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Assessment of climate change impact in the hydrological regime of River Pinios Basin, central Greece

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ABSTRACT

In order to assess the potential impacts of climate change in the hydrologic regime of River Pinios Basin, an area-differentiated model for total run-off (Qt) estimation based on the GROWA model was applied with bias-corrected precipitation and temperature data from four regional climate models (RCMs) for the projected periods 2020–2050 (period A) and 2050–2080 (period B). Bias correction was performed using the linear scaling approach. As a reference basis, monthly precipitation data from 57 meteorological stations and average temperature data from 17 stations were analyzed for the period 1980–2000. Relative assessments were achieved by comparing reference to projected periods values for Qt, after incorporating bias-corrected projected climate data from the four RCMs driven by several general circulation models (GCMs) as input data to the hydrological model. Results showed that all RCM–GCM combinations lead to a considerable decrease in total run-off with variable rates between the examined projected periods; the greatest reduction of Qt (62%) from the reference period was forecasted for period A (2020–2050), and was simulated when GROWA model ran with input data from HIRHAM5 model driven by ARPEGE GCM, which indicated greater decrements in precipitation and increments in temperature. Regarding the estimations of total run-off for the end of the projected periods (2080) with simulated climatic data input from HIRHAM–ARPEGE, RACMO–ECHAM5 and REMO–ECHAM5 RCM–GCM combinations, a significant adverse impact to the overall water budget is forecasted, as the total amount of Qt is decreased from 46 to 66%. On the contrary, when Qt was simulated with climatic data from RCA4 RCM driven by HadCM3, smoother rates were exhibited due to smaller variations of precipitation and temperature from the reference period and the relevant Qt reduction by the end of the projection (2080) is 22%.

Keywords: Climate change impact; Water balance; Total run-off; Thessaly; River Pinios Basin

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1. Introduction

Water is an essential element for socioeconomic development and preservation of healthy ecosystems. Properly managed water resources are critical components of growth, poverty reduction, and equity, while increasing rates of urbanization and population growth raise significantly the demand for clean water and put stress on existing sources. In support of this, Global Water Partnership [1] acknowledged the paramount importance of water resources management through the admission that is being regarded as an integrated procedure which promotes the coordinated development and management of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Additional uncertainty stresses like climate change increase the complexity of managing water resources, especially in arid or semi-arid areas like Mediterranean regions which already suffer from increased environmental pressures [2]. The adverse impacts of climate change in such regions may include a significant decrease in the available water resources (both surface and groundwater), soil degradation and desertification, salinization of coastal aquifers, and water quality deterioration, all leading to environmental and economic problems with subsequent social controversies. Hence, the application of suitable water resources management strategies is a key element for modern societies in order to adapt and prepare for the already experienced and the foreseen adverse impacts of climate change, and satisfy the arising competing needs. Therefore, acquisition of accurate and reliable data is rather critical in order to successfully apply the envisaged strategic plans. The current practice implemented for the assessment of climate change impacts on water resources incorporates the application of models which simulate a wide range of hydrological and hydrogeological processes. The steps that are usually followed in such studies are summarized as follows: (a) selection of projected data from climate change scenarios simulated by global circulation models (GCMs) or regional climate models (RCMs), (b) downscaling or bias correction of GCM or RCM climate data, (c) input of downscaled or bias-corrected data into hydrological or hydrogeological models and simulation of water related processes, and (d) assessment of simulated results and identification of future trends through the comparison to historical (reference) data.

In this context, the present study assesses the potential effects of climate change in the hydrological budget of a large Mediterranean basin through the estimation of total run-off (Qt), regarded as the cumulative component of groundwater recharge, and direct run-off (surface and sub-surface). The estimation was made on the basis of comparison between a mean total run-off value of a reference time span (1980–2000) and the calculated mean values for two projected future periods (2020–2050 and 2050–2080) based on climatic data (precipitation and temperature) retrieved from four different scenarios. Total run-off calculations were made with the use of GROWA water balance model for the River Pinios Basin (RPB) which is the largest fully developing basin in Greece and its significance is paramount in terms of regional and national socioeconomic development and stability. Pinios Basin (Fig. 1) is considered as one of the highest productive basins of the country, located in Thessaly (central Greece) with total surface area of approximately 11,000 km^2. It is characterized by highly diversified geological, hydrological, and hydrogeological conditions and marked by the systematic exploitation of water resources since early 1960s. Due to water resources, mismanagement signs of overexploitation have appeared as early as mid 1980s and a deficient water balance has been established in the last three decades [3–5].

2. Materials and methods

2.1. Conceptual approach of GROWA model

GROWA [6] is a grid based empirical model, which has been developed to support practical water resources management issues of large river basins. It employs an empirical approach with a temporal resolution of one or more years. It calculates annual averages of the main water balance components, e.g. total run-off, percolation water rate, direct run-off, and groundwater recharge as a function of climate, soil, geology, topography, and land use conditions. GROWA has been applied to regions ranging typically between mesoscale river basins [7,8] of approx. 1,000 km^2 up to entire States or river catchments of 100,000 km^2 and more [9].

