

# Modelling hydrological characteristics of Mediterranean Temporary Ponds and potential impacts from climate change

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**Abstract** ‘Mediterranean Temporary Ponds’ (MTP) constitutes a priority, substantially vulnerable and unstable habitat (Natura code: 3170\*). In this article, the influences of climate change on the hydroperiod of two MTPs in Crete, have been quantitatively explored by using: (i) a physically based, semi-distributed lake basin model of Lake Kourna, where the hydrology of the lake is directly related to that of the adjacent MTP and (ii) a conceptual/mathematical model of an MTP in Omalos plateau. A water balance model was also set up to estimate net groundwater inflows for Lake Kourna and the basin. The water balance estimates and GIS tools were then used to set up the physically based model which was calibrated for the hydrological year 2005–2006 and validated for two periods: April–September 2005 and the

hydrological year 2006–2007 (two split-sample tests). Calibration of the mathematical model was very good, while for the physically based model calibration was satisfactory. The two models were then setup and simulated for two future Intergovernmental Panel for Climate Change (IPCC) scenarios: A2 (pessimistic) and B2 (more optimistic). The responses of Lake Kourna and Omalos MTP water levels and their hydroperiods were then predicted. Results for IPCC B2 and A2 climate scenarios show longer hydroperiod and smaller decreases in the future for Omalos MTP than in Lake Kourna MTP. Results for Lake Kourna MTP demonstrated a hydroperiod decrease of more than 52 days after the application of the IPCC scenarios. Scenario A2 does not present a significantly different higher impact on the MTPs’ hydroperiod.

**Keywords** Lake Kourna · Omalos · Mediterranean Temporary Ponds · Hydroperiod · Climate change

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## Introduction

The targets of the National Strategy for Sustainable Development, regarding the management of water resources in Greece, are related to the sustainable use of water resources, the efficient protection of water ecosystems and the attainment of high quality standards for all the surface and ground water bodies by the year 2015. The main sectors of action are climate change abatement; water resources management;

combating desertification; protection of biodiversity and natural ecosystems (MEPPW, 2004).

Mediterranean Temporary Ponds (MTPs) constitute a priority habitat (Natura code: 3170\*) in Annex I of the Directive 92/43/EC. This substantially vulnerable and unstable habitat exists in areas that, due to their specific characteristics, are under significant human and natural pressures and have become prone to extinction. The hydrology of MTPs can be characterised as self-adjusting and presents significant variations not only at the length of the ponds' hydroperiod but also at the start of their flooding period. These habitats often occur in small depressions with impermeable substratum and usually belong to a relatively small catchment area. They may also occur in karstic areas where groundwater flow originating from their catchment area results in the ponds' water level rise (Dimitriou et al., 2006). The point at which the pond passes into the dry phase depends on when the last significant rainfall or snowfall occurs in the region. According to Stamati & Nikolaidis (2006), the pond retains very small volumes of water for a day even with rainfall as low as 2 mm/day. The length of the hydroperiod defines the developing flora and fauna. These hydrological alterations are totally natural and as the water volume changes, the developing aquatic vegetation and invertebrates change, as well. During the pond's flooding, the aquatic habitat has available trophic resources, and the predatorial faunal activity is low. During the drought period, the higher faunal density leads to higher competition and appropriate conditions for predatorial activity (Collinson et al., 1995; Warwick & Brock, 2003; Grillas et al., 2004).

The threats that MTPs in Western Crete face are mainly due to human activities and interventions. Omalos MTP is frequented daily by many sheep and goats which use the pond for both watering and grazing, while Lake Kourna MTP is threatened by water abstractions as well as agricultural and grazing sources of pollution. Therefore, climate change constitutes an important factor to investigate to assess its relative potential impact on the MTPs' hydroperiod.

Hydrological models provide a framework to conceptualise and investigate the relationships between climate, human activities (e.g. land use changes in agriculture, urban areas, etc) and water resources and also to assess different management alternatives as well as land use and climate change scenarios.

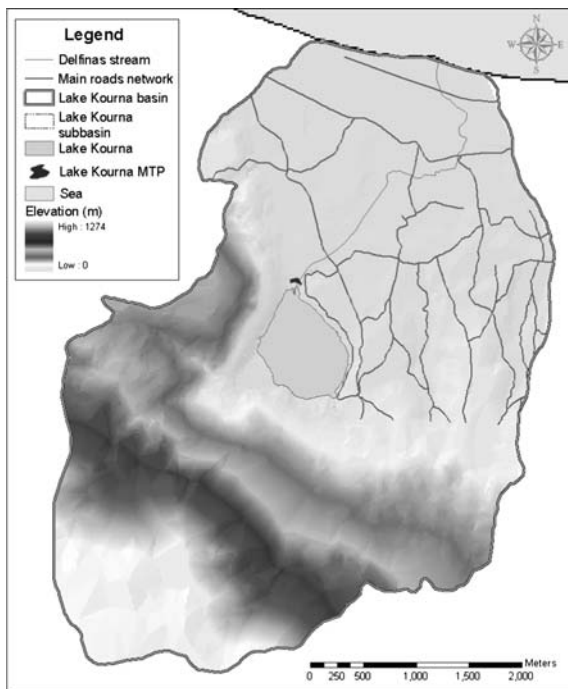
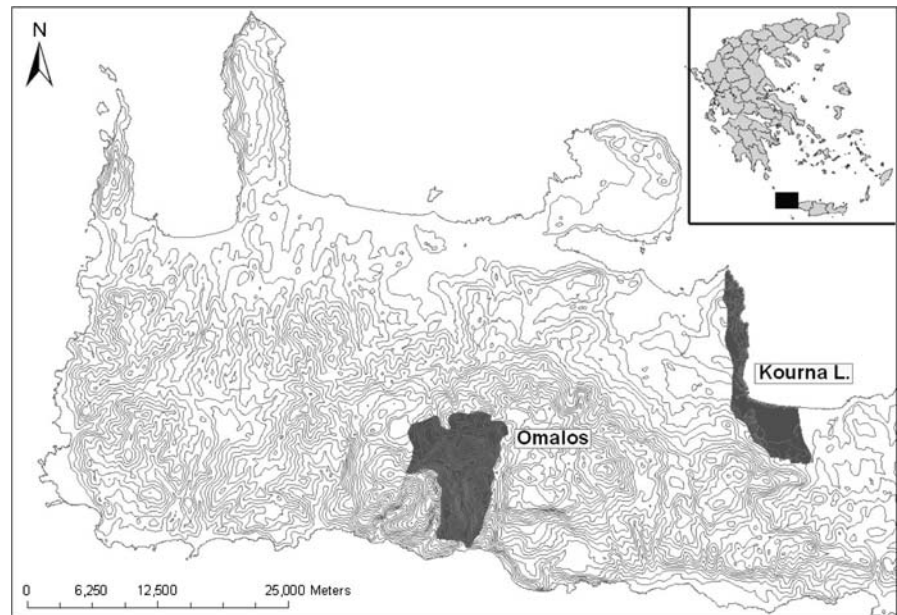
In this article, the main objective is to quantitatively explore the influences of climate change on the hydroperiod of two MTPs in Crete. For this purpose, two different hydrologic models have been used: (i) a physically based, distributed lake basin model in the case of Lake Kourna, where the hydrology of the lake is directly related to that of the adjacent MTP and (ii) a conceptual/mathematical model of an MTP in Omalos based on previous study by Stamati & Nikolaidis (2006). The effects of two IPCC climate scenarios on Lake Kourna and Omalos MTP water levels will then be investigated.

