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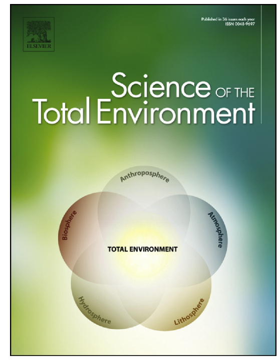


# Impacts of climate change on reservoir water availability, quality and irrigation needs in a water scarce Mediterranean region (southern Portugal)

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**Impacts of climate change on reservoir water availability, quality and irrigation needs in a water scarce Mediterranean region (southern Portugal)**

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**Abstract**

Future climate for the Mediterranean climatic region is expected to bring an increase in temperatures, decrease in the precipitation quantity and shifts in the seasonal precipitation pattern. Although the impacts of climate change on water resources have been relatively well explored for the Mediterranean climatic region, the specific consequences for reservoirs and, in particular, water availability and irrigation issues have been less studied. The objective of this work is two-fold: (i) to assess the impacts of future climate changes on water resources availability, quality (focusing on phosphorus loads as this is the limiting nutrient for eutrophication) and irrigation needs for two multipurpose reservoirs in southern Portugal; (ii) to suggest climate change adaptation strategies, especially for the agricultural sector. To this end, the SWAT model was first calibrated against existing data on reservoir inflows as well as phosphorus loads. Then, SWAT was run with climate derived EURO-CORDEX models (RCA4/RACMO22E) for four periods (1970-2000, 2010-2040, 2040-2070 and 2070-2100). Water availability was analysed using the Water Exploitation Index (WEI) that was calculated for both reservoirs combining changes of inflows and irrigation requirements. The results indicated that climate change will negatively impact water availability in both reservoirs, especially under RCP8.5. In the case of the Monte Novo reservoir, future domestic water supply could be constrained by water quality problems related with phosphorus loads. For Vigia reservoir, the high water exploitation will lead to water scarcity problems, mainly as this reservoir on present-day conditions is restrictive on irrigation requirements. Adaptation strategies such as the implementation of high end technology (e.g. soil moisture and plant water stress probes, satellite imagery and drones to evaluate water stress – NDVI) as well as the renewal of the irrigation network and adequate crop selection can help attenuating the effects of climate change on the water resources in this region.

**Highlights:**

SWAT was applied to two multipurpose reservoirs in Alentejo (Portugal)

Reservoir water availability and irrigation needs were assessed under different climate scenarios

Climate change will negatively impact water quantity and quality in reservoirs

The water exploitation index will increase under climate change

**Keywords:**

Water availability

Climate change

SWAT modelling

WEI – Water Exploitation Index

Alentejo multipurpose reservoirs

## 1. Introduction

The Mediterranean bioclimatic region is highly vulnerable to the effects of climate changes, especially concerning water resources (Garcia-Ruiz et al., 2011). Hydrological and erosive responses are expected to be strongly affected by changes on climatological conditions (precipitation, temperature, relative humidity, wind, solar radiation; Giorgi et al., 2008, IPCC 2014). Shifts on climatological conditions will also impact ecosystem integrity, crop suitability and yields, plant´s growth cycle and physiological and biological rhythms (e.g. stomata conductance, intrinsic water-use efficiency, potential evapotranspiration, biomass production, drought resilience, Butcher et al., 2014, Gray et al., 2016), land management operations and irrigation water requirements (Mehdi et al., 2015, Teshager et al., 2016).

The projected impacts include decreases in runoff and streamflow, progressive shifts in seasonal rainfall distribution and in the intensity, frequency and severity of extreme meteorological events (Sánchez et al., 2004; Senatore et al., 2011; Nunes et al., 2013) as well as variations in atmospheric $CO_2$ concentrations (Nunes et al. 2008, 2017; Ludwig et al., 2010; Serpa et al., 2015).

Some areas in the Mediterranean climate region will need 35% more water for irrigation than in the present conditions, upon extra crop demand and modernization (Fader et al., 2016). Therefore, the vulnerability of water resources in such areas will require management plans for adapting irrigation demand to climate change, which could consider improvements in water use efficiency, water prices, and changes to more water-efficient and resilient crops (Chavez-Jimenez et al., 2014). This need for specific management tools is well-illustrated by the fact that less than 20% of the area of the European Mediterranean basins have adequate policies for facing water vulnerability under climate change (Garrote et al., 2015).

Future climate change scenarios also foresee a decrease in water quality due to higher concentrations of pollutants and sediments, through reduced dilution as a result of less water in the rivers and reservoirs. Larger runoff events in winter due to more extreme rainfall events may lead to higher sediment and nutrient loads into streams and reservoirs (Whitehead et al., 2009). Reservoirs are particularly susceptible to decreases in water quality, especially if provision of drinking water is a primary function.

The climate change paradigm has been the scope of many studies and the focus of decision-makers, policies and environmental/climate legislation (Dietrich et al., 2009; Estrela et al., 2012). The European Water Framework Directive (WFD-2000/60/EC) requires the identification and quantification of human activities and their impacts on pollution exports to characterize pressures and thus the status of water bodies. However, the WFD has been failing to explicitly consider the impacts of climate changes on water resources (Wilby et al., 2006; Francés et al., 2017).

Although the impacts of climate change on water resources have been relatively well explored for the Mediterranean bioclimatic region, the specific consequences for reservoirs have been less studied. This is especially true for reservoir water availability and quality. Recent studies on climate change impacts have addressed water availability (quantity and quality) in combination with socio-economic conditions, including changes in land cover/use and water uses (regarding reservoirs: Garcıa-Ruiz et al., 2011; Milano et al., 2013; La Jeunesse et al., 2015; Sellami et al., 2015: 2016; Lutz et al., 2016; Nunes et al., 2017 and, regarding streams: Ludwig et al., 2010; Serpa et al., 2015; Carvalho-Santos et al., 2016; Bucak et al., 2017). Other studies have discussed potential management and conservation strategies (in the context of agricultural activities) for reducing soil degradation as well as water depletion under present-day (Rocha et al., 2015; Prosdocimi et al., 2016; Majone et al., 2016) and/or future climate conditions (Iglesias et al., 2015; Garrote et al., 2015). Few studies, however, have addressed the impacts of climate scenarios on water availability for lakes (artificial and natural origin) or reservoirs. López-Moreno et al. (2014), Valverde et al. (2015) and Nunes et al. (2017) are some of the few examples that have analysed, in an integrated manner, reservoir inflows, storage capacity and irrigation water requirements for future climate conditions.

For this study, two medium-sized reservoirs (Monte Novo and Vigia) were selected due to their elevated importance for the district of Évora, to which they supply water for urban (including drinking water) as well as irrigation purposes. The Soil and Water Assessment Tool (SWAT) was selected to assess the impacts of climate changes on the water resources availability of these multipurpose reservoirs.

The specific research objectives were to:

- assess the impact of future climate scenarios on water inflow and phosphorus loads in both reservoirs;
- explore potential changes on irrigation water requirements;
- discuss possible climate change adaptation strategies for water management of multipurpose reservoirs.

## 2. Methods

### 2.1. The study-area

The Monte Novo and Vigia catchments (Fig.1) are located in the wider Degebe river basin, in the Alentejo region of southern mainland Portugal. The catchment covers an area of about 81473 ha that is relatively flat, with elevations ranging from 206 to 570m. The average annual rainfall is about 500 mm, shaped by a mild winter and a dry warm summer with a Köppen-Geiger classification of Csa, i.e. temperate with dry or hot summer (Köppen, 1931). The area is classified as a sub-humid mesothermal, with a severe water-deficit, mostly during summer period (C2 B´2 – Thornthwaite 1948; Morais 1950; Reis 1987). The catchment is largely occupied by rainfed croplands, agroforestry areas and broad-leaved forest (Table 1). The catchment includes a multipurpose reservoir system that comprises the Monte Novo and Vigia reservoirs and is connected to the Alqueva reservoir with 4150hm$^3$ of water storage capability which is the largest artificial lake in the Iberian Peninsula (Diogo et al., 2008). This multipurpose reservoir system is part of the water supply system and is used also for domestic and industrial use, crop irrigation, and livestock consumption. The Monte Novo reservoir has a total storage volume of 15.3hm$^3$ with a flooded area of about 277ha. It is the principal freshwater supply for human consumption for the municipalities of Évora, Redondo and Reguengos. The Vigia reservoir has a total storage volume of 16.7hm$^3$ with a flooded area of about 262ha. It is mainly used for crop irrigation but also contributes to urban water supply. In total, the two reservoirs provide water to 65000 habitants.

