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A Modelling Approach to Forecast the Effect of Climate Change on the Tagus-Segura Interbasin Water Transfer

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Abstract
This study was conducted in the upper Tagus River basin (UTRB), whose available water resources are partially transferred from the Entrepeñas and Buendía reservoirs after local needs satisfaction to the Segura River basin using the Tagus-Segura water transfer (TSWT), the largest hydraulic infrastructure in Spain. This study evaluates the climate change impact on the TSWT by considering future evaporation rates and bathymetric changes in the Entrepeñas and Buendía reservoirs. The findings of this study indicate a consistent decline in precipitation and an increase in temperature and evaporation under all climate impact scenarios. Consequently, inflows to the reservoirs will decline by 19% (RCP 4.5) and 53% (RCP 8.5) for 2070–2099, which could reduce water volumes that could be transferred to the Segura basin by more than 60%. The simulation of the TSWT operation rules, taking into account the impact of future evaporation and bathymetric changes, demonstrates an additional increase in reductions of water transfer of around 4%, which reveals the need to consider these effects in hydrological planning.

Keywords Tagus-Segura water transfer · SWAT · Climate change · Evaporation · Water management · Mediterranean

1 Introduction

Rigorous quantification of the impact of climate on water resources under different levels of global warming and representative concentration pathways (RCPs) is necessary to design appropriate adaptation water policies (Krysanova et al. 2017). This is especially the case in the Mediterranean and semi-arid regions, where water resources have become a

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critical element of socio-economic development (Thornes and Rowntree 2006). Due to its geographic and socio-economic characteristics, Spain is considered one of the European countries with the highest vulnerability to global warming (Vargas-Amelin and Pindado 2014). For example, Lobanova et al. (2018) provided a snapshot of the impact of climate change on hydrology in several regions of Europe, showing a general increase in water availability in the northernmost river basin (Lule River, Sweden) and a significant decreasing trend in discharges in the southernmost river basin (Tagus River, Spain). From early analysis at the end of the past century (Ministerio de Medio Ambiente (MIMAM 2000), several investigations analysed the expected climate change impact on water resources in Spain (Estrela et al. 2012) and specifically on the Tagus River headwater area (Pellicer-Martínez and Martínez-Paz 2018). All the studies conclude that hydrological stress is expected to intensify mainly in the semi-arid areas of Spain, which currently suffer from severe water scarcity and a weak balance between water availability and water demands.

Within Spain, the Tagus and Segura River basins are of special interest since they are vital basin districts in the Spanish water management system. The Tagus River, in the central part of Peninsular Spain, provides water for more than 10 million inhabitants (including in Madrid and Lisbon) and is the largest river in the Iberian peninsula, with a total length of over 1,000 km and a total drainage area of over 80,000 km^2 (Lobanova et al. 2018). As Fig. 1 shows, the upper Tagus River basin (UTRB) is a source of water for southeast Spain through the Tagus-Segura water transfer (TSWT). Since 1979, when the TSWT began operation, the average transfer has been about 350 hm^3/year (Morote et al. 2017), both for urban water supply and advanced agricultural systems. The TSWT constitutes the largest Spanish hydraulic infrastructure and is one of the Gordian knots of water management in Spain, being a source of socio-economical development for the peninsular southeast and social and political conflicts that have been untangled now for several

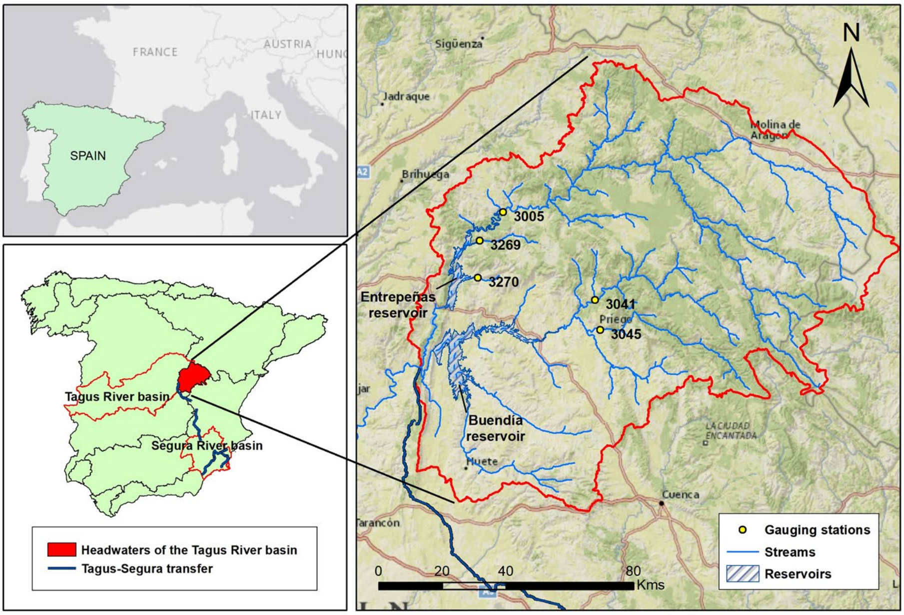

Fig. 1 Location of study area

decades (Lorenzo-Lacruz et al. 2010). According to PricewaterhouseCoopers (2013), the TSWT has generated over 100,000 jobs and contributes a national gross domestic product of 2,364 million euros annually. The Segura River basin is one of the most-stressed water basins in Europe (Senent-Aparicio et al. 2017). In other Mediterranean regions, the basin is characterized by scarce and unevenly distributed water resources in both space and time (Belmar et al. 2011). Water availability is low and the potential water demand exceeds the supply capacity of the natural system (Aldaya et al. 2019), and this structural water deficit will be aggravated by climate change (Rupérez-Moreno et al. 2017).

