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ORIGINAL ARTICLE

The impact of climate change on a Mediterranean shallow lake: insights based on catchment and lake modelling

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Abstract
Shallow lakes in the semi-arid climate zone of the Mediterranean are sensitive to drought due to the low annual precipitation and high evaporation. Changes in precipitation and temperature as projected by climate change scenarios will have an effect on the hydrology of these shallow lakes with secondary effects on nutrient dynamics and ecological state. In this study, we used a combined modelling approach that included the catchment model Soil and Water Assessment Tool (SWAT) and the lake model PCLake to study the possible effects of several climate scenarios on a shallow lake in semi-arid central Anatolia, Turkey. Our results show that lower precipitation and higher temperatures may reduce inflow rates and water levels drastically. Diffuse nutrient loading depended highly on precipitation and thus decreased as well. The lake model predicts an interaction between external nutrient loading and water levels. Low water levels benefited submerged macrophytes if nutrient concentrations were low, but low inflow rates and high evaporation during dry periods increased in-lake nutrient concentrations and chlorophyll-a. Cyanobacteria biomass was also higher in the drier and warmer scenarios. Overall, the results show that lower hydraulic loads and reduced flushing rates as a result of drier and warmer conditions lead to lower water levels and higher in-lake nutrient concentrations unless nutrient loading decreased as well. This implies that catchment-scale nutrient management is essential to maintain low nutrient concentrations in the lakes with increasing temperature and decreasing precipitation in a dry climate.

Keywords Nutrients · Arid region · Water level fluctuation · Eutrophication · PCLake · SWAT

Introduction

The Mediterranean climate zone is considered to be very sensitive to climate change (Giorgi and Lionello 2008), as emphasized by projected major increases in air temperature and reductions in precipitation in this century (Erol and Randhir 2012). For the semi-arid region in central Turkey, a 3–4 °C increase in temperature and a 10% decrease in precipitation are projected between 2070 and 2100 relative to 1960–1970 (Önol and Unal 2014). Such changes may have profound effects on the hydrology of shallow lakes in the region, even without an expected compensatory increase in water abstraction. Higher temperatures cause increased water loss through evaporation, while lower precipitation may lead to decreased inflows and lower runoff, potentially producing lower hydraulic and nutrient loading to the lakes. Despite lower annual precipitation, rainfall may be concentrated in fewer but more extreme events, however. Extreme rainfall events cause high runoff, thus potentially resulting in a higher nutrient loading (Jeppesen et al. 2009, 2011).

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The effects of the global climate change are expected to enhance eutrophication symptoms of shallow lakes (Jeppesen et al. 2009; Moss 2012). Direct effects on the lakes can be expected from higher water temperature, creating higher primary production and favouring certain cyanobacteria species (Paerl and Huisman 2008; Wagner and Adrian 2009). Higher temperatures can also affect the stratification of lakes producing lower oxygen levels and higher internal P loading since under anoxic conditions, iron-bound P in the lake sediment may be released into the water column (Blenckner et al. 2007). Changes in zooplankton and fish communities have been observed when moving from a temperate to a warmer climate (Gyllström et al. 2005; Meerhoff et al. 2007a; Brucet et al. 2012). Experimental studies have also shown changes in phytoplankton community structure (Yvon-Durocher et al. 2011), zooplankton community biomass and composition (Strecker et al. 2004) and fish populations (Moran et al. 2010) due to increasing temperature. Warmer and drier conditions lead to reduced inflow rates from the catchment and increased evaporation. While lower inflow rates might cause lower nutrient loading to the lake, water loss through evaporation, however, may increase nutrient concentrations in the lake, leading to eutrophication problems even when external loading is lower (Özen et al. 2010; Coppens et al. 2016). Besides lower water levels, evaporation also increases salinity with numerous effects on the ecology and trophic dynamics in lakes (Jeppesen et al. 2015; Beklioğlu et al. 2017).

In this study, we aimed to estimate the effects of the projected climate change on shallow Lake Mogan located on the semi-arid Anatolian plateau in Central Turkey using a holistic modelling approach. In order to predict the impact of climate change on the water and nutrient balance as well as the ecosystem structure of the lake, a combined approach of catchment modelling and lake modelling was implemented. We used the Soil and Water Assessment Tool (SWAT) to assess the impact of changes in temperature and precipitation on the hydrology and nutrient loading to the lake. We then used the modelled changes in flow rate and nutrient loading as input to the lake model PCLake to evaluate the effects of changes in water temperature, evaporation, inflow volume and nutrient loading on the nutrient concentration, macrophyte development and phytoplankton concentration in the lake.

Methods

Study area

The study area encompasses the catchment of Lake Mogan (39° 47′ N 32° 47′ E) located near Ankara on the Central-Anatolian plateau in Turkey. The urbanization pressure from nearby Ankara is high, and Lake Mogan is a recreational hotspot littered with lakeshore facilities. Nonetheless, the catchment of Lake Mogan and the downstream nearby Lake Eymir has a high biodiversity value. The lakes and wetlands in the catchment are part of the Gölbası Special Environmental Protection Area, 1 of 16 in Turkey, and are declared an “Important Bird Area” and nominated for Ramsar status.

Due to the inland location on the Anatolian high plateau, (mean elevation is 1100 m.a.s.l.), the local climate is characterized as arid cold steppe (Peel et al. 2007) with an average daily temperature of 12 °C and an average yearly total rainfall of around 400 mm (Turkish Meteorological Office). There are large seasonal differences with hot and dry summers (on average 23 °C and 20 mm rainfall per month) and cold winters (on average 2 °C), with most rainfall in winter and spring (43 mm rainfall per month).

Lake Mogan has a surface area of 5.6–8 km^2, depending on the water level. The mean depth ranged from 1.6 to 3.5 m in 1997–2010. The catchment has an area of 940 km^2 and contains three major subbasins: Çölovası, Yavrucak and Sukesen (Appendix Fig. A.1). These major inflows contribute 90% of the measured water flow to Lake Mogan, while several mostly seasonal inflows account for the remaining flow (Appendix Table A.1). The elevation of the basin ranges from 973 to 1700 m.a.s.l. The basin has mostly gentle topographical slopes, with 83% of the slopes being less than 10%. Only in the Sukesen subbasin, slopes are predominantly higher than 10% and at places exceed 40%.

