



Climate Change Impacts on Water Resources and Reservoir Management: Uncertainty and Adaptation for a Mountain Catchment in Northeast Portugal

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Abstract Reservoirs often play an important role in mitigating water supply problems. However, the implications of climate change are not always considered in reservoir planning and management. This study aimed to address this challenge in the Alto Sabor watershed, northeast Portugal. The study analysed whether or not the shortage of water supply can be effectively addressed through the construction of a new reservoir (two-reservoir system) by considering future climate projections. The hydrological model Soil and Water Assessment Tool (SWAT) was calibrated and validated against daily-observed discharge and reservoir volume, with a good agreement between model predictions and observations. Outputs from four General Circulation Models (GCM) for two scenarios (RCP 4.5 and 8.5) were statistically downscaled and bias-corrected with ground observations. A general increase in temperature is expected in the future while the change in precipitation is more uncertain as per the differences among climatic models. In general, annual precipitation would slightly decrease while seasonal changes would be more significant, with more precipitation in winter and much less in spring and summer. SWAT simulations suggest that the existence of two-reservoir will better

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solve the water supply problems under current climate conditions compared to a single-reservoir system. However in the future, the reliability of this solution will decrease, especially due to the variability of projections from the different climatic models. The solution to water supply problems in this region, adopted taking only present-day climate into account, will likely be inefficient for water supply management under future climate conditions.

Keywords Alto Sabor watershed · Climate change · SWAT model · Reservoir management · RCP scenarios · Water supply

1 Introduction

There is evidence that climate is changing in the Mediterranean region of Europe, with warmer temperatures and a change in the intensity and pattern of precipitation predicted for the future (Giorgi and Lionello 2008; Feng et al. 2014). One of the main concerns related with future climate is the potential change in the availability of water resources, common to dry regions around the world such as the Mediterranean (Kundzewicz et al. 2008; Shen et al. 2010;). This is particularly important because water is a primary resource for household, hydropower production, industry and irrigation (Falkenmark and Rockstrom 2004). Therefore, ensuring water quantity, quality and seasonality is an important concern for policy makers and stakeholders under the European agenda (Tsakiris 2015). On the other hand, water scarcity is not only dependent on meteorological drought, that is, the lack of precipitation during a certain period, but also on non-meteorological factors, such as high water demands and lack of or inadequate water related infra-structures (e.g. reservoirs) (Martin-Carrasco and Garrote 2007; Iglesias et al. 2011).

In Portugal, future change in the pattern of precipitation is a very important issue, as it can aggravate the typical seasonality with dry, hot summers and wet winters. The main hydrological consequences for the basins in northern Portugal are a reduction of discharge in spring and summer, and an increase of runoff in winter (Cunha et al. 2002). From the demand side, Portugal is generally considered a low water stress country (abstractions are lower than 40% of available water) when compared to other Mediterranean countries such as Spain, Malta and Cyprus (EEA 2003). However, some regions in Portugal frequently suffer from water supply problems during summer, namely in the south and in the interior north (Cunha et al. 2002; Nunes et al. 2008; Mourato et al. 2015). Water management strategies, especially the construction of reservoirs for water storage, have significantly influenced the natural hydrological response to meteorological droughts thus minimizing the impacts of precipitation deficits (Lorenzo-Lacruz et al. 2013).

Many studies have shown the impact of climate change on natural hydrological regimes in the Mediterranean watersheds, but the impact on regulated systems is much less known. These studies are important to evaluate the reliability of current and future water supply, anticipating the consequences of prolonged precipitation deficits (Iglesias et al. 2011). In Spain, studies have shown that water level in reservoirs can be severely impacted by climate change, especially during summer (Bangash et al. 2013; Molina-Navarro et al. 2014; López-Moreno et al. 2014). In Sardinia, Italy, Mereu et al. (2016) described a reservoir with good resilience to future climate change. The resilience is mostly because of a large basin feeding it. The reservoir was only affected if associated with increasing water demand from the agricultural sector. The authors, however, argue that this may not be the case for other reservoirs in the region and that a detailed assessment is needed (Mereu et al. 2016). The resilience of

vulnerable reservoirs must be studied and should take climate change into account, otherwise they might become inadequate in adverse climate conditions.

This study aimed to simulate the impacts of climate change on reservoir water supply in a mountain watershed of northeast Portugal (Alto Sabor) and to test if the water supply system will be reliable under climate change. This watershed suffers from water supply limitations during dry summers, coinciding with higher demand from increasing population. A new reservoir for water supply was built in the upper catchment and started filling in 2015, complementing an older reservoir in a neighbouring location. However, it is currently not known whether the system is prepared for the climate change impacts. Therefore, this study will answer the following three questions: (1) Is the two-reservoir system improving the current capacity of water supply? (2) Is the two-reservoir system better prepared for future climate conditions, compared to the single-reservoir condition? and finally (3) Will this solution be enough to ensure reliable water supply under future climate conditions?

2 Methods and Data

2.1 Study Area

Alto Sabor (403km²), in northeast Portugal, corresponds to the upstream part of the Sabor river watershed; a quarter of the Alto Sabor area (the headwaters) is located in Spain (Fig. 1).

