Thermal stratification of Portuguese reservoirs: potential impact of extreme climate scenarios

Manuel C. Almeida, Pedro S. Coelho, António C. Rodrigues, Paulo A. Diogo, Rita Maurício, Rita M. Cardoso and Pedro M. Soares

ABSTRACT

Changes in water temperature and stratification dynamics can have a significant effect on hydrodynamics and water quality in reservoirs. Therefore, to assess future climate impacts, projections of three regional climate models for Europe, under the IPCC A1B emission scenario (2081–2100), were used with the CE-QUAL-W2 water quality model to evaluate changes in the thermal regime of 24 Portuguese reservoirs, representing different geographic regions, morphologies, volumes and hydrological regimes. Simulation results were compared with reference simulations for the period 1989–2008 and changes in water temperature and thermal stratification characteristics were evaluated. Future inflow scenarios were estimated from precipitation-runoff non-linear correlations and outflows were estimated considering present water uses, including hydropower, water supply and irrigation. Results suggest a significant increment in the mean water temperature of the reservoirs for the entire water volume and at water surface of 2.3 and 2.5 °C, respectively, associated with a runoff reduction of approximately 23%. Overall, variations in annual stratification patterns are characterized by changes in the mean annual length of stratification anomaly that ranged from −21 to +39 days. Results also show the influence of depth and volume over the reservoir's temperature anomaly, highlighting the importance of future water uses and operation rule curves optimization for reservoirs.

Key words | climate change, modeling, reservoir thermal regime, water quality

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INTRODUCTION AND OBJECTIVES

Water temperature and thermal stability dynamics have a significant influence on the water quality and ecology of lakes and reservoirs (Wetzel 2001), therefore these systems are particularly vulnerable to increasing temperatures. Observed climate change has already led to a systematic temperature increase in lakes all over the World and has been estimated to range from 0.03 to 0.11 °C per year in the epilimnion, as described by several authors (Austin & Colman 2007; Hampton *et al.* 2008; Arvola *et al.* 2010) and from 0.01 to 0.10 °C per year in the hypolimnion (Salmaso 2005; Matzinger *et al.* 2006; Arvola *et al.* 2010). According to the European Environmental Agency (EEA), water temperature in European rivers and lakes increased between 1.0 and 3.0 °C during the last century and the annual length of stratification periods in lakes show the same tendency to increase (EEA 2012). As a result, freshwater ecosystems have shown changes in productivity, organism abundance, species composition and phenological shifts (Parmesan & Yohe 2003; Bates *et al.* 2008). Also, the severity and intensity of droughts are increasing in Europe, in particular in the southern regions (EEA 2012; Lorenzo-Lacruz *et al.* 2013; IPCC 2013), which exposed the vulnerability of the Mediterranean water resources to climate extremes. Therefore, projected climate change represents an added risk regarding water quality issues of Mediterranean reservoirs (Ibáñez & Caiola 2013) that must be evaluated.

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These effects represent significant impacts which require the identification and implementation of mitigation and adaptation measures toward a consistent water resources management strategy that ensures future water quality and resource availability under climate change scenarios. These scenarios are nonetheless still shrouded with uncertainty as Global Climate Models (GCMs) do not always agree on the intensity of the effects associated with climate change. In Europe, modeled projection on the basis of the A2 Intergovernmental Panel on Climate Change (IPCC) scenario for the period 2070–2099 indicate an increase ranging from 2.5 up to 5.5 °C, as compared with the baseline period of 1961–1990 (Alcamo *et al.* 2007). For the Mediterranean region, although several features of simulated climate change are consistent among GCMs, substantial uncertainties remain: seasonal mean temperature results vary at the sub-continental scale by a factor of two or three and results disagree on the magnitude and geographical detail of summer precipitation decrease in southern Europe (Giorgi & Lionello 2008; Alcamo *et al.* 2007). Also, temperature anomalies predicted by several GCMs for the Iberian Peninsula under the IPCC scenario IS92a vary from 4.0 to 7.0 °C for the year 2100 (SIAM II 2006). Due to this high degree of uncertainty, the use of worst case scenarios, such as climate projections for the end of the 21st century can be a solution to anticipate potential impacts in lakes and reservoirs. It is important to state that the use of the worst case scenario represents a precautionary principle approach, broadly used in European Union countries (Wiener & Rogers 2002).

Experimental observations integrated with mathematical modeling can be used to test the sensitivity of surface waters to observed and projected climate changes, playing a key role in describing the physical processes responsible for variations in the thermal structure of these systems (Samal *et al.* 2012). Most lake and reservoir thermal regime simulation studies, associated with meteorological forcing data obtained with different GCMs emission scenarios, agree that by the end of the 21st century there will be a significant increase in epilimnic and hypolimnic temperatures associated with an earlier onset, longer and more stable periods of thermal stratification (Kirillin 2010; Perroud & Goyette 2010; Samal *et al.* 2012; Lee *et al.* 2012). As a consequence of the described changes in surface waters thermal regime and its relation with effects in water quality, Jankowski *et al.* (2006) concluded that the extremely high degree of thermal stability of two Swiss Lakes (Lake Zurich and Lake Greifensee) during the summer of 2003 heat wave, resulted in extraordinarily strong hypolimnetic oxygen depletion.

Komatsu *et al.* (2007) applied a watershed runoff and water quality model to the Shimajigawa reservoir, located in western Japan, using climate scenario A2 for the period 2091–2100. Simulation results indicate that surface water temperature will increase on average by 3.8 °C and at the hypolimnion by 2.8 °C, when compared to the reference period, 1991–2000. Fang & Stefan (2009) used the model MINLAKE to simulate water temperature of 209 small lakes in the USA (some are real but others are hypothetical), under past climate and for projected doubled atmospheric carbon dioxide. Results project an increase in lake surface temperatures by up to 5.2 °C and in seasonal summer stratification length by up to 67 days. The Cannonsville reservoir, located in the USA, was simulated with two coupled models under climate projections for the 2081–2100 period and results indicate a substantial increase in surface and bottom temperatures under different future climate scenarios as well as an increase in the stratification period length, reaching 7 and 12 days for the A1B and A2 IPCC scenarios, respectively (Samal *et al.* 2012). Perroud & Goyette (2010) used a turbulence lake model to simulate Lake Geneva, in Switzerland, under the A2 IPCC scenario in the 2070–2099 timeframe and simulation results indicate a monthly increase of 2.3–3.8 °C and 2.2–2.3 °C in epilimnion and hypolimnion temperatures, respectively. These modeling efforts constitute an important contribution to climate change adaptation measures that should be considered as stated by Keskinen *et al.* (2010) at all stages of planning, national and regional levels, and it should be complemented as much as possible with a geographic-based adaptation approach.

Although important conclusions can be derived from the study of individual lakes or reservoirs, the consideration of a wide number of waterbodies, as in the present research, provides a clearer picture of the effects that climate change may induce over the water resources of a particular region. With that purpose, 24 Portuguese reservoirs were selected on the basis of geographical location and morphological features, like volume and depth, to enable the assessment of climate change in the thermal regime of Portuguese reservoirs, including water temperature variation range and stratification duration. Simulation results under tested climate change scenarios should be a contribution to the definition of adaptation strategies to climate change impacts on water resources in Portugal. Reservoirs rule curves should play a relevant role in adaptation strategies allowing accomplishment of the main objectives for the reservoirs and also minimize the effects of climate change in the reservoirs' stratification patterns, by promoting water circulation in these water bodies.