The major land use in the basin is agriculture with non-irrigated wheat farming as the dominant crop (71%). Grasslands cover 16% of the basin, with barren lands and wetlands accounting for 2% each. The remainder of the basin is urban areas (8%), mostly in the town of Gölbaşı and the surrounding industrial zones.

Between 1997 and 2010, the average TP concentration was 90 $\mu g\ L^{-1}$ and the average TN concentration 1.69 $mg\ L^{-1}$. The average Chl-a concentration was 14 $\mu g\ L^{-1}$. Percentage volume inhabited by aquatic macrophytes (PVI) was higher than 40% in 2001, 2004 and 2008, all years with low water levels, whereas few plants were observed during the wet period with high water levels from 2009 to 2013 (Beklioğlu et al. 2017).

Model set-up and calibration

To assess the impact of climate change scenarios on Lake Mogan, the catchment model SWAT (Arnold et al. 1998) and the lake model PCLake (Janse and Van Liere 1995) were used in a linked approach. The effects of climate change scenarios on the hydrology and nutrient loading from the catchment to the lake were modelled with SWAT. The outputs of SWAT were used as inflows to the lake in PCLake to model the effects of changes in water temperature, hydraulic loading and nutrient loading on the internal physical, chemical and biological processes in the lake.

Soil and Water Assessment Tool

SWAT is a physically based, semi-distributed model aimed at analysing the impact of different land use forms, management practices and climate effects on the hydrological, sediment and chemical dynamics of a hydrological catchment (Neitsch et al. 2011). The model simulates physical processes related to the water and nutrient cycles based on input data from the catchment. ArcSWAT version 2012.10.13 was used.

Catchment delineation and stream positioning was done using a digital elevation model (DEM) with a resolution of 30 m. Next, 18 subbasin outlets were designated at the reservoirs, the measurement stations and all inflows to Lake Mogan. Based on the DEM, five slope classes were assigned (< 5%, 5–10%, 10–20%, 20–40% and > 40%).

Soil data was taken from the Harmonized World Soil Database and matched with the closest soil type in the SWAT database based on texture and soil properties. Land cover was deduced from data from the CORINE 2006 land use data. Based on field observations, the area of irrigated agricultural land was reduced in the SWAT model, while the extent of built-up urban area was increased to reflect recent developments. The agriculture land use class was further divided into wheat (91%) and barley (9%), the dominant crops in the basin. Information provided by the Turkish Food, Agriculture and Livestock Ministry was used to model the farming practices in the basin (Appendix Table A.2). The overlay and intersection of the different land use, soil and slope classes resulted in 585 hydrological response units (HRU), which are the basic simulation unit of the SWAT model (Neitsch et al. 2011).

Daily data on precipitation, wind speed, maximum and minimum temperature, solar radiation and relative humidity was taken from the central Ankara station of the Turkish State Meteorology Service (DMI), which is located 30 km north of the catchment.

The model was set up for the 1995–2010 period. The first 5 years were used as warm up for the model. The SWAT model was calibrated (2000–2005) and validated (2006–2010) based on monthly averages of daily flow measurements for the three major inflows provided by the Turkish General Directorate of Electrical Power, Resources Survey and Development Administration (EIE). Calibration for nutrient loading was performed for total monthly NO_3 and SRP loading, which was calculated from monitoring data obtained at the flow measurement stations on the major streams between 2000 and 2010. Derived data on organic N and P was available but too limited to use for calibration.

The Sequential Uncertainty Fitting (SUFI-2) procedure in the SWAT Calibration and Uncertainty Analysis Programs (SWAT-CUP) (Abbaspour et al. 2007; Abbaspour 2012) was used. A global sensitivity analysis was performed, and 32 parameters sensitive for flow rate or nutrient loading were identified in at least one subbasin of the three major inflows (Appendix Table A.3).

During the calibration, weights were assigned to the inflows based on their respective discharge and nutrient loading rates in the objective function to find the best fit. Best fit was determined based on the bR^2 (slope of the regression relation × R^2 coefficient) and the Nash-Sutcliffe (Nash and Sutcliffe 1970) model efficiency coefficients.

PCLake

PCLake is a dynamic ecosystem model that incorporates both the biotic and abiotic components of the lake ecosystem. The primary purpose of the PCLake model is to simulate the shifts between the Alternative Stable States of shallow lakes, which are defined as a macrophyte-dominated clear water versus a phytoplankton dominated-turbid water state (Scheffer et al. 1993), and to determine the critical loading levels that cause these shifts (Janse and Van Liere 1995). The basic structure of the model consists of a mixed water column, the top layer of the sediment (10 cm) and the key biotic factors and abiotic factors. The model is originally developed for shallow non-stratifying lakes so no horizontal or vertical dimensions are taken into account (0D). The DATM (Database Approach To Modelling) version of PCLake was used (Mooij et al. 2014).

The hydrological inputs to PCLake consist of inflow data, outflow data and evaporation. Daily evaporation was calculated based on pan evaporation measurements and seasonal pan coefficients. During the winter months, evaporation was calculated using the Penman equation for an open water surface (Penman 1948). This approach was deemed most accurate based on an analysis of the water budget of the lake; other approaches created too large assumed groundwater fluxes (Coppens et al. 2016). Inflow data consisted of the combined hydraulic loading of all the inflows, direct precipitation and groundwater flow into the lake. Outflow data included the discharge from the lake through the regulated outflow and groundwater seepage from the lake. Groundwater inflow and seepage were estimated as the remaining factor of the water budget of the lake, taking into account the changes in the lake water levels.

Daily water temperature was calculated based on the relationship between daily average air temperature and water temperature measured on sampling days twice a month during 1997–2010. Daily values for nutrient loading to the lake were entered into the model for NH_4, NO_3 and PO_4 based on linear extrapolation of monthly and biweekly measurements taken at the major inflows between 1997 and 2010. For organic N, organic P and sediment-bound particulate P, daily values were estimated in the same manner for years with sufficient measurements, while average, stream-specific ratios between inorganic and organic N and P fractions were used in the other years.

The state variables of the model were initialized based on sampling data for January 1997 for N, P, silicate, dissolved oxygen, lake fetch and water level. All other state variables, including the sediment parameters, were estimated based on running the model for 25 years with average hydraulic and nutrient loading. Afterwards, the model was run with inputs based on measurements for 1997–2010. The model was calibrated and validated for the 2000–2010 period, with the years from 1997 to 1999 serving as warm-up period.

Sampling data from the lake between 2000 and 2010 was used to calibrate and validate the model. Details on sampling, chemical analyses and processing can be found in Özen et al. (2010) and Beklioğlu et al. (2017).

