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Assessing the Impacts of Climatic and Water Management Scenarios in a Small Mountainous Greek River

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Abstract: The water resource management of transboundary mountainous river basins under climate change is expected to be challenging. In order to contribute to the better understanding of climate change effects on the water resources of the mountainous and transboundary Prespa Lakes basin, a hydrological model of the Agios Germanos River, one of the main rivers discharging to Great Prespa Lake, was developed, and two water management plans under two different climate scenarios were examined. Based on the results, the impact of climate change on surface water resources was evident in all climate change scenarios examined, even under the most favorable water abstraction practices. Nevertheless, sensible water management can moderate the impact of climate change by up to 10% in an optimistic scenario in both the near- and long-term, and by up to 6% and 1% for the near- and long-term, respectively, in a pessimistic scenario. Integrated water management practices that moderate the impact of climate change on the water ecosystem services should be prioritized. Nature-based approaches could provide solutions regarding climate change adaptation and mitigation. Transboundary cooperation, data exchange mechanisms, common policy frameworks, and monitoring, reporting, and evaluation systems, could reduce human and ecosystems' vulnerabilities and improve the water security of the area.

Keywords: hydrological model; river outflow; SWAT+; IPCC-AR6; Agios Germanos River; Great Prespa Lake; transboundary basins; climate change adaptation

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1. Introduction

Mountainous areas are considered to be among the most valuable ecoregions due to their biological and cultural diversity and the ecosystem services they provide to their residents and the residents of the downstream areas [1,2]. However, they are very vulnerable to possible changes [3] due to their inherent biophysical characteristics [4]. The Mediterranean mountainous areas in particular are liable to suffer from the degradation of their ecological status due to climate and land-use changes [5]. Based on the most recent 6th Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), the Mediterranean mountainous river systems are considered to be hotspots for biodiversity loss and ecosystem changes related to climate change and anthropogenic activities (*high confidence*) [1,6]. Climate changes are *likely* to shift the mountain areas of the Balkans towards more subtropical climate conditions [6]. Recent studies have highlighted the fact that mountainous areas are more vulnerable to temperature increase in comparison to low-altitude areas [7,8], while changes in the amount, frequency, intensity, and seasonality of precipitation are expected to increase water-related hazards and jeopardize water security in these areas [6]. Finally, both precipitation decrease and air temperature increase

are expected to affect snowfall and snow cover in mountainous areas [9], impacting the system's hydrological processes and dynamics, as well as the interactions between water cycle components [10,11].

Water resource management in mountainous areas following climate change and water availability reduction is expected to be challenging [12]. Very often, these management plans are regionally oriented and tend to be confined to specific administrative boundaries, failing to foresee impacts on downstream areas or to provide an integrated approach [13]. Therefore, transboundary climate change adaptation can be even more challenging, since it combines the risks associated with the impacts of climate change that cross borders with the risks associated with the transboundary effects of the applied management plans [14]. Climate change adaptation in transboundary mountainous areas is even more ambitious due to the complexity of the pressures applied, and requires regional cooperation among the countries involved as well as knowledge sharing [3,15]. Nevertheless, often the lack of a good understanding of the complicated hydrological processes and water resource response to climate change and anthropogenic water management practices can hamper the successful implementation of possible adaptation strategies [16,17].

Prespa Lakes basin water management, undergoing the effects of climate change, is an example of a challenging area that stakeholders need to address. This mountainous transboundary complex system, which is located in the Western Balkan region and is a global hotspot of biodiversity and endemism [18], is already under multiple pressures related to land cover changes and intensive water use [19]. Although the wider area is well documented, and many common agreements and protocols among the countries involved dictate the primary water management scheme [20], the high uncertainty regarding climate change's impact on the area still lingers.

This specific study aims to contribute to a better understanding of the impacts of potential climate change induced by changes in atmospheric CO_2 concentrations on the water resources of the mountainous and transboundary Prespa Lakes basin. Moreover, this study focuses on investigating the impacts of climatic water management scenarios on the Agios Germanos River, one of the main rivers discharging to Great Prespa Lake. More specifically, two water management plans concerning water withdrawal from the river for irrigation needs under different predicted climate scenarios were examined. It should be noted that at the local scale of our study area, any changes in CO_2 concentrations beyond those already incorporated in current climate models would have minimal impact on the complex and nonlinear feedback loop associated with plant growth, evapotranspiration, and water availability. For this reason, a hydrological model of the Agios Germanos River basin was set up and calibrated, and two climate change scenarios (one optimistic, e.g., low-forcing sustainable pathway, and one pessimistic, e.g., high-end forcing pathway) under two different water management schemes were investigated. The final scope was to examine the response of annual Agios Germanos River outflows to Great Prespa Lake to these water withdrawal practices and climate change projections, and to assess their impact on the water resources of the study area. Finally, the aim of the present study was to facilitate a further understanding of the water management implications and to discuss possible approaches to reduce future water resource scarcity and vulnerability in the area.

2. Materials and Methods

2.1. Study Area

The Agios Germanos River is located at the northeastern part of Greece and is the only river of the Greek territory that feeds the Great Prespa Lake, along with the Golema, Instonca, Kranska, and Brajcinska rivers in North Macedonia. River outflows and catchment runoffs consist of about 55% of the total water recharge of Great Prespa Lake [21]. The

Agios Germanos River watershed is located at the southeastern part of the transboundary Prespa Lakes basin, which is shared between three countries: Greece, North Macedonia, and Albania (Figure 1a). The watershed covers an area of about 65 km^2, and the average altitude is 1635 m (range of between 845 and 2320 m).

