Climate change impact assessment on the establishment of maximum water level in Lake Vegoritida, Greece

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ABSTRACT

Purpose: Lake Vegoritida has undergone substantial fluctuations on 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 support any suggested maximum water level.

Methods: The hydrologic model of Lake Vegoritida catchment has been developed to assess the water inflows and outflows of the lake. In particular, a lumped 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.

Results: The hydrologic model was calibrated based on water level measurements in Lakes Vegoritida, Petron, Cheimaditida and Zazari. 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 period 1980-1996. Furthermore, the application of three climatic scenarios for the projected period 2021-2050 revealed contradictory water balances and associated water level fluctuations in Lake Vegoritida.

Conclusions: Based on this work, it is uncertain if climate change will affect the current lake's water level. More scenarios should be used to elucidate further the effect of climate change on the establishment of maximum water level in Lake Vegoritida.

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, an 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 modelling framework, involving their physical, chemical and biological properties, should be applied. The integrated modelling framework, in conjunction with lake's properties monitoring, would enable the formulation of a series of measures for the mitigation of climate change impacts.

The potential effects of climate change on the physical, chemical, and biological characteristics of lakes have been discussed by Vincent [6]. In Mediterranean region, Dimitriou and Mousoulis [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%. Fatoric et al. [8] explored the climate change effects in 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 Lake Cheimaditida and Lake 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] modelled the brackish endorheic Lake Qinghai in China to reveal the major features of lake response to climate change.

Lake Vegoritida has undergone substantial fluctuations 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 early 1980's and dropped down to 509 m in 20 years whereas has partially recovered to around 518-519 m during the last decade. This water level fluctuation has affected the natural, social and economic environment of the lakeside area. The recent recovery of the water level triggers a discussion on the definition of lake's maximum allowable level which by itself becomes a source of conflict among stakeholders including farmers, fishermen, tourists, entrepreneurs, scientists–practitioners. To 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 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.

In this paper, the historical and projected climatic conditions are considered to examine if the available water potential of the catchment may lead to, and sustain, a proposed maximum lake level, by using a hydrologic model for Lake Vegoritida catchment. The model assess the water inflows and outflows of the lake by combining a lumped rainfall-runoff model of the lake's catchment and a water balance model of the lake for the simulation of its water level. After the model calibration, the effect of historical and projected climatic conditions, in conjunction with water withdrawal from the lake, is investigated on lake's water 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 Natura 2000 network and is included in a Site of Community Importance area (SCI). The hydrological catchment of Lake Vegoritida (Fig. 1) covers an area of 2,145 km^2, and includes also the Lakes Petron, Cheimaditida 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 Cheimaditida via a canal. Similarly, the excess of water in Lake Cheimaditida 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 is 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 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. 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 (DEH) in the catchment and directly from the lake; the water abstraction from the lake has been ceased in 1997. Agriculture is another important source of income and agricultural land covers 31.1% of the catchment area (https://www.eea.europa.eu/publications/COR0-landcover). According to data from the Hellenic Statistical Authority (http://www.statistics.gr/en/home), 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. In Table 1 is given the estimated annual water use for irrigation, industry etc. in the subcatchments of Lake Vegoritida catchment.

The morphology of the shallow lakes Cheimaditida 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 (http://nmwn.ypeka.gr/en). Specifically, the bottom elevation of the lakes Vegoritida, Zazari and Cheimaditida has been recorded by using a portable shallow water echo sounder equipped with GPS 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 GIS 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 [16].

