ORIGINAL ARTICLE

Assessment of future climate and hydrological changes in semi-arid catchment using the SWAT model and bias-corrected EURO-CORDEX ensemble: a case of the Ouergha catchment, North of Morocco

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Abstract

The Ouergha catchment, located in northern Morocco, is one of the most important water resource areas for Morocco's Sebou region, and is also a hotspot for climate change and variability, like the entire Mediterranean region. The present study aims to assess the impact of climate change on water resources in this catchment and to discuss the vulnerability of agriculture production, which has the potential to significantly impact its limited water resources and agricultural output. Specifically, the study investigates potential impacts of climate change on the hydrology of the Ouergha catchment by quantifying changes in hydro-climatic conditions simulated by the Soil and Water Assessment Tool (SWAT) hydrological model, and by analyzing projections from the climate multimodel ensemble from the EURO-CORDEX for reference (1979–2005) and future (2041–2080) periods. The results predicted drier and hotter climatic conditions with projected 14%, 13% and 15% decreases in precipitation, runoff, and soil water content, respectively, in the Ouergha catchment, while evapotranspiration is expected to increase by 12%, suggesting a higher risk for drought conditions. While these projected trends were consistent with other studies that have been conducted in the Mediterranean catchments, the magnitude of hydrologic alterations indicates that the Ouergha catchment is subject to significant hydrologic alteration due to climate change and highlights the need for urgent adaptation and mitigation measures.

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Graphical abstract
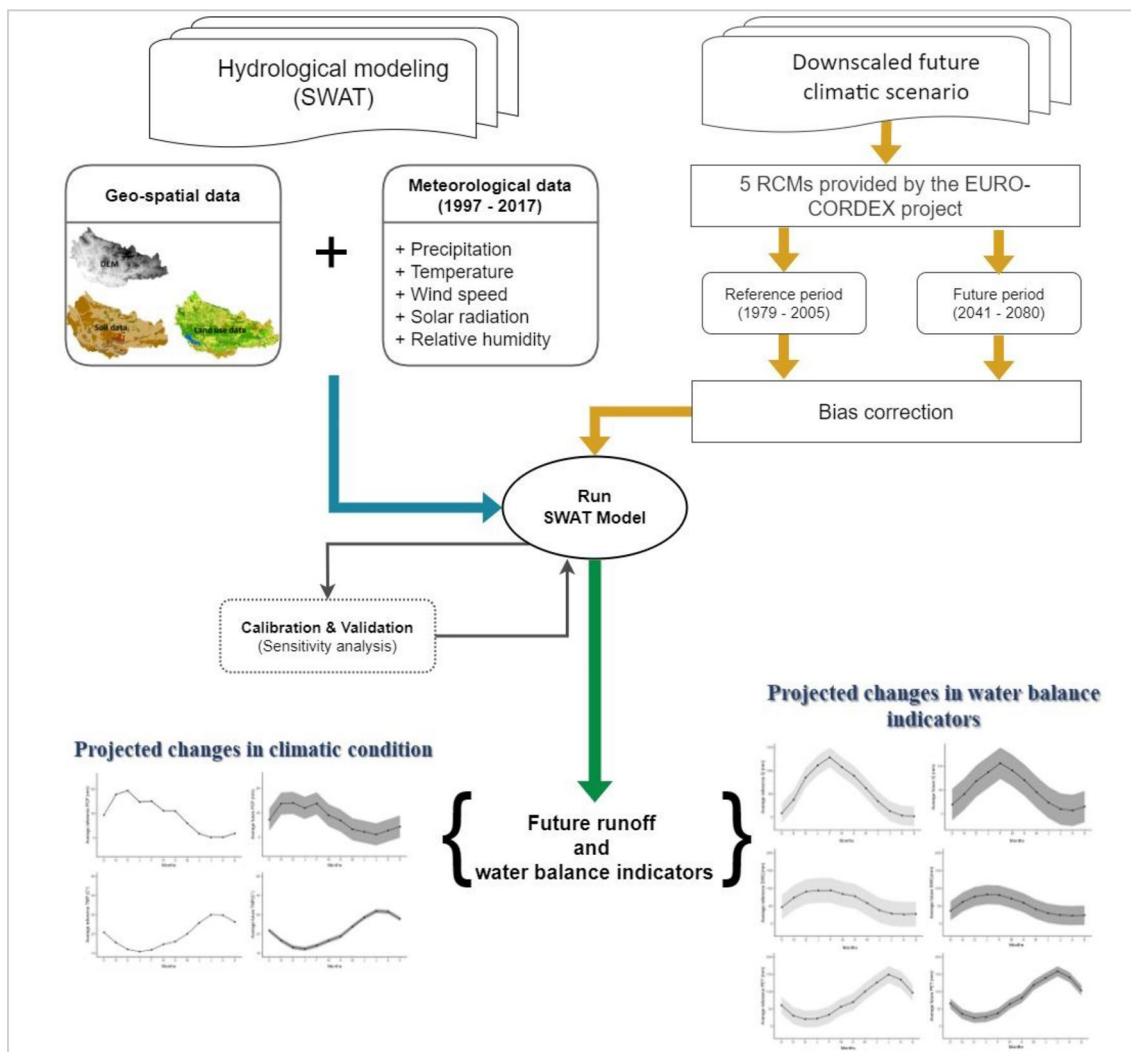
Keywords Climate change · Mediterranean region · SWAT model · Euro-Cordex Ensemble models · Bias correction

Introduction

Studies assessing the impacts of climate change on catchment flow regimes have shown distinct hydrological alteration projections depending on catchment location and characteristics, climate model projections, and temporal and spatial scales of the study. For instance, the availability of water resources is projected to increase because of an increase in precipitation in mountainous, Himalayan and tropical regions (Meehl et al. 2005; Abbaspour et al. 2007; Piani et al. 2010; Fan and Shibata 2015; Hattermann et al. 2015; Torma 2019; Roy et al. 2021; Karakoyun and Kaya 2022; Roy et al. 2022a, b), but it is expected to decrease in Mediterranean catchments as a consequence

of the projected drier and hotter climatic conditions in the future (Meehl et al. 2005; Raymond et al. 2019; Fonseca and Santos 2019; Torma 2019; Rocha et al. 2020; Martinez-Salvador and Conesa-Garcia 2020; Marras et al. 2021; Martinez-Salvador et al. 2021). In addition, the degree of hydrological alteration within the same region can vary depending on prevailing hydrological processes and local catchment attributes (Oni et al. 2014; Lespinas et al. 2014). Other researchers have found that the choice of climate model projections as well as model parameterization and resolution could also result in different magnitudes of hydrological indicator alteration (Ludwig et al. 2009; IPCC 2021; Marras et al. 2021). As such, hydrological impacts of climate change studies have been proposed at the catchment scale for accurate quantification of these

impacts and for identifying practical adaptation measures (Ludwig et al. 2011; Ben Nsir et al. 2022; Roy et al. 2022a, b).

In order to accurately measure the potential effects of climate change on hydrology in the Mediterranean, it is important to utilize climate projections that are both high-resolution and precise. CORDEX (Coordinated Regional Climate Downscaling Experiment) is a global initiative aimed at providing climate projections at regional scales to better understand the impacts of climate change on various sectors. This initiative includes several domains that cover different parts of the world and utilize different sets of regional climate models (RCMs) to downscale the output from global climate models (GCMs). In the Mediterranean area, Med-CORDEX is commonly used due to its specific focus on the region and its ability to provide suitable resolution for hydrological impact studies at the catchment scale. However, Euro-CORDEX can also be used to provide projections for the region at a higher resolution, which may be useful for certain applications (Ha et al. 2022).

The significance of studying climate-induced hydrologic alterations in the Mediterranean catchments is highlighted by the area's identification as a climate change and water security hotspot, as discussed in various studies (Meehl et al. 2005; Fonseca and Santos 2019; Torma 2019; Raymond et al. 2019; Rocha et al. 2020; Martinez-Salvador and Conesa-Garcia 2020; Marras et al. 2021; Lachgar et al. 2021; De Girolamo et al. 2022), which also acknowledged the issue of uncertainty in quantifying the extent of hydrologic change due to climate change. on the catchment flow regime in the Mediterranean. Uncertainty stems from the model structure, greenhouse gas concentration driven by the climate model, model structure and parametrization, inputs, etc. In addition to the variability in local hydrological processes and physical attributes, this uncertainty makes the quantification of hydrological alteration more complex under climate change. As such, the concept of multimodel ensemble methods has been proposed to improve the long-term reliability and stability of climate models and to provide consistent and reliable forecasts (Ruti et al. 2015; Ilori and Balogun 2022). The use of an ensemble of multi-hydro-climate models for assessing the hydrological impacts of climate change has proven superior to a single model projection. The multimodel ensemble approach has been reported to be more effective than a single model approach under various climatic conditions in different complex catchments, including the Mediterranean (Tan et al. 2020; Balhane et al. 2021; Marras et al. 2021; Martinez-Salvador et al. 2021).

Considering adaptation to climate change impacts, the spatial distribution of hydrological processes and environmental settings in the catchment need to be considered while assessing the hydrological impacts of climate change. This calls for physical-based and spatially distributed hydrological models to be used in conjunction with climate model projections. The Soil and Water Assessment Tool (SWAT) is a continuous-time and semi-distributed model that has proven its effectiveness under various climatic conditions in different complex catchments especially in the Mediterranean catchment (Tan et al. 2020; Harraki et al. 2020; Balhane et al. 2021; Marras et al. 2021; Martinez-Salvador et al. 2021; Hachemaoui et al. 2022; Ben Saad et al. 2023; Mahdaoui et al. 2023). This model is widely considered one of the most dependable approaches for assessing the impacts of climate change on hydrology.

Recent studies conducted in the Mediterranean area have incorporated SWAT with climate model ensembles to evaluate water resources under future climate conditions (Torma 2019; Marras et al. 2021; Balhane et al. 2021; Ha et al. 2022). These studies reveal a potential decline in mean precipitation and a reduction in streamflow discharge, along with an increase in extreme precipitation events. The results underscore the value of using ensemble modeling to improve our understanding of future climate changes and emphasize the need for continued research to refine and enhance these methods.

