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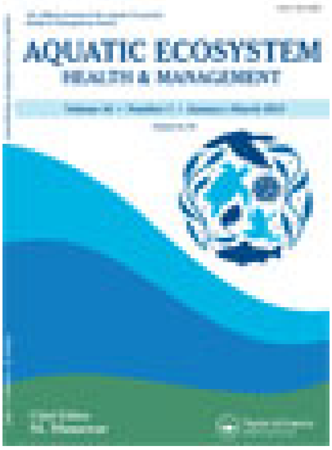

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Impact of climate change on the hydrology of shallow Lake Trasimeno (Umbria, Italy): History, forecasting and management

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Impact of climate change on the hydrology of shallow Lake Trasimeno (Umbria, Italy): History, forecasting and management

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Lake Trasimeno is the largest lake of the Italian Peninsula. Because of the small extent of its watershed, meteorological conditions have caused dramatic floods and droughts over the centuries. Although numerous attempts have been made to regulate the lake level since Etruscan or Roman times, the problems related to water level changes remain unsolved, and the recently adaptive management strategies seem to be ineffective in the current climatic conditions. This study evaluates past and future management scenarios with the aim of identifying effective strategies to limit the lake level fluctuations. A lumped hydrological model, which incorporates climate forcing and water regulation policies adopted currently and in the past, is calibrated and validated using a fifty-year data series. Future scenarios (present–2090) of water level change are simulated on the basis of IPCC (Intergovernmental Panel on Climate Change) regional projections for precipitation and temperature. Possible mitigation measures, such as those involving the enlargement of the catchment basin, the water diversion from nearby dams and the adoption of more restrictive rules on abstractions are also considered. The model indicates that critical prospects emerge if the intermediate or the maximum rates of change estimated by global climate models are assumed. Under these circumstances, currently feasible mitigation measures seem effective in preventing severe water shortage in the next decades, but ineffective in preventing the drainage of the lake in the second half of the century. We recommend that plans for water resource management should be put in place as a matter of urgency to ensure the conservation of the hydrologically vulnerable Lake Trasimeno.

Keywords: hydrological model, water resource management, drought

Introduction

Climate change can exert severe pressures on shallow water systems, given that their hydrological, thermal and hydrochemical regime is strongly influenced by meteo-climatic conditions. Drought, warming, salinisation and water quality changes, often amplified by water use and pollution, have been experienced over the last decades in shallow water systems of Central Africa (e.g. Lake Chad and Lake Tonga; UNEP, 2006), south eastern Europe (e.g. Lake Balaton and Lake Velence; Wantzen et al., 2008) and south eastern Australia (e.g. Lake George), where climate-driven drought risk is

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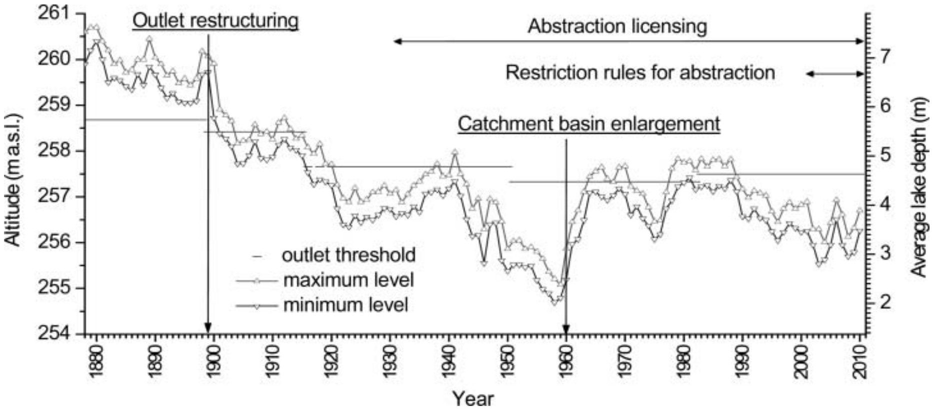

Figure 1. Annual maximum and minimum water levels at Lake Trasimeno and management interventions from 1878 to 2010 (data were partially extracted from Gambini [2000]).