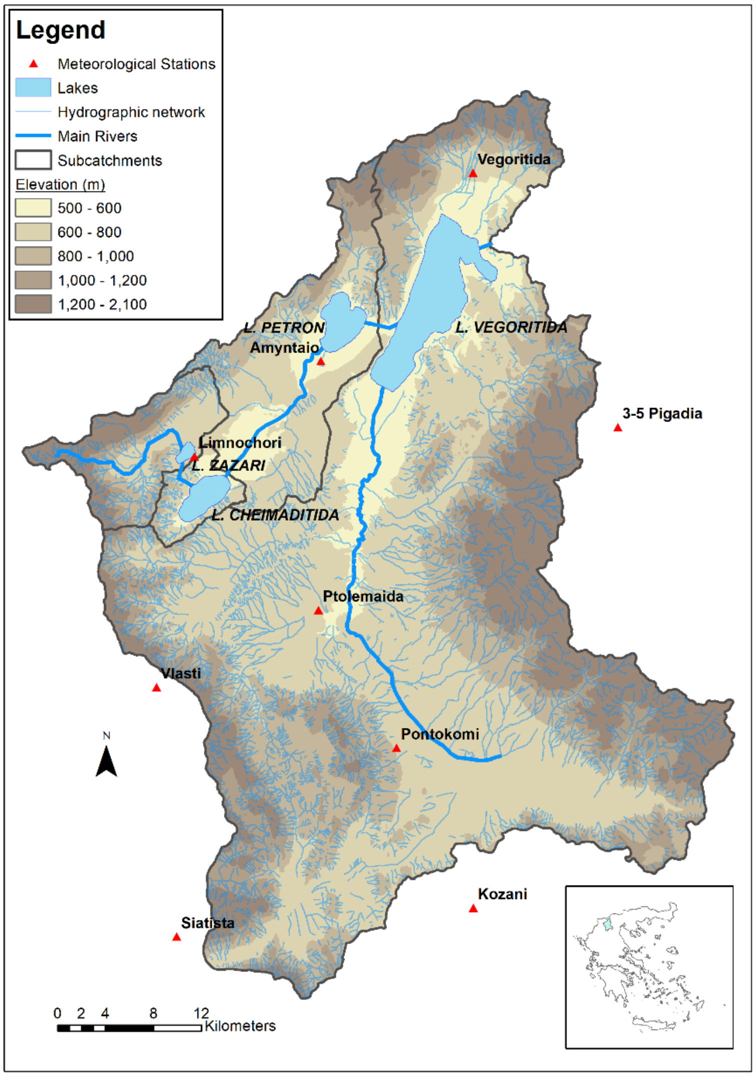

Fig 1. Hydrological catchment of Lake Vegoritida

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

	Groundwater[1]				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[1]** (10^6 m^3)	**Industry[2]** (10^6 m^3)
Zazari	5.3	0.4	0.3		1.5	
Cheimaditida	0.24	0.14				
Petron	12.9	0.4	0.2	12.4		
Vegoritida	70.8	7.2	1.0	30.8		37.7

[1]average values for the period 1990-2000, source [17]
[2]average value for the period 1980-1996, source [15]

Meteorological data for the period 1980-2015 of monthly air temperature (maximum and minimum) and precipitation were obtained by 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 stations plus two additional stations (Siatista, Pontokomi) were used for precipitation data. The potential evapotranspiration of the catchment and the evaporation from lakes' surface area were estimated based on air temperature data by the Hargreaves and

Samani [18] equation. 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 (http://nmwn.ypeka.gr/en), while a longer term data record is maintained by the Public Power Corporation (DEH) 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, i.e. irrigation, industry et cetera. In particular, the NAM rainfall-runoff model [19] 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, Cheimaditida 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:

$$S(i+1) = S(i) + Qin + P - E + Gin - Gout - Qusers - Qout \quad (1)$$

where S is the volume of water stored in the lake in time i and i+1, Qin is the surface inflow into the lake from the catchment, P is precipitation and E is evaporation in/from lake's surface, Gin is the groundwater inflow, Gout is the groundwater outflow, Qusers is the water outflow to water users and Qout is the surface outflow. The simulation time step is monthly and the equation terms are expressed in m^3. The groundwater inflow and outflow was not taken into account, i.e. Gin=Gout=0 or Gin=Gout, considering that groundwater flow has 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. In that case, all the other water balance parameters, except for Qin, 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. Qout is estimated as the water volume in excess when the lake level reaches its overflow level and Qusers is estimated based on water users demands. Since Qin is the only unknown parameter in eq. 1, the use of a lake's water balance spreadsheet to make an estimate of 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 subcatchment was set up to estimate the water inflow from the subcatchment into the lake. NAM model can be characterized as a deterministic, lumped, conceptual model with moderate input data requirements [20]. 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 (Qin in eq. 1) is used to a computer-based automatic calibration procedure in the modelling environment of MIKE 11-NAM (www.dhigroup.com). In Table 2 are given the calibrated NAM model parameters for the sub-catchments of Lake Vegoritida catchment.

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

Parameters	Description and bandwidth	Zazari	Cheima-ditida	Petron	Vegori-tida
Umax (mm)	Max. water content in surface storage	5	5	20	20
Lmax (mm)	Max. 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	2164	2164	2164	3500

Finally, the MIKE BASIN water resources management model (www.dhigroup.com) was used to efficiently handle the simulation and the analysis of the water balance of the lakes and their subcatchment for the historical period (1980-2015) and the projected period (2021-2050). MIKE BASIN includes a NAM module for rainfall-runoff modelling and a rather simple but comprehensive algorithm for the simulation of water balance in a catchment, including lakes or reservoirs [21].

