

Article

Assessing Spatio-Temporal Hydrological Impacts of Climate Change in the Siliana Watershed, Northwestern Tunisia

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Abstract: Climate change is one of the most critical factors impacting hydrological dynamic systems. This study investigated how climate change influences the hydrological dynamics within the Siliana watershed in northwestern Tunisia, employing the Soil and Water Assessment Tool (SWAT) model. The analysis compared streamflow patterns for the future period (2046–2072) with a baseline period (1979–2005). Simulations were carried out using four combinations of regional and global climate models from EURO-CORDEX, based on two Representative Concentration Pathways (RCP4.5 and RCP8.5). The results indicate a projected annual precipitation decrease of 22% with RCP4.5 and 27% with RCP8.5, accompanied by a temperature rise of up to 7 °C under RCP8.5. Streamflow is anticipated to decrease by 44% under RCP4.5 and 69% under RCP8.5. Extreme events show intensified high flows of shorter durations and increased low flows. Analysis using the Standardized Precipitation Evapotranspiration Index (SPEI) revealed longer and more intense droughts. Under the RCP8.5 scenario, 24% of the watershed faces extreme drought, while 76% experiences severe drought conditions. These findings highlight notable changes in hydrological indicators, emphasizing the urgent need for adaptive strategies in water resource management within the Siliana Basin to mitigate the effects of climate change.

Keywords: climate change; streamflow; climate models; SPEI; SWAT; hydrologic indicators



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1. Introduction

The Mediterranean region is particularly vulnerable to the impacts of climate change, with significant implications for its hydrological systems. Rising temperatures, combined with a marked decrease in precipitation, are expected to drastically alter water availability across the region. According to the Sixth Assessment Report [1], mean temperatures in the Mediterranean are projected to increase by 1.5 °C to 4 °C, while precipitation could decrease by as much as 27%. The results also project that mean dry climate impact drivers will rise, including aridity and hydrological, agricultural, and ecological drought. Additionally, according to previous predictions [2–7], the Mediterranean region will inevitably experience a future potential decrease in water resources. Consequently, these effects impede all socioeconomic sectors, including water management. Recently, there has been an increase in demand for relevant and useable climate information as well as an adjusted infrastructure known as “climate services” to assist climate change mitigation and adaptation [8,9].

In the literature, numerous hydrological models are used across various scales and environmental conditions to assess the impacts of climate change. Scientists use hydrologic modelling with the expected future climate data from Global Climate Models (GCMs) and Regional Climate Models (RCMs) to assess and quantify responses to hydrologic processes [10]. Among other climate data providers, CORDEX (Coordinated Regional

Climate Downscaling Experiment) provides consistent climate projections on regional scales. For instance, the study by Martínez-Salvador et al. [6] reported future streamflow reductions ranging from 46.3 to 55.8% in two semi-arid watersheds in Spain using sixteen RCMs from EURO-CORDEX and SWAT. Using eight GCMs, two RCMs from CORDEX-Africa (RCA4 and CCLM4-8-17), and SWAT, Mami et al. [4] evaluated the hydrological response to climate change for RCPs 4.5 and 8.5 in the Tafna Basin in Algeria. They predicted a reduction in river discharge (ranging from 42 to 54%) and surface flow (ranging from 20 to 48%) for the projected period of 2020–2099 due to decreased precipitation. The CORDEX goal is to gain a better understanding of how climate change impacts various sectors. This initiative comprises different regions covering various parts of the world and employs different sets of RCMs to refine the data from GCMs.

However, there are still considerable biases in climate model projections at the global and regional scales, as indicated by Martínez-Salvador et al. [6] and Teutschbein and Seibert [11]. These biases can be either due to GCM outputs or model discrepancies. Therefore, it is essential to correct these biases in RCM/GCM data before utilizing them to examine the potential impacts of climate change on communities, as emphasized by Luo et al. [12]. Several bias-correction methods have been introduced for this purpose, including linear scaling, local intensity scaling, power transformation, distribution mapping, and quantile mapping. These methods were also suggested in previous studies to decrease observed–simulated differences in climate variables [4–6,13–15]. Despite the availability of bias-correction methods, significant residual uncertainties persist in climate projections. Numerous researchers have focused on studying uncertainty due to the prevalence of various biases and their complicating effect on accurately quantifying hydrological changes driven by climate change. One approach to addressing structural variability in climate forecasts is the use of multi-model ensemble methods. These methods have been suggested to enhance the long-term reliability and stability of climate models, providing more consistent and dependable forecasts [16,17]. Utilizing an ensemble of multi-hydroclimate models to assess the hydrological effects of climate change has been shown to outperform individual model projections. The multi-model ensemble approach has been reported to be more effective than a single-model approach under various climatic conditions in different complex watersheds, including the Mediterranean [6,18,19].

Another complex issue in hydrological impact studies related to climate variations is identifying hydrologically meaningful metrics that encompass all aspects of the flow regime and align with the modeling scale. Hydrological impact indicators, as proposed by Sellami et al. [2], are intended to support the operational management of watershed rivers. Although numerous hydrologic indicators exist in the literature, further work is required to develop a comprehensive watershed-scale evaluation of the hydrological impacts of climate change. This evaluation should encompass flow characteristics related to the water balance, such as flow magnitude, along with the frequency, timing, and duration of extreme events like low flows.