After conducting a thorough evaluation of each individual EURO-CORDEX model, a multi-model ensemble was created to predict future precipitation changes in Ouergha catchment in Morocco, which is a crucial agricultural region reliant on dams to mitigate drought. Additionally, this study aims on the flow patterns of the Ouergha catchment by combining the multi-model ensemble with the SWAT model. The study solely concentrates on the RCP 4.5 scenario, which is not commonly used in hydrological studies. The chosen RCP 4.5 represents an optimistic scenario with greater potential for emissions reductions and mitigation efforts, which is particularly important for regions or sectors pursuing decarbonization strategies. The study provides valuable contributions to the study of climate change impacts in the Mediterranean region, where changes are happening faster than in other areas, highlighting the significance of using this methodology for informed decision-making of the importance of safeguarding the ecosystem and ensuring the sustainability of the dam and its associated benefits.

Materials and methods

Study area

The Ouergha catchment is located on the Mediterranean coast, north of Morocco, between the sub-Rifian mountains to the north and the pre-Rifain mountains to the south. It is also the main tributary of the Sebou River catchment, which drains an area of approximately 6139 km^2, with an altitude ranging from 85 to 2447 m. As a sub-catchment of

the Sebou, the Ouergha catchment contains four dams positioned from upstream to downstream (Asfalou, Bouhouda, Sahla, and Al Wahda). The catchment feeds Al Wahda, the largest dam in Morocco with an annual storage capacity of 3.7 billion m³ (Jaouda et al. 2018) (Figs. 1, 2).

The climate of the catchment is Mediterranean with dry summers and rainy winters. Rainfall is irregular from year to year. The average rainfall is 973 mm, ranging from 500 mm in the east to approximately 1700 mm in the central mountainous area in the south, and the annual average temperature is 28 °C.

The predominance of clay soils and disaggregated layers of marl and shale increases the impermeability of the catchment, thus explaining the lack of groundwater in the

Ouergha catchment (Senoussi et al. 1999). As a result, hydrological modeling is concentrated on examining surface water flows (Fig. 2).

The Ouergha catchment is useful for the cultivation of various agricultural products (Fig. 2) that are very important for the national economy. More than 35% is occupied by orchards, consisting of olive trees, fig trees, and carob trees.

Data collection

To evaluate the hydrological processes and develop future projections of water parameters within the Ouergha catchment, we used the following variables:
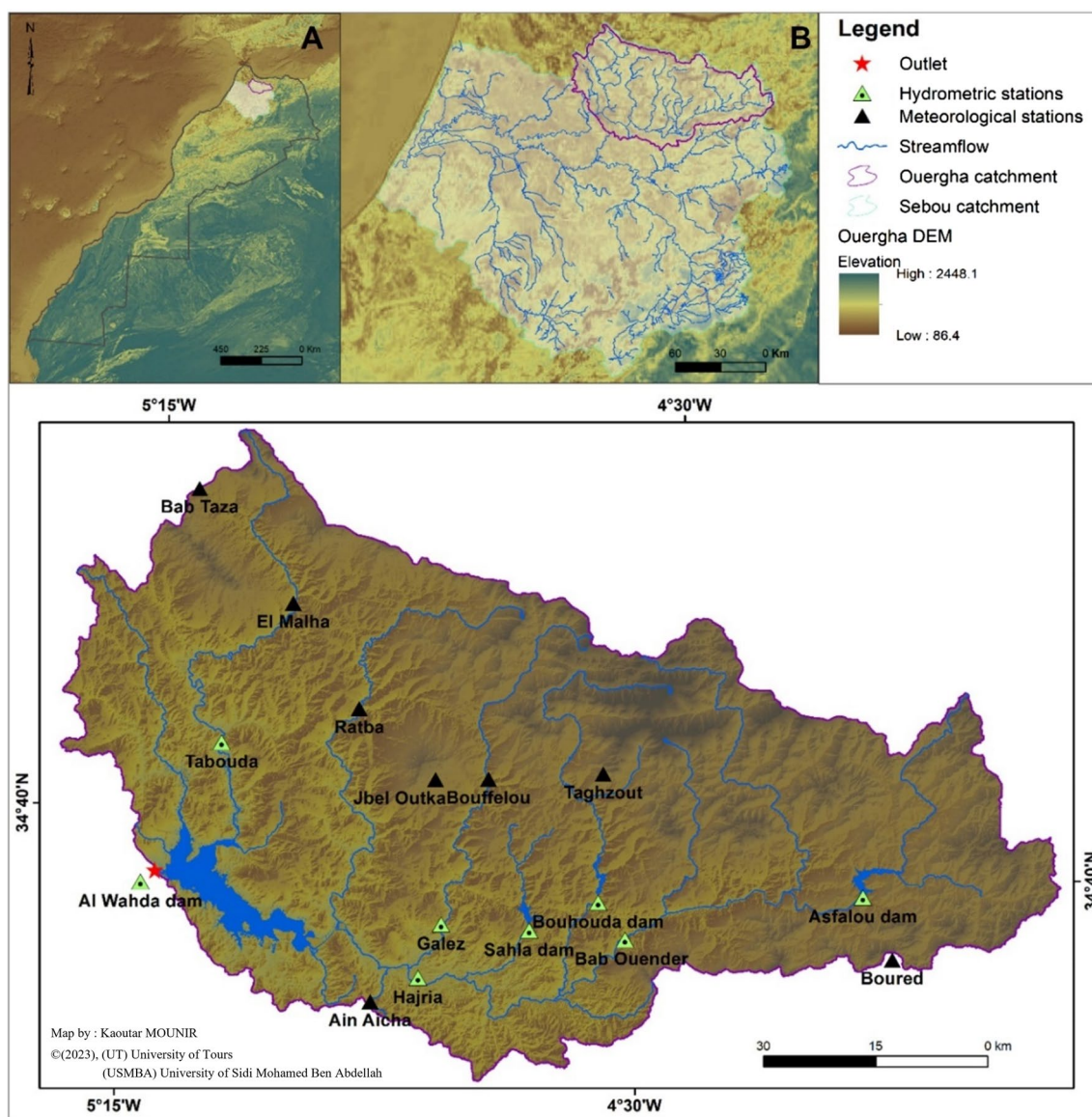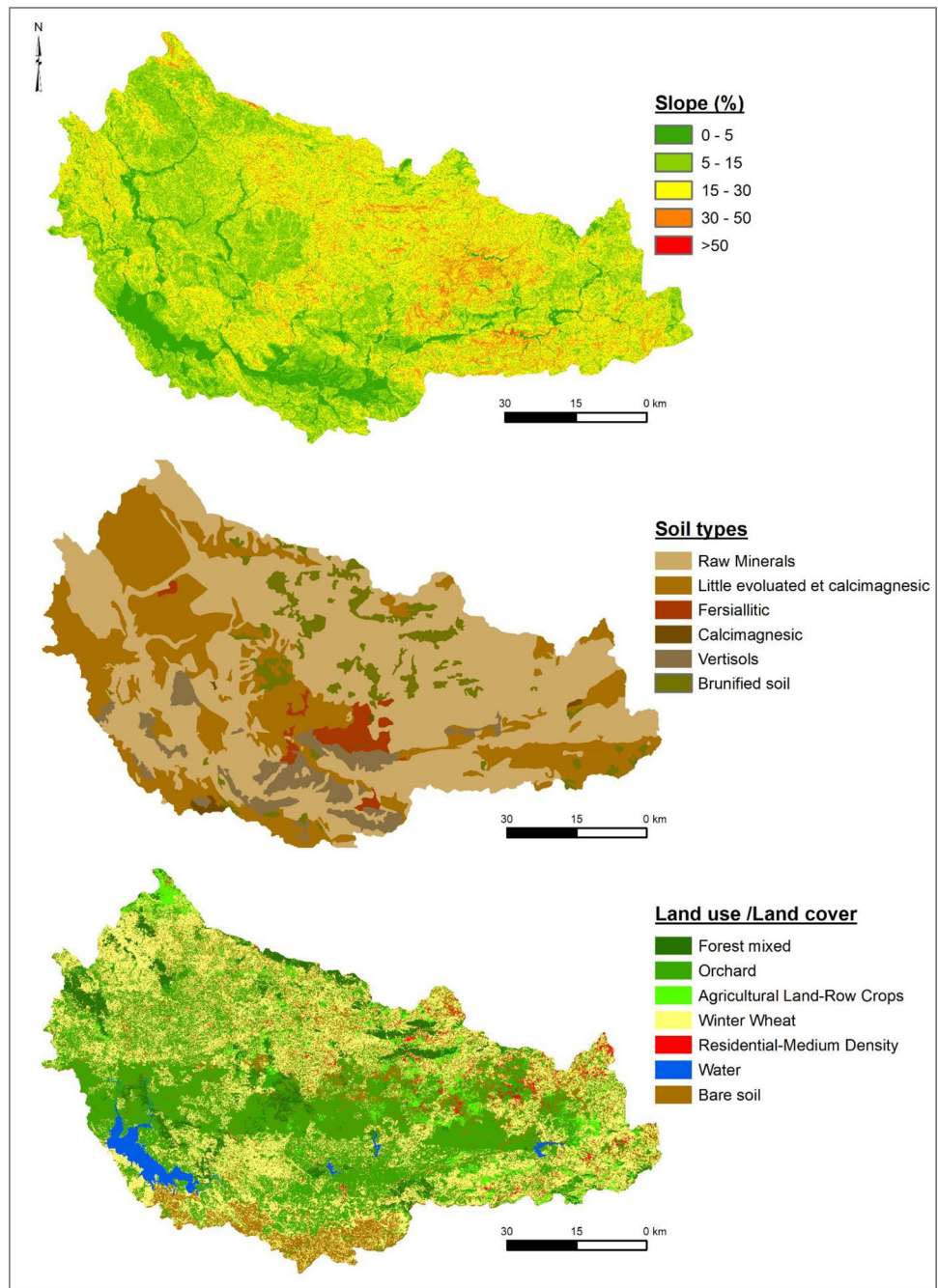

Fig. 1 Location of the Ouergha catchment in Morocco (**A**) and the Sebou catchment (**B**)

Fig. 2 Characteristics of the slope, soil and land use/land cover in the Ouergha catchment

- A digital elevation model (DEM, 25 m resolution) (USGS 2011) was used to define the catchment and extract its morphological characteristics (Table 1).
- The soil properties used were obtained from a detailed study conducted in the Ouergha catchment in 1994 by the Regional Directorate of Water and Forestry and desertification mitigation (DREFLCD 1994) (Fig. 2, Table 1). However, we completed the soil database by calculating parameters such as hydraulic conductivity (Soil_K), bulk density (Soil_BD), and available water content (Soil_AWC). These parameters were calculated according to

the Van Genuchten (1980) (Eq. 1) and Mualem (1976) (Eq. 2) mathematical models (Table 2).