Water balance modeling is performed in three steps. In the first step, the mean long-term evapotranspiration rates (Eta) are determined according to an approach from Renger & Wessolek [10], which has been extended for mountainous areas [11], urban areas [12,13], and regions of sallow groundwater table [14]. In the second step, mean annual total run-off rates are calculated gridwise as the difference between the mean annual precipitation rate and the mean annual actual evapotranspiration rates. Finally, in the third step, total

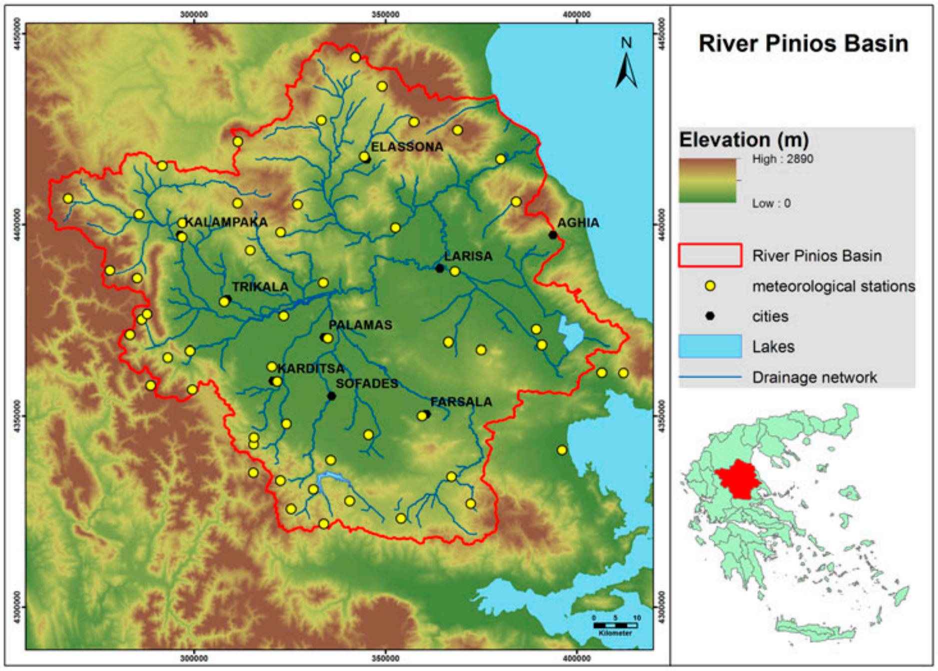

Fig. 1. Delineation of River Pinios Basin and location of considered meteorological stations.

run-off is separated into direct run-off and groundwater recharge. Whereas, direct run-off designates the sum of the fast run-off components (surface run-off, natural interflow, and drainage run-off), groundwater recharge is equal to the run-off components, which reach the surface waters after passing through an aquifer. The separation is done on the basis of several geofactors which take into account the degree of sealing, artificial drainage, petrographic properties, depth to groundwater, perching water, and slope.

2.2. Input data

Prior to GROWA model run, initial data preparation and regionalization were required. Spatially distributed grid-based (100 × 100 m) digital maps (climatic, hydrological, pedological, topographic, and hydrogeological) were produced as a combination of the variable sources, frequently existing in different scales; hence, regionalization and homogenization was inevitable and fundamental. The basic input data included information about soil properties (texture, soil depth, organic content, effective field capacity, capillary rise, and stagnant moisture), land use (CORINE land cover) [15], climate (precipitation and temperature), hydrology (drainage network, reservoirs, artificial irrigation channels, etc.), geology (lithological and hydrolithological characterization), and topography (Digital Elevation Model-DEM, slope, and aspect).

The initial model run for the reference time span of 1980–2000 was based on the above data-sets that included climatic data from 57 meteorological stations for precipitation and 17 stations for temperature (Fig. 1); hence, the extracted area-differentiated values for potential evapotranspiration were calculated according to Thornwaite method [16] from the stations for which both precipitation and temperature data were available. Regarding the model runs that account for the projected climatic scenarios, the basic input data were assumed to be constant and only the climate related parameters (precipitation and temperature) changed accordingly with the downscaled predictions of four different scenarios (see below). Therefore, the derived results of the water budget as a function of total run-off were focused on the direct impacts of climate change to key meteorological parameters and not to indirect ones like changes in soil properties and land use which are rather possible but when on purpose, filtered out as they are expected to increase dramatically the uncertainty of the model estimation.

