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Impacts on water level fluctuation in Lake Vegoritida: insights for the historical and projected climate period

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ABSTRACT

Lake Vegoritida, one of the largest natural lakes in Greece, has undergone substantial fluctuations in its water level in the past century caused by severe water abstraction directly from the lake. The recent recovery of the water level triggers a discussion on the definition of lake's maximum level which by itself becomes a source of conflict among stakeholders. However, it is still vague if the current and future climatic conditions can provide the available water inflow to the lake to sustain any suggested maximum water level. In this direction, a hydrologic model of Lake Vegoritida catchment has been developed to assess the water inflows and outflows of the lake. In particular, a rainfall-runoff model is used to assess the water inflow to the lake from the catchment, combined with a water balance model of the lake for the simulation of its water level. The hydrologic model was calibrated based on water level measurements in the four lakes located in the catchment, namely Lakes Zazari, Chimaditida, Petron, and Vegoritida. The calibrated model was used to assess the effect of water abstraction by the Public Power Corporation (DEH) in the water level of Lake Vegoritida for the historical period. Furthermore, the application of nine climate scenarios, based on the representative concentration pathways 4.5, 8.5, and 2.6 and driven by three global circulation models, revealed contradictory water balances and associated water level fluctuations in Lake Vegoritida for the projected period 2021–2050. Specifically, three scenarios show that the lake level will remain at its current level or higher while the other six scenarios show that a significant decline of lake level will occur.

Keywords: Lake Vegoritida; Lake level management; Hydrological modelling; Climate change

1. Introduction

Lakes are sensitive to climate, respond rapidly to change, and integrate information about changes in the catchment [1]. Particularly, the water level in lakes is a sensitive sentinel of changes in hydrologic balance induced by changing temperature and precipitation [2]. Climate change might exert an influence upon lakes and the most pronounced impacts will be associated with modifications to hydrological regimes, as a result of lower rainfall and higher evaporation (due to higher temperature) as well as the combined impact of these changes on lakes' catchment runoff [3]. Thus, efficient water resources management is of critical importance to sustain anthropogenic activities and preserve ecological functions, especially in the Mediterranean region in which climate change impacts are expected to be severe [4,5]. To assess the climate change impacts in lakes, an integrated modeling framework, involving their physical, chemical, and biological properties should be applied. The integrated modeling framework, in conjunction with the lake's properties monitoring, would enable the formulation

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of a series of measures for the mitigation of climate change impacts.

The potential effects of climate change on the physical (e.g. water balance, thermal stratification), chemical (e.g. chemical composition affected by hydraulic residence time), and biological (e.g. biological responses to the physical and chemical changes related to ecosystem integrity, habitat structure, fish communities, etc.) characteristics of lakes have been discussed by Vincent [6]. In Mediterranean region, Dimitriou and Moussoulis [7] studied the impact of climate change on Lake Trichonida (Greece) for the climate scenarios A2 and B2 and found that the lake water level will show a decrease of 24.2 and 12 cm, respectively, and an increase of total nitrogen concentrations by 3.4% and 10%. Fatorić et al. [8] explored the climate change effects in the Mediterranean protected coastal wetlands, Aiguamolls de l'Empordà (Spain) and Kotychi-Strofylia (Greece), and concluded that about two-thirds of the interviewed stakeholders in both areas perceived their coastal wetlands as unsustainable. Niedda et al. [9] used a physically-based rainfall-runoff model, combined with the energy budget method for estimating lake evaporation, to simulate the hydrological response to recent climate and land-use changes of the small closed-basin Lake Baratz in Sardinia, Italy. Doulgeris et al. [3] studied the impacts of climate change on the hydrology of Lakes Chimaditida and Kerkini, Northern Greece, and concluded that their surface area will undergo a decrease from 20% to 37% and from 5% to 14%, respectively. Su et al. [10] modeled the brackish endorheic Lake Qinghai in China to reveal the major features of lake response to climate change.

Lake Vegoritida has undergone substantial decline on its water level in the past century caused by water abstraction directly from the lake and its catchment; the water level was around 525 m a.m.s.l. in the early 1980s and dropped down to 509 m in 20 y whereas has partially recovered to around 518–519 m during the last decade. Probably, one of the major factors that disturbed the water balance of the lake and caused its water level decline was the water abstraction directly from the lake by the Public Power Corporation. This water level fluctuation has affected the natural (e.g. lake shrinkage, habitat loss), social (e.g. impact on recreational activities, conflicts for claiming property rights on revealed land), and economic (e.g. new farmland revealed, impact on tourism and fishing) environment of the lakeside area. The recent recovery of the water level from 509 to 518–519 m, and the subsequent flooding of lake's area that the last 20 y was used as an agricultural area, triggers a discussion on the definition of lake's maximum allowable water level among stakeholders including farmers, fishermen, tourists, entrepreneurs, scientists, mainly due to the antagonistic uses that are favored or not by the potential increase of the lake's level, thus raising conflicting viewpoints on the issue. In this direction, Doulgeris and Argyroudi [11] examined three maximum water level scenarios and discussed the associated potential impacts on economic and social activities in the area in conjunction with the sustainability of the lake's ecosystem. However, it is still vague if the current and future climatic conditions can provide the available water inflow to the lake to support any suggested maximum water level in Lake Vegoritida.