Hydrological models are a widely adopted procedure to assess the future impact of climate changes on water resources (Al-Safi and Sarukkalige 2020). Among them, the Soil and Water Assessment Tool (SWAT) has been applied widely in ecological, hydrological and environmental studies (Tan et al. 2020) and can operate on a daily scale and simulate different hydrological processes, such as evapotranspiration, soil and snow evaporation, soil and root zone infiltration, surface runoff and return flow (Arnold et al. 1998). SWAT is widely recognised as a comprehensive tool for integrated and multidisciplinary assessments of climate change at regional scales under different physiography and climate conditions (Krysanova and Srinivasan 2015). To our knowledge, although some works related to the TSWT have been developed, none have developed a multi-calibration site and considered the reservoir's evaporation by combining the SWAT and simulation of the TSWT operation rules. For example, Lobanova et al. (2016, 2017), who applied the Soil and Water Integrated Model (SWIM) model to the Tagus River basin, just calibrated the model at a single outlet in Almourol (Portugal), which might have resulted in an imprecise representation of hydrological processes at a sub-basin level. Pérez-Blanco et al. (2020) coupled a microeconomic model with the SWAT model to assess trading opportunities and return flow externalities in the UTRB, but without applying the operation rules of the TSWT or considering the effects of climate change. Pellicer-Martínez and Martínez-Paz (2018) used the lumped water balance model called ABCD, whose name is due to the four parameters of the model: a, b, c and d, to model the water resources of the basin and a decision-support system (Andreu et al. 1996) to simulate the water resource exploitation system without considering the impacts of the reservoir's evaporation. However, evaporation is a vital issue in water resources planning and management, as it directly affects water use and allocation. Therefore, the effect of climate change on evaporation losses can no longer be ignored and must be evaluated (Althoff et al. 2020). Martínez-Granados et al. (2011) estimated that annual evaporation from reservoirs in the Segura basin represents 8.7% of the total water resources currently available for irrigation, which represents a decrease in the market value of the basin's agricultural production of 134 million euros. Wurbs and Ayala (2014) argue that reservoir evaporation is an essential component of the water balance in Texas and has a significant effect on the water supply capacity. Moreover, they estimate that the reservoir evaporation from 3,415 reservoirs located in the state of Texas is 7.53 billion m^3/year, which is equivalent to 126% of the municipal water supplied during 2010 in Texas. While numerous recent studies investigate the impact of climate change on water resource systems (Kolokytha and Malamataris 2020; Aghapour Sabbaghi et al. 2020; Yazdandoost et al. 2020), to our knowledge, none of them consider variables that at initially may seem insignificant, such as increased evaporation or bathymetric changes. Therefore, the main goal of this study is to evaluate the climate change impact on the operation of the TSWT, highlighting the relevance of considering the effects of climate change on evaporation rates or changes in reservoir bathymetry. This study addresses this objective in four stages: (1) evaluation of the SWAT model performance on a monthly scale in the UTRB; (2) simulation of future streamflows under emission scenarios of both 4.5 and 8.5 representative concentration pathways (RCPs), based on the global climate models (GCMs) that present a best fit in comparison with historical observed data; (3) the use of SWAT outputs as inputs to the simulation of the TSWT operation rules to estimate the water resources that could be delivered to the SRB; and, finally, as another novel contribution of this work, (4) assessment of the effect of climate change on the reservoir's evaporation, comparing the results obtained and considering the changes in evaporation expected to take place in the reservoirs with those obtained without considering this impact.

2 Study Area

2.1 Description of the UTRB

The UTRB has a surface area of 7,418 km^2 and is located in the middle of Spain at a latitude of 41°50' N - 40°00' N and a longitude of 2°50' W - 1°25' W (Fig. 1). As the UTRB has a Mediterranean climate, it is typically characterized by cold winters and warm summers (Lorenzo-Lacruz et al. 2010). For the period 1985–2011, the annual mean rainfall and average annual temperature were 640 mm and 10.4 ºC, respectively. Altitudes in the study area range between 632 m and 1,933 m above sea level (m.a.s.l.), with an average elevation of 1,114 m.a.s.l. Regarding land use, the landscape is mainly divided between forest (42%), non-irrigated arable land (21%) and natural grasslands (16%). The dominant soil type is cambisols, which is characterized by high sand and silt contents. The geology of the basin is very singular and varied, with outcrops from the Paleogene to the Quaternary, earning the area the declaration as UNESCO Global Geopark. In summary, detrital Cenozoic deposits are found in the western section, while Mesozoic calcareous rocks dominate the eastern section, thus configuring relevant aquifers (Molina-Navarro et al. 2014). The UTRB is regulated by two reservoirs, Entrepeñas and Buendía. However, these reservoirs are connected by a tunnel to give them the functionality of a unique reservoir with a total combined storage of over 2400 hm^3. Water resources in the headwaters of the Tagus River basin circulate through its main course, the Tagus River, and its tributary, the Guadiela River.

2.2 Tagus-Segura Water Transfer

The TSWT consists of a 286 km-long and 33 m^3/s channel that starts at the Bolarque reservoir, just downstream from both reservoirs. The water is pumped from Bolarque to the Bujeda reservoir, where it is taken towards the Alarcón reservoir in the Júcar River and, from there, it proceeds to the Talave reservoir on the Mundo River or the main tributary of the Segura River (Melgarejo-Moreno et al. 2019). Water transferred to the Segura Rivera basin is estimated according to the volumes stored in the Entrepeñas and Buendía reservoirs. More information on the operation rules of the TSWT can be found in Supplementary 1.