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) [22] under RCP4.5 emissions scenario, driven by three different Global Circulation Models (GCMs) namely EC-Earth [23], HadGEM2-ES [24, 25] and MPI-ESM-LR [26]. The above mentioned RCM data is distributed from the CORDEX Initiative for the EURO-CORDEX domain and the analysis is 0.11ox0.11o.

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. [27], simple bias-correction methods have the advantage of affecting climate change signal as little as possible. Linear scaling was chosen to be applied in the context of the present study, which is a method widely applied in climate change impact studies on the river basin scale [28, 29]. 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 annually averages of meteorological data for the historical period and the three climatic scenarios – S1: EC-Earth, S2: HadGEM2-ES and S3: MPI-ESM-LR – in Lake Vegoritida catchment. Compared to the historical period, precipitation decreased by 10%, 18% and 17% and potential evapotranspiration increased by 17%, 14% and 11%, for the scenarios S1, S2 and S3, respectively.

Table 3. Meteorological data for the historical period and the scenarios of the projected period in Lake Vegoritida catchment

Scenario/time period	**Precipitation** (mm/year)	**Temperature** (°C)	**Evapotranspiration** (mm/year)
1980-2015	587	11.4	979
S1/2021-2050	530	15.0	1142
S2/2021-2050	479	14.4	1120
S3/2021-2050	489	13.3	1084

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, Cheimaditida, Petron and Vegoritida for the historical period. Fig. 2 shows the simulated and observed water level in Lakes Zazari, Cheimaditida 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. Furthermore, the correlation coefficient between simulated and observed water level is 0.98, 0.76 and 0.81 for lakes Zazari, Cheimaditida and Petron, respectively.

Fig. 3 shows the annual average, simulated and observed, of water level in Lake Vegoritida for the period 1980-2015. 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 (DEH) was abstracting water from the lake, as well as for the period after 1997 that the direct abstraction from the lake has stopped. Also, the high value of correlation coefficient (R=0.98) indicates that the model can simulate the lake's hydrologic response safely and reliably.