The objective of this paper is two-fold. The first is to examine if the projected climate conditions will disturb the current water balance of Lake Vegoritida and thus cause its water level decline in the future. The second is to examine the effect of severe water abstraction by the Public Power Corporation on the lake's water level for the historical period. To achieve these objectives, a hydrologic model for Lake Vegoritida catchment is used to assess the water inflows and outflows of the lake and its water level fluctuation, by combining a catchment rainfall-runoff model and a water balance model of the lake. To increase the reliability of the hydrological analysis, the calibration of the hydrologic model is based on water level measurements in the four lakes of the catchment, that is, Lakes Zazari, Chimaditida, Petron and Vegoritida. The hydrologic model of Lake Vegoritida catchment is applied for the projected climatic conditions of nine scenarios, based on the representative concentration pathway (RCPs) scenarios 4.5, 8.5 and 2.6 and driven by three global circulation models (GCMs) namely EC-Earth, HadGEM2-ES, and MPI-ESM-LR, in order to reduce the uncertainty of future climate conditions on lake level sustainability.

2. Material and methods

2.1. Study area and data sets

Lake Vegoritida, located in the water district of Western Macedonia in Northern Greece, is part of the Natura 2000 network and is included in a site of community importance area. The hydrological catchment of Lake Vegoritida (Fig. 1) covers an area of 2,145 km^2 and includes also the Lakes Petron, Chimaditida, and Zazari. The four lakes are connected through the hydrographic network of the catchment and the excess of surface water is transferred from one lake to the other. Specifically, the water level in Lake Zazari is controlled by a weir and above the altitude of 599.7 m a.m.s.l., the excess of water overflows into Lake Chimaditida via a canal. Similarly, the excess of water in Lake Chimaditida overflows above 592.0 m into a drainage canal, which is joined downstream to the Amyntas stream, which ends up to Lake Petron. The latter overflows above 573.1 m and the water are driven through a tunnel into Lake Vegoritida. Key inflows in Lake Vegoritida, which is the final recipient of the catchment, are the excess of surface water from Lake Petron and the water flow of River Pentavryso. Apart from river inflows, precipitation, and evaporation from the lake's surface area, another natural process that may influence the water balance of Lake Vegoritida is associated with the existence of karst sinkholes as a characteristic of its carbonate bed [12,13].

The economic activities in the catchment that exert pressures in the lake ecosystem are mainly associated with industry and agriculture. The exploitation of lignite mines in the catchment has environmentally affected the soil and water resources of the area, due partly to the dewatering measures undertaken to protect the mines [14]. Dimitrakopoulos [15] presented analytically the water abstractions by the Public Power Corporation in the catchment and directly from the lake. The water abstraction from the lake by the Public Power Corporation has been ceased in

1997 since the water demands for the operation of a number of thermo-electrical power stations are covered nowadays by water transfer from the neighboring hydrological catchment of River Aliakmonas. Agriculture is another important source of income and agricultural land covers 31.1% of the catchment area [16]. According to data from the Hellenic Statistical Authority [17], the main crops in the catchment of Vegoritida are tree crops (30,061 km^2), wheat (26,414 km^2), corn (4,742 km^2), alfalfa (4,428 km^2), and vineyards (2,376 km^2). The most populated urban areas in the catchment are Ptolemaida and Amyntaio, and the sewage treatment plant of the latter outflows into Lake Petron. Table 1 is given the estimated annual water use for irrigation, industry, etc. in the sub-catchments of Lake Vegoritida catchment.

The morphology of the shallow Lakes Chimaditida and Petron, as well as the deeper Lakes Zazari and Vegoritida, has been studied recently by the Greek Biotope/Wetland Centre, in the context of the National Water Monitoring Network [18]. Specifically, the bottom elevation of the Lakes Vegoritida, Zazari, and Chimaditida has been recorded by using a portable shallow water echo sounder equipped with global positioning system and dual-frequency capabilities. Elevation data from in situ measurements were enriched by data available in maps from the Hellenic Military Geographical Service and processed by using geographic information system tools to create the bathymetric digital elevation model (DEM) of each lake. The bathymetric DEMs were used to extract a high accuracy hypsographic curve and water level-volume curve for each lake [19].