3 Methodology

The potential climate change impact on the TSWT is assessed for the medium term (2040–2069) and the long term (2070–2099) under two emission scenarios (RCP4.5 and RCP8.5). Figure 2 presents the methodology used in this study, which includes the

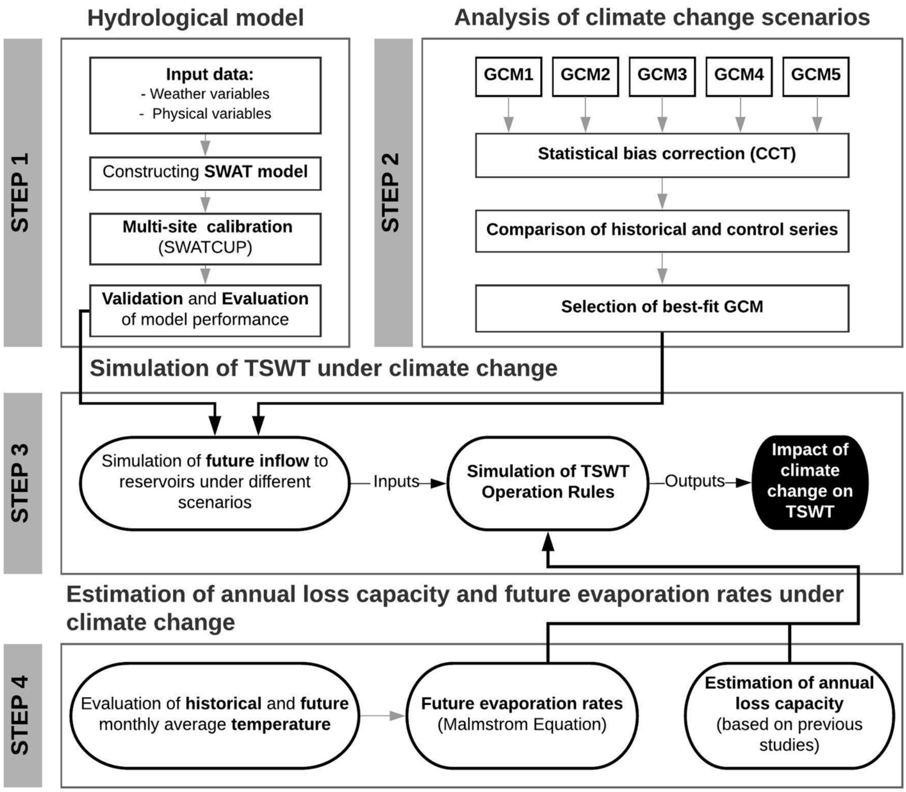

Fig. 2 Methodological flowchart adopted in this study

following steps: (1) SWAT model multisite calibration and validation in the UTRB; (2) selection of the best-fit GCM using CCT software and comparing historical and control-period rainfall and temperature series; (3) using the calibrated SWAT model and selected GCM, obtaining future inflows to the Entrepeñas and Buendía reservoirs and using them as inputs for the simulation of the TSWT operation rules and analysis of the climate change effect on the TSWT; (4) estimation of annual loss capacity based on previous studies (Molina-Navarro et al. 2014) and of future evaporation rates through historical and future temperatures and use of the Malmstrom equation; and, finally, (5) new simulation of the TSWT operation rules to evaluate the impact of considering not only increasing evaporation rates under climate change but also annual loss capacity.

3.1 Hydrological Modelling

3.1.1 SWAT Model Description

SWAT is a semi-distributed and physically based hydrological model (Arnold et al. 1998) that can predict long-term flows and hydrologic alterations over complex watersheds, making it a commonly adopted approach for climate change analysis (Senent-Aparicio et al. 2017; Ndhlovu and Woyessa 2020). In the SWAT, the watershed is first divided into sub-basins, and each sub-basin is further separated into hydrologic response units (HRUs). HRUs are the smallest spatial units and are defined by homogeneous combinations of land use, soil type and topography. The SWAT simulation process is produced daily and can be divided into two phases: a hydrologic cycle phase and a routing phase. During the hydrologic cycle phase, the water, sediment, and nutrient balances are calculated for each HRU. In the routing phase, the HRU outputs are aggregated and routed via the stream network to the basin outlet (Neitsch et al. 2011).

3.1.2 Model Inputs and Setup

The SWAT model requires data on topography, land use and soil properties as well as daily weather data to determine HRUs and simulate hydrologic processes (Neitsch et al. 2011). The 25 m resolution Digital Elevation Model (DEM) of the study area, obtained from the National Geographic Institute, was used to provide basin delineation and topography estimation. The 1:100.000-scale land-use map, obtained from Corine Land Cover of 2012, was resampled to the raster file and matched to the SWAT format. As soil properties data, the 1 km resolution soil map from the Harmonized World Soil Database was implemented. Using a 10% percentage of each sub-basin as a threshold operation for land use, soil and slope, 1,873 HRUs were generated, which supposes an average of 10 HRUs per sub-basin.