One-at-a-time sensitivity analysis was performed by adding or subtracting 20% of the default value in every iteration, and the change in the response variables (SRP, TP, DIN, Chl-a and plant coverage) was determined. All parameters were then ranked according to sensitivity for each response variable, and the 16 most sensitive parameters were used in the calibration.

Complex models like PCLake may have several parameter combinations that reproduce observations to a certain extent but that may have diverging model predictions when scenarios are applied. For this reason, 250 runs of PCLake were combined, with a random value within a certain range applied to each parameter in the calibration set for each run. This approach takes into account the uncertainty related to determining the parameter values (Nielsen et al. 2014).

Calibration aimed to include > 75% of observed Chl-a and plant coverage measurements and > 50% of the observed concentrations for N and P in the simulation band while keeping the parameter ranges as small as possible within a − 20 to + 20% range. The simulation band was determined by selecting the highest and lowest value simulated at each time step after exclusion of the 2.5% most extreme values at the top and bottom. The range for each parameter in the calibration parameter set are presented in Appendix Table A.4.

Scenario design

In order to simulate the impact of climate change on Lake Mogan, two steps were taken. Firstly, temperature and precipitation changes based on the downscaled MPI-ESM-MR (MPI) global climate model (GCM) for 2020–2090 were taken into account. Secondly, a range of general climate scenarios were designed and implemented where temperature and precipitation were transformed uniformly.

For the first approach, the projections of two representative concentration pathways (RCP 4.5 & RCP 8.5) in the MPI model were used as the basis for the climate scenarios in SWAT. Bias correction was applied for the temperature projection using the relationship between the observed and simulated daily average temperature in the reference period (1985–2000). For precipitation, scenarios for 2020–2090 were designed using a seasonal correction based on the difference between the future projection and the reference period. No projections for changes in wind speed, solar radiation or relative humidity were available, and long-term daily average data were used instead. The projections for temperature and precipitation for both scenarios are given in Table 1. Temperature change in the first decades is negative due to the relatively high temperatures observed in the reference period.

For the second approach and based on the projections of the MPI-RCP 4.5 and 8.5 scenarios, five temperature scenarios (A–E: − 1 °C, 0 °C, + 1 °C, + 2 °C, + 3 °C) and five precipitation scenarios (1–5: − 30%, − 20%, − 10%, 0, + 10%) were designed, resulting in 25 general scenarios when combined (A1–E5). These scenarios were used to elucidate how changes in temperature and precipitation interact to influence flow rates and nutrient loading of the streams.

For every climate scenario, the relative effect on flow rates and nutrient loading in the streams compared with the baseline scenario was determined in SWAT and consequently used as input in the climate scenarios for PCLake. The years 2013–2020 were used as warm-up years, and data were analysed for 2020–2089.

For the climate scenarios, water temperature in PCLake was calculated by adding the temperature scenario to the observed air temperature and calculating the new daily water temperature based on the existing regression. Evaporation was changed in accordance with the change in potential evaporation as calculated by SWAT in the different scenarios. Inflow to the lake was adjusted based on the change in flow rates simulated by SWAT for each climate scenario. Nutrient loading input was adjusted based on the output of the SWAT model for the respective climate scenarios.

The outflow of Lake Mogan is regulated, and in order to estimate the lake water level under changing conditions, a simple decision model was created that simulated the control of the outflow gate. The decision model sets maximum flow rates and average ratios between inflows and outflow rates for different water level, based on observed flow rates for 1997–2013. Regulation of the outflow is aimed at protecting the low-lying area around the lake from flooding in spring while trying to prevent severe water level drops in summer due to evaporation. The outflow model therefore projects a near closing of the outflow gate if the lake water level drops below 3.5 m, while it would be opened stepwise to a maximum capacity of 5 $m^3 s^{-1}$ above 4.5 m. Based on this outflow model, the relation between simulated and observed daily water levels during 1997–2010 had a bR^2 value of 0.66. This decision model was used to simulate lake outflow rates under different inflow scenarios generated by the climate scenarios in SWAT.

For the general scenarios, average N, P and Chl-a concentrations were determined in PCLake by taking the average of

Table 1 Temperature (a) and precipitation (b) projections per decade for 2020–2090 and relative change compared with the reference period (2000–2010) for MPI-RCP 4.5 and 8.5

	MPI-RCP 4.5	MPI-RCP 8.5	MPI-RCP 4.5	MPI-RCP 8.5
(a)	Temp (°C)	Temp (°C)	ΔTemp (°C)	ΔTemp (°C)
2020–2030	12.41	12.50	− 0.44	− 0.35
2030–2040	12.71	12.64	− 0.15	− 0.21
2040–2050	12.79	13.23	− 0.06	0.38
2050–2060	13.16	13.77	0.31	0.92
2060–2070	13.18	14.39	0.33	1.54
2070–2080	13.20	14.92	0.35	2.07
2080–2090	13.27	15.39	0.42	2.54
(b)	Precipitation (mm)	Precipitation (mm)	ΔPrecipitation (%)	ΔPrecipitation (%)
2020–2030	356	323	− 5	− 14
2030–2040	346	355	− 8	− 5
2040–2050	362	354	− 4	− 6
2050–2060	349	337	− 7	− 10
2060–2070	363	276	− 3	− 16
2070–2080	348	294	− 7	− 12
2080–2090	349	294	− 7	− 12

all iterations and all years. For each ensemble of 250 runs in every scenario, the proportion was determined of runs that predict a macrophyte-dominated state (> 30% vegetation coverage in all years), a phytoplankton-dominated state (< 10% vegetation coverage in all years) and intermediate states with macrophyte development or macrophyte loss (an increase or decrease of 15% in vegetation coverage in any given year).

For the MPI-scenarios, annual average TP, DIN and Chl-a concentrations in PCLake were calculated for 2020–2089 by taking the average of the 250 iterations for every time step while excluding the 2.5% largest and smallest results. For every year, the percentage of iterations that predicted macrophyte coverage above 50% or below 5% was also determined.