Meteorological data of monthly air temperature (maximum and minimum) and precipitation were obtained for the historical period 1980–2015 by the national authorities that keep updated the relevant data records of meteorological stations in the catchment. Seven stations (Kozani, Ptolemaida, 3–5 Pigadia, Amintaio, Vegoritida, Vlasti, Limnochori) were used for temperature data and the same

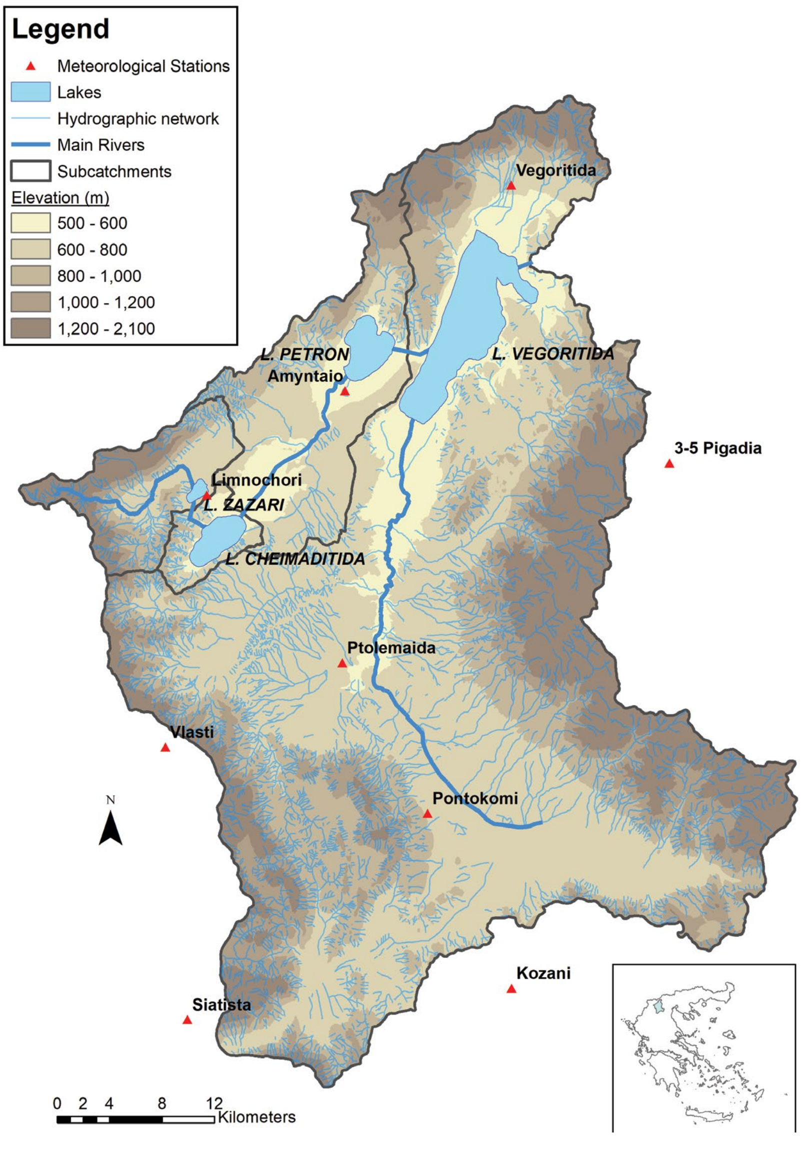

Fig. 1. The hydrological catchment of Lake Vegoritida.

Table 1
Estimated annual water use in the catchment of Lake Vegoritida

	Groundwater[a]				Abstraction from lakes	
Subcatchment	Irrigation (10^6 m^3)	Domestic (10^6 m^3)	Livestock (10^6 m^3)	Industry (10^6 m^3)	Irrigation[a] (10^6 m^3)	Industry[b] (10^6 m^3)
Zazari	5.3	0.4	0.3		1.5	
Chimaditida	0.24	0.14				
Petron	12.9	0.4	0.2	12.4		
Vegoritida	70.8	7.2	1.0	30.8		37.7

[a]average values for the period 1990–2000, source [20]
[b]average value for the period 1980–1996, source [15]

stations plus two additional stations (Siatista, Pontokomi) were used for precipitation data. Other meteorological data (e.g. relative humidity, wind speed) were available only at two stations (Kozani and Ptolemaida) for an insufficiently short period. In absence of comprehensive climate data to employ a more appropriate methodology for the calculation of potential evapotranspiration (e.g. Penman-Monteith), and since temperature data were available for the period 1980–2015 at seven of the stations of the catchment, the Hargreaves and Samani [21] equation was used to estimate the potential evapotranspiration of the catchment. Regarding the evaporation from lakes' surface area, the approach to use methods that were originally developed to estimate potential evapotranspiration was adopted (Rosenberry et al. [22]; Vieira et al. [23]), and thus, the Hargreaves and Samani [21] equation was also used to estimate the monthly evaporation from the four lakes. The Thiessen method was used for the areal distribution of meteorological parameters. The water level fluctuation of lakes is monitored from 2012 by the Greek Biotope/Wetland Centre in the context of the National Water Monitoring Network [18], while a longer-term data record from the early 1950s is maintained by the Public Power Corporation for Lake Vegoritida.

2.2. Hydrological model set up

The hydrologic model of Lake Vegoritida catchment has been developed to assess the water inflows and outflows of the lake, taking also into account the pressures imposed in the catchment by the water users, that is, irrigation, industry et cetera. In particular, the NAM rainfall-runoff model [24] is used to assess the water inflow to the lake from the catchment, using meteorological data on a monthly time step. The rainfall-runoff model is combined with a water balance model of the lake for the simulation of its water level. For a comprehensive hydrological analysis and due to the connection of the lakes through the hydrographic network, the same methodological approach is applied to the other three lakes in the catchment, Petron, Chimaditida and Zazari.