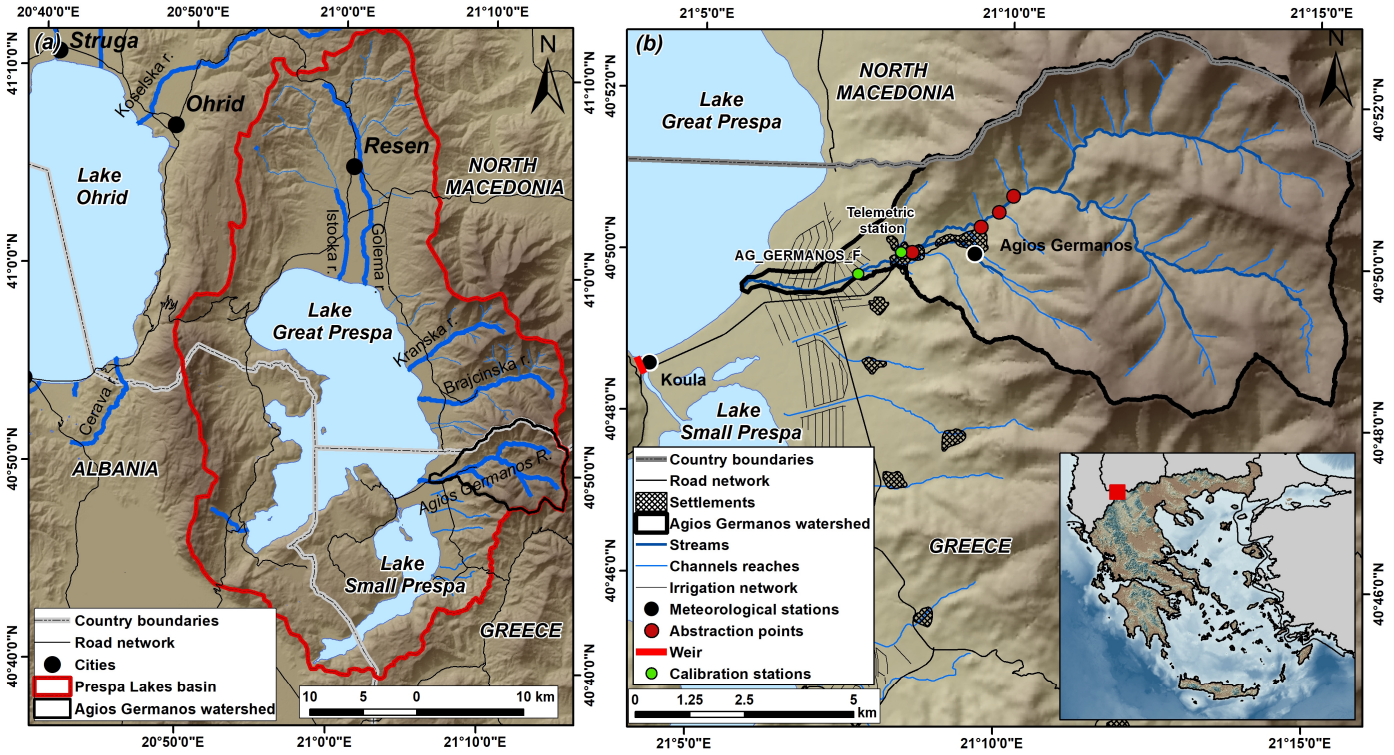


Figure 1. Orientation maps of the study area: (**a**) Prespa Lakes basin and (**b**) Agios Germanos River watershed.

The water resources of the wider area consist of a complex, natural, and interdependent system. The karstic groundwater aquifers of the Prespa Lakes and the adjacent Ohrid Lake basins are well developed and highly anisotropic [22,23]. The groundwater flow direction indicates the hydraulic communication between the Small Prespa and Great Prespa lakes and Lake Ohrid, from the former towards the latter [24]. The Agios Germanos River watershed is structured by quaternary sediments in the area close to the lakes and metamorphic (schists, phyllites, gneisses) and igneous (granites) rocks upstream [25].

The Agios Germanos River watershed has been subjected to multiple hydromorphological alterations during the past few decades, which have impacted the water resources in the area. Aiming at the protection of the Small Prespa Lake's biodiversity and at better water resource management, the water level of the lake is regulated through an artificial weir by the Management Body for Prespa National Park and the Wetland Management Committee (WMC) (Figure 1b) [26]. In the 1930s, a diversion project for flood protection and drainage rearrangement changed the Agios Germanos River watercourse and outflow, from the Small Prespa Lake to Great Prespa Lake [27]. Moreover, direct water abstractions and irrigation channels affect the Agios Germanos River flow, especially during summer. Finally, numerous technical works and human interventions (bridges, culverts, weirs, etc.) affect the river's watercourse [28].

Due to the ecological value of the area, the Agios Germanos River watershed is included in many environmental protection networks (NATURA 2000—codes GR1340001 Ethnikos Drymos Prespon and GR1340003 Ori Varnounta [29]; Mikri and Megali Prespa

lakes and their watershed National Park [30]; Corine Biotopes—codes A00010027 and A00060005 [31]; Ramsar site 3EL008 [32]).

2.2. Hydrological Model

The modeling tool used in the present study was the Soil and Water Assessment Tool Plus (SWAT+), developed by the United States Department of Agriculture—Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research, part of The Texas A&M University System. SWAT+ is a physically based, semi-distributed model that uses physiographic (e.g., elevation, land cover, soil), and climate (e.g., precipitation, temperature) data to simulate the quality and quantity of surface and ground water and to predict the environmental impact of land use, land management practices, and climate change [33,34]. In the present study, the QSWAT+ v.2.4.6 was used, which is a plug-in for the Quantum Geographical Information System (QGIS v.3.22.11), a free and open-source Geographic Information System (GIS), that also incorporated SWAT+ editor v.2.3.3, a user interface for modifying SWAT+ inputs and running the model [35]. The smallest spatial units used in the SWAT+ hydrological model are the hydrological response units (HRUs), in which it is assumed that the response to weather inputs is similar and which are delineated based on the topography, the soil conditions, and the land use [33].

The necessary inputs of the hydrological model's initial set up were the following:

- For the watershed delineation, the Digital Elevation Model (DEM) 5 × 5 m was used [36]. It should be noted that due to the anthropogenic interventions on the watercourse of the Agios Germanos River, the shapefile of the existing stream network was burned in the DEM during the network delineation procedure, for more accurate results (Figure 2a). Based on the DEM of the study area, the altitude of the Agios Germanos River watershed ranges between 851 m and 2319 m (average 1616 m). Over 82% of the watershed area can be characterized by a very steep slope (>15°).
- The specific soil map for the study area was recreated based on bibliographical data [37–40]. Based on all available information, the wider area is dominated at lowland by calcaric fluvisols (Jc), and at the mountainous areas by dystric cambisol (Bd) or dystric leptosol (LPeu) (Figure 2b). Due to a lack of other information regarding the physical and chemical properties of the soil types of the study area, the already incorporated database in SWAT based on the soil maps produced by the Food and Agriculture Organization of the United Nations (FAO) was used [40,41]. Based on this database, two soil layers of 0.30 m and 1.00 m thickness were included. Finally, some soil parameters (for example, the available water capacity of the soil layer—awc and USLE equation soil erodibility K factor—usle_k) were considered as calibration factors, based on the results of the sensitivity analysis discussed below (see also Table 1).
- The necessary information regarding land use in the study area was retrieved from the CORINE Land Cover CLC2018 dataset [42]. Each CORINE land use class was related to the corresponding land cover/plant or urban land type of the databases incorporated in SWAT containing information regarding plant growth and urban landscape attributes, respectively. Based on Figure 2c, the dominant land use classes are Range-Grasses (RNGE; 50%), Forest-Deciduous (FRSD; 21%), Barren (BARR; 14%), and Range-Brush (RNGB; 12%). Likewise, some land cover/plant and urban land parameters were regarded as calibrations factors, based on the results of the sensitivity analysis examined below (see also Table 1).
- During HRU delineation, the option "Filter by area" and a 5% area threshold were used.