The Van Genuchten water retention function (Eq. 1) is defined by the water retention curve $\Theta(h)$ where Θ_r and Θ_s are residual and saturated water contents ($cm^3 cm^{-3}$).

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^{1-1/n}} \tag{1}$$

Table 1 Input data for the SWAT model

SWAT database	Data	Scale	Date	Source
Geographic	DEM	50 grid	–	http://www.usgs.gov/pubprod/data.html
	Soil types	1/100,000	1994	Regional Directorate of Water and Forestry and the fight against desertification in Rabat (report)
	Land use/land cover	Remote sensing (ENVI 1/50,000) + Mapping and validation in the study field	2017	https://earthexplorer.usgs.gov/
Climatic	PCP	Daily	1993–2017	Hydraulic Sebou Catchment Agency (HSBA)
	TMP (min and max)			

Table 2 Regional climate projections obtained with different couplings of global models (GCMs) and regional models (RCMs) of the EURO-CORDEX initiative with a resolution of 0.11° (~ 12 km)

RCMs	Variant	PCP	TMP	WS	SR	RH
MPI-M-MPI-ESM-LR_ SMHI-RCA4	r1i1p1	✔	✔	✔	✔	✔
ICHEC-EC-EARTH_DMI-HIRHA5	r1i1p1	✔	✔	✔	✔	✔
NCC-NorESM1-DMI-HIRHAM5	r1i1p1	✔	✔	✔	✔	✔
MOHC-HadGEM2-ES-KNMI-RACMO22E	r1i1p1	✔	✔	✔	✔	✔
IPSL-IPSL-CM5A-MR_ SMHI-RCA4	r1i1p1	✔	✔	✔	✔	✔
MPI-M-MPI-ESM-LR	r1i1p1	✔	✔			
CNRM-CERFACS-CNRM-CM5	r1i1p1	✔	✔			
CNRM-CERFACS-CNRM-CNRM_Aladin	r1i1p1	✔	✔			
ICHEC-EC-EARTH_ KNMI-RACMO22E	r1i1p1	✔	✔			
MOHC-HadGEM2-ES-CLMcom-CCLM	r1i1p1	✔	✔			
IPSL-IPSL-CM5A-MR_IPSL-INERIS-WRF331F	r1i1p1			✔	✔	✔
NCC-NorESM1-M-DMI-HIRHAM5	r1i1p1			✔	✔	✔
MOHC-HadGEM2-ES-SMHI-RCA4	r1i1p1			✔	✔	✔

PCP precipitation; *TMP* temperature; *WS* wind speed; *SR* solar radiation; *RH* relative humidity; red colour: rejected parameters; Green colour: accepted parameters

The following Eq. (2) was used in conjunction with the pore-size distribution model by Mualem (1976) to yield the Van Genuchten–Mualem model (1980):

$$K(s_e) = K_o S_e^L \{1 - [1 - S_e^{n/(n-1)}]^{1-1/n}\}^2 \qquad (2)$$

n where K_o is the matching point at saturation (cm/day) and similar, but not necessarily equal, to the saturated hydraulic conductivity, Ks. The parameter L (–) is an empirical pore tortuosity/connectivity parameter that is normally assumed to be 0.5 (Mualem 1976).

- The land use/land cover data were derived from satellite images from Landsat 8 (USGS 2017) using ENVI 5.3 and validated in the field (Table 1).
- Daily meteorological data were provided by the Hydraulic Sebou Catchment Agency (HSBA). The precipitation and temperature data cover the period 1954–2017. We considered 10 hydrometric stations with temporal continuity in the data from 1993 to 2017 and good spatial

coverage of the Ouergha catchment. Wind speed (WS), solar radiation (SR), and relative humidity (RH) were simulated automatically using ArcSwat. In addition, the daily flow at the Al Wahda dam station provided by the HSBA was used to calibrate and validate the SWAT Model (Table 1).

- The Coordinated Regional Climate Downscaling Experiment (CORDEX) was used to assess the impact of climate change on the Ouergha catchment from 2041 until the end of 2080. Daily meteorological data such as precipitation (PCP), temperature (TMP), WS, SR, and RH were obtained from the results of five regional climate models (RCMs) provided by the EURO-CORDEX project (http://www.euro-CORDEX.net/).

SWAT model

As shown in the general framework flowchart (Fig. 3), the multi-step formulation modeling was performed entirely in the GIS environment to evaluate the performance of the multi-GCM climate model ensembles to adequately describe the future climate of the Ouergha catchment.

Firstly, the input data for the model, which includes weather, land use, soil, and climate data, is prepared. Next, the SWAT model simulation is set up, with a defined simulation period (1997–2017) and specified hydrological response units (HRUs). The model is then calibrated and validated using the SUFI-2 algorithm with a calibration period of 1997–2010 and a validation period of 2011–2017. Secondly, the climate model data is downscaled to improve its resolution and relevance to local conditions. A bias correction is then applied to improve the accuracy and reliability of climate model simulations. The SWAT model is then coupled with the climate model ensemble from EURO-CORDEX for the reference (1979–2005) and future (2041–2080) periods under the RCP4.5 scenario. The coupling process involves downscaling climate data to a finer resolution and using it as input for the SWAT model. Finally, the results of the model simulations are analyzed to assess the projected changes in climatic conditions and water balance indicators in the
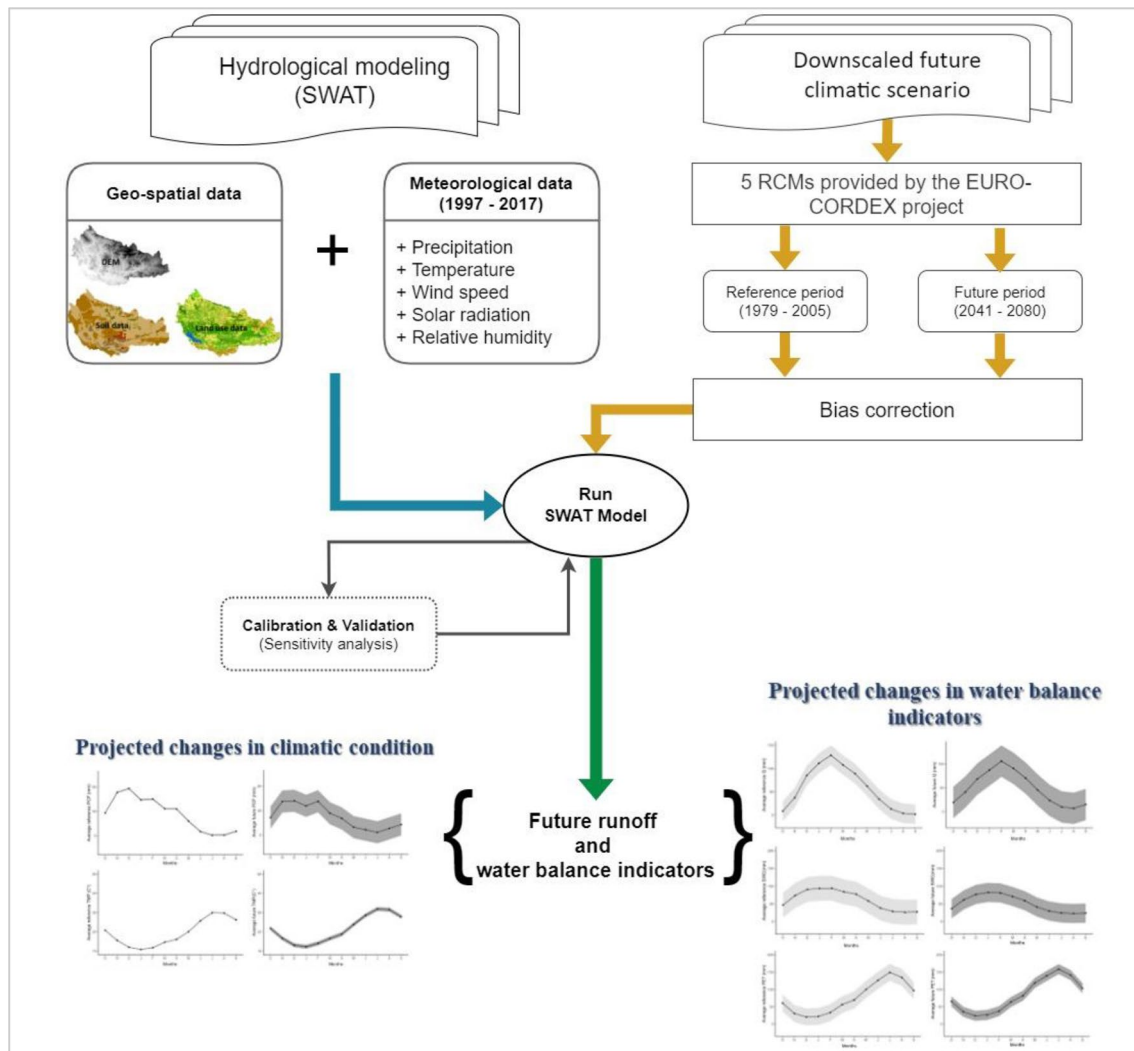
Fig. 3 General framework flowchart of the adopted methodology

Ouergha catchment. This involves comparing the future period results to reference period data and assessing the model's uncertainty.

Hydrological modelling

The Soil and Water Assessment Tool (SWAT) is a continuous-time semi-distributed model based on a hydrological modelling program. It was developed by Neitsch et al. (2011) to evaluate the effects of alternative management decisions on hydrological processes, and pollution sources related to agronomic practices on water quality (Arnold et al. 2012).

The SWAT Model has been widely used in different climate regions to support water management decision-making, and has been shown to be effective even in environmentally sensitive areas (La Jeunesse et al. 2015; Brouziyne et al. 2018). Furthermore, the model has been successfully applied in Morocco to simulate flow, erosion,

and sediments deposition (Fadil et al. 2011; Brouziyne et al. 2018; Markhi et al. 2019; Briak et al. 2019). These studies have shown that the SWAT model can represent observed hydrological variables, but exhibits a significant variance between observations and simulations. The model results are represented in a distributed format, which is useful for assisting the management and practices of local water resources.