As a first step, the water balance of each lake is simulated based on a simple algebraic equation that takes into account the water inflows and outflows:

$$S(i+1) = S(i) + Q_{\text{in}} + P - E + G_{\text{in}} - G_{\text{out}} - Q_{\text{users}} - Q_{\text{out}} \quad (1)$$

where S is the volume of water stored in the lake in time i and i + 1, Q_{in} is the surface inflow into the lake from the catchment, P is precipitation and E is evaporation in/from lake's surface, G_{in} is the groundwater inflow, G_{out} is the groundwater outflow, Q_{users} is the water outflow to water users and Q_{out} is the surface outflow. The simulation time step is monthly and the equation terms are expressed in m^3. The groundwater inflow and outflow were not taken into account, that is, $G_{\text{in}} = G_{\text{out}} = 0$ or $G_{\text{in}} = G_{\text{out}}$, considering that groundwater flow has a minor contribution to lake's water balance compared to the other parameters due to the significant decline of groundwater table compared to lake level in the area. Even though the assumption related to the groundwater component is rough and rather simplistic, it is thought that it only bears deviations from the theoretical approach of a detailed representation of the lakes' water balance. Therefore, it is strongly believed that this assumption holds in the particular case, and it does not affect significantly their water balance, as it may be proved and demonstrated from the successful calibration of the model (Figs. 2 and 3). Obviously, this means that the surface inflow into the lake from the catchment (Q_{in}) is overestimated by the current model if groundwater outflow is higher than groundwater inflow (i.e. $G_{\text{out}} > G_{\text{in}}$), and vice versa. Nevertheless, the successful calibration of the hydrological model allows us to use the model to safely examine the scenarios discussed afterwards for Lake Vegoritida. After all, the scope of the modeling exercise is to assess the evolution of the lakes' level under various scenarios and not to explore in detail each and every element of their water balance.

Following the aforementioned considerations, all the other water balance parameters, except for Q_{in}, are known. S is extracted from the water level-volume curve of the lake based on water level measurements. P and E are estimated based on meteorological data and the hypsographic curve of the lake. Q_{out} is estimated as the water volume in excess when the lake level reaches its overflow level and Q_{users} are estimated based on water user's demands. Since Q_{in} is the only unknown parameter in Eq. (1), the use of a lake's water balance spreadsheet to estimate monthly surface inflow into the lake from the catchment is straight forward for the period that lake level measurements are available.

After that, the NAM rainfall-runoff model for each lake sub-catchment was set up to estimate the water inflow from the sub-catchment into the lake. NAM model can be

