



# Simulation and Evaluation of Water Resources Management Scenarios Under Climate Change for Adaptive Management of Coastal Agricultural Watersheds

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## Abstract

The main objective of this paper is to analyze the impact of climate change on water resources management and groundwater quantity and quality in the coastal agricultural Almyros Basin, in Greece. Intensive groundwater abstractions for irrigation and nitrogen fertilization for crop production maximization, have caused a large water deficit, nitrate pollution, as well as seawater intrusion in the Almyros aquifer system. Multi-model climate projections for Representative Concentration Pathways (RCPs 4.5 and 8.5) from the Med-CORDEX database for precipitation and temperature have been used to evaluate the impacts of climate change on the study area. The multi-model climate projections have been bias-corrected with Delta, Delta change of Mean and Variance, Quantile Delta Change, Quantile Empirical Mapping, and Quantile Gamma Mapping methods, and statistically tested to find the best GCM/RCM multi-model ensemble. Simulation of coastal water resources has been performed using an Integrated Modelling System (IMS) that contains connected models of surface hydrology (UTHBAL), groundwater hydrology (MODFLOW), nitrate leaching/crop growth (REPIC), nitrate pollution (MT3DMS), and seawater intrusion (SEAWAT). The results indicate that the best climate multi-model ensemble consists of three (3) climate models for both RCP4.5 and RCP8.5 using the Quantile Empirical Mapping bias-correction method. The IMS was applied for historical and future periods with observed and simulated meteorological inputs (e.g. precipitation and temperature) and various irrigation and agronomic scenarios and water storage works development (i.e. reservoirs). The results indicate that at least deficit irrigation and deficit irrigation along with rain-fed cultivation schemes, combined with or without the development and operation of reservoirs, should be applied to overcome the degradation of groundwater quality and quantity in the study basin. Based on the findings of this work, the water resources management should be adaptive to tackle the water resources problems of the Almyros Basin.

**Keywords** Integrated Water Resources Management · Coastal Agricultural Watershed · Groundwater Nitrate Pollution · Seawater Intrusion · Climate Change · Adaptation

## 1 Introduction

Climate change is a complicated and international phenomenon that describes the rate of change in the average trends of climatic variables. Climate change is already experienced globally as the influence of the alteration of the synthesis of the atmosphere due to Greenhouse Gas emissions (GHGs) originating from anthropogenic activities (IPCC 2014). Diversified volatilities and shifts are expected to occur in hydrological drivers such as precipitation, temperature, evaporation/evapotranspiration, soil moisture content, sea levels, groundwater recharge, as well as in water demands of arable lands, urban water demands, reliability of surface water systems, nutrient use efficiency, groundwater abstractions, and evolution of seawater intrusion in coastal aquifer systems (García-Mollá et al. 2021; Rachid et al. 2021).

Currently, precipitation is increasing in high latitudes whilst declining along several lower mid-latitude locations, including those of the Mediterranean area (Tzabiras et al. 2016). The temperature increase is larger in arid and semiarid regions as compared to wetter areas (Jalota et al. 2018). Numerous semi-arid territories around the Mediterranean Sea are typified by deficit water balance, overexploitation of groundwater resources for irrigation, nitrate pollution phenomena due to fertilizers, and chlorides due to seawater intrusion. Accounting for the effects of climate change such as reduction of renewable water resources, higher irrigation requirements, agricultural yields production, nitrate contamination, and/or seawater intrusion could facilitate the high performance of water resources management under climate change (Sidiropoulos et al. 2019; Busico et al. 2021; Felisa et al. 2022; Roshani and Hamidi 2022). Integrated water resources management necessitates forethought and strategic planning for adaptive policies under climate change because water resources, and especially aquifer systems, are characterized by a lagged environmental response to irrigation and fertilizer application practices (Lyra et al. 2022). Adaptive water resources management under climate change is different from adaptation measures to climate change because it addresses with an integrated and holistic approach the minimization of process-based uncertainty of climate projections that relate to adaption measures i.e. sustainability targets (Mysiak et al. 2010; Gaur and Simonovic 2015).

The projections of climate change scenarios lead to different future climates and introduce significant uncertainty about the changes in hydrological drivers, especially after the middle of the 21st century (Mysiak et al. 2010; Jalota et al. 2018). Present, past, and future climatic changes are simulated by coarse grid-scale simulators (200–300 km) of the long-term atmosphere-ocean movements, the Global Circulation Models (GCMs) while the socio-economic aspects are integrated into the climate forcing with the use of Representative Concentration Pathways (RCPs) of possible future economic development trends. However, watershed studies require finer resolution outputs than those provided by the GCMs, because regional natural characteristics such as topography, elevation, rivers, or lakes, are not considered, while they affect and define the hydrologic regime of smaller extents (Mechoso and Arakawa 2015). For this reason, the GCMs' principal components of the hydrologic cycle, undergo the process of downscaling, meaning the transformation from a coarse to a finer scale, by eliminating inherent biases from their coarse-scale origin, to achieve a better and more representative match of climate conditions of large regions (e.g. the Mediterranean) and form Regional Climate Models (RCMs) (Jalota et al. 2018). Regional Climate Models (RCMs) regularly are still biased, and their geographical accuracy