Regarding weather data, precipitation values were collected from the Spanish National Meteorological Agency (AEMET) grid, which provides daily precipitation over Spain for the period of 1951 to the present day with a 5 km spatial resolution (Peral et al. 2017). Temperature data values were extracted from the last version of the SPAIN02 gridded dataset with a resolution of 0.1°, available from 1951 to 2016 (Herrera et al. 2016). Precipitation and temperature are the meteorological variables most influential on streamflow simulation (Zaman et al. 2018). The remaining required climate variables were obtained from the Climate Forecast System Reanalysis (CFSR) gridded daily data set (Saha et al. 2010). Streamflow data for five gauging stations belonging to the Spanish National River Flow Network (ROEA) were provided by Hydrographical Studies Centre. These stations, which are well distributed throughout the basin (Fig. 1), were used to calibrate the SWAT model.

In the present study, the Quantum Geographical Information System (QGIS) interface of SWAT version 1.9 (QSWAT 1.9) was used (Dile et al. 2016). The two main reservoirs of the headwaters of the Tagus River basin, Entrepeñas and Buendía, were implemented in the SWAT model using the SWAT2lake tool (Molina-Navarro et al. 2018). This tool allows the modeller to delineate the whole watershed flowing into a reservoir, including the small areas between a river's sub-basins that flow directly into the reservoir.

3.1.3 Model Calibration and Validation

Most SWAT model simulations of the headwaters of the Tagus River basin were performed for the period 1985–2011 using monthly time steps. However, due to the data limitations of the Pareja and Cereceda stations, their simulation periods were adjusted to the available data years. In all simulations, we used the first five years as a warm-up period to allow the SWAT model to estimate the initial soil and water conditions (Abbaspour et al. 2015). More information on the calibration, validation, and sensitivity analysis can be found in Supplementary material 2.

The final selection of sensitive parameters was as follows: CN2, RCHRG_DP, GWQMN, Alpha_BNK, ESCO and GW_REVAP. Subsequently, we ran 1000 simulations in two batches of 500 simulations. Three frequently used statistical indices were used to assess the model performance monthly according to the statistical criteria proposed by Moriasi et al. (2015): the coefficient of determination (R^2), the percent bias (PBIAS), and NSE. Visual comparisons between the observed and simulated flow were also applied to evaluate the SWAT performance in the headwaters of the Tagus River basin.

Additionally, a spatial validation was conducted of the inflows to the Entrepeñas and Buendía reservoirs for the whole simulation period (1990-2011). This extra validation was performed separately by comparing the SWAT-simulated inflows with the observed inflows of each reservoir. A spatial validation consists of validating the model at a different gauging location than the calibration site (Chen et al. 2020a), which supposes a reinforcement of the SWAT model performance.

3.2 Climate Change Scenarios

The five GCMs available in the Climate Change Toolkit (CCT) software (Vaghefi et al. 2017) were downscaled and bias-corrected. CCT applies to each GCM a statistical scale reduction and a correction factor over the climate data using the multiplicative bias correction method. Detailed information about CCT processes is presented in Vaghefi et al. (2017).

In addition, a comparative analysis of the selected GCMs was applied to reduce the uncertainties of the climate change scenarios, based on the approach suggested by Pulido-Velazquez et al. (2015). This analysis was applied for the historical period (1970–1999), and it consists of comparing monthly averages and standard deviations for an average year using historical precipitation and temperature time series and control series obtained from the regionalized GCMs for the same period. In the comparative analysis, each GCM was assessed by calculating the indicator (Id) expressed in Eq. (1):

$$\mathrm{Id} = \sum\nolimits_{n,m=1}^{2} \mathrm{Id}\left(V_n S_m\right), \mathrm{Id}\left(V_n S_m\right) = \sum_{j=1}^{12} \left[\left(V_n S_m\right)^j_{GCM} - \left(V_n S_m\right)^j_{Observed} \right] / \left(V_n S_m\right)^j_{Observed} \tag{1}$$

where V_n and V_m are the climate variables (V_1 = precipitation, V_2 = temperature), S_1 is the monthly average, S_2 is the monthly standard deviation and j is the number of the month.

Once the four Id indicators were obtained for each RCM, corresponding to the mean and standard deviation of both precipitation and temperature, the best model in terms of goodness of fit to the observed time series was selected. Finally, the simulation results from the selected GCM were used as inputs for the SWAT model to generate future inflows to the Entrepeñas and Buendía reservoirs.

3.3 Simulation of the Current TSWT Operation Rules

Current TSWT operation rules are mainly based on the two considered basic state variables of the system: available water in the reservoirs (present situation) and moving accumulative inflows to them over the previous 12 months (recent trend). For the practical operation of the system, these two variables are determined at the beginning of each month, and the transferred water is determined by the rules according to specified criteria, which are shown in Table S1.

Parameters shown in the table were determined by a multi-criteria optimization process following the next steps:

1. A simulation code for the system was developed, using as inputs the monthly series of inflows to the reservoirs, the priority discharge requirements for the Tagus (including all water demands) and the expected losses (mainly evaporation), which are expressed as a tabular function of the month of the year and the stored water at the beginning of the month. This evaporation table requires the expected mean evaporation from the water body every month (mm/month) computed from meteorological records, and the bathymetric curve of the reservoir expressed as the open water surface as a function of the storage.
2. For the monthly inflows series, a stochastic generation model with a seasonal lognormal autoregressive structure was developed and calibrated with the historical records from 1980 to 2012. After calibration, the model was validated by checking the main statistics preservation as well as the independence and expected zero value for the residuals.
3. After calibration and validation, for the regular operation of the model, the observed inflow over the prior month was specified as an initial condition, and a set of any number of hypothetical time series for the future (routinely 10.000 series of 24 months in length) – all beginning with the actual hydrological conditions – is generated.
4. With the model, losses and demands developed in step 1, the synthetic flow model described in step 2 and the different time series generated in step 3, a set of simulations is executed at the beginning of each month that should obtain both the expected transferable water for the coming months and the risk or probability of different levels that define the status of the system.
5. By regular updating of the described data and analysis – i.e., off-line studies according to the six-year period established in the WFD for planning processes – the parameters of the rule should be updated and improved in a search for different indicators of performance and so help to refine the system behaviour. Impacts of climate change on hydrology – mainly inflows and evaporations – could thus be considered.

