Evaluation of the trophic status in a Mediterranean reservoir under climate change: An integrated modelling approach

Carina Almeida, Paulo Branco, Pedro Segurado, Tiago B. Ramos, Teresa Ferreira, Ramiro Neves and Rodrigo Proença de Oliveira

ABSTRACT

This study describes an integrated modelling approach to better understand the trophic status of the Montargil reservoir (southern Portugal) under climate change scenarios. The SWAT and CE-QUAL-W2 models were applied to the basin and reservoir, respectively, for simulating water and nutrient dynamics while considering one climatic scenario and two decadal timelines (2025–2034 and 2055–2064). Model simulations showed that the dissolved oxygen concentration in the reservoir’s hypolimnion is expected to decrease by 60% in both decadal timelines, while the chlorophyll-a concentration in the reservoir’s epilimnion is expected to increase by 25%. The total phosphorus concentration (TP) is predicted to increase in the water column surface by 63% and in the hypolimnion by 90% during the 2030 timeline. These results are even more severe during the 2060 timeline. Under this climate change scenario, the reservoir showed a eutrophic state during 70–80% of both timelines. Even considering measures that involve decreases in 30 to 35% of water use, the eutrophic state is not expected to improve.

Key words | climate change, modelling, reservoir, trophic status

HIGHLIGHTS

- Mediterranean reservoirs typically show heavily modified water quality due to irrigation needs that are predicted to increase under future climate change and will pose new management challenges.
- With this work, we filled an important gap of knowledge by modelling how water quality variables and quantity will decrease under future climate change and societal scenarios in a typical Mediterranean reservoir.
- Predictions were accomplished by integrating basin and reservoir modelling tools, allowing analysis of the continuous inflow to the reservoir and its changes in water quality under the influence of climate change.
- The reservoir under study is predicted to evolve to a eutrophic status, even with the implementation of measures to reduce irrigation water consumption.
- The study indicates that global changes will pose greater challenges than expected on the implementation of effective management actions to prevent the general decrease in water quality.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (http://creativecommons.org/licenses/by/4.0/).

INTRODUCTION

The European Water Framework Directive (WFD; 2000/60/EC) was adopted in 2000 as the main policy instrument for reaching a good ecological status of European surface waters by 2015. However, this objective fell short as 47% of the European surface waters still fail to meet such conditions (EC 2012). Such outcome begs for a more sustainable and holistic approach to water management (Voulvoulis et al. 2017), particularly in the context of climate change (CEC 2009). In a future scenario perspective, climate change is expected to impact the availability, seasonality and variability of water resources (IPCC 2013). The adoption of climate change adaptation strategies by member states is one of the concerns of the European Commission, who underlined the importance of an integrated analysis of impacts and a comprehensive adaptation strategy to that problem (Biesbroek et al. 2010).

In southern Portugal, many hydro-agricultural infrastructures (reservoirs) exist and are used to face water scarcity resulting from the Mediterranean climate seasonal and intra-annual variability. These aquatic systems are classified as heavily modified water bodies (HMWB) by the WFD. According to the Commission of the European Communities (CEC 2015), only 30% of these heavily modified water bodies showed good ecological potential in 2015, with problems arising from difficulties in the management of riverbanks and drainage basins, and the occurrence of frequent eutrophication episodes with cyanobacteria blooms and high ichthyofaunal mortality (Godinho et al. 2019).

The use of predictive models for simulating the ecological conditions has many advantages over simple monitoring, allowing prediction of the future status of a system resulting from changes of different environmental factors. The ecological status of reservoirs is inextricably linked to its drainage basin, and models enable the assessment of basin-originated impacts on reservoirs in an integrated way according to the Driver-Force–Pressure–State–Impact–Response (DPSIR) approach (EEA 2007; Marty et al. 2014), offering also the possibility of addressing scenarios for future conditions. The integration of basin and reservoir models has been often used to study the water quality and trophic status of the Mediterranean reservoirs. For example, Saddek & Casamitjana (2018) applied a one-dimensional hydrodynamic and water quality model to study the water quality behaviour in the Boadella reservoir, Catalonia, Spain. Zouabi-Aloui & Gueddari (2014) analysed three scenarios involving the impacts of severe drought season, summer rainfall and total suspended solids load on hydrodynamics and water quality of a stratified dam reservoir on the southern side of the Mediterranean Sea. Also, Nsiri et al. (2016) applied a modelling approach to study the thermal stratification and its effect on water quality in four reservoirs in Tunisia. In Portugal, the National Water Institute (INAG) carried out an integrated modelling study to gain knowledge of the trophic levels of 30 reservoirs under the scope of the Waste Water Treatment Plant directive (INAG 2009). Several other studies were carried out to analyse water quality and, consequently, the trophic state of reservoirs in southern Portugal, including: those aimed at finding a solution for the constant eutrophic state of the Enxó reservoir (Fontes 2010; Ramos et al. 2015a, 2015b, 2018; Brito et al. 2017, 2018); the assessment of water quality in the Alqueva reservoir through data analysis techniques and numerical modelling (Fontes 2010); and the quantitative and qualitative assessment of the relationship between eutrophication and ground baiting in angling competition in the Maranhão reservoir (Amaral et al. 2013). Nevertheless, there is a gap in studies including water quality status predictions in typically Mediterranean climate study cases under future environmental global changes.