The climate is Mediterranean with three dry months in summer (June, July and August), but with transition to humid (Mesquita and Sousa 2009). Precipitation varies from about 700 mm annual averages in lowlands to 1100 mm upstream in the mountains. The mean annual discharge is about two thirds of precipitation.

The watershed is almost totally located in a mountainous area of the Montesinho Natural Park, a natural wooded and traditional mountain agricultural landscape, with high natural value (Castro et al. 2010). Regarding land cover, shrubland and forest areas occupy the highlands, whereas agriculture is common in lowlands (Fig. 1a). In the last two decades, the agricultural area for annual crops decreased, either by changing into permanent crops (chestnut production), or due to land abandonment with fields being occupied by shrubland. Currently, shrubland areas occupy about 52% of the watershed (Table 1).

Slopes are very steep (above 25%) in 22% of the area, and steep (between 10 and 25%) in 46% of the area.

The geology is granitic in the upper regions and schist in the lower areas. Soils are shallow, mainly umbric leptosols from granite or schist (70%), and eutric leptosols (15%); the rest of the area is covered by cambisols and luvisols (Fig. 1b).

Urban areas have been increasing since 1990, mainly in Bragança (the major city located in the south of the watershed). There is a small reservoir (Serra Serrada) and a new major reservoir (Veiguiñas) upstream in Montesinho mountain for the main purpose of domestic water supply (Fig. 1).

2.2 SWAT Hydrological Model Setup

SWAT is a physically based semi-distributed model with daily and monthly calculations of hydrological balance parameters in a watershed (Arnold et al. 1998; Neitsch et al. 2011). The Alto Sabor watershed was divided into homogeneous simulation

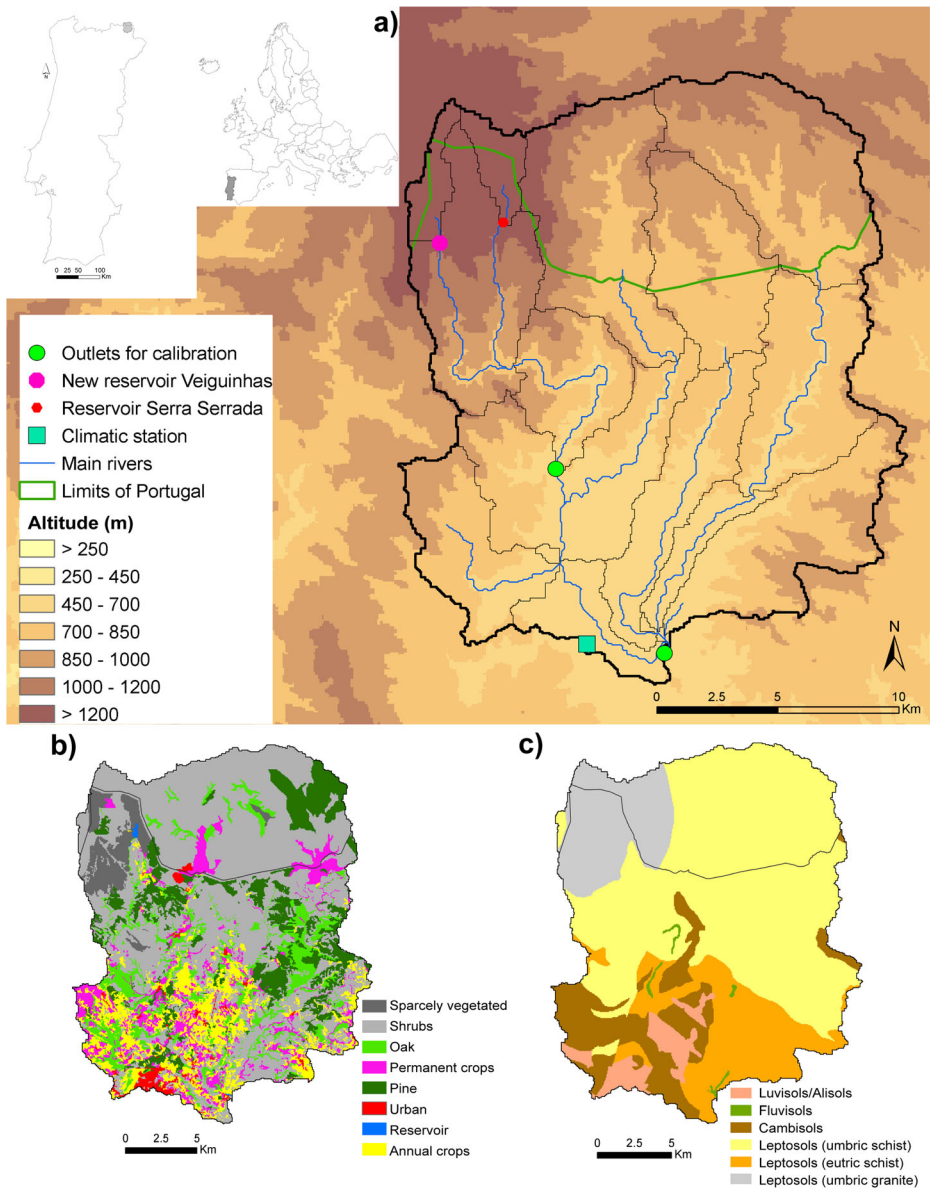


Fig. 1 **a** Location map of Alto Sabor watershed in northeast Portugal with 14 sub-basins (brown limits), and the altitude classes; **b** Land cover map 2007 (IGP 2007); **c** Soil map (Agroconsultores-COBA 1991)