### Study areas

Lake Kourna is located in northern Crete (latitude 35°20', longitude 24°16' and altitude of 19 m ASL), at the foot of Lefka Ori mountains, about 2.5 km from the sea. Lake Kourna is the only big natural lake of Crete and the most southern lake of Europe, with a surface area of 0.6 km<sup>2</sup>. The deepest point is found at 3.5 m below sea level, while the maximum water elevation is at 22 m. It is notable that two fish species which occur in Lake Kourna (*Blennius fluviatilis* and *Atherina boyeri*) do not exist in other freshwaters of Crete. The MTP habitat is located adjacent to the northern lake coastline, at roughly 50–100-m distance and is hydrologically directly connected to Lake Kourna, in the sense that when there is a water level rise above 19.5 m, the pond gets flooded with lake water.

The hydrologic basin of Lake Kourna has a surface area of approximately 19.7 km<sup>2</sup> and mean altitude 152 m above sea level. Its northeastern part is flat with altitude ranging from sea level to less than 100 m and slopes of less than 4%, while the southwest part of the basin is mountainous with altitudes reaching 1,200 m and slopes above 10% (Dimitriou et al., 2006) (Figs. 1, 2).

The region's climate is typically Mediterranean with dry-hot summers and mild winters. For the Lake Kourna region, historical data show that annually local rainfall has a mean 1,100 mm with values fluctuating from roughly 700 to 1,800 mm. The month with the highest rainfall is January (19% of the total), followed by December (18% of the total) while the lowest rainfall is observed during the period July–August (0.4% of the total) (Dimitriou et al., 2006). Temperature in the region is also relatively high with values

**Fig. 1** Hydrologic basins of Omalos and Lake Kourna**Fig. 2** Topographic map of Lake Kourna basin

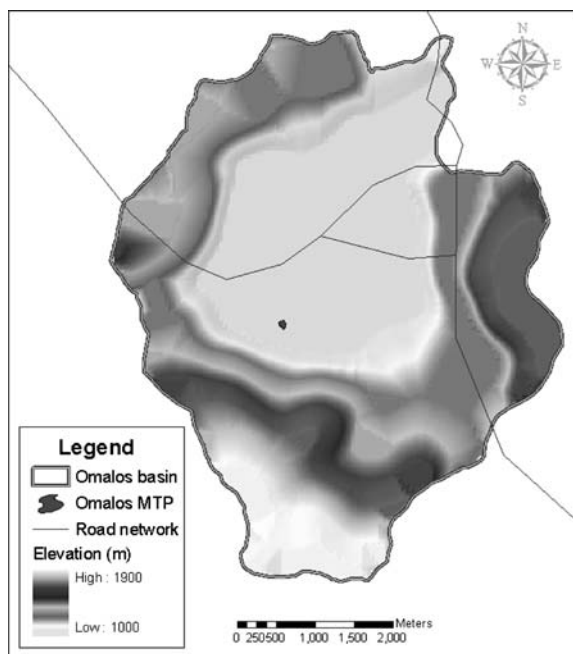
fluctuating from 12 to 27°C (January and July, respectively) while mean annual temperature is approximately 19°C. The case of relatively high temperatures is expected in the region, since it concerns a coastal, mostly lowland area, influenced

mainly by hot air masses from the Cretan Sea (Dimitriou et al., 2006).

Omalos plateau is located in the middle of Chania prefecture in the mountains of Lefka Ori. The surface extent and average elevation of the basin reach 26.7 km<sup>2</sup> and 1,183 m, respectively, while average slope of the basin is approximately 12°. Omalos MTP is located at the central part of the basin at an altitude of 1,050 m, and covers an area of 5.9 ha (Fig. 3).

Omalos basin is characterised by high rainfall/snowfall, therefore presenting longer hydroperiod compared to other MTPs in western Crete (Stamati & Nikolaidis, 2006). Observations showed that the aquifer's head elevation in the winter is marginally at the same height with the MTP, thus relative interaction occurs between groundwater and the pond's surface water. The time at which the pond passes from the wet to the dry phase depends mainly on the time that the last snowfall occurs, and therefore the point up to which snowmelt occurs (Stamati & Nikolaidis, 2006).

Mean precipitation in the region is 1,600 mm, while higher values (more than 300 mm per month) have been observed in December and November. The dry period occurs between May and September, where monthly rainfall does not exceed 25 mm, while in June, July and August, rainfall is almost absent. The significant amounts of precipitation in this particular region leads to extended MTP



**Fig. 3** Topographic map of Omalos basin

hydroperiod, which can go up to 10 months per year. February and March are the colder months with average minimum temperature of  $-0.6^{\circ}\text{C}$ . July is the hottest month with an average maximum temperature of  $23.2^{\circ}\text{C}$ . The relatively low temperatures combined with lack of strong winds, because of the geomorphology (plateau), leads to low levels of evaporation which also contributes to the extended MTP hydroperiod (Stamati & Nikolaidis, 2006).

## Materials and methods

In the absence of a model that can adequately describe both the MTPs, two different models have been used to illustrate the significant differences in their scale, hydrogeological regime and dynamics.

### Model for the MTP in Lake Kourna

The pond in the area of Kourna is located on the shore of the lake and is greatly dependent on the lake, as it is mainly supplied by the flood runoff of the lake when lake's water level increases during the winter. The sediment in the area of the pond presents limited infiltration capacity, and thus, the