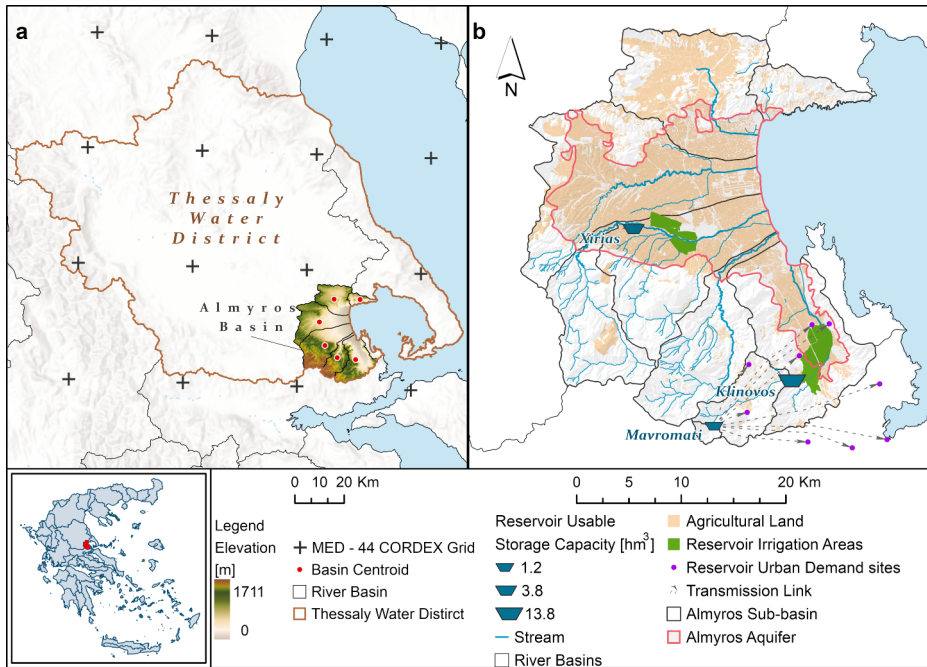
may still be too coarse for hydrological studies. To establish bias-corrected high-spatial-resolution predictions, statistical downscaling of Regional Climate Models (RCMs) is often employed to reduce the regional uncertainty of climate models. The rationale underpinning the statistical downscaling methodologies is that a correlation can be outlined between the larger scale GCMs and RCMs and the localized scale of a watershed.

The main objective of this paper is to estimate and evaluate the climate change impacts on groundwater quantity and quality, and the adaptive efficiency of management plans and reservoirs' operation scenarios, in the Almyros Basin in Thessaly, Greece. The evaluation is based on (a) the assessment of precipitation and temperature changes through the construction of high-performance bias-corrected multi-model ensembles, and (b) the simulation of adaptive management scenarios of water resources in the coastal and agricultural Almyros Basin in Thessaly, Greece, under climate change. The simulation has been performed using a calibrated, validated, and high-efficient Integrated Modeling System (IMS) for agricultural coastal watersheds, developed in earlier studies by Lyra and her associates (Lyra et al. 2021c; 2022). The Integrated Modeling System (IMS) is constituted of interacting and interconnected models of surface water hydrology and reservoir operation, an agronomic/nitrate leaching model, and groundwater models that simulate the fluxes of water and water pollutants of nitrates and chlorides (Lyra et al. 2021c; 2022). The potential benefits of the scenarios/strategies over the existing agricultural and water management schemes are highlighted by the assessment of the future projected groundwater budget, seawater intrusion, and nitrate contamination, while the water use efficiency is estimated by the Crop Water Productivity index. The findings make prominent how the different scenarios (agronomic-irrigation, and water resources development) would affect the water balance and quality status of the Almyros aquifer system, and how they could be utilized to achieve adaptive water resources management under two climatic scenarios, RCP4.5 and RCP8.5.

## 2 Materials and methods

### 2.1 Study area

The Almyros basin is situated in central Greece, in the Thessaly area (Fig. 1a). The basin has an extent of 856 km<sup>2</sup>. Its elevation range is 0–1700 m, and its mean elevation is 370 m. The basin has a semi-dry Mediterranean climate, with hot, dry summers and cold, rainy winters with an average annual rainfall of 570 mm, and an average annual temperature of 15.0 °C. The basin is divided into six (6) watersheds with intermittent flow streams, namely from north to south, Kazani, Lahanorema, Holorema, Xiria, Platanorema, and Xirorema (Fig. 1b). The average annual runoff is about 110 mm, and the average annual aquifer recharge is about 55 mm. Almyros aquifer is in communication with the sea and extends over the basin's coastal lowlands, where clay layers with sandy porous materials exist. Within the southernmost section of the area, limited limestone protrusions generate karstic formations which have physical contact with seawater (open karst) but no hydraulic connection with the alluvial groundwater. At the western and high elevation zones, wedge-shaped clay as well as clay, sand, and gravel intercalate among volcanic and conglomerate rocks and mold low permeability formations (Lyra et al. 2021c). Water demands for agriculture and other water uses are being covered by groundwater abstractions during the historical



**Fig. 1** Map of (a) Almyros basin and Med-CORDEX grid and (b) Almyros basin and aquifer, watersheds, reservoirs' irrigated areas, and positions of the reservoirs of Xirias (under-construction), Klinovos (planned), and Mavromati (constructed)

period 1991–2018 as no other water sources exist. Agricultural activities occur in 205 km<sup>2</sup>, covering almost 70% of the Almyros aquifer area for the historical period (Fig. 1b). The crops cultivated in the aquifer area were in 2010 and 2018, respectively, 7.7% and 16.8% alfalfa, 10.3% and 25.1% cereals, 8.55% and 8.4% cotton, 2.55% and 1.6% maize, 10.9% and 12.9% olives, 1.3% and 2.4% trees, 1.6% and 6.6% vegetables, 2% and 2.5% vineyards and 32.8% and 9.9% wheat. Mean annual groundwater abstractions equal to 30 hm<sup>3</sup>, while the water resources availability is characterized by a water deficit of -12 hm<sup>3</sup>. The aquifer's quantity and quality state have deteriorated, and water piezometric level declination, nitrate contamination, and seawater intrusion have also emerged as estimated in previous work by Lyra et al. (2021c).

Currently, to mitigate the urban water supply problems of the region, the Mavromati reservoir was constructed to meet the urban water demands (0.51 hm<sup>3</sup>) of nine (9) settlements in and around of Almyros basin, while the remaining urban water demands continue to be covered by groundwater abstractions (Lyra et al. 2022). In the center of the basin, the Xirias reservoir is being planned and constructed to meet the irrigation demands of 7 km<sup>2</sup> and prevent seawater intrusion (Fig. 1b). Furthermore, the Klinovos reservoir was proposed as a surface water development plan although, no policy decision has been taken for its construction yet, and especially in the research project of Lyra et al. (2022) its irrigated area extent was optimized at 10.2 km<sup>2</sup>. None of the three reservoirs existed/operated before 2018 and thus, they didn't participate in the calibration/validation of IMS (Lyra et al. 2021c). However, they have been used in the development of surface water development scenarios

because the concept of operating water reservoirs as an alternative water source to groundwater, and their contribution to the region, has not been extensively studied. Only two water resources development studies considering reservoir development and operation exist for the study area (Dervisiz 2010; Lyra et al. 2022). However, these studies are referred to the historical period and they did not include the impacts of climate change.