Therefore, the objective of this study is to evaluate the present and future trophic status of a typical Mediterranean reservoir located in southern Portugal using modelling as an integration tool of the drainage basin and reservoir. For this purpose, a climate model is used as boundary condition to a basin model which, in turn, is integrated into a reservoir model. The specific objectives are: (1) to determine the trophic status of the reservoir while considering baseline
conditions and future climate scenarios; and (2) to model possible management actions as measures to improve the trophic status under future climate change and socio-economic scenarios. This study is particularly relevant in performing an integrated modelling approach to analyse the trophic status of a HMWB under the context of climate change and sustainable use of water resources in the future and its implications. Therefore, although it is a case study undertaken at a local scale, it may provide insights with a wider application to reservoirs within the Mediterranean region with similar future climatic trend.

This study is an articulation between the hydrological modelling with the Soil and Water Assessment Tool (SWAT) and an integration of a reservoir (Montargil) modelling using the Hydrodynamic and Water Quality Model (CEQUAL-W2). Climate models and future societal storylines, including future scenarios of basin usage, were analysed to understand how future practices may impact negatively or positively the trophic status of a Mediterranean reservoir. The results are presented and discussed within a broader context, departing from the outputs of the case study to wider generalizations and further supported by relevant scientific literature.

MATERIALS AND METHODS

Study area

The Montargil reservoir with a drainage area of 1,200 km² is located in one sub-basin of the Sorraia River, southern Portugal, as shown in Figure 1. The climate has a typical Mediterranean behaviour with dry and hot summers, and mild and wet winters. The maximum reservoir capacity is 164 hm³; the maximum water surface elevation is 80 m; and the minimum water surface elevation acceptable for operation is 65 m, which correspond to a dead storage pool of 143 hm³. The reservoir is part of the Vale do Sorraia watering system, controlled by the local Water Board (Associação de Regantes e Beneficiários do Vale do Sorraia, ARBVS) since 1970. The Sôr River, a tributary of the Sorraia river, supplies most of the water to the reservoir (60–70%), with minor contributions from several ephemeral streams during winter. The water level is regulated by water demand for irrigation and meteorological conditions. Additional uses are electric power generation, fishing and recreation (water sports). The tourist potential of the location (close to Lisbon) is currently recognized in the reservoir ordinance plan (approved by the Portuguese Minister Council resolution no. 94/2002).

The use of the reservoir for recreational purposes has increased, but some bathing water quality issues have been raised at some locations with the reservoir occasionally failing to comply with the 2006/7/EC (EU 2006) directive due to high bacterial concentrations. The reservoir has also registered cyanobacteria blooms over the years, with reports going back to 1995 (Pereira et al. 2001). The worst year was 1996 with several blooms of toxic species (Aphanizomenon flos-aquae, Aphanizomenon gracile, Anabaena spiroides, and Microcystis aeruginosa) being recorded (Ferreira et al. 2009).

The main land use in the upstream catchment is forest with oak trees, covering more than 40% of the watershed area. Annual crops account for 13% of the watershed area while some irrigation cropping is present on 2% of the area. The connection between agricultural activities, point sources and nutrient enrichment of the reservoir is an open subject for this area as is the relationship between nutrient enrichment and cyanobacteria domination over certain periods of time. These relationships are fundamental for improving both policies related to reservoir management.