considered most significant (Bates et al., 2008). The effects of drought on water quality are expected to accelerate as a system approaches evaporative conditions (closed basin and water losses exceeding water supplies). In these conditions, the water level decreases and the renewal time of the lake increases, thereby inducing a series of changes that affect the lake functioning. As drought progresses, the water recedes from the littoral zone, stranding some of the littoral flora and fauna (Balogh et al., 2008; Furey et al., 2006; Gaino et al., 2012). The reduced renewal rate causes salt accumulation and the lowering of water level is generally accompanied by an increase in wind-induced turbidity and a reduced dilution of the nutrient inputs. Catastrophic transitions toward more eutrophic conditions (sensu Scheffer, 1998), may also be expected as a consequence of reduced depth and changes in the nutrient dynamics. The change of nutrient concentration and dynamics may boost massive blooms of—possibly toxic—cyanobacteria and algae, thus increasing the risk of anoxic crisis, which stress the aquatic fauna and promote the proliferation of microorganisms potentially harmful to human health. The evaluation of the potential impacts of current climate change on the hydrology of shallow water systems is therefore of relevance from scientific, conservation and health perspectives.

Lake Trasimeno (Umbria, Italy) is a shallow meso-eutrophic lake of a considerable conservation importance (Site of Community Interest, Special Protection Zone and Regional Park). Because of the small catchment (261.9 km^2) with respect to the lake area (121.5 km^2), the water balance of the lake is heavily dependent on precipitation inputs (Dragoni, 1982, 2004). Dramatic floods and droughts have occurred over the centuries and management interventions have been made to regulate the lake level since Etruscan or Roman times (Gambini, 2000; Dragoni, 2004). The outlet restructuring undertaken at the end of the 19th century and the subsequent displacement of the artificial outflow threshold led to a dramatic hydrological crisis in the 1950s (Figure 1). Some ecological consequences of the crisis were described by Moretti (1982), who reports a significant expansion of the macrophyte bed, a massive proliferation of cyanobacteria (*Microcystis*), planktonic (*Peridinium, Gymnodinium*) and epiphytic (*Gloeotrichia*) algae during summer, to which followed the occurrence of anoxic conditions at the lake bottom, with a severe stress on the ichtyofauna, particularly on the indigenous roach (*Rutilus rubilio*).

The enlargement of the catchment basin in 1957–1962 allowed the lake to rapidly recover from drought, but seems to be ineffective in the current climate change phase (Dragoni, 2004). The lake level is currently in a low phase and the maintenance works on the inflowing rivers, as well as the restriction rules on abstraction recently adopted seem insufficient to restore the water level to the outlet threshold. The recent water crisis encouraged the local authorities to consider further interventions, which include the further enlargement of the catchment basin (Casadei et al., 1993) and water diversion from nearby dams (Ubertini et al., 2007).

To assist decision-makers on the adoption of proposed projects, a thorough evaluation of the amount of water (if any) necessary for ensuring the long-term maintenance of the water level is required. This requires the generation of realistic scenarios of future regional changes of the main meteorological variables (precipitation and temperature) that affect the water balance of the lake. In this study, following calibration and validation of a lumped hydrological model (Ubertini et al., 2007), we use one widely employed climate change scenarios for simulating the water level changes in Lake Trasimeno during the current century. Several intervention measures are also combined with climate change scenarios to evaluate their effectiveness in mitigating the effects of the climate change on the lake water level.

Methodology

Monthly water level change in Lake Trasimeno (A_m - mm) was calculated using the following hydrological lumped model (Ubertini et al., 2007), assuming the complete impermeability of the substratum:

$$A_m = \frac{(P_s \cdot S_s + P_b \cdot S_b \cdot C)}{S_s} - E - \frac{V_d + V_a}{1000 \cdot S_s}, \tag{1}$$

where P_s and P_b are the monthly precipitation (mm) over the lake area (S_{s}) and over the watershed area (S_b), respectively, and C is the monthly run-off coefficient, which is the calibration parameter of the model (in the calibration phase, C is allowed to vary between 0.1 and 0.8). E represents monthly evaporation from the lake surface (mm), calculated by the equation derived by Dragoni and Valigi (1994) for lakes located in Central Italy:

$$E = 19.007 \cdot i_m^{3.063} \cdot T_m^{0.486}, \tag{2}$$

where i_m is the Thornthwaite insolation monthly index (43° N latitude) and T_m is the monthly average air temperature. In Equation (1), V_d is the monthly water volume (m^3) flowing through the lake outlet once the overflow level (257.8 m a.s.l.) is reached and V_a (m^3) is a term accounting for agricultural abstraction, estimated from data provided by Local Administration offices. Three main abstraction phases were identified, depending on the policy adopted: years 1963–1989 (90 mm years^{-1} - in terms of water level reduction), years 1990–1999 (60 mm years^{-1}); years 2000–2010 (30 mm years^{-1}).

The long-term time-series of water levels in Lake Trasimeno was generated from the literature (Dragoni, 1982) and from the Umbria Region database. The precipitation and temperature data series utilised for the calibration and validation of the hydrological model were collected at several public meteorological stations located within the lake basin (Casadei et al., 1993) and published in the yearbooks of the Italian Ministero dei Lavori Pubblici. The data were first checked by cross validation and, after the removal of erroneous data, monthly series were calculated and homogenized by Craddock's homogeneity test (Brunetti et al., 2006; Ludovisi and Gaino, 2010). Min-max monthly series of air temperature collected in a station located near the shoreline of the lake (Monte del Lago) were then averaged for arranging the air temperature series.

The future temperature and precipitation scenarios were constructed by using IPCC projections for Southern Europe and Mediterranean - A1B scenario (Table 1), as follows: the monthly data of the reference period (1980–1999) were replicated several times from the end of the reference period to 2090, and the predicted changes, differentiated by season, were added to the replicated series by assuming a constant rate of change. Three series of predictions were generated by considering the median (Med), the minimum (Min) and the maximum (Max) projections reported in Table 1. Among the possible scenarios arising from the combination of precipitation and temperature changes, we considered two "extreme" scenarios, together with median one:

Scenario 1: Median Temperature and Median precipitation (TMed-PMed);
Scenario 2: Minimum temperature and Maximum precipitation (TMin-PMax);
Scenario 3: Maximum temperature and Minimum precipitation (TMax-PMin).

The above configuration allows us to explore the range of meteorological changes offered by the combination of IPCC projections and to give a measure of the uncertainty associated with IPCC median projections.

With the aim of examining the impact of different water resource management measures, the above scenarios were combined with the following mitigation measures:

Mitigation 1: Maintenance of the restriction rule on abstraction at 30 mm year^{-1};

Table 1. IPCC projection for temperature and precipitation changes in southern Europe and Mediterranean (30–48 N; 10W-40E) for the A1B scenario (IPCC, 2007). The table shows seasonal and annual minimum, maximum and median predictions obtained from a set of 21 global models. Predicted changes of temperature (°C) and precipitation (%) are for the period 2080–2099 with respect to the averages 1980–1999. The signal is assumed to increase linearly with time.

	Temperature response (°C)			Precipitation response (%)		
Season	Minimum	Median	Maximum	Minimum	Median	Maximum
DJF	1.7	2.6	4.6	−16	−6	6
MAM	2.0	3.2	4.5	−24	−16	−2
JJA	2.7	4.1	6.5	−53	−24	−3
SON	2.3	3.3	5.2	−29	−12	−2
Annual	2.2	3.5	5.1	−27	−12	−4

Mitigation 2: Maintenance of the restriction rule on abstraction at 30 mm year^{-1} + 6 Mm^3 year^{-1} of water input from external basins;

Mitigation 3: Abolition of abstraction licensing + 10 Mm^3 year^{-1} of water input from external basins.

Results

Model calibration and validation

The calibration phase, performed on data from 1963–1999, produced monthly average run-off coefficients *C* between 0.25 and 0.39, with the maximum values in January and the minimum values in July and November. These values agree with those obtained in previous investigations (Dragoni, 2004). The mean error between observed and predicted values during the calibration period (Figure 2) is 1.3%, with only 3% of cases exceeding 5%. The mean error is lower than the instrumental uncertainty associated with the measurement of the water level.