- The necessary daily precipitation data were retrieved from the Agios Germanos meteorological station (owner: Public Power Corporation S.A.—PPC; latitude: 40.83972°; longitude: 21.15676°; altitude: 1016 m) (Figure 1b) [43].
- The necessary daily maximum and minimum air temperature data were retrieved from the Koula meteorological station (owner: Society for the Protection of Prespa—SPP; latitude: 40.811409°; longitude: 21.070945°; altitude: 853 m) (Figure 1b) [43].
- Due to the small altitude of both meteorological stations in comparison to the average altitude of the Agios Germanos River watershed, the precipitation rate is expected to be underestimated and the air temperature is expected to be overestimated [44]. For this reason, all meteorological data were elaborated using the Precipitation Lapse Rate and the Temperature Lapse Rate of the area of the Prespa Lakes [45].
- Due to lack of necessary meteorological data for the calculation of reference evapotranspiration using the more accurate Penman–Monteith equation, the Hargreaves empirical method [46] was employed, which provides satisfactory results with an error rate of 10–15% or 1 mm/d, whichever is greater [47].
- All other meteorological parameters necessary during simulation, but not available from observation stations, were retrieved from the incorporated SWAT weather database and the Weather Generator—wgn tool [48].
- Based on the Society for the Protection of Prespa (SPP) personnel, four abstraction sites withdraw water directly from the Agios Germanos River for irrigation needs and affected the hydrological regime of the watercourse [43]. These water abstractions were incorporated into the model using negative values in the point source module.

Table 1. SWAT+ parameters affecting river flow used in sensitivity analysis—Results of sensitivity analysis.

Group	Name	Description	Change Type	Order
hru	cn2	SCS curve number—function of the soil's permeability	Percent	1
rte	chn	Manning's N for channel	Replace	2
sol	awc	Available water capacity of the soil layer	Relative	3
hru	snomelt_tmp	Snowmelt base temperature	Replace	4
hru	snomelt_min	Minimum snowmelt temperature	Replace	5
hru	snomelt_max	Maximum snowmelt temperature	Replace	6
hru	epco	Plant uptake compensation factor	Replace	7
hru	perco	Percolation coefficient	Replace	8
hru	latq_co	Lateral flow coefficient	Percent	9
bsn	msk_co1	Calibration coefficient related to the storage time constant	Replace	10
bsn	ffcb	Initial soil water storage (fraction of field capacity water content)	Replace	11
aqu	revap_min	Water table depth for revap to occur	Replace	12
hru	esco	Soil evaporation compensation factor	Replace	13
rte	ch_bd	Bulk density in the main channel	Replace	14
sol	usle_k	USLE equation soil erodibility (K) factor	Replace	15
hru	ovn	Manning's "n" value for overland flow	Percent	16
aqu	bf_max	Baseflow rate when entire area is contributing to baseflow	Replace	17
hru	cn3_swf	Pothole evaporation coefficient	Percent	18
aqu	flo_min	Minimum aquifer storage to allow return flow	Replace	19
sol	bd	Moist bulk density	Percent	20
aqu	revap_co	Groundwater revap coefficient	Replace	21
hru	snomelt_lag	Snowmelt lag coefficient	Replace	22
hru	slope	Average slope steepness in HRU	Percent	23
aqu	alpha	Baseflow alpha factor	Replace	24
sol	k	Saturated hydraulic conductivity	Replace	25
sol	z	Depth from soil surface to bottom of layer	Percent	26
hru	lat_ttime	Exponential of the lateral flow travel time	Replace	27
bsn	surlag	Surface runoff lag time	Replace	28
hru	lat_len	Slope length for lateral subsurface flow	Replace	29
hru	snofall_tmp	Snowfall temperature	Replace	30
rte	chk	Effective hydraulic conductivity of the main channel	Replace	31
hru	canmx	Maximum canopy storage	Replace	32

aqu: physical and chemical aquifer properties. bsn: basin-level parameters. hru: HRU properties. rte: elemental part of Routing Unit and its topographic and field properties. sol: physical soil properties.

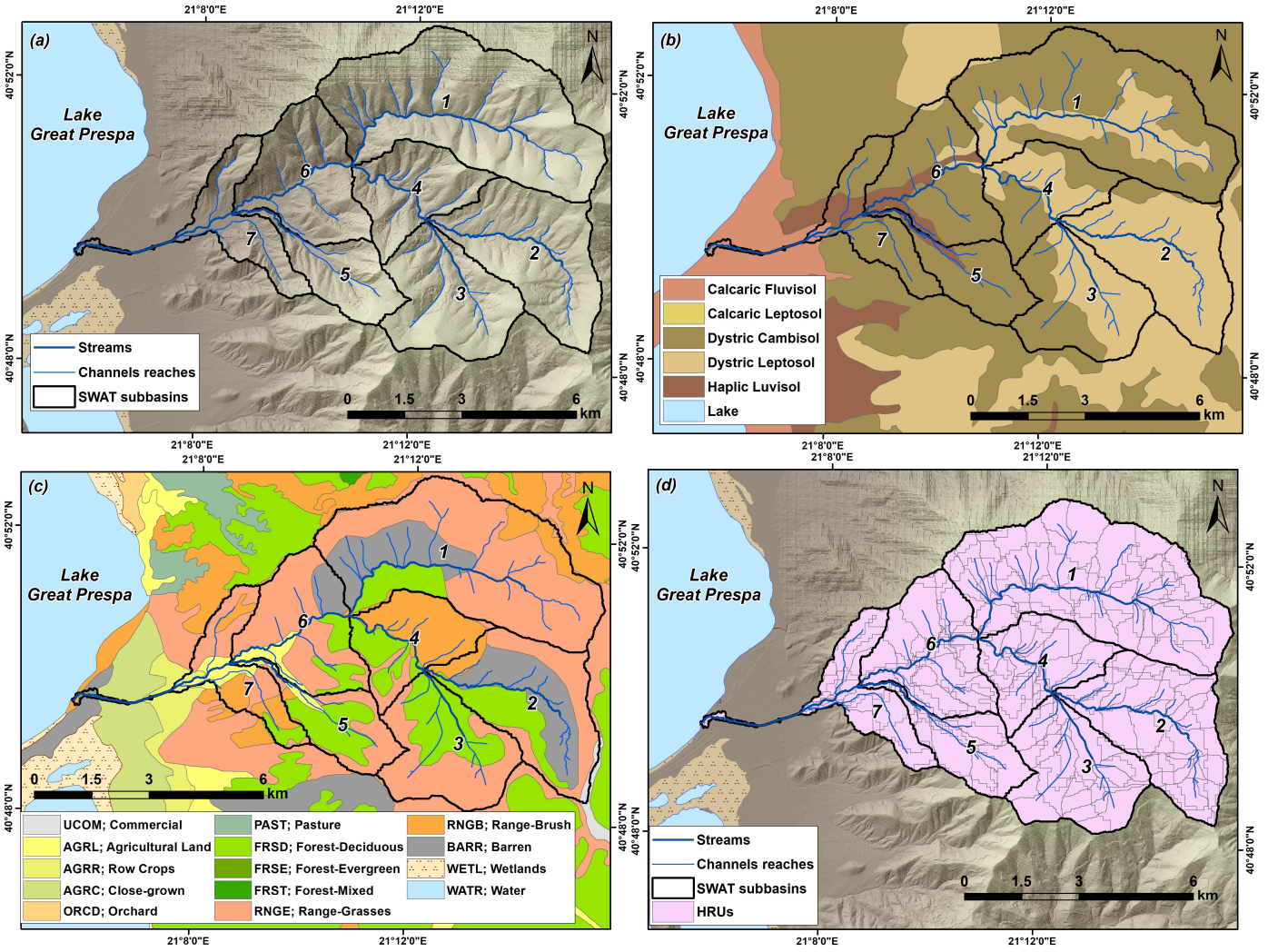


Figure 2. (**a**) Watershed delineation, (**b**) soil map, (**c**) land use map, and (**d**) Hydrological Response Units (HRUs).