Both reservoirs are equipped with a water adduction/transport system to collect water from the Alqueva reservoir in order to fulfil monthly water requirements for irrigation and human consumption. These adduction infrastructures (primary and secondary network of canals and ducts) are working since 2009 in the Monte Novo reservoir and since 2015 in the Vigia and they intend to supply public irrigation works and to promote the transition from rainfed crops to irrigated crops. The transfer from the Alqueva reservoir must be a balance between water needs and consumptions and the linked high-energy linked costs. Also, present water transfer capacity to Vigia is far from fulfilling irrigation needs and urban water supply. As urban water supply is first priority (including a two year water reserve in reservoir), agriculture as the most intensive user is also the one more restricted under drought situations.

Under present-day meteorological conditions, the Alentejo region is already under hydrological stress with deficient water availability (Diogo, 2012, Nunes et al., 2017) and is prone to meteorological extreme events (e.g. severe droughts), the last three having occurred in 2003-2005, 2011-2012 and 2016-2017. The meteorological conditions impact not only water quantity and water quality (Diogo et al., 2008) but may also lead to changes in land cover/use, through the selection of more suitable crops and associated changes in management operations. Water quality issues have been identified for both reservoirs, mainly linked with algal blooms that result from diffuse agriculture pollution (Diogo et al., 2008; Diogo, 2008; 2012). Aalgal blooms are mainly driven by the availability of P in both reservoirs thus potential sediment and the associated P transport from the watershed presents increases risks for reservoir eutrophication which is  the main water quality issue in the region and particularly in the Monte Novo and Vigia reservoirs.

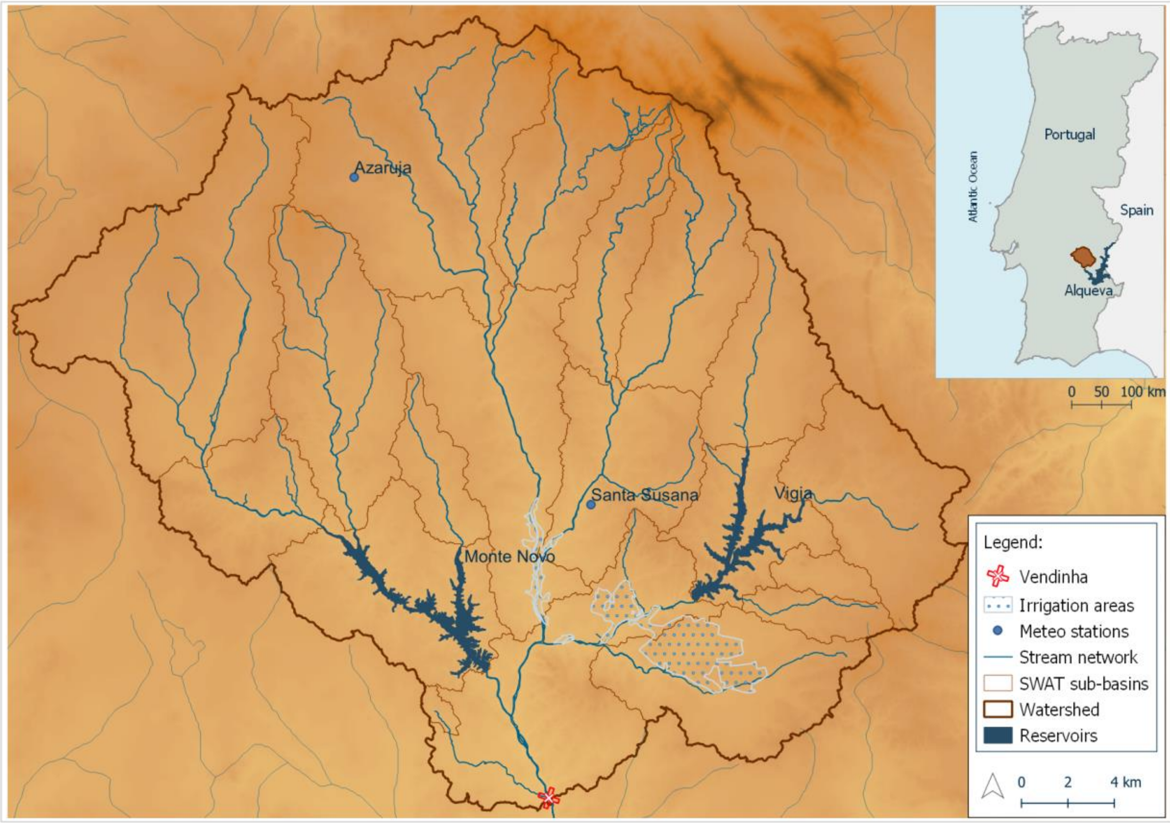


Fig. 1 The Monte Novo and Vigia catchment (including SWAT sub-basins) and reservoirs with the SWAT sub-basins

Table 1 Land use distribution and description (CORINE land cover data, Caetano et al., 2009).

| Land use | Area (%) | Description (SWAT land uses) |
|---|---|---|
| Non-irrigated crops | 43.7 | Oats (60%); Winter Pasture (40%) |
| Agro-forestry areas | 29.7 | "Montado" - Pasture (70%) with evergreen cork and cork oak (30%) |
| Broad-leaved forest | 12.9 | Cork oak |
| Vineyards | 3.6 | Vineyard |
| Scrubland | 3.3 | Mediterranean scrubland |
| Irrigated crops | 3.3 | Corn(40%); Sunflower (22%); Irrigated Olive trees (19%) Irrigated vine (19%) |
| Olives | 2.6 | Olive trees |
| Mixed forest | 0.5 | Eucalyptus |
| Discontinuous urban | 0.4 | Residential-Low Density |

### 2.2. **Catchment modelling**

In this work, the Soil and Water Assessment Tool (SWAT) was used to simulate catchment responses under present-day conditions and under climate scenarios, through the ArcGIS interface ArcSWAT (version 2012). The SWAT model is a process based, semi-distributed river basin model (Di Luzio et al., 2001; Neitsch et al., 2011; Arnold et al., 2012) that can be used to simulate, on a daily basis, different ecohydrological scenarios and responses, under present day meteorological conditions and also under potential climate change conditions.

The model divides the watershed into smaller sub-basins (19 sub-basins were defined in the model - Fig.1), which are divided into multiple hydrological response units (HRUs – smallest model units) with homogeneous combinations of soil type, land use and slope, in order to better simulate continuous time landscape processes and catchment responses (e.g. hydrological patterns processes, water balance, water quality, and nutrient exports).

The model requires a set of input data and parameters to run. For the model setup, the available data included: topography (10m resolution; 1:25000 scale, IGEO), stream network (10m resolution; 1:25000, IGEO/SNIRH), soil map (1:500000 scale, CNA, SROA, FAO), and land use (Corine Land Cover 2006, 1:100000 scale).

Model database parameterization is important to ensure a proper representation of the catchment and to improve model performance. Land cover, crop parameters and management operations, as well as soil database and parameters, were defined based on the SWAT database and literature and also updated and improved following previous research and field work (Nunes et al., 2008, 2017; Rocha et al., 2015; Serpa et al., 2015). Parameters for reservoir characteristics and management were taken from existing databases (SNIRH; DGADR; Diogo 2008, 2012).

The SWAT model was run for the 1973-2012 period (baseline) with 4 years of spin-up period, using daily precipitation from three stations (Azaruja and Santa Susana and Mitra - Évora). This last station also provided temperature, wind speed, solar radiation and relative humidity data. The spin-up period minimizes the effect of the initial systems variables, ensuring appropriate initial conditions and processes (e.g. operational hydrological cycle and processes, vegetation growth) for the model simulations.