In the validation period (2000–2010), the estimates closely match the observed data, except in the years 2002–2005 (Figure 2). This may be due to two specific anomalous weather events: the very dry summer of 2002 and flood events in November-December 2005. During these events, the calibrated average runoff coefficients were inadequate to quantify the water inflow from the watershed: in fact, the run-off coefficients calculated on the basis of observed data are very unusual in these periods: $C = 0.10$ in summer 2002 and $C > 0.60$ in November and December 2005. However, the opposite effect

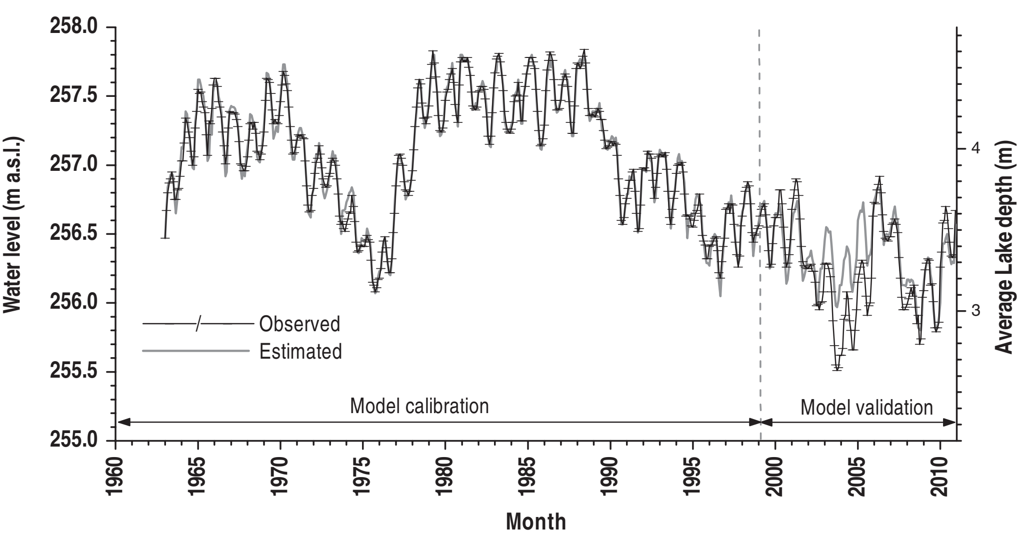

Figure 2. Comparison between observed and estimated water levels in Lake Trasimeno from 1963 to 2010. The hydrological model was calibrated using the observed data from 1963–1999 and tested on observed data from 2000–2010.

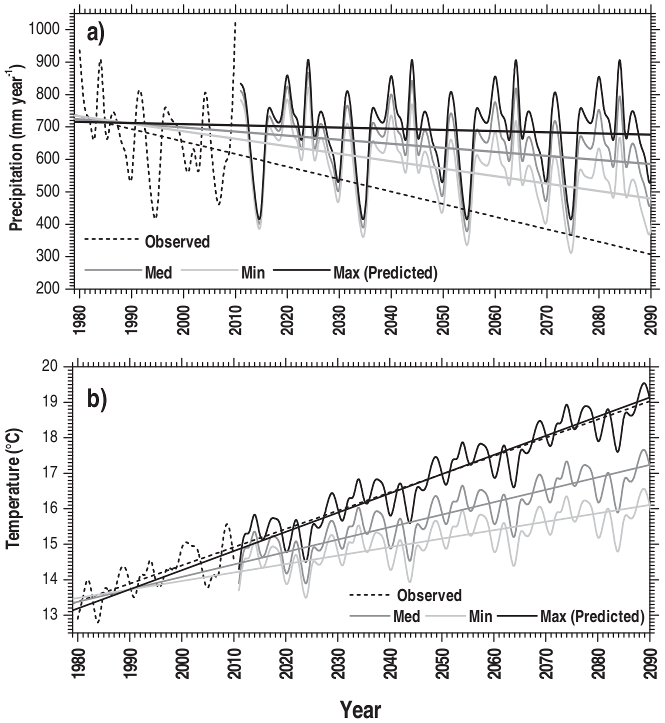

Figure 3. Observed and predicted trends of annual precipitation (a) and average air temperature (b) in the Lake Trasimeno basin in the period 1980–2090. Predictions were generated on the basis of IPCC's projections for southern Europe and Mediterranean, using seasonal median (Med), minimum (Min) and maximum (Max) rate of change obtained from a set of 21 global models for the A1B scenario.

of these anomalies turned out to be compensated at the end of the validation period (Figure 2), thus supporting the reliability of the adopted model in long-term simulations.