Based on the data availability, the model was set-up for the period 2018–2023 using daily time steps. A two year warm-up period (2018–2019) was set based on the minimum recommendations [49]. The model was calibrated for the period 2020–2023 based on monthly river discharge measurements conducted under the national projects "Monitoring and Recording of the Water Status (Quality, Quantity, Pressures, Use) in Greece"—station AG_GERMANOS_F [50], while additionally daily discharge measurements provided by the telemetric station installed at Agios Germanos River by the Hellenic Centre for Marine Research, Institute of Marine Biological Resources and Inland Waters (HCMR-IMBRIW) for the period July 2020–September 2022 were used (https://hydro-stations.hcmr.gr/station/agios-germanos/daily (accessed on 30 September 2024)) (Figure 1b).

The model's performance was evaluated using the most common statistical metrics (mean absolute error—MAE; root mean square error—RMSE; correlation coefficient—R; coefficient of determination—R2; Nash–Sutcliffe coefficient—NSE [51]; percent bias—PBIAS; ratio of the root mean square error to the standard deviation—RSR; and the Kling–Gupta Efficiency—KGE [52]); as well as the criteria proposed by Moriasi et al. [53] concerning R2, NSE, and PBIAS and by Knoben et al. [54] concerning KGE. Finally, scatter plots and Bland–Altman plots [55] were employed for the model performance interpretation. Bland–Altman plots in particular are a graphical method for visually assessing the agreement between observed and predicted values by plotting the averages between the two data sets against

their differences in a scatterplot. The limits of agreement (LoA) can be used to assess how spread apart the individual differences are from the mean bias.

Sensitivity analysis aims to assess the uncertainty of a model or system to changes in its forcing data [56]. During sensitivity analysis, the input parameters of a model are changed and the effects on the final result are calculated, compared to real field measurements. In this particular case, the goal was to identify the sensitivity of the most important parameters of the model, so that we can then prioritize them during the calibration process. The selection of the model parameters to participate in the sensitivity analysis was based on a literature review [57–60] and are presented in Table 1. Due to the high altitude of the study area, parameters related to the contribution of snow to the river flow and groundwater storage were also included into the analysis. The sensitivity analysis was performed using the SWAT+ toolbox tool v.1.0.5 [61], which incorporates the following sensitivity analysis methods: Sobol, Fourier amplitude, Random Balance Design Fourier amplitude, and Delta moment independent measures. In this specific study, the Sobol sensitivity analysis method was used [62,63], which is the most widely-applied method [57,59].

2.3. Climate Change and Water Management Scenarios Examined

In the most recent 6th Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), five illustrative scenarios that cover the range of possible future development of anthropogenic drivers of climate change—also representing different combinations of challenges to mitigation and to adaptation, named Shared Socio-economic Pathways (SSPs) [64]—were adopted. In the present study, the following two experiments were investigated [65]:

- SSP1-2.6 scenario (Sustainability—"Taking the Green Road"): low greenhouse gases (GHG) emissions and CO_2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions, and
- SSP5-8.5 scenario (Fossil-fueled Development—"Taking the Highway"): very high GHG emissions and CO_2 emissions that roughly double from current levels by 2050.

It should be noted that the abovementioned emission scenarios represent an optimistic (low-forcing sustainable pathway) and a pessimistic (high-end forcing pathway) scenario, respectively. For this reason, and taking also into consideration the data availability for the specific study area, these scenarios were selected for further investigation.

The Copernicus Climate Change Service (C3S) of the European Union (EU) provides free and open access to climate data. In order to investigate the impact of climate change on the surface water resources of the study area, the median (50th percentile) of the daily projected climate data (precipitation, maximum and average air temperature) from four models developed in the framework of the sixth phase of the Coupled Model Intercomparison Project (CMIP6) and provided by C3S [66] were used for hydrological model forcing (Table 2, Figures 3 and 4). The models used were chosen based on the availability of the meteorological parameter (precipitation, maximum and minimum air temperature), the experiment, and its spatial distribution. Due to the small study area, only one representative grid point from each CMIP6 model was used.

The impact of climate change to the study area was assessed using the annual Agios Germanos River outflows anomalies, e.g., the variation of the predicted variables relative to a baseline. With this approach, it is possible to reduce the uncertainties that may arise due to the local spatial variation of meteorological parameters and the expected deviations of absolute climate values estimated by different climate models [75]. Because the choice of baseline can affect the final result, it should not be chosen arbitrarily. Based on common practice, the baseline length varies between 20 and 50 years [75], while the World Health Organization (WHO) proposes a 30-year-length period of reference for the calculation of

the climate normals [76]. In the present study, the recommendations of the WHO [76] were adopted, and the period 1985–2014 was used as the baseline. Likewise, the anomalies of simulated river outflows were investigated against the following 30-year-length future reference periods:

- near term: 2031–2060, and
- long term: 2071–2100.

Table 2. General Circulation Models used in the present study.

a/a	General Circulation Model—GCM	Ensemble	Developer	Reference
1	CNRM-ESM2-1	r1i1p1f2	CNRM [1]	[67,68]
2	EC-Earth3-Veg-LR	r1i1p1f1	EC-Earth-Consortium [2]	[69,70]
3	GFDL-ESM4	r1i1p1f1	NOAA-GFDL [3]	[71,72]
4	HadGEM3-GC31-MM	r1i1p1f3	MOHC [4]	[73,74]

[1] Centre National de Recherches Meteorologiques, CERFACS (Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique). [2] AEMET, BSC, CNR-ISAC, DMI, ENEA, FMI, Geomar, ICHEC, ICTP, IDL, IMAU, IPMA, KIT, KNMI, Lund University, Met Eireann, NLeSC, NTNU, Oxford University, surfSARA, SMHI, Stockholm University, Unite ASTR, University College Dublin, University of Bergen, University of Copenhagen, University of Helsinki, University of Santiago de Compostela, Uppsala University, Utrecht University, Vrije Universiteit Amsterdam, Wageningen University. [3] National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory. [4] Met Office Hadley Centre.

