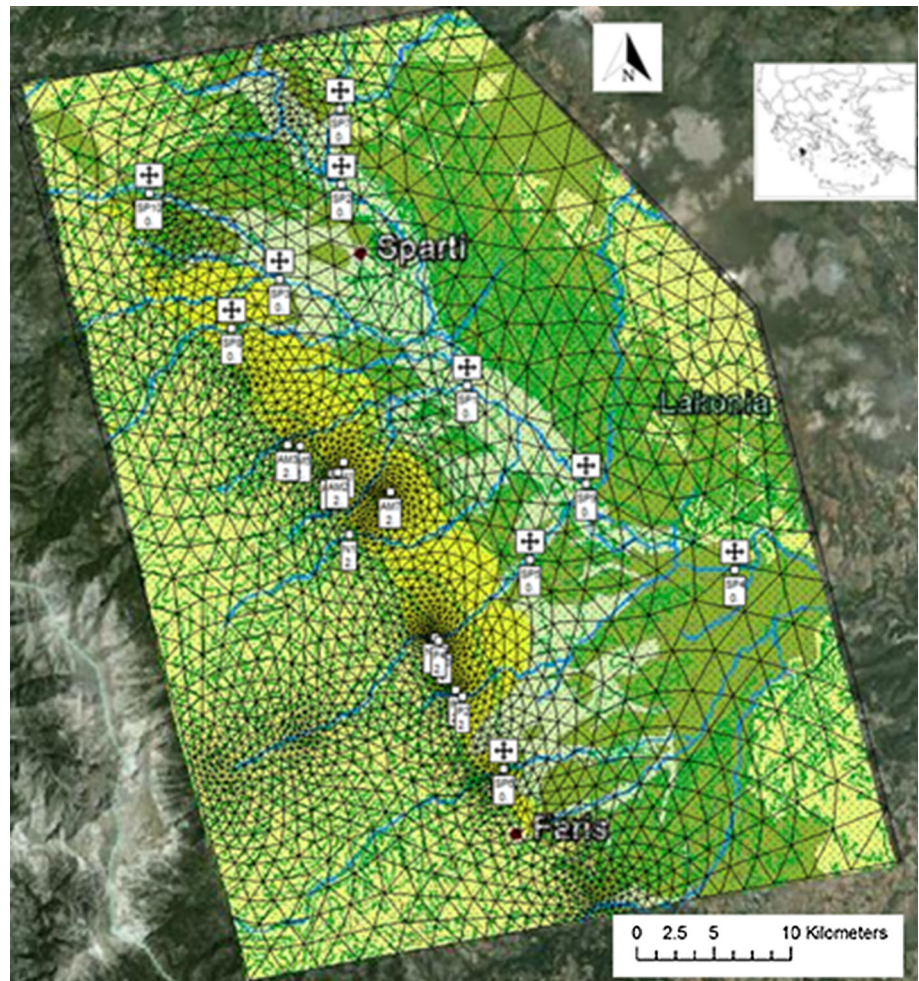




**Fig. 14** Relative change of hydraulic heads (m) in 10 reaches—KNMI-RACMO-ECHAM5

substantial for a sustainable use of the precious surface and groundwater resources. To reduce the uncertainty due to changing patterns of climate change as well as to improve long range forecasting, more research is needed to understand the dynamics associated with multiple meteorological, and hydrological processes as well as local socioeconomic factors like regional water demand. The development of data assimilation based on the integration of data from a variety of sources with different resolutions demonstrates the potential to improve model
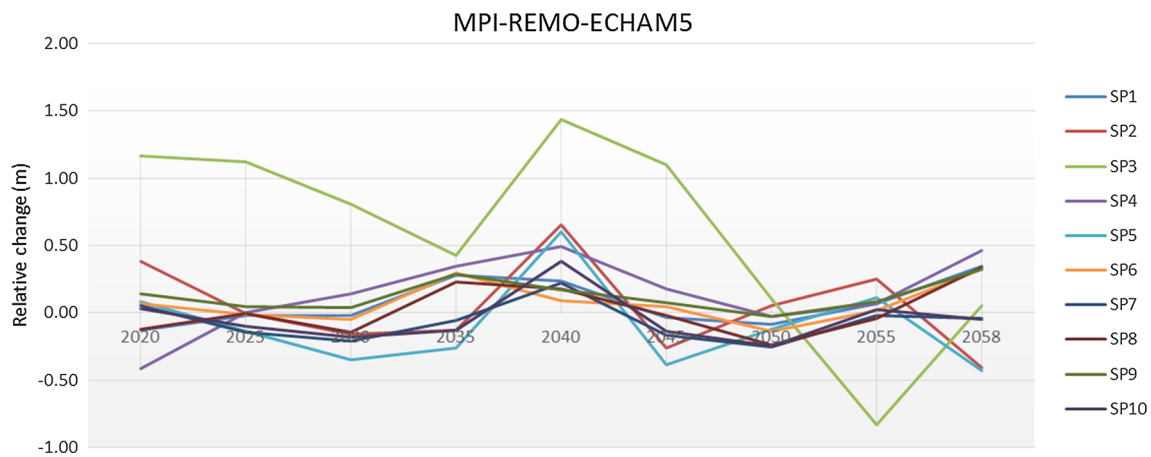
**Fig. 15** Relative change of hydraulic heads (m) in 10 reaches—MPI-REMO-ECHAM5
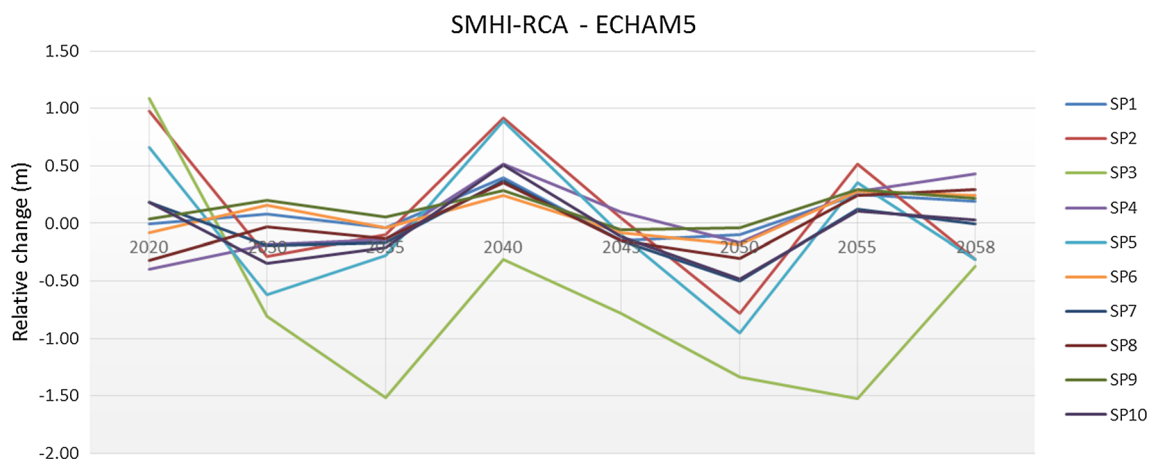


**Fig. 16** Relative change of hydraulic heads (m) in 10 reaches—SMHI-RCA-ECHAM5

predictions. Spatiotemporal drought analysis based on the combination of duration, severity, area and inter-arrival time is critical for short- and long-term water management. The demand for groundwater is likely to increase in the future because of the need to offset the substantial declines in surface water availability. The potential increase in rates of extraction could exacerbate declining water tables, the loss of groundwater storage and decreasing water quality in many already stressed aquifer systems. The EU Water Framework Directive and the policies of droughts and adaptation to climate change provides a specific framework of objectives, principals, definitions and measures to adopt, for assessing the impact of climate change on water resources.

To estimate the impact of climate change on groundwater reserves requires an adequate characterization of the concerned aquifers and robust modeling tools. For the purposes of this study, a comprehensive modeling framework for integrating a hydrologic (SWAT) and a groundwater (PTC) model was conceptualized, developed and tested in Sparta alluvial plain to address all the above issues. This study provides new insights in the evaluation of climate change impact on surface and groundwater, from data collection, the implementation of catchment-scale models. The methodology used here, however, relies on a series of assumptions that could be verified in the future with improved data.

The results provide relevant insights not only within the field of surface–groundwater interactions, but also in the broader area of drought risk management. The results indicate also that the study area is very sensitive to potential future climate changes. This study will help decision-makers and stakeholders for devising sustainable groundwater management strategies.

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