Hydrological modelling

The soil and water assessment tool model (SWAT)

Diffuse pollution and inflows to the Montargil drainage basin were simulated with the SWAT model (Neitsch et al. 2009) in Segurado et al. (2018) and Almeida et al. (2018, 2019). Readers are thus directed to those studies (Almeida et al. 2018, 2019; Segurado et al. 2018) for a detailed description of the modelling approach adopted for quantifying water and nutrient yields from the watershed. The SWAT model was applied to the Montargil basin using the ArcSWAT version. The model application relied on available GIS maps for topography from Shuttle Radar Topography Mission with 90 m resolution, land use from

...
Earth Observation (EO) GSE Land M2.1 with 20 m and 300 m detail, and Cardoso (1965) soil maps (1:25,000 scale) and properties from reference soil profiles. Climatic maps, including daily precipitation, temperature, relative humidity and wind speed were derived from the Portuguese National Institute of Water Resources, SNIRH (SNIRH 2018). Downstream the Montargil reservoir, daily discharge data provided by the reservoirs’ manager (ARBVS – Farmers Association from the Sorraia Valley) were considered in the model for the period from 1996 to 2015. The baseline simulation was thus defined for this period (1996 to 2015). The SWAT model calibration and validation for the Montargil basin was carried out by comparing simulated and observed flows at the Moinho Novo hydrometric station (latitude 39.228°; longitude –8.029°). The model was manually calibrated by trial and error and, when a satisfactory match was found between the observed and the computed discharge, the coefficient of determination ($R^2$), the root mean square error (RMSE) and the modelling efficiency (NSE) were used to evaluate the calibration performance and subsequently the validation. The calibration covered the period between January 1996 and January 2005, while the validation covered the period from January 2005 to January 2015.

Reservoir modelling

Hydrodynamic and water quality model (CE-QUAL-W2)

The CE-QUAL-W2 is a bidimensional model that assumes lateral homogeneity and supports vertical and horizontal gradients of all calculated properties (Cole & Wells 2015). The current version (version 4.1) simulates the systems hydrodynamics and water quality both vertically and longitudinally in both stratified and not stratified systems.

This model computes biogeochemical processes such as nitrogen, phosphorus, carbon and oxygen cycles, as well as the dynamics of algae and organic matter. In the organic matter (OM), the dissolved non-refractory OM (LDOM), the dissolved refractory OM (RDOM), the particulate

\[ \text{Figure 1: Montargil sub-basin, reservoir and locations of gauging stations.} \]
non-refractory OM (LPOM) and the particulate refractory OM (RPOM) are considered in the model.

The model boundary conditions included daily river inputs of $\text{NO}_3^-$, $\text{NH}_4^+$, organic matter, orthophosphate, total suspended solids and $\text{O}_2$ computed with the SWAT model (Almeida et al. 2018, 2019; Segurado et al. 2018). Daily weather data (air temperature, humidity, wind velocity and direction, cloud cover and solar radiation) were provided by SNIRH for the period 2005–2014 (SNIRH 2018).

Bathymetry was constructed considering the work already done in Almeida et al. (2019), where the topography map with 90 m resolution was converted and adjusted until the model elevation–volume curve adherence to measurements was obtained. Owing to the model requirements this bathymetry was defined in longitudinal and vertical segments, and cell widths. Therefore, the Montargil reservoir was described at full capacity with a geometry consisting of 13 segments with lengths of 360–2,700 m and widths of 500–3,000 m at the surface, as shown in Figure 2. These segments and respective lengths and widths were defined in relation with the elevation–volume curve to better represent the reservoir variation from upstream to downstream, mainly the stratification and volume. The larger the segment discretization, the better the representation of water processes. Nonetheless, a significant increase of number of segments can further compromise computational efficiency. As shown in Figure 2 (a), a minimum of four vertical layers upstream and a maximum of 32 layers near the dam, all of 1 m high, were considered to represent each water column. Also, the effluent reservoir discharge provided from ARBVS, which translates the water used for irrigation purposes in the downstream area, was used as outflow.

The calibration and validation exercise was based on the comparison of in-field measurements of hydrodynamic and water quality variables against model results. The 2005–2014 period was considered as the baseline for reservoir operation simulation. The measured data used for calibration of the CE-QUAL-W2 model were: water level; seasonal profiles of temperature and dissolved oxygen measured by Ferreira et al. (2009) during February, May and August 2006; and water surface elevation provided by SNIRH for the period 2005–2013. For validation, the data used were: reservoir surface data of water temperature, dissolved oxygen, total N, total P, chlorophyll-a, and TSS obtained from SNIRH for the period 2005–2013. The validation exercise considered the comparison between model and field measurements of water surface temperature, dissolved oxygen, total N, total P, chlorophyll-a, TSS, as well as the average, standard deviation and median analysis of each property.