Results

Calibration

The relation between the simulated and observed total flow rate to Lake Mogan between 2000 and 2010 had a bR^2 of 0.50 and an NS-value of 0.44 (Table 2). During the calibration period (2000–2005), a reasonably good fit was obtained (Fig. 1) with an average observed flow rate of 0.23 $m^3\ s^{-1}$ and a simulated flow rate of 0.31 $m^3\ s^{-1}$ ($bR^2 = 0.47$, NS = 0.57). During the validation period, the observed flow rates were much lower at 0.12 $m^3\ s^{-1}$ and the simulated model overestimated flow rates ($bR^2 = 0.65$, NS = -0.08), especially in the Çölovası subbasin.

SRP and NO_3 loading to the lake were simulated reasonably well by the model (Fig. 1). The average monthly observed SRP load was 72 kg, and the model simulated 77 kg ($bR^2 = 0.21$, NS = 0.31). Simulated monthly NO_3 loading was 739 kg-N compared with the observed 846 kg-N per month ($bR^2 = 0.23$, NS = 0.01).

The calibrated model for Lake Mogan in PCLake included 90% of macrophyte coverage observations and 81% of Chl-a measured values. With regard to the lake nutrient concentrations, 63% of SRP, 41% of TP, 56% of NH_4 and 59% of NO_3 measurements were included in the simulation bands, respectively (Fig. 2).

Scenario results

The SWAT results of the MPI-RCP4.5 and 8.5 scenarios are given in Table 3. Flow rates decreased in most decades compared with the baseline period, up to − 33% in the 4.5 scenario and − 60% in the 8.5 scenario. NO_3 and SRP loading were predicted to decline as well (− 15 to − 11% on average), although in certain simulated years, increased NO_3 and SRP loading were found even if inflow rates generally declined.

Table 2 Monthly performance statistics for the calibrated and validated SWAT model of the Lake Mogan basin

Period	Statistic	Flow rate	NO_3 load	SRP load
2000–2005	bR^2	0.47	0.14	0.26
	NS	0.57	− 0.08	0.00
2006–2010	bR^2	0.65	0.44	0.29
	NS	− 0.08	0.52	− 0.01
2000–2010	bR^2	0.50	0.21	0.23
	NS	0.44	0.31	0.01

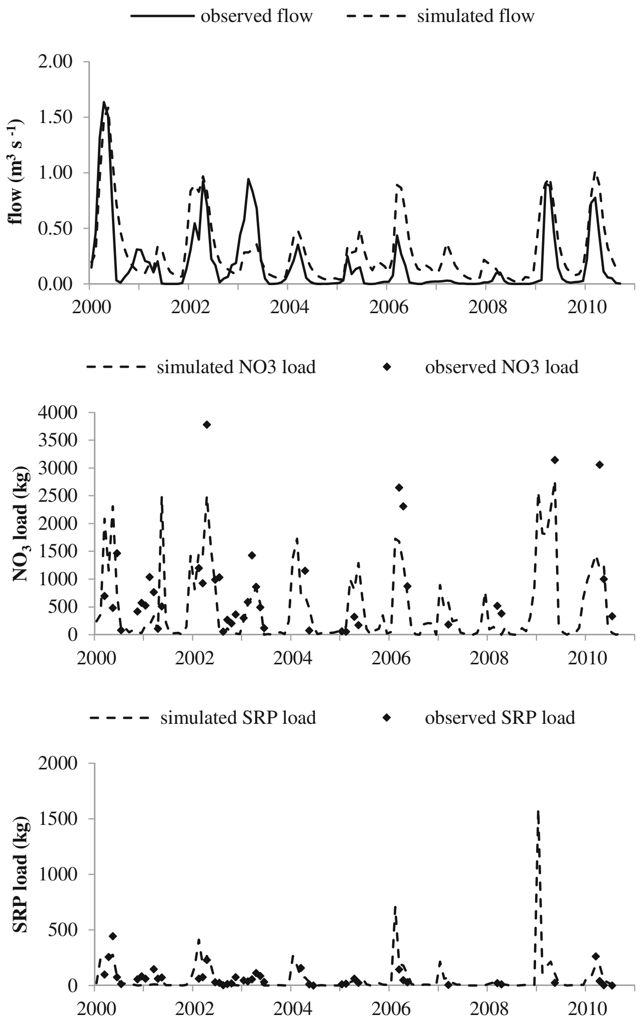


Fig. 1 Comparison between observed and simulated **a** monthly average flow rates, **b** monthly NO_3^- loading and **c** monthly SRP loading of the Lake Mogan basin. Calibration (2000–2005) and validation (2006–2010) are separated by a dashed black vertical line

This was due to large rainfall events during some years, leading to increased runoff and nutrient loading.

Based on the predicted flow rates and the outflow decision model, changes in mean water level were calculated (Appendix Fig. A.2). In the MPI-RCP 4.5 scenario, periods of low water levels were predicted on several occasions with water levels below 2 m, and especially between 2030 and 2040, a prolonged drought period was simulated. The MPI-RCP 8.5 scenario predicted four severe drought periods under 2 m and two occasions where the lake dried out for 1–2 years between 2061 and 2080.

Results for the general climate scenarios in SWAT are shown in Fig. 3. Average flow rates to the lake decreased with increasing temperature and decreasing precipitation to a minimum of 16% of the baseline flow in the E1 scenario. An increase in flow is expected if precipitation increases by 10% or if mean annual temperature decreases by 1 degree. Maximum monthly flow rates changed to the same extent as average flow rates with a decrease to 17% of the baseline scenario in the E1 scenario. NO_3 loading was mostly determined by runoff and therefore more linked with changes in precipitation than with changes in temperature. All of the precipitation decrease scenarios resulted in a reduction of NO_3 loading to around 45% in case of a 30% decrease in precipitation. SRP loading declined in almost all scenarios to a minimum of 8% of the baseline loading in the E1 scenario.

The results of the MPI scenarios in PCLake are shown in Figs. 4 and 5. Results for the MPI-RCP8.5 scenario are only given until 2060 before the scenario predicted the lake to dry out. The MPI-RCP8.5 predicted higher cyanobacteria biomass. Abundance of piscivorous fish and zooplankton was related to macrophyte coverage. The P content of the sediment decreased in both scenarios for two decades and then increased steadily again to starting levels.

Figure 6 shows the changes in mean water level in the general scenarios. The results show decreasing water level with increasing temperature (A–E) and decreasing precipitation (5–1) and drying out of the lake in many scenarios. Both in-lake TN and TP increased with increasing temperature (and thus decreasing water level), while differences between the precipitation scenarios were small (Fig. 6). The proportion of runs predicting a macrophyte-dominated state did not change much between the scenarios (Fig. 6).