2.3. Climate change scenarios–bias correction

The classification of downscaling or bias correction methods relies on two main categories: (a) dynamic downscaling methods corresponding to the application of RCMs and (b) statistical or empirical downscaling methods (bias correction methods), implying the application of statistical techniques to translate GCM or RCM climate data output into a finer resolution. Fowler et al. [17] reviewed thoroughly downscaling methods and techniques for hydrological modeling applications, and their conclusion was that generally there is no evidence proposing a specific downscaling technique or method (dynamic or statistical) as better for use in hydrological and water resources management studies. As the availability of reanalysis-driven RCM simulations is increasing, the combination of both downscaling methodologies is suggested for climate change impact studies [18].

Considering the above, precipitation and temperature data from the ENSEMBLES project were extracted, where state-of-the-art RCMs were used to produce regional simulations at a 25 or 50 km resolution [19] which were further corrected using the linear scaling approach. These regional simulations are driven by ERA40 reanalysis data [20] for the control period and by several GCMs under SRES A1B socioeconomic scenario which is the moderate scenario concerning CO_2 emissions. Among the various models of ENSEMBLES project, data for the periods 1980–2000 and 2020–2080 were used from the following four RCMs:

(1) HIRHAM5 [21], hereafter referred as HA, developed by the Danish Meteorological Institute (DMI) and driven by ARPEGE GCM for the A1B scenario.
(2) RACMO2 [22], hereafter referred as RA, developed by the Koninklijk Nederlands Meteorologisch Instituut (KNMI) and driven by ECHAM5 GCM for the A1B scenario.
(3) REMO [23], hereafter referred as REE, developed by the Max Planck Institute for Meteorology (MPI) and driven by ECHAM5 GCM for the A1B scenario.
(4) RCA3 [24], hereafter referred as RH, developed by the Swedish Meteorological and Hydrological Institute (DMI) and driven by HadCM3 GCM for the A1B scenario.

Among the several bias correction methods proposed by the scientific community, simple methods have the advantage of altering the RCMs results as little as possible [25]. The simplest methods proposed for bias correction of RCM output are the delta change and the linear scaling methods, the advantages and disadvantages of which are described by Teutschbein and Seibert [26]. Despite the fact that delta change method is considered more robust because observed climate data is used as a basis, it does not account for potential future changes in climate dynamics [26]. In contrast, linear regression does account for potential future changes in climate dynamics, while the degree of consistency between the variability of corrected and raw RCM data remains high. Linear scaling has been previously used in several studies for the assessment of climate change in watersheds hydrology, such as those of Graham et al. [25] and Lenderink et al. [27].

In terms of precipitation, a scaling factor was calculated for each calendar month and each RCM as the ratio between the average observed and average simulated monthly precipitation for the period 1980–2000. Those scaling factors were subsequently multiplied by monthly precipitation data for the period 2020–2080 for each calendar month. Monthly temperature was corrected in a similar way except that addition of scaling factor to project monthly average temperature was used rather than multiplication.

3. Results

3.1. Reference period (1980–2000)

The mean annual summer and winter precipitation corresponding to wet and dry hydrological periods (from April to September and from October to March, respectively), and the mean annual temperature for the reference period were interpolated using the inverse distance weighted (IDW) algorithm. The results indicated that mean annual precipitation is 701 mm and mean annual temperature is 14.6˚C. Accordingly as intermediate step, the mean annual potential evapotranspiration was calculated (900 mm/year) and the final output after the GROWA model run resulted to the estimation of mean annual total run-off (Fig. 2).

The average annual total run-off levels vary between few millimeters and 1,303 mm/year with a mean value of 324 mm/year. The lowest values are exhibited at the eastern part of the basin (eastern Thessaly basin) and are less than 50 mm/year. Overall, a decrease trend is captured from the mountainous to the plains areas and also from the west to the east, which is in good agreement with the analyzed distribution of precipitation and evapotranspiration. In general, low levels of total run-off (<200 mm/year) within Pinios Basin are indicated at nearly 70% of the total areal extent. On the contrary, in the mountainous areas at the west and northeast, total run-off reaches its highest values as a result of low temperatures (hence, low evapotranspiration) and high precipitation depths.

