

Modeling thermal structure variations in a stratified reservoir

Lindim^a, C., Hayter^b, E. J., Pinho^c, J. L. S., Vieira^d, J. M. P.

^aCivil Eng. Dept, University of Minho, 4710-553 Braga, Portugal. lindim@civil.uminho.pt

^b US Army Corps of Engineers, ERDC-CHL, Vicksburg, MS, USA.
Earl.Hayter@usace.army.mil

^cCivil Eng. Dept, University of Minho, 4710-553 Braga, Portugal. jpinho@civil.uminho.pt

^dCivil Eng. Dept, University of Minho, 4710-553 Braga, Portugal. jvieira@civil.uminho.pt

ABSTRACT

In this work the effects of hydrologic and atmospheric conditions changes in the thermal structure of the Alqueva reservoir are investigated. Reservoir water temperatures and thermal stratification have a strong influence on ecological processes; therefore a good understanding of their dynamics is of major importance when studying eutrophicated reservoirs. A finite element model (RMA10) was used to simulate flow and temperature in the Alqueva reservoir, the largest western European lake. Survey and monitoring data for different years were used to calibrate and validate the model. Simulated temperatures compared well with observations at different monitoring stations. Model results showed that the reservoir has a stable thermal stratification during summer. A sensitivity analysis was performed to determine the relative importance of environmental factors, such as tributary inflows and wind, affecting water temperatures and heat fluxes in this stratified reservoir. Model results show that the Guadiana river inflow dynamics has an impact in the upper part of the reservoir. Inflow rate variations affect water temperatures and the distributions of dissolved oxygen and nutrients in that area. Consequently Guadiana inflow changes can shift in time and location phytoplankton populations.

Keywords: Thermal stratification; Modeling; Reservoir; Alqueva.

1. INTRODUCTION

Thermal stratification and water temperature dynamics have profound effects in chemical and biological reservoir processes. Temperature variations are responsible for inducing changes in dissolved oxygen levels and in biochemical reactions kinetic rates which consequently have strong impacts on biological productivity (Kim et al, 2006). In a stratified reservoir like the Alqueva the thermocline hinders oxygen transfer between the epilimnion and hypolimnion. Thus during summer the hypolimnion oxygen levels are low. Hot season stratified conditions also favor the release of phosphorus from the sediments, a process known as internal loading (Wetzel, 2001). Together with wind, density gradients shaped by the spatial distribution of temperature are accountable for any water motions occurring in systems where hydraulic flow is small as is the case in most reservoirs. Therefore these mechanisms are largely responsible for the distribution of algae and constituents in the water column (Serra et al., 2007). Numerical modeling has been used to successfully simulate thermal stratification and water temperature distributions in innumerable ecological and climate change studies for a variety of different waterbodies

(Schertzer et al., 2003; Komatsu et al., 2007). In this work the RMA10 finite elements numerical model was applied to the Alqueva reservoir in order to simulate the hydrodynamics and water temperature vertical and longitudinal distributions throughout a year. The main objective of the current work is to describe the seasonal temperature cycle and thermal structure of the Alqueva reservoir.

2. STUDY AREA AND FIELD MEASUREMENTS

The Alqueva reservoir is located in the south of Portugal at the eastern border with Spain (Figure 1a). The reservoir is the largest man-made impoundment in Western Europe, with a surface area of 250 Km² and a volume of 4150 hm³ at his maximum water level. The primary inflow of this 83 Km long reservoir is the Guadiana River located at the north margin. The Guadiana River has an irregular hydrological regime with strong seasonal variations, ranging from a 10-20 m³/s flow in summer to values tenfold higher during the wet season. The dam is located at the south most part of the lake, controlling the outflow of the Guadiana. The whole reservoir has a weak circulation and long residence times. Wind stress has been shown to play an important role in transport (Lindim et al., 2010).