Climate model and storyline

This work followed the framework established by Grizzetti et al. (2014) and Birk et al. (2018) during the Project ‘Managing Aquatic Ecosystems and Water Resources Under Multiple Stress – MARS’ (Hering et al. 2015), which was also adopted by Segurado et al. (2018) and Almeida et al. (2018, 2019) for the Montargil basin and reservoir. Hence, this study adopted the IPSL-CM5A-LR model (Dufresne...
et al. 2013; O’Neill et al. 2014) for defining the atmospheric boundary conditions. This is one of the global circulation models developed to study the long-term response of the climate system to natural and anthropogenic forcing as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5). This model considers a decrease of 50% precipitation when compared to the historical data, while air temperature predictions show larger monthly amplitudes, as shown in Table 1.

Bias-corrected time-series of air temperature and precipitation downscaled at a 0.5° resolution (Hempel et al. 2013) were considered. Additionally, historical air temperature and precipitation data for the case study area and for the period 2005–2014 were corrected using a linear scaling bias correction method developed by Shrestha (2015), as shown in Almeida et al. (2018). This method is based on the average difference between monthly observed and historical time series for the same period, and is considered as having identical performance compared to complex bias correction techniques (Shrestha et al. 2011). This ten-year period (2005–2014) was selected as a reference for the present condition (baseline simulation) and two distinct temporal intervals were set up to run the future simulations: 2030 (defined as a ten-year average from 2025 to 2034) and 2060 (defined as a ten-year average from 2055 to 2064).

This study further considered the storyline proposed by O’Neill et al. (2014) and Moss et al. (2010), which results from the combination of the Shared Socioeconomic Pathway-2 (SSP-2) defined as an intermediate stage in the evolution of society and ecosystems over a century timescale (Warszawski et al. 2014; Riahi et al. 2017), and the Representative Concentration Pathways 4.5 (RCP 4.5). It has been shown elsewhere (Almeida et al. 2018, 2019; Segurado et al. 2018) that severe impacts resulted even when considering a storyline which reproduces some environmental concerns. Therefore, this storyline was selected to explore the effects of managing irrigation, even with a non-severe scenario. Thus, the underlying premise in selecting this storyline is that in case substantial effects of management scenarios are predicted to occur, they will most certainly also occur if more severe scenarios were to be taken into account.

The downscaling of management practices change in Montargil catchment was performed with the support of the local water board stakeholders (ARBVS), similarly as in Almeida et al. (2018, 2019). Accordingly, as shown in Table 2, in the scenario here considered, the application of fertilizers was predicted to decrease by 10 and 15% in the 2030 and 2060 timelines, while irrigation needs would decrease by 20 and 25% during the same time periods.

### RESULTS AND DISCUSSION

#### Water quality of reservoir inflows

A good agreement was found between the SWAT model (basin model) and measured discharge at Moinho Novo location (Figure 1) data during the calibration period (1996–2005), especially on a monthly basis, resulting in a

| Table 1 | Average monthly temperature (°C) and precipitation (mm) for the baseline condition and climate model timelines – 2030 and 2060 |
| --- | --- | --- | --- | --- | --- | --- |
| Month | Temperature | Precipitation |
| | Baseline | 2030 | 2060 | Baseline | 2030 | 2060 |
| January | 8.0 | 4.2 | 4.7 | 56 | 14 | 36 |
| February | 9.4 | 5.3 | 6.1 | 41 | 30 | 47 |
| March | 11.0 | 8.2 | 9.5 | 47 | 32 | 33 |
| April | 13.4 | 9.3 | 10.6 | 47 | 14 | 17 |
| May | 16.7 | 14.0 | 15.8 | 36 | 20 | 10 |
| June | 20.2 | 22.5 | 23.7 | 11 | 12 | 8 |
| July | 23.1 | 29.5 | 31.3 | 3 | 0 | 0 |
| August | 22.6 | 29.2 | 30.9 | 6 | 2 | 2 |
| September | 20.4 | 25.4 | 26.9 | 30 | 7 | 8 |
| October | 16.1 | 17.6 | 18.3 | 84 | 50 | 39 |
| November | 11.9 | 8.0 | 8.9 | 64 | 40 | 23 |
| December | 9.0 | 4.6 | 5.7 | 62 | 43 | 28 |
| Difference | − | −2% | +5% | − | −46% | −48% |

| Table 2 | Input values used for simulating the scenario in SWAT and CE-QUAL-W2 models |
| --- | --- | --- | --- |
| Management practices | Baseline | Timeline | Variation (%) |
| Fertilization (kg/ha) | 492 | 2030 | −10 |
| | | 2060 | −15 |
| Irrigation (mm) | 430 | 2030 | −20 |
| | | 2060 | −25 |
R² value of 0.71, a RMSE value of 6 m³/month and a NSE value of 0.71. During the validation period the same behaviour was found, with a R² value of 0.68, a RMSE value of 7.5 m³/month and a NSE value of 0.67. Due to the lack of continuous data and for a longer period of time, no calibration of the model in the water quality parameters was performed. However, the validation was performed by comparing the observed and computed results, in order to observe if there were outliers or values that might not represent the reality of the area. The SWAT model validation of N and P simulations was performed at Ponte de Coruche station (Figure 1) from 2005 to 2015. For total N, a R² value of 0.59 and a bias of 0.22 mg N L⁻¹ was found. For total P, model comparison to measured data produced a R² value of 0.14 and a bias of -0.067 mg P L⁻¹. Further results of simulations of the SWAT model can be found in Segurado et al. (2018) and Almeida et al. (2019, 2018).