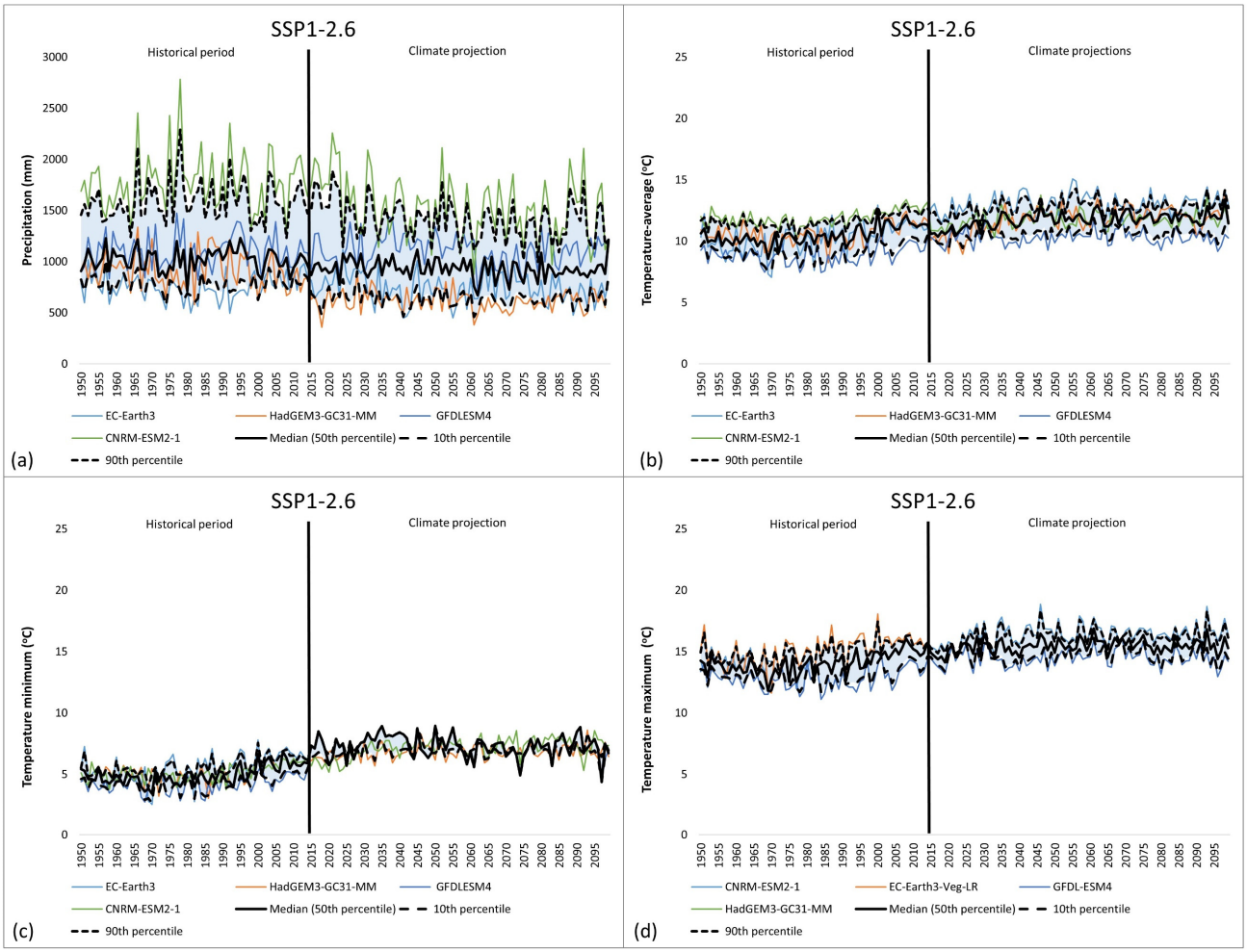


Figure 3. Projected annual time series used in the present study for the SSP1-2.6 scenario: (**a**) precipitation, (**b**) average air temperature, (**c**) minimum air temperature, and (**d**) maximum air temperature.

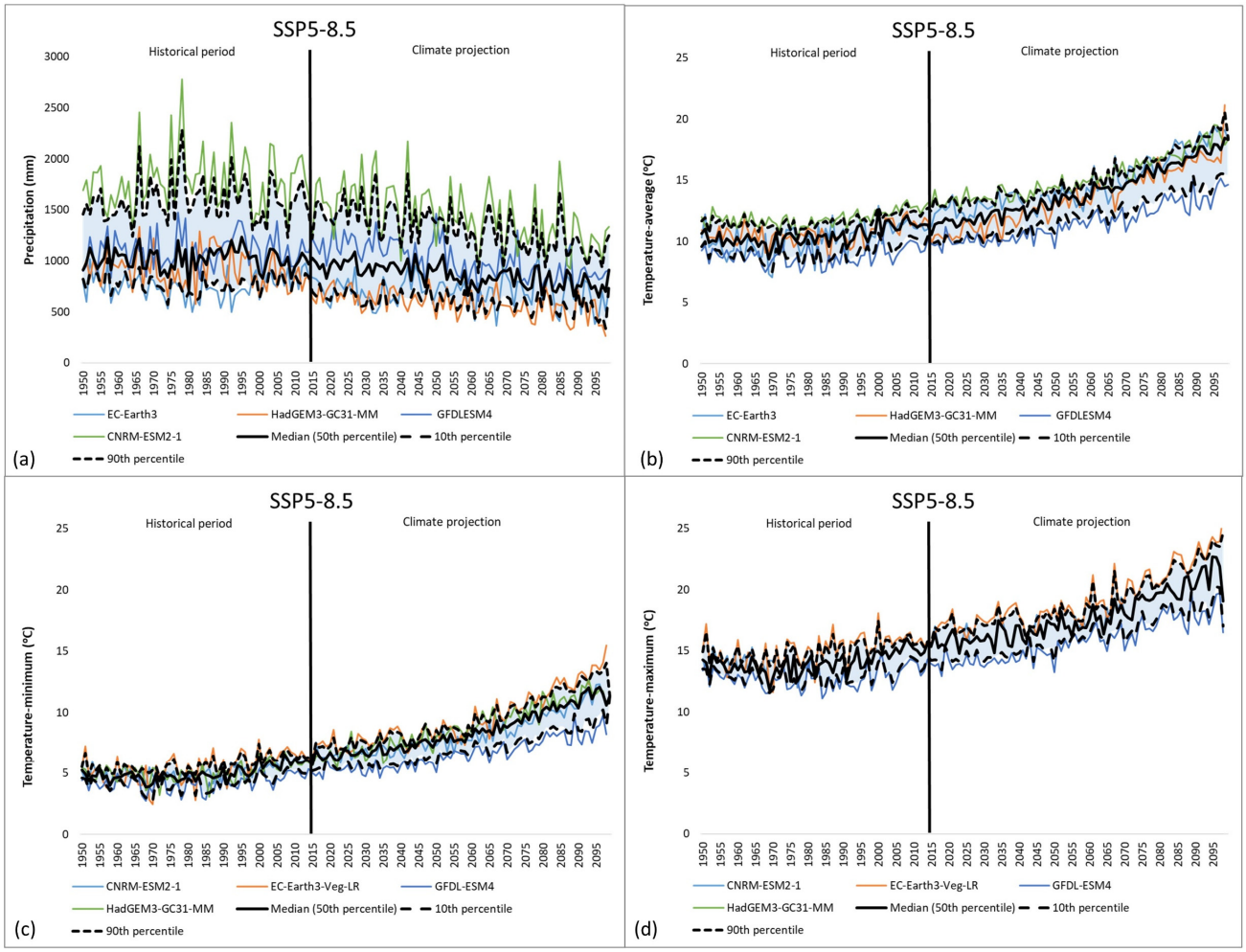


Figure 4. Projected annual time series used in the present study for the SSP5-8.5 scenario: (**a**) precipitation, (**b**) average air temperature, (**c**) minimum air temperature, and (**d**) maximum air temperature.