STUDY AREA AND RESERVOIRS MAIN MORPHOMETRIC DETAILS

All selected reservoirs included in this research are located in Portugal, although Alto Lindoso and Alqueva are partially located in Spain (Figure 1). These two countries share five main watersheds, Minho, Lima, Douro, Tejo and Guadiana, with a total watershed area of 268,500 km^2, 21% located in Portuguese territory. Portugal has a mild Mediterranean climate with daily minimum mean temperatures varying from 5 °C in the highlands of the northwestern and central region to 18 °C in the southern regions, and daily maximum mean temperatures ranging from 13 °C in the central highlands to 25 °C in the southeast near the Spanish border (Soares *et al.* 2012a). Mean annual precipitation is temporally and spatially heterogeneous due to complex topography and coastal processes, which are typical of Mediterranean climate (Soares *et al.* 2012b). In the northwest mountains, the maximum annual precipitation is approximately 3,000 mm/yr and in the southeast it is approximately 400 mm/yr (Soares *et al.* 2012b). The annual mean runoff, 380 mm/yr, represents approximately 40% of the annual mean precipitation. The highest runoff annual values, about 1,300 mm/yr, are observed in the northwestern river watersheds, while the lowest annual values, of 160 mm/yr and less are observed in the southern regions (SIAM II 2006).

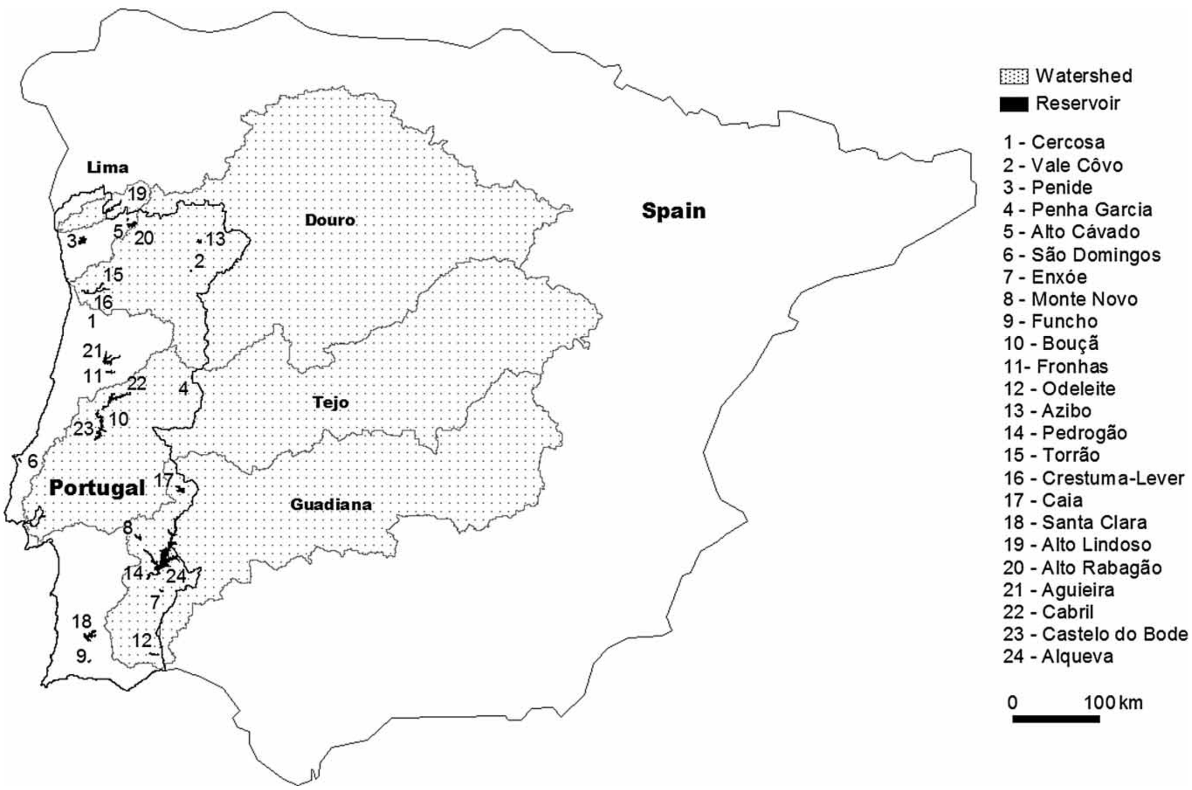

Figure 1 | Reservoirs location in the Iberian Peninsula (reservoirs ordered according to volume from smallest to largest).

Selected reservoir storage volumes range from 0.06 hm^3 (Cercosa) up to 4,150 hm^3 in the Alqueva reservoir, one of the largest reservoirs in western Europe. This wide volume range, as well as morphological variability, was chosen in order to evaluate the effects of volume, depth and surface area in the thermal structure, under future climate scenarios (Table 1). Almost all reservoirs are warm monomictic, with a defined and well-stratified period from May to September, and one mixing period each year, during the colder season, from October to April. The exceptions are Penide, Alto Cávado, Bouçã, and Pedrogão reservoirs, which are weakly stratified, and Crestuma-Lever, a run-of-river reservoir located in the north coastal region, that is always well mixed during the entire year. The reservoir's thermal stability was evaluated with the densimetric Froude number (Fr > 1, fully mixed; 0.1 < Fr < 1.0, weakly stratified; Fr < 0.1, strong stratification periods) (Table 1) (Fischer *et al.* 1979), and with observed field data obtained during the period 1989–2008.

METHODOLOGY

Water quality simulation was performed for all reservoirs using the CE-QUAL-W2 model version 3.6 (Cole & Wells 2011). CE-QUAL-W2 is a two-dimensional (longitudinal-vertical) hydrodynamic and water quality computer simulation model. The model assumes lateral homogeneity, making it suitable for modeling the characteristics of

Table 1 | Morphometric details of the reservoirs and main water uses.

	Reservoir	Maximum volume ($\times 10^6$ m^3)	Mean volume* ($\times 10^6$ m^3)	Maximum mean* depth (m)	Water surface area ($\times 10^6$ m^2)	Watershed area ($\times 10^6$ m^2)	Residence time (days)	Densimetric Froude number	Main uses
1	Cercosa	0.06	0.05	11.80	0.02	60	1	0.0841	P
2	Vale Covo	0.20	0.19	14.00	0.12	53	44	0.0001	W
3	Penide	0.50	0.04	8.20	0.69	4	0	0.9243	P
4	Penha Garcia	1.10	0.38	7.65	0.20	15	88	0.0036	W, I
5	Alto Cávado	3.30	1.17	15.50	0.50	101	3	0.1261	P
6	São Domingos	7.90	4.61	25.30	0.96	42	762	0.0007	W, I
7	Enxoé	10.40	6.48	9.30	2.10	61	278	0.0035	W
8	Monte Novo	15.30	10.75	19.85	2.77	261	830	0.0017	W, I
9	Funcho	43.40	24.37	17.50	3.60	212	85	0.0062	I
10	Bouçã	48.40	27.69	56.70	1.85	2,602	7.2	0.1952	P
11	Fronhas	62.10	45.62	34.00	5.35	96	35	0.0761	P
12	Odeleite	130.00	28.08	28.22	7.20	347	114	0.0151	W, I
13	Azibo	54.50	86.16	41.00	4.10	93	1262	0.0019	W, I
14	Pedrogão	106.00	101.08	10.00	11.04	59,160	29	0.1331	P, I
15	Torrão	124.00	91.57	54.80	6.50	3,268	14	0.0701	P
16	Crestuma-Lever	110.00	42.58	13.62	12.98	96,932	1	3.7060	P, W
17	Caia	203.00	112.35	38.06	19.70	563	531	0.0029	W, I
18	Santa Clara	485.00	274.57	70.54	19.86	520	1,456	0.0047	P, F, W, I
19	Alto Lindoso	347.80	335.59	69.00	10.72	1510	98	0.0420	P
20	Alto Rabagão	569.00	205.74	51.00	22.12	107	361	0.0028	P
21	Aguieira	450.00	317.82	68.04	20.00	3,063	86	0.0681	P, F, W, I
22	Cabril	719.00	344.79	78.70	20.23	2,416	103	0.0871	P
23	Castelo do Bode	1,095.00	859.46	86.80	32.91	3964	151	0.0604	P, W, F
24	Alqueva	4,150.00	2,974.66	86.60	250.00	55,289	929	0.0108	I, W, P

P – Power generation; W – Water supply; I – Irrigation; F – Flood prevention (*mean values of the period 1989–2008).

dendritic impoundments (relatively long and narrow waterbodies) that exhibit obvious water quality gradients along the longitudinal axes. The governing equations for hydrodynamics and transport are derived from the conservation of fluid mass and momentum equation. The model uses a hydrostatic approximation for vertical fluid movement instead of the real conservation of momentum equation (Cole & Wells 2011). Hydrodynamics and water quality are coupled. The effects of water quality on hydrodynamics are included through an equation of state that describes the effects of temperature and solids on density. This model is capable of reproducing a variety of reservoir thermal regimes with minimum adjustment of hydrodynamic/temperature calibration parameters. The grid geometry that allows the finite difference representation of the reservoir is determined by the longitudinal spacing (segment length), vertical spacing (layer height), average cross-sectional width and waterbed slope.