After calibration and validation, the SWAT model was used to simulate water quantity and quality of reservoir inflows for the baseline and climate timeline scenarios (2030 and 2060 periods) in order to analyse the future impacts that may result from these future changes. These results were obtained from daily outputs of the SWAT model, with the monthly average being then analysed. A decrease of 47 and 69% of reservoir inflows was estimated for the 2030 and 2060 timelines, respectively, which is in agreement with the results found by Almeida et al. (2018, 2019). These authors found an average decrease of inflows by 31% for the 2030 timeline and 66% for the 2060 timeline. This decreasing trend in streamflow is expected in several Mediterranean case studies, resulting mainly from precipitation reduction as shown in De Luis et al. (2009), García-Ruiz et al. (2011), Pascual et al. (2015) and Bucak et al. (2017). Nitrate concentration increased by 64 and 75% during the 2030 and 2060 timelines, mostly due to the decreasing of the water flows. The difference in the orthophosphate concentration was not so pronounced, decreasing by 23% in 2030 and increasing by 11% in 2060. This slight variation may be due to the low mobility of P, which is dependent on runoff and soil erosion when compared to N, which is mainly transported through leaching. The dissolved oxygen concentration was observed to decrease by 1 and 2% during the 2030 and 2060 timelines, respectively. The deterioration of water quality was thus noticed even though agriculture was not predominant in the Montargil basin and fertilizer application also decreased as considered in the simulated scenario. These long-term results were afterwards considered as boundary condition for reservoir model Ce-QUAL-W2.

**Calibration and validation of reservoir model**

The reservoir model, like the discharge model, was manually calibrated by trial and error, for water levels and for temperature and dissolved oxygen profiles. The performance measures (R², RMSE and NSE) were used to evaluate the performance of the calibration and subsequently the validation. As presented in Figure 3, the simulation of the baseline period showed a close match between the CE-QUAL-W2 model results and observed water surface elevation, with a R² of 0.92. This is the first step in the calibration procedure: adjust the water quantity before water...
quality calibration and validation. The model kinetic coefficients were used for calibrating the temperature and dissolved oxygen, as shown in Table 3. The parameters related to extinction coefficients that control light availability at lower depths were first reduced. The different parameters related to growth rates and optimum temperatures for the different algal species were also adjusted while considering mainly oxygen depletion.

The model after calibration was able to describe temperature and dissolved oxygen profiles particularly during the main seasons, summer and winter, as shown in Figure 4. The results for the vertical temperature profiles showed a noticeable seasonality in the surface layer where the influence of solar radiation, air temperature and wind were evident. This is a typical behaviour of Mediterranean reservoirs where a marked seasonality is obvious (Sellami et al. 2010; Tornés et al. 2014; Hassen et al. 2019). As presented in Figure 4, the thermocline occurred around 5–10 m depth during August, when air surface temperatures were higher and flows were reduced, with differences reaching 15 °C from surface to bottom while the dissolved oxygen changed from 9 mg·L⁻¹ to 0 mg·L⁻¹. During February 2006, stratification disappeared, probably due to the combined action of increased wind velocity in the surface layer, cooling and increased flows. During this season, a homogeneous temperature profile was observed (Figure 4). The thermal stratification and mixing influenced the dynamics of primary production, controlling light and nutrient availability. During winter, the decreased stratification effect created a homogeneous profile of temperature, while nutrient availability existed from the bottom to surface layers.