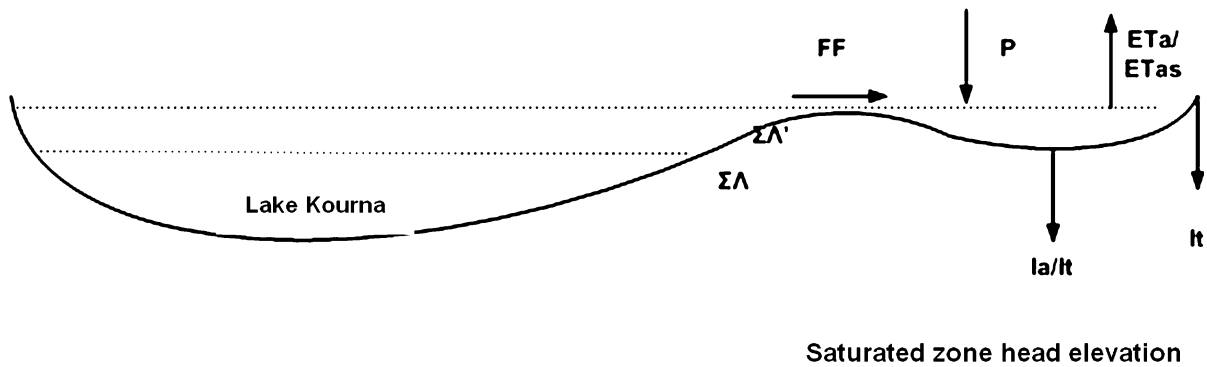
main hydrologic processes are lake's flood runoff, rainfall, evaporation and infiltration. Therefore, the MTP's hydroperiod in Lake Kourna principally depends on the fluctuation of the lake's water level, since the lake's flood discharge constitutes the MTP's main water supply source. It was, therefore, considered that if lake's water elevation was over the altitude for 100% coverage of the MTP (at 19.5 m), then the MTP was in flooding phase.

For Lake Kourna MTP, MIKE SHE modelling software has been used (Abbott et al., 1986) which is a comprehensive, deterministic, physically based, spatially distributed hydrological model that has been widely used to study a variety of water resource and environmental problems under diverse climatological and hydrological regimes (Refsgaard & Storm, 1995; in Thompson et al., 2004).

Figure 4 presents the main hydrological processes affecting the MTP's hydroperiod.

The simulation period covered one hydrological year (2005–2006) for which hydrological (lake's water levels) and meteorological data were available. Daily time steps were considered for the hydrological model. The guiding principle in the parameterisation was to construct a simple model with as few parameters, subject to calibration, as possible. Topography, land use, soil and geological maps were preprocessed in GIS software and imported into the model. Precipitation, potential evaporation/evapotranspiration and pumping time series were used to define temporal variability.

The basin model domain was uniformly distributed into a finite-difference grid of fine cell size of  $50 \times 50$  m, so that the ratio of grid cell area to basin surface area was from 1 to  $\sim 7,800$ , which allowed for realistic representation of hydrological variables without, at the same time, placing excessive demands on computational time. The Digital Bathymetric Model (DBM) of the lake has been developed by elaborating in GIS the lake's bathymetry contours (2-m resolution obtained by topographic maps 1:5,000, produced by the Greek Military Geographical Service). The Digital Elevation Model (DEM) of the basin has been developed by combining in GIS the DBM and topographical contours (20 m produced by the Greek Military Geographical Service) of the land part of the basin. For each land use in the basin (derived from the CORINE 2000 database) an appropriate vegetation/crop/land use type was



**Fig. 4** Schematic diagram of the conceptual model describing the hydrologic cycle of the MTP in Lake Kourna (Adapted from Stamati & Nikolaidis, 2006). *P* precipitation, *ETa*

evapotranspiration—aquatic, *ETs* evapotranspiration—terrestrial, *Ia* infiltration—aquatic, *Ir* infiltration—terrestrial, *FF* flood flow

selected from a vegetation/crop/land use property database along with its associated time series of Leaf Area Index (LAI) and Root Depth (RD).

Geological units were grouped in terms of their hydrogeological characteristics and specifically based on their permeability (high, medium and low) to keep the model as simple as possible. The saturated zone was defined using one impermeable flysch layer (350–1,000 m deep), on top of which three geological layers were placed: one thick limestone layer (350 m deep) of high permeability, covering the whole basin; one thin alluvial layer (80 m deep) of medium to high permeability extending at the central and north part of the basin; one thin layer consisting of silty and marly lake sediments (20 m). The geometry of these geological units was defined based on available geological cross-sections and geological maps.

Lake water levels were used as calibration targets. Model calibration was conducted by altering the hydraulic conductivity and storativity values until the simulated lake water levels matched closely the observed ones. Fifteen reference points evenly distributed ( $\sim 200$  m distance) within the lake ( $\sim 1$  point/3.8 ha) were used since it was not possible to account for all temporal variations of water level in every grid cell (230 cells within the lake). Additional check points were used to test the model's performance across the land part of the basin and throughout the calibration procedure. These fifteen calibration points inside the lake area have been used because the modelled lake's water levels present slight differences in the fluctuations at a spatial scale. This is due to the large water volumes entering the lake in winter and late spring, mainly through submerged springs. This

particular lake is considered to be an extension of the local groundwater body, and therefore the respective water level fluctuations are partially transferred to the lake. However, the spatial differences in the lake's water level are at the magnitude of few centimetres, and the 15 calibration points have been chosen to ensure elimination of potential inconsistencies.

The model was calibrated for the hydrological period 2005–2006 and temporally validated for two split sample tests: (i) the period from April to September 2005 (6 months prior to the start of the original calibration period); (ii) the next hydrological year (2006–2007). Correlation-based and error-based numerical criteria were subsequently used to assess model's calibration and validation. The correlation-based performance criteria used in this study include the Correlation Coefficient (*R*) and the Nash–Sutcliffe Correlation Coefficient ( $R^2$ ) while the error-based measures include the root mean squared error (RMSE), the mean absolute error (MAE), the mean error (ME) and the Standard Deviation of the Residuals (STDres) (Legates & McCabe, 1999).

#### Model for the MTP in Omalos

In the area of Omalos where the pond is located, the water table depth during the summer is found at approximately 18 m, while during the winter at 4 m below the ground surface. Thus, no direct interaction occurs between groundwater and pond's surface water. The pond's proximate drainage basin is small due to local topography (low slopes), and therefore overland inflow is expected to have minimum contribution to the MTP's water storage. Infiltration

capacity experiments conducted in situ by Stamati & Nikolaidis (2006) showed that at the distance of 8 m from the pond’s wet perimeter, infiltration velocity was low, in the order of 0.014 cm/min, while on the shore of the pond infiltration velocity was nil. This finding justifies observations that Omalos pond retains water during the summer months (longer hydroperiod). Thus, although infiltration/percolation processes cannot be omitted, the main hydrological processes are rainfall/snowfall, evaporation, evapotranspiration from the terrestrial part of the pond and overland inflow (Fig. 5). Thus, the model assumes three compartments: that of snow, terrestrial sediment (proximate direct drainage basin) and the pond (Fig. 5).

Figure 5 presents the main hydrological processes affecting the MTP’s hydroperiod.

The conceptual approach of the MTP hydrologic cycle in Omalos allowed the development of a mathematical model named HPM in Matlab software for the determination of the MTP’s hydroperiod. Input parameters of the HPM model such as surface extent and volumes of the terrestrial sediment and the pond’s water resulted from the bathymetry/topography 3D model developed in GIS by Stamati & Nikolaidis (2006). At first, two relationships could be established between the pond’s surface extent and water level, and between the pond’s volume and water level. Then, the relationship between the pond’s surface and the pond’s volume was explicitly defined and presented in Fig. 11. Thus, the pond’s surface and water level may then be calculated from the corresponding volume that results from the HPM model output.