## 2.2 Climate Change-Multi-model Bias-correction

Bias-correction methods are Statistical Downscaling Methods (SDMs), characterized as Model Output Statistics (MOS) methods because they establish a transfer function of statistical attributes from the observed to the simulated variables of climate models, utilized for the meta-analysis of the GCMs/RCMs results (Maraun and Widmann 2018). In the meta-analysis, observed measurements and climate model outputs can be considered as parts of two probability distributions, with marginal, time and space, and multi-variable conditions. When the climate model output distribution differs substantially and systematically from the observed variable distribution, then the climate model output is considered biased. The base period of a climate model is set the one with a time range equal and identical to the time step of the observed variable. The future period is set the one that extends beyond the historical period, integrating a variety of climate dynamic forcings (Lee and Singh 2018). The bias-correction methodologies applied in this work are the Delta method, the Delta change of Mean and Variance, the Delta Quantile Mapping, the Quantile Empirical Mapping, and the Quantile Gamma Mapping as described in the “Supplementary Material”. The climate models’ ensembles have been based on bias-correction efficiency scores with goodness-of-fit metrics, against the observed data, to determine the most appropriate multi-model ensemble per RCP forcing emission, and the most efficient bias-correction method (Supplementary Material, Sections S.1 and S.2).

Since there are various sources of uncertainty on climate model outputs, (e.g. alternate GCMs develop alternative climate projections for a single GHG emission scenario, internal variability), the use of multiple models can increase their efficiency and confidence, if the input models are at least partly independent (Evans et al. 2013; Pakdaman et al. 2022). For this reason, in this study, the projections of precipitation and temperature from seven GCMs combined with eleven RCMs were investigated and bias-corrected with five methods of downscaling for emissions scenarios RCP4.5 and RCP8.5 until the end of the 21st century. Precipitation and temperature for the two forcing emissions scenarios and two spatial resolutions, i.e.,  $11^{\circ}\times 11^{\circ}$  and  $44^{\circ}\times 44^{\circ}$  were retrieved by the Med-CORDEX database (Mediterranean branch of the Coordinated Downscaling Experiment) (Panthou et al. 2018) for the synthesis of the multi-model ensembles and their bias-correction for the wider area of Almyros basin (Supplementary Material, Table S.2). The flowchart for constructing high-efficiency multi-model ensembles with Med-CORDEX climatic data is presented in Fig. 2(a).

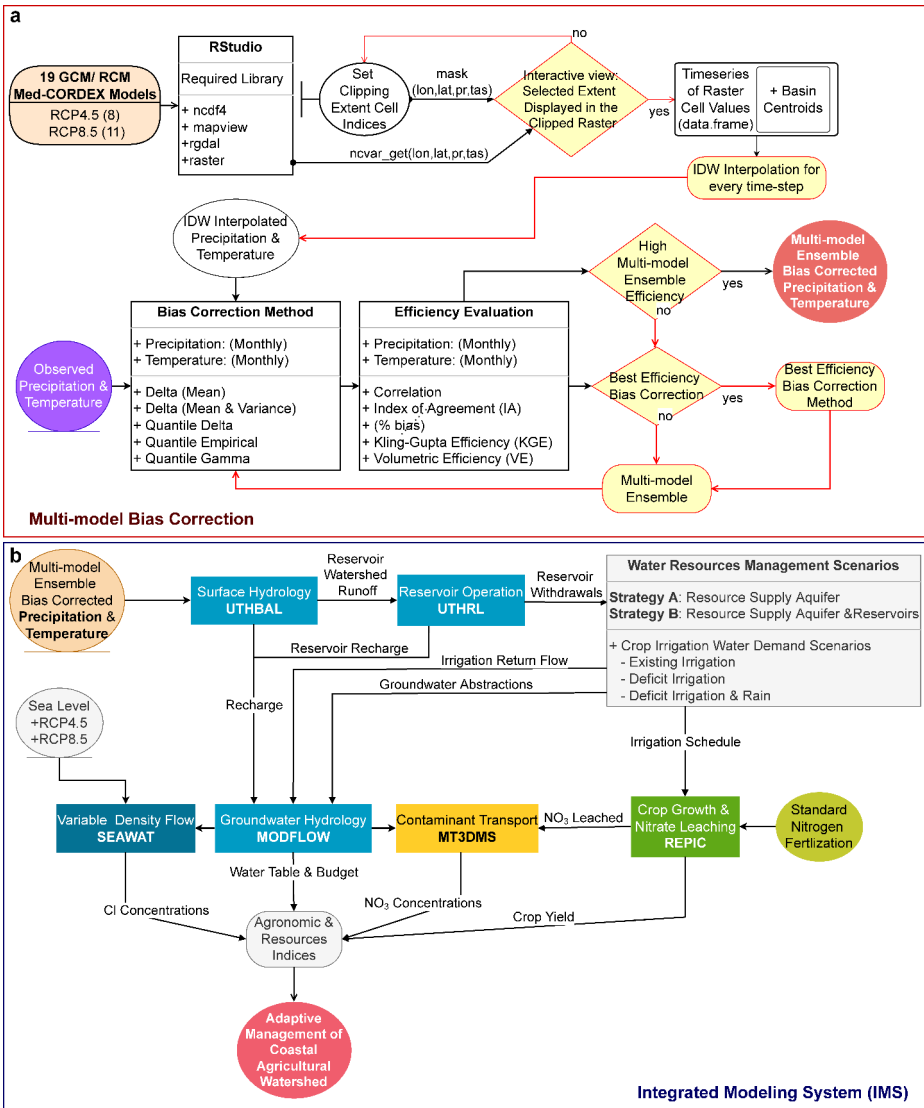


Fig. 2 Flowchart of (a) Multi-model Bias-Correction and (b) Integrated Modeling System (IMS).