CE-QUAL-W2 requires meteorological data as input, including air temperature, dew-point temperature, wind speed and direction and radiation. Meteorological datasets of air temperature, wind speed and wind direction used to calibrate the baseline period of 20 years (1989–2008) were obtained with a dynamically downscaled climatology of Portugal, produced by a high resolution simulation (9 km, horizontal grid spacing) with the Weather Research and Forecasting model (WRF; Skamarock *et al.* 2008), forced by 20 years of ERA-Interim reanalysis (1989–2008), nested in a domain with 27 km of resolution. WRF is a non-hydrostatic model with an assembly of physical parameterizations and model core options making it suitable for simulating a wide range of temporal and horizontal scales. A more detailed description of the model set-up and simulation results can be found in Soares *et al.* (2012a) and Cardoso *et al.* (2013). These results were validated against registrations and gridded data for maximum and minimum temperatures and precipitation, showing a good agreement with observations.

Inflows and outflows were obtained from the Portuguese Water Institute (INAG), Energias de Portugal (EDP) and the Alqueva Development and Infra-structure Company (EDIA). Monthly inflows and outflows were used to calibrate reservoir volumes during the baseline period simulations (1989–2008). Inflow daily temperatures of 39 reservoir tributaries were estimated with linear regressions between air and water temperature. This approach was considered in face of the lack of information on the wide range of hydrometeorological parameters that are required to apply more sophisticated deterministic models. Linear correlations have been used successfully in studies seeking to project future stream and river temperatures that may result from climate changes (Webb 1996; Eaton & Scheller 1996; Mohseni *et al.* 1999). The initial reservoir water temperatures were specified as a single value in each reservoir, according to surface observed temperatures. During the period 1989–2008, sampling campaigns were conducted in the reservoirs by INAG and EDP, which included vertical profile measurements at multiple depths through the water column, at intervals of approximately 1 m. Combined with the hydrological records, these data were used to calibrate the model.

To quantify and reduce the uncertainty in modeling climate change, the European-funded project ENSEMBLES provides high resolution regional climate scenarios using several downscaling methods to exploit the Regional Climate Models (RCM) full potential. Under this project 18 institutes ran their state-of-the-art RCM at 25 km spatial resolution, with current climate boundary conditions from ERA-40 reanalysis (Uppala *et al.* 2005) and future and control climate from seven different GCMs, all using the A1B IPCC (1960–2100) emissions scenario (van der Linden & Mitchell 2009). Soares *et al.* (2012b) evaluated present climate mean and extreme precipitation regimes representation in the ENSEMBLES RCM models concluding that RCMs produce a good representation of the main spatial patterns of annual precipitation, although 10 out of the 12 underpredict precipitation in Portugal.

After the calibration process, the model CE-QUAL-W2 was used to run three different forcing meteorological datasets of air temperature, wind speed and wind direction, obtained with three RCMs at 25 km resolution, from the ENSEMBLES set, for the definition of the baseline period of 20 years (1989–2008): ETHZ – Swiss Institute of Technology (Jaeger *et al.* 2008), KNMI – Koninklijk Nederlands Meteorologischtituut (van Meijgaard *et al.* 2008) and SMHI – Swedish Meteorological and Hydrological Institute (Samuelsson *et al.* 2011). From all ENSEMBLES models, these three were shown to be the best performing models in describing the Portuguese climate (Soares *et al.* 2012b). Hydrologic boundary conditions considered in the definition of these scenarios are the same as those used during model calibration, which describe the baseline period of 1989–2008. Inflow temperatures were estimated with the air–water correlations used for the model calibration.

Future scenarios for each reservoir were run with CE-QUAL-W2 forced with meteorological datasets of air temperature, wind speed and wind direction, obtained with the three RCM for the period 2081–2100. Tributaries water temperatures were estimated with the air–water correlations already considered for the definition of baseline scenarios. Inflows are estimated through the use of change factors, calculated from the differences in monthly precipitation between baseline (1989–2008) and future (2081–2100) simulation of time periods, associated with the three RCM. The monthly variation in precipitation described by the change factor is applied to the monthly inflow, which is reduced or increased accordingly (Equations (1) and (2))

$$Q_f = Q_r + \left(\frac{\alpha^* Q_r}{100}\right) \quad \text{if} \quad \alpha > 0 \tag{1}$$

$$Q_f = Q_r - \left(\frac{|\alpha|^* Q_r}{100}\right) \quad \text{if} \quad \alpha < 0 \tag{2}$$

where Q_f is the monthly inflow for the period 2081–2100, Q_r is the monthly inflow for the period 1989–2008, and α is the monthly precipitation change factor, expressed in percentage. If the projected inflow exceeds the monthly maximum flow observed in the tributary during the baseline period, it is replaced with the maximum monthly value. Outflows are controlled by an algorithm that regulates reservoirs water levels and calculates hydroelectric releases, water supply and irrigation needs on the basis of the baseline simulation period, whenever possible. If the reservoir maximum volume is reached, water is turbinated or discharged according to the type of reservoir. On the other hand, if the minimum reservoir volume is attained, hydroelectric releases and irrigation needs are reduced.

Initially the reservoirs' water temperature used in the first day of simulation was obtained from correlations between air temperature and water temperature. However, this approach does not consider the time lag that exists between air and water temperature (Stefan & Preud'homme 1993), which can increase considerably the error associated with the simulations. Another possible solution was the use of the pseudo-periodic regime approach, in which the model is repeatedly forced with the same meteorological input and with the initial values of the previous run until there were no changes in water temperature (Kourzeneva 2010). However, this approach was also excluded because it generates a mean temperature value that can be considerably different from the initial temperature value. The values obtained with the linear correlations were very similar to those that were used to characterize the baseline scenario. Thus, to eliminate another source of uncertainty, the initial water temperature values used in the definition of the baseline scenario were also used for future simulation of climate scenarios.

Changes in stratification length periods were evaluated by comparing the temperature difference between surface and bottom ($\Delta T = T_s – T_b$). This method implies that stratification is a dual process: the reservoir is either mixed (ΔT values lower than the threshold stability) or stratified (values greater than the threshold). Initially a sensitivity analysis was conducted to evaluate the variation of reservoirs baseline scenario (forced with WRF model meteorological datasets) and thermal stability length was evaluated under three different threshold stability values (TSV), 1, 2 and 3 °C. Mean annual thermal homogenization periods length varied from 98 days (standard deviation, SD: 75) for a TSV of 1 °C, 120 days (SD: 76) for a TSV of 2 °C, and 142 days (SD: 78) for a TSV of 3 °C. The analyses of these results led to the conclusion that the consideration of any one of the TSV would be appropriate for the vast majority of the reservoirs, to assess significant changes in the length of stratification periods. Therefore, a TSV of 1 °C was chosen as it corresponds to a more accurate definition of thermal homogeneity. A similar approach was used by Fang & Stefan (2009), as an indicator of the temperature strength and density stratification, but the authors have rather considered the maximum difference between surface and bottom water temperatures.