The model solves the water storage balances for three compartments (snow, terrestrial sediment, pond) with the method of Euler on a daily basis. The equations that describe the hydrologic processes for each compartment are given below.

*Snow, S*

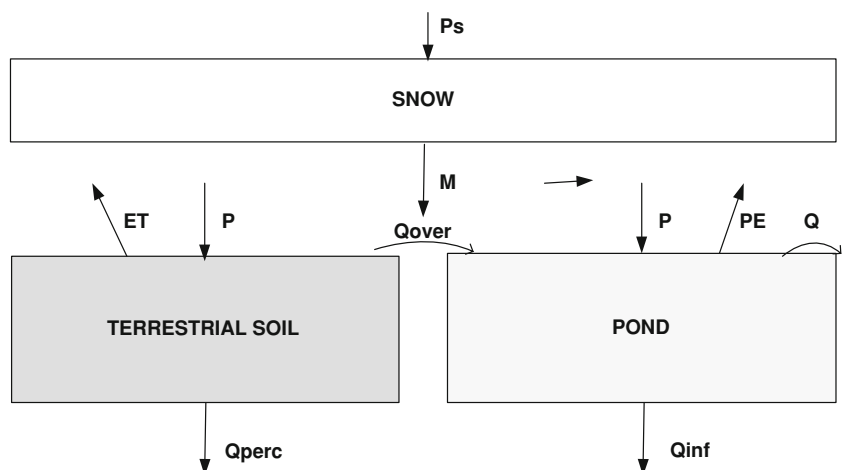
The water balance for the compartment of snow appears in Eq. 1. The change of snow storage ( $V_s$ ) with time equals the difference of snowmelt from snowfall. When mean daily temperature ( $T$ ) is lower than the temperature below which precipitation is in the snow phase ( $T_s$ ), then snowmelt does not occur ( $M_s = 0$ ) during that day and snowfall occurs ( $P_s = cs \times P$ ), equal to the rainfall recorded that day multiplied by a correction factor ( $cs$ ). When mean daily temperature ( $T$ ) is higher than temperature,  $T_s$ , then snowfall does not occur ( $P_s = 0$ ). If snowfall occurs then, if no rainfall occurs, snow melts according to Eq. 2 or, if rainfall occurs, snow melts according to Eq. 3. Factor  $k$  ( $1.8 \text{ TEMPC}^{(n+1)}$ ) characterises the day (degree day factor) while  $n$  usually takes the value of 0.25. Finally, if snow that is able to melt is more than storage,  $V_s$ , then snowmelt is corrected at this volume,  $V_s$  (Stamati & Nikolaidis, 2006)

$$\frac{dV_s}{dt} = \underbrace{P_s \times A_{sf}}_{\text{snowfall}} - \underbrace{cm \times M_s \times A_s}_{\text{snowmelt}} \tag{1}$$

$$M_s = \left( (T \times 1.8)^{(n+1)} \right) \times k / 1000, \tag{2}$$

$$M_s = \left( ((P \times 0.007 + 0.074) \times T \times 1.8 + 0.05) \times 0.254 \right) / 1000. \tag{3}$$

**Fig. 5** Schematic diagram of the conceptual model describing the hydrologic cycle of the MTP in Omalos (Stamati & Nikolaidis, 2006).  $P/P_s$  rainfall/snowfall,  $M$  snowmelt,  $PE$  evaporation—aquatic,  $ET$  evapotranspiration—terrestrial,  $Q_{inf}$  infiltration—aquatic (central or peripheral),  $Q_{perc}$  infiltration/percolation—terrestrial,  $Q_{over}$  overland inflow,  $Q$  flood discharge



*Terrestrial sediment, T*

The water balance for the compartment of terrestrial sediment is given by Eq. 4, while the equations for the calculation of storages of percolation, evapotranspiration and overland flow from the terrestrial sediment are given by Eqs. 5, 6 and 7, respectively. The change of water storage in the terrestrial sediment ( $V_t$ ) equals the difference of evapotranspiration, percolation and overland flow from the sum of rainfall and snowmelt (Stamati & Nikolaidis, 2006). The following conditions apply:

- when snowfall occurs ( $P_s > 0$ ) during that day, rainfall, evapotranspiration and percolation are nil;
- when no inflow (rainfall or snowmelt) occurs in the compartment and the existing volume of water is equal to minimum ( $V_{tmin}$ : porosity volume multiplied by minimum humidity), evapotranspiration and percolation are nil;
- when the volume of water is more than minimum volume ( $V_{tmin}$ ) and the active volume ( $V - V_{tmin}$ ) is less than evapotranspiration and percolation, then the latter parameters are corrected to this volume with the corresponding percentages;
- similarly, when rainfall and/or snowmelt occur and the existing active volume of water along with the inflows are less than evapotranspiration and percolation, then the latter parameters are corrected to the volume given by the existing active volume of water with the inflows, with the corresponding percentages;
- finally, if the resulting volume is more than the maximum volume of terrestrial sediment ( $V_{tmax}$ : porosity volume), then the surplus volume gives additional overland flow ( $O_t$ ).

$$\frac{dV_T}{dt} = \underbrace{M_{st}}_{\text{snowmelt}} + \underbrace{P_t}_{\text{rainfall}} - \underbrace{E_t}_{\text{evapotranspiration}} - \underbrace{PR_t}_{\text{percolation}} - \underbrace{O_t}_{\text{overland flow}} \quad (4)$$

$$PR_t = c_p \times f_c \times A_t \quad (5)$$

$$E_t = c_{et} \times E_t \times A_t \quad (6)$$

$$O_t = P \times A_{tf} + (M_s - f_c) \times A_t \quad (7)$$

where  $f_c$ : field’s infiltration velocity (cm/min),  $c_p$ : percolation coefficient,  $A_t$ : surface of the terrestrial

sediment,  $c_{et}$ : evaporation coefficient,  $A_{tf}$ : flat surface of the terrestrial sediment,  $M_s$ : snowmelt, and  $E_t$ : evapotranspiration.

*Pond, P*

The water balance for the pond compartment is given by Eq. 8, while the equations for calculating the storages of infiltration and evaporation from the pond’s surface are given by Eqs. 9 and 10, respectively. The change of the pond’s water storage ( $V_p$ ) with time equals to the difference of evaporation, infiltration and outflow (flood runoff) from the sum of rainfall and snowmelt (Stamati & Nikolaidis, 2006).