It should be noted that according to the described process, actual evaporation from the reservoirs is an explicit component of the system behaviour and has a direct effect on the TSWT performance. Therefore, if future changes are expected because of climate change, these changes should have a direct impact on this performance, as shown below.

3.4 Analysis of Future Evaporation Rates Under Climate Change

Evaporation as a major constituent of both energy and water balances has prompted the development of empirical methods, such as ones based on temperature, radiation, pans, humidity, mass transfer and water budget, to estimate evaporation with incomplete weather variables (Chen et al. 2020b). The main strength of these methods is their potential to predict physiological, hydrological and meteorological responses to a range of climate change scenarios. Xu and Singh (2001) analysed seven temperature-based methods for estimating evaporation and concluded that all of them worked satisfactorily when determining average seasonal evaporation values. In this study, where temperature was an available variable, the Malmström ratio (Eq. 2) (Malmström 1969) was applied to obtain the increase in evaporation because of the increase in temperature under both scenarios (RCP 4.5 and RCP 8.5).

$$\Delta E_m = \frac{e^{\left(\frac{17.27\cdot(T+\Delta T)}{T+\Delta T+237.3}\right)}}{e^{\left(\frac{17.27\cdot T}{T+237.3}\right)}} \tag{2}$$

where ΔE_m is the monthly evaporation change ratio, T is the monthly average temperature for the historical period and ΔT is the increment of the monthly average temperature under a future scenario. Once the twelve-month indicators were obtained for each scenario, these ratios were applied for the simulation of the TSWT operation rules under future scenarios. This simulation was also done without considering these ratios to assess the importance of the effect of climate change on evaporation within the TSWT exploitation system.

3.5 Effect of Sedimentation and Bathymetric Changes in the Reservoirs

Another effect that must be considered in the system operation is that of expected changes in the reservoir system due to increases in sediment retention and associated changes in bathymetric curves. No systematic studies have considered the expected future reservoir volumes due to both regular and systematic reduction over time or additional sediment inputs resulting from higher oil losses, gross sediments mobilized during storms and delivery ratios within the watersheds. Expected intensification of extreme rainfall events will increase the volume and intensity of these events in magnitudes not yet evaluated for our area of interest.

To obtain an initial overview of the possible impact, we limit our focus to systematic reductions over time. To present a globally representative picture, we adopt 0.07% of annual loss capacity, assuming, in the absence of more information, that sediments are accumulated in the lower segment of the bathymetric curve. With these criteria, estimated decreases in storage capacity would be 45 and 100 hm^3 in the medium (2040) and the long term (2070), respectively.

4 Results and Discussion

4.1 SWAT Model Calibration and Performance

After the sensitivity analysis (Supplementary material 2), the six more influential SWAT parameters in the UTRB were automatically calibrated with the SWAT-CUP. Table 1 presents detailed information about the calibration process of the SWAT parameters. The decrease of CN2 could be a result of the better cover and stronger interception characteristic of UTRB natural vegetation. ESCO was reduced in most of the sites to final values suitable for semi-arid climates (de Almeida Bressiani et al. 2015). Calibrated parameter values were consistent with previous modelling efforts (Molina-Navarro et al. 2014). The final calibrated values were applied to the drainage sub-basins of each gauging station. Gauge stations 3041 and 3045 present unique calibrated values because both were included in the same SWAT-CUP project.

Following the previous process, the model performance was assessed for both the calibration and the validation period. Most of the statistical monthly values represented display an NSE over 0.5, an R^2 over 0.6 and a PBIAS of ±15%, which means a suitable model performance according to the criteria recommended by Moriasi et al. (2015). The NSE values range from 0.61 to 0.91, which indicates an overall good performance of the SWAT

Table 1 Calibrated values of the selected SWAT parameters

Parameter	Default value	Calibration range	Calibrated values			
			3041/3045	3005	3270	3269
CN2	-	± 30%	-2.28%	-7.53%	-9.35%	-5.94%
RCHRG_DP	0.05	0.01 - 1	0.052	0.483	0.127	0.910
GWQMN	1000	0 - 5000	435	132	209	3257
ALPHA_BNK	0	0 - 1	0.495	0.411	0.769	0.671
ESCO	0.95	0 - 1	0.965	0.726	0.486	0.746
GW_REVAP	0.02	0.02 – 0.2	0.026	0.116	0.056	0.075

streamflow simulations. The streamflow trend and timing are also well suited, as shown in the high values of the R^2 (0.63-0.92) and the graphical comparisons. Moreover, all PBIAS values are satisfactory (below 25%) except the validation in station 3269, which can be attributed to the short length of the validation period in that station (2011–2012). There is a general trend towards positive PBIAS values, indicating a slight underestimation of the simulated flows.

Regarding the extra validation in the Entrepeñas and Buendía reservoirs, a good SWAT model performance was reached in the simulated inflows. Monthly NSE, R^2 and PBIAS values for the Entrepeñas reservoir were 0.8, 0.8 and -0.4 %, respectively. For the Buendía reservoir, the NSE value was 0.7, the R^2 0.89 and the PBIAS -9.5%. Figure 3 shows observed and simulated inflows of the Entrepeñas and Buendía reservoirs.