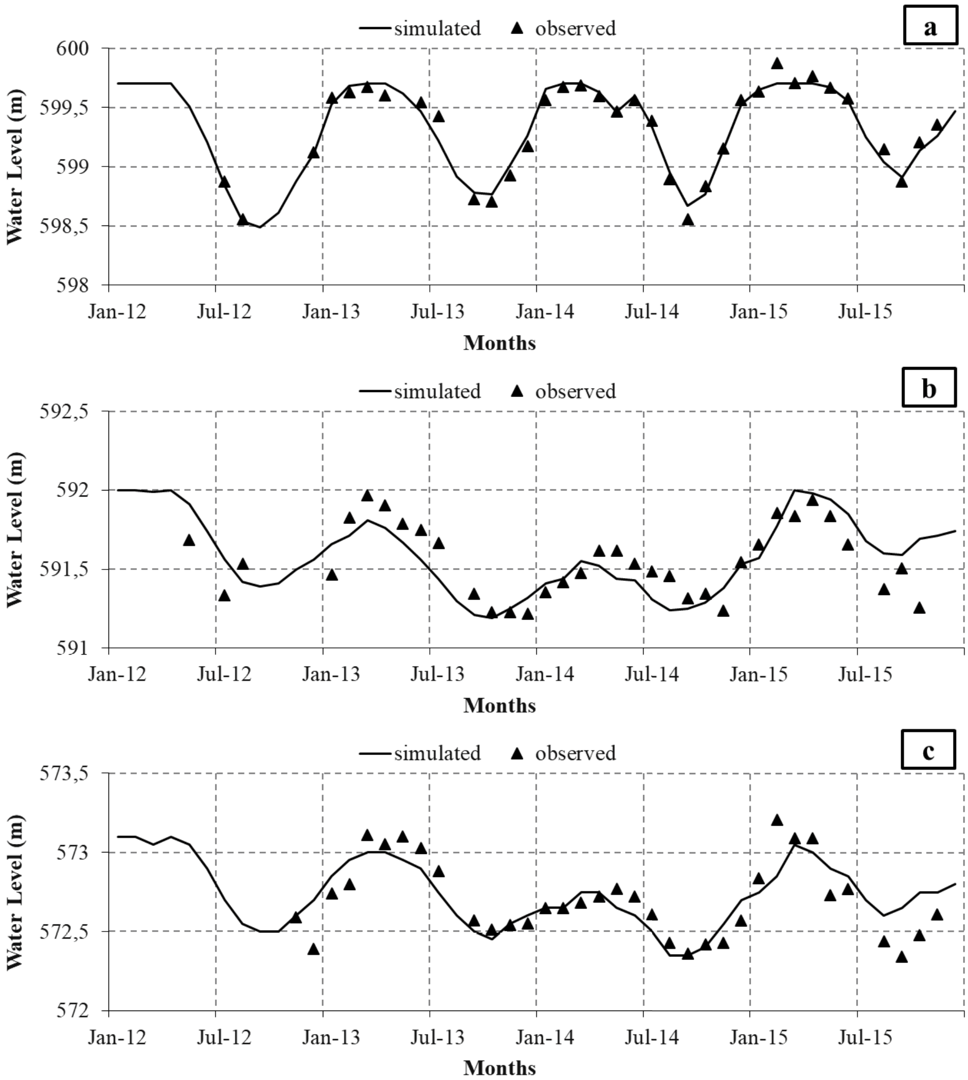

Fig. 2. Water level fluctuation in (a) Lakes Zazari, (b) Chimaditida, and (c) Petron for the period 2012–2015.

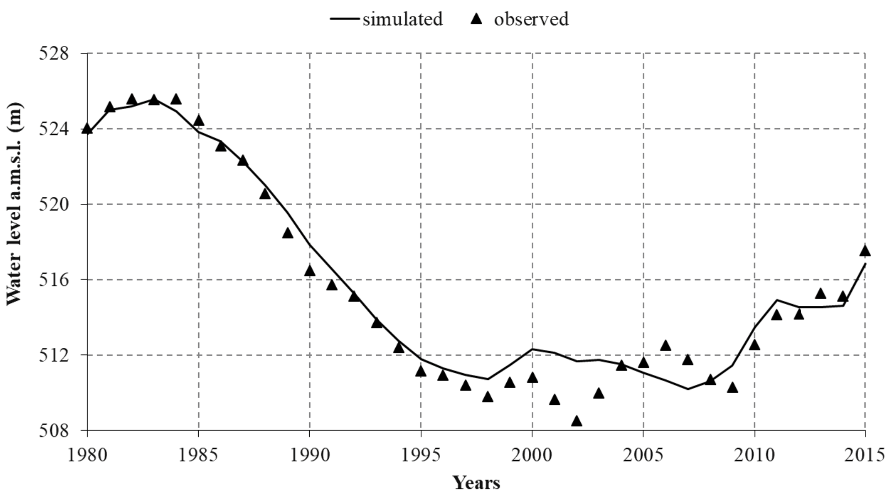

Fig. 3. Water level fluctuation in Lake Vegoritida for the historical period 1980–2015.

characterized as a deterministic, lumped, conceptual model with moderate input data requirements [25]. It represents various components of the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated reservoirs. Each reservoir represents different physical elements of the catchment and, depending on the requirements and the data available, the NAM can be prepared in a number of different modes. By default, it can be prepared with nine parameters representing surface-root zone storage as well as groundwater storage. The values of the model parameters are defined for the entire catchment and some of them can be inferred from the catchment's physiographic, climatic, or soil characteristics. Yet, to estimate the final parameters, the model must be calibrated against a time series of hydrological observations, usually the runoff of the catchment. Herein, the time series of estimated monthly surface inflow from the catchment into the lake [Q_{in} in (Eq. (1)] is used to a computer-based automatic calibration procedure in the modeling environment of MIKE 11-NAM [26]. In Table 2 are given the calibrated NAM model parameters for the sub-catchments of Lake Vegoritida catchment.

Finally, the MIKE BASIN water resources management model [26] was used to efficiently handle the simulation and the analysis of the water balance of the lakes and their sub-catchment for the historical period (1980–2015) and the projected period (2021–2050). MIKE BASIN includes a NAM module for rainfall-runoff modeling and a rather simple but comprehensive algorithm for the simulation of water balance in a catchment, including lakes or reservoirs [27].

2.3. Projection of climatic conditions

The historical climatic conditions used in the hydrological analysis are described based on precipitation and temperature data for the period 1980–2015. The projected climatic conditions are studied using precipitation and air temperature data (minimum and maximum) from RCA4 regional climate model (RCM) [28] under RCP4.5, RCP8.5 and RCP2.6 scenarios, driven by three GCMs namely EC-Earth [29], HadGEM2-ES [30,31] and MPI-ESM-LR [32]. The RCM data is distributed from the CORDEX Initiative for the EURO-CORDEX domain and the analysis is 0.11° × 0.11°.

Bias-correction was applied in RCM data in order to improve the local representation of climate variability in Lake Vegoritida catchment. In literature, a wide range of bias-correction methods has been applied for the purposes of climate change impact on hydrological studies ranging from relatively simple (such as delta change and linear scaling) to more sophisticated. According to Graham et al. [33], simple bias-correction methods have the advantage of affecting climate change signal as little as possible. Delta change approach is applied only on the observed time series and RCM data is used only in order to derive the climate change signal. In contrast, the linear scaling approach, which is widely applied in climate change impact studies on the river basin scale [34,35], is able to produce future time series, and thus, it was chosen to be applied in the context of the present study. The period 1980–2005 was used for the determination of linear scaling factors, while the period 2021–2050, considered as representative of the near future, was chosen to be the climate projected period.