### 2.3. **Calibration routines**

The model was first manually calibrated, and later a narrower range was considered in the automatic (SWAT-CUP) calibration. Soil and vegetation parameter ranges were obtained from previous SWAT applications in this region by Serpa et al. (2015) and Nunes et al. (2017).

Reservoir inflows, volumes and water balances, irrigation water demands, phosphorus loads and irrigation extractions (monthly data) for the 1994-2005 period were derived from Diogo (2008, 2012). Inflow monthly data was calculated from the water balance for both reservoirs. Reservoir inflows and outflows were calibrated using monthly reservoir data (water balance calculations based on measured volumes at Monte Novo and Vigia). The Vendinha hydrometric station (catchment outlet) was calibrated first with daily data and later with monthly data, in order to assess overall model performance and to refine initial parameter input ranges.

Calibration for storage volume was made using the available data (SNIRH, Diogo 2012). Calibration of P input loads to each reservoir was based on land use export rates estimated by Nunes et al (2017), input loads calculations using reservoir water quality modelling (with CE-Qual-W2 model) obtained from Diogo (2012) for both reservoirs and in reservoir water quality monitoring data.

In a second stage, the calibration of SWAT was refined using the Calibration and Uncertainty Analysis Program (SWAT-CUP; Abbaspour 2007, 2015). Automatic calibration, sensitivity and uncertainty analysis were done using the SUFI2 algorithm within the SWAT-CUP. This algorithm accounts for potential sources of uncertainty and helps to determine the parameter set (and respective confidence intervals) with the greatest impact on model calibration and performance.

SUFI2 will not lead to a single best parameters value, but will produce a set of good solutions linked to the combination of parameters and their ranges. SUFI2 is an iterative procedure, and for each iteration the algorithm will narrow the parameters range. Each iteration will produce better parameters range comparing with the previous iteration. The calibration was done with 3 iterations, each counting 600 simulations.

SUFI2 begins by assuming a parameter uncertainty range, which is gradually decreased through several iterations, where new sets of narrowed smaller parameter ranges are calculated from those leading to the best simulation. In SUFI2, uncertainties are mapped by the 95% prediction uncertainty (95PPU) that is calculated by the levels (2.5% and 97.5%) of cumulative distribution of an output variable achieved by Latin Hypercube Sampling. The best simulation results are given by the 95% prediction uncertainty (95PPU) band and by the final parameter ranges (see Abbaspour et al., 2007; Abbaspour 2015). Automated calibration procedures (with SWAT-CUP) allow the incorporation of a large number of parameters within the iterations as well as the option to use different optimization algorithms (e.g. SUFFI2, GLUE) and different objective functions to provide the goodness-of-fit criteria (given by the P-factor and R-factor), the prediction of uncertainty (given by the 95PPU) and parameters sensitivity analysis. This leads to a more computationally efficient calibration (Abbaspour et al., 2015).

The comparison between observations and simulations to assess model performance was done using both graphical analysis and statistical indicators. Overall model performance was evaluated using three indicators: (i) the Nash-Sutcliffe model efficiency index (NSE), ranging from the optimal value of 1 (perfect fit) to 0, whereas values lower than 0 indicates unacceptable model simulation; (ii) the Coefficient of Determination ($R^2$) multiplied by the coefficient of the regression line ($bR^2$), ranging from the optimal 1 value to 0; (iii) the average percent model error (PBIAS – percentage of bias) where 0 is the optimal value and positive values indicate model underestimation (positive values) or overestimation (negative values) (Gupta et al., 1999; Krause et al., 2005; Moriasi et al., 2007).

### 2.4. **Climate change scenarios**

Climate models were selected from the regional high-resolution EURO-CORDEX initiative using a 12km horizontal resolution grid and considering two representative concentration pathways (RCP) scenarios (RCP4.5 and RCP 8.5) (Jacob et al., 2014).

The EC-Earth/Regional Atmospheric Climate Model (RACMO22E - Koninklijk Nederlands Meteorologisch Instituut) and the EC-Earth/Regional Climate Model (RCA4 - Swedish Meteorological and Hydrological Institute) were used to obtain climate patterns for 2010-2040, 2040-2070 and 2070-2100 periods. From an initial group of five regional climate models (CCLM4, HIRHAM5, WRF331F, RACMO22E, RCA4) two models were selected for their capability to represent the actual biophysical conditions of the study area for the reference period (1971- 2000) (Soares et al., 2015).

Future (daily) climate data simulated by both models and for both scenarios (RCP´s) were included in SWAT using a grid of eight model cells inside the study area to obtained more realistic distribution patterns and to account for the actual biophysical conditions (e.g. orography, precipitation). RCP 4.5 is a mid-level $CO_2$ concentration scenario where total radiative forcing stabilizes at 4.5 $Wm^{-2}$ after 2100 (equivalent to 650 ppm $CO_2$) and where all countries simultaneously apply mitigation policies. RCP 8.5 represents a growing radiative forcing stabilizing at 8.5 $Wm^{-2}$ in 2100 (equivalent to 1370 ppm $CO_2$) (Thomson et al., 2011; Vuuren et al., 2011).

The scenarios indicate a decrease in annual rainfall, although the magnitude varies between both models (RACMO and RCA) and scenarios (RCP 4.5 and 8.5). This decrease should occur by the end of the century, mainly in RCP 8.5 (-15.2% 2070-2100). In seasonal terms, there is a trend for lower rainfall in spring (April and May) and autumn (October, November and December), also stronger in RCP 8.5. There is also an increase in rainfall during winter months (January, February and March), more visible in RACMO. In RCP 4.5 there is an increase of summer rainfall in all periods, while in RCP 8.5 there is a decrease in the last two periods, 2040-2070 and 2070-2100 (Fig 2). These projections result in an increase of average temperature in the study area, especially in RCP 8.5 at the end of the century. In seasonal terms, temperature increases should be higher in summer, especially for the end of the century in RCP 8.5. The RACMO model foresees a gradual temperature increase in summer and autumn months, while in RCA this increase is more abrupt and with higher oscillations.

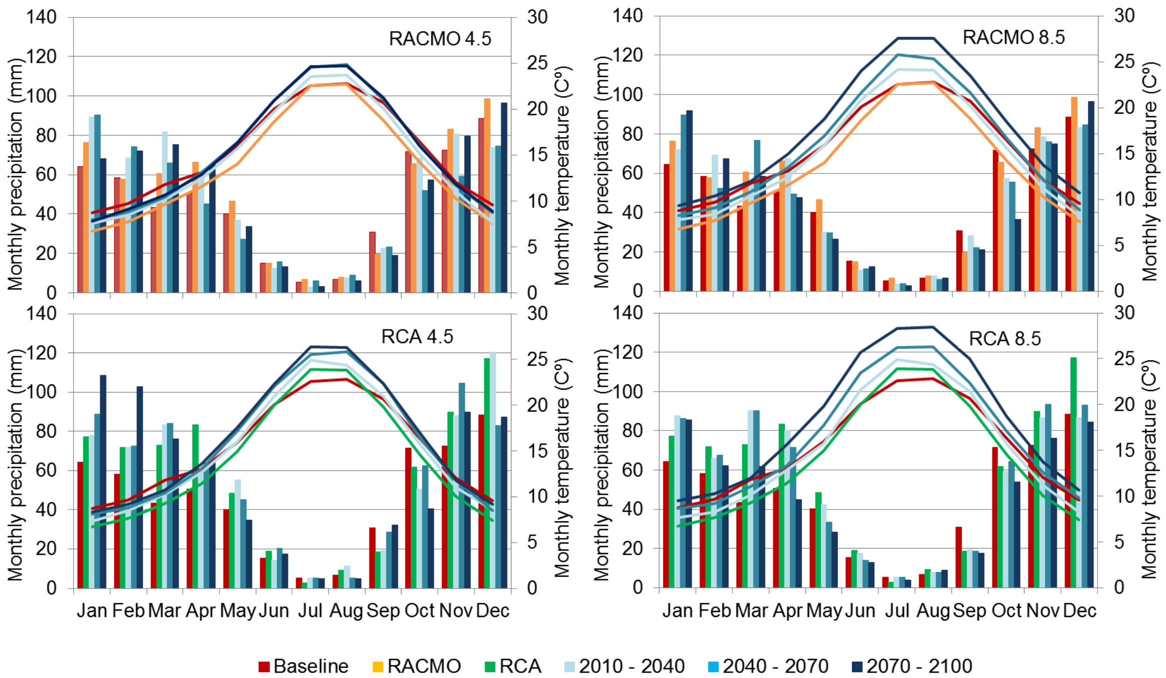


Fig. 2 Monthly average precipitation and temperature for the baseline simulation and for the climate models (RACMO and RCA) reference periods and future periods (under RCP4.5.and 8.5)