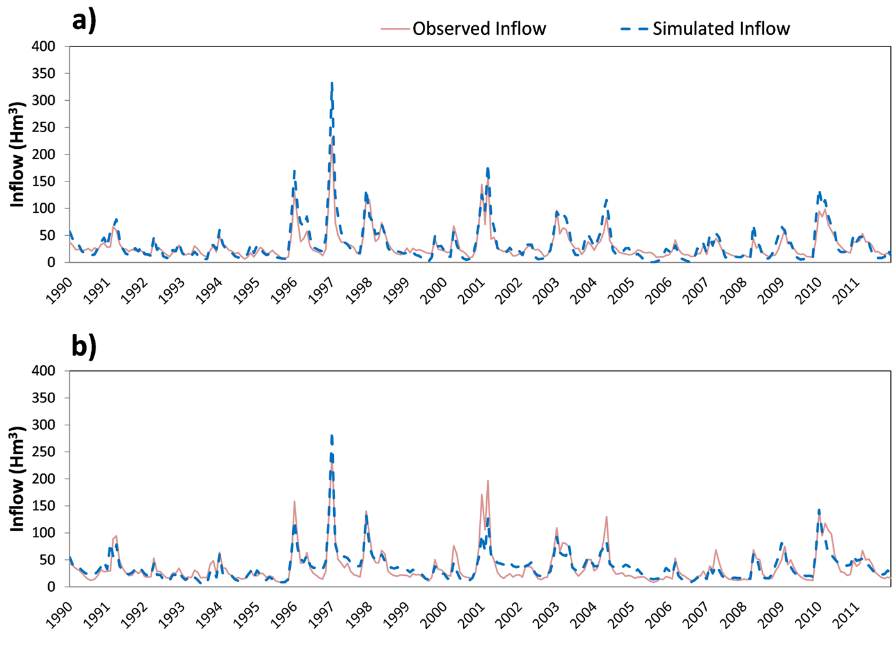

Fig. 3 Monthly inflows comparison in **a**) the Buendía and **b**) the Entrepeñas reservoir

4.2 GCM Selection

Before analysing the effects of climate change on the UTRB, the best-fitted GCM was selected using the method described by Pulido-Velazquez et al. (2015). Results of the comparative analysis are shown in Table 2.

Four indicators were obtained for each selected GCM, which were divided into precipitation and temperature. These Ids assessed the overall accuracy of each GCM's climate data. The sum of the four indicators provided the total Id of each GCM, where the lowest Id value indicated the GCM data that was closest to the observed climate variables. Accordingly, HadGEM2-ES rainfall and temperature data were selected to simulate the projected behaviour of the headwaters of the Tagus River basin.

4.3 Projected Precipitation, Temperature and Streamflow Changes

The assessment of climate change impact was performed by applying the HadGEM2-ES climate data to the calibrated SWAT model of the headwaters of the Tagus River basin. The effect of climate change was quantified by comparison of a historical period (1970–1999) with a medium-term (2040–2069) and a long-term period (2070–2099). Additionally, these future periods were simulated under both RCP 4.5 and RCP 8.5 emission scenarios. Table 7 highlights the future variation values due to climate change of the precipitation, temperature and reservoir inflows in the UTRB.

Decreasing precipitation and increasing temperatures are projected for the UTRB. Similar climate change trends have been observed by other researchers in the study area (Lobanova et al. 2016; Pellicer-Martínez and Martínez-Paz 2018). However, once this trend is accepted, the quantification of these changes must be viewed with caution, not only because of the existing uncertainties but also because the historical reference period 1970–1999 includes 1980, in which there appears to have been a sharp increase in the hydrological behaviour of the basin and a significant decrease in its average flow (Cabezas 2013). This anomaly (called the *80 effect*) could distort the results and requires further research.

With that caveat, by the end of the century, the amount of precipitation to be received by the study area shows a reduction of 26% for the RCP 8.5 scenario in addition to an increase of 6.3 °C in average temperature. Therefore, the Entrepeñas and Buendía reservoirs present a significant reduction of their inflows, with a total decrease of over 50%. (Lobanova et al. 2017) reported similar reductions of the Entrepeñas and Buendía inflows. In the case of RCP 4.5, the future climate change will be less severe, with a precipitation reduction of 13% and an inflow reduction of about 20%. These results were

Table 2 Indicators of the selected GCMs

GCM	Precipitation		Temperature		Id
	Id (V_1S_1)	Id (V_1S_2)	Id (V_2S_1)	Id (V_2S_2)	
GFDL-ESM2	0.84	4.71	0.24	1.58	7.37
HadGEM2-ES	0.49	2.47	0.64	1.85	5.45
IPSL-CM5A-LR	0.65	3.01	0.33	1.62	5.61
MIROC-ESM-CHEM	0.53	3.42	0.21	2.04	6.19
NorESM1-M	0.91	4.52	0.20	2.41	8.04

expected because the RCP 8.5 scenario presents higher emissions of greenhouse gases than the RCP 4.5 scenario. Regarding the impact of climate change in the mid-future, trends on precipitation, temperatures and inflows will be similar to those in the long term but with moderate variations, as shown in Table 3. In the mid-future (2040–2069), reservoir inflows will decline by 10% and 31% in the RCP 4.5 and the RCP 8.5 scenario, respectively. These results are consistent with those obtained in CEDEX 2020b (reduction of 8% under RCP 4.5, 2040). The largest alterations to reservoir inflows are also projected for 2070–2099 when they will decline by around 20% (RCP 4.5) or more than 50% (RCP 8.5).