The validation exercise considered the comparison between the model outputs and the available daily field measurements of water surface temperature, dissolved oxygen, total N, total P, chlorophyll-a and TSS. The comparison made for simulated and measured surface water temperature showed that the model was able to represent the seasonality of the reservoir as well as minimum and maximum values for the period considered. As described in Figure 5, the average temperature was 18 °C (Table 4), ranging from 10 °C in winter to 25 °C during the warmer

### Table 3 | The kinetic coefficients and values for the Montargil reservoir

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Default value</th>
<th>Calibrated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXH2O</td>
<td>Extinction for pure water (m⁻¹)</td>
<td>0.25 or 0.45</td>
<td>0.25</td>
</tr>
<tr>
<td>EXOM</td>
<td>Extinction coefficient for organic matter (m⁻¹)</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>EXZOO</td>
<td>Extinction coefficient for zooplankton (m⁻¹)</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>BETA</td>
<td>Fraction of incident solar radiation absorbed at the water surface (%)</td>
<td>0.45</td>
<td>0.55</td>
</tr>
<tr>
<td>AG-1</td>
<td>Algal growth rate for diatoms (day⁻¹)</td>
<td>0.3–3.0</td>
<td>1</td>
</tr>
<tr>
<td>AG-2</td>
<td>Algal growth rate for Chlorophyceae (day⁻¹)</td>
<td>0.7–9.0</td>
<td>0.7</td>
</tr>
<tr>
<td>AG-3</td>
<td>Algal growth rate for Cyanobacteria (day⁻¹)</td>
<td>0.5–11</td>
<td>0.5</td>
</tr>
<tr>
<td>AT1-2</td>
<td>Algal minimum temperature for Chlorophyceae (°C)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>AT1-3</td>
<td>Algal minimum temperature for Cyanobacteria (°C)</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>AT2-1</td>
<td>Algal first optimum temperature for diatoms (°C)</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>AT2-2</td>
<td>Algal first optimum temperature for Chlorophyceae (°C)</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>AT2-3</td>
<td>Algal first optimum temperature for Cyanobacteria (°C)</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>AT3-1</td>
<td>Algal last optimum temperature for diatoms (°C)</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>AT3-2</td>
<td>Algal last optimum temperature for Chlorophyceae (°C)</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>AT3-3</td>
<td>Algal last optimum temperature for Cyanobacteria (°C)</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>AT4-1</td>
<td>Algal maximum temperature for diatoms (°C)</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>AT4-2</td>
<td>Algal first maximum temperature for Chlorophyceae (°C)</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>AT4-3</td>
<td>Algal first maximum temperature for Cyanobacteria (°C)</td>
<td>40</td>
<td>30</td>
</tr>
</tbody>
</table>
season. The model was able to reproduce the trend of surface dissolved oxygen (average 9 mg·L⁻¹ and a standard deviation of 1.6 mg·L⁻¹ in the modelled data and 1.9 mg·L⁻¹ in the field data) as shown in Table 4, including saturation resulting mostly from the rapid increase/accumulation of algae (algae bloom). In general, the dissolved oxygen concentration in the Montargil reservoir did not vary below the limit value of 5 mg·L⁻¹, which is where the potential ecological state may be compromised (Ferreira et al. 2009; INAG 2009). The field data on total nitrogen concentration were too scarce to infer significant differences, although the recorded and modelled mean values were within the same order of magnitude (average 1.4 mgN·L⁻¹ and range from 0.5 mgN·L⁻¹ to 5 mgN·L⁻¹, and a standard deviation of 0.8 mg·L⁻¹ modelled and 0.3 mg·L⁻¹ in the field data), as indicated in Table 4 and Figure 5. Total phosphorus concentration was acceptably reproduced (average 0.2 mgP·L⁻¹), despite producing a slight overestimation of the measured values. Likewise, the chlorophyll-α data in the reservoir was in agreement with the measured data, averaging 22.0 μg·L⁻¹ (Table 4), and revealing maximum concentrations reaching values above 50 μg·L⁻¹ during the simulated time period. In general, the concentration values related with algae blooms are above the limit of eutrophication when higher than 10 μg·L⁻¹ (Chapra 1997). The measured data presented significant variation, with the model reproducing well the seasonal pattern, as presented in Figure 5. The CE-QUAL-W2 model was also able to reproduce the trends of TSS during the period (average of 11 mg·L⁻¹ modelled and 9 mg·L⁻¹ in the field data, and a standard deviation of 8.9 mg·L⁻¹ modelled and 7 mg·L⁻¹ in the field data), which were consistent with the inflows from the drainage basin.

Assessment of climate change impact on reservoir water quality

After the CE-QUAL-W2 model calibration and validation, the baseline and climate change scenario (SSP-2/RCP 4.5) results were analysed on an annual, monthly and daily basis to understand and evaluate the evolution of Montargil’s trophic state.

The predicted decrease of reservoir inflows in both timelines (2030 and 2060) led to a decrease of water levels by
10% even when assuming a decrease of 20 and 25% in future irrigation needs, as presented in Table 2. This is in accordance with Almeida et al. (2019), who considered more severe climate scenarios for the Montargil basin, which limited even more water availability in the reservoir. In the Mediterranean region, Milly et al. (2005) predicted a decrease by 10–30% in runoff; and Bucak et al. (2017) predicted the possibility in the future of drying out of the Lake Beyşehir catchment in Central Anatolia, Turkey.