### 2.5. Water exploitation index

The water exploitation index (WEI; EEA, 2005) is the ratio between water requirements and availability (WEI= total water abstraction / total water availability) for a given catchment and has been widely used as a water stress indicator by the European Environment Agency. WEI values between 0 and 20% are regarded as low stress; between 20 and 40% as moderate stress; above 40% as severe stress. Future water requirements for each reservoir were calculated as the sum of irrigation and urban requirements. Irrigation requirements were calculated by SWAT according to different climate scenarios. Urban requirements were considered to be the same for present day and future scenarios, i.e. 6.38 $hm^3$/yr from Monte Novo and 0.70 $hm^3$/yr from Vigia, as future population change in the region is expected to be small (as referred by Nunes et al., 2017) for a nearby catchment.

## 3. Results and discussion

### 3.1. SWAT model performance

Figure 3 compares the reference and SWAT simulation for reservoir inflows, volumes and phosphorus (total Phosphorus - P) concentrations for the 1995-2005 period, while Table 2 gives the corresponding values for the three model performance indicators. Table 2 gives also the goodness-of-fit indicator values with respect to the (daily and monthly) discharge at the Vendinha gauging station.

Inflow monthly data was calculated from the water balance for both reservoirs. Calibration for storage volume was made using the available data (SNIRH, Diogo 2012).

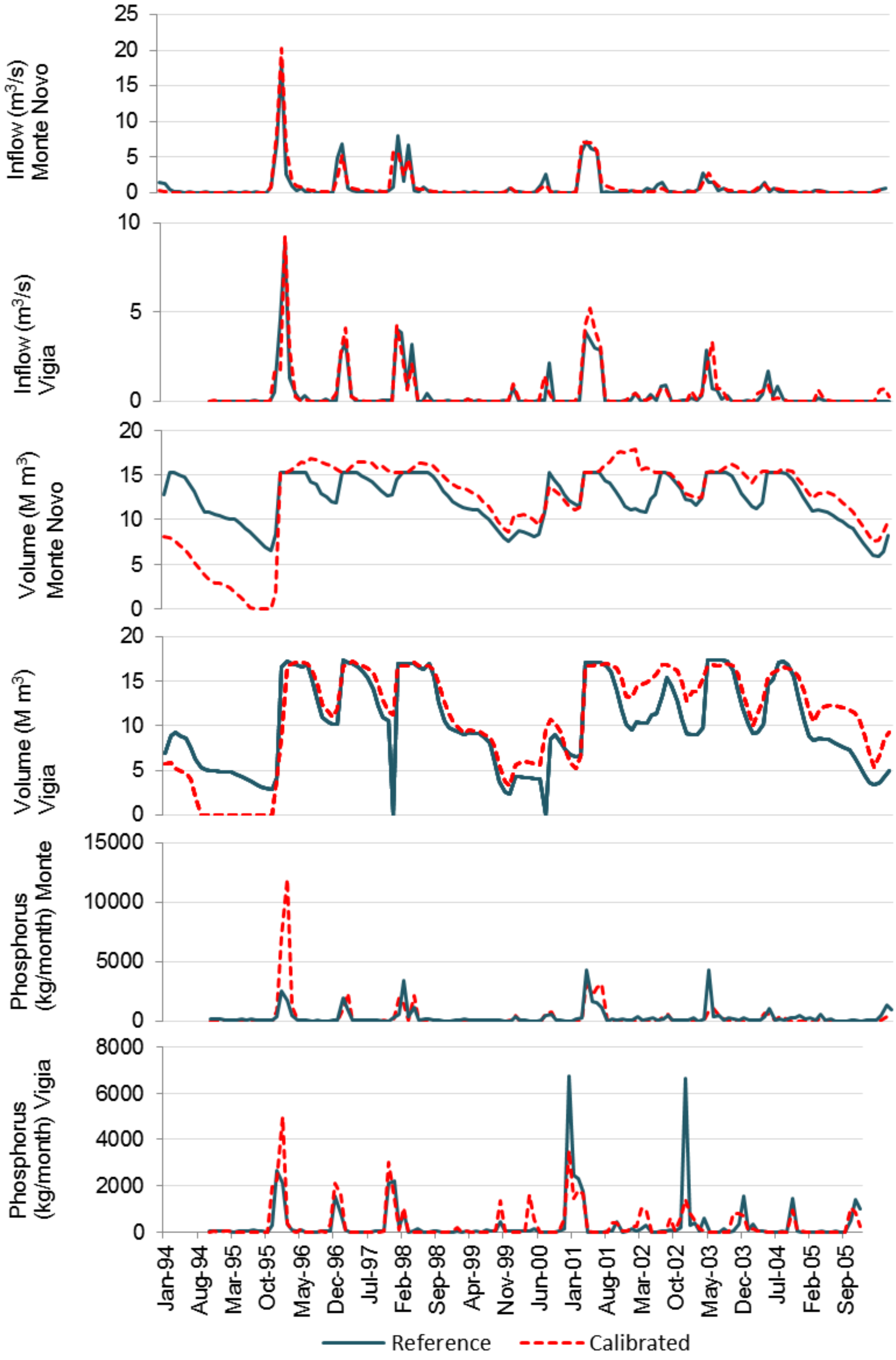


Fig. 3 Monthly calibration of reservoirs inflows, water volume and phosphorus loads for the Monte Novo and Vigia reservoirs.

Table 2 Goodness-of-fit indicators for Vendinha (daily and monthly discharge) and for Monte Novo and Vigia reservoirs inflow, water volume and phosphorus loads.

| | NSE | bR² | Pbias |
|---|---|---|---|
| Vendinha (daily discharge) | 0,67 | 0,30 | 28,8 |
| Vendinha (monthly discharge) | 0,48 | 0,51 | 20,5 |
| | | | |
| Monte Novo (monthly inflow) | 0,89 | 0,89 | 7,3 |
| Vigia (monthly inflow) | 0,84 | 0,83 | 6,3 |
| | | | |
| Monte Novo (monthly water volume) | 0,44 | 0,43 | 6,3 |
| Vigia (monthly water volume) | 0,70 | 0,72 | 10,1 |
| | | | |
| Monte Novo (monthly phosphorus loads) | 0,15 | 0,49 | 1,7 |
| Vigia (monthly phosphorus loads) | 0,33 | 0,33 | 9,4 |

The calibrated parameters values for each sub-basins are presented in Table 3.