The SWAT Model divides catchments into subcatchments. Each subcatchment is further discretized into a series of hydrologic response units (HRUs) that define the hydrological balance by combining soil and land use. For each HRU, the model simulates numerous properties, such as soil water content, flow, sediment yield, and agricultural management practices, and is then aggregated for each subcatchment by a specific average. The hydrological balance of each subcatchment was calculated using Function 3.

$$\frac{\partial SW}{\partial t} = Pday - Qsurf - Ea - Wseep - Qgw \tag{3}$$

where SW_t is the soil water content (mm), P_{day} is precipitation rate (mm/day), Q_{surf} is the surface runoff (mm/day), E_a is evapotranspiration rate (mm/day), W_{seep} is the water percolation rate from the soil profile (mm/day), Q_{gw} is the groundwater flow rate (mm/day).

Modelling approach

Despite the effectiveness of the model, it is known as a greedy model that requires many input parameters (maps, soil data, etc.) (Table 2). In this study, model execution was performed using ArcSwat2012, which is an extension of ArcGIS-ArcView Software (ArcMap10.3). The aim is to facilitate catchment data encoding using a spatial scale imbricated unit of HRU. These units were defined by the superposition of topography (DEM), land use, and soil type (Table 1). In this study, the HRU distribution formed 170 units of soil, Land use/land cover (LULC), and slope class combinations dispersed in 13 subcatchments. For each HRU, water was stocked in the flow, soil, aquifer, and snow.

To run the ArcSwat model for a given period, it was necessary to define the simulation period. In this study, we selected a daily simulation period from 1993 to 2017, with a three-year warm-up period from 1993 to 1996. The model was then run for the simulated catchment and each subcatchment. We used the variable storage or Muskingum method (Linsley et al. 1982) to obtain the calculated process directed through flow for each catchment and subcatchment. The catchment concentration time was estimated using Manning's kinematic Equation (Neitsch et al. 2011).

Calibration and validation

Hydrological modelling is challenging and prone to uncertainty. Many algorithms have been developed to calibrate hydrological uncertainties in the SWAT–CUP interface, such as the Generalized Likelihood Uncertainty Estimation (GLUE) developed by Beven and Binley (1992), the Parasol Method (Parameter Solution) by Van Griensven et al. (2006), and SUFI-2 (Sequential Uncertainty FItting) developed by Abbaspour et al. (2007).

We used Sufi-2 (The Sequential Uncertainty Fitting version 2) in our study to perform a sensitivity analysis. This algorithm has been recommended by many researchers (Yang et al. 2008; Sellami et al. 2013; Martinez-Salvador and Conesa-Garcia 2020) because of its low number of interactions, moderate process time during calibration and validation to reach optimal results many researchers worldwide have recommended the model for surface flow

(Sellami et al. 2013), water quality (Fan and Shibata 2015) and erosion (Markhi et al. 2019).

The calibration period was from 1997 to 2010 and the validation period was from 2010 to 2017. Multiple simulation iterations were run with a minimum of 500 simulations in each run (Thavhana et al. 2018). Then, for each run, SWATCUP suggests new parameter range values to optimize the statistical values.

After running 500 simulations on the observed streamflow, the model performance and efficiency are judged on the basis of the P-factor, R-factor, R^2, and NS values (Table 4), which are based on the following factor equations (Thavhana et al. 2018).

The p-factor (Eq. 4) is computed as the percentage of discharge that represents the measured data included in the 95% prediction band limit, frequently mentioned as the 95PPU. It is calculated at 2.5% and 97.5% levels of the cumulative outflow distribution obtained by sampling the Latin hypercube (Abbaspour 2015).

$$p - factor = \frac{NQin}{n} \times 100 \tag{4}$$

R-factor (Eq. 5) is the average width of the band divided by the standard deviation of the corresponding measured variable. A low value of the R-factor near 0 is desirable to explicate less uncertainty; it is the inverse of the P-factor, where a p-factor close to 1 is judged as satisfying.

$$R - factor = \frac{\frac{1}{n} \sum_{t_{i=1}}^{n} \left(Q_{t_{i,97.5\%}}^{M} - Q_{t_{i,2.5\%}}^{M} \right)}{\sigma_{obs}} \tag{5}$$

The Nash–Sutcliffe (NS) (Eq. 6) is calculated using the following Equation to evaluate the model performance. Simulations with an NS value below 0.5 are not considered acceptable (Nash and Sutcliffe 1970).

$$NS = 1 - \frac{\sum_i^n (P_i - O_i)^2}{\sum_i^n (O_i - \overline{O})^2} \tag{6}$$

R^2 equation (Eq. 7) is considered as the determination coefficient, which ranges between 0 and 1. A low correlation is described by an R^2 value near 0, and a good correlation is represented by an R^2 value near 1.

$$R^2 = \left(\frac{\sum_{i=1}^{n} \left(O_i - \overline{O} \right)^2 (P_i - \overline{P})^2}{\sqrt{\sum_{i=1}^{n} \left(O_i - \overline{O} \right)^2} \sqrt{\sum_{i=1}^{n} \left(P_i - \overline{P} \right)^2}} \right)^2 \tag{7}$$

where O_i observed flowout, $\overline{P}$ mean value of observed flowout, P_i is the simulated flow out value.

Finally, SWAT was forced using an ensemble of climate model projections. This method is intended to ensure that any changes in hydrological function are correlated with climate forcing.

Climate models auditing

The Coordinated Regional Climate Downscaling Experiment (CORDEX) was initiated by the World Climate Research Program (WCRP). It is an international regional climate downscaling experiment that integrates model evaluation and climate projection frameworks to improve regional climate change projections worldwide (Giorgi et al. 2009).

The use of CORDEX climate models to improve GCMs driving climate models has multiple advantages. These include their spatial and temporal accuracy and the possibility of improving the representation of future and current climates. The quality and accuracy of a regional climate change scenario are defined by both the RCM and driving GCM (Christensen and Kjellström 2020). Therefore, ensemble simulations of different climate models should be performed to gain a better understanding of the uncertainties associated with each model (Onyutha et al. 2016).

Despite the gaps between GCMs and local grid cells being filled to some extent by downscaling, RCM performance is still prone to two major limitations. On the one hand, the spatial adjustment performance varies from the observations by the dynamic process and the physical parameterization of the RCM. However, the RCM, which is steered by the GCM results as lateral boundary conditions, inherits the GCM bias, which cannot be removed by increasing the resolution (Liang et al. 2006; Fiseha et al. 2014; Christensen and Kjellström 2020). Additionally, the uncertainty in the data due to the downscaled models and data series was removed using the bias correction method.

In this study, we used five models obtained from different couplings of global models (GCM) and regional models (RCM) of the EURO-CORDEX initiative, with a resolution of 0.11° (~ 12 km). The projections of the multimodel climate ensemble are for reference (1979–2005) and future (2041–2080) periods under the RCP4.5 scenario.

Statistical bias correction

The extension method of the cumulative distribution function (CDF) was used to generate the same distribution of GCM outputs as the distribution mapping (DM) method (Tan et al. 2020). According to the statistical data, the temperature and precipitation variables obey the gamma distribution, whereas the precipitation variable does not (Piani et al. 2010). Moreover, the theoretical CDF was estimated only from rainy days, without considering non-rainy days. To overcome this problem, the ECDF is employed for both the wet (October–April)

and dry periods (May–September), and is therefore applicable to almost all possible climate parameters (Jakob Themessl et al. 2011)

$$F(x) = \int_0^x f(t|a, b)\mathrm{d}t = \frac{1}{\beta^\infty T(a)} t^{a-1} \mathrm{e}^{-\frac{t}{\beta}} dt\, x \geq 0; \infty, \beta > 0$$

$$G(x) = \int_{-\mu}^x g(t|u, s^2)\mathrm{d}t = \int_{-\mu}^x \frac{1}{\sqrt{2\pi}\sigma} \mathrm{e}^{-\frac{(t-m)^2}{2s^2}} \mathrm{d}t \qquad (8)$$

where x signifies the precipitation or temperature variable, $f(t|\alpha, \beta)$ is the probability density function of the gamma distribution with two parameters, α and β, and $g(t|\mu, \sigma^2)$ is the probability density function of the normal distribution with two parameters, μ and σ^2.

$$P_{\mathrm{cor}}^{\mathrm{ECDF}}(t) = ecdf_{\mathrm{obs}}^{-1}[ecdf_{\mathrm{GCM}}(P(t))]$$

$$T_{\mathrm{cor}}^{\mathrm{ECDF}}(t) = ecdf_{\mathrm{obs}}^{-1}[ecdf_{\mathrm{GCM}}(T(t))] \qquad (9)$$

Hydrological indicators

Changes in flow regime can be assessed using various existing hydrological indicators. Although several hydrologic indicators can be used to assess the impact of climate change, they are not universal. The chosen sites were based on their characteristics and data availability.

Hence, these indicators (Table 3) should cover various functions related to the flow response, such as the frequency and magnitude of the flow. The following table shows the various hydrological indicators applicable to the Ouergha catchment. These indicators can be used to evaluate potential changes in various aspects of a given site's water supply, such as precipitation (PCP), temperature (TMP), flow (Q), soil water content (SWC), and evapotranspiration (PET). Furthermore, the choice is also based on the significance of these indicators, not only from the hydrological perspective but also deemed informative and useful for adaptation decision making.