units, the Hydrologic Response Units (HRUs). Each of the HRUs consists of a unique combination of land use, soil type, and slope features (Gassman et al. 2007). To predict surface runoff from precipitation or different types of soil and land cover, the curve number (CN) equation method was used in this simulation (Arnold et al. 1998). SWAT includes also routines allowing the simulation of vegetation growth from seedling to mature stands, considering plant phenological development, leaf area, radiation interception, and biomass (Gassman et al. 2007).

Input datasets and data sources for SWAT calibration in the Alto Sabor watershed are presented in Table 2. Land cover classes of the original dataset were divided into seven major groups, representing the similarities in terms of hydrological properties (Table 1). The generic parameterization of vegetation was based on the previous SWAT application in the Vez watershed, northwest Portugal (Carvalho-Santos et al. 2016). Six major soil groups were used (Table 2). Both land cover and soil maps were aggregated with similar datasets for the Spanish part of the watershed and the same parameters were applied (the headwaters of Alto Sabor). Climate parameters (precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed) were used from the Bragança weather station, located in the south of the watershed (Fig. 1). Four extra precipitation data series inside the basin were rejected because of large gaps. However, they were used to calculate a rate of precipitation change with altitude using several years with data for all stations between 1974 and 2007. To improve precipitation representation, a virtual station was created in the centroid of each of the fourteen sub-basins, in which daily precipitation measured at the Bragança weather station is multiplied by a topographic lapse ratio for each sub-basin (Galván et al. 2014). Solar radiation data (Srad) was available only for the period 1974–1984 (WRDC 2015). In the absence of solar radiation data for the simulation period, solar radiation was then estimated based on a modified Hargreaves-Samani equation ($Srad = KT * Ho * (TD)^{0.5}$) (Samani 2000), in which KT is an empirical coefficient, calculated from a linear regression between observed Srad data and other meteorological variables (wind speed, relative humidity and average temperature); Ho is the extra-terrestrial solar radiation, calculated based on astronomic equations and latitude; and TD is the difference of maximum and minimum daily temperature. The observed Srad data at Bragança weather station was useful to validate the estimation, resulting in $r^2 = 0.74$.

Model setup was done using the ArcSWAT 2009.93.7a interface for ArcGis (Winchell et al. 2010). A digital elevation model (DEM) was used for watershed discretization and delineation, resulting in 14 sub-basins. In this step a reservoir (Serra Serrada) was added to the simulation. Subsequently, slope, land cover and soil data (Table 2) were applied for model parameterization, resulting in 660 HRUs. Slope was divided into 3 classes, defined in order to represent the heterogeneity of this variable in the watershed: 0–10%; 10–25%; > 25%. The land cover class permanent crop was divided into 85% traditional orchard and 25% of vineyard (Table 1). A management operation was applied for the land cover class WWHT (wheat) based on literature for crop management practices in this watershed (Lucas 2011).

SWAT was forced with climate datasets and simulated for the period 1997–2007 with extra six years of warming-up period to start the initial conditions of the model.

2.3 Calibration and Validation

A split-sample approach was applied to calibrate discharge, using part of the dataset for calibration (1997–2007) and an independent dataset for validation (1986–1996), without further parameter adjustment. The Gimonde hydrometric station (outlet 14) was used for daily calibration and validation. Rabal (outlet 6) was only used for monthly calibration and validation, since the station is highly influenced by the reservoir (Serra Serrada) and daily reservoir management is difficult to correctly implement in SWAT, limiting the reproducibility of daily discharge data.

SWAT calibration was done manually by adjusting some sensitive parameters against daily-observed discharge for the period of 1997–2007 (Table 3). The parameters changed to improve discharge simulation were: Alpha_{BF} (Baseflow alpha factor) initial value: 0.048,

Table 1 Land cover classes used in SWAT and percentage of land cover (Fig. 1b)

SWAT abbreviation for land cover	Land cover class description	Major vegetation species for each land cover class	1990% area	2007% area
URLD	Urban low density	-	1	1
WWHT	Temporary crop	Winter wheat	23	11
ORCH	Permanent crop	Orchard (75%) (<i>Castanea sativa</i> , <i>Olea europaea</i> ; <i>Prunus dulcis</i>) and Vineyard (25%)	2	8
PINE	Pine	<i>Pinus pinaster</i>	18	13
OAK	Oaks and other broadleaved trees	<i>Quercus robur</i> ; <i>Quercus pyrenaica</i> , <i>Betula celtiberica</i> , <i>Alnus glutinosa</i> , <i>Salix atrocinera</i>	8	11
BSVG	Baren rock and sparse vegetation	Heath (<i>Erica spp.</i>) and dry perennial grasslands	4	4
MIGS	Atlantic shrubland	Heath and Gorse (<i>Erica australis</i> , <i>Calluna vulgaris</i> , <i>Pterospartum tridentatum subsp.</i> , <i>Catabricum</i> , <i>ulex sp.</i>) Broom (<i>Cytisus spp.</i>) and transitional forest (<i>Quercus robur</i>)	44	52