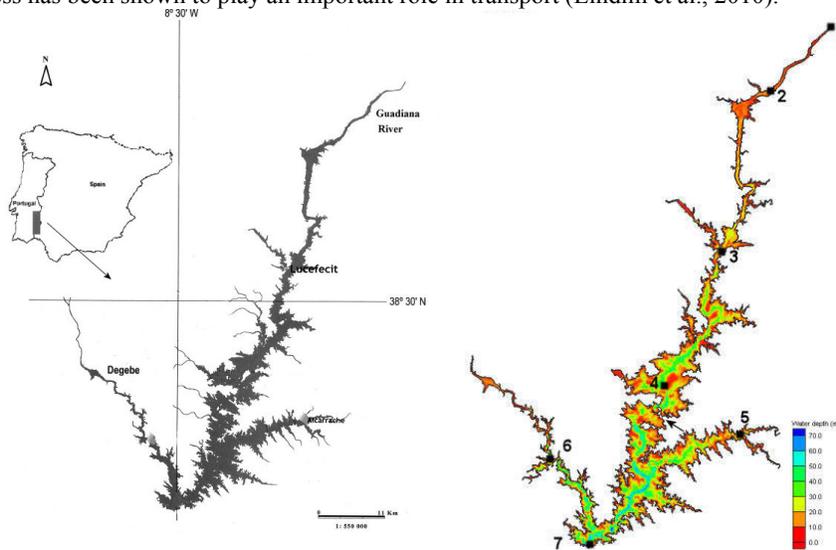


Figure 1 – The Alqueva reservoir (8° 30'W, 38°30'N). a) location. b) bathymetry and main sampling stations. The dam is located at 7. Hydrometric and water quality monitoring stations. Meteorology stations are located at 1, 3, 4 and 7.

The Alqueva is monitored for water quality, meteorological and hydrometric parameters using an automated network of sensors. The reservoir bathymetry and the location of the monitoring stations used in the current work are shown in Figure 1b). Hydrometric and meteorological data are measured hourly while most water quality data are sampled monthly at different water depths. Observed data for years 2005 and 2006 are shown in Figure 2. Air temperatures and short wave measured radiation (figures 2a and 2b) for the different meteorological stations in the analyzed years were not significantly different. Both years can be considered average in terms of climatic conditions, with similar seasonal variations and observed values for temperatures and solar radiation. Water surface temperatures (Figure 2c) closely follow the seasonal solar radiation variations but station 7 located in the deepest area of the reservoir and station 2 located in the upper shallow riverine part of the reservoir present different seasonal responses in terms of water surface temperatures. Warming and cooling occurs faster and earlier in time at station 2. Wind speed (figure 2d and e) was always lower than 10 m/s at all the stations for the full two year period studied. Wind predominantly blows to North and East directions.

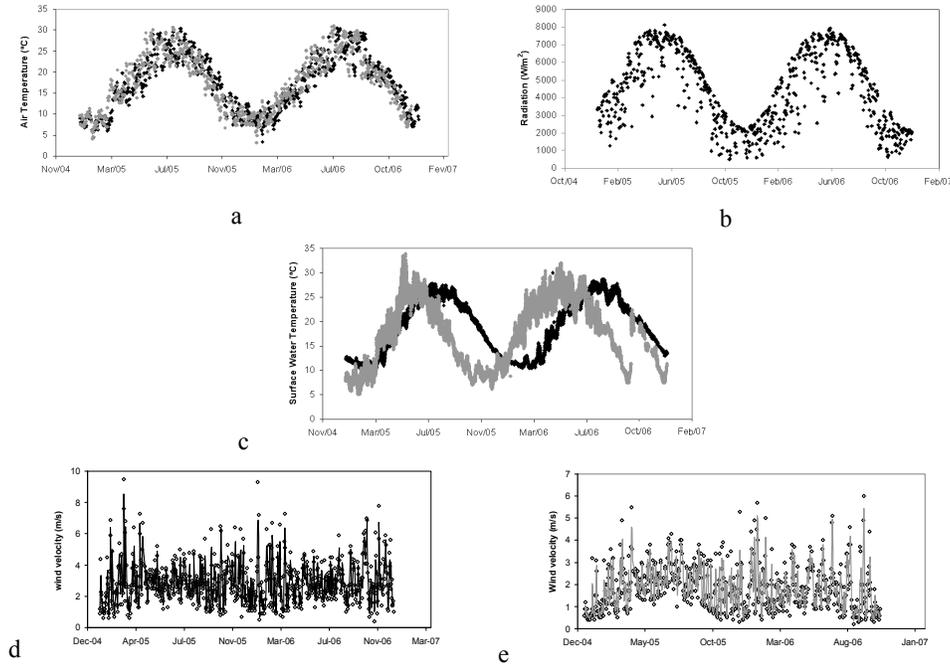


Figure 2– Reservoir measurements for years 2005 and 2006. a) Daily averaged air temperature (°C) at sts 7 (black) and 2 (grey). b) Shortwave daily radiation (W/m^2) at st 7. c) Hourly surface water temperature (°C) at st 7 (black) and 2 (grey). d) Daily averaged wind speed (m/s) at st 7 (points). Black line is a two days moving average. e) Daily averaged wind speed (m/s) at st 3 (points). Grey line is a two days moving average.