The expected deviation for each indicator was calculated and averaged to represent the ensemble mean of the multiclimate model. Both the relative and absolute changes for the reference and future periods in the hydrologic indicator were calculated using the following equations:

$$\Delta v = \frac{v_{\mathrm{Fut}} - v_{\mathrm{Ref}}}{v_{\mathrm{Ref}}} \times 100\, \mathrm{Relative\, change}(\%)$$

$$\Delta v = v_{\mathrm{Fut}} - v_{\mathrm{Ref}}\, \mathrm{Absolute\, change}(\mathrm{indicator\, unit})$$

Table 3 Selected hydrological indicators for climatic change impact assessment

Process group	Hydrologic indicators
Climatic conditions	Cumulative monthly precipitation (PCP)
	Monthly temperature (TMP)
	Monthly potential evapotranspiration (PET)
Water balance	Monthly runoff
	Monthly soil water content (SWC)
Extreme flow magnitude and frequency	Flow duration curve (FDC)
	Number of low flow days per month
	Number of high flow days per month
Flow duration timing of flow	Minimum flow duration (1, 7, 30, 90 days)
	Maximum flow duration (1, 7, 30, 90 days)
	Average annual Julian date of 1-day maximum
	Average annual Julian date of 1-day minimum
	Average annual Julian date of 90-days maximum
	Average annual Julian date of 90-days minimum

$$\overline{\Delta v} = \frac{1}{N} \sum_{i=1}^{N} \Delta v_i \tag{10}$$

where N is the total number of climate model members ($N=4$), Δv is the multimodel mean of the relative change for indicator v, and the ensemble uncertainty in the projected magnitude of change can be estimated using Eq. (11) according to Giorgi and Mearns (2002).

$$\delta_{\Delta v} = \delta_{\Delta v} \left[\frac{1}{N} \sum_{i=1}^{N} \left(\Delta v_i - \overline{\Delta v} \right)^2 \right]^{1/2} \tag{11}$$

where $\delta_{\Delta v}$ corresponds to the root-mean-square difference of the change in indicator v, and the uncertainty interval around the mean projected magnitude of change is given by $\delta_{\Delta v} \pm \delta_{\Delta v}$ and centered around Δv.

Table 4 Ranking of the most sensitive parameters in the flow simulation

Parameter name	Rank	t-Stat	p-Value	Fitted value
CN2.mgt	1	−13.22	0.00	−0.11
TIMP.bsn	2	−7.20	0.00	0.20
SOL_BD(..).sol	3	4.58	0.00	−0.05
SURLAG.bsn	4	1.81	0.07	8.28
ESCO.hru	5	−0.87	0.39	0.86
EPCO.hru	6	−0.81	0.42	0.20
OV_N.hru	7	0.68	0.49	14.92
SOL_ALB(..).sol	8	−0.68	0.50	0.25
SOL_AWC(..).sol	9	0.59	0.56	−0.02
SHALLST	10	−0.48	0.63	19,763.66
DEP_IMP.hru	11	−0.19	0.85	3319.67

model was evaluated using monthly observed data from the Al Wahda Dam station.

Table 4 displays the first four most sensitive parameters: (1) the initial SCS runoff curve number (CN2), which depends on soil parameters and land use properties; (2) the Snowpack temperature lag factor (TIMP), which differs based on the influence of the previous day's snow pack temperature or snow pack density depth and exposure; (3) the soil bulk density (SOL_BD), which depends on the humidity of soil; and (4) the surface runoff lag time (SURLAG), which controls the fraction of the total water that is allowed to enter the stream on any specific day.

Hydrological model

Figure 4 and Table 5 show the best simulations of the period required for calibration and validation in the Ouergha catchment area. The SWAT model was well fitted during the
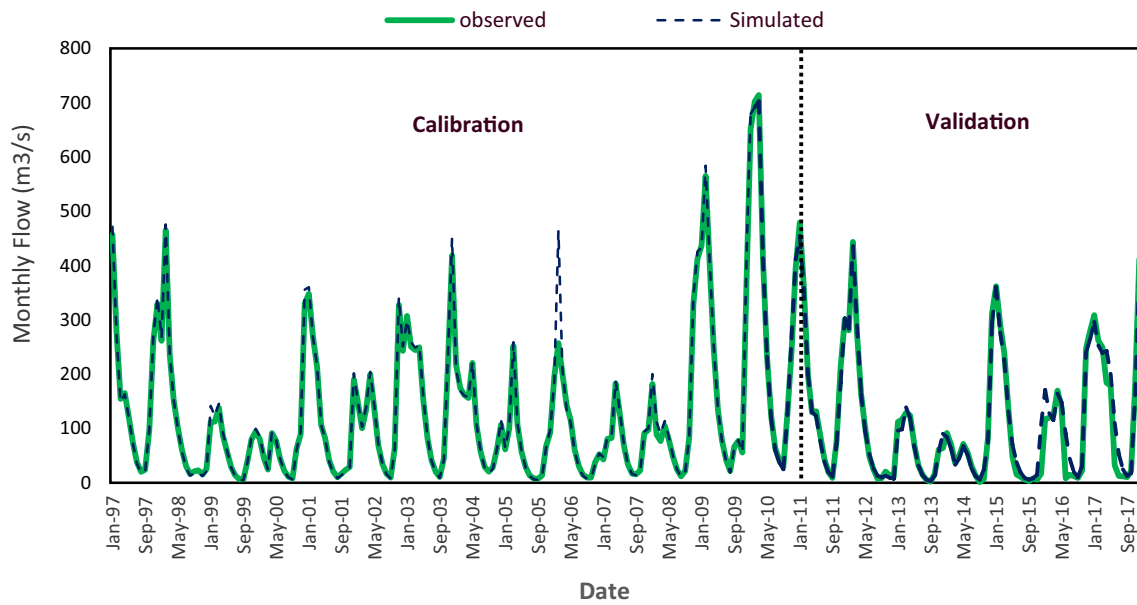
Results

Sensitivity analysis

In this study, the data were used to estimate the daily flow delivered from the NE (catchment upstream) toward the SW (Al Wahda dam). The SWAT Model was executed for daily flow simulations in 13 subcatchments of the Ouergha catchment. The NS factor criteria considered in this study were adopted from the Moriasi evaluation (Moriasi et al. 2007), with a performance limit of 0.5. This method was widely used in sensitivity analysis studies in the Mediterranean area, such as Sellami et al. (2013) and Aouissi et al. (2016).

Table 4 lists the most sensitive parameters identified by global sensitivity analysis. The response of the hydrological

Fig. 4 Monthly flows in the Ouergha catchment (calibration and validation periods)

Table 5 Evaluation of the performance of the SWAT model in the calibration and validation of monthly runoff simulations

Periods	Best simulation	NS	PBIAS	p-factor	R^2	r-factor	RSR
Calibration	426	0.78	−2.7	0.94	0.82	0.44	0.47
Validation	206	0.92	−3.4	0.8	0.92	0.49	0.29

calibration with an NS value of 0.78, whereas the validation period showed an improvement in NS, which reached 0.92. The PBIAS values in the calibration and validation periods showed a slight underestimation of flow with high consistency. The RSR, NS, and R^2 values in the validation period showed an improvement in the goodness of fit compared with the calibration values (Table 5). This indicates that the simulation results had a smaller uncertainty range.

Figure 4 displays that the simulated data are closely related, and the flow is slightly overstated during the dry period (i.e., 2006). This overestimation can be justified by many parameters such as hydraulic conductivity, soil, or evapotranspiration. In addition, the model's sources of structural uncertainty include processes that are not considered in the model, like unknown activities in the catchment, as well as inaccuracy in the model due to over-simplification of the processes considered in the model (Yang et al. 2008; Sellami et al. 2013). In general, the resulting simulation of validation and calibration showed a slight underestimation of the average flow (Sellami et al. 2013; Rocha et al. 2020).

Changes in climate variables under RCM scenarios

The performance of bias correction was established on the set of selected RCMs over the reference period (1979–2005)

Table 6 Average values of the flow Q (m^3/s), precipitation PCP (mm), and temperature maximum (T_{max}) and minimum (T_{min}) (°C) in the Ouergha catchment

Variable	Reference period (1997–2017)	Future period (2041–2080)
Q	122.7	117.5 (−8.4%)
P	18.8	11.7 (−37.8%)
T_{max}	24.1	28.9 (+20%)
T_{min}	10.2	(+34%)

and the future period (2041–2080) for minimum and maximum temperatures and precipitation at Ain Aicha station. The choice of the latter station was based on its localization and representativeness at the level of the Ouergha catchment area.

Table 6 shows the average trends of each hydrological and meteorological variable over the future period using the bias-corrected climate scenarios in the SWAT model. The results for each variable show a significant increase in the average minimum and maximum temperature, which can exceed 34% and 28.9%, respectively, for the period 2041–2080. A significant decrease of more than 37% in precipitation can be stated for the period 2041–2080. Therefore, climate change is expected to have a significant impact on climatic

components and may impact water inputs and reduce the flow by approximately 8% for the period 2041–2080.

Projected changes in climatic condition

The expected changes in climate conditions were assessed by coupling the SWAT model with climate models under RCP4.5 emissions scenario. The climate multimodel ensemble (ENS) was assessed for the future period (2041–2080) using the average relative deviation in monthly cumulative precipitation and absolute changes in monthly temperature with respect to the reference period (1979–2005) for the Ouergha catchment.

Seasonally, precipitation is projected to vary between − 8 to − 21% in autumn (OND), − 10 to − 8% in winter (JFM), − 16 to +1% in spring (AMJ), and +3 to +9% in summer (JAS). On an annual scale, the average precipitation during the reference period of 421.5 mm is projected to be 358.8 mm in the future period, which represents an average decrease of 14.8% (Fig. 5).

In the future, the temperature is expected to increase in all seasons by 0.89–1 °C in autumn, 1.3–1.9 °C in winter, 2.7–2.8 °C in spring and 1.6–1.9 °C in summer. On a seasonal scale, the average temperature within the reference period is 18.5 °C, whereas the average annual temperature is expected to be 21.3 °C, representing an increase of more than 2.5 °C in the catchment (Fig. 6).

Projected changes in water balance indicators

Flow (Q) Figure 7 shows the predicted variation in flow volume between the reference and future periods. It is calculated based on the ENS.

The projected change in the flow volume can vary between − 87% to − 8% in autumn, +24% to +21% in winter, +18% to +37% in spring, and +45% to −45% in summer. On an annual basis, the average flow is projected to reach 105 mm in the future against 128 mm in the reference period, which represents a decrease of − 13%. In addition, uncertainty is associated with the magnitude of the variation in monthly flow, which tends to be relatively constant in all months.

Furthermore, the examined relationship between the predicted rainfall and flow showed a high positive correlation coefficient of 0.75, which was significant at 0.5%. This finding indicates that less rainfall significantly affects the flow in the Ouergha catchment area.