Table 2 SWAT data variables for model setup and calibration/validation (Alto Sabor)

Variables	Source	Description
DEM	(SRTM 2007)	Digital Elevation Model at 90 m resolution
Land cover	(IGP 2007)	Calibration period – Land cover map 2007 for Portugal (COS2007), 1:25,000. Corine Land Cover 2006 for Sabor part in Spain
	(IGN 2006)	Validation period - Land cover map 1990 for Portugal (COS90), 1:25,000. Corine Land Cover 1990 for Sabor part in Spain
Soil	(Agroconsultores-COBA 1991)	Soil map 1:100,000, with 6 main soil types (Luvisols, Fluvisols, Cambisols, Leptosols umbric and Leptosols eutric derived from schist, Leptosols umbric derived from granite)
Precipitation (mm) and Temperature (°C)	(ECAD 2015)	Soil Atlas of Europe (1:1,000,000) for Sabor part in Spain
		Daily values for station Bragança (1971–2007). To improve precipitation and temperature representation, estimates based on Prec. Lapse and Temp. Lapse were derived for 14 stations (centroid of each sub-basin)
Relative humidity (%)	(NCDC 2015)	Daily relative humidity and wind speed from climate station Bragança, (1971–2007)
Wind speed (m/s)	(WRDC 2015)	Daily solar radiation from climate station Bragança
Solar radiation (MJ/m ²)		Due to lack of data, values were estimated using astronomic equations and validated with some observed values from World radiation Datacenter.
River discharge (m ³ /s)	(SNIRH 2015)	Daily river discharge for Gimonde (outlet 14, outlet of the watershed).
Reservoir volume (m ³)		Hourly observed river stage from station Ponte Rabal (1986–1996) were converted into daily river discharge values using stage-discharge relationships
		Calibration period: 1997–2007
		Validation: 1986–1996
		Monthly volume in the reservoir Serra Serrada (1994–2007)

Table 3 Modified SWAT general parameters for Sabor watershed

Parameters	Description	Initial value	Calibration value
Alpha_BF	Baseflow alpha factor (days)	0.048	0.08 (upstream outlet6) 0.15 (downstream outlet 6)
RCHGR_DP	Deep aquifer percolation fraction	0.05	0
GW_delay	Groundwater delay time (days)	31	10
DEPIMP_BSN	Depth to impervious layer (mm)	0	2000
USLE_P	Support practice factor	1	0.5 (WWHT, ORCD)
USLE_K	Soil erodibility factor	0.26	0.038
OV_N	Manning's roughness coefficient	0.14/0.15	0.8 (Oak, Pine, MIGS) 0.17 (WWHT)/ 0.2 (ORCD)
RES_K	Effective saturated hydraulic conductivity of the reservoir bottom (mm/h)	0	2
WURES_N	Average water removal from the reservoir (10^4 m^3)	0	0.8 (Jul. to Sep.) 0.5 (Oct. and Jan. to May); 0.3 (Nov.); 0.4 (Dec.)

used value: 0.08 for the sub-basins upstream outlet 6, and 0.15 for the sub-basins downstream outlet 6; RCHGR_DP (Deep aquifer percolation fraction) initial value: 0.05, used value: 0; GW_delay (Groundwater delay time) initial value: 31, used value: 10; and DEPIMP_BSN (Depth to impervious layer) initial value: 0, used value: 2000. The USLE_K (Soil erodibility factor) was changed according to values mapped for Europe (Panagos et al. 2014). The OV_N (Manning's roughness coefficient) was updated with new values according to land cover (USDA 1986).

The monthly-observed volume of the Serra Serrada reservoir, which started functioning in 1989, was used to calibrate the reservoir volume. A continuous dataset of monthly-observed volumes (m^3) was available for 2001–2003 (Table 2). The parameters changed in the reservoir input table were based on the public hydrological information system (SNIRH 2015). Among other parameters, WURES_N (Average water removal from the reservoir 10^4 m^3) and RES_K (Effective saturated hydraulic conductivity of the reservoir bottom (mm/h)) were changed. RES_K was set as 2. WURES_N was set monthly as 0.8 from July to September; 0.5 in October and from January to May; 0.3 in November and 0.4 in December (APA 2012).

Model performance was evaluated with statistics commonly used in hydrological modeling, namely the coefficient of determination (r^2), the percentage bias (PBIAS), and the Nash–Sutcliffe-Efficiency (NSE). The corresponding equations and how they relate with model performance can be found in Moriasi et al. (2007).

2.4 Future Climate Scenarios

Future climate was considered by forcing SWAT model with daily conditions in precipitation, maximum and minimum temperature for the scenarios RCP 4.5 and 8.5 (Representative Concentration Pathways), from the IPCC AR5 (Fifth Intergovernmental Panel on Climate Change assessment report) (Lenderink et al. 2007; Hurkmans et al. 2010; Meinshausen et al. 2011) during two periods (2021–2040 and 2041–2060). RCP 4.5 is a medium stabilization scenario where total radiative forcing is stabilized at 4.5 W m^{-2} post year 2100 (approximately 650 ppm CO_2 -equivalent) with all countries undertaken emissions mitigation policies simultaneously and effectively (Thomson et al. 2011; Vuuren et al. 2011). RCP 8.5 is a rising

scenario with total radiative forcing increasing at 8.5 W m^{-2} in 2100 (approximately 1370 ppm CO_2 -equivalent).