As mentioned above, the irrigation needs of the cultivated areas near the Lake Small Prespa are mainly met by water abstractions directly from the Agios Germanos River. Four irrigation channels on the left riverbed have been constructed and water is routed to the drainage system of the area. Based on the SPP, the existing irrigation scheme operates during summer and for the period between 15/06 and 30/09, while the total water withdrawal has been calculated to be $1.8 * 10^6$ m^3/y [43].

Under the current study, two water management scenarios were examined:

- with abstractions, during which, the current water withdrawal scheme from the Agios Germanos River does not alter, and
- without abstractions, during which, a sustainable approach is adopted and the water withdrawals from Agios Germanos River cease.

3. Results

3.1. Hydrological Model

The results of the Agios Germanos River hydrological model set up for the period 2020–23 indicate that there was a satisfactory agreement between the observed and the simulated discharge values (Table 3, Figure 5). The correlation coefficient R was calculated to be 0.77 in both stations and can be characterized as high [77], indicating the sufficient performance of the model. Based on the criteria proposed by Moriasi et al. [53], the model can be characterized as satisfactory regarding the coefficient of determination R2

(higher than 0.60) and the Nash–Sutcliffe coefficient NSE (higher than 0.50), although the model does not meet the criteria concerning the percent bias PBIAS (lower than ±15%). Nevertheless, the Kling–Gupta Efficiency KGE in all cases was higher than −0.41, indicating the acceptable performance of the model, and was even higher than 0.30; therefore, the simulation can be considered behavioral [54]. The intercept a of the box plots (Figure 5a,d) was smaller than one, indicating the underestimation of the predicted values [78]. Likewise, the error metrics MAE, RMSE, and PBIAs were positive, supporting the conclusion of the predicted values underestimation [79].

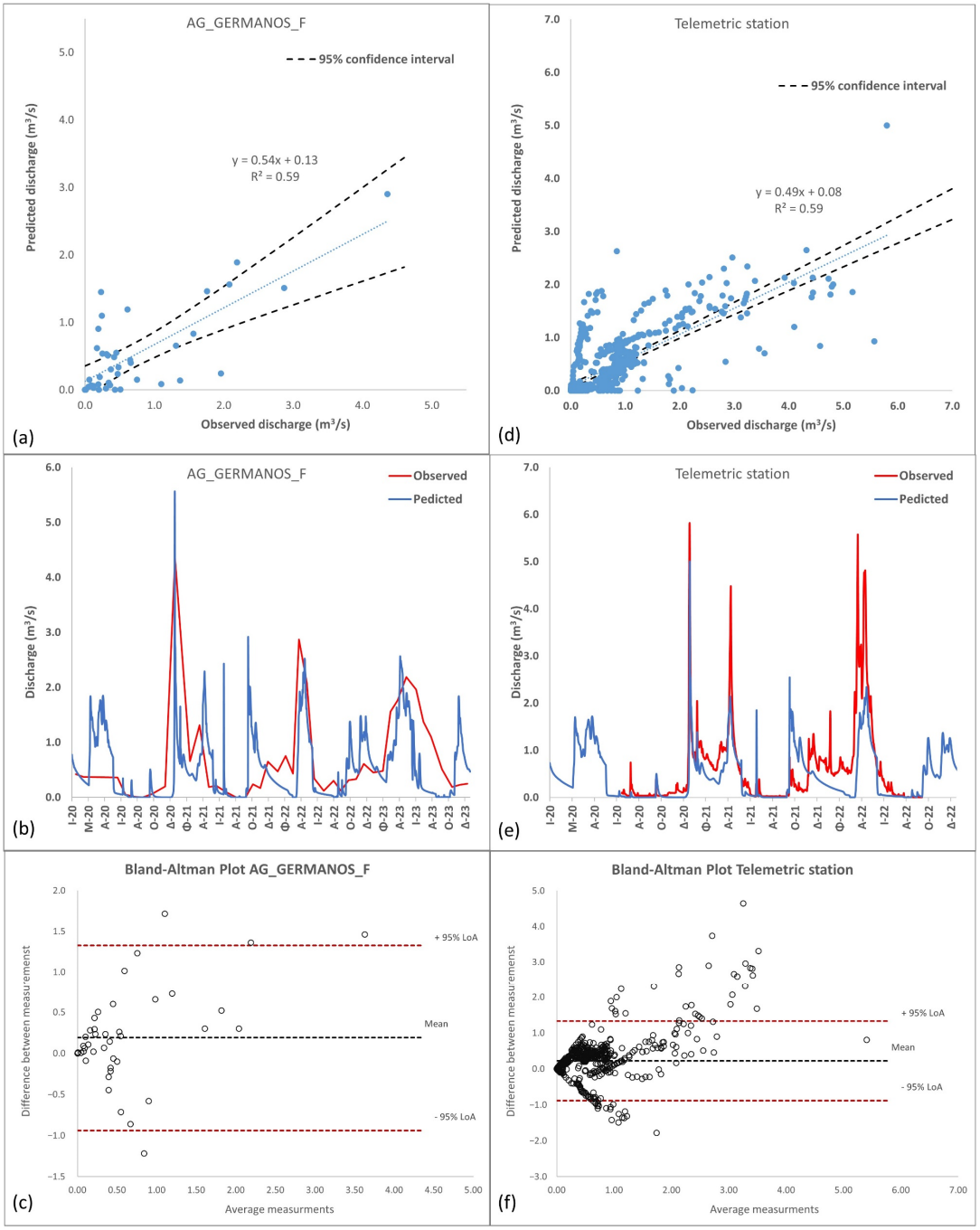


Figure 5. Simulated and observed discharge, and Bland–Altman Plot of Agios Germanos River during calibration for the (**a**–**c**) AG_GERMANOS_F station and the (**d**–**f**) Agios Germanos telemetric station.

Table 3. Statistical characteristics and efficiency criteria for the calibration of Agios Germanos River hydrological model.