### 2.3 Simulation and Evaluation of Water Resources Management Scenarios

#### 2.3.1 Databases and Sources

For the baseline historical period, 1991 to 2018, meteorological, hydrogeological and groundwater pollution observations were used in the prior work by (Lyra et al. 2021c) to calibrate and validate the modules of the Integrated Modelling System (Supplementary Material, Section S.3). Regarding the development of water reservoirs, technical information for the Xirias reservoir was provided by the Regional Government of Thessaly and the

construction study by (MINAGRIC 2018) which was pre-processed for this research, while data from the study of Dervisis (2010) were used for the simulation of the Mavromati and Klinovos reservoirs.

Datasets for precipitation, temperature, and sea-level trends were required to simulate the water system of Almyros under climate change for the historical and future periods, 1991–2018, and 2019–2100, respectively. The mean sea level rise is approximately 0.05 m for the historical period 1991–2018, based on a gridded dataset of daily satellite observations for the Mediterranean Sea by (E.U.Copernicus-Marine-Service-Information Copernicus Climate Change Service (C3S)). The linear trend of mean sea level rise was estimated at 3.6 mm/yr ( $R^2=0.63$ ), during the historical period. The historical sea-level rise trend corresponds to the estimated net increase of 0.3 m under RCP4.5 emissions until 2100. Similarly, under RCP8.5 emissions, a net sea level rise of 0.6 m corresponds to a linear trend of 6.3 mm/yr at the coast of the study basin (EEA 2019; Oppenheimer et al. 2019).

### 2.3.2 Integrated Modelling System (IMS)

The Almyros basin's surface and groundwater resources were simulated with an Integrated Modelling System (Lyra et al. 2021c; 2022) with coupled models of surface hydrology (UTHBAL), reservoir operation (UTHRL) (Loukas et al. 2007), groundwater hydrology (MODFLOW) (Harbaugh et al. 2000), agronomic/crop planning, and nitrates leaching (REPIC, an R-ArcGIS based EPIC model) (Lyra et al. 2021c), aquifer's nitrates transport (MT3DMS) (Zheng and Wang 1999), and seawater intrusion (SEAWAT) (Guo and Langevin 2002).

UTHBAL model uses areal temperature, precipitation, and potential evapotranspiration in monthly-step to calculate watershed surface runoff and natural groundwater recharge. The total groundwater recharge is, then estimated by adding the natural groundwater recharge and the weighted mean irrigation return flow of crop types per sub-basin. UTHRL model uses as input variables the catchment's runoff, the reservoir's storage capacity, the demanded water abstractions from the reservoir, the precipitation and evaporation on the reservoir's surface, and the leakage to the groundwater. The net groundwater recharge, reservoir groundwater leakage, irrigation return flow, net monthly sea-level rise are considered as the inputs to MODFLOW model, while groundwater abstractions were distributed to the wells on a monthly-step based on the water requirements for agricultural, urban, or other water uses. The REPIC model was used to simulate the agronomic operations considering irrigation water and fertilizer requirements per watershed and crop type. The input data of REPIC are land use, climate, irrigation, as well as additional variables. REPIC results include crop yields and nitrate leaching into groundwater. The latter is used as input to the MT3DMS model. Seawater's chloride concentrations are the input to the SEAWAT model, and the outputs are the chloride concentration in the Almyros aquifer and the interflows of seawater at the coastline. The flow chart of the Integrated Modelling System (IMS) is presented in Fig. 2(b). The Integrated Modelling System (IMS) is implemented in Almyros basin, on a semi-distributed mode for surface hydrology modeling (i.e.on watersheds' scale) and fully distributed for groundwater modeling (i.e.on grids of  $200 \times 200$  m for the basin aquifer) with the necessary mapping of surface and groundwater hydrology domain to simulate the basin's groundwater balance, the nitrates, and chlorides concentrations in groundwater.

Two adaptive strategies of water resources management scenarios have been developed, Strategy A (groundwater pumping to cover the water demands) and Strategy B (groundwater pumping and reservoir water withdrawals to cover the water demands). In addition to existing irrigation (hereafter, Strategy A and B), agronomic/irrigation scenarios of deficit irrigation (Strategy A1 and B1), and rain-fed cultivation (Strategy A2 and B2), were integrated. Crop water requirements for deficit irrigation were minimized to 90% for alfalfa, 80% for cereals, 80% for cotton, 90% for maize, 89% for olives, 76% for orchards, 90% for vegetables, 60% for vineyards, and 80% for wheat compared to typical irrigation schemes based on field experiments in the Mediterranean area and Greece as presented in the former work by Lyra et al. (2021a, 2021b, 2022). Rain-fed cultivation is feasible only for cereals, olives, and wheat for which crops is applied.

### 2.3.3 Crop Water Productivity (CWP<sub>I</sub>)

The Crop Water Productivity index (CWP<sub>I</sub>) for the applied irrigation water and crop yields was estimated using Eq. (1) (Lyra et al. 2021a, 2022) to assess the efficiency of the water management scenarios in improving the farmland benefits, based on simulation results by the REPIC model, groundwater abstractions by MODFLOW model, and reservoir withdrawals by UTHBAL-UTHRL module for the Almyros' cropland.

$$\text{Crop Water Productivity (CWP}_I\text{)} = \frac{\text{Crop Yield (kg} \cdot \text{ha}^{-1}\text{)}}{\text{Irrigation Water (m}^3 \cdot \text{ha}^{-1}\text{)}} \quad (1)$$