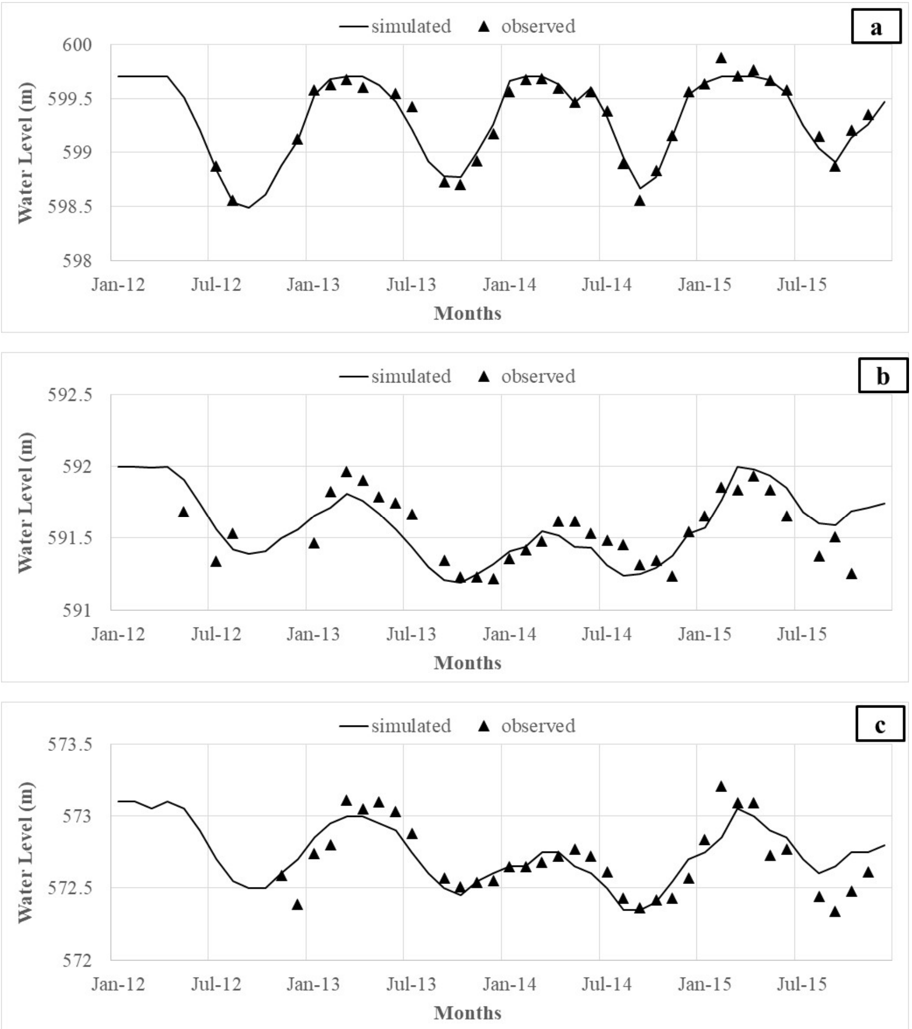

Fig 2. Water level fluctuation in Lakes Zazari (a), Cheimaditida (b) and Petron (c) for the period 2012-2015

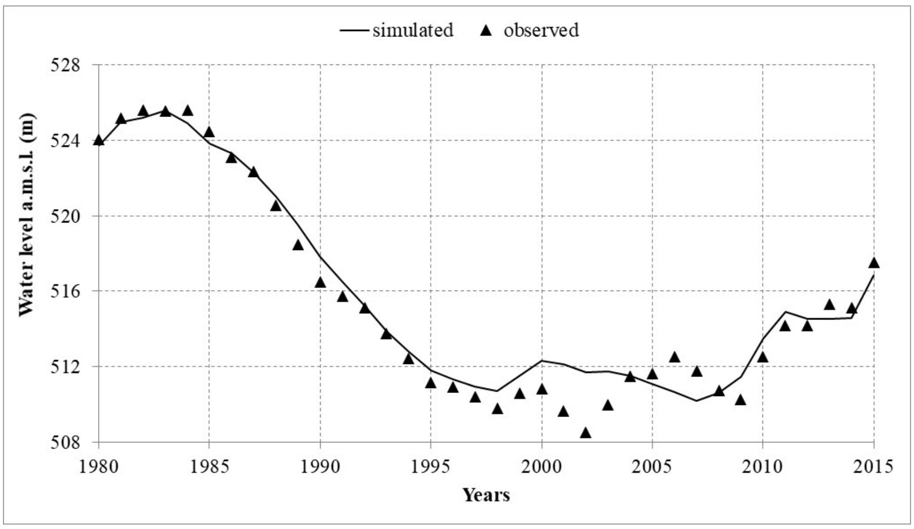

Fig 3. Water level fluctuation in Lake Vegoritida for the historical period 1980-2015

Fig. 4 shows the simulated water level in Lake Vegoritida for the historical period in the case that the Public Power Corporation (DEH) was abstracting water from the lake during the period 1980-1996 (labelled "with DEH") and in the scenario that water was not abstracted from the lake by DEH (labelled "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 [30, 31].

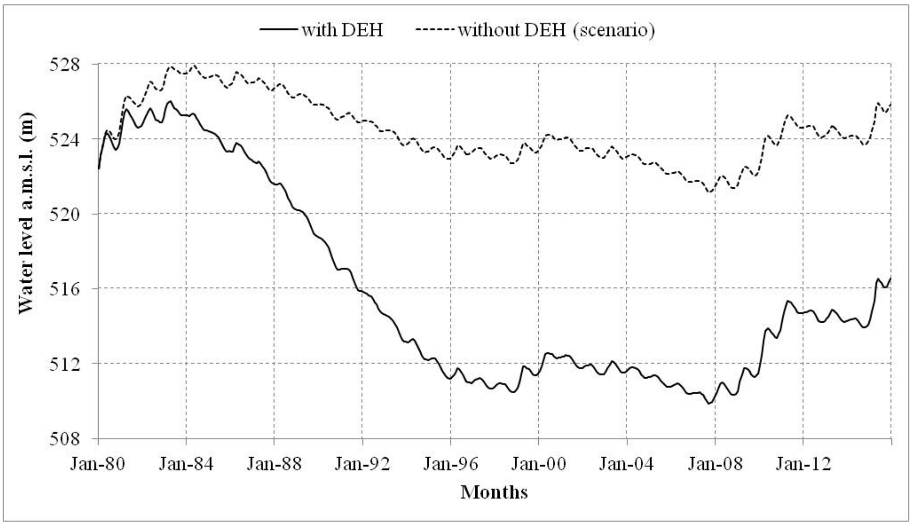

Fig 4. Impact on the water level of Lake Vegoritida by the Public Power Corporation (DEH) water abstraction