The linear scaling approach applied for downscaling and bias-correction of climate data follows a previous study in Portugal (Carvalho-Santos et al. 2016). The following Global Circulation Models (GCMs) were used: CNRM-CM5 (Centre National de Recherches Meteorologiques, France), CSIRO-MK3.6 (Commonwealth Scientific and Industrial Research Organisation, Australia), MRI-CGCM3 (Meteorological Research Institute, Japan) and MPI-ESM-LR (Max Planck Institute for Meteorology, Germany). Precipitation and temperature data from the weather station of Bragança (1981–2000) was considered for the bias-correction of future climate. Three 20-year time windows were used to generate climate variables: 1981–2000 (baseline), 2021–2040 and 2041–2060 (scenario periods).

2.5 Indicators for Reservoir Water Supply

Bragança, located in the southern limits of Alto Sabor watershed, is the main city in the study-area and where the majority of the population lives (23,186 inhabitants) (INE 2016). Water supply to the city and the surrounding municipality, which comprises the Alto Sabor and adjacent watersheds, has been based in Serra Serrada reservoir (water supply of $2.1 \text{ hm}^3 \text{ yr}^{-1}$), a medium-sized reservoir built in 1989 (Fig. 1), and also in several small water sources, such as wells and springs spread through the west part of the watershed ($2.14 \text{ hm}^3 \text{ yr}^{-1}$). This system has shown persistent water supply problems, especially during dry summers due to a combination of lack of water supply and increasing demand from population, emigrants returning for summer holidays. In recent years, about 25% of total water requirements had to be supplied by external sources, including occasional emergency supply by fire departments. This is further complicated by the fact that the current water uptake from Serra Serrada is only guaranteed at 95% and can fail in drought years. To address this issue, a new reservoir (Veiguiñas) was projected, which started to function in 2015 and works together with the existing reservoir. Small water sources will be phased out of the supply system. Both reservoirs will therefore be expected to supply $4.24 \text{ hm}^3 \text{ yr}^{-1}$, with Serra Serrada now supplying $1.82 \text{ hm}^3 \text{ yr}^{-1}$ and Veiguiñas supplying $2.42 \text{ hm}^3 \text{ yr}^{-1}$ (APA 2012). The water supply capacity of these two reservoirs was designed with a 99% supply guarantee rate, but this was calculated without taking into account future climate conditions.

To evaluate water supply from the reservoir system, two scenarios were compared: the previous situation of a single reservoir (Serra Serrada) supplying $2.1 \text{ hm}^3 \text{ yr}^{-1}$, ignoring the part of the system supplied by small water sources; and the situation starting in 2015, with two reservoirs (Serra Serrada + Veiguiñas) supplying $4.24 \text{ hm}^3 \text{ yr}^{-1}$. SWAT was used to simulate the water volume in the reservoir under the previously described climate change simulations (four models and respective RCP 4.5 and RCP 8.5). The SWAT parameters were set as the calibration simulation, with the exception of WURES_N for the water extractions in the reservoir that was changed according to the environmental impact assessment report of Veiguiñas reservoir (APA 2012). For the two-reservoir scenario, WURES_N (10^4 m^3) was set as: Serra Serrada (0.47 from October to May; 0.55 from June to September); Veiguiñas (0.63 from October to May; 0.73 from June to September). To compare the reservoir scenarios, an indicator of service satisfaction vs. service reliability was calculated (Martin-Carrasco and Garrote 2007; Iglesias et al. 2011). For this, the simulated average of the actual monthly consumptions of each reservoir (i.e., consumption limited by the available water supply in the reservoir) was estimated and compared to the average water demand introduced in the

reservoir file (WURESN). Service satisfaction is simply the ratio between actual consumption and water demand. Given the high inter-annual and seasonal variability of supply and demand, service reliability is the ratio of months where actual consumption is above an acceptable ratio of water demand. In this work, a supply above 90% of demand was considered acceptable, in line with the value of 85% proposed by Martin-Carrasco and Garrote (2007), but slightly higher to reflect the domestic supply nature of this system vs. the irrigation supply that the authors studied. Finally, service reliability is compared to service satisfaction, in the control period and in the future climate scenarios (including the four climate models). This comparison gives an idea of water stress under future climate conditions in both the single-reservoir and the two-reservoir systems.