Discussion

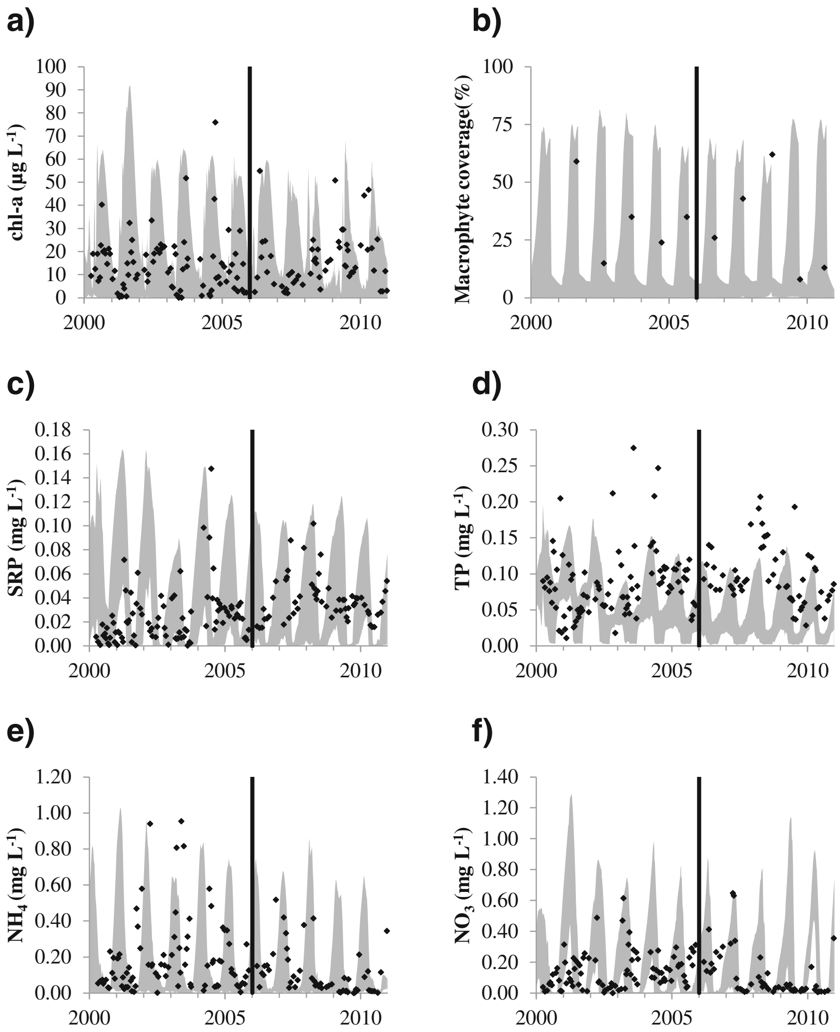
We used a holistic modelling approach linking catchment modelling and lake modelling to study the effects of potential future changes in temperature and precipitation on the water level, nutrient and Chl-a concentrations and coverage of macrophytes in Lake Mogan. Climate scenario projections and stepwise temperature and precipitation scenarios were assessed.

Results of the catchment model

Our results show that lake inflow rates in this semi-arid climate can decline by up to 60%, with an average decline of 15–27% depending on the RCP projection, leading to major drops in water levels and even potential drying out of the lake. Furthermore, the model predicted drops in NO_3 and SRP loading to the lake due to reduced runoff and diminished groundwater flow. General delta change climate scenarios showed that inflow flow rates decreased with increasing temperature and decreasing precipitation, while the NO_3 and SRP load responded mostly to changes in precipitation.

The results of the catchment model for the warmer and drier climate scenarios predicted lower flow rates in the streams, lower runoff and lower nutrient loading, and this is

Fig. 2 Performance of the PCLake model for Lake Mogan against observed values of **a** Chl-a, **b** macrophyte coverage, **c** SRP, **d** TP, **e** NH_4^+ and **f** NO_3^- Grey bands represent the daily range between the 2.5th percentile and the 97.5th percentile based on 250 iterations of the model with parameter values inside the calibration ranges



in line with the results of other studies undertaken in the Mediterranean climate zone (Nunes et al. 2008; Molina-Navarro et al. 2014; Bucak et al. 2018). The large decreases or increases in flow rates with modest changes in precipitation correspond with observations from the 1997–2010 reference period, with, for example a 25% precipitation decrease from 2006 to 2007, leading to a 80% reduction in the inflow to the lake (Coppens et al. 2016). Lower nutrient loading during this period with lower hydraulic loading was also supported by observations made between 1997 and 2010, showing lower runoff and reduced groundwater flow to the lake (Coppens et al. 2016).

Table 3 Average results per decade from the SWAT-model on Lake Mogan basin for the MPI-RCP 4.5 and MPI-RCP 8.5 scenarios (2020–2090)

Period	MPI-RCP 4.5			MPI-RCP 8.5		
	Flow rate change (%)	NO_3 load change (%)	SRP load change (%)	Flow rate change (%)	NO_3 load change (%)	SRP load change (%)
2020–2030	− 23	− 22	− 41	− 43	− 31	− 63
2030–2040	− 33	− 24	− 49	− 28	− 26	− 38
2040–2050	− 10	− 7	− 26	− 11	− 11	− 15
2050–2060	− 18	− 21	− 10	− 11	+ 9	− 1
2060–2070	+ 7	− 3	+ 35	− 60	− 42	− 66
2070–2080	− 18	− 5	− 7	− 35	− 24	− 31
2080–2090	− 13	+ 2	+ 23	− 4	+ 23	+ 114