The seasonal variations of annual rainfall, temperature and streamflow are shown in Fig. 4. Seasonal precipitation is expected to decrease for all tested RCP scenarios, except for the projected mid-future spring season under the RCP 4.5 scenario. The largest decrease is expected for the far-future summer season under the RCP 8.5 scenario (57%). The increment of the temperature in summers is high compared to colder months, increasing the intra-annual variability of temperature. Moderate warming of around 2° C is expected in the winters and springs of the mid-future under the RCP 4.5 scenario, while the most significant increases occur during summers in the long term under the RCP 8.5 scenario, which is consistent with previous findings in similar Mediterranean basins in Spain (Molina-Navarro et al. 2014). Interaction between the expected reduction of rainfall and the projected increase in temperature leads to significant impacts on river flow, with a hypothetical decrease of reservoir inflows of up to 69% in summer for the 2070–2099 period.

4.4 Effect of Water Surface Evaporation on the Water Transferred from the Tagus River

Through the Malmstrom equation, future evaporation rates were estimated under the RCP 4.5 and RCP 8.5 scenarios (Table 4) for the mid- (2040–2069) and far future (2070–2099) for the average values for the 1970–1999 period and based on expected temperature increases. Evaporation changes in the mid-future vary between 15 and 25% for most months, except for a potentially substantial evaporation increase in summers of more than 40%. By the end of this century, and according to the RCP 8.5 scenario, the possible evaporation change is higher, varying in most of the months between 35 and 45% – again, except for during the summer, for which evaporation changes reaching +70% were predicted.

Table 3 Relative change in annual precipitation, temperature and inflows under RCP 4.5 and 8.5 scenarios in the UTRB

Period	RCP	Climate change variation			
		Precipitation (%)	Temperature (ºC)	Inflow (%)	
				Entrepeñas reservoir	Buendía reservoir
2040-2069	4.5	-7	+2.9	-10	-9
	8.5	-15	+3.8	-31	-30
2070-2099	4.5	-13	+3.8	-17	-22
	8.5	-26	+6.3	-54	-51

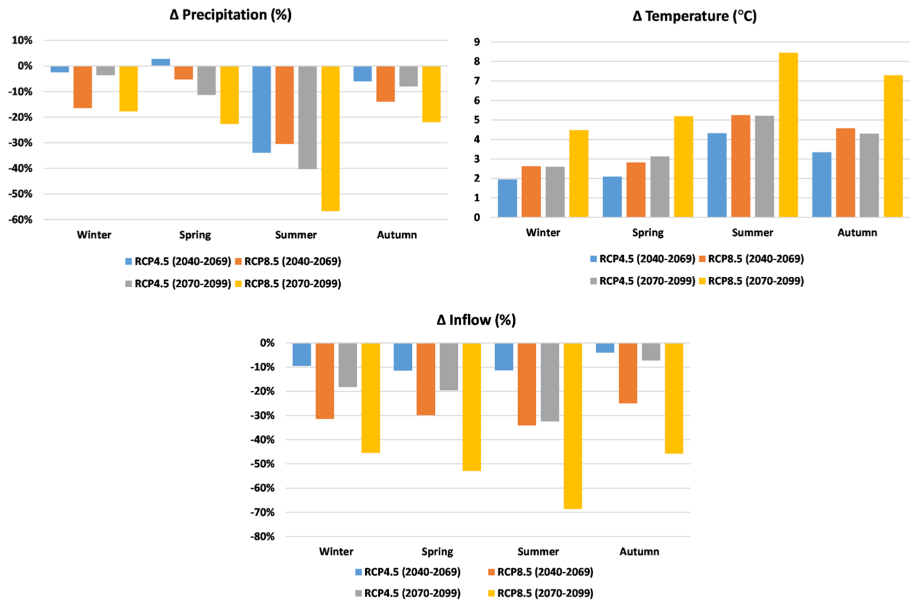

Fig. 4 Seasonal variations of rainfall, temperature and streamflow under RCP 4.5 and RCP 8.5 scenarios

4.5 Climate Change Global Effects on the TSWT

As a synthesis of the several simulated scenarios, Table 5 demonstrates that the effects of the decreasing precipitation and streamflows and increasing temperatures and evaporation rates will translate into maximum decreases of more than 60% in the water volume transferred under the RCP8.5 climate scenario (2070–2099), followed by the mid-future period (2040–2069) under the same scenario, for which a 37% reduction of water transfer was estimated. While similar directional changes are shown under the RCP4.5 scenario, lower reductions of water transfer volumes are expected (between 13 and 17%). In addition, long periods without transfers are expected, especially under the RCP8.5 scenario, where, for years, both the medium and the long term in which the water is transferred will be zero. By comparing the scenarios and considering the effect of increased evaporation from the reservoirs, the decreases obtained in annual average water transfer visibly exceed by 3-4% those obtained without considering the same effect. Therefore, the impact of considering reservoir evaporation is very significant, and it should be incorporated into similar case studies.