Model predictions in the climate change scenario

Observed and predicted trends of precipitation and temperature in the Lake Trasimeno basin are shown in Figure 3. For air temperature, the increasing linear trend observed over the last thirty years is significant (slope $= +0.5$ °C decade^{-1}; $R = 0.62$; $p < 0.001$) and agrees well with the maximum increase predicted by the global models considered by IPCC (Table 1). For precipitation, the trend found by linear regression is poorly significant (slope $= -38.6$ mm decade^{-1}; $R = -0.2$; $p = 0.28$), but suggests a tendency more negative than IPCC's projections (Table 1). The observed patterns are consistent with the results obtained by a progressive trend analysis performed at a National scale in Italy (Brunetti et al., 2006): the analysis highlights a rate of change for temperature of about $+5$°C century^{-1}, and a rate of change for precipitation of about -30% century^{-1} (corresponding to about -36 mm decades^{-1} for the Lake Trasimeno basin) in the last thirty years of the 20th century. The National trends are significant at 95%.

The simultaneous changes in precipitation and temperature produce significant modifications to the hydrological balance of the lake. Based on the hydrological model presented, the water supplied by precipitation input (1126 mm years^{-1}) slightly exceeded the evaporation losses (1056 mm years^{-1}) in the period 1980–2010. When applying the model for forecasting the effects of predicted climate change, evaporation losses are estimated to balance water supplies in the current decade or in the next decade, if the "pessimistic" scenario (Scenario 3) or the median scenario (Scenario 1), respectively, come to pass. Only in the case of the "optimistic" scenario (Scenario 2) are evaporative conditions not expected

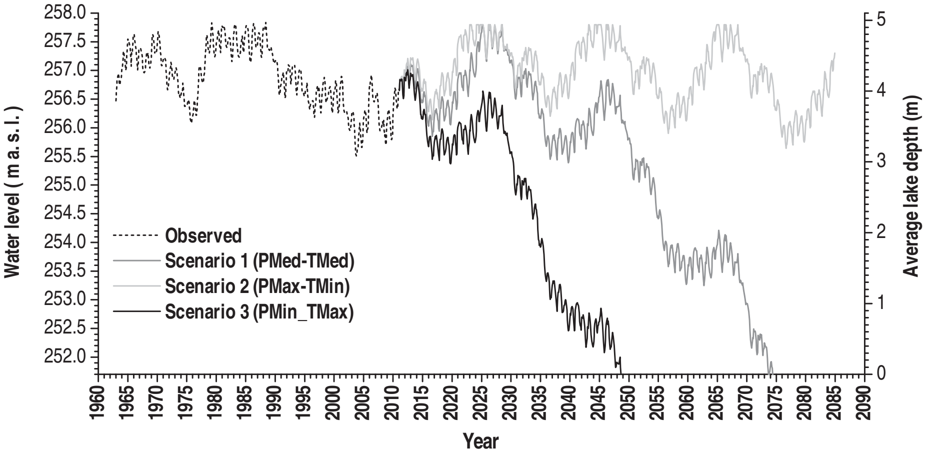

Figure 4. Observed and predicted trends of the water level in Lake Trasimeno in the period 1963–2090. Predictions encompassed a median scenario (Scenario 1) and two extreme scenarios (Scenarios 2 and 3) generated from IPCC's projections for southern Europe and Mediterranean (see Methodology section for explanation).

to dominate in the 21st century. The predicted patterns of water level changes are shown in Figure 4. Only under Scenario 2 is the water level expected to fluctuate within the current range without reaching critical conditions. On the other hand, Scenario 1 and 3 produce dramatic drought phases, with the complete drainage of the lake being predicted within decades.