3 Results and Discussion

3.1 SWAT Model Performance

The comparison between daily observed and simulated discharge in the calibration and validation periods indicated that SWAT was able to capture and reproduce the average flows and seasonal variations in the Alto Sabor watershed, except during major high flows or extreme conditions, as it was the case of the period between the end of 2000 and beginning of 2001 (Fig. 2). Concerning model performance (Table 4), in Gimonde predictions for calibration can only be considered satisfactory, because of the strongly negative PBIAS being

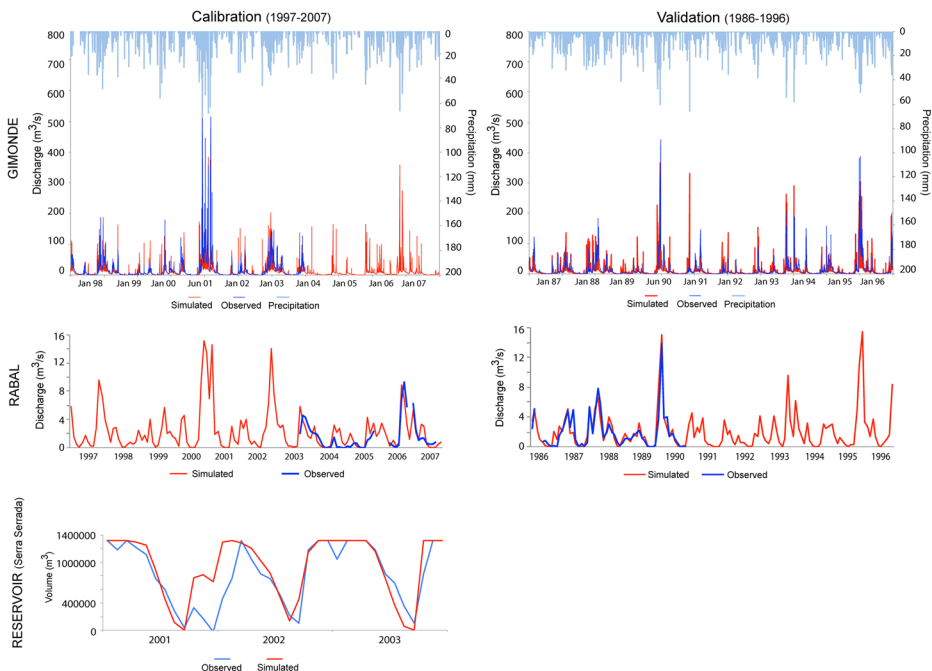


Fig. 2 Observed and simulated discharge (daily for Gimonde and monthly for Rabal) for calibration and validation period, and monthly reservoir volume, after parameter calibration (Table 3). Performance statistics are presented in Table 4

Table 4 Calibration and validation goodness-of-fit statistics for discharge in SWAT model in Alto Sabor watershed

		Discharge calibration (1997–2007)		Discharge validation (1986–96)		Reservoir calibration (2001–2003)
		Gimonde	Rabal	Gimonde	Rabal	Serra Serrada
R^2	Monthly	0.89	0.63	0.85	0.85	0.68
	Daily	0.56	-	0.63	-	-
PBIAS (%)	Monthly	-21	9	-19	8	12
	Daily	-21	-	-19	-	-
NSE	Monthly	0.77	0.57	0.78	0.83	0.65
	Daily	0.56	-	0.62	-	-

under -15% (Moriassi et al. 2007). The same applies for validation performance statistics (1984–1989). Satisfactory results for calibration and good results for validation were obtained for Rabal, with a slightly higher but still very good PBIAS, under 10% (Moriassi et al. 2007). The observed discharge dataset in Rabal was incomplete, with a major data gap between the years 1991 and 2003. Possible reasons for the difference between both stations can be the weak representation of precipitation in the watershed, especially as a function of the topographic gradient, and the lower reliability of observed discharge data during peak flows.

The calibration of the volumes of the reservoir Serra Serrada can be considered good (Moriassi et al. 2007). It was only possible to calibrate against three complete years of reservoir volumes, but these years are representative of different hydrological conditions, namely an unusually wet year (2001) and a dry year (2003). It can therefore be concluded that SWAT was able to correctly represent both available water in the upper reaches of the Sabor and water storage in mountain reservoirs.

3.2 Future Climate in Alto Sabor Watershed: Model and Scenario Variability

In the future, a general increase of temperatures and a decrease in precipitation is expected in the Alto Sabor watershed (Fig. 3a). The temperatures will increase up to 6 °C in summer under RCP 8.5. The change in the precipitation however, is more uncertain due to seasonal variations (Fig. 3a) and the variability given by the four different climate models used (Fig. 3b). In seasonal terms it is expected

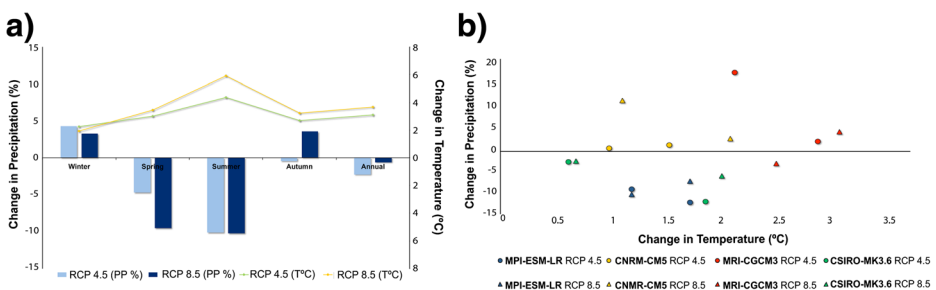


Fig. 3 Future climate, models and scenarios: **a** Seasonal variation in the average temperature (°C) and precipitation (%), for the scenarios RCP 4.5 and 8.5, compared to 1981–2000. **b** Variability of the four different climate models (CNRM-CM5; CSIRO-MK3.6; MPI-ESM-LR; MRI-CGCM3) related to changes in precipitation (%) and temperature (°C) when compared to 1981–2000, and under different climate scenarios (circles refer to RCP 4.5 and triangles to RCP 8.5)