The contribution of rainy seasons to the catchment's water supply and seasonal distribution is significant. However, future flow will be impacted by a reduction in precipitation
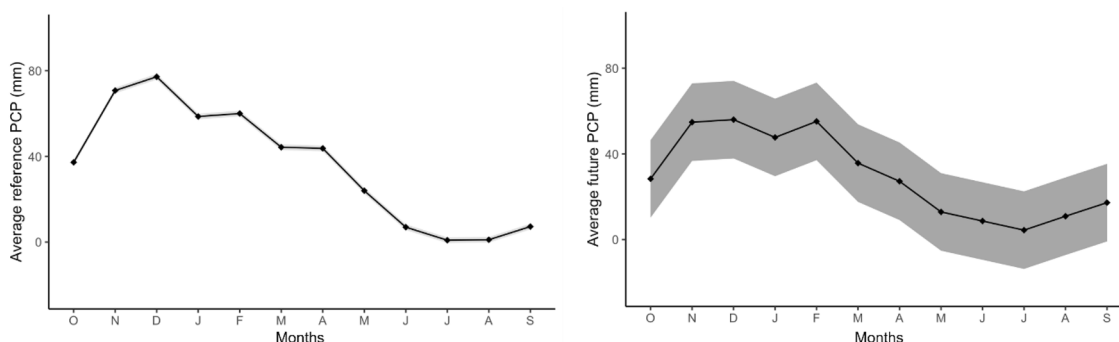

Fig. 5 Monthly precipitation (PCP) in the Ouergha catchment for reference (1979–2005) and future (2041–2080) periods
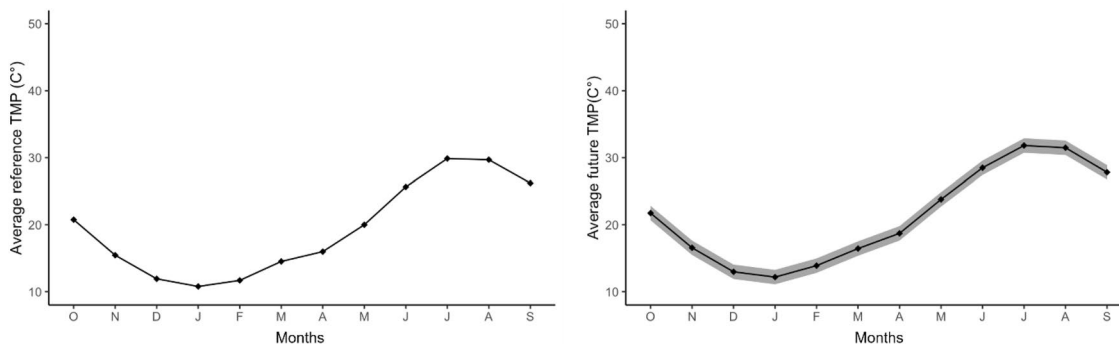

Fig. 6 Monthly temperature (TMP) (°C) in the Ouergha catchment for reference (1979–2005) and future (2041–2080) periods
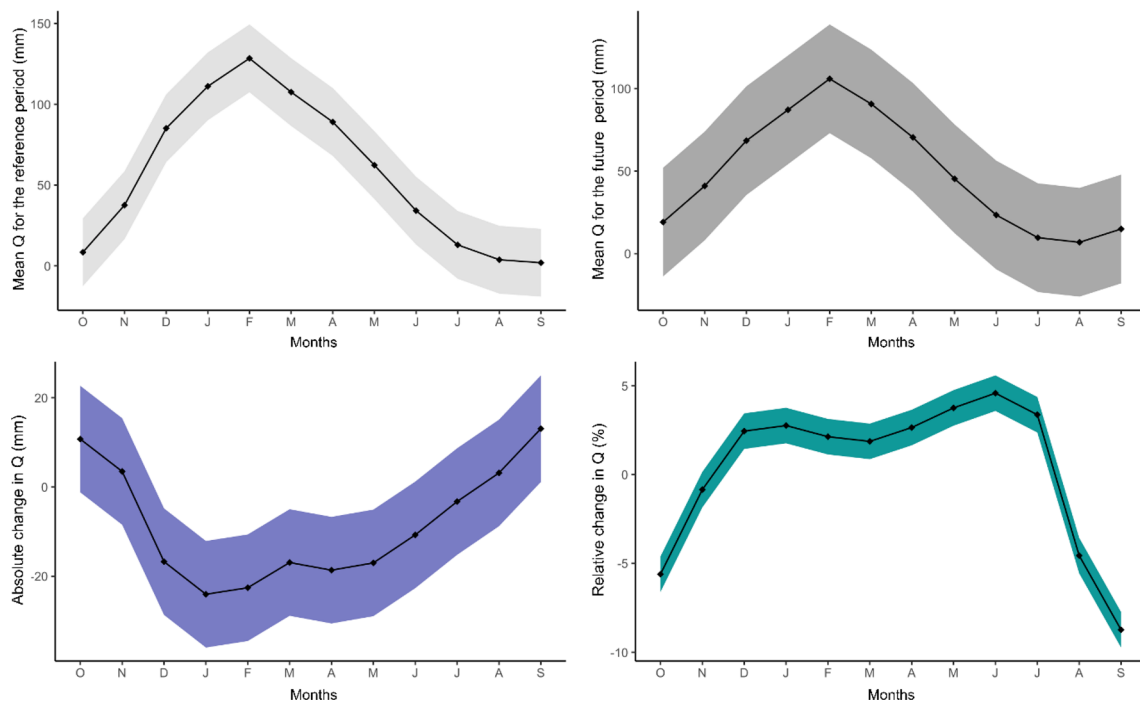
Fig. 7 *Flow* (*Q*) indicator in the Ouergha catchment for reference (1979–2005) and future (2041–2080) periods

frequency and amount (Orkodjo et al. 2022). While the relationship between climate forcing and flow is understood, the findings emphasize the high reliance of flow on precipitation and suggest that uncertainties in precipitation projections affect flow predictions.

Soil water content (SWC) The SWC is an essential component of the hydrological cycle and is responsible for partitioning precipitation into flow and infiltration. Figure 8 shows that the annual SWC is expected to decrease significantly to below 15% in the Ouergha catchment area. This is in line with the seasonal projections ranging from − 21% to − 15% in fall, − 12% to − 15% in winter, − 24% to − 21% in spring and − 15% to − 12% in summer. The reduction in projected precipitation was the main factor causing the SWC to decrease in the Ouergha catchment. Precipitation shows a significant correlation with flow and soil water content (SWC), of $r = 0.75$ and $r = 0.80$, respectively. Furthermore, the amount of soil evaporation and plant transpiration affect the water cycle of plants.

Potential evapotranspiration (PET) PET is a vital component of the water balance and can lead to the loss of up to 90% of annual rainfall in the Mediterranean region (Wilcox et al. 2003). Thus, it is important to understand the relationship between climate and water balance.

The projected changes in the average monthly PET of the Ouergha catchment are presented in Fig. 9. On a seasonal

scale, the increase in PET varied from + 7% to + 15% in fall, + 17% to + 11% in winter, + 15% to + 5% in spring, and + 5% to + 6% in summer. On an annual basis, the results indicate a positive trend that is expected to continue in the future, exceed + 12% annually. Furthermore, the change in PET was strongly affected by temperature and seasonality, where the relationship between these two variables had a positive correlation of 0.96.

Magnitude of flow extremes duration The increasing occurrence of low flows in the Ouergha catchment is expected to have a negative impact on the region's water supply. This study investigated the changes in flow extremes during different time durations.

This study considered the yearly maximum and minimum flows during different time periods (1, 3, 7, 30, and 90 days). The mean value of the ENS was calculated using the moving average of the daily SWAT simulations for reference and future periods. The mean ENS value is calculated using Eq. (2), and its associated uncertainty is given by $\Delta v \pm \delta \Delta v$, where $\delta \Delta v$ is estimated using Eq. (3).