The following conditions apply:

- when snowfall occurs ( $P_s > 0$ ), at a particular day, rainfall, evaporation and infiltration are nil;
- on the other hand, when no inflows occur (rainfall or snowmelt) in the compartment and the existing water volume is nil, then evaporation and infiltration are nil;
- in the same case, when there is water storage available, if this is less than evaporation and infiltration, then the latter parameters are corrected to this volume with the corresponding percentages;
- similarly, when rainfall and/or snowmelt occur and the existing water volume along with the inflows are less than the sum of potential evaporation and infiltration, then the latter parameters are corrected down to the sum of the existing water volume and the inflows, with the corresponding percentages.

$$\frac{dV_p}{dt} = \underbrace{M_{st}}_{\text{snowmelt}} + \underbrace{P_p}_{\text{rainfall}} + \underbrace{O_t}_{\text{overlandinflow}} - \underbrace{E_p}_{\text{evapotranspiration}} - \underbrace{I_t}_{\text{infiltration}} - \underbrace{Q_p}_{\text{flood discharge}} \quad (8)$$

$$I_p = c_i \times f_c \times (Apwet - A_c) \quad (9)$$

$$E_p = c_{pe} \times P_e \times Apwet \quad (10)$$

where  $I_p$ : infiltration from the pond,  $c_i$ : infiltration coefficient,  $A_c$ : surface of the central part of the pond,  $Apwet$ : surface of the pond’s wet area,  $c_{pe}$ : evaporation coefficient and  $P_e$ : evaporation.

## Scenarios

In order to have an indication of the impact of climate change on Lake Kourna water level (and consequently on the adjacent MTP) and on the MTP water level in Omalos, two future climate scenarios were applied according to the IPCC (2007) climate predictions:

- One ‘pessimistic’ A2 IPCC scenario for 3.5°C increase in temperature (with respective increase of evaporation and evapotranspiration) and 0.25 mm/day decline of precipitation and
- one more ‘optimistic’ B2 IPCC scenario for 2.5°C increase in temperature (with respective increase of evaporation and evapotranspiration) and 0.25 mm/day decline of precipitation.

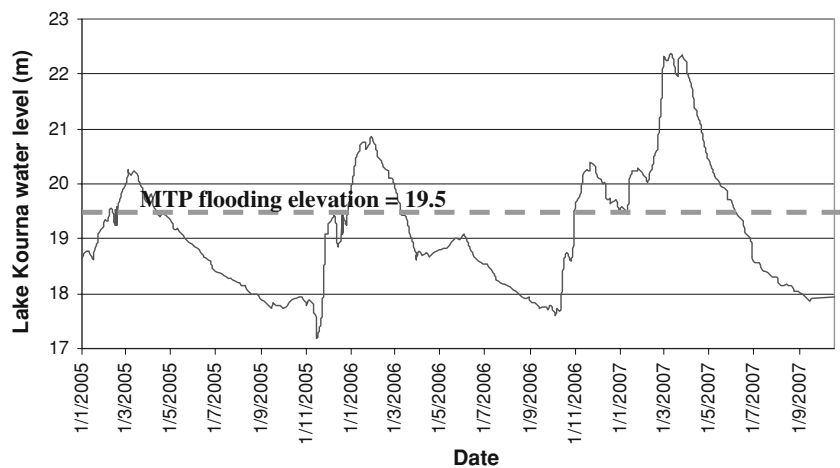
The only variables changed in the model were precipitation, evaporation and evapotranspiration. The results were then assessed by comparing the simulated water levels with the baseline-current scenario.

## Results

### Kourna lake MTP

The average hydroperiod value for the hydrological year 2005–2006 is 72 days, while for the next hydrological year 2006–2007 was estimated at 213 days (Fig. 6). Table 1 shows the hydroperiod values for calendar years 1996–1999 and for the hydrological years 2005–2006 and 2006–2007.

**Fig. 6** Lake’s Kourna water level fluctuation and the threshold water level above which the MTP is flooded (MTP’s wet phase)



**Table 1** Estimation of the hydroperiod of Lake Kourna MTP

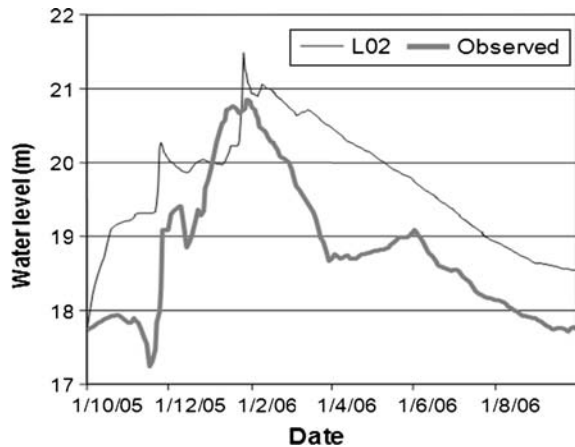
Simulation period	Hydroperiod (days)
1996 <sup>a</sup>	70
1997 <sup>a</sup>	77
1998 <sup>a</sup>	21
1999 <sup>a</sup>	76
2005–2006	72
2006–2007	213

<sup>a</sup> Stamati & Nikolaidis (2006)

Figure 7 shows the simulated Lake Kourna water level (at calibration target point L02) and the observed water level for the calibration period 1 October 2005–30 September 2006. Numerical criteria tested on the calibration receptors (15 points in the lake) revealed satisfactory calibration of the model with an average of 72% for the  $R$  correlation coefficient and 31% for the  $R^2$  (Nash–Sutcliffe) coefficient, while the average values for the error-based criteria MAE, RMSE and STDres were 0.68, 0.83 and 0.66, respectively. Apart from calibration receptors L02 and L05, which presented the lowest  $R$  correlation coefficient of 69 and 53%, respectively, the model worked well on simulating Lake Kourna water level.

The model was also tested on an annual basis to ensure its bulk performance by comparing the simulated overland (lake) storage change water balance output with the expected lake storage change estimated using the bathymetry/topography model of the lake in GIS. The results were similar and therefore, on an average, satisfactory behaviour of





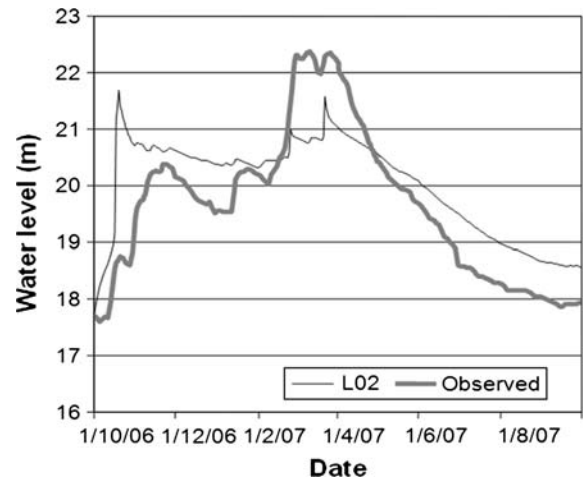
**Fig. 7** Comparison between the simulated Lake Kourna water level (at 15 calibration target points within the lake) and the observed water level fluctuation (*double width line*) during the calibration period (hydrological year 2005–2006)

the hydrological model across the surface of Lake Kourna was achieved.