In light of these challenges, our study aimed to offer solid insights into how climate change affects streamflow in a Mediterranean watershed. This region faces faster changes compared to others, highlighting the importance of using this approach for informed decision making to protect the water system. With this understanding, highly accurate decisions can be made regarding water resource management, offering potential benefits for other socioeconomic sectors impacted by climate change.

For our study, we selected the Siliana watershed in northwestern Tunisia as the chosen study area. This watershed is crucial for agriculture and depends on the Siliana Dam to manage drought conditions.

In order to examine changes in watershed flow regimes between a reference period (1979–2005) and future climate change scenarios (2046–2072), we forced a reference hydrological model (SWAT) [20] validated for the study region using outputs from a multi-climate model ensemble. The study allowed the quantification of average changes and uncertainty

in relevant hydrological variables related to the watershed's water balance, flow magnitudes, extremes, duration, and timing.

2. Materials and Methods

2.1. Study Area

The Siliana watershed, situated in northwestern Tunisia, covers an area of 1028 km² (Figure 1). It plays a crucial role within the Medjerda Basin, which is the primary hydrological basin in Tunisia, impacting the hydrological dynamics of the region.

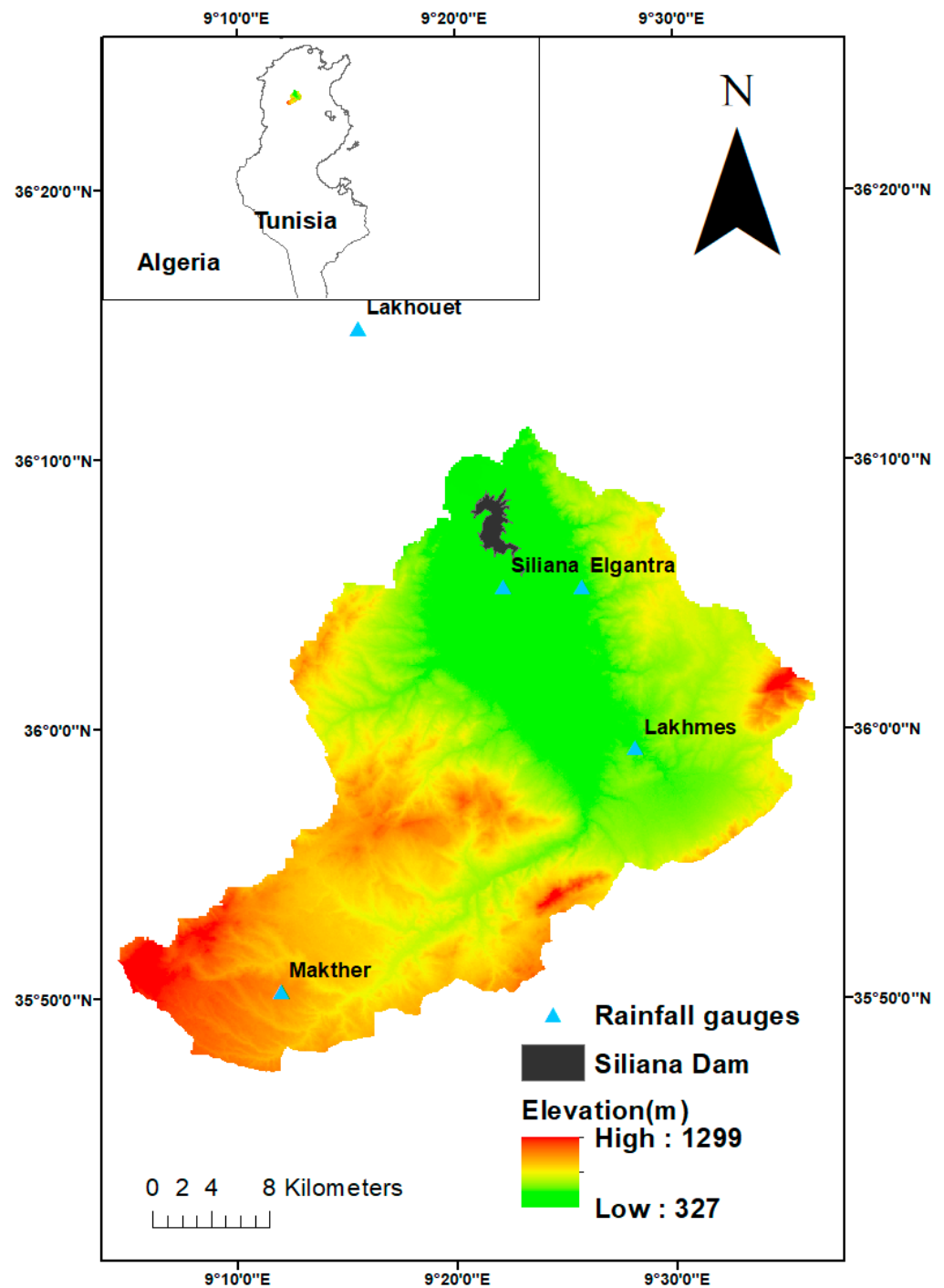


Figure 1. Location of the study area.

In the south, the terrain is mountainous, with elevations reaching up to 1299 m and an average altitude of 947 m. The region experiences a temperate climate, with an average annual precipitation of approximately 580 mm, most of which occurs between October and April. The dry season spans from May to September, with temperatures often surpassing 28 °C. Agriculture is the dominant economic activity in the watershed, primarily centered on cereal and olive production, both of which are economically important at local and national levels. More than 80% of the available water is allocated for irrigation, with significant reliance on