RESULTS AND DISCUSSION

To evaluate the performance of the different climate models in representing the main spatial and temporal features of the Portuguese climate, annual daily mean air temperature and total annual watershed precipitation, obtained from WRF and from the ENSEMBLES RCM for each watershed, were compared with available records. The WRF model was found to achieve a good representation of mean and maximum air temperature in mainland Portugal, with good spatial correlations with observations (Figure 2(a)). The overall mean average mean error (AME) value, between daily mean air temperature obtained with WRF and measured data, varies from 0.9 to 2.2 °C (mean: 1.6 °C; SD: 0.3 °C) (Figure 2(b)). EMSEMBLES RCM models results also characterized reasonably well the spatial variability of mean air temperature in Portugal (Soares *et al.* 2012b). However, accuracy was, as expected, considerably worse due to the lower resolution grid and to the meteorological forcing, as described by the mean AME obtained for each model, 3.6 °C (SD: 0.5), 3.5 °C (SD: 0.5) and 3.5 °C (SD: 0.5), for ETHZ, KNMI and SMHI, respectively. The spatial variability of minimum daily air temperatures values were poorly characterized by all RCM (Figure 2(a)). In contrast, all models had good spatial correlations between mean, maximum, and minimum total annual precipitation and observations (Figure 2(c)). The major discrepancies that were found in that the RCMs results appear in total annual precipitation values, described by a large variability of AME values (Figure 2(d)). These

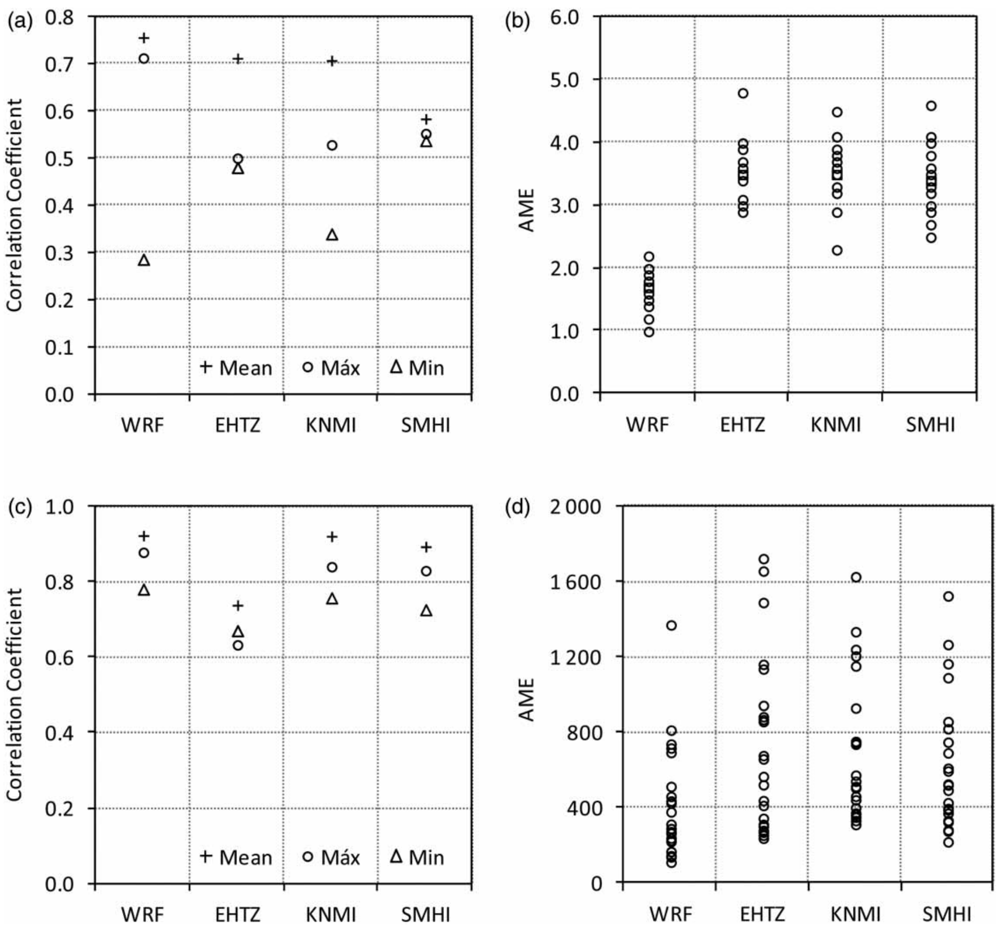

Figure 2 | Error measures of the WRF model and ENSEMBLES RCM – (mean, maximum and minimum annual daily air temperature and total annual precipitation): (a) model to observed data correlation (air temperature); (b) model to observed data AME (air temperature); (c) model to observed data correlation (total annual precipitation); and (d) model to observed data AME (total annual precipitation).

differences were greater in northern Portugal regions, where observed precipitation values are higher. Despite the differences found between model results and observations, the meteorological datasets obtained with the RCMs describe reasonably well the climate of the baseline period (1989–2008).

Due to the lack of available air and water temperature data, it was not possible to calculate linear air–water correlations for each of the 39 reservoir tributaries. It was only possible to obtain 26 linear air–water correlations. Thus, in some reservoirs a single air–water correlation was used to estimate inflow water temperature for all tributaries. Air and water temperature data series used to obtain the linear air–water correlations had different lengths, accordingly with the available data, which vary from a minimum of 43 pairs of values, to a maximum of 2,779 (mean: 292; SD: 746). The coefficient of determination (R^2) obtained for the linear air–water correlations varied from 0.75 to 0.90, with a SD of 0.03 and with a mean value of 0.83.

During CE-QUAL-W2 calibration for the period 1989–2008, the wind-sheltering coefficient (WSC) had a significant effect on water temperature. This coefficient was altered until the predicted surface water temperatures during the simulation period were in agreement with the measured values. The overall mean value of WSC was of 0.6, with a minimum value of 0.1 in Bouçã reservoir and a maximum of 1.0 in Fronhas, Pedrogão, Aguieira and Alqueva reservoirs. Other coefficients affecting temperature remained with the following reference values: longitudinal Eddy viscosity, $1.0\,m^2\,sec^{-1}$; Chezy coefficient, $70\,m^2\,sec^{-1}$ and solar radiation percentage absorbed in the surface layer, 0.45. During calibration, two statistical properties were used to compare simulated and measured values: the absolute mean error (AME) and the root mean square error (RMSE). The predicted water temperature profiles during the simulation period are in agreement with the measured values, with the AME and RMSE values varying from 1.4 to 3.0 °C and from 1.7 to 3.8 °C, respectively. The thermocline depth and the fall overturn were generally well simulated by the model, during the entire simulation period.

To assess the effect of climate change in the thermal regime of the reservoirs, baseline simulation results for the period 1989–2008, were compared with future simulations under climate projections for the 2081–2100 timeframe, obtained with the ENSEMBLES models. Future scenarios obtained with the models ETHZ, KNMI and SMHI, project for the period 2081–2100, the following mean annual values: (a) air temperature increase of 4.7 °C (SD: 0.36), 4.6 °C (SD: 0.37) and 4.5 °C (SD: 0.45); (b) runoff reduction of 23.7% (SD: 8.2), 23.0% (SD: 8.9) and 22.9% (SD: 6.5); and (c) hydroelectric releases reduction of 8.3% (SD: 10.3), 8.6% (SD: 21.3), and 12.3% (SD: 9.3).

The use of change factors to estimate future inflow scenarios led to the underestimation of the annual inflow to each reservoir in approximately 7%, when compared with the mean annual precipitation variation between present and future scenarios. Data scarcity, particularly rainfall and flow observations in the majority of the catchments prevented the consideration of rainfall-runoff models to improve this estimate.