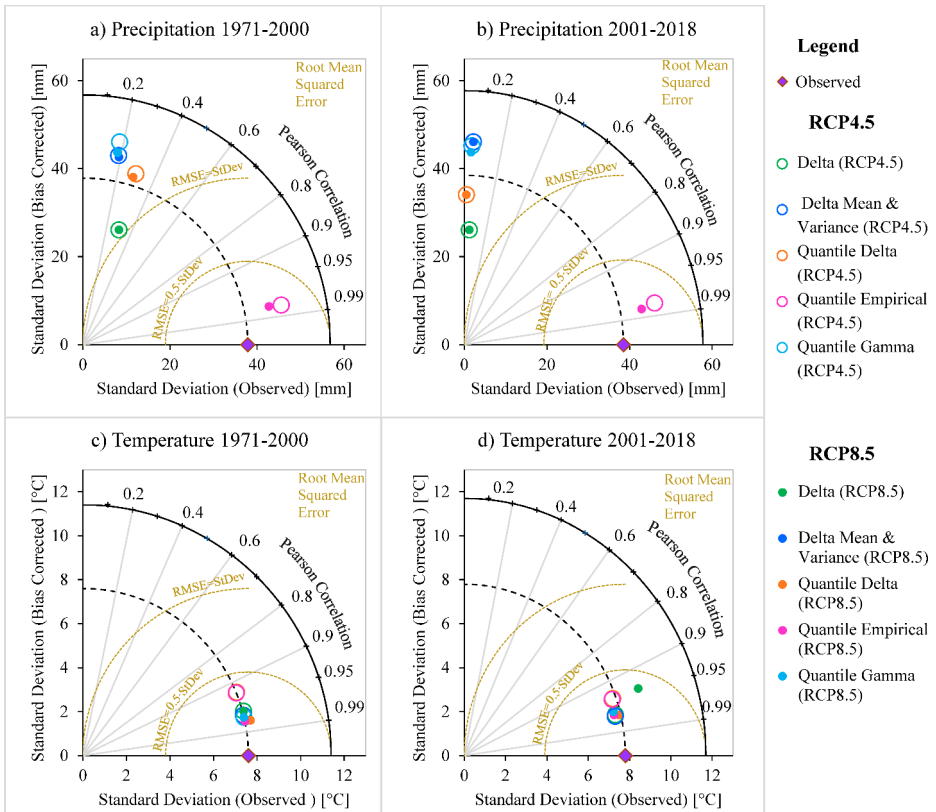
## 3 Application – Results

The Multi-model Bias-Correction results under RCP4.5 and RCP8.5 climate change scenarios, and the Integrated Modeling System results for the developed water resources management scenarios in the Almyros basin are presented and discussed in the next sections.

### 3.1 Climate Change-Multi-model Bias-correction

Med-CORDEX climate models were downloaded in \*.nc file format and proximate grid-cell values to the Almyros area were extracted interactively in RStudio and interpolated to the watersheds' centroids of the basin using Inverse Distance Weighting (Racine 2012; Bivand et al. 2015; Hijmans et al. 2015; Appelhans et al. 2016; Pierce 2019). Precipitation and temperature were bias-corrected using the methods Delta change, Delta Change of Mean and Variance, Quantile Delta Mapping, Quantile Mapping, and Quantile Gamma Mapping. Goodness-of-fit metrics were calculated for each bias-correction method and model, to define the best ones for the multi-model ensembles' construction (Supplementary Material, Table S3). The bias-correction methods were applied to the outputs of monthly precipitation and temperature of climate models (GCM/RCM), calibrated for the historical period 1971–2000 and validated for the historical period 2001–2018 against observed precipitation and temperature data. The multi-model ensembles were combined with an iterative trial-and-error process and Models 3, 9, and 11 compose the RCP4.5 ensemble, while Mod-





**Fig. 3** Taylor Diagram of Monthly Observed and Bias-Corrected a) Precipitation 1971–2000, b) Precipitation 2001–2018, c) Temperature 1971–2000, and d) Temperature 2001–2018 RCP4.5 (empty-circle) and RCP8.5 (filled-circle) climate scenarios

els 3, 7, and 10 compose the RCP8.5 ensemble. The best-performing method as indicated by the closest symbol to the observed values of the Taylor diagram (Fig. 3), is (QEM). The best-performing ensemble is the RCP8.5 ensemble which falls as close to the black dashed-curve of standard deviations. The highest correlations, smallest RMSE, and deviations among the observed values and the monthly averages of precipitation and temperature occur under RCP8.5(QEM) rather than under RCP4.5(QEM). According to Fig. 3(a,b) precipitation (QEM) is overestimated for both RCPs because it falls right further and higher than the observed precipitation, the magnitude of which is evaluated based on the RMSE. Hence, precipitation is more overestimated under RCP4.5 than under RCP8.5, and more overestimated in 2001–2018 than in 1971–2000. Respectively, according to Fig. 3(c,d), all methods perform a high correlation to the observed temperature. As indicated by the RMSE, temperature (QEM) is underestimated in both RCPs, more underestimated under RCP4.5 than under RCP8.5, and more underestimated in 1971–2000 than in 2001–2018. It should be noted that variability and uncertainty still exist among the results of climate models.