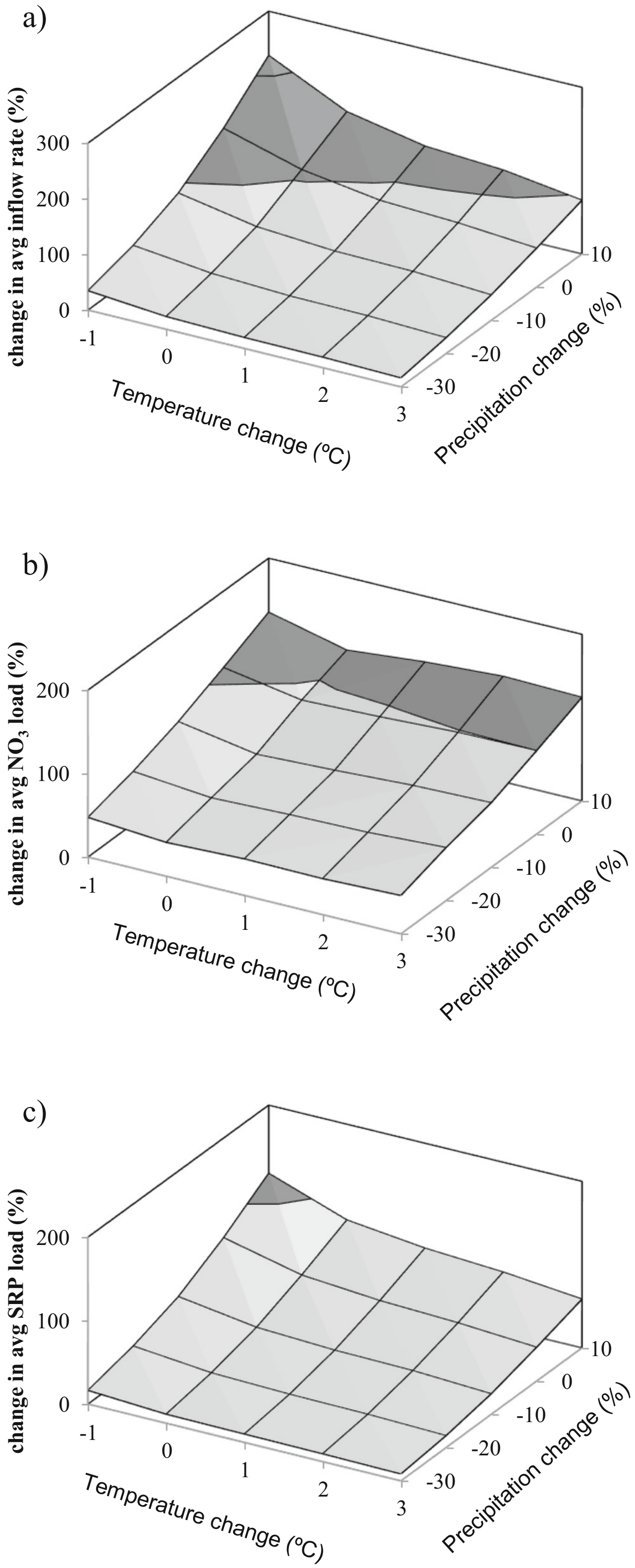


Fig. 3 Results of SWAT for the general scenario consisting of a change in mean daily air temperature and annual precipitation. Shown are the relative change in average **a** inflow rate, **b** annual NO_3^- load and **c** annual SRP load. Dark grey shading represents simulated values larger than the baseline model, while light grey shading shows simulations with values smaller than the baseline model

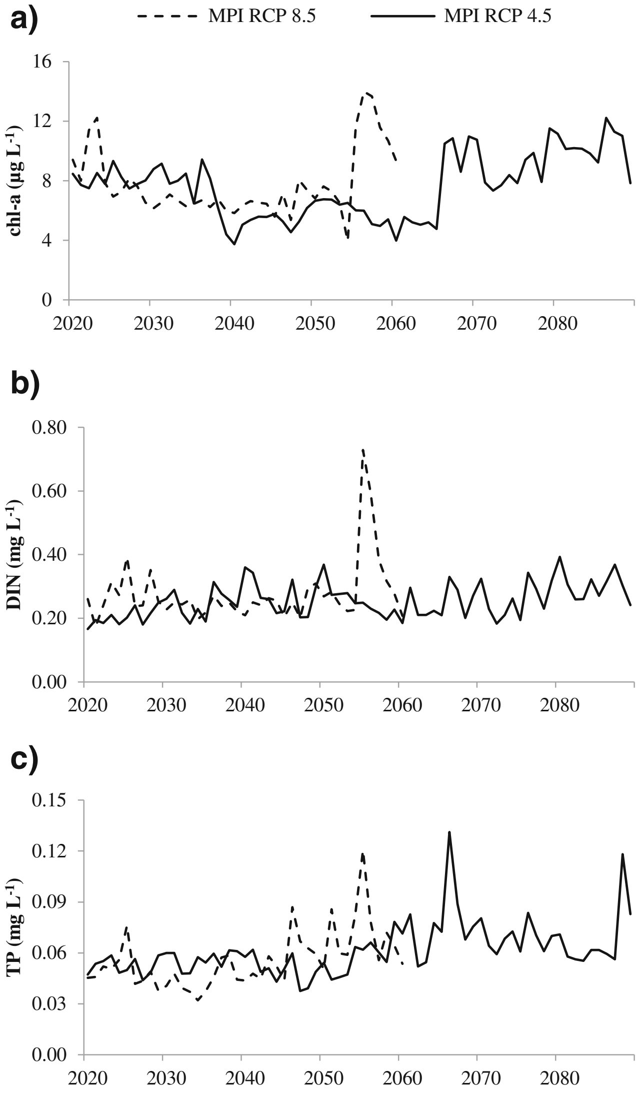


Fig. 4 Predicted **a** Chl-a, **b** DIN and **c** TP concentrations in the PCLake model of Lake Mogan for the MPI-RCP4.5 (line) and MPI-RCP48.5 (dashed line) scenarios (2020–2090); in the MPI-RCP48.5 scenario, the lake dries out after 2060

Lower runoff in the climate scenarios caused by lower precipitation was the principle cause of lower nitrate loading, which is in accordance with the results of Panagopoulos et al. (2011) and Bucak et al. (2018). On the other hand, inflow nitrate concentrations increased because inflow volumes decreased to a larger extent. Simulated SRP inflow concentrations did not vary much between the different scenarios. SRP loading decreased and seemed to be more associated with lateral groundwater flow than with surface runoff. Similar decreases in SRP loading have been found in Bucak et al. (2018) and Shrestha et al. (2017). The MPI-RCP projections show an enhanced nutrient loading in certain decades, even when average flow rates do not increase, probably caused by more extreme rainfall events that lead to higher runoff and nutrient loading.