more precipitation in winter and much less in spring and summer. These projected increases in temperature and changes in the intensity and pattern of precipitation are consistent with previous studies in Portugal (Cunha et al. 2005; Nunes et al. 2008; Carvalho-Santos et al. 2016) and in Galicia, northwest Spain (Álvarez et al. 2011). When comparing climate scenarios, RCP 8.5 has a higher change in temperature and a marked difference in seasonal precipitation when compared to RCP 4.5 (Fig. 3a). This pattern in scenarios was also shown in a study with high-resolution Regional Climate Models (RCM) in Europe, Euro-Cordex (Jacob et al. 2013).

If a consensus was observed between different climate models regarding an increase in temperature (annual change between +0.5 °C and +3 °C), precipitation in turn shows high variability in the pattern of change according to the selected model (results ranging between −15% and +7%). The CNRM-CM5 and MRI models project an increase in annual precipitation, whereas CSIRO-MK3.6 and MPI-ESM-LR project a decrease (Fig. 3b). Internal model variability for precipitation is recognized as an important source of uncertainty in climate projections (Northrop and Chandler 2014). A similar situation was found in a recent study of reservoir resilience under climate change in Italy, where changes in precipitation ranged from −170 mm to +31 mm (Mereu et al. 2016). This variability given by the different models may also be due to the location of the Alto Sabor watershed, namely in the transition zone between Mediterranean and Atlantic types of climate (Metzger et al. 2005).

3.3 The Reservoirs and Water Supply under Climate Change

In general, our results indicate that there will be less water in the reservoirs in the future, especially in 2041–2060 (Fig. 4). This was more visible for the new reservoir Veiguinhas. Taking the variability of the modelling projections into account, RCP 4.5 forecasts more water in the reservoirs in 2021–2040 and a drastic reduction in 2041–2060. Another general trend is a reduction in the summer reservoir volumes and an increase in the winter volumes, more visible under RCP 8.5.

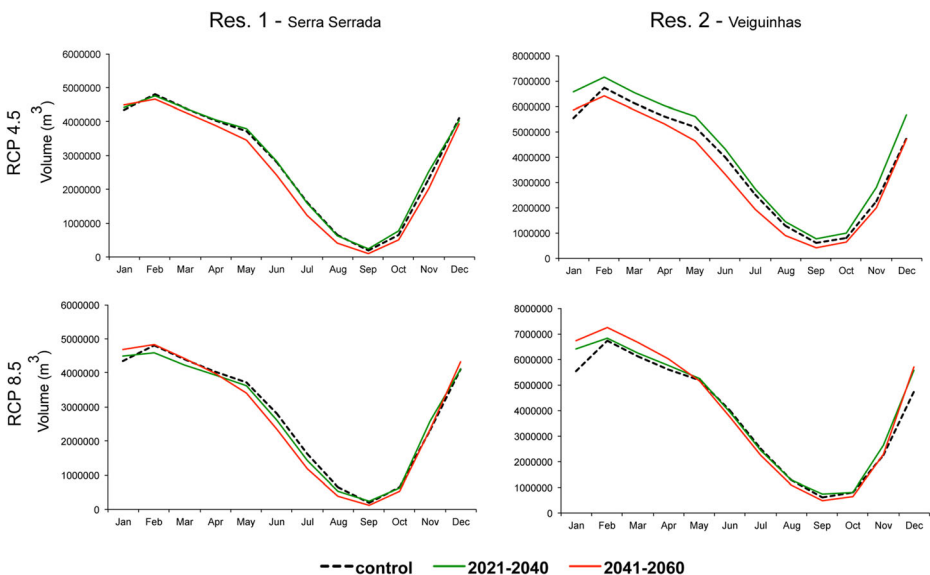


Fig. 4 Climate change impacts on seasonal reservoir volume (10^4 m^3), for the periods 2021–2040 and 2041–2060 compared to control (1981–2000), RCP 4.5 and 8.5

In terms of reliability of the system (both with one and two reservoirs) to supply water under future climate conditions (Fig. 5), one major result is that the two-reservoir system would have solved the problem of water supply in the last decades (1981–2000), with service satisfaction above 90%. In turn, the single-reservoir system always shows water stress, becoming worst under future climate, especially in 2041–2060. The two-reservoir system should supply water with satisfaction and reliability above 90% in the period 2021–2040, although under scenario RCP 8.5 the situation is closer to the 90% threshold. Failure of reliability in water supply occurs mostly during summer months (Fig. 4). After 2040, service reliability decreases to values around 80%, especially under the RCP 4.5 scenario (Fig. 5).

When considering the result of specific climate models, projections for service reliability can still be more negative (see grey dots in Fig. 5). Here, the different precipitation inputs from the different climate models (Fig. 3b) enlarge the window of uncertainty. Models predicting more precipitation show an increase in the reliability of the system, whereas models predicting less precipitation decrease the levels of service reliability.