The decrease in the inflows to the reservoir will increase residence time, which leads to an increase in the nutrient concentration and, in turn, a decrease in dissolved oxygen concentration. This decrease of water inflow will thus decrease the dilution and flushing effect resulting in an increase of nutrient concentration and, consequently, also of the plankton algae biomass (Bartoszek & Koszelnik 2015).

The dissolved oxygen concentration in the water surface layer epilimnion (considered at 0.8 m depth) showed a minor decrease for both timelines, with reductions reaching 4% when compared to the baseline mean value, as
presented in Table 5. The highest reduction is observed in the hypolimnion (considered at 20 m depth), with the model predicting a reduction of 58% and 62% for the 2030 and 2060 timelines, as shown equally in Table 5.

The monthly averages of the dissolved oxygen concentration for the 30 years considered (baseline, 2030 and 2060 decades) revealed, as expected, a decrease during months with higher temperature and lower inflow rate. In the epilimnion layer, values did not vary considerably and were maintained above the minimum limit considered for a water body to be classified as having good ecological potential, which is above 5 mg·L\(^{-1}\) according to INAG (2009). Nonetheless, for dissolved oxygen, the focus of the analysis should be the hypolimnion where the dissolved oxygen registered values close to 0 mg·L\(^{-1}\) for several months for both timelines. A daily basis analysis showed that DO concentration was lower than 5 mg·L\(^{-1}\) in 36% of the baseline simulated days; contrarily, that condition was predicted to occur in 66 and 69% of the simulated days for the 2030 and 2060 timelines, respectively, thus clearly indicating a tendency for the Montargil reservoir to evolve to a hypereutrophic state.

In addition to DO concentration, chlorophyll-\(a\) and total phosphorus concentration are essential for trophic analysis. Chlorophyll-\(a\) is a pigment common in most primary producers and appears as a biological variable of easy determination, indicative of plant biomass. This is the reason why it has been used in different water classification systems, namely, in the classification of the trophic state by the Organisation for Economic Co-Operation and Development (OECD) (Caspers 1984).

In Table 5, the increase in the chlorophyll-\(a\) concentration in the epilimnion layer is visible during both timelines, averaging 25% and 20% when compared to the baseline mean value. In contrast, a reduction of 13% in the 2050s and 46% in the 2060s was observed in the hypolimnion layer, as presented in Table 5. This decrease was mainly due to photosynthesis and DO limitation. Monthly chlorophyll-\(a\) concentration values increased mainly during the spring months (mainly during April and May). The reservoir was considered as oligotrophic (chlorophyll-\(a\) <2.5 μg·L\(^{-1}\)) during most part of the baseline period (55%), yet presenting a eutrophic state (chlorophyll-\(a\) >10 μg·L\(^{-1}\)) during the remaining period. Model simulations showed that for the 2030 and 2060 timelines, there is a tendency for an increase of the number of days in which a eutrophic state is recorded, covering 69 and 81% of the days in the 2030 and 2060 periods, respectively, and a decrease of the number of days predicted to attain an oligotrophic state was only noticed on 15 and 31% of the days. Total phosphorus concentration increased in both layers during the period under analysis. In the epilimnion layer, total phosphorus concentration increased by 62% in both scenarios when compared with the baseline mean value, as shown in Table 5. In the hypolimnion layer, that increase reached 90 and 118% during the 2030 and 2060 timelines, as presented in Table 5, being mostly explained by the availability of phosphorus in the sediment bottom (Jouni 2011) and the lower percentage of oxygen saturation. This is in line with the studies in Mediterranean lakes and lagoons which reported nutrient release from the bottom sediment (Gikas et al. 2006; Beklioglu et al. 2007; Chamoglou et al. 2014). Considering the maximum limit established by INAG (2009) to maintain the good ecological status of a reservoir (0.07 mg·L\(^{-1}\)), the annual average of total phosphorus concentration in the Montargil reservoir indicates mostly a eutrophic state.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Layer</th>
<th>Temperature</th>
<th>DO</th>
<th>CHLA</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>Epilimnion</td>
<td>+3</td>
<td>-4</td>
<td>+25</td>
<td>+63</td>
</tr>
<tr>
<td></td>
<td>Hypolimnion</td>
<td>-8</td>
<td>-58</td>
<td>-13</td>
<td>+90</td>
</tr>
<tr>
<td>2060</td>
<td>Epilimnion</td>
<td>+3</td>
<td>-4</td>
<td>+20</td>
<td>+62</td>
</tr>
<tr>
<td></td>
<td>Hypolimnion</td>
<td>-14</td>
<td>-62</td>
<td>-46</td>
<td>+118</td>
</tr>
</tbody>
</table>
Model simulations show that the trophic status is expected to deteriorate due to climate change, similarly as in Karla’s Lake in Greece where phosphorus concentration far exceeded the limit of good ecological status (Chamoglou et al. 2014). Several studies have already shown unacceptable ecological status in many reservoirs, such as the eutrophic Enxó reservoir in southern Portugal, according to Brito et al. (2017), where only with structural measures trophic state may improve; Navarro et al. (2014) also predicted a deterioration of trophic conditions in the Pareja limnoreservoir, Spain, in most of the future scenarios considered; and the same in the study of Chang et al. (2015), which related the thermal stratification caused by the rising temperature in the future, with the higher risk of eutrophication.