Figure 10 shows that the minimum and maximum flow magnitudes for both the future and reference periods are likely to decrease in the 2080s in the Ouergha catchment. The impact of increasing the flow duration was more pronounced in terms of the duration from 1 to 90 days. The most critical reduction was expected to occur in the 90-days minima with an average of 43.5%. As the flow
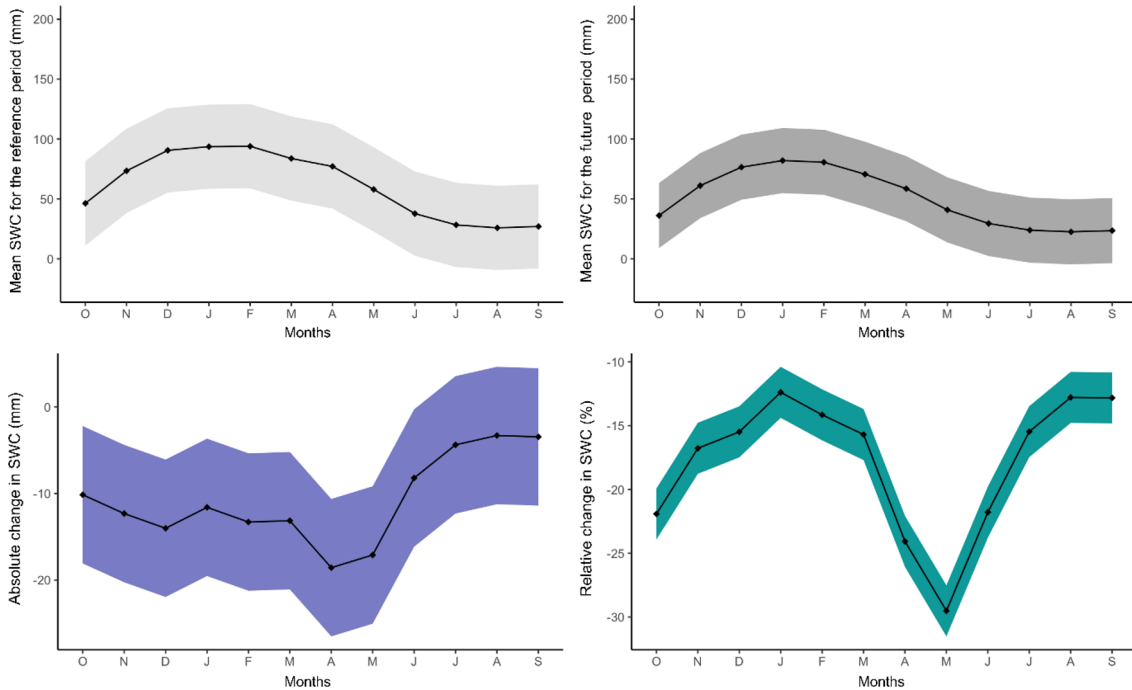
Fig. 8 Soil water content (SWC) indicator in the Ouergha catchment for reference (1979–2005) and future (2041–2080) periods
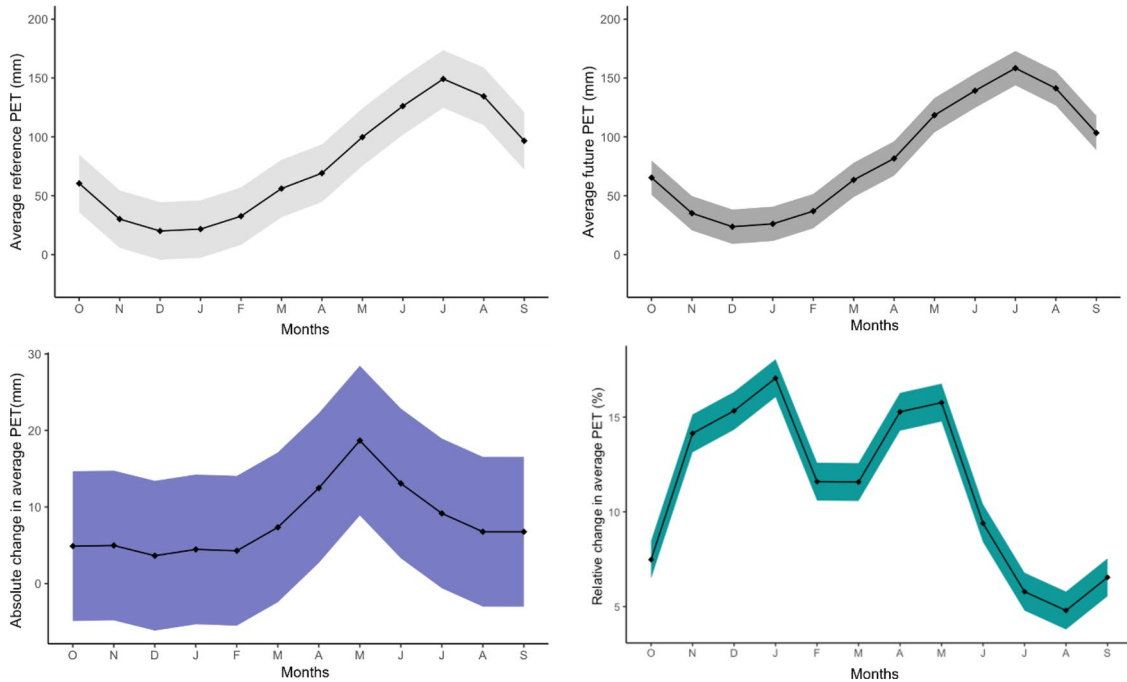

Fig. 9 Potential evapotranspiration (PET) indicator in the Ouergha catchment for reference (1979–2005) and future (2041–2080) periods

duration increases, the intensity of the reduction gradually decreases. The changes in annual flow extremes suggest that the frequency and magnitude of extreme flows are likely to decrease in the future in the Ouergha catchment area.

Timing of flow extremes Studying the timing flow aims to explore the possibility of changes in the timing of annual flow extremes between the reference and future periods owing to the changing climate conditions in the catchment.
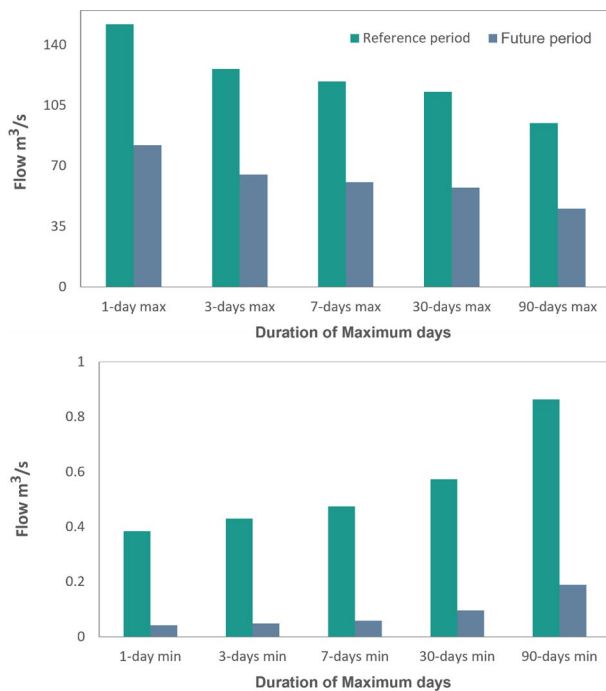
Fig. 10 Changes in minimum and maximum flow extremes for various time durations in the Ouergha catchment for reference (1979–2005) and future (2041–2080) periods

This analysis was conducted based on the average Julian date of the annual minimum and maximum flows. The annual flow timing is only presented in terms of the 1-day, 30-days, and 90-days periods. This method facilitates easy interpretation and displays annual flows in a simple and practical manner.

Despite the projected changes in magnitude, the average timing of annual flow extremes in the Ouergha catchment displays an important change. For instance, in the future, the annual 90-days minimum flow in the Ouergha catchment is expected to occur during the fall and autumn seasons, whereas the maximum flow is expected to occur during spring and summer (Fig. 11).

Discussion

Data collected from a variety of sources, such as land and water resources and weather patterns, are needed to develop models that can predict the effects of climate change on various aspects of the human population and environment. These models are then used to address water resource management and agriculture. Modeling of hydrological processes related to climate change is improved when the data collected by large-scale global climate models are downscaled to smaller levels. This makes it easier to analyze the data and develop effective predictions. Among the most critical factors that a

hydrologic model considers when developing its models is the availability of precipitation data. Thus, if the precipitation data is not of sufficiently high quality, it can lead to uncertainty and bias in the model's flow and water resource management predictions. Therefore, the quality of the data collected is very important in SWAT model development. This study evaluated the projected changes in climatic condition and in water balance indicators over the reference period (1979–2005) according to the RCP4.5 emission scenario in the future periods (2041–2080).

In the current study, projected precipitation tends to decrease and is associated with greater uncertainty, particularly during wet periods (October through March). Compared to precipitation, temperature changes in the watershed are associated with uncertainties that are consistent in both wet and dry periods. This result is in line with many studies that have been conducted in the Mediterranean basin (e.g., Ludwig et al. 2011; La Jeunesse and Quevauviller 2016; IPCC 2021; Martinez-Salvador et al. 2021) and especially studies that have been carried out in different catchments in Morocco. For example, Balhane et al. (2021) analyzed the projected changes in temperature and precipitation over northern Morocco using three ensembles (NEXGDDP, Euro-cordex and bias-adjusted Euro-cordex) downscaling under the two emission scenarios considered (RCP4.5 and RCP8.5) for 2071–2100, with respect to the historical period 1971–2005. Thus, the three ensembles of models projected that by the end of the century, the temperature would increase by about 1.5 to 3 degrees Celsius. Warming would vary depending on the location and model, while the annual precipitation would decrease. The Euro-CORDEX predicted the biggest decreases, with a change ranging from 20% to 40%. According to Harraki et al. (2020) the temperatures are expected to increase in Morocco by 1–2 °C, by 2–3 °C and by 4–7 °C for a warming of 1.5, 2 and 4 °C, respectively. Precipitation would change by −20% to −40% for 4 °C warming in the northern of Morocco and by −10% to −20% for the other levels of warming. The study of Mahdaoui et al. (2023) used the projections of CanESM2 climate model over the Bouregreg catchment. It showed that the annual and seasonal precipitation would decrease in winter and autumn. On the other hand, the mean temperature would increase during the summer and spring seasons under the RCP4.5 and 8.5 scenarios.

Rainy seasons also contribute significantly to the overall volume of water supply and seasonal distribution in the catchment. Future flow will be influenced by decreases in the frequency and amount of precipitation (Orkodjo et al. 2022).

However, when assessing the effects of climate change on a region, it is important to identify and map hydrologic indicators that can cover the different components of a flow regime. Although there is a vast literature on the different aspects of a flow regime, assessment of the effects
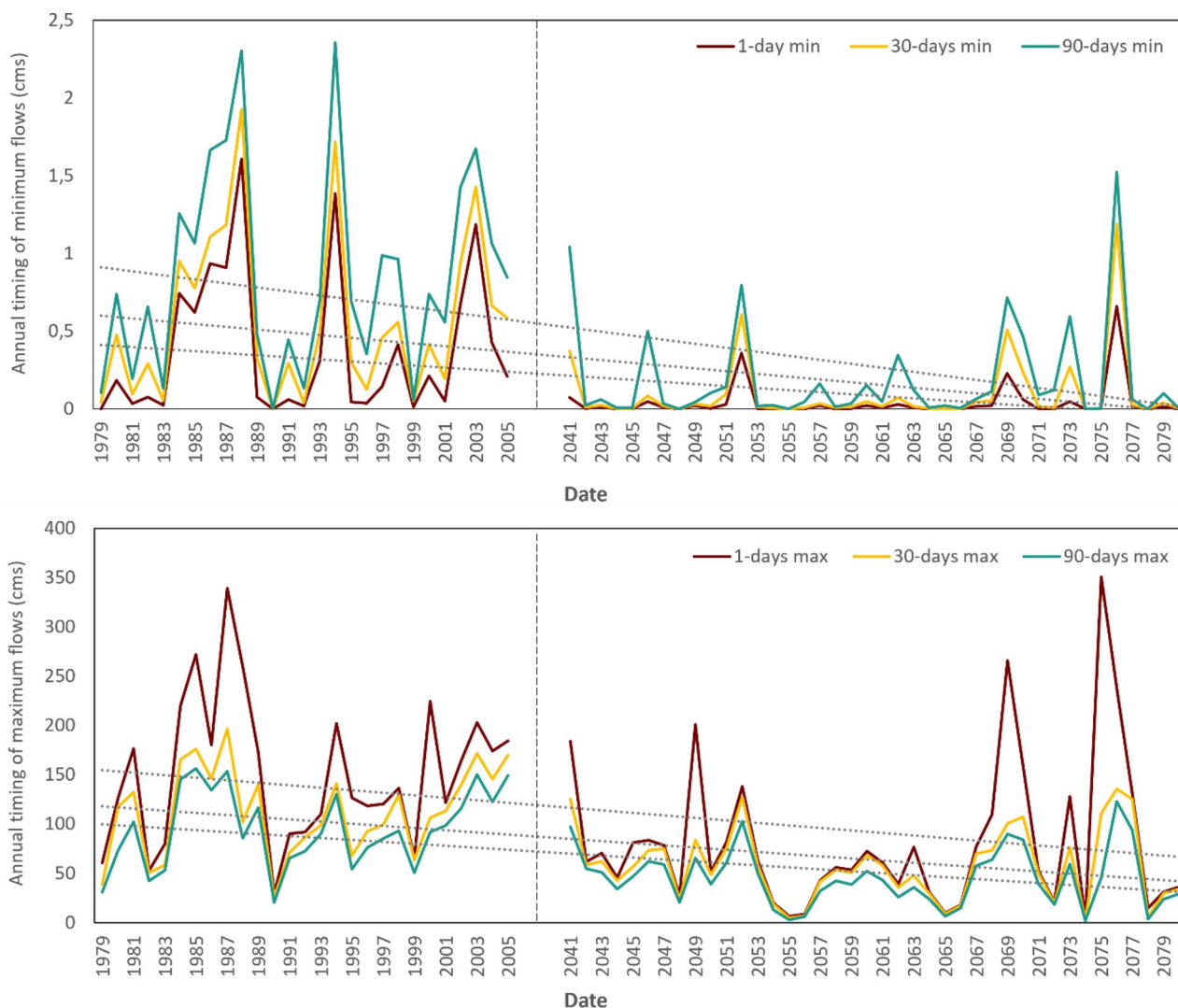
Fig. 11 The annual timing for 1-day, 30-days, and 90-days minimum and maximum flows in the Ouergha catchment for reference (1979–2005) and future (2041–2080) periods