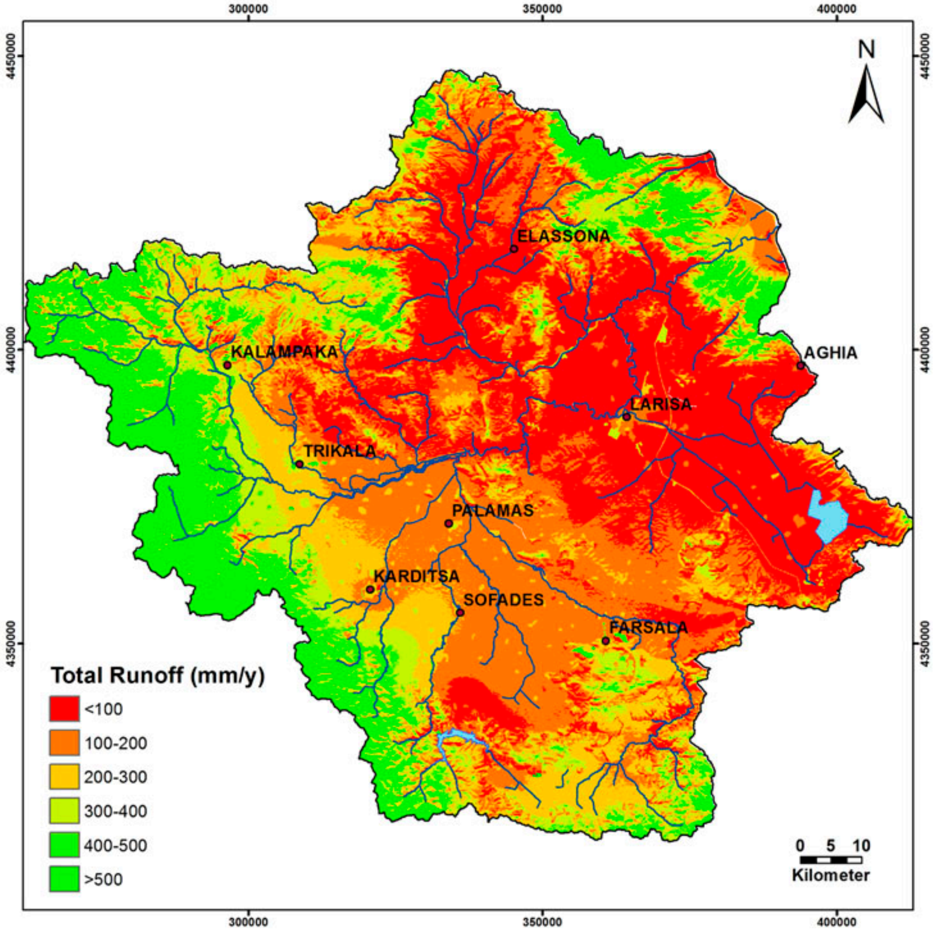

Fig. 2. Spatial distribution of estimated mean annual total run-off (Qt) for the reference period of 1980–2000.

3.2. *Projected period A (2020–2050)*

The results of precipitation and temperature change for the projected period A in relation to the reference period are presented in Fig. 3. All projections indicate increment in mean annual temperature and decrement in mean annual precipitation, except from RH models, which indicate increment in mean annual precipitation by 85 mm (or 12%) when compared to the reference period.

The strongest climate change signal is indicated by HA models, as mean annual precipitation is presented

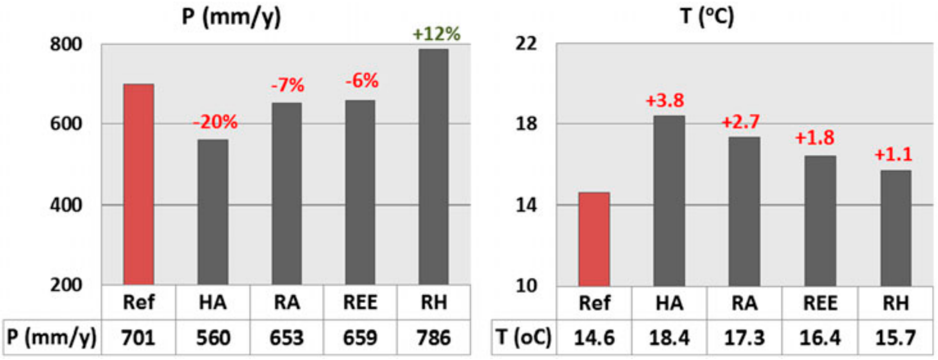

Fig. 3. Projections of mean annual precipitation and mean annual temperature for period A (2020–2050).

to be decreased by 141 mm (or 20%), while the corresponding change in mean annual temperature is 3.8˚C. The RA and REE precipitation decrements are very close (48 mm or 7% and 42 mm or 6%, respectively), while temperature increments are 2.7 and 1.8˚C, respectively. The lowest temperature increase is indicated by RH and accounts for 1.1˚C, while precipitation increases by 12%.

Based on the above climatic data, GROWA model estimated the mean total run-off (Qt) for the projected period A (2020–2050) which is displayed in Table 1. The HA models appear to lead to the lowest mean Qt value (124 mm/year) which is significantly decreased by 200 mm/year (62%) compared to the reference period. Accordingly, when Qt was simulated with precipitation and temperature input from RA and REE models, it was found to be decreased by 123 mm/year (38%) and 116 mm/year (36%), respectively. Finally, Qt as simulated with input from RH models, which by definition are the most optimistic results, exhibits a decrement of nearly 8% corresponding to 27 mm/year.