Station	AG_GERMANOS_F	Telemetric Station
N	43	803
MAE	0.41	0.34
RMSE	0.60	0.60
R	0.77	0.77
p-Value	<0.00001. The result is significant at $p < 0.05$.	<0.00001. The result is significant at $p < 0.05$.
R2	0.59	0.59
NSE	0.54	0.51
PBIAS	28%	38%
RSR	0.67	0.52
KGE	0.54	0.43

N—sample. MAE—mean absolute error. RMSE—root mean square error. R—correlation coefficient. R2—coefficient of determination. NSE—Nash–Sutcliffe coefficient. PBIAS—percent bias. RSR—ratio of the root mean square error to the standard deviation. KGE—Kling–Gupta Efficiency.

Finally, based on the Bland–Altman plots, there was an acceptable agreement between the observed and predicted discharge values, since most of them were between the 95% statistical limits of agreement (LoA) (represented by ± 1.96 standard deviations of the mean). The underestimation of some measurements was confirmed, while outliers could also be reported, especially in the case of the telemetric station. The LoA in both stations were quite small, indicating good agreement, although the scatter around the bias line got larger as the average of the measurements got higher and positive, indicating that the model did not always predict high flows of the river successfully (Figure 5c,f).

3.2. Agios Germanos River Outflow Anomalies

The impact of climate change on the Agios Germanos River outflows at Great Prespa Lake was prominent. In both the optimistic (SSP1-2.6) and the pessimistic (SSP5-8.5) scenarios, the outflows decreased (negative anomalies). As expected, in the case of the SSP5-8.5 scenario, the outflow decrease was more profound in comparison to the SSP1-2.6 scenario (higher negative anomalies). Finally, if the current water management status remained unchanged and water abstractions from the river were not ceased, the negative anomalies were higher in both the SSP scenarios examined (Figure 6a,c).

More specifically, in the case of the optimistic SSP1-2.6 scenario, and assuming that the water abstraction management practices from the Agios Germanos River will not change, the water outflow anomalies from the river to Great Prespa Lake appeared to be reduced by 48% ($-0.53 * 10^7$ m^3/y) in the near-term (2031–2060) and by 54% ($-0.60 * 10^7$ m^3/y) in the long-term (2071–2100), compared to the baseline (1985–2014). If water abstractions from the Agios Germanos River ceased, the river's outflows anomalies were estimated to be decreased by 37% ($-0.41 * 10^7$ m^3/y) in the near-term and by 45% ($-0.50 * 10^7$ m^3/y) in the long-term.

In the case of the pessimistic SSP5-8.5 scenario, and assuming that the water abstraction management practices from the Agios Germanos River will not change, the water outflows anomalies from the river to Great Prespa Lake were estimated to be reduced by 63% ($-0.70 * 10^7$ m^3/y) in the near-term and by 87% ($-0.97 * 10^7$ m^3/y) in the long-term. If water abstractions from the Agios Germanos River ceased, the river's outflows anomalies were estimated to be reduced by 57% ($-0.64 * 10^7$ m^3/y) in the near-term and by 86% ($-0.96 * 10^7$ m^3/y) in the long-term (Tables 4 and 5).

Based on the box-plots, if water abstractions from the Agios Germanos River do not cease, the range of the annual outflows anomalies will be wider, as shown in both SSP scenarios examined for both future reference periods (near-term and long-term) (Figure 6b,d).

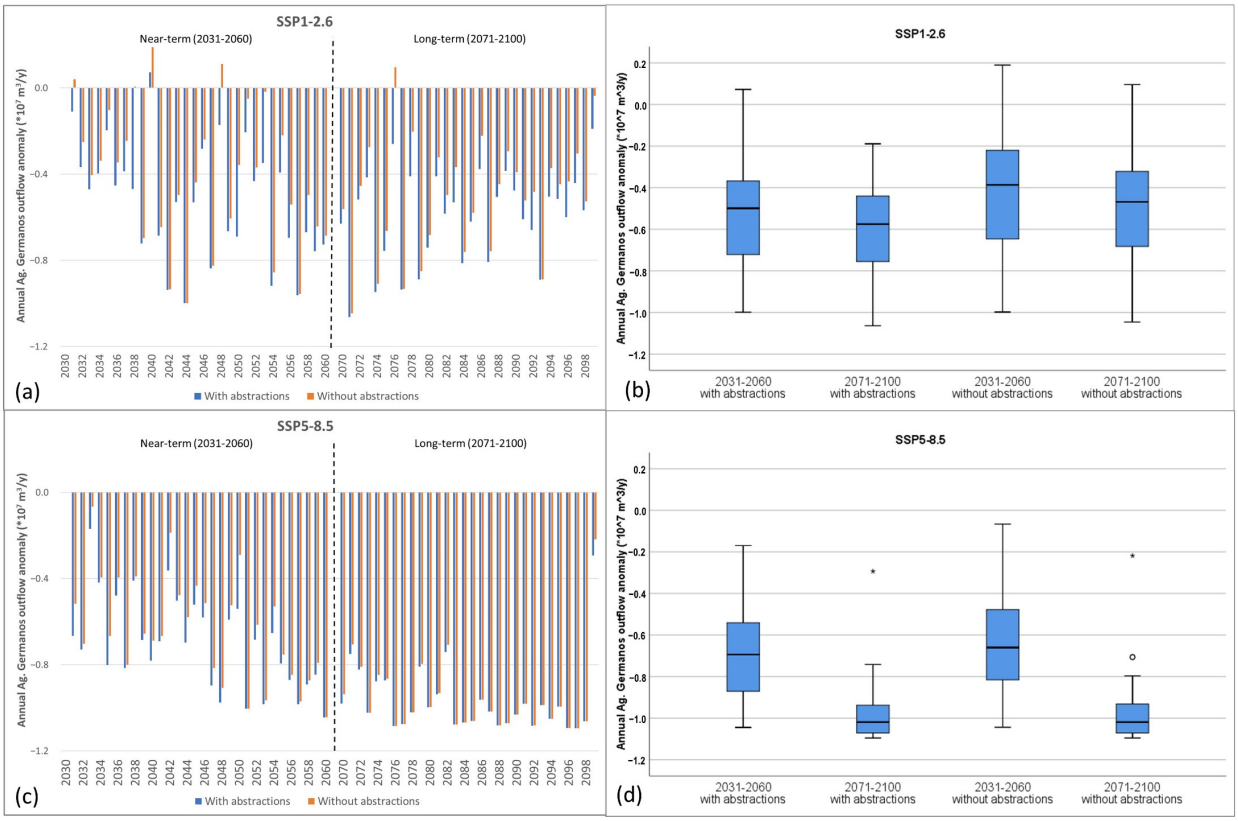


Figure 6. Annual Agios Germanos River outflow anomalies and corresponding box plots for scenarios SSP1-2.6 (**a**,**b**) and SSP5-8.5 (**c**,**d**) (baseline: 1985–2014). Circles and asterisks in (**c**,**d**) represent outlier and extreme outlier, respectively.

Table 4. Statistical characteristics of the annual outflow anomalies of the Agios Germanos River for the SSP1-2.6 and SSP5-8.5 scenarios examined, the two future reference periods (short term: 2031–2060, and long term: 2071–2100), and the two water management scenarios (with and without water abstractions from the river) (baseline: 1985–2014).