It is important to note that none of these predictions includes impacts due to abstraction for agricultural use, which currently amount to about 30 mm year^{-1}. Figure 5 shows the predictions resulting from combining IPCC scenarios with the current and proposed mitigation measures (see Methodology section). A combination of the "optimistic" scenario (Scenario 2) with the current mitigation measure (Mitigation 1), requires no further measures to avoid critical drought phases over the next 90 years. On the other hand, for the median and the "pessimistic" scenarios (Scenario 1 and 3), intermediate and strong mitigation measures (Mitigation 2 and Mitigation 3) seem effective in preventing severe water loss in the next three or four decades, but completely ineffective in preventing the drainage of the lake in the second half of the century.

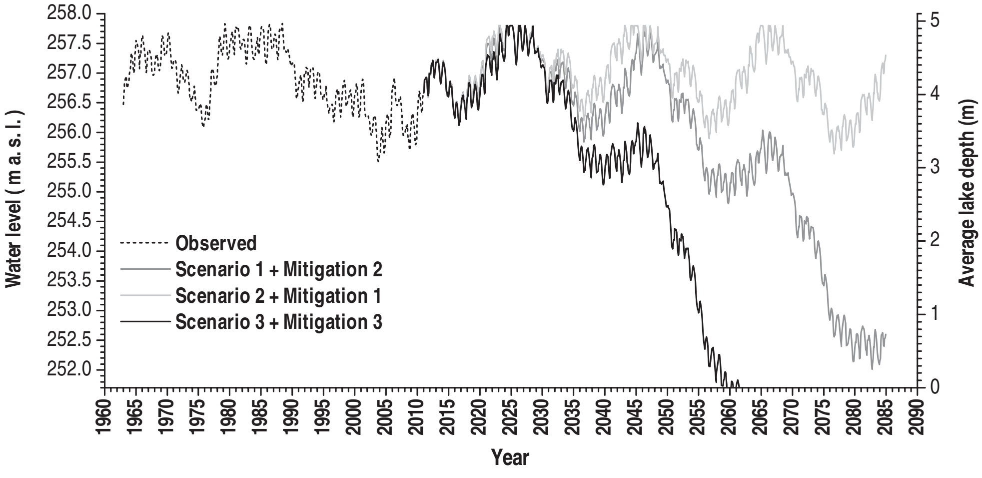

Figure 5. Lake level simulation combining IPCC future scenarios and the modelled mitigation measures (see Methodology section for explanation).

Conclusions

On the whole, the results highlight the extreme hydrological vulnerability of Lake Trasimeno in relation with climate change. The hydrological model here adopted shows that the hydrological regime of the lake closely matches the evaporative condition. This implies that relatively small shifts towards a drier climate are likely to have a dramatic impact on the lake level. Recent meteorological trends in the Lake Trasimeno basin show that the rates of change of precipitation and temperature are close to the most pessimistic IPCC climate change projections based on the A1B scenario. Given this, the hypothesis that Lake Trasimeno will experience extensive drought periods in coming decades must be taken seriously. The implementation of appropriate water management policies is therefore urgent to prevent or mitigate the impact of future climate changes on the water levels, as well as on the water quality and the biocoenosis of the lake. As shown by Ludovisi and Gaino (2010), the recent drought phase is accompanied by a significant reduction of the water transparency and by a significant accumulation of dissolved salt. Paleolimnological evidence (Gaino et al., 2012) suggests that the water level reductions during the 20th century have also endangered the spongofauna of the lake.

The model simulations show that management of inflows is likely required for long-term protection of the lake. However, where exogenous waters are directly piped into the lake, very detailed risk assessments are required to prevent potential chemical and biological contamination.

As in the past, the fate of Lake Trasimeno is entrusted to humankind and to the capacity of appropriate management to mitigate anthropogenic impacts, both at a local and global scale. The present study provides a framework for future and more focused investigations. More model flexibility is required to improve the accuracy of the predictions, especially in relation with extreme meteorological events, which are expected to occur more often in the future (IPCC, 2007).

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