3.3. Projected period B (2050–2080)

The precipitation and temperature changes for the projected period B in relation to the reference period are summarized in Fig. 4. Similarly to period A, all projections indicate increment in mean annual temperature and decrement in mean annual precipitation, except from RH models which indicate negligible change when compared to the corresponding value for the reference period. The strongest climate change signal is indicated by HA models, as mean annual precipitation is presented to be decreased by 151 mm (or 22%) in relation to the reference period, while the corresponding change in average annual temperature is 4.2˚C. The RA and REE precipitation decrements are very close (140 mm or 20% and 149 mm or 21%, respectively), while temperature increments were 4.1 and 3.4˚C, respectively. The lowest temperature increase is indicated by RH models (2.2˚C), while precipitation was found to be slightly increased by 6% (41 mm). Pisinaras et al. [28] have also reported increased precipitation by 13% for the period 2011–2100 in Vosvozis river basin located in northeastern Greece, as indicated by bias-corrected precipitation data from RCA3-HADCM3-Q0 models.

For the projected data for period B (2050–2080), the estimation of mean Qt with precipitation and temperature data from HA and RA models (Table 2) were found to have nearly the same major decrement in Qt compared to the reference period, corresponding to 214 mm/year (66%) for HA and 210 mm/year (65%) for RA. Total run-off results as simulated with REE climate input data indicated smaller but still significant decrease (150 mm/year or 46%). Finally, Qt estimated with climate data from RH models yielded the smallest decrease by 70 mm/year (22%).

4. Discussion

As derived from the data processing of the four RCM–GCM combinations, significant variations in total run-off either as absolute Qt values or as relative rates between the reference and the projected periods do exist (Fig. 5), but is worth mentioning that at the end of the projection (2080), the estimations for the overall reduction of total run-off roughly coincide for the simulations made with input from HA and RA models (66 and 65%). The relevant variations in Qt values are greater during period A (compared to reference period) than in period B (compared to period A). On the contrary, projected Qt results with RH models input are by far more optimistic compared to the other three models, and the final overall decrement is significantly smaller (22%) with nearly constant variation rate for both projection periods.

Qt reduction as simulated with HA models climate input is major for period A (66%) compared to reference period, but minor for period B (4%) compared to period A; this trend is also reflected to both precipitation and temperature, where variations are greater in

Table 1
Results of mean total run-off for the projected period 2020–2050

	Mean total run-off				
	Min (mm/year)	Max (mm/year)	Mean (mm/year)	Dif (mm/year)	Dif%
Reference (1980–2000)	0	1,303	324		
HIRHAM-ARPEGE (HA)	0	1,060	124	−200	−62
RACMO-ECHAM5 (RA)	0	1,356	201	−123	−38
REMO-ECHAM5 (REE)	0	1,365	208	−116	−36
RCA-HADCM3 (RH)	0	1,379	297	−27	−8

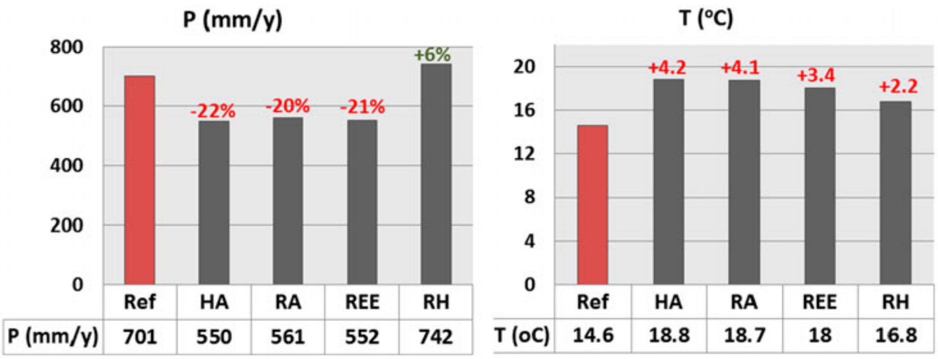

Fig. 4. Projections of mean annual precipitation and mean annual temperature for period B (2050–2080).

Table 2
Results of mean total run-off for the projected period 2050–2080

	Mean total runoff				
	Min (mm/year)	Max (mm/year)	Mean (mm/year)	Dif (mm/year)	Dif%
Reference (1980–2000)	0	1,303	324		
HIRHAM-ARPEGE (HA)	0	1,020	110	−214	−66
RACMO-ECHAM5 (RA)	0	1,119	114	−210	−65
REMO-ECHAM5 (REE)	0	1,307	174	−150	−46
RCA-HADCM3 (RH)	0	1,416	254	−70	−22