Table 3 Parameters definition with the calibrated values per sub-basins

| Designation | Parameter | Monte Novo linked sub-basins | Vigia linked sub-basins | Remaining sub-basins |
|---|---|---|---|---|
| ALPHA_BF | Groundwater discharge decay factor (alpha) | 0.5 | 0.58 | 0.13 |
| CH_K(2) | Effective hydraulic conductivity in main channel alluvium | 0.9 | 0.5 | 0.4 |
| DEEPST | Initial depth of water in the deep aquifer | 1000 | 1000 | 950 |
| DEP_IMP | Depth to impervious layer for modelling perched water tables | 6000 | 6000 | 4500 |
| EPCO | Plant uptake compensation factor for the soil profile | 1 | 1 | 0.95 |
| ESCO | Soil evaporation compensation factor for the soil profile | 0.2 | 0.18 | 0.14 |
| GW_DELAY | Groundwater discharge delay | 3.6 | 2.8 | 1 |
| GW_REVAP | Groundwater re-evaporation coefficient | 0.15 | 0.2 | 0.1 |
| GW_SPYLD | Specific yield of the shallow aquifer | 0.003 | 0.0045 | 0.005 |
| GWQMIN | Threshold depth of water in the shallow aquifer required for return flow to occur | 95 | 100 | 10 |
| OV_N | Manning's "n" value for overland flow | 0.3 | 0.35 | 0.18 |
| PPERCO | Phosphorus percolation coefficient | 11 | 11.5 | 10 |
| RCHGR_DP | Deep aquifer percolation fraction | 0.5 | 0.5 | 0.5 |
| REVAP_MN | Threshold depth of water in the shallow aquifer for re-evaporation to occur | 0.05 | 0.5 | 1 |
| SHALLST | Initial depth of water in the shallow aquifer | 0.5 | 0.5 | 0.5 |
| SOL_WAC | Available water capacity for the soil layer | 0.75 | 0.8 | 0.34 |
| SURLAG | Surface runoff lag time in the HRU | 1.8 | 1.75 | 2.10 |

The performance indicators suggested good model performance for the inflows into the two reservoirs and, to a lesser extent, for the discharge at the Vendinha station. This is probably because Vendinha gauging station, is located downstream of both reservoirs and is thus potentially affected by unregistered dam releases. Daily results were only better than monthly results for the NSE parameter, which is highly sensitive to extreme values. In this case, a good simulation of peak flows in Vendinha could explain the higher NSE, despite the worse performance for other indicators.

The simulations of the reservoir volumes were less satisfactory, especially in the case of Monte Novo.

Reservoir water consumption in SWAT depends only on irrigation requirements and storage volume, so changes in irrigated area and crops as well as implementation of water conservation measures during drought periods cannot be accounted directly. This limits the simulation of inter-annual variations due to changes in irrigated area or crops, or due to water conservation measures in dry years or droughts periods.

SWAT was also not entirely successful in simulating the reservoir phosphorus concentrations in the reservoirs, over-predicting peak concentrations during the 1995/96 wet season and, especially in the case of Vigia, under-predicting (some of) the later peaks. Worth stressing is that SWAT suffers from marked uncertainties in its phosphorus transport predictions, as the phosphorus modelling routines have some limitations (White et al., 2010; Collick et al., 2016). These routines have been described by Chaubey et al (2006) in a comprehensive manner, emphasizing that SWAT assumes reduced dynamics between the P pools of the different soil layers (intended to represent inorganic and organic P forms) so there is reduced P transfer between layers. More specifically, SWAT's phosphorus availability index is set to be constant for the entire simulation period resulting in a soil P under-estimation, although dynamic P transfer rates could better support SWAT estimations in solution P(Vadas et al., 2012).

Furthermore, SWAT tends to under-predict soil total P, which, in turn, may lead to an under-prediction of P losses. Also, the export of organic and mineral P from the slopes into the streams is simulated as largely occurring through surface runoff, ignoring export through subsurface flow. Overall, SWAT typically has major constraints to simulate P transport dynamics that are linked to runoff events (White et al., 2014; Vadas et al., 2010). No slope-scale erosion data or catchment-scale sediment yield data were available to calibrate SWAT for P associated to sediments. Finally, is important to stress the reservoir inflows, volumes and water balances, irrigation water demands, phosphorus loads and irrigation extractions are reference values obtained from previous studies (Diogo 2008, 2012).

In spite of these limitations SWAT predictions are expected to give reasonable clues about the relative changes in phosphorus transport with changes in climate and land cover/use.

### 3.2. Impacts of climate changes on reservoir inflows

The RCP 4.5 and 8.5 scenarios include different atmospheric $CO_2$ concentrations. SWAT uses a default $CO_2$ concentration of 330 ppm. The model should therefore consider average values of 383 ppm (2010-2040), 490ppm (2030-2070) and 597ppm (2060-2100) for RCP 4.5; and 503 ppm (2010-2040), 850ppm (2030-2070) and 1197ppm (2060-2100) for RCP 8.5. However, test runs of the SWAT model with these high concentrations (above 999 – three digits) suggest that the model is not ready to consider them, since they are over the values for which the $CO_2$ response equations were developed. The increase in $CO_2$ concentrations was therefore not explicitly considered (as we could not represent the $CO_2$ concentration of 1197ppm for 2060-2100), and all simulations assumed the default $CO_2$ concentration of 330 ppm. In addition, SWAT does not account for the increase of leaf area index (LAI) with different $CO_2$ concentrations which in turn, may have an effect of evapotranspiration, hydrological responses, soil water content (Arias et al., 2014).

However, previous results show that not considering this parameter induces a minor error (Nunes et al., 2008; Gabriel et al., 2016). In addition, SWAT model does not account for both continuous decrease or increase on $CO_2$ concentrations as it assumes a constant value for the simulation period. The simulation does not account gradual for increases of $CO_2$ parts per million and does not reflect the fact that the atmospheric $CO_2$ concentrations are incessantly on the rise.

The simulation of climate scenarios resulted in different reservoir inflow trends by 2070-2100 (Fig. 4): RCP 4.5 lead to a small decrease in the RACMO model (-8 and -4% in Monte Novo and Vigia), and to a moderate increase in the RCA model (49 and 42% in Monte Novo and Vigia); while RCP 8.5 leads to a moderate decrease in both models (RACMO: -19 and -23% in Monte

Novo and Vigia; RCA: -19 and -7% in Monte Novo and Vigia). This is due to contradictory trends in the annual and seasonal rainfall predictions:

(i) the small to moderate decrease in annual rainfall by 2070-2100 (-2 and -1% for RCP4.5 and -10 to -20% for RCP 8.5, for the RACMO and RCA models, respectively) , associated with an increase in temperature and, consequentially, in potential evapotranspiration, creating conditions for lower runoff and inflows;

(ii) the increase of winter rainfall in most scenarios (RACMO:2% for RCP4.5 and 10% for RCP8.5; RCA: 12% for RCP4.5 but -13% for RCP8.5) creates conditions for an increase in runoff and inflows (in line with Nunes et al., 2017), since the shallow soils in this region are not able to retain this added rainfall (see Nunes et al., 2013).

The different combination of both these trends leads to different outcomes:

(i) in scenario RCP4.5, both models predict a small decrease in annual rainfall, and therefore seasonal changes are more important: the RACMO model predicts almost no changes to winter rainfall, leading to lower inflows, while the RCA model predicts a moderate increase in winter rainfall, leading to higher inflows;

(ii) in scenario RCP8.5, both models predict a moderate decrease in annual rainfall, which therefore dominates over seasonal changes: the RACMO model predicts a moderate increase in winter rainfall while RCA predicts a moderate decrease, but both models predict lower inflows.