Table 3 shows the annual averages of meteorological data in Lake Vegoritida catchment for the historical period and the nine climate scenarios (for RCP4.5 are included three scenarios, S1_4.5: RCP4.5 driven by EC-Earth, S2_4.5: RCP4.5 driven by HadGEM2-ES and S3_4.5: RCP4.5 driven by MPI-ESM-LR, and accordingly the other six scenarios for RCP8.5 and RCP2.6). Compared to the historical period, precipitation decreased from 3% to 22% and potential evapotranspiration increased from 7% to 11%, depending on the scenario.

3. Results

3.1. Historical period 1980–2015

The hydrologic model of Lake Vegoritida catchment was calibrated successfully based on water level measurements in Lakes Zazari, Chimaditida, Petron, and Vegoritida for the historical period. The calibrated model parameters are given in Table 2. Fig. 2 shows the simulated and observed water level in Lakes Zazari, Chimaditida, and Petron for the period 2012–2015, and from the graphical comparison, we notice that the model simulates satisfactorily the water level fluctuation in the three lakes. The squared formula of correlation coefficient (R^2) between simulated and observed water levels is 0.96, 0.58, and 0.66 for Lakes Zazari, Chimaditida, and Petron, respectively.

Fig. 3 shows the annual average, simulated and observed, of water level in Lake Vegoritida for the period 1980–2015.

Table 2
Rainfall-runoff model parameters (NAM module) in the sub-catchments of Lake Vegoritida

Parameters	Description and bandwidth	Zazari	Chimaditida	Petron	Vegoritida
Umax (mm)	Maximum water content in surface storage	5	5	20	20
Lmax (mm)	Maximum water content in root zone storage	50	50	200	500
CQOF (–)	Overland flow runoff coefficient	0.35	0.35	0.4	0.2
CKIF (hour)	Time constant for routing interflow	501.1	501.1	700	700
CK1,2 (hour)	Time constant for routing overland flow	10.1	10.1	20	20
TOF (–)	Threshold value for overland flow	0	0	0	0.3
TIF (–)	Threshold value for interflow	0	0	0	0.3
TG (–)	Threshold value for groundwater recharge	0	0	0	0
CKBF (hour)	Time constant for routing baseflow	2,164	2,164	2,164	3,500

Similarly with the other three lakes, we notice a quite good agreement between simulated and observed water level, both during the period 1980–1996 that the Public Power Corporation was abstracting water from the lake, as well as for the period after 1997 that the direct abstraction from the lake had stopped. Also, the high value of the correlation coefficient (R^2 = 0.97) indicates that the model can simulate the lake's hydrologic response safely and reliably.

Fig. 4 shows the simulated water level in Lake Vegoritida for the historical period in the real case that the Public Power Corporation (DEH) was abstracting water from the lake during the period 1980–1996 (labeled "with DEH") and in the scenario case that water was not abstracted from the lake by DEH (labeled "without DEH (scenario)"). We see that the impact on the water level of Lake Vegoritida by DEH's water abstraction was quite significant. If water had not been abstracted from the lake (without DEH scenario), the water level of the lake would always be above 520 m, providing equilibrium and sustainability in the lake area. During the period that water abstracted from the lake by DEH, the lake has lost 45% of its volume and 29% of its surface area [11] and the water quality of the lake has progressively deteriorated, causing a decline in the fish population and an increase in eutrophication, from oligotrophic to mesotrophic status [36,37].

3.2. Future period 2021–2050

The hydrologic model of Lake Vegoritida catchment is also used to simulate the water balance and the water level of the lake for the projected climatic conditions. In Table 4 is given the annual water balance for the historical period 1980–2015 and for the nine climate scenarios for the period 2021–2050. Compared to the historical period, the inflow to the lake from the catchment increases in scenario S1_4.5 by 5% mainly because precipitation is higher in winter months for S1_4.5, even though the annual precipitation is 9% lower (Table 3). In the scenario S1_2.6, the inflow from catchment slightly decreases by 6%, while in the other scenarios substantially decrease from 22% to 68%, compared to the historical period. Similarly, precipitation to the lake (in mm) decreases from 7% to 24% while evaporation from the lake

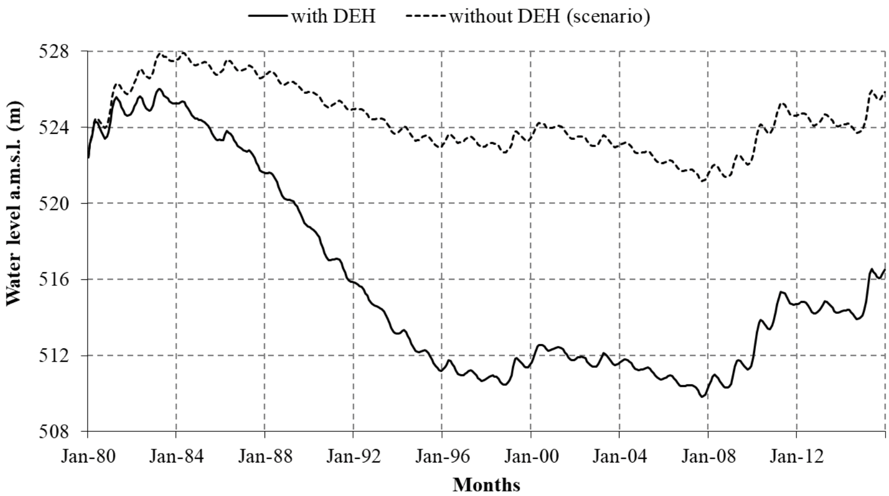

Fig. 4. Impact on the water level of Lake Vegoritida by the Public Power Corporation (DEH) water abstraction.