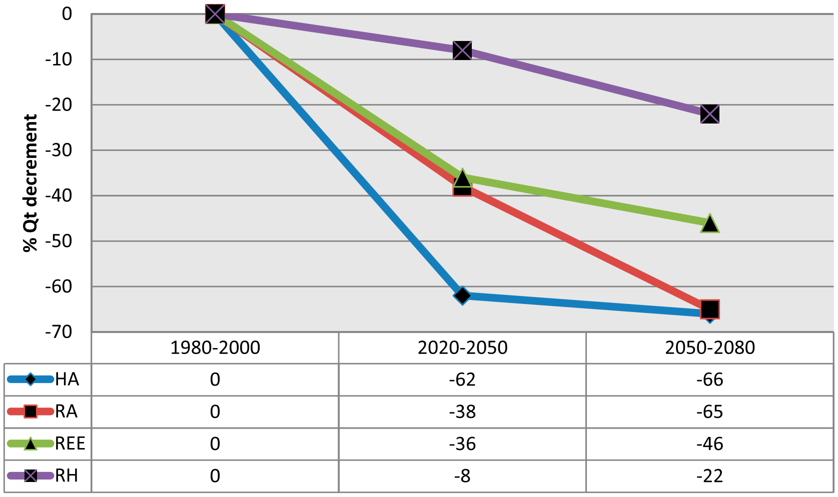

Fig. 5. Percentages of Qt decrement for four RCM–GCM combinations in respect to the reference period.

projected period A compared to the reference period (1980–2000), than the variations between the projected periods A and B which are much smaller (precipitation was found to be further decreased only by 10 mm and temperature increased by 0.4˚C). Regarding Qt results with climate input from RA and REE models, reduction rate is similar for the projection period A, but is differentiated for the projection period B. As seen in Fig. 5, mean total run-off values of RA and REE models are decreased by 38 and 36%, respectively. By the end of the projection (2080), RA models decrease rate is nearly constant and reach a similar value with HA models for the overall Qt decrease from the reference period. On the other hand, REE variation

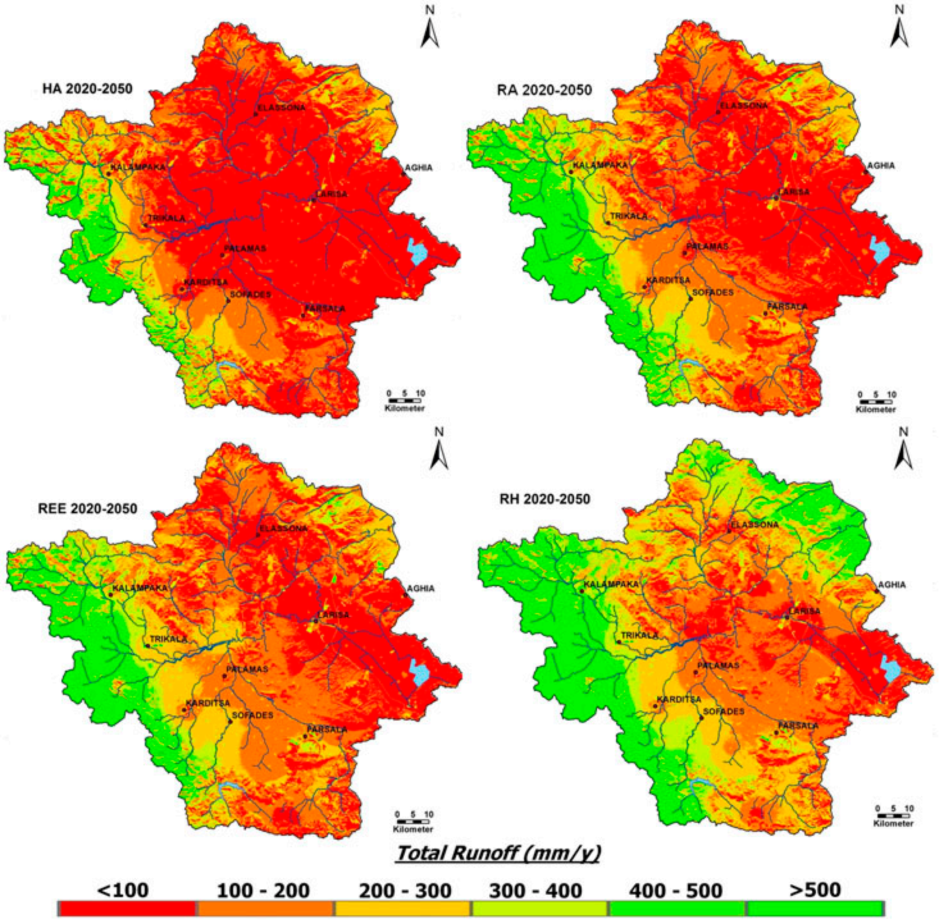

Fig. 6. Total run-off as simulated by GROWA model with climate data from four RCM–GCM combinations for the period 2020–2050.