It should be highlighted that this study considers changes in water supply in the future under climate change, whereas water demand was kept constant throughout the simulation period. Since this is a small watershed located in inland Portugal, a significant increase in urban water demand is not foreseeable. In fact, demand for water is even likely to decrease in the future due to water efficiency measures and education of urban population (Jacinto et al. 2013).

3.4 Implications for Watershed and Reservoir Management

To our knowledge, this study is a first contribution for climate impact assessment of a local reservoir system for water supply. These studies are important to create adaptive capacity to cope with climate change (Iglesias et al. 2011). The approach considers not only water availability, but also demand for domestic use. The two-reservoir system is effectively prepared to supply water with high reliability until 2040. Still, during the dry years the system may not respond effectively during the critical summer months. One option to cope with this problem is to create an alert system for a drought management plan, which may include the definition of a demand reduction (Rossi et al. 2012).

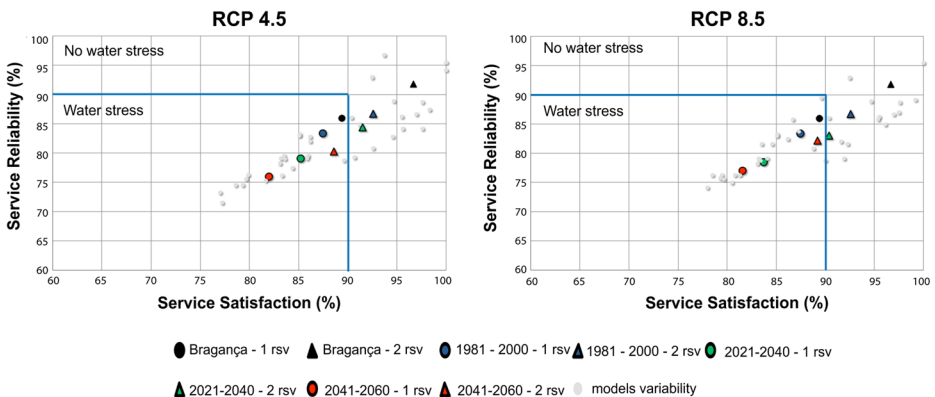


Fig. 5 Reservoir service satisfaction vs. service reliability (ensemble SWAT climate models simulations, for RCP 4.5 and RCP 8.5 scenarios, period 2021–2040 (green) and 2041–2060 (red)). Circles refer to single-reservoir system, and triangles to two-reservoir system. Control period from climate models in blue (1981–2000), “Bragança” refers to SWAT simulation using observed data from climate station Bragança (1981–2000). Grey dots show the simulations driven by each individual climate model. Supply above 90% demand is considered acceptable

When reservoirs become inadequate, either there is an increase in reservoir volume maintaining the same target demand, or a reduction in demand while maintaining the same reservoir volume (Liuzzo et al. 2014). Considering that the two-reservoir system is located in a small drainage area in the top of the mountain (a preferable place for maintaining water quality), increasing reservoir volume is not an option. One suggestion could be a possible reservoir downstream to increase the drainage area. However, the consequences for habitat requirements for aquatic species downstream the reservoirs should be considered, as it was shown in a study in a similar watershed in northern Portugal (Santos et al. 2015). Thus, land management for water regulation at the watershed level would be a preferred solution, more compatible with nature conservation regulations and with potential wider benefits for biodiversity and for other ecosystem services (Carvalho-Santos et al. 2016).

Regarding the consequences of seasonal changes for general water resources, more water in the system during autumn and winter can bring benefits for agriculture and irrigation, but on the other hand it may bring risk of floods, especially if precipitation occurs in strong and short episodes. This was shown in a medium watershed in northwest Portugal, in which under scenarios of climate change, the increase of precipitation in autumn may increase the risk of floods (Carvalho-Santos et al. 2016). Attention should be paid to the lower streamflow and reservoir volumes during spring and summer under future climate, which may cause water shortages, problems in water quality and consequences for aquatic biodiversity (Hughes et al. 2012).

4 Conclusions

In the future, a general increase of temperatures is expected in the Alto Sabor watershed, but the change in precipitation is more uncertain, with differences according to the selected climate model. However, seasonal changes would be more significant, with more precipitation in winter and much less in spring and summer, with impacts on the water resources.

In the future, the volume of water stored in the reservoirs of Alto Sabor watershed will decrease, especially during spring and summer. The existence of two reservoirs will likely solve the water supply problems under current climate conditions, but in the future the reliability of this solution will decrease, especially under scenario RCP 8.5 for 2041–2060. Here, the variability given by the different climate models simulated in SWAT brings some uncertainty with respect to the precipitation inputs. This variability has to be taken into account in the future, considering the general tendencies described in this study. One general concern is the limitations on water supply in very dry summer months, which is predicted as a problem independently of the climate model used.

The main conclusion of this study is that the solution projected for water supply in this region, calculated taking only present-day climate into account, will probably be inefficient for water supply management under future climate. Taking climate change into account would have avoided the need for further investment in the future, and calls for an integrative strategy that favours water regulation ecosystem services in the wider landscape.

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