Table 3
Meteorological data for the historical period and the climate scenarios in Lake Vegoritida catchment

Scenario/time period	Precipitation (mm/y)	Temperature (°C)	Evapotranspiration (mm/y)
Historical period/1980–2015	579	11.4	979
S1_4.5/2021–2050	530 (–9%)[a]	12.8	1,056 (+8%)
S2_4.5/2021–2050	479 (–17%)	13.5	1,088 (+11%)
S3_4.5/2021–2050	489 (–16%)	13.1	1,074 (+10%)
S1_8.5/2021–2050	484 (–16%)	13.2	1,061 (+8%)
S2_8.5/2021–2050	499 (–14%)	13.6	1,084 (+11%)
S3_8.5/2021–2050	452 (–22%)	12.7	1,065 (+9%)
S1_2.6/2021–2050	561 (–3%)	12.5	1,044 (+7%)
S2_2.6/2021–2050	540 (–7%)	13.3	1,073 (+10%)
S3_2.6/2021–2050	484 (–16%)	12.9	1,071 (+9%)

[a]percentage change compared to the historical period

Table 4
Annual water balance in Lake Vegoritida for the historical period and the climate scenarios period

Scenario/time period	Inflow from catchment	Precipitation to lake		Evaporation from lake	
	(10^6 m^3)	(10^6 m^3)	(mm)	(10^6 m^3)	(mm)
Historical period/1980–2015	40.5	26.5	596	48.9	1,099
S1_4.5/2021–2050	42.6	29.4	545	61.6	1,142
S2_4.5/2021–2050	22.1	20.0	474	49.5	1,174
S3_4.5/2021–2050	25.0	23.5	507	53.5	1,157
S1_8.5/2021–2050	12.9	19.3	475	46.5	1,145
S2_8.5/2021–2050	21.9	21.4	505	49.5	1,168
S3_8.5/2021–2050	16.3	19.2	452	48.6	1,147
S1_2.6/2021–2050	38.0	27.2	553	55.4	1,127
S2_2.6/2021–2050	31.7	23.3	521	51.8	1,160
S3_2.6/2021–2050	14.8	20.5	495	47.8	1,153

(in mm) increases from 3% to 7%, depending on the scenario. Lake precipitation and evaporation are also given in units of m^3 in Table 4 for comparison with the inflow from the catchment, but please note that the comparison of precipitation or evaporation among the scenarios and the historical period may be misleading, as in this case they are expressed in units of volume and thus they also depend on the surface area of the lake, which is varying among the scenarios.

Fig. 5 compares the water level fluctuation in Lake Vegoritida for the historical period 1980–2015 and the future period 2021–2050 according to the three scenarios of RCP4.5. In scenario S1_4.5 (RCP4.5 driven by EC-Earth model), the water level increases remarkable and varies from 518 m to 528 m (average 524.5 m), similar or higher to the water level existed in the early 1980s. On the other hand, in scenarios S2_4.5 (RCP4.5 driven by HadGEM2-ES model) and S3_4.5 (RCP4.5 driven by MPI-ESM-LR model), we notice that the water level is significantly affected by climate change. Especially in scenario S2_4.5, the water level is expected to fall to 508 m circa in 2050, as it was at the beginning of the century due to the severe water abstraction by the Public Power Corporation.

Figs. 6 and 7 compare the water level fluctuation in Lake Vegoritida for the historical period 1980–2015 and the future period 2021–2050 according to the scenarios of RCP8.5 and RCP2.6, respectively. Based on the RCP8.5 scenarios (Fig. 6), the water level is expected to follow a substantial downward trend for the next 30 y without showing any sign of stabilizing, except maybe for the scenario S2_8.5. On the other hand, two of the RCP2.6 scenarios (Fig. 7), S1_2.6 and S2_2.6, show that the water level will remain at its current level, that is, among 516 and 520 m, while the other scenario S3_2.6 shows a downward trend for the water level similar to that of the scenarios of RCP8.5.

Table 5 summarises the water level trend in Lake Vegoritida under the three climate scenarios (RCP4.5, RCP8.5, RCP2.6) and the three climate models (EC-Earth, HadGEM2-ES, MPI-ESM-LR) used in this work. As expected, the water level follows a downward trend under the “pessimistic” scenario RCP8.5 for all the climate models. For the

Fig. 5. Water level fluctuation in Lake Vegoritida according to RCP4.5 scenarios.