3. DESCRIPTION OF MODELS

RMA10 is a three-dimensional finite element hydrodynamic model able to simulate temperature and density in lakes and reservoirs (King, 1993). The model can be used to simulate turbulent flow using one, two (both depth and laterally averaged) or three dimensional elements. RMA10 uses a standard Galerkin weighted residuals formulation for the finite element derivation. RMA10 has previously been applied to simulate successfully hydrodynamics and thermal variations in waterbodies (Cook et al., 2002; Liu et al., 2006). Although many one-dimensional models applied in the vertical direction at one location in a water body are able to simulate fairly the temperature dynamics in stratified lakes, simulations for morphologically complex reservoirs such as the Alqueva usually require the use of multi-dimensional models. The Alqueva has abrupt spatial variations in area and depth that cannot be adequately modeled using a one-dimensional vertical model. The use of RMA10 in its version as a 2D laterally averaged model allows the introduction of a lateral dimension and bed slopes in addition to the vertical dimension. This is sufficient to simulate thermal dynamics in the Alqueva. Tests with RMA10 showed that using the full three-dimensional version did not result in significant improvement of results and had a much higher computational cost. The computational grid used had 217 longitudinal elements and a maximum of 10 vertical collapsible layers. Each longitudinal element has an associated lateral dimension and bed slope based on bathymetric and map information. Longitudinal elements lengths vary between 50 m and 1680 m. All nodes forming the elements have associated depths based on the bathymetric data. Vertical layers have smaller thicknesses at the top of the water column and are progressively thicker with increasing water depth. Minimum layer thickness was 2 m. For the simulations water surface elevation was used as the open boundary condition at the dam. Daily flow measurements from the river Guadiana and hourly wind data were used as forcing. Data for 2005 were used for calibration and verification was done with data for year 2006.

4. TEMPERATURE AND SURFACE HEAT BUDGET MODELING

The temperature transport equation can be expressed as

$$\frac{\partial T}{\partial t} = v \nabla T + \frac{\partial}{\partial z} \left(D_z \frac{\partial T}{\partial z} \right) + \frac{1}{\rho_o C_p} \frac{\partial I}{\partial z} \quad (1)$$

where T is the water temperature, t is time, z is the vertical coordinate, v is the velocity vector, D_z is the vertical eddy diffusivity, ρ_o is the reference density, C_p is the specific heat of water and I is the irradiance. The irradiance represents the absorption of short-wave radiation by the system. Solar short wave radiation penetrates the water column through the water surface and is absorbed in part of the water column. In the model the flux of solar radiation penetrating the water surface (H_{SN}) is given by the insolation reaching the water surface reduced by the Albedo (reflectivity) and corrected for cloud cover and atmospheric transmissivity attenuation. The flux of solar radiation penetrating the water surface is calculated after Henderson-Sellers (1986) as

$$H_{SN} = H_0 t' (1 - R) (1 - 0.65C^2) \quad (2)$$

where H_0 is the incoming solar short wave radiation to earth's atmosphere, t' is the Albedo, R is the reflectivity of water surface and C is the cloud cover (expressed as [0-1]). To calculate the radiation penetration a modified form of the Beer-Lambert law is used

$$H_S(z) = H_{SN} e^{-\eta z} \quad (3)$$

Where $H_S(z)$ is the short wave radiation at depth z and η is the extinction coefficient. Besides short wave radiation, the other heat transfer processes (evaporation, long wave radiation, conduction and back radiation) included in RMA10 are considered to be surface heat transfer phenomena. For the computation of net heat flux at the surface

$$H_N = H_{SN} + H_{AN} - (H_B + H_E + H_C) \quad (4)$$

where H_N is the net energy flux at interface air-water, H_{SN} is the short wave radiation flux penetrating the water surface, H_{AN} is the long wave radiation flux, H_B is the back radiation from water surface, H_E is the evaporation flux and H_C is the heat conduction flux. Units used in the model are $\text{kJ m}^{-2} \text{h}^{-1}$. Long wave radiation flux at the water atmosphere interface is dependent on water and air emissivity, cloud cover and reflectivity (Swinbank, 1963)