Numerical criteria tested on the validation receptors revealed good validation of the model with an average of 98% for the  $R$  correlation coefficient and 55% for the  $R^2$  (Nash–Sutcliffe) coefficient, while the average values for the error-based criteria MAE, RMSE and STDres were 0.36, 0.42 and 0.23, respectively.

Figure 8 shows the simulated Lake Kourna water level (at L02 validation target point) and the observed water level for the validation period 1 October 2006–30 September 2007. Numerical criteria tested on the validation receptors revealed satisfactory validation of the model with an average of 77% for the  $R$  correlation coefficient and 32% for the  $R^2$  (Nash–Sutcliffe) coefficient, while the average values for the error-based criteria MAE, RMSE and STDres were 0.84, 1.10 and 0.89, respectively. However, as it is evident from Fig. 8, the model is unable to simulate adequately the peaks in March and April 2007, as it underestimates the peaks by approximately 1 m. In addition, it overestimates observed values at the start of the simulation, whereas it follows water levels well during the recession months May–September.

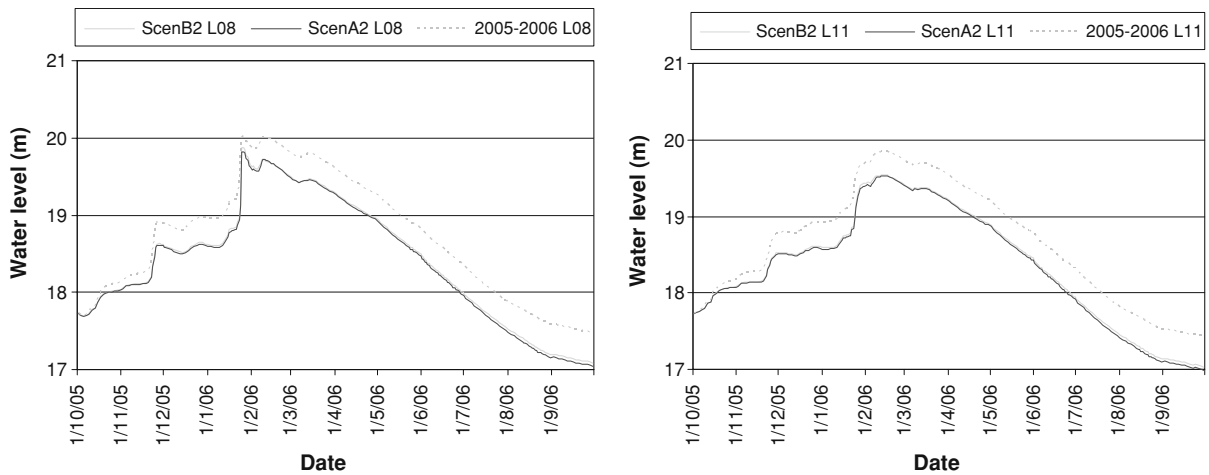
The impact of climate change on Lake Kourna water level (and consequently on the adjacent MTP) and on the MTP water level in Omalos, was assessed by applying two future climate scenarios (IPCC B2



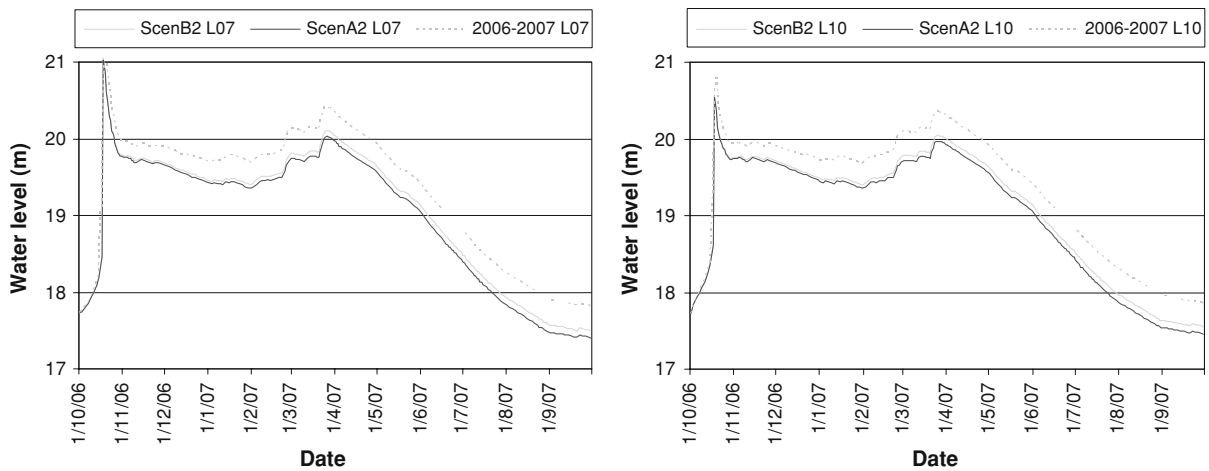
**Fig. 8** Comparison between the simulated Lake Kourna water level (at 15 calibration target points within the lake) and the observed water level fluctuation (*double width line*) during the validation period of the 2006–2007 hydrological year (2nd split-sample test)

and A2) both on the calibrated 2005–2006 model (Baseline scenario 1) and the validated 2006–2007 model (Baseline scenario 2). Figures 9 and 10 present a pictorial view of the results from the application of the scenarios on Lake Kourna water levels for the periods 2005–2006 (receptors L08 and L11) and 2006–2007 (receptors L07 and L10), respectively (Tables 2, 3).

Tables 4 and 5 present a comparison between the predicted water levels and hydroperiod by the B2 and A2 IPCC scenarios and the baseline scenarios for the calibration and validation periods 2005–2006 and 2006–2007, respectively. Results show, for both the baseline scenarios tested, a reduction of 52 days for IPCC scenario B2, while there is close agreement for IPCC scenario A2, since a reduction of 55 and 67 days are predicted for baseline scenarios 1 and 2, respectively. Results also demonstrate close agreement between water level reduction predicted by the B2 IPCC scenario for baseline scenarios 1 (39 cm) and 2 (31 cm), as well as by the A2 IPCC scenario (43 and 41 cm, respectively, for baseline scenarios 1 and 2). The large difference between hydroperiod (or water level) values for the two baseline scenarios 1 and 2 and the agreement of the relative predicted reduction of B2 and A2 hydroperiod (or water level) values provide another indication of the satisfactory calibration and validation of the model (Fig. 11).