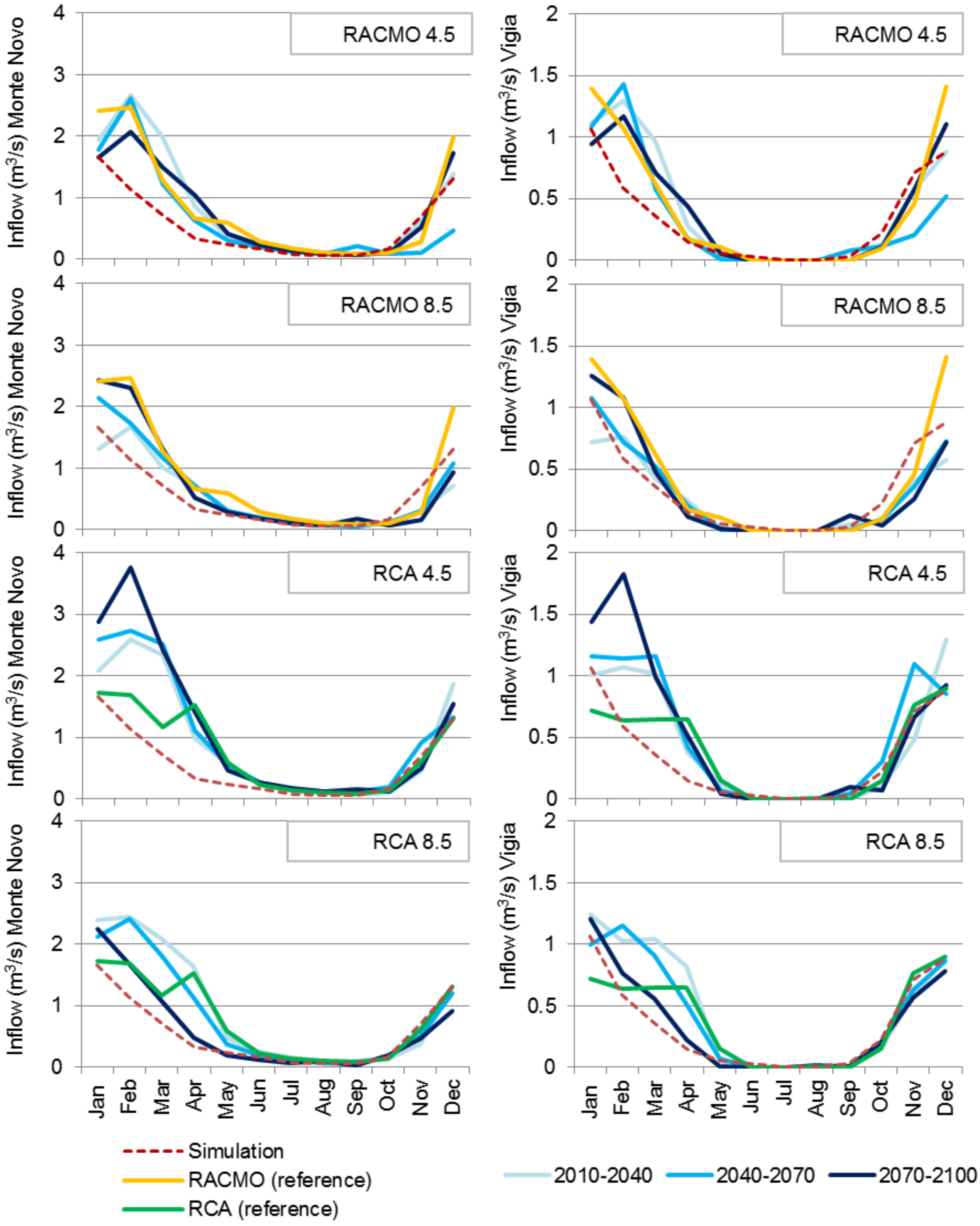


Fig. 4 Reservoir inflows for the baseline period and for the climate models (RACMO and RCA) reference periods and future periods (under RCP4.5.and 8.5)

Each climate scenario has a different combination of these contradictory trends, leading to different results, also varying with each future period:

(i) RACMO 4.5 inflow follows the rainfall signal, with little evolution along the century and slight seasonal differences;

(ii) RCA 4.5 shows a gradual increase of annual inflow, following a rainfall concentration in winter despite little change to annual totals;

(iii) RACMO 8.5 initially shows a decrease in inflow due the decrease in annual rainfall, followed by a slight increase until 2100 probably because the increase in rainfall in winter is more important than annual rainfall;

(iv) RCA 8.5 initially shows a slight increase of inflow, followed by a decrease until 2100, following a trend of decreasing rainfall which, in contrast with other scenarios, does not indicate an increase in winter rainfall.

Overall, there is a tendency for decreasing reservoir inflows, which in turn may influence reservoir volumes under future climate conditions. This is in line of what was already addressed in other studies in the Iberian Peninsula that show a reduction in reservoir water levels under climate change scenarios (Molina-Navarro et al., 2014, Carvalho-Santos et al., 2017, Nunes et al., 2017, Lobanova et al., 2017).

### 3.3. Impacts of climate change on phosphorus loads

Future phosphorus scenarios are variable, but have a long-term increasing trend, moderate (19%) in scenario RCP 4.5 and light (6%) in RPC 8.5. Scenarios are variable with different trends by 2070-2100: in the RACMO model the RCP 4.5 lead to a small decrease (9%) while RCP 8.5 leads to a moderate increase (5%); in the RCA model the RCP 4.5 lead to a moderate increase (39%) and while RCP 8.5 leads to a small decrease (2%). The RACMO model in the RCP4.5 leads to a moderate decrease in Monte Novo (23%) and small increase in Vigia (-5%); while the RCP 8.5 leads to a moderate increase in Monte Novo and Vigia (-6% and 17%, respectively). The RCA model in the RCP 4.5 leads to a moderate increase in Monte Novo (59%) and a small increase in Vigia (18%); while the RCP 8.5 leads to a small decrease in both Monte Novo and Vigia (4% and 1%, respectively).

Phosphorus trends result from the combination of two processes: (i) an increase in phosphorus exports, due to rainfall and runoff in the wet season, with higher impacts on soil losses; (ii) changes to phosphorus transport until the reservoirs, which closely follows the inflow variation trends (Fig. 5).

The Monto Novo reservoir seems to be much more vulnerable to this problem than Vigia. This is due to the different land uses upstream: while the Monte Novo watershed has a larger occupation with more intensive croplands (annual cultures), resulting in higher use of fertilizers and soil mobilization, in the Vigia watershed there are larger agroforestry and forest areas with a lower phosphorus export potential. These results are in line with the influence of future climate scenarios on phosphorus exports stressed by El-Khoury et al. (2015), Cerkasova et al. (2018) and Stefanidis et al. (2018).

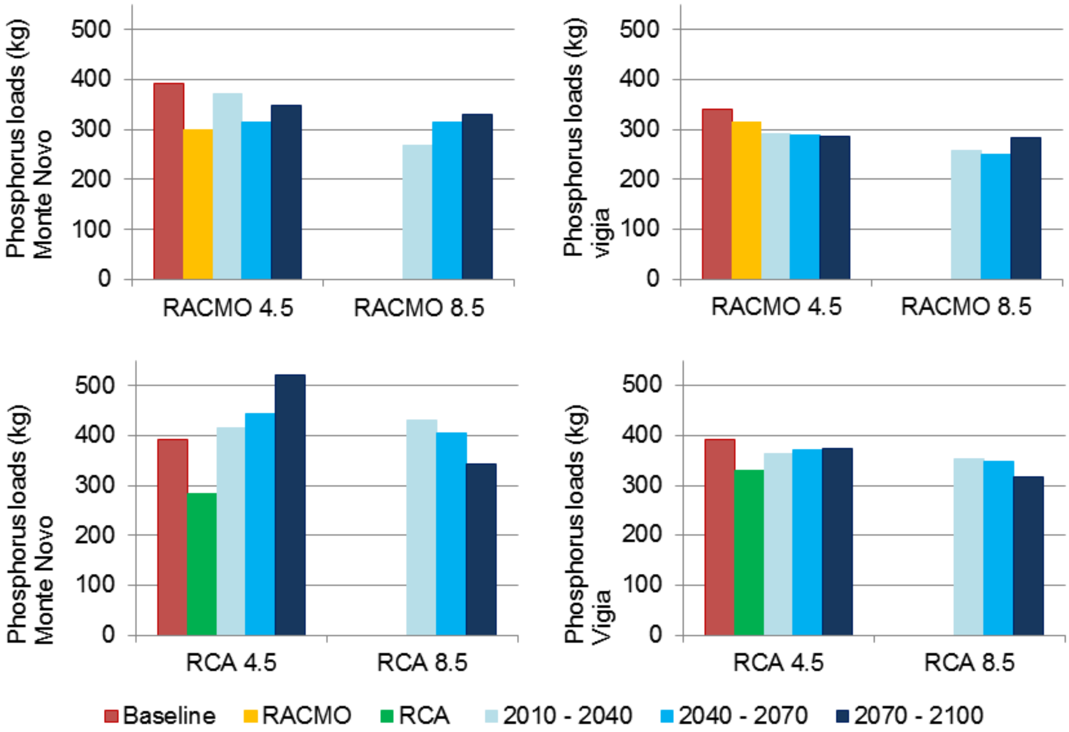


Fig. 5 Reservoir phosphorus loads for the baseline period and for the climate models (RACMO and RCA) reference periods and future periods (under RCP4.5.and 8.5)

### 3.4. Impacts of climate changes on irrigation needs

SWAT results for irrigation requirements per reservoir are shown in figure 6.