$$H_{AN} = 9.37E-06 \sigma T_a^6 (1 + 0.17C^2) (1 - R) \quad (5)$$

where σ is the Stefan-Boltzmann constant ($2.0412 \times 10^{-7} \text{ kJ}/(\text{hK}^2 \text{m}^2)$), T_a is air temperature (K). The evaporative heat loss is expressed as a function of wind speed and the difference between saturation (e_s) and atmospheric vapor pressure (e_a), after Henderson-Sellers (1986)

$$H_E = \gamma L (a + bS)(e_s - e_a) \quad (6)$$

where γ is the specific weight of water (Kgf/m^3), L the latent heat of vaporization (kJ/Kg) and S the wind speed (m/s). Coefficients a and b are taken from Roesner (1969). Surface heat conduction accounts for heat transfer at the interface due to temperature differentials not associated with water vapour exchange (Edinger et al., 1974)

$$H_C = 0.6096 L (a + bW) \frac{P_a}{1013.25} (T - T_a) \quad (7)$$

where P_a is the atmospheric pressure (Pa) and T is the water surface temperature (K).

5. MODEL CALIBRATION

During calibration the vertical turbulent diffusion coefficient value was adjusted to $1 \times 10^{-6} \text{ m}^2/\text{s}$, a value equivalent to the kinematic viscosity of water at 20°C since vertical mixing in the Alqueva is minimal. Calibration was done without wind forcing. Instead evaporation rates were adjusted to include the effects of wind. Calibrated light extinction coefficient was 0.5 m^{-1} . This is an adequate value given that Secchi disk measurements in the Alqueva are on average 3m. The performance of the model was assessed by comparing model results

with measured data for 2005. A statistical evaluation was done using the root mean square deviation (RMSE)¹.

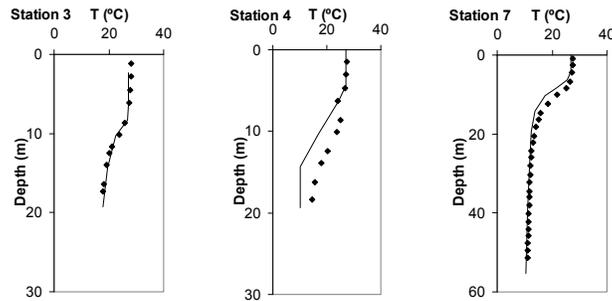


Figure 3- Vertical temperature profiles measured and modeled for stations 3, 4 and 7 for Julian day 220 (year 2005). Black points represent data. Black line represents simulation.

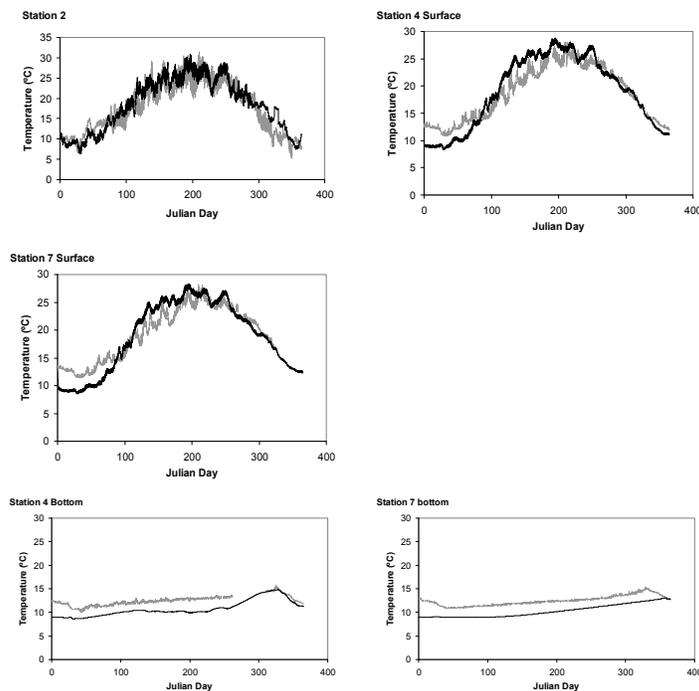


Figure 4– Temperature time series for surface and bottom water at stations 2, 4 and 7 for year 2005. Grey points represent monitoring data. Black line represents model results.