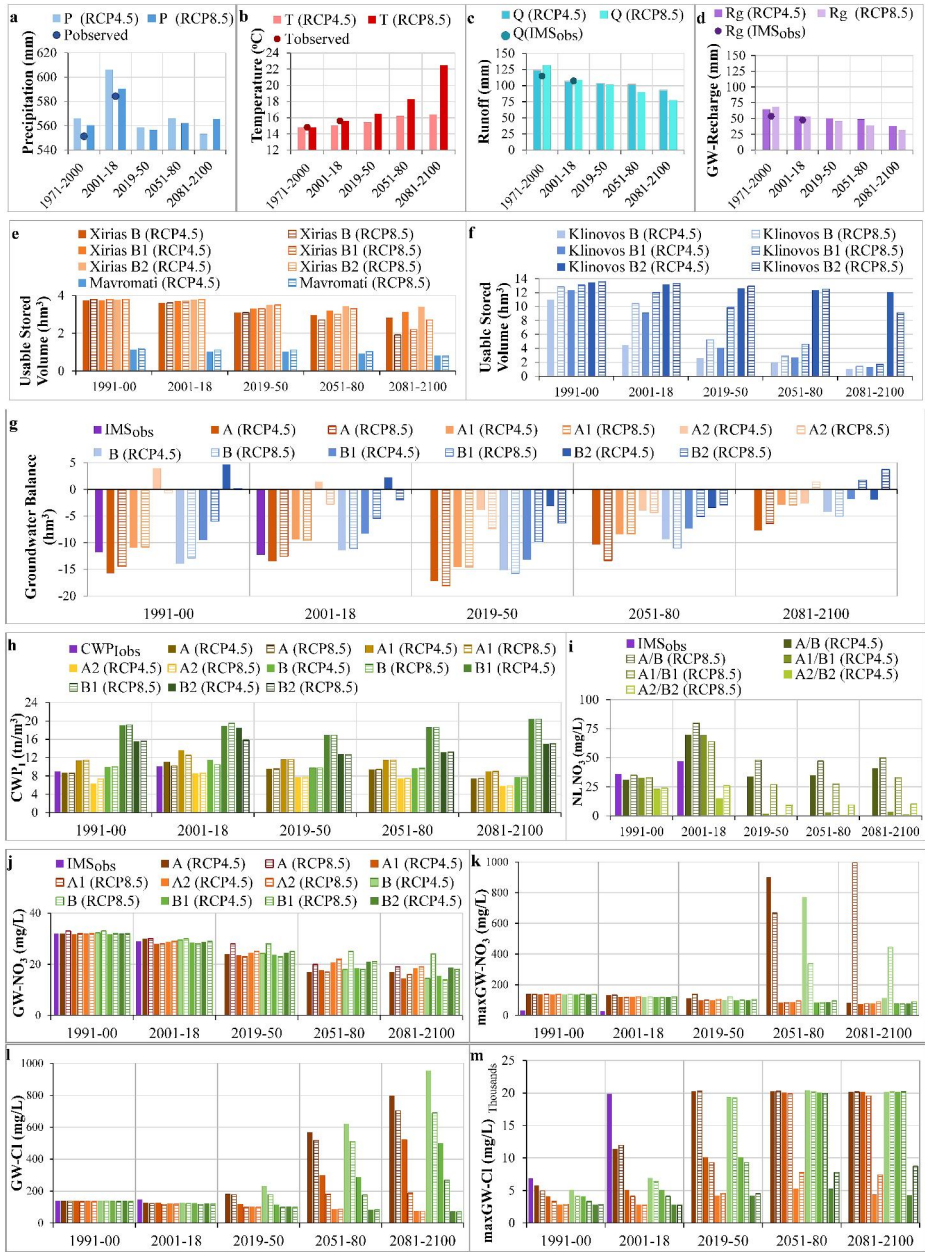
### 3.2 Integrated Modeling System (IMS)

Water resources management scenarios were implemented under climate change scenarios in the Almyros basin, using the Integrated Modeling System (IMS). The simulation results of the (IMS) are shown in Fig. 4 for the historical periods of 1971–2000, and 2001–2018, and the projected periods of 2019–2050, 2051–2080, 2081–2100 highlighting the differentiation of simulation results among the various strategies and climate change scenarios from the simulations for the observed periods. The simulated and validated results of the IMS for the historical period (Lyra et al. 2021c) represent the observed-reference values. According to the calibration/validation periods of bias-correction of climate models (GCM/RCM), 1971–2000 (calibration), and 2001–2018 (validation), the historical periods of surface IMS simulations were similarly defined. Groundwater data were available after 1991, but to reflect the bias-correction calibration/validation periods, the historical periods for the groundwater IMS simulations were defined as 1991–2000 and 2001–2018. The historical cultivation pattern was kept unchanged in the simulations for future periods.

The mean annual bias-corrected precipitation and temperature for the periods of 1971–2000 (calibration), 2001–2018 (validation), 2019–2050, 2051–2080, 2081–2100 are presented in Fig. 4(a,b). Precipitation shows the largest decrease during 2019–2050 but then, presents a small increase during 2051–2080 under both RCPs. Noticeably, precipitation decreases until 2100 for RCP4.5, but it slowly increases for RCP8.5. However, the precipitation for future periods remains lower as compared to historical periods. Temperature shows an upward trend until 2100, having a steeper increase under RCP8.5 than RCP4.5 (Fig. 4). The performance of bias-corrected precipitation and temperature affects the water resources' budgets, the groundwater abstractions and recharge, the nitrate leaching and pollution, the seawater intrusion, and the Crop Water Productivity.

The UTHBAL results indicate that surface runoff has a decreasing trend until 2100, and recharge is almost reduced by 50%. The (UTHRL) results show that the Xirias and Klinovos reservoirs have a larger reduction of their usable storage capacity for Strategies B, and B1 of existing and deficit irrigation schemes than for Strategy B2 of deficit/rainfed cultivation. The usable stored reservoir volume under the RCP8.5 scenario is larger than RCP4.5 scenario, but it gradually reduces towards the end of the century (2100). The quantity and quality status of surface water and groundwater would deteriorate under climate change. The groundwater simulation (MODFLOW results) shows that the groundwater balance is greatly negative, but the groundwater deficit gradually decreases for Strategies B1, A1, A, B, B2, and A2 in future periods for both climatic scenarios. The water balance of Strategy A (RCP8.5) in the period 1991–2000 (calibration) and 2001–2018 (validation) is closer to the reference water deficit than the water balance of Strategy A (RCP4.5). This difference indicates that large groundwater abstractions occur over the dry periods of RCP4.5, and the overestimated precipitation of RCP4.5 (QEM) is distributed mostly over the wet periods.