		With Abstractions				**Without Abstractions**			
		SSP1-2.6		**SSP5-8.5**		**SSP1-2.6**		**SSP5-8.5**	
		2031–2060	**2071–2100**	**2031–2060**	**2071–2100**	**2031–2060**	**2071–2100**	**2031–2060**	**2071–2100**
Mean		−0.53	−0.60	−0.70	−0.97	−0.41	−0.50	−0.64	−0.96
Median		−0.50	−0.58	−0.69	−1.02	−0.39	−0.47	−0.66	−1.02
Std. Deviation		0.27	0.21	0.22	0.16	0.33	0.27	0.25	0.18
Variance		0.07	0.05	0.05	0.03	0.11	0.07	0.06	0.03
Minimum		−1.00	−1.06	−1.04	−1.10	−1.00	−1.05	−1.04	−1.10
Maximum		0.07	−0.19	−0.17	−0.29	0.19	0.10	−0.07	−0.22
Percentiles	25	−0.72	−0.77	−0.88	−1.07	−0.66	−0.70	−0.82	−1.07
	50	−0.50	−0.58	−0.69	−1.02	−0.39	−0.47	−0.66	−1.02
	75	−0.36	−0.43	−0.54	−0.92	−0.19	−0.32	−0.47	−0.91

Table 5. Annual outflow anomalies of the Agios Germanos River for the SSP1-2.6 and SSP5-8.5 scenarios examined, the two future reference periods (short term: 2031–2060, and long term: 2071–2100), and the two water management scenarios (with and without water abstractions from the river) (baseline: 1985–2014).

Scenario		**2031–2060**		**2071–2100**	
		$*10^7$ **m^3/y**	**%**	$*10^7$ **m^3/y**	**%**
SSP1-2.6	with abstractions	−0.53	−48%	−0.60	−54%
SSP5-8.5		−0.70	−63%	−0.97	−87%
SSP1-2.6	without abstractions	−0.41	−37%	−0.50	−45%
SSP5-8.5		−0.64	−57%	−0.96	−86%

4. Discussion

The Prespa Lakes basin is a small, mountainous, transboundary area and is one of the most valuable ecoregions of Europe. The ecosystem services that such regions provide are transboundary by nature [1]. Water resource management in these areas under climate change projections can be a complicated task that involves multiple participants and consists a challenge, especially with regards to the current fragmented knowledge of the system's processes and operations [3]. Recent studies have highlighted the possible impact of climate change on the water resources of the Prespa Lakes basin, due to increased vulnerability due to low resilience, very high sensitivity to altered environmental conditions, and very high exposure to climate change [80]. The Great Prespa Lake in particular is highly probable to be affected by possible increase in interannual water level fluctuations and by the extreme low water levels [81,82].

Under this scope, this specific study aimed to exploit the development of a hydrological model and the application of two climate change and two water management scenarios, so as to contribute to a better understanding of the surface water resources' response to possible future precipitation amount decreases and air temperature rises. The present study aims to contribute to a better understanding of how water management practices in the Agios Germanos River's will affect the river's outflows and may amplify long-term decreases in the Great Prespa Lake. Based on the results, the impact of possible future climate change is evident in all the climate projections and water abstraction scheme examined. Nevertheless, when a more favorable water management practice was considered, the impact was moderated. In the case of the optimistic SSP scenario (SSP1-2.6), the change in the water abstraction policy from the river was able to lead to a decrease in the negative anomaly water outflow to Great Prespa Lake by approximately 10%, in both the near- and long-term future reference periods. In the case of the pessimistic SSP scenario (SSP5-8.5), this decrease in the negative anomaly water outflow was limited to 6% in the near-term, while in the long-term, this decrease was eliminated.

Although most studies are in agreement concerning the water stress in mountainous areas under future climate trends, it is difficult to make generalizations, due to the high dependence of precipitation, snow cover, and air temperature to elevation [83]. Despite the potential rise in air temperature that would lead to higher snow melt, due to the corresponding reduction in precipitation and snowfall, many studies highlight the reduction in river discharge in similar environments [9]. Based on a recent study, the mean annual river discharge is expected to decrease by up to 20% by the end of 21st century in Swiss alpine catchments higher than 1400 m [84]. Other studies have reported a decrease in annual river discharge of 25% at 2100 in the mountainous Italian Alps [85], and a decrease of up to 30% of annual river discharge at a mountainous basin in Ukraine for the worst-case scenario by the end of 21st century [86]. It should be noted that the comparison of the results of these studies regarding the impact of climate change on river flows is difficult, due to the different reference periods and climatic scenarios used for the analysis, and the different hydrological characteristics of the rivers. Smaller drainage basins, such as the Agios Germanos watershed, are more vulnerable to climate change [87] and respond differently to it, since they are more sensitive to local, high-intensity storms and to land use changes [88]. These aspects should also be taken into consideration when developing water resource management plans of mountainous areas.

This specific study highlights the importance of sensible water management practices for effective and sustainable adaptation to climate change. Since climate change will inevitably affect water resource availability and may jeopardize the water security of an area, focusing on the restoration of degraded systems to their historical condition or on the maintenance of their current state is not always realistic [89,90]. In these cases, stakeholders,

scientists, and local communities should prioritize management practices that moderate the impact of climate change on water ecosystem services. In the Prespa Lakes basin in particular, this approach is even more challenging and requires integrated management plans, transboundary cooperation, and joint actions [91,92]. More specifically, adaptation strategies that presume a good knowledge of climate risks could aim at the replacement of the current irrigation scheme of the area with alternative, less water-consuming techniques. The establishment of ecological flow under changing hydrological conditions for compatible sustainable water allocation would benefit Agios Germanos River's health. Basin-wide, nature-based approaches enhancing the water retention capacity, such as reforestation and watershed restoration, could increase the system's resilience to climate change. Finally, the continuous monitoring of the water resources on a transboundary scale could provide vital information of the progress, the outcomes, and the possible adjustments necessary to be applied to the implemented management plan [93].

5. Conclusions

The most recent 6th AR of the IPCC emphasizes the vulnerability of sensitive mountainous ecoregions to future climate change and the challenges that have arisen concerning successful water resource management. Sustainable transboundary mountainous river basin management could be even more ambitious. Based on the current study, the impact of climate trends on surface water resources was evident in all cases of climatic scenarios, and even under the most favorable water abstraction practices. This paper highlights the fact that since climate change effects on water resources are uncertain but inevitable, sensible water management can moderate the impact of the predicted precipitation amount decrease and air temperature rise. The rational use of water resources and nature-based approaches could provide solutions regarding climate change adaptation and mitigation. Integrated approaches should take into consideration the impact of the actions and policies adopted in the downstream areas. Transboundary cooperation for water scarcity adaptation, data exchange mechanisms, common policy frameworks, and monitoring, reporting, and evaluation systems, could reduce humans' and ecosystems' vulnerabilities to climate change and improve water security in the area.

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