Table 1- Root mean square deviations for results in figure 4.

Location and layer	RMSE
Station 2	2.46
Station 4 surface	4.41
Station 7 surface	5.44
Station 7 bottom	2.37
Station 4 bottom	5.28

¹ $RMSE = \sqrt{\frac{\sum_{i=1}^N (x_{obsi} - x_{modi})^2}{N}}$, N is the number of observations, X_{obsi} is the observed value for the i^{th} observations and x_{modi} is the predicted value for the i^{th} observation.

Figure 3 presents simulated water temperatures vertical profiles and measured data for the same locations. The simulated profiles matched well the measured vertical profiles. Deviations (RMSE) were 0.81 (station 3), 4.01 (station 4) and 2.04 (station 7). The model also performed well when simulating seasonal temperature variations, including turnover and onset of stratification times. Figure 4 compares model results over time with monitoring data collected at several stations and depths. Table 1 presents the goodness of fit for the time series in figure 4. The observed higher bottom deviations are possibly due to the fact that the model considers that the vertical eddy diffusivity simply varies uniformly with depth

6. MODEL RESULTS: THERMAL STRATIFICATION

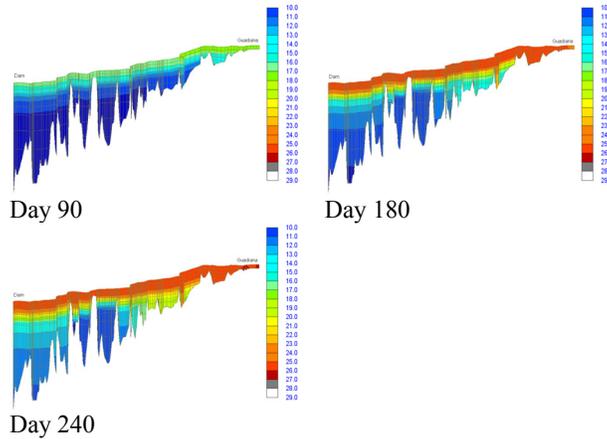


Figure 5– Simulated vertical temperature profiles in the Alqueva for Julian days 90, 180 and 240 (year 2006). No wind forcing.

Figure 5 presents a longitudinal elevation view of the Alqueva reservoir model domain evidencing the longitudinal and vertical modeled dimensions. The upstream Guadiana river inflow and the downstream dam location are shown. Figure 5 shows model results in terms of temperature profiles for Julian days 90, 180 and 240 of year 2006 obtained without wind forcing. The results show that a stable thermal stratification is formed in the water column and occurs from April to October. Metalimnion top and bottom temperatures are 26°C and 10°C, respectively, for the deepest areas of the reservoir, and higher bottom temperatures for more shallow locations. The shallower upstream areas of the reservoir contain only small longitudinal gradients of temperature during the wet season due to river input. These results follow closely measurements made *in situ* for both horizontal and vertical variations.

7. MODEL RESULTS: THERMAL RESPONSE TO WIND

Several meteorological stations measure wind speed and direction in the influence area of the reservoir. Measured values for different stations tend to present dissimilar values in magnitude and sometimes also in wind direction. Therefore it is difficult to determine the boundaries of the areas of the reservoir influenced by each measured set of wind. In addition, the measured wind may have intensities and directions different from the wind directly affecting the reservoir. Small hills and low vegetation are usual topographic elements surrounding the Alqueva that may cause a sheltering effect to the water, thus reducing the wind velocity at the water surface. Wind data sets are measured 8 m above the reservoir waters and do not account for this effect. Wind forcing in the model was done with wind data from station 4 located in a central area of the reservoir. Figure 6 presents model results for a scenario similar to that shown in figure 5 but with wind forcing added. Results show that applying wind forcing had the effects of adding a mixing disturbance to the top water layers and of accelerating water cooling the surface. However, the results obtained with wind forcing do not represent well the thermal variations in the reservoir.

Instead the results without wind reproduce much better water temperatures in the Alqueva. This can partially be due to the wind data issues described above. Further work with averaged wind datasets is currently been done.