Table 4 Relative change in monthly evaporation for the reference period (1970–1999) under RCP 4.5 and 8.5 scenarios in the UTRB

Period	RCP	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2040-2069	4.5	+17	+13	+19	+21	+16	+33	+37	+34	+33	+30	+14	+17	+24
	8.5	+20	+16	+23	+29	+28	+41	+42	+41	+41	+36	+24	+26	+30
2070-2099	4.5	+21	+20	+19	+24	+29	+42	+42	+40	+43	+36	+28	+21	+30
	8.5	+36	+35	+37	+42	+50	+65	+70	+67	+69	+62	+45	+37	+51

Table 5 Results obtained for different scenarios from simulation of current TSWT operation rules. MF = mid-future (2040–2069), FF = far future (2070–2099), E = operation rules simulated considering future evaporation rates, S = operation rules simulated considering future bathymetric changes

Scenario	AAWT (hm^3 $year^{-1}$)	Δ (%)	AAE (hm^3 $year^{-1}$)	Pr(n1-2)	MinAWT (hm^3 $year^{-1}$)	DD (hm^3 $year^{-1}$)
Historical	580		124	100	324	85
RCP4.5-MF	523	-9.8	114	98.0	282	66
RCP4.5-MF-E	506	-12.8	141	97.1	211	57
RCP8.5-MF	385	-33.6	84	77.6	43	0
RCP8.5-MF-E	365	-37.1	106	75.6	0	0
RCP4.5-FF	498	-14.1	108	96.6	180	35
RCP4.5-FF-E	480	-17.2	140	93.7	149	22
RCP8.5-FF	230	-60.3	66	62.1	0	0
RCP8.5-FF-E	214	-63.1	93	51.7	0	0
RCP8.5-FF-E-S	211	-63.6	102	49.7	0	0

AAWT annual average water transfer, Δ change with respect to historical period, *AAE* annual average evaporation, *Pr(n1-2)* probability of the system being in operational level 1 or 2, *MinAWT* minimum annual water transfer, *DD* downstream forced discharge

Pr(n1-2) is the probability of the system being in operational level 1 or 2, which is a proxy of the stability of the water transfer. As expected, this indicator declines when RCP increases the pressure on the system or when evaporation and bathymetric changes are considered.

DD is downstream forced discharge, or simulated mean averaged forced release from the reservoirs due to filling conditions. These releases are expected to reduce in the RCP4.5 scenario and disappear under RCP8.5. Analysis of the simulated monthly reservoir-releases time series demonstrates that occasional filling always took place in the past, decades ago, before the 1980 step anomaly. From these years until now, the reservoirs levels move seasonally and with low-frequency inter-annual periods but they never spill.

It is interesting to point out that the expected change of AAWT in the mid-future moves between 10 and 37%, even under the RCP8.5 scenario. These figures are of a similar or lower order of magnitude than possible reductions in AAWT due to planning decisions such as the environmental flow regimes in the Tagus, the downstream reservoir and the transfer intake, which some proposals fixed at 25%.

This illustrates an important point for understanding the role of climatic change in some water resources systems: decisions made in the planning process, which depend on diverse socio-economic and environmental weighting factors, may have a more significant effect on the future than expected hydrologic effects of climatic change.

5 Conclusions

This study evaluated the impact of expected climate change on the TSWT. Hydrological processes were simulated using the SWAT model, and a comparison between observed and GCM control-period data was applied to identify the best-fitting model. The calibrated model was then run for the mid- (2040-2069) and far (2070-2099) future under the RCP4.5

and RCP8.5 scenarios. SWAT outputs were used as inputs to simulate TSWT operation rules.

The SWAT model successfully reproduced the historical inflows to the Entrepeñas and Buendía reservoirs. In the Entrepeñas reservoir, NSE = 0.80, R^2 = 0.80 and PBIAS = -0.4%, while in the Buendía reservoir, NSE = 0.70, R^2 = 0.89 and PBIAS = -9.5%. Future reservoir inflows were simulated using HadGEM2-ES, as it was selected as the best-fitted GCM. A significant increasing trend in annual average temperature and a significant decrease in precipitation were projected by the middle and end of the twenty-first century. Compared with the reference period (1970–1999), a significant change is expected in the future water resources of the UTRB, which will be driven by changing temperatures and precipitation. In the mid-future (2040–2069), reservoir inflows will decline by 10% and 31% under the RCP 4.5 and the RCP 8.5 scenario, respectively. The most significant shifts to reservoir inflows are also expected for 2070–2099, when they will decline by 19% (RCP 4.5) and 53% (RCP 8.5).

To evaluate the impact of these hydrological changes on the TSWT operation, the simulation process previously described was applied to five different monthly inflow series (historical, RCP45-MP, RCP85-MP, RCP45-LP and RCP85-LP), allowing comparisons of future scenarios with the historical period. In the second step, simulations were repeated but included the effect of increased monthly evaporation. The third step included additional effects of bathymetrical changes owing to sediment retention in the reservoirs. The combined effects of these processes were evaluated and present a clear picture of the future impact on the system that could be expected due to climate change. Overall, climate change would imply a reduction of more than 60% in the possible flows that could be transferred to the Segura basin under the RCP8.5 scenario for 2070–2099. Notably, from the second step, the effect of future evaporation rates is very significant and must be considered in similar case studies. Finally, compared to the considered future evaporation, bathymetrical changes also suggest reduced water transfer volumes, albeit of lesser quantity (3 hm^3/year). Based on these results, the authors strongly recommend the consideration of both effects in hydrological planning.

Other effects could be considered for further refinement of these findings. Thus, seasonally needed volumes for flood control in the reservoirs will probably increase in the future due to expected higher-design floods. These new freeboards imply a reduction in available storage for regulation of demands that must be supplied from the reservoir, which could decrease the available water for the system. Moreover, changes in evapotranspiration will probably increase the volume and modify the seasonality of water demands, which could also affect the system response. The relative and joint effects of all these issues deserve attention and will be analysed in further research.

Despite their high uncertainty, these findings offer valuable insights for water resources planning in both the Tagus and the Segura river basins and alert about possible negative impacts for the involved water resources system in the face of climate change.

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Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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