3.2. Future period 2021-2050

The hydrologic model of Lake Vegoritida catchment was also used to simulate the water balance and the water level of the lake for the projected climatic conditions of the period 2021-2050. In Table 4 is given the annual water balance for the three climatic scenarios and is compared with the water balance for the historical period 1980-2015. Compared to the historical period, the inflow to lake from catchment was decreased by 9%, 48% and 36%, for the scenarios S1, S2 and S3, respectively. Similarly, precipitation to lake (in mm) decreased by 8%, 21% and 15% and evaporation from lake (in mm) increased by 12%, 10% and 6%, for the scenarios S1, S2 and S3, respectively. The comparison of precipitation or evaporation among the scenarios is complex in the case they are represented in units of m^3, as they also depend on the surface area of the lake, which is quite different among the scenarios.

Table 4. Annual water balance in Lake Vegoritida for the historical period and the climatic 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)
1980-2015	40.7	26.5	596	48.9	1099
S1/2021-2050	37.2	27.4	547	61.4	1228
S2/2021-2050	21.1	19.4	474	49.4	1208
S3/2021-2050	25.9	23.4	507	53.9	1167

Fig. 5 shows the water level fluctuation in Lake Vegoritida for the historical period 1980-2015 and the future period 2021-2050 according to the three climatic scenarios examined in this work. The impact of future climatic conditions on lake’s water level is contradictory. In scenario S1, the water level is not particularly affected by climate change and varies from 518 m to 526 m (average 521.4 m). On the other hand, in scenarios S2 and S3, the water level is significantly affected by climate change, especially in scenario S2, according to which the water level in 2050 is expected to fall to 508 m circa, as it was in the beginning of this century.

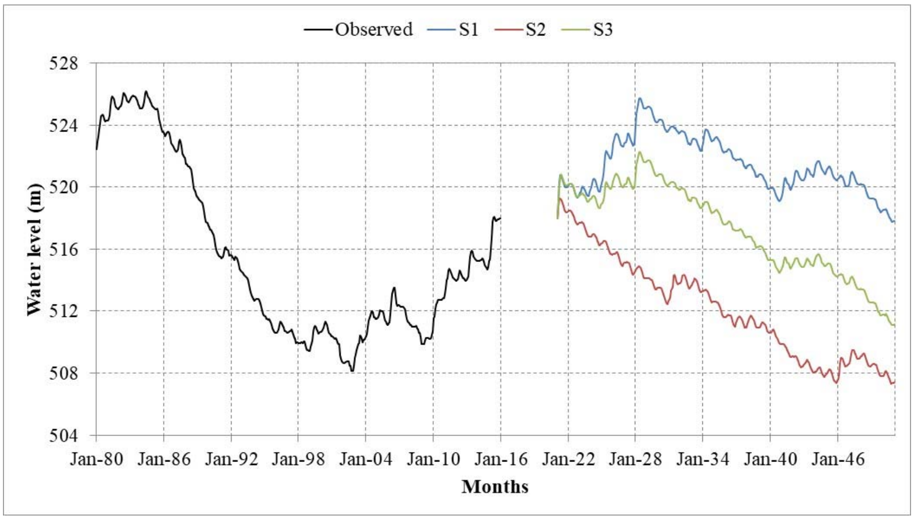

Fig 5. Water level fluctuation in Lake Vegoritida for the period 1980-2050

4. Conclusions

A hydrologic model for Lake Vegoritida catchment was applied and calibrated successfully based on water level measurements of the four lakes, Vegoritida, Petron, Cheimaditida and Zazari. The model was also used to disclose the significant impact on the water level of Lake Vegoritida by the Public Power Corporation (DEH) water abstraction during the period 1980-1996. The application of three climatic scenarios, under RCP4.5 emissions scenario, for the projected period 2021-2050 revealed contradictory water balances and associated water level fluctuations in Lake Vegoritida for the near future. In one of the scenarios, the water level is not particularly affected by climate change while in the other two scenarios is significantly affected. Therefore, it is uncertain if climate change will affect the current water level and more scenarios would be necessary to clarify safely the impact of climate change on the establishment of a maximum water level in Lake Vegoritida.

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