Simulation results obtained with ETHZ, KNMI and SMHI models, project a mean water temperature increase in the entire water volume of the reservoirs of 2.5 °C (SD: 0.7), 2.2 °C (SD: 0.6) and 2.2 °C (SD: 0.6), respectively. Changes in reservoir surface water temperature indicate an increase of 2.7 °C (SD: 0.6), 2.4 °C (SD: 0.5), and 2.4 °C (SD: 0.5), under ETHZ, KNMI and SMHI forcing, respectively. These changes are consistent with the mean surface increment of 3.3 °C (SD: 0.8), estimated by Fang & Stefan (2009), for 209 lakes located in the contiguous USA, under the 2xCO_2, climate scenario, which projects an increase of mean annual air temperature up to 6.7 °C.

To obtain a broad brush picture of the temperature anomaly, results were aggregated by combining mean, maximum and minimum values (Figure 3). This approach led to the conclusion that despite the morphological and meteorological forcing variability, mean water temperature anomaly for the entire water volume and at each reservoir surface had a small deviation from the mean value (Figure 3(a) and 3(b)). The overall mean water temperature anomaly for the entire water volume and at water surface reveals an increase of 2.3 °C (SD: 0.7) and 2.5 °C (SD: 0.5), respectively. This corresponds to an increase rate of 0.021 °C per year for the entire water volume, and 0.023 °C per year at the surface, considering the period 1989–2100. Maximum and minimum water temperature anomaly had a large variability, due to the meteorological forcing (Figure 3(c)–3(f)),

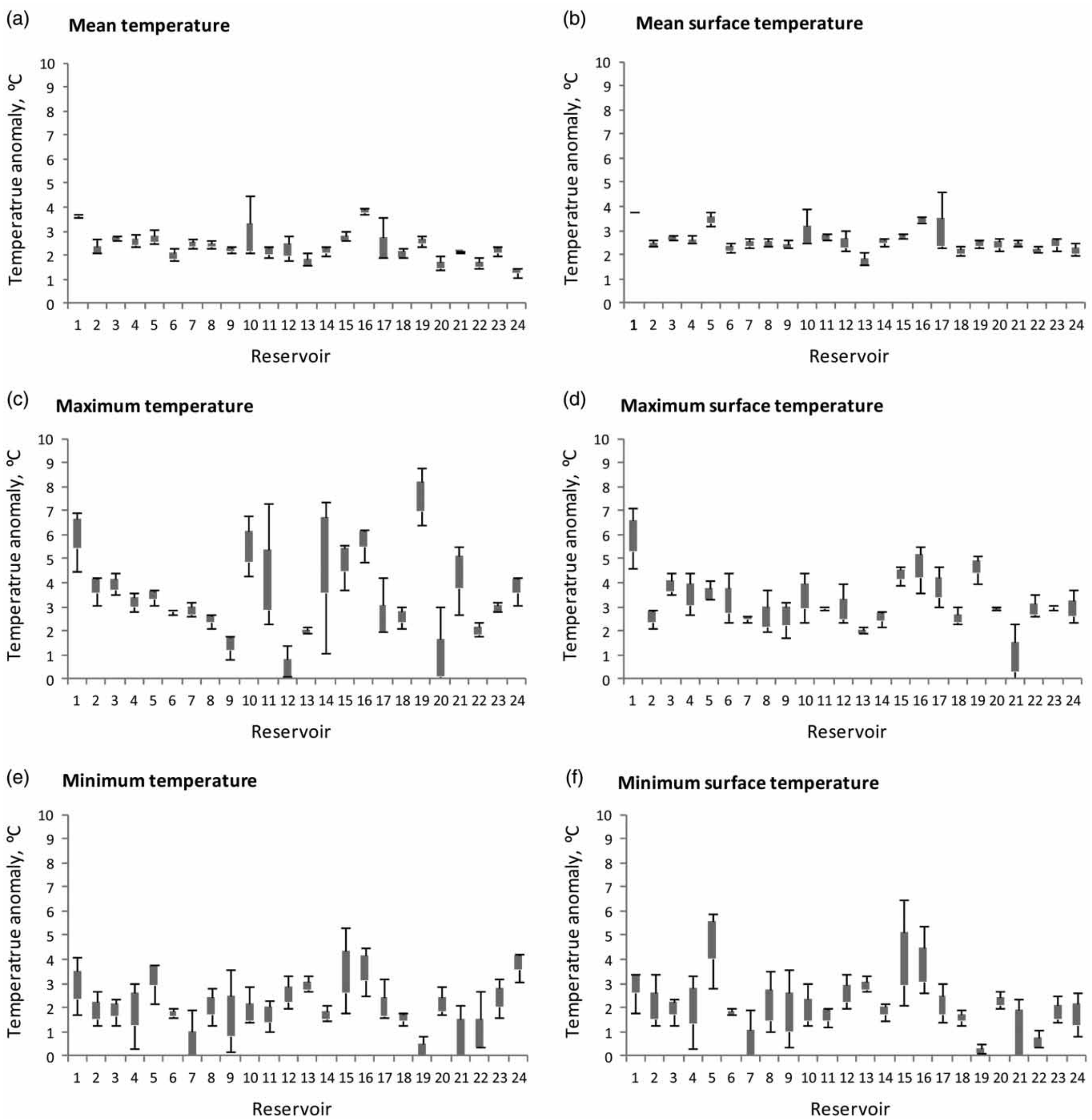

Figure 3 | Mean, maximum and minimum water temperature anomaly values over the entire water volume of the reservoirs (a, c and e) and at the surface (b, d and f), respectively. Variation between baseline conditions and the average of the future (2080–2100) time period scenarios results forced with the output of the RCM projections (box-plot description: maximum – 75th percentile , median, minimum – 25th percentile).

ranging from 0.0 to 8.8 °C (mean: 3.1 °C; SD: 1.9), for the entire water volume and from 0.0 to 7.1 °C (mean: 3.0 °C; SD: 1.2) at the surface. In 46% of the reservoirs considered in this study (reservoirs 2, 7, 10, 11, 14, 15, 16, 19, 21, 23 and 24; see Figure 1), the maximum temperature anomaly was greater in the entire water volume compared with the surface values (Figures 3(c) and 3(d)). Higher water temperatures and the volume reduction that occurred during the summer months in the 2081–2100 timeframe scenarios, led to thermal homogenization at elevated temperatures. Thus, temperature anomaly was greater in the entire reservoirs' water volume which, with the exception of some annual short periods of convective cooling, is always colder than the surface layer. Minimum temperature anomaly values also increased significantly, reaching 6.5 °C at the surface (mean: 2.0 °C; SD: 1.4) and 5.3 °C (mean: 2.0 °C; SD: 1.2), for the entire water volume (Figure 3(e) and 3(f)). Minimum reservoir surface water temperatures are essentially the same as minimum reservoir water temperatures for the entire water volume, because they typically occur at overturn. Simulation results project up to 7.1 and 6.5 °C, increase in maximum and minimum surface temperature, respectively. These results are higher but similar to those estimated by Fang & Stefan (2009), 5.2 and 5.1 °C, for southern latitude lakes of the USA.

The evaluation of changes in the thermal stability of the reservoirs indicated that some periods of thermal stratification, characteristic of the hottest months of the year, were replaced by thermal homogenization at high temperatures, due to the water volume decrease and air temperature increase (Figure 4). The overall results describe considerable changes in the annual stratification length: (a) mean annual length of stratification anomaly, ranged from: −21 days to 39 days (SD: 14) (Figure 4(a)); (b) maximum annual increase in length of stratification anomaly, ranged from: 15 days to 79 days (SD: 17) (Figure 4(b)); and (c) maximum annual decrease in length of stratification anomaly, ranged from: −119 days to 10 days (SD: 28) (Figure 4(c)).