**Fig. 9** Comparison of simulated Lake Kourna water level for the calibration period 2005–2006 with IPCC predictions for scenarios B2 and A2 at calibration receptors L08 and L11



**Fig. 10** Comparison of simulated Lake Kourna water level for the validation period 2006–2007 with IPCC predictions for scenarios B2 and A2 at calibration receptors L07 and L10

**Table 2** Comparison of simulated and observed Kourna MTP water level and hydroperiod values for the calibration period (hydrological year 2005–2006) at calibration receptors (L08, L10, L11, L13)

Location in lake	Observed 2005–2006			Model 2005–2006		
	WL end of simulation (m)	Hydroperiod (days)	WL difference end-start of simulation (m)	WL end of simulation (m)	WL difference end-start of simulation (m)	Hydroperiod (days)
Mean	17.746	72	−0.013	17.48	−0.17	75

Omalos conceptual model (HPM) calibration and validation

Figure 12 show the volume of water in the pond (calibration target) simulated by the HPM model as

opposed to that observed in the field during the calibration (2005–2006) period. Numerical criteria tested for both periods show good correlation of the model with the observed measurements with *R* correlation and *R*<sup>2</sup> (Nash–Sutcliffe) coefficients

**Table 3** Comparison of simulated and observed Kourna MTP water level and hydroperiod values for the validation period (hydrological year 2006–2007)

Location in lake	Observed 2006–2007			Model 2006–2007		
	WL end of simulation (m)	Hydroperiod (days)	WL difference end-start of simulation (m)	WL end of simulation (m)	WL difference end-start of simulation (m)	Hydroperiod (days)
Mean	17.926	213	0.193	17.92	0.19	224

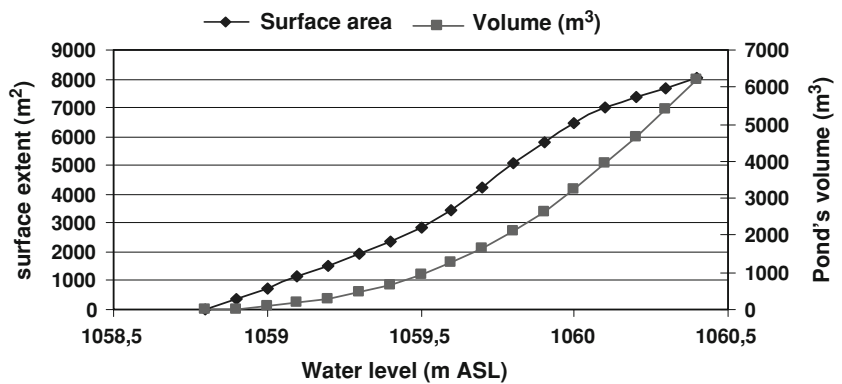
**Table 4** Comparison of simulated 2005–2006 model and IPCC predictions (scenarios B2 and A2) for Kourna MTP water level and hydroperiod

Location in lake	B2			A2		
	WL difference Baseline scenario 1 end of simulation (m)	Hydroperiod (days)	Hydroperiod decrease from Baseline scenario 1 (days)	WL difference Baseline scenario 1 end of simulation (m)	Hydroperiod (days)	Hydroperiod decrease from Baseline scenario 1 (days)
Mean	−0.39	23	−52	−0.43	20	−55

**Table 5** Comparison of simulated 2006–2007 model and IPCC predictions (scenarios B2 and A2) for Kourna MTP water level and hydroperiod

Location in lake	B2			A2		
	WL difference Baseline scenario 2 end of simulation (m)	Hydroperiod (days)	Hydroperiod decrease from Baseline scenario 2 (days)	WL difference Baseline scenario 2 end of simulation (m)	Hydroperiod (days)	Hydroperiod decrease from Baseline scenario 2 (days)
Mean	−0.31	172	−52	−0.41	156	−67

**Fig. 11** Relationship between Omalos pond’s surface, volume and water level (ASL above sea level) (Stamati & Nikolaidis, 2006)

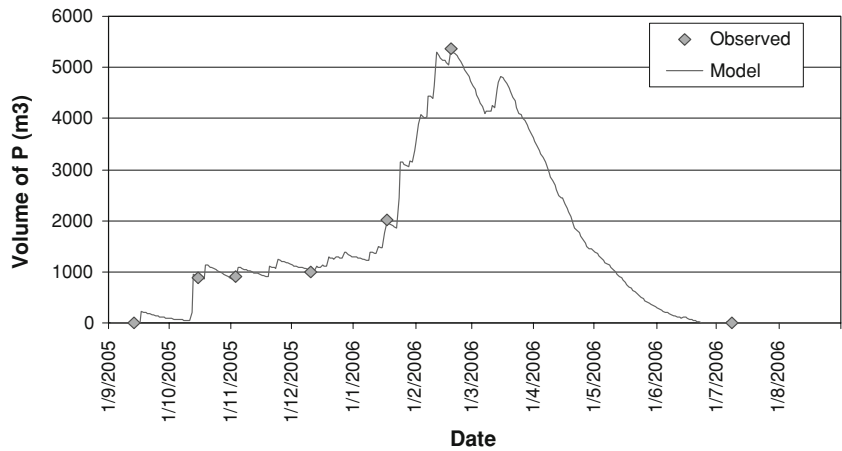


approaching perfect model value of 1, both for the calibration (99.9%) and the validation period (98.2%) (Table 6). Error-based measures present lower values for the calibration period since during this period more measurements were available.

Comparison between the baseline scenarios (2005–2006: calibration period and 2006–2007: validation

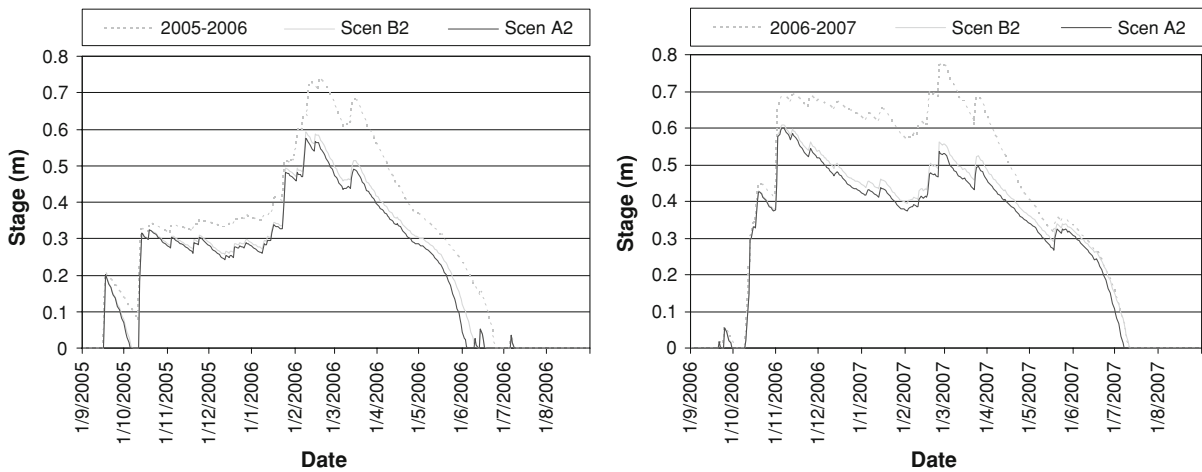
period) and IPCC scenarios is illustrated in Fig. 13. Results for 2005–2006 show there is a reduction in the pond’s water level, especially the peaks from February to April, and the hydroperiod by 10–20 cm and approximately 20 days, respectively. Results for the hydrological year 2006–2007 (although the model was validated only for the first 3 months) also indicate a