Nitrates leaching (REPIC) results indicate a decrease of leached concentrations analogous to irrigation water applied, but leachates are quite different between RCP4.5 and RCP8.5 scenarios, especially for the deficit irrigation and rain-fed cultivation scenarios, due to the overestimation of bias-corrected precipitation under RCP4.5. This overestimation possibly leads to greater dilution of the pollutant. Nitrate concentrations (MT3DMS results) are significantly decreased for Strategies B, B1, and B2, while most decreased in Strategy B1, and follow the trends of nitrates leached under RCP4.5 and RCP8.5 scenarios. Chlo-



**Fig. 4** Mean annual (a) precipitation, (b) temperature, (c) surface runoff, (d) GW-recharge, (e,f) reservoir volume, (g) GW-balance, (h) CWP<sub>1</sub>, (i) nitrates leaching, (j) average and (k) maximum GW-nitrates, and (l) average and (m) maximum GW-chlorides concentrations under RCP4.5(solid columns) and RCP8.5 scenarios(dashed columns). *Note: UTHBAL results (Runoff and GW-Recharge) for the bias-corrected climate model meteorological timeseries are compared with the simulated results using the observed meteorological timeseries for the historical periods*

ride concentrations (SEAWAT results) are significantly decreased for Strategies A2 and B2, while groundwater quality deteriorates up to the medium saline state (Figs. 4 and 5). The seawater intrusion is affected mainly by the groundwater abstractions than the sea-level rise. Seawater intrusion will continue to advance in the future due to sea-level rise and groundwater abstractions. The operation of reservoirs has small impact on seawater intrusion in the long-term, because their effect depends on the distance from the shore of the areas supplied water from the reservoirs.

### 3.2.1 Crop Water Productivity (CWP<sub>i</sub>)

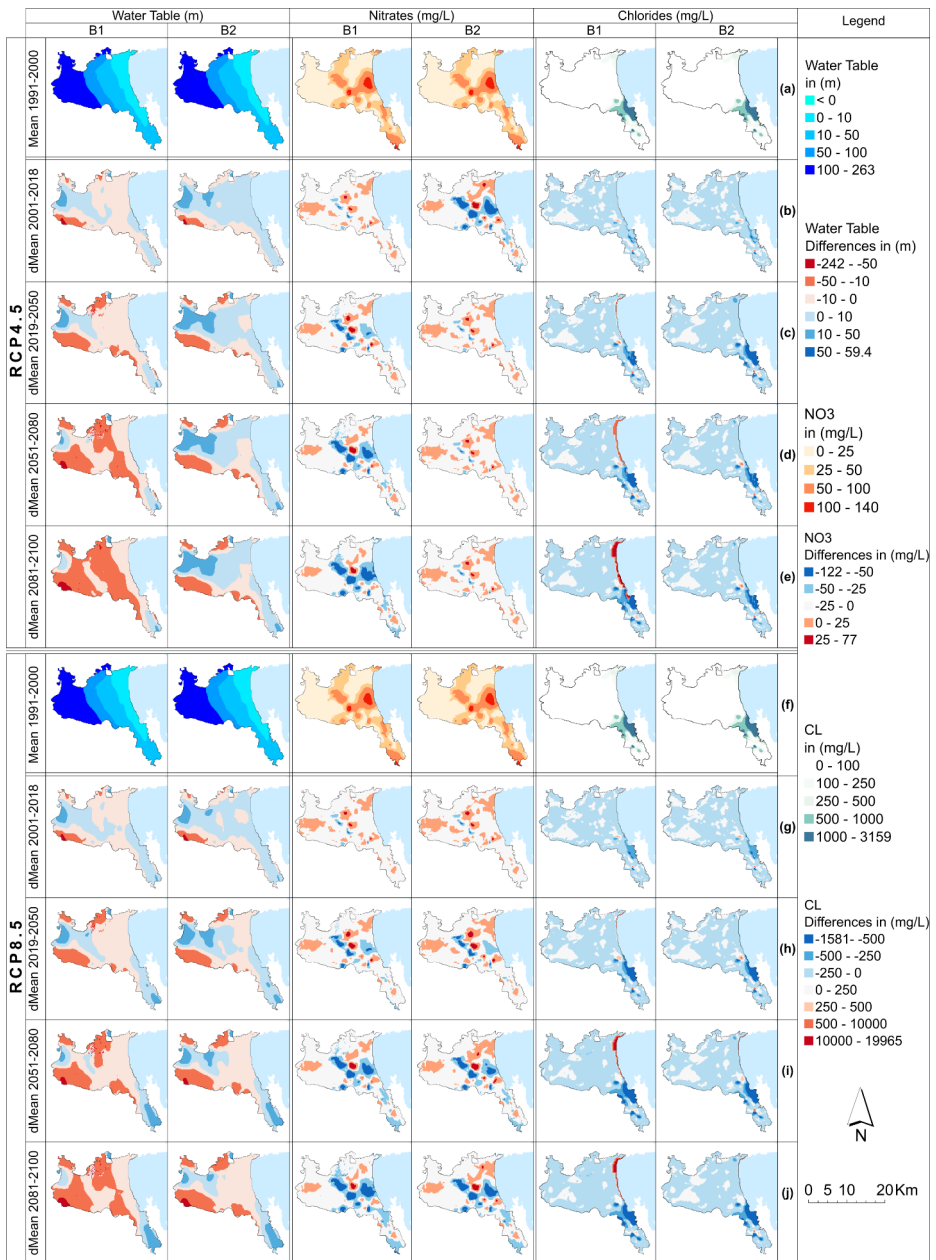
The Crop Water Productivity (CWP<sub>i</sub>) index was calculated for Almyros' arable land based on the simulation results of REPIC and MODFLOW models for crop yield and water withdrawals for irrigation, respectively (Fig. 4 h). CWP<sub>i</sub> gets the highest score for Strategy B1 (withdrawals from aquifer and reservoirs with deficit irrigation) for all future periods. Comparatively to the other strategies, the operation of reservoirs greatly improves and optimizes the water used for irrigation.

### 3.2.2 Spatial Effects of Water Resources Management Strategies

Spatial mean monthly values of the water table, nitrates, and chlorides concentrations for the base period 1991–2000 and their averaged differences between the future periods (2001–2018, 2019–2050, 2051–2080, 2081–2100) and the base period under RCP4.5 and RCP8.5 scenarios were estimated for all water resources management scenarios and strategies. The best results are displayed in Fig. 5 for Strategies B1 and B2 under RCP4.5 and RCP8.5 scenarios. The spatial results follow the trend of their averaged values presented in the previous section.