The range of the mean and maximum annual stratification length estimated for the reservoirs is of the same order of magnitude as the range of values observed in different studies conducted in several lakes worldwide for the 21st century, where reported annual increment rates vary from 14 to 56 days (e.g. McCormick & Fahnenstiel 1999; Austin & Colman 2007; Livingstone 2003; Winder & Schindler 2004; Stainsby *et al.* 2011). Fang & Stefan (2009) estimated a maximum increase in the seasonal summer stratification of several lakes located in the USA by up to 67 days, which is also in agreement with the maximum annual stratification length anomaly estimated in the present research for the Portuguese reservoirs. The reduction on the stratification length (Figure 4(c)) as a consequence of climate change is

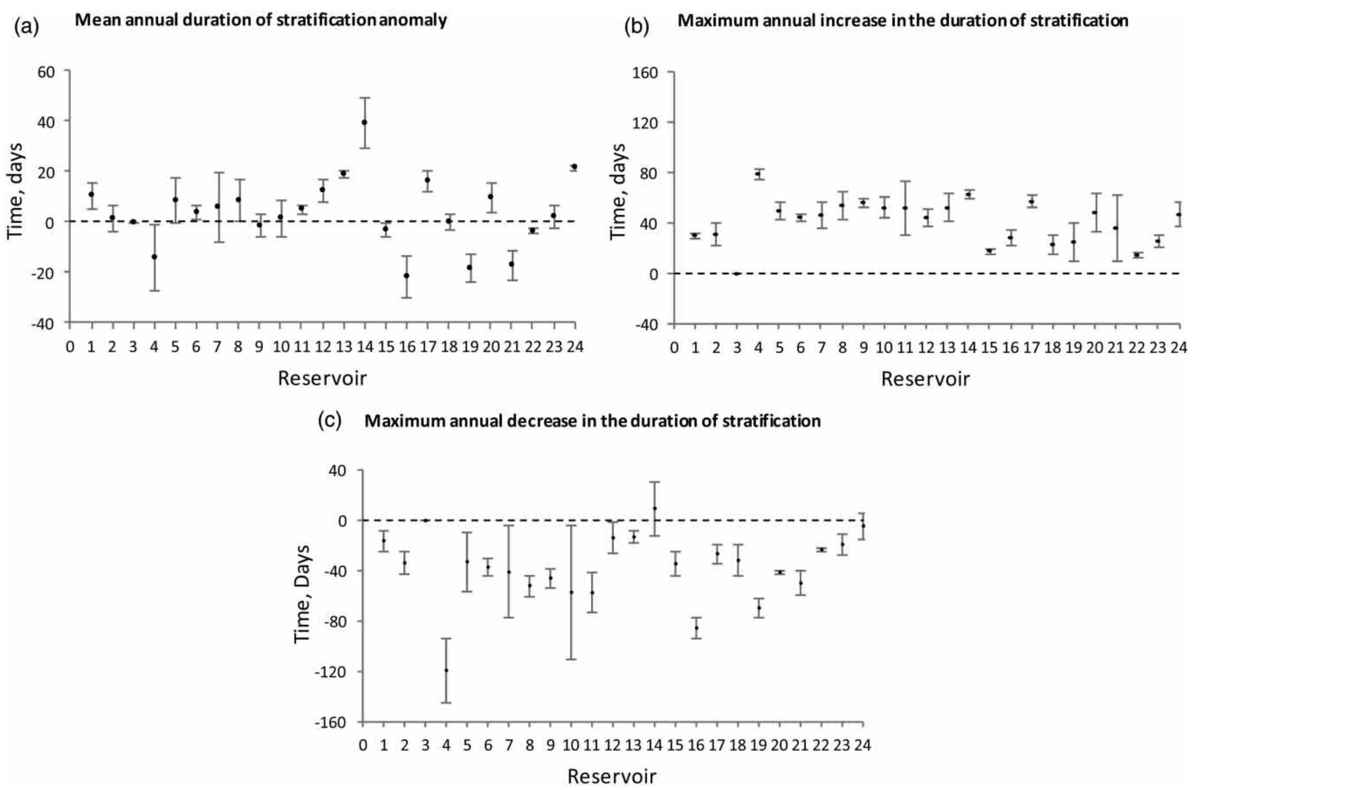

Figure 4 | Length of stratification anomaly between baseline conditions and the average of the future time period scenarios (2080–2100) forced with the output of the RCM projections (errors bar-standard deviation).

mainly caused by the operation of the reservoirs, and therefore it could be avoided. However, it should be noted that the definition of future scenarios respected the minimum volume defined for each reservoir. Thus, if the water uses in the end of the 21st century are similar to those considered in this research (the outflows observed during the period 1989–2008), then stratification length periods may be reduced. Reservoir operation curves should thus be changed to minimize the effects of climate change and to optimize hydropower generation (Mehta *et al.* 2011). The assessment of present and future water uses and the optimization of operation rules curves for a sustainability-oriented water management are two examples of adaptive measures that can prevent significant deterioration of the ecological condition of the water resources.

Alto Lindoso reservoir, located in the north of Portugal, is an example of the volume reduction that was projected by the future scenarios. During the baseline scenario simulation, forced with meteorological data from the ETHZ model results, the reservoir volume lies near its maximum, with the exception of the summer periods (Figure 5). The results obtained with the future climate projections, indicate a mean annual volume reduction of 47% (SD: 28) and the consequent thermal homogenization during seven summer periods, at temperatures above 25 °C (Figure 6). Maximum annual stratification length anomaly varied from +25 to −69 days, respectively. This wide annual variation of the stratification duration, combined with the water temperature increase, suggests that the reservoir physical, chemical and biological processes will be exposed to an increasing pressure that might disrupt the ecological condition, and therefore, affect the water quality of this system. For example, Nicolle *et al.* (2012), in a mesocosm study conducted to evaluate the effect of water temperature increase in aquatic ecosystems in northern Europe, found that increased water temperature changed the phytoplankton and zooplankton dynamics of these systems, and overall results suggests an earlier onset of the phytoplankton spring growth.

There are some significant advantages derived from the elimination of thermal and density differentials, namely the vertical distribution of heat, nutrients, dissolved substances and the reduction of hypolimnetic anoxia (Wetzel 2001; Reynolds 2006). Marshall *et al.* (2009) conducted a study in Lake Victoria, located in east Africa, which shows that lake thermal gradients have weakened over the last decade and that anoxia in deeper waters is less pronounced. Since 1927, surface water temperature has risen 1.0 °C and in deeper waters has risen 1.3 °C, causing the reduction of thermal stability. Additionally Marshall *et al.* (2009) also suggest that climate warming effects on tropical lakes are highly variable and may not, in the short term, have a negative impact. Nevertheless, this issue needs to be treated with some caution, due to the complex ecology of these systems and the lack of studies on the effects of thermal homogenization in summer periods. On the other hand, cyanobacterial dominance in many aquatic ecosystems is enhanced by the increase in the length and strength of the stratification periods because of their competitive advantages at elevated temperatures (Paerl & Huisman 2008) which poses a serious threat to the water quality of lakes and reservoirs. The thermal stability increase may also induce unpredictable ecological shifts in lakes and reservoirs, such as phenological shifts, defined by the loss of thermally suitable habitat

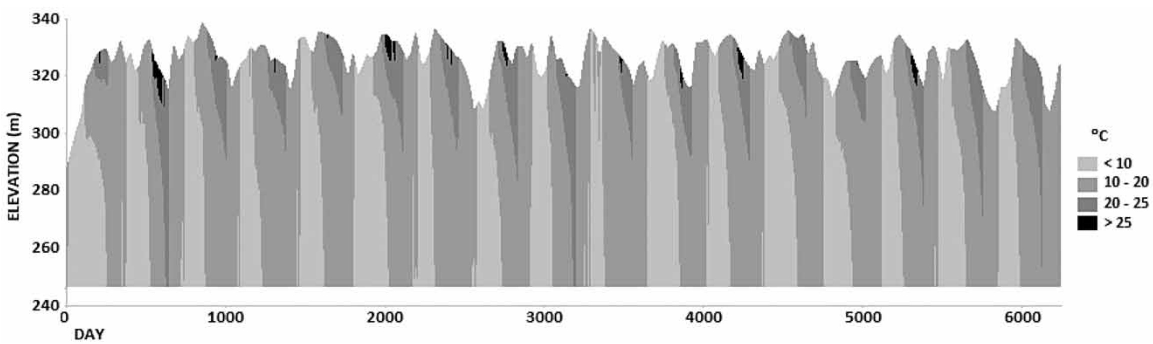

Figure 5 | Alto Lindoso reservoir water temperature profile evolution during the baseline scenario simulation 100 m from the dam – Meteorological forcing with ETHZ RCM data series.