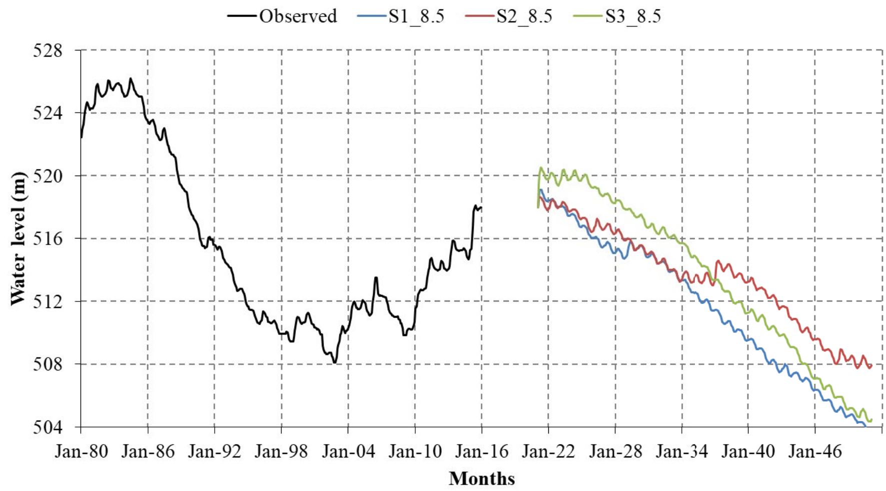

Fig. 6. Water level fluctuation in Lake Vegoritida according to RCP8.5 scenarios.

Fig. 7. Water level fluctuation in Lake Vegoritida according to RCP2.6 scenarios.

"optimistic" scenario RCP2.6, two of the models show a constant trend for the water level while one model shows a downward trend. Surprisingly, the "intermediate" scenario RCP4.5 shows an upward trend for one of the models while two of the models show a downward trend.

Table 5
Water level trend in Lake Vegoritida for the next 30 y (2021–2050) under three climate scenarios and three climate models

Climate scenario Climate model	RCP4.5	RCP8.5	RCP2.6
EC-Earth (S1)	Upward	Downward	Constant
HadGEM2-ES (S2)	Downward	Downward	Constant
MPI-ESM-LR (S3)	Downward	Downward	Downward

4. Discussion and conclusions

A hydrologic model for Lake Vegoritida catchment was developed to study the climate change impact on lake level fluctuation for the near future (2021–2050) and to disclose the significant impact on lake level caused by the severe water abstraction from the Public Power Corporation (DEH) during the period 1980–1996. The hydrological model, consisting of a rainfall-runoff model to assess the water inflow to the lake from the catchment and a water balance model of the lake for the simulation of its water level, was calibrated successfully based on the water level measurements in the four lakes of the catchment, Zazari, Chimaditida, Petron and Vegoritida. This model was used to elucidate the past and the future of Lake Vegoritida, which faced a substantial decline in its water level, as it was around 525 m a.m.s.l. in the early 1980s, dropped down to 509 m in 20 y and has partially recovered to around 518–519 m during the last decade. The application of the calibrated model for the historical period 1980–2015 showed that the water abstraction directly from Lake Vegoritida by the Public Power Corporation was the main reason for the decline of its water level in the last century, causing a significant loss of its volume and its surface area and progressive deterioration of its water quality, affecting the fish population and increasing the eutrophication status.

It has to be mentioned that the severe water abstraction by the Public Power Corporation in Lake Vegoritida started in the 1950s when the lake level was around 540 m. Specifically, the large volume of water discharged from the lake catchment to satisfy a hydro-electrical power plant between the years 1956 and 1985 was the main reason for the decreased lake volume [13]. In addition to that, the water abstraction from the lake by the Public Power Corporation has been continued until 1997 to cover the water demands for the operation of a number of thermo-electrical power stations in the catchment. In the last 20 y or so, the Public Power Corporation has no longer any stake on the lake and no more water is abstracted to supply the electrical power stations. Ever since the water demands for the operation of these power stations are being covered by water transfers from the neighboring hydrological catchment of the River Aliakmonas [11]; the possibility to revert to the previous source of water is ruled out by legislative acts, predominantly due to environmental constraints.

As the water abstraction by the Public Power Corporation ceased to exist, the lake level is rising nowadays and it is likely to approach in the near future the level it was in the early 1980s. However, the hydrological analysis presented herein for the near future climatic conditions shows contradictory water balances and associated water level fluctuations in Lake Vegoritida for the projected climate period 2021–2050, based on the RCPs scenarios 4.5, 8.5, and 2.6 and driven by three GCMs namely EC-Earth (S1), HadGEM2-ES (S2), and MPI-ESM-LR (S3). Specifically, three of the nine scenarios (S1_4.5, S1_2.6 and S2_2.6) show that the water level will remain at its current level or higher while the other six scenarios show a significant decline in the water level of Lake Vegoritida for the near future. Therefore, there is a high degree of uncertainty if climate change will affect the water balance of Lake Vegoritida. In any case, the scientific community and competent authorities should be alert for potential adaptation measures to protect the lake's ecosystem.

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