Considering the results found in this study and taking as well into consideration previous studies focused on the same study area (Almeida et al. 2018, 2019; Segurado et al. 2018), where the major impact on water quality was shown to be mainly related to water scarcity, as a result of precipitation decrease, scenarios considering a decreasing irrigation need (by 30 and 35%, respectively, for 2030 and 2060) were considered. These scenarios, comparable to a decreasing water abstraction measure, were considering analysis of whether a less abrupt decrease in water level would result in an improvement of the future trophic state.

As shown in Figure 6, with the implementation of a 30 and 35% reduction in water abstraction for irrigation, a small improvement in the reservoir water quality concerning total phosphorus (on average −10% in 2030 and −20% in 2060) and chlorophyll-a (on average −14% in 2030 and −31% in 2060) was observed. On average, the dissolved oxygen concentration has remained constant, although in the years where the concentration is predicted to increase, the reservoir does not reach an acceptable good quality status, as presented in Figure 7.

Concerning the impact of these water quality indicators on aquatic life, additional measures should be tested,
considering the limitations of these strategies: these include reduction on water abstraction for irrigation by an improved adaptation to seasonal changes, or through incentives to encourage land use transition from irrigated crops to rainfed crops. Nevertheless, both considered scenarios may be treated as measures to be implemented in the future.

CONCLUSIONS AND FUTURE RESEARCH

The integrated modelling approach used here proved to be an asset for management purposes since it allowed continuous analysis of the inflow to the reservoir and its changes in the water quality under the influence of climate change. It is concluded that the case-study reservoir, as a consequence of the decrease of the inflows and increase of nutrient concentrations as well as consequence of the decrease of precipitation observed in the region, will suffer an increase in nutrient and chlorophyll-a concentrations and a decrease in dissolved oxygen. In general, considering all water quality variables here analysed, the future tendency of the studied reservoir is for an increasing eutrophic state, even considering a scenario of decreasing water abstraction. These results suggest that the ecological status of this reservoir will be strongly impacted, compromising the survival of many fish species, mainly due to the high variation of dissolved oxygen with low levels during long periods of time.

Measures should be implemented to counteract more efficiently the predicted effects of climate change and should be preferably preventive, in opposition to corrective, to reduce both financial and environmental costs. Alternative management scenarios could be incorporated within the integrated modelling approach developed in the present study to predict their outcomes and anticipate cost-effective measures. As similar climatic future tendencies are foreseen across the Mediterranean region (Chamoglou et al. 2014; Molina-Navarro et al. 2014; Chang et al. 2015), the trophic status trends under climate change scenarios predicted by this study, as well as the outcomes of the management scenarios, might be generalized to similar Mediterranean basins. These studies should provide tools to water managers allowing them to act in a timely fashion without compromising the ecosystem, and in this way accomplishing more effectively the community objectives established by Water Framework Directive.

ACKNOWLEDGEMENTS

This work was supported by FCT/MCTES (PIDDAC) through project LARSys - FCT Plurianual funding 2020-2023 (UIDB/50009/2020). Tiago Ramos was supported by contract CEECIND/01152/2017. Pedro Segurado was supported by the contract funded by the Fundação para a Ciência e Tecnologia (FCT) under the IF Researcher Programme (IF/01304/2015). Paulo Branco was supported by national funds through FCT under ‘Norma Transitória – DL57/2016/CP1382/CT0020’. The Forest Research Centre (CEF) is a research unit funded by Fundação para a Ciência e a Tecnologia I.P. (FCT), Portugal (UIDB/00239/2020).

REFERENCES


Shrestha, M. 2015 Data analysis relying on linear scaling bias correction (V.1.0) 2015, Microsoft Excel file.