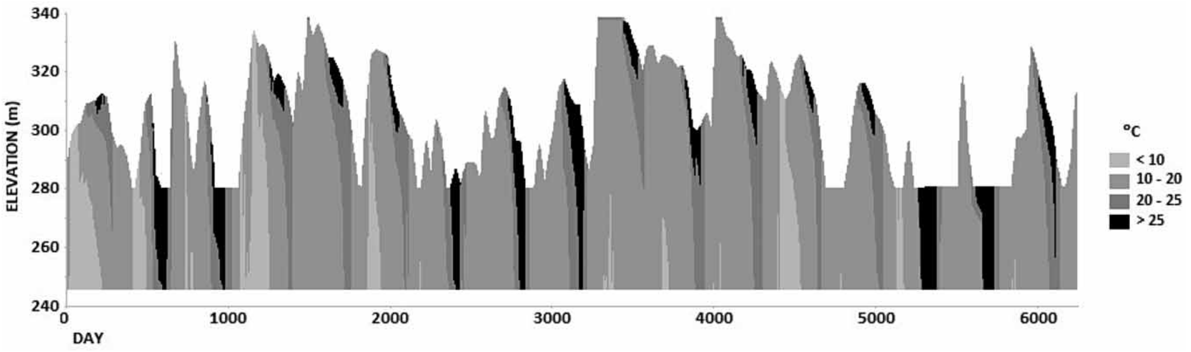

Figure 6 | Alto Lindoso reservoir water temperature profile evolution during the future climate simulation 100 m from the dam – Meteorological forcing with ETHZ RCM data series.

and population fragmentation for cold water fish and the dissemination of aquatic invasive species (Hellmann *et al.* 2008; Rahel & Olden 2008).

The effects of climate change in the reservoirs' thermal regime might be minimized with the establishment of a minimum water storage level. To evaluate the effectiveness of this adaptation measure, the future scenarios considered for Alto Lindoso reservoir were redefined to include a conservative minimum volume of 252.7 hm^3, which corresponds to the mean annual volume that characterizes the baseline period of 20 years (1989–2008). To implement this scenario, hydroelectric releases were modified to respect the minimum reservoir volume. Table 2 shows the mean volumes and the hydroelectric releases of each simulation scenario.

Simulation results obtained for the modified future scenarios (2080–2100) with ETHZ, KNMI and SMHI models project a mean water temperature increase in the entire reservoir water volume, of 2.0, 1.8 and 1.6 °C, respectively, when compared with the baseline scenario (1989–2008). Nevertheless, when compared with the future scenarios (2080–2100) results, the definition of the minimum reservoir stored volume reduced the mean water temperature in the entire reservoir water volume by 0.8 °C (SD: 0.2), mainly due to the reduction of the maximum water temperature values that ranged from 5.7 to 7.4 °C (mean: 5.4 °C; SD: 2.3 °C) (Figure 7(a)). The major reduction occurs, as expected, during the summer season (June, July, August and September), varying from 1.3 to 2.8 °C (mean: 2.1 °C; SD: 0.8 °C) (Figure 7(b)).

Table 2 | Mean volume and hydroelectric releases considered for the future scenarios (2080–2100) and for the modified future scenarios (2080–2100) (Alto Lindoso reservoir)

	Mean volume (hm^3)		
Scenario	**(1989–2008)**	**Future scenarios (2080–2100)**	**Modified future scenarios (2080–2100)**
ETHZ	252.7	182.4	290.2
KNMI	252.7	124.8	277.8
SMHI	252.7	152.1	284.0
Minimum reservoir volume	8.7	8.7	252.7
Mean hydroelectric releases (m^3/s)	36.2	27.9	28.0

The mean annual volume increase of Alto Lindoso reservoir defined by the modified future scenarios (2080–2100) caused significant changes to the stratification duration of the reservoir when compared with the baseline period (1989–2008) (Table 3). In some years, the number of stratification days increased reaching a maximum of 55 days. However, the thermal homogenization in summer periods was considerably reduced when compared with the results projected by the future scenarios (2080–2100). The mean maximum decrease in the stratification duration was reduced in approximately 38% (SD: 26) (Table 3). Despite the negative effects, the modified future scenarios (2080–2100) stratification duration projections are closer to the usual annual stratification patterns that characterizes the baseline period (1989–2008) than the future scenarios (2080–2100) results.

Results obtained with the modified future scenarios (2080–2100) simulation for Alto Lindoso reservoir, show that the definition of a minimum volume and the consequent reservoir operation changes are an effective

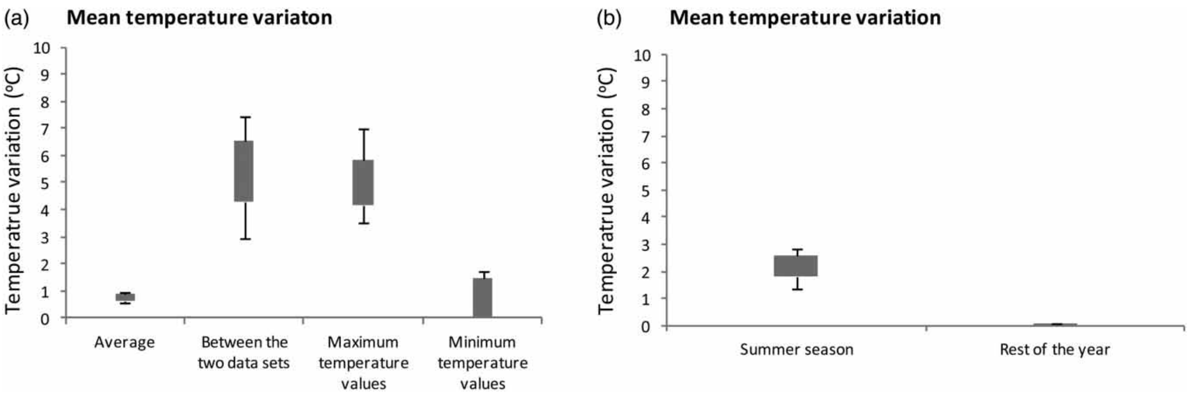

Figure 7 | Mean water temperature anomaly values over the entire reservoir water volume for (a) annual, and (b) summer and rest of the year data. Variation between the average of the future (2080–2100) scenarios and the modified future (2080–2100) scenarios results, forced with the output of the RCM projections (box-plot description: maximum – 75th percentile, median, minimum – 25th percentile) for Alto Lindoso reservoir.

Table 3 | Length of stratification anomaly between baseline conditions and the average of the future time period scenarios (2080–2100) with and without operation changes, forced with the output of the RCM projections for Alto Lindoso reservoir (days)

	Future scenarios (2080–2100)			Modified future scenarios (2080–2100)		
	Average	Maximum increase	Maximum decrease	Average	Maximum increase	Maximum decrease
ETHZ	−24.1	21.0	−78.0	−4.7	34.0	−60.0
KNMI	−17.5	13.0	−62.0	10.5	48.0	−20.0
SMHI	−12.8	42.0	−68.0	10.6	55.0	−53.0
Average	−18.1	25.3	−69.3	5.5	45.7	−44.3
SD	5.7	15.0	8.1	8.8	10.7	21.4

adaptation measure that can reduce considerably the effects of climate change. However, there are still some significant changes in the reservoir thermal regime that clearly indicates that this type of response might not be sufficient to preserve the reservoir ecological condition. The combined effect of water temperature and volume variation was an evidence of the potential impact that projected climate scenarios might have in Mediterranean reservoirs.