**Fig. 12** Omalos MTP’s simulated water volume as opposed to the observed volume (estimated using the 3D bathymetry/topography model) for the simulation period 1 September 2005–31 August 2006



**Table 6** Numerical criteria for the calibration and validation of the HPM model for the hydrological year 2005–2006 and the period 1 September 2006–31 December 2006, respectively

Name	ME	MAE	RMSE	STDres	R (Correlation)	R <sup>2</sup> (Nash–Sutcliffe)
2005–2006	4.92	27.23	13.43	35.19	0.997	0.9996
September 2006–December 2006	–180.60	180.60	128.78	23.50	0.995	0.982



**Fig. 13** Comparison of Omalos MTP water level for the calibration period 2005–2006 with IPCC predictions for scenarios B2 and A2

reduction in the pond’s water level, although reduction in the pond’s hydroperiod is much smaller (Table 7) as a result of higher precipitation.

Table 7 shows model results for the hydroperiod of the MTP in Omalos. The MTP presents stationarity in its hydroperiod (281–282 days) between the calibration and validation period (assuming the

validated model is extended to apply during the whole hydrological year), although there is much higher precipitation observed during the validation period. Reduction of the MTP’s hydroperiod is comparatively (to Lake Kourna MTP) small, with only 16 and 24 days’ decrease in hydroperiod as a result of IPCC scenarios B2 and A2, respectively.

**Table 7** Comparison of simulated (2005–2006 and 2006–2007) HPM models and IPCC predictions (scenarios B2 and A2) for Omalos MTP hydroperiod

Omalos MTP	Hydroperiod (days)	Hydroperiod for IPCC B2 scenario (days)	Hydroperiod decrease for B2 (days)	Hydroperiod for IPCC A2 scenario (days)	Hydroperiod decrease for A2 (days)
2005–2006	281	265	–16	257	–24
2006–2007	282	279	–3	274	–8

## Discussion and conclusions

Different approaches in methodology for the determination of the hydroperiod of the two MTPs were adopted in this particular study. Incorporation of a conceptual view of the hydrologic cycle of the MTPs in Lake Kourna and Omalos has assisted to determine the respective modelling approaches that were adopted to simulate the MTPs hydroperiod and subsequently predict their changes based on IPCC climate change scenarios. Thus, with regard to the MTP in Lake Kourna, modelling of its hydrologic cycle and estimation of its hydroperiod presupposes modelling of the lake's hydrology, since there is direct communication between the two water bodies, while the lake's flood runoff contributes to the MTP's main inflow.

A physically based distributed model of Lake Kourna was, therefore, applied to determine the MTP's hydroperiod. A critical factor in the setup of the model was, as accurately as possible, the representation of the catchment groundwater inflows boundary condition, which was achieved using the lake's water balance and recharge coefficients for the geological units of the lake's sub basin. Numerical criteria tested on the calibration receptors revealed satisfactory calibration of the model with an average of 72% for the  $R$  correlation coefficient and 31% for the  $R^2$  (Nash–Sutcliffe) coefficient, while the majority of the model points falls between the  $\pm 5\%$  error bounds (83%) for the perfect model line. Results also show close agreement between the modelled average hydroperiod value of 75 days and the observation of 72 days. Numerical criteria tested on the validation receptors for the first split-sample test (April–September 2005) revealed good validation of the model with an average of 98% for the  $R$  correlation coefficient and 55% for the  $R^2$  (Nash–Sutcliffe) coefficient with 91% of model points falling between the  $\pm 5\%$  error bounds for the perfect model line. Numerical Satisfactory validation of the model has been recorded for the second split-

sample test (hydrological year 2006–2007) with an average of 77% for the  $R$  correlation coefficient and 32% for the  $R^2$  (Nash–Sutcliffe) coefficient, although the model was unable to simulate adequately the peaks in March and April 2007.

Nevertheless, 72% of model points fall between the  $\pm 5\%$  error bounds for the perfect model line, while results show close agreement between the modelled average hydroperiod value of 224 days and the observation of 213 days. It is noteworthy that the model for both split-sample tests performed slightly better than the calibration.

In the case of Omalos, a more simplistic approach was followed with application of the mathematical representation of the conceptual model of the MTP using the mathematical software Matlab, developed by Stamati & Nikolaidis (2006). Numerical criteria tested for the calibration and the validation periods (hydrological years 2005–2006 and 2006–2007) show good correlation of the model with the observed measurements with  $R$  correlation (99.9%) and  $R^2$  (Nash–Sutcliffe) (98.2%) coefficients.

The impact of climate change on Lake Kourna water level (and consequently on the adjacent MTP) and on the MTP water level in Omalos, was assessed by applying two future climate scenarios. Results for IPCC B2 and A2 climate scenarios show longer hydroperiod and smaller decreases in the future for Omalos MTP than in Lake Kourna MTP. Results for Lake Kourna MTP demonstrated a hydroperiod decrease of more than 52 days after the application of the IPCC scenarios. Scenario A2 does not present a significantly differentiated-higher impact on the MTPs' hydroperiod. In particular, a difference of 3–15 days and 5–8 days compared with IPCC scenario B2 predictions was estimated for the MTP in the case of Lake Kourna and in Omalos, respectively.

Thus, the lowland MTP proved to be far more vulnerable to climate change in relation to the mountainous one since the percentage decrease of its hydroperiod reaches 68% which could be

detrimental for the pond fauna, and flora if it occurs. This difference between the lowland and the mountainous pond is consistent with results from similar climate change impact studies (Blenckner, 2005) that indicated different responses in various lakes depending on the local geographic and biological conditions. There are no similar applications focussing on modelling hydroperiod of MTPs in the literature since this habitat is not yet well studied. Nevertheless, temporary water bodies and particularly this priority habitat (MTP) are highly vulnerable to hydrologic disturbances including climate change since potential, significant changes in their hydroperiod will lead to the alteration of their typical ecological characteristics. Thus, there is a need for more similar studies regarding climate change impact assessment on temporary water bodies to design and undertake the appropriate restoration activities. The particular modelling approaches used in this effort could be easily adapted for similar applications in areas hosting temporary water bodies.

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