All scenarios foresee a moderate increase (28% in the RCP4.5 and 31.4% in the RCP8.5, by 2070-2100) of water requirements, generally in line with the decrease in annual rainfall, coupled with an increase in temperature and potential evapotranspiration. By 2070-2100 the RACMO model in the RCP4.5 leads to a moderate increase in Monte Novo (23%) and Vigia (26%) and the RCP 8.5 leads to similar moderate increases in Monte Novo and Vigia (35% and 34%, respectively). The RCA model in the RCP 4.5 leads to a moderate increase in Monte Novo (43%) and a small increase in Vigia (6%) and similarly RCP 8.5 leads to a moderate increase in Monte Novo (51%) and a small increase in Vigia (15%).

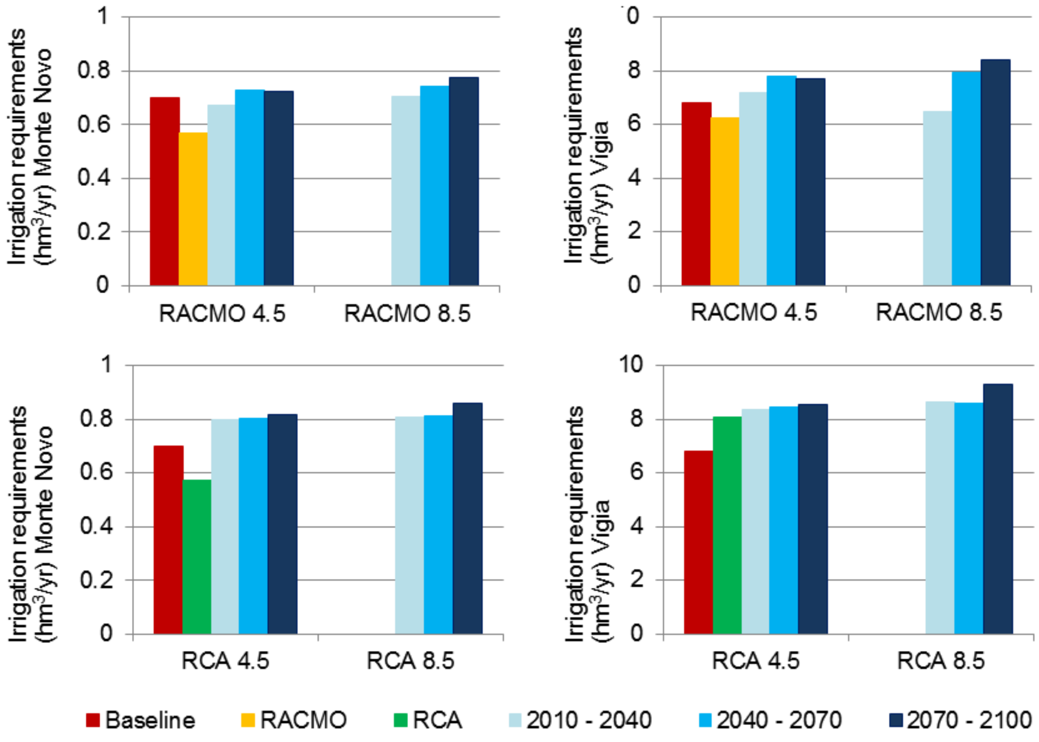


Fig. 6 Reservoir irrigation requirements for the baseline period and for the climate models (RACMO and RCA) reference periods and future periods (under RCP4.5.and 8.5)

Scenario RACMO 4.5 is an exception, where little rainfall changes leading to a moderate increase in water requirements, not only to higher temperatures but also with seasonal rainfall changes, specifically the concentration of rainfall in winter (Fig. 2) with a consequent increase in runoff at the expense of soil water storage. These increases might negate higher inflows to the Vigia reservoir, leading to a higher water deficit.

Water requirement changes do not vary greatly with crop, as it can be seen in figure 7. The RACMO model indicates lower irrigation requirements per crop, for RCP 4.5 and RCP 8.5 when comparing with the RCA model for the same RCP´s. The RCA model indicates that annual crops (sunflower and corn) are less sensitive to climate changes than permanent crops (olive trees and vineyards). This is due to seasonal changes, namely a decrease in autumn rainfall forecasted by this model, a time when only permanent cultures are being irrigated.

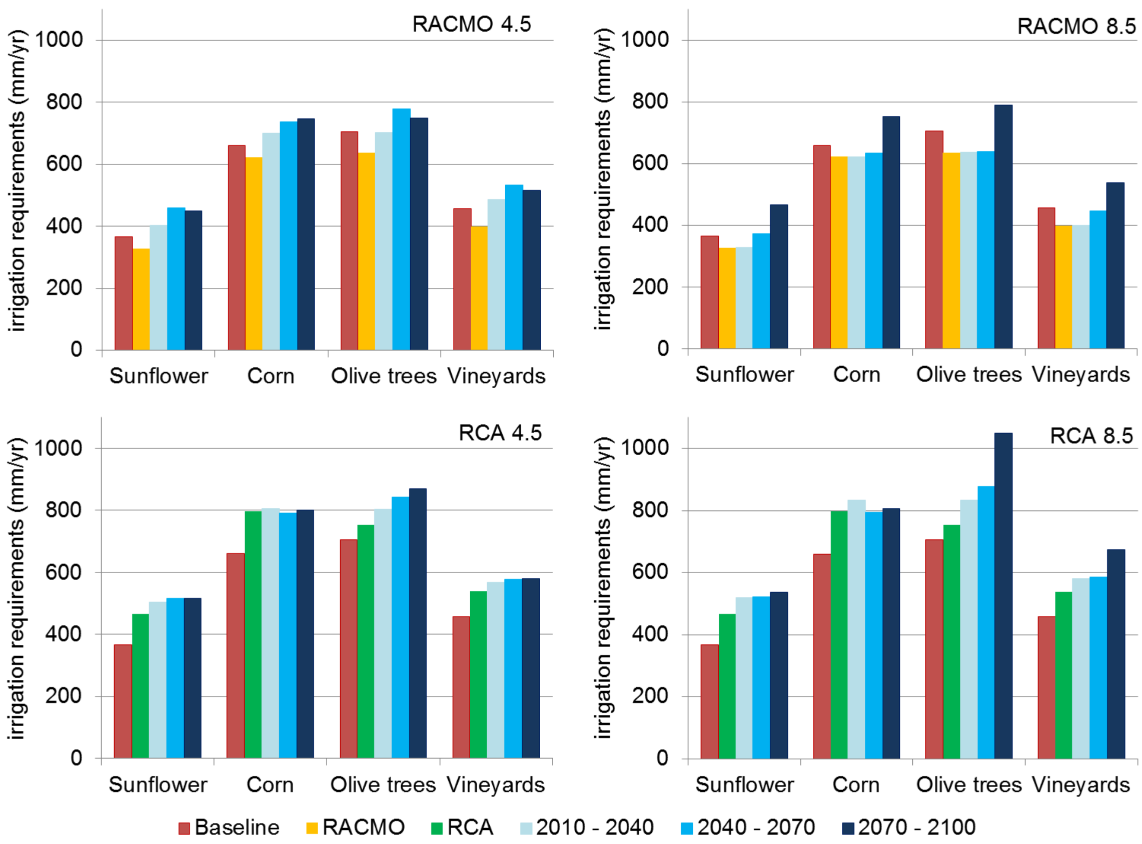


Fig. 7 Irrigation requirements per irrigated crop (sunflower, corn, olive trees and vineyards) for the baseline period and for the climate models (RACMO and RCA, reference periods and future periods (under RCP4.5.and 8.5)

### 3.5. Water exploitation index and adaptation options

WEI showed a tendency to increase from moderate or severe with future climate, influenced not only by lower inflow, but also higher irrigation requirements in both reservoirs, especially in Vigia, more oriented for irrigation purposes (Fig.8). For scenario RCP 4.5 there are generally slight changes to the WEI, except for the RACMO model where it increases in 2040-2070 but lowers again at the end of the century. For scenario RCP 8.5 there is an important increase in water exploitation, starting in 2010-2040 in the RACMO model, and from the mid-21$^{st}$ century onwards for the RCA model. In any case, both scenarios do not change from present-day situation: Monte Novo reservoir is, and will continue to be, under moderate water stress, while Vigia reservoir is and will continue to be in severe water stress.