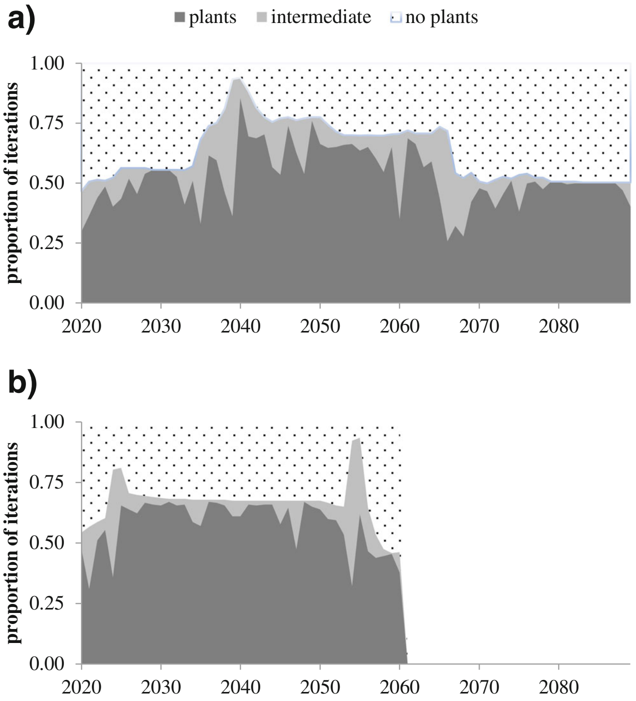


Fig. 5 Percentage of iterations predicting **a** submerged plants (> 30% submerged plant coverage) or **b** no plants (< 10% macrophyte coverage) for the **a** MPI-RCP4.5 and **b** MPI-RCP 8.5 scenario (2020–2089); in the MPI-RCP 8.5 scenario, the lake dries out after 2060

Results of the lake model

The results of the lake model PClake exhibited similar predictions in N, P and Chl-a concentrations in both RCP scenarios. Sharp increases in nutrient concentrations were predicted when water levels dropped unless nutrient loading decreased as well to compensate it. Higher precipitation lead to higher water levels and can cause a decrease in plant coverage and an increase in Chl-a concentrations. Prolonged periods of low water levels seemed to encourage macrophyte development. Twenty years of monitoring of Lake Mogan, which covered both wet and dry periods, found similar results: drought periods with low water levels were associated with macrophyte dominance, whereas during wet periods, the lake water level was high and macrophyte coverage was sparse, and concentrations of Chl-a were high (Beklioğlu et al. 2017). Similarly, no strong effect of increased nutrients on submerged macrophyte development was observed in the general scenarios, probably due to the compensating effect of water level reduction that overrides the high availability of nutrients as has been shown in mesocosm studies from Turkey (Özkan et al. 2010; Bucak et al. 2012). The results of the general scenarios confirm the risk of drying out of the lake with changes in precipitation and temperature. This might be inevitable as was also found for the largest freshwater lake in Turkey, Lake Beyşehir (Bucak et al. 2017). The general scenario also indicated higher TP and TN with increasing temperature. This was the opposite

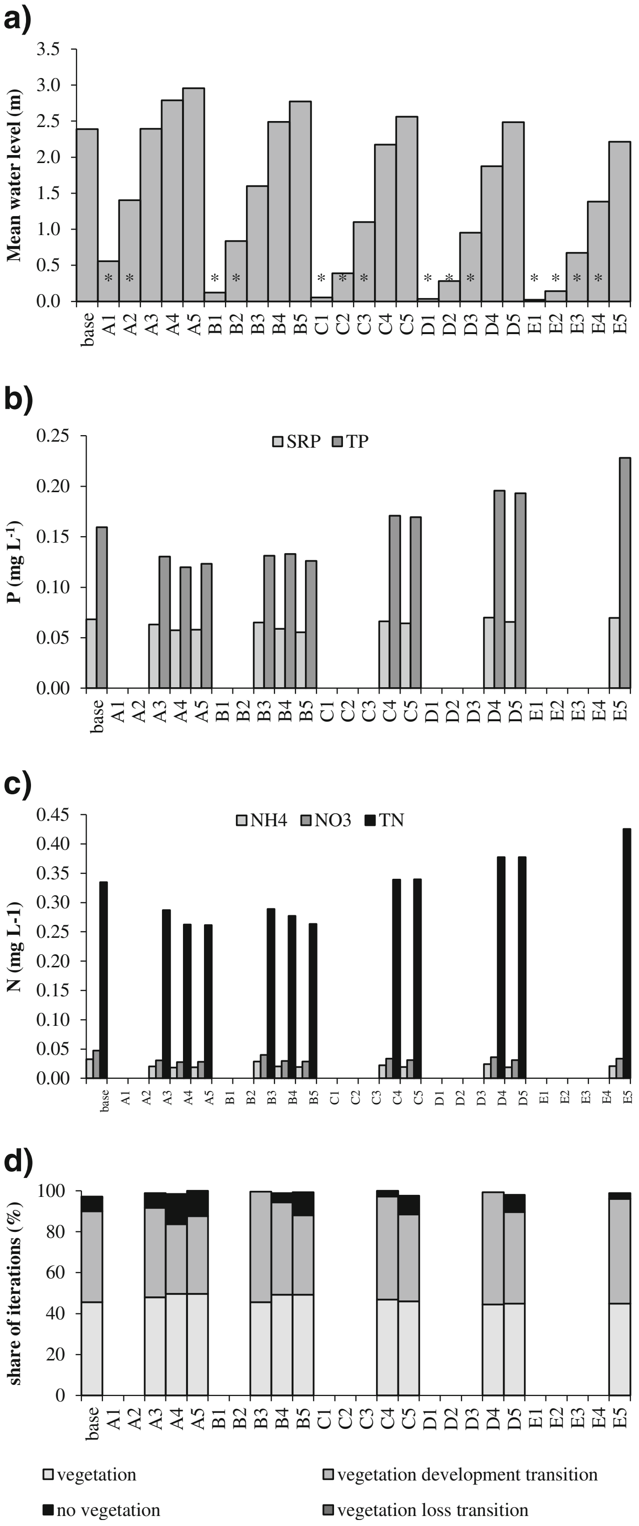


Fig. 6 **a** Mean water level, **b** P and **c** N concentrations and **d** vegetation development states for the baseline simulation and the general scenarios for the baseline simulation and the general scenarios: a combination of five temperature scenarios (A–E: − 1 °C, 0 °C, + 1 °C, + 2 °C, + 3 °C) and five precipitation scenarios (1–5: − 30%, − 20%, − 10%, 0, + 10%) (asterisk marks scenarios predicting lake dry out at some points during the 10-year simulation)

of Lake Beyşehir, perhaps because this lake is currently in an oligo-mesotrophic state (Bucak et al. 2018).