of environmental change on a region is still lacking with respect to the timing, frequency, duration, and magnitude of extreme flows and other water balance factors.

In the current study we explored the future flow, SWC and PET. The examined relationship between predicted rainfall and flow showed a high positive correlation coefficient of 0.75, which was significant at 0.5%. This result indicates that less rainfall significantly affects flow in the Ouergha catchment. Accordingly, the results of this study support the projections provided by other studies, which have predicted a decrease in discharge that could exceed 15% (Rocha et al. 2020; Marras et al. 2021).

The SWC is projected to decrease significantly to less or more than 15% in the Ouergha watershed on annual and seasonal basis (Fig. 7). The reduction in projected precipitation was the primary factor in the decrease in SWC in the

Ouergha watershed. Precipitation showed a significant correlation with streamflow and soil water content (SWC), of $r = 0.75$ and $r = 0.80$, respectively. In addition, the amount of soil evaporation and plant transpiration affect the plant water cycle. Several studies have identified various factors that affect soil moisture, such as temperature, vegetation cover, and soil type. For instance, Mohamed et al. (2018) used GIS and SWAT model to evaluate soil moisture content in the Wadi Al-Naft region in Iraq and found that areas with low elevation, steep slopes, and high drainage density have the lowest soil moisture content, which is similar to the Ouergha catchment that has a predominance of clay and the presence of disaggregated layers of marl and shale that increase catchment impermeability.

Other studies, such as Heinrich and Gobiet (2011), Houle et al. (2012), Ramos and Martínez-Casasnovas (2014), Zare

et al. (2022), and Leij et al. (2022), have also investigated the effects of different factors on soil moisture. These studies found that dry spells and increasing temperature can reduce soil moisture content, while wet spells can increase it. Vegetation cover can also influence soil moisture by altering evapotranspiration rates and soil infiltration capacity. Soil type and topography can impact soil moisture by regulating water infiltration and drainage rates.

Karakoyun and Kaya (2022) used the SWAT model to simulate and predict the hydrological response and soil erosion of the Murat River Basin in Turkey. Although the study did not specifically focus on soil moisture, the findings suggest that land use changes, particularly the conversion of forested areas to agricultural land, can significantly impact soil erosion and hydrological response, which in turn can affect soil moisture by altering infiltration rates and surface runoff.

The predicted changes in the average monthly PET of the Ouergha catchment are presented in Fig. 8. On an annual basis, the results indicate a positive trend that is expected to continue in the future, exceeding +12% per year. In addition, the change in PET was strongly affected by temperature and seasonality, where the relationship between these two variables had a positive correlation of 0.96. Several studies conducted in various catchments in the Mediterranean area have projected that potential evapotranspiration (PET) is likely to increase by the end of the century, which would have significant impacts on water demand, water availability, and crop yield (Lovelli et al. 2012; Aouissi et al. 2016; Mostafa et al. 2021; Pulighe et al. 2021). These studies, which used the SWAT model, are consistent with our findings. The projected increase in PET is mainly attributed to rising temperatures, which are expected to cause greater water loss through evapotranspiration, resulting in decreased water availability for agricultural use. This would, in turn, lead to increased water stress and reduced crop yields in affected areas. While the relationship between climate forcing and flow is understood, the results highlight the strong correlation between water indicators with decreasing precipitation and increasing temperature.

In term of the changes in annual extreme flows suggest that the frequency and magnitude of extreme flows are likely to decrease in the future in the Ouergha watershed. The reduction in annual minimum and maximum flows may have adverse effects on dam operations and water conservation measures. For example, the timing of water releases from the dams may be adjusted in the future due to reduced annual flows. The annual flow schedule is presented only in terms of 1-day, 30-day and 90-day periods. This method facilitates interpretation and displays annual flows in a simple and convenient manner.

The impact of increasing the flow duration was more pronounced in terms of the duration from 1 to 90 days. The most critical reduction was expected to occur in the 90-days minima with an average of 43.5%. The results indicate that the reduction in seasonal low flows is gradual and consistent with flow duration expansion. As the flow duration increases, the intensity of the reduction gradually decreases. The changes in annual flow extremes suggest that the frequency and magnitude of extreme flows are likely to decrease in the future in the Ouergha catchment area.

The findings of this study are consistent with other studies conducted on flow extremes in the Mediterranean region, such as Forzieri et al. (2014) and Tramblay et al. (2020), which also found that changes in streamflow characteristics are related to low flows, such as drought duration, severity, and frequency. Satoh et al. (2022) further suggests that hydrological droughts in the future are expected to occur earlier in the year and with greater severity compared to historical records due to increasing temperature and decreasing snow accumulation in mountainous areas. These findings are in line with De Girolamo et al. (2022), which indicates a shift in the timing of the maximum and minimum flows in a Mediterranean basin due to changes in precipitation patterns and evapotranspiration rates.

Despite the projected changes in magnitude, the average timing of extreme annual flows in the Ouergha watershed shows a significant change. For example, in the future, the 90-day annual minimum flow in the Ouergha watershed is expected to occur during the fall seasons, while the maximum flow is expected to occur during the spring and summer. Therefore, this can be considered a change in seasonality or a change in rainy months.

For instance, Satoh et al. (2022)found that the timing of unprecedented hydrological droughts is likely to shift towards earlier months in several regions of the world, including the Mediterranean. Tramblay et al. (2020) highlighted the challenges of assessing drought in the Mediterranean region under future climate scenarios, due to the complex interactions between precipitation, evapotranspiration, and soil moisture. De Girolamo et al. (2022) showed that climate change is expected to reduce the duration and frequency of high flow events in a Mediterranean basin in Italy, while increasing low flow events. These findings are consistent with the results of this study, which also indicate a shift in the timing of extreme annual flows in the Ouergha watershed under future climate scenarios.

Conclusion

The Ouergha catchment is known for its agricultural production, which depends on the supply of dams, especially during drought events. However, dam safety is important because of the potential impact of climate change on structural vulnerability. These include changes in flow, siltation, and extreme weather conditions. Long-term flow projections

are generally subject to uncertainties due to the impacts of climate change. The current study proposes to study projected changes in the flow regime of the Ouergha catchment area. The changes and associated uncertainties were assessed using the SWAT hydrological model with an ensemble of climate model projections. The impact of these changes was quantified using an ensemble of hydroclimatic indicators.

The results reveal that the effects of climate change on the water resources of the Ouergha catchment during the future period of 2041–2080 are important and should be seriously considered by water resource management bodies. The precipitation and flow are expected to decrease by 14% and 8%, respectively, by the end of the century. Moreover, the study indicated that climate change is expected to cause prolonged and intense droughts in the future (2041–2080), as temperature and PET are expected to increase by 1 to $+3$ °C and 1.5% to 16%, respectively.

Furthermore, the study showed that a decrease in precipitation will inevitably drastically affect the water cycle in the Ouergha catchment area. The Pearson correlation showed a strong relationship between precipitation with flow and soil water content with a coefficient of $r = 0.75$ for flow and $r = 0.80$ for soil. Furthermore, the correlation between temperature and evapotranspiration was very strong (0.96). Thus, a decrease in precipitation will inevitably drastically affect the water cycle in the Ouergha catchment area. Additionally, the study indicated that the SWC is expected to decrease significantly, and the reduction in projected precipitation is the main factor causing the SWC to decrease. Moreover, the increase in PET is expected to continue in the future, exceeding $+12\%$ annually.

Regarding the magnitude of the extreme flow, a clear decrease is observed in both high and low flows for different durations considered in this study, that is, 1, 7, 30, and 90 days. Moreover, in the timing of the extreme flows forecasted during the different durations (1, 30, and 90 days), the 90-days minimum flow catchment is expected during the winter and autumn seasons, whereas the maximum flow is expected in spring and summer. The main result of the present study is certainly this important change in seasonality, which is expected to occur in the second part of the century.

The significance of this study lies in its innovative approach to evaluating the potential influence of climate change on the hydrology of the Ouergha catchment, particularly using the RCP 4.5 scenario. The findings of this study can be used to inform decision-making in the relevant domain, particularly in the agricultural sector. However, the uncertainties associated with the magnitude of the variation of flow, particularly during wet periods still need to be assessed. Additionally, the study only focused on one scenario, and further research is needed to explore the impact of other scenarios on the hydrology of the Ouergha catchment. These findings reaffirm that the region is a hotspot for climate change and identify the need for further research to address urgent adaptation measures.

Declarations

Conflict of interest The authors confirm that there is no conflict of interest regarding this manuscript.

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