rate is smoothed and is further decreased only by 10% until the end of the projection in 2080 (46% decrement in total from reference period). On the contrary, the relative variation rate for the RH models is totally different than the previous climate change scenarios. During period A, total run-off values are slightly decreased by 8% compared to the reference period, whilst by the end of the second projection period (2080), Qt decrease reaches 22% compared to the reference period. Overall reduction by the end of the projection (2080) after RH models is roughly 45% less than Qt estimated after climate input from HA and RA and 24% less than REE models. The strong influence of projected climate data in major hydrologic budget constituents in the Mediterranean region has been also reported in other studies. Senatore et al. [29] investigated future climate change effects in a part of Crati River basin located in Italy by applying a hydrological model with climate data from three climate models for the period 2070–2099. In terms of run-off, the results indicated a significant decrease when compared to the corresponding values for the period 1961–1990 that ranges between 19.4 and 46.1%. Elguindi et al. [30] applied ARPEGE-CLIMATE V4 GCM for three different horizontal resolutions and their results that concerns the Mediterranean sea basins indicated significant fresh water run-off decrease for the period 2046–2070 compared to the period 1979–2002, ranging between 18 (high resolution) and 48% (low resolution). The potential impacts of climate change in the hydrologic regime of three medium-sized catchments in northeastern Spain were assessed by Pascual et al. [31] and the results indicated that the predicted river flow change for the period 2076–2100 ranged between 25 and 34%.

In order to assess in more detail the overall variations in total run-off and their spatial distribution, the grid-based mean annual total run-off values (Qt) for the projected periods A and B are illustrated below (Figs. 6 and 7, respectively).

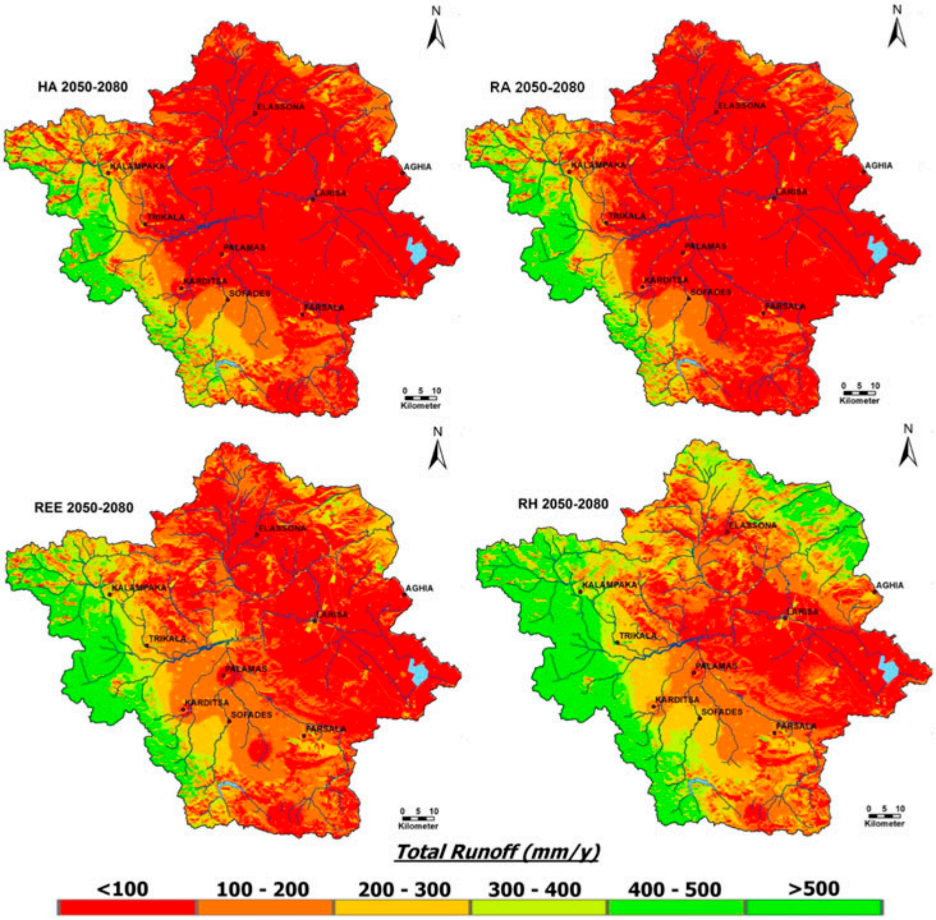

Fig. 7. Total run-off as simulated by GROWA model with climate data from four RCM-GCM combinations for the period 2020–2080.

The spatial distribution of Qt values for HA models for the projected period A shows that nearly 80% of total area coverage is characterized by low values below 100 mm/year. This trend is not only delineated at plain parts but also extends to the semi-mountainous and mountainous areas at the northern part of the basin. Despite the significant decrease in the mean total run-off by 66%, few mountainous regions located in the western part of the basin still exhibit elevated values (e.g. over 500 mm/year), indicating a strong contrast with the adjacent semi-mountainous and plain areas (western Thessaly subbasin) as expected. The spatial distribution of Qt for period B is similar to period A, as expected by the low difference of the mean annual Qt values (−4%).