The results of the present study also indicate that there are weak correlations between reservoirs' water temperature anomaly projected by the climate change scenarios and the reservoirs morphological characteristics, as mean volume and depth and water surface area, even after the elimination of some spurious values (Figure 8(a)–8(c)), and even weaker correlations with residence time/depth and Froude number (Figure 8(d) and 8(e)). However, these weak correlations are important because they clearly show the existence of a trend toward the reduction of water temperature anomaly with the increase of reservoirs' mean depth, volume and water surface area. Furthermore, they also demonstrate the relative contribution of morphology and geographic location to reservoirs' water temperature anomaly, as described by the determination coefficients presented in Figure 8. Therefore, results suggest that regional climate conditions defined by Portuguese reservoir locations (Figure 8(f)) had a weaker effect over this variable than reservoir geometry and operation.

To evaluate the partial effect of each independent variable (volume, mean depth and water surface area) in the water temperature for the entire reservoirs water volume, a multiple regression analysis was conducted. A significant correlation was obtained, after the exclusion of five reservoirs from the total of 24 (reservoirs 10, 15,

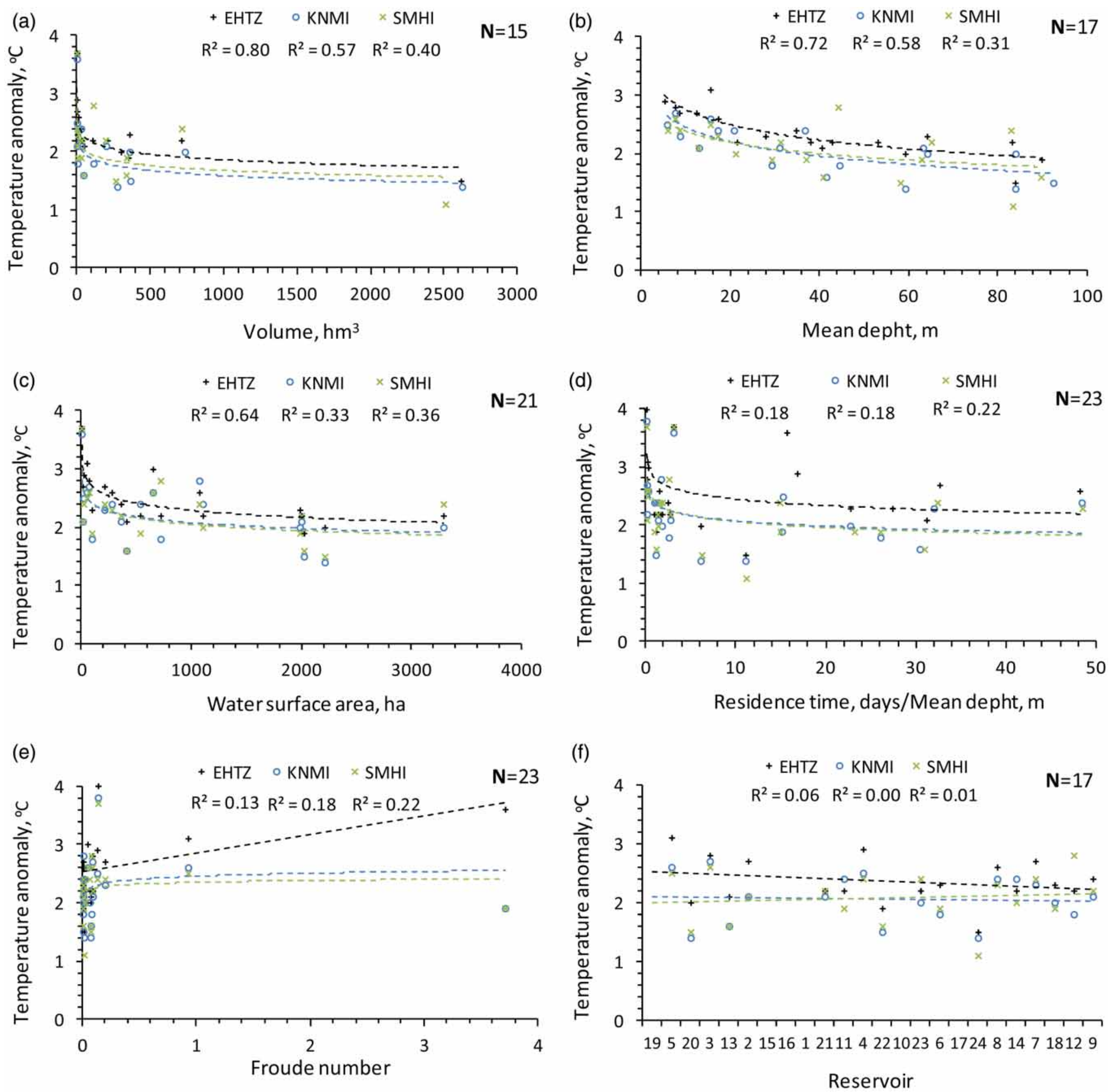

Figure 8 | Correlations between water temperature for the entire reservoir water volume under the future climate scenarios (ETHZ, KNMI and SMHI) and (a) reservoir mean volume, (b) mean depth, (c) surface area, (d) residence time/depth, (e) Froude number and (f) geographic location (ordered from north to south of Portugal).

16, 17 and 19), with a confidence level of 95% (Table 4, $N = 19$). However, the P-value obtained for each coefficient output shows that only the mean depth appears to be significant ($P < 0.05$). The number of reservoirs was then reduced to 14 to assess the evolution of the regression model and the output of all three variables' coefficients were considered significant, however, a positive correlation appeared for the reservoir's volume (Table 4). This variable suppressed the error of the model, mostly by being weak as a predictor contribution to the correlation. Overall results indicate mean depth to be the strongest influence over the water temperature for the entire reservoirs' water volume and that significant correlations might be derived between these two variables. Nevertheless the other morphological variables could also be of importance, which determines that each reservoir should be considered as a case study, namely, at the definition of specific adaptation measures.

Table 4 | Multiple regression parameters

N = 19			
Adjusted $R^2 = 0.63$			
$F = 11.2$			
Significance $F = 0.0004$			
	Coefficient	t Stat	P-value
Intercept	3.0648	21.1	1.5E − 12
Volume	0.0024	2.1	0.0487
Mean depth	−0.0191	−4.1	0.0009
Surface area	−0.0002	−2.3	0.0379
N = 14			
Adjusted $R^2 = 0.88$			
$F = 32.7$			
Significance $F = 0.00002$			
	Coefficient	t Stat	P-value
Intercept	2.8455	35.4	7.7E − 12
Volume	0.0017	3.6	0.0045
Mean depth	−0.0143	−6.6	0.0001
Surface area	−0.0002	−4.0	0.0025

Correlation between water temperature for the entire reservoirs water volume under the future climate scenario, ETHZ and reservoirs' volume, mean depth and water surface area.

CONCLUSIONS

In southern Europe, the majority of water supply systems are derived from reservoirs which enhances the importance of preserving and defining an effective adaptation strategy to the impacts of climate change on water resources. The results of this research suggest that climate change may induce some profound changes in Portuguese reservoirs' annual thermal regime. The projected inflow volume reduction of approximately 23%, and the air temperature anomaly (mean: +4.6 °C) define a more artificial thermal regime, characterized by higher and extreme water temperature values. Simulation results project up to 7.1 and 6.5 °C, increase in maximum and minimum surface water temperature, respectively, and less water availability. Some stratification periods characteristic of summer months should be replaced with thermal homogenization at higher temperatures (changes in the mean annual length of stratification anomaly ranged from: −21 to +39 days). Results also show the influence of depth and volume over the reservoirs' temperature anomaly highlighting the importance of future water uses and the optimization of the reservoirs' operation rule curves. Thus, further research regarding surface water temperature tendencies under climate change scenarios is certainly a relevant issue and downscaled climate change scenarios and water quality models are a suitable methodological association.

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