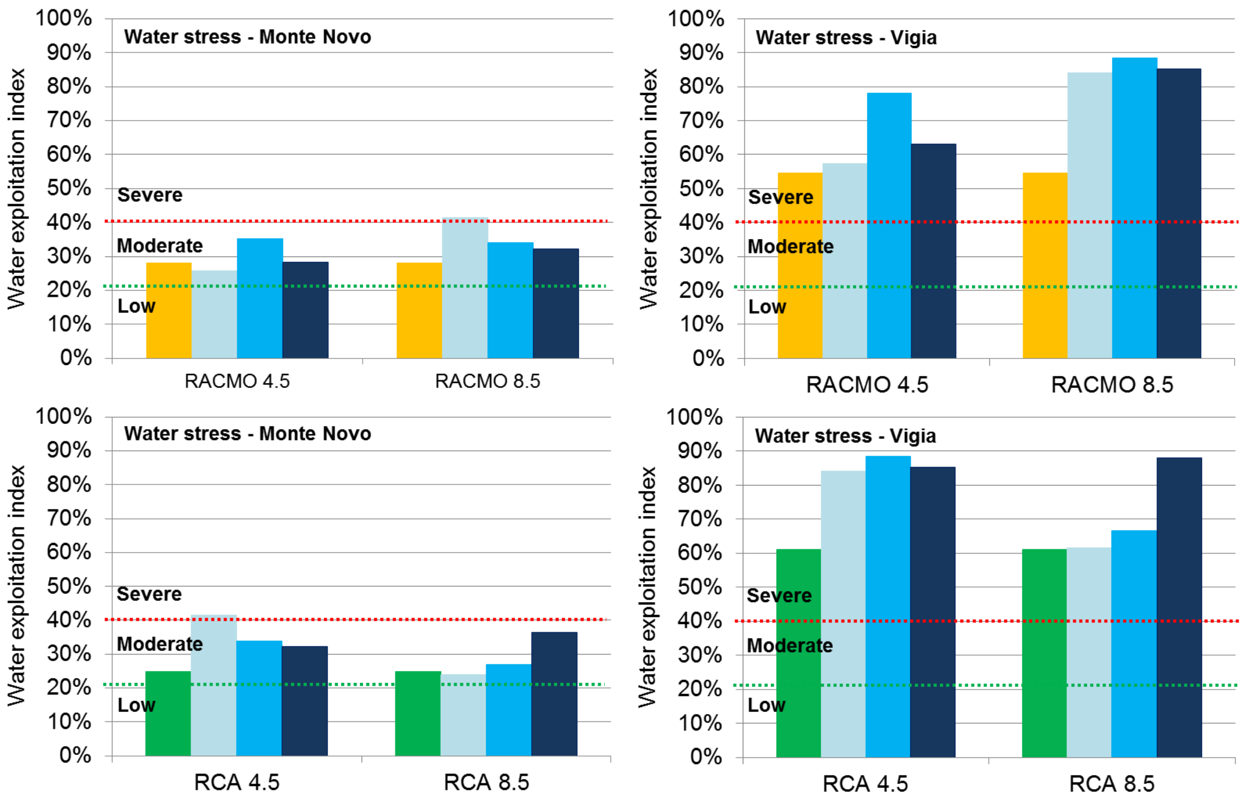


Fig. 8 Water exploitation index for the baseline period and for the climate models (RACMO and RCA) reference periods and future periods

These scenarios indicate that might occur a moderate increase in irrigated area, especially in scenario RCP 4.5, when followed by water use efficiency measures. But this could further reduce water availability and thus increase water stress in the system. Results also indicate little potential to increase the irrigated area for Vigia reservoir, and eventual water use efficiency measures would be required just to support the present situation regarding water stress. This is in line of results from a previous study in the region concluding that there will be an increasing water demand for irrigation to maintain current crop yield (Rolim et al., 2017). The higher water exploitation in Vigia leads to water scarcity problems, a recurrent problem that has been observed in this reservoir and which has limited irrigated cultures in drier years, especially in the 2000s. Transfers from the Alqueva dam have mitigated this problem since 2015, therefore, any compensation for an increase in irrigated area must come from there. A study carried out in a neighbouring watershed in southern Portugal also revealed the usefulness of Alqueva dam for supporting climate change impacts on irrigated agriculture, but not for a scenario of an ambitious expansion of irrigated area (Valverde et al., 2015).

The WEI is based on the mean annual water demand with respect to the mean annual water availability and not on a monthly basis. In this sense, uncertainty in water demands, seasonality, and especially drought periods may not be totally accounted, as suggested by Pedro-Monzonís et al (2015). >Thus a monthly based index could produce on a more truthful assessment of water availability.

However, these scenarios indicate that Monte Novo and Vigia have potential for measures increasing water use efficiency, i.e. either in the irrigation system or on crop selection. As referred earlier, an increase in rainfall and temperature during the humid season might allow earlier sowing and harvest of irrigated annual crops, limiting irrigation needs. On the other hand, permanent crops might use more water throughout the year, and in some scenarios have higher in irrigation requirements.

Another way of increasing water use efficiency would be to change irrigated crop selection, using the results of this work for future crop irrigation requirements. For example, corn and olive trees can be replaced by sunflower (for biodiesel) and vineyards, both with lower water requirements (Fig. 7). In fact, a study carried out in Monte Novo irrigation perimeter suggested a statutory rise in water price towards full-cost recovery, which would weaken the commercial viability of some crops with high water demand, such as current corn cultivation (Levidow et al., 2014).

Adaptation strategies that involve changing crops should be implemented considering farmers and end-user needs as well as markets trends. In addition, the recommendations for a more sustainable use of water should be focused on water consumption, so stakeholders engagement is essential.

## 4. Conclusions

Reservoirs play an important role in water management, especially in Mediterranean areas like Alentejo (southern Portugal), where water is typically scarce during summer and is forecasted to become even scarcer under climate change scenarios.

Climate change will have mostly negative impacts on the water resources of the Monte Novo and Vigia reservoirs, especially in the case of the more extreme scenario (RCP 8.5). In the case of the moderate scenario (RCP 4.5), the main problem seems to be associated with an increase in phosphorus loads and its potential impacts on water quality. A minor increase in irrigation water requirements might be compensated by the minor increase in reservoir inflows, largely resulting from a greater concentration of rainfall in winter. The Monte Novo reservoir appeared to be more sensitive to possible water quality issues than the Vigia reservoir, in particular due to its more intense agriculture practices.

In the case of the extreme scenario (RCP 8.5), the main problem seems to be associated with a decrease in inflows. In the case of Monte Novo, this decrease in inflow will be associated with higher phosphorus concentrations, potentially worsening water quality problems. In the case of Vigia, this decrease inflow will be accompanied by a strong increase of irrigation requirements, further aggravating the current water scarcity situation.

Both reservoirs seemed to have a limited capacity to support climate change adaptation measures that envisage an increase in irrigated area until the end of the century. However, measures increasing water use efficiency, both of the irrigation systems and of the selected crops, could help overcoming future water stress conditions. At the same time, such climate change adaptation measures cannot be expected to produce marked improvements in water resources on the short term, especially since both Monte Novo and Vigia are already under water stress.

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**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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**Cláudia Carvalho-Santos**: *Validation, Formal analysis, Writing, Writing - Review & Editing, Visualization*

**Paulo Diogo**: *Conceptualization, Validation, Investigation, Writing – Review & Editing, Project administration, Funding acquisition*

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Graphical abstract

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