The groundwater levels will decline in the future at the margins of the Almyros aquifer regardless of the irrigation scheme for both climate change scenarios. The deficit irrigation-rain-fed cultivation strategy (column of Strategy B2) results in the rise of water levels in the Klinovos irrigated area under both RCPs. The operation of Klinovos reservoir has a larger positive influence on the water table than the operation of Xirias reservoir. Although the construction of the Xirias reservoir intends to alleviate the water deficit of the Almyros aquifer and prevent seawater intrusion, it was found, in a previous study (Lyra et al. 2022), that it cannot affect seawater intrusion because its location is away from the coast. In this paper, the Almyros aquifer system was simulated for many decades ahead, and the chloride differences of Fig. 5 for the strategy of deficit irrigation (column of Strategy B1) indicate that seawater intrusion exacerbates regardless of the operation of the Xirias reservoir and supports the previous results. Seawater intrusion is mostly affected by groundwater abstractions and is greatly delayed in the strategy of deficit irrigation-rain-fed cultivation (Strategy B2).

Interestingly, the operation of the Xirias reservoir affects the reduction of nitrates concentration because the direction of the aquifer layers, in the wider area of the reservoir's location, favors the groundwater flow toward the coast of the Almyros Basin. If the Xirias reservoir was located in the southern parts of the Almyros Basin, it wouldn't have the same beneficial result. The aquifer layers in the south, change directions and groundwater flow is not facilitated to head only to one main direction (Lyra et al. 2021c). Thus, nitrates and chlorides tend to locally accumulate when groundwater abstractions are stopped (Lyra et al.



**Fig. 5** Mean monthly (a,f) water table, nitrates, and chloride concentrations for the base period 1991–2000 and (b,c,d,e,g,h,i,j) averaged differences of future periods (2001–2018,2019–2050,2051–2080,2081–2100) from the base period, for Strategies B1 and B2 under RCP4.5 and RCP8.5 scenarios

2022). Consequently, the irrigated area by the Klinovos reservoir presents local assimilations of nitrates in the south of the aquifer in the strategies of deficit irrigation (Strategy B1) and deficit irrigation-rainfed cultivation (Strategy B2). The evolution of nitrate contamina-

tion in Strategy B2 is similar to the results of the strategy of deficit irrigation (Strategy B1) for the Almyros aquifer.

An important issue was found during and at the end of the simulations concerning the drying of groundwater wells at the north-central boundaries of the aquifer. Local depletion of groundwater will likely appear in the north-central part in the future period of 2019–2050, which won't recover before the long-term application of rain-fed cultivation and cessation of pumping wells. Unfortunately, neither existing strategies (Strategies A and B) nor deficit irrigation strategies (Strategies A1 and B1) can safeguard the groundwater's existence in that particular area. The well locations that will likely go dry in the future are presented in Fig.S1 in "Supplementary Material".

## 4 Conclusion

The simulation of water resources management strategies and scenarios provides an estimation of the system's capacity to address forward-looking water demands and socio-economic and environmental targets under the inherent uncertainty of climate change. A methodology was presented to find the best climate models for the construction of high-efficiency multi-model ensembles and evaluate adaptive water resources management scenarios under climate change. The methodology is applied in the coastal agricultural Almyros Basin, which is located in eastern Thessaly, Greece. Combinations of climate models' outputs (precipitation and temperature) were bias-corrected with five methods of bias-correction, and evaluated against observed data of precipitation and temperature for the base historical period 1971–2000, for two climatic scenarios (i.e. RCP4.5 and RCP8.5). The results indicated that two ensembles of three (3) climate models from the Med-CORDEX database and for the two climatic scenarios are the most efficient for the Almyros basin, using the bias-correction method of Quantile Empirical Mapping.

Adaptive water resources management scenarios were simulated for the historical and projected periods with an Integrated Modelling System (IMS). The water balance deficit is mostly reduced by the strategies of deficit irrigation-rain-fed cultivation (Strategy A2) and (Strategy B2). Groundwater abstractions and the groundwater water level determine the rate of seawater intrusion. The intensity of seawater intrusion is significantly delayed in the strategy deficit irrigation-rainfed cultivation (Strategy B2). Nevertheless, the phenomenon will continue to exist in the future due to sea-level rise under the two climate change scenarios, +0.3 m for RCP4.5 and +0.6 m for RCP8.5. Hydraulic conductivity and directions of aquifer layers seem to determine the duration of nitrates in groundwater when groundwater abstractions are diminished or stopped for all strategies. The nitrate pollution is mostly reduced through the strategy of deficit irrigation with the operation of reservoirs (Strategy B1). The Crop Water Productivity gets the highest values for the strategy of deficit irrigation combined with the reservoirs' operation (Strategy B1).

In general, the water table fluctuations depend on: (i) the volumes of groundwater abstractions for irrigation, (ii) the extent of the irrigated areas and (iii) the hydraulic conductivity of the aquifer layers. The results of the (IMS) and the Crop Water Productivity index (CWP<sub>1</sub>) show that irrigated agriculture will be viable in the future if there are surface and groundwater reserves. Rain-fed cultivation and partly cessation of groundwater abstractions should be applied in the north-central boundary area of the Almyros aquifer that will likely

dry in the future. The construction and operation of reservoirs is a decisive action toward the sustainability of the degraded coastal agricultural basin of Almyros and local agriculture.

The present study evaluated a variety of strategies that could be implemented to address the hazards of deficit water balance, nitrate pollution, and seawater intrusion in the Almyros Basin. The simulation of the coastal water resources under bias-corrected multi-model climate ensembles provides future projections of the water resources' quantity and quality and the expected agricultural viability of the study area. Water storage works for irrigation should be developed in the future period 2019–2050 to promote the sustainability of water resources and local agriculture. The planning of water resources management in the Almyros basin should be adaptive in space and time, while adaptive water resources management strategies are critical for the successful implementation of water resources management plans under climate change in the Almyros Basin.

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**Data Availability** Data and materials developed by the authors are freely available. The use of data and materials developed by others requires consent to be used.

## Declarations

**Supplementary Information** Yes

**Ethical Approval** Not applicable

**Consent to Participate** Not applicable

**Consent to Publish** Not applicable

**Competing Interests** Not applicable

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