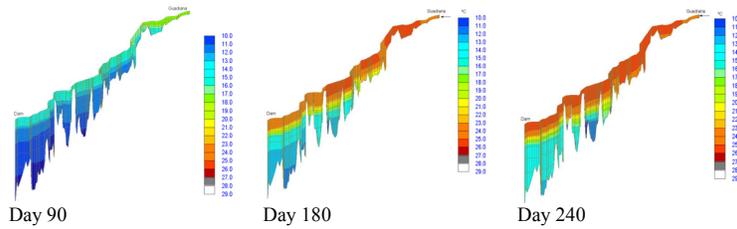


Figure 6– Simulated vertical temperature profiles in the Alqueva reservoir for Julian days 90, 180 and 240 (year 2006). with wind forcing.

8. MODEL RESULTS: THERMAL RESPONSE TO INFLOW VARIATIONS

The river Guadiana inflow temperature follows closely air temperature conditions. During the dry season the inflow presents water temperatures similar to the air temperature. During wet season the inflow is usually colder than the reservoir waters and air temperature. Understanding the effects that variations in the Guadiana inflow can have on the reservoir is rather important. The River is the main source of nutrients to the reservoir. Particularly it is the main source of phosphorus, the reservoir limiting nutrient. Temperature variations in the river inflow are likely to affect oxygen water solubility and kinetic biogeochemical rates in the reservoir area that is influenced by the Guadiana river flow and consequently affect biological behavior. Fluctuations in temperature and flow rate of the inflow may therefore shift in time and location the appearance and disappearance of phytoplankton populations. A simulation was done using Guadiana inflow daily values twice as much the 2006 values (scenario 2x Normal 2006 inflow in Figure 7). Water inflow temperature was considered the same as in the 2006 daily dataset. Results are compared with the 2006 situation (scenario Normal 2006 inflow in Figure 7). Results hint that no major alterations in water thermal profiles will occur during summer. A stable stratification is still observed during the same period and similar characteristics for the metalimnion are found. In contrast, for the wet season flow variations will affect the upper part of the reservoir (figure 7) and the higher the flow rate the longer the extension of the reservoir that is affected. The introduction of colder water from the river into the reservoir will lead to the development of a longitudinal temperature gradient starting at the Guadiana entrance and extending downstream. When inflow was doubled the extension of the reservoir that was affected by the cold stream was larger. This will cause a lowering of the temperature in the affected area of up to 6 °C. Thus inflow rate variations will influence nutrients and constituents distribution and concentration in the reservoir during the wet season.

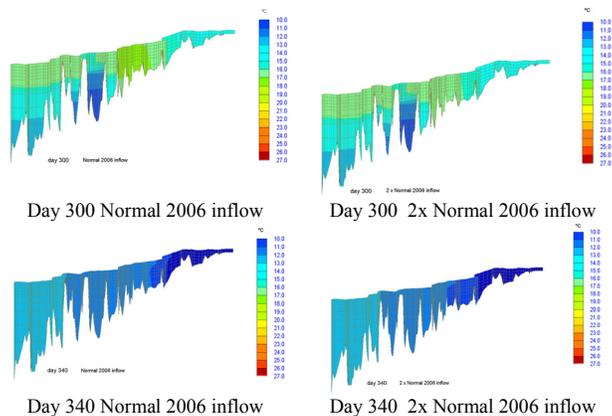


Figure 7 – Simulated vertical temperature profiles in the Alqueva reservoir for Julian days 300 and 340 (year 2006) for two Guadiana inflow situations.

CONCLUSIONS

The finite element model RMA10 was used to simulate the thermal structure of the Alqueva reservoir. After successful calibration, the model was used to simulate temporal and spatial distribution of water temperature for the year 2006 and subsequently used to test the influence of hydrological and meteorological conditions changes. An assessment of model results against data collected for the simulated periods showed that the model accurately predicted thermal behavior. The reservoir has a stable thermal stratification during summer (April-October period). Metalimnion top and bottom temperatures are 26°C and 10°C respectively for the deepest areas of the reservoir. Higher bottom temperatures can be found in more shallow locations. The circulation in reservoir lower part has been shown to depend strongly on wind (Lindim et al., 2010). Wind accelerates cooling at water surface and contributes to enhancing mixing at water top layers. This effect was added in the model by changing evaporation rates and vertical diffusion. When forcing the model directly with wind data results did not reproduce well thermal reality in the reservoir mostly due to the quality and representativity of wind data sets available. The model results show that the Guadiana river inflow dynamics has an impact in the upper part of the reservoir. Inflow rate variations affect water temperatures in that area and the distributions of dissolved oxygen and nutrients. Consequently Guadiana inflow changes can shift in time and location phytoplankton populations.

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