The peaks in Chl-a, P and N in Lake Mogan projected by the MPI-RCP4.5 and 8.5 scenarios are caused by periods of low water levels with higher internal loading and lower plant biomass as well as periods with high water levels and high external loading. The general scenario results of the PCLake model can be explained by the increase in phytoplankton biomass, particularly cyanobacteria at higher temperature (Paerl and Huisman 2008), leading to higher biomass and higher organic N and P.

Model performance and evaluation

The calibration performance of SWAT was within the acceptable standards based on the review made by Moriasi et al. (2007), with an NS-estimate near 0.50 for the entire 2000–2010 period. A better calibration fit was probably hindered by a combination of factors, mainly related to the largest subbasin, Çölovası. The Çölovası stream connects with the lake through a wetland area. Water loss through evaporation from this wetland area was underestimated by SWAT, which consequently led to overestimation of flow rates especially during the dry years. The two reservoirs in the Çölovası subbasin also had an unknown water release regime during the calibration period that might have complicated the modelling of the flow contributions from large parts of the subbasin. During winter periods with high precipitation, the lake also expanded through the wetland area up to the Çölovası sampling station of the monitoring programme, causing low flow rates, a phenomenon that could not be incorporated into the SWAT model. For this reasons, the calibration was first focused on the Yavrucak and Sukesen subbasin to fix the basin-wide parameters and later applied to the Çölovası subbasin to obtain the best fit for total inflow to the lake. Furthermore, the calibration approach used in this study for the catchment with SWAT resulted in one set of values for every parameter for the calibrated subbasins. This deterministic approach can fail to take into account uncertainty related to the available data and knowledge about the characteristics of the catchment, and this uncertainty should be considered when interpreting the results of the model.

A potential caveat of our study is that the scenarios did not include any changes in any other primary meteorological parameters except temperature and precipitation. Water temperature in the climate scenarios was only affected by air temperature. This may cause the increase in water temperature to be underestimated since not only increases in air temperature but also the increase in solar radiation by itself (Schmidt and Köster 2016) and the decrease in wind speeds with climatic warming (Woolway et al. 2019) cause higher water temperatures. This would cause even higher evaporation and would likely lead to an increased risk of drying out of the lake. Furthermore, land use changes were not incorporated into this modelling study, which focuses on providing insight into the effects of changes in climate. However, changes in land use in the next 70 years will likely also have large effects on the hydrology and nutrient loading in the catchment and can both mitigate or enhance the effects of changes in climate. Management practices can be adopted to reduce the nutrient loading from the catchment, although it should be noted that agriculture in the catchment is not intensive and fertilizer use is already low.

In contrast to the deterministic calibration of the SWAT model, a more stochastic approach was used for PCLake, following Nielsen et al. (2014). The main reason was the difficulty in modelling the fast year-to-year changes in submerged macrophyte coverage in Lake Mogan with PCLake. The model was originally developed to model the dynamics of changes between a clear water state with macrophyte dominance and a turbid water state with phytoplankton dominance in northern temperate lakes as a response to changes in nutrients and light availability (Janse and Van Liere 1995). In this case, PCLake was applied to a cold semi-arid climate with prolonged drought periods. In shallow semi-arid lakes, water level fluctuations play an important role in determining macrophyte occurrence (Havens et al. 2004; Coops et al. 2003; Beklioğlu et al. 2006; Beklioğlu et al. 2017; Bucak et al. 2018), both directly through the changes in area available for submerged plant growth at different water levels and indirectly through the effect on nutrient concentrations in the water column. PCLake in its current form reduces the lake to a 0D water column and determines plant biomass for one standard square meter before converting it to an estimate of total plant coverage in the lake. In a lake with V-shaped morphometry, like Lake Mogan, the area available for plant coverage fluctuates relative to light penetration and water depth, and the current 0D approach of PCLake cannot adequately capture these processes. Therefore, we did not aim to model the yearly changes in macrophyte coverage exactly but rather to create a simulation band including both runs with and without macrophytes. The new Framework for Aquatic Biogeochemical Models (FABM) approach to PCLake allows taking multi-dimensional differences in the lake into account and might remedy this problem (Hu et al. 2016). Other new versions in the second generation of PCLake also hold promise (Janssen et al. 2019; Chen et al. 2020) to allow to account for stratification. While Lake Mogan is a shallow lake that rarely stratifies, in a warmer and drier climate, temporary stratification might increase and this will have effects on the nutrient dynamics and likely lead to higher internal loading and eutrophication.

The calibration of the PCLake model was moderately successful. Thus, the model was able to incorporate many of the observed values, but the simulation band was wide, even though parameters did not vary more than 20% from the default value. This indicates that a few parameters, mostly related to macrophyte and phytoplankton growth, can have a very large effect on the modelled nutrient concentrations.

PCLake is focused on the food web structure in northern temperate lakes, but the food web structure in warmer lakes is markedly different from that in colder lakes (Meerhoff et al. 2007a; Meerhoff et al. 2007b). Although the effect of macrophyte biomass or fish biomass on zooplankton was incorporated into the model, changing the relevant parameters did not have a significant effect on the model outcome, nor did it improve calibration of Chl-a. This may be because the refuge effect of macrophytes was not important for zooplankton abundance in Lake Mogan since Tavşanoğlu et al. (2012) showed that the sediment is a more important refuge in Mediterranean lakes or that the top-down effects on zooplankton in PCLake are underestimated.

Conclusions

Our linked approach of catchment modelling and lake modelling demonstrates the threats to shallow lakes in the Mediterranean semi-arid climate region caused by the global climate change. Reduced precipitation and increased temperature in combination with higher evaporation create lower inflows to lakes, higher water loss and an increased risk of low water levels and even complete drying out. Due to reduced runoff, nutrient loading from diffuse sources is expected to decrease, though extreme events with high precipitation may lead to enhanced external loading to the lake. Lower inflow rates cause low water levels and nutrient concentrations increase due to evaporation unless nutrient loading decreases proportionally. Submerged macrophyte development increases under low water level conditions, but higher nutrient concentrations and higher temperatures lead to higher phytoplankton biomass. These results show that under a warmer and drier climate, control of nutrient inflows is essential to protect the shallow lake ecosystems. While diffuse nutrient loading may decrease due to lower precipitation, the effect of point sources may be critical. Further research including salinity, spatial development of macrophytes and changes in the food web is necessary to be able to undertake more accurate model projections on the impact of climate change on warm shallow lakes.

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