Regarding RA and REE models for period A, spatial distribution of Qt exhibits a progressive decrease trend from southwest to northeast at discrete zones of northwest–southeast direction. In general, low Qt values (<100 mm/year) have wider areal extension for RA than REE models, but both are likely to be delineated mainly at eastern Thessaly subbasin. Significant differences of Qt values between the mountainous areas at the west and their adjacent parts of the basin are documented, similar to those of HA models, but with a higher contrast probably due to the increased maximum values for Qt (see Table 1) as a result of increased precipitation at the mountainous areas. The trend of spatial distribution for period B is differentiated; the low Qt values for RA models are extended to the western Thessaly subbasin and their spatial distribution and areal coverage is similar to HA models. On the contrary, low Qt values of REE models are slightly increased (compared to RA models), expressed by a more dense distribution at the northern part of the basin and locally as few “hot spots” (e.g. around Palamas and Karditsa city) which are more likely to be artifacts of the interpolation method rather than climatic impact.

Finally, the spatial distribution of mean annual Qt for RH models varies greatly compared with the aforementioned. In respect to period A, low values exhibit a percentage of nearly 7% and are located at a part of eastern Thessaly subbasin as well as scattered individual spots within an area in the central part (delineated by a rectangle formed by the cities of Larisa, Elassona, Kalampaka, and Palamas). The elevated Qt values (>500 mm/year) are located mainly at the western mountainous areas but are also distributed at the deltaic area of River Pinios at northeast. Similarly to RA and REE models, a progressive decrease trend from southwest to northeast at discrete zones of northwest–southeast direction is also depicted. A zonal trend from southwest to northeast with decreasing Qt values ranging from 500 to 100 mm/year is also exhibited like in previously discussed models, but the spatial coverage of Qt classes is different compared to RA and REE models. The distribution for period B is slightly changed compared to period A, mainly expressed by the extension of low Qt values towards west that include the entire eastern Thessaly subbasin and its fringes to the west.

5. Conclusions

Precipitation and temperature data from four different RCM–GCM combinations accounting for the periods 2020–2050 and 2050–2080 were used as a basis for the assessment of the potential changes in the water budget of RPB. The overall assessment was achieved with the aid of GROWA hydrological model by estimating the mean total run-off values (Qt) that accounted for the total amount of water resources that RPB receives at a given time span. Total run-off represents the available volumes of water that can be potentially utilized, hence is the subject of water resources management at river basin scale. Relative comparisons were made taking into account the reference values for the period 1980–2000.

Despite the different sources of uncertainties incorporated in climate change impacts assessment, simulation results with GROWA model showed that all RCM–GCM combinations lead to a considerable decrease in total run-off by the end of 2080 (22–66%). The variation rates between the two projected periods were considerably different; the HA models which indicate greater decrements in precipitation and increments in temperature appear to have the greatest reduction of Qt during projected period A. On the contrary, when Qt is simulated with input from the RH models, which indicated smaller variations of precipitation and temperature from the reference period, it presents smooth variations which are more likely to be efficiently managed by future strategic plans and increase the possibility of successful adaptation of future societies.

In respect to RH models, total run-off decrease is likely to change almost linearly and the total amount of reduction by the end of the projection periods (2080) reaches 22%, and it is spatially distributed mainly at the central plain parts especially affecting the eastern part of the basin, while the mountainous areas exhibit a slight increase of total run-off. On the contrary, Qt simulated with input from HA, RA, and REE models was estimated to have a significant adverse impact to the overall water budget, as the total amount of Qt is decreased by the end of the projection (2080) from 46 to 66%. It is easily comprehensible that the anticipated effects of such a dramatic decrement would significantly affect both the anthropogenic and the natural environment, especially in the case of RPB that already exhibits signs of water reserves depletion due to groundwater overexploitation owed mainly to irrational water management practices.

Since the reversibility of climatic change phenomenon is not likely to occur, it is of paramount importance to be adequately prepared and adapted to the foreseen effects by applying integrated water resources management plans, including groundwater artificial recharge, effective irrigation schemes, rational exploitation of water reserves, continuous monitoring of water quality and quantity, and targeted technical interventions, but primarily rising of public awareness and participation to common efforts. Moreover, in depth consideration of extensive restructuring of cropping pattern in the framework of the new common agricultural policy (CAP) should be given, shifting to crops and varieties that have low irrigation demands but high market value. In parallel, adoption of deficient irrigation techniques appear to be imperative as means of effective reduction of water demands.

As noted in the beginning, the examined scenarios assume no effective changes in the soil characteristics, land use, and water use patterns. Inevitably, such large changes in the water budget of the basin are bound to lead to critical changes in the landscape and the overall land and water use patterns. As known from the past, societies develop adaptation capabilities in response to a given drought or flood incident or period of incidents. However, so far, such historical episodes are remoted and of limited time extent. Moreover, it is clearly documented that the societal response was not always appropriate and often led only to short term alleviation of the impacts but overall establishment of adverse effects (groundwater heads decline, water quality deterioration, soil denudation, etc.). Therefore, based on the alternative climate change, scenarios and their projected effects are nowadays more urgent than ever to design and implement an integrated set of measures in the direction of adaptation and preparedness, so that the anticipated impacts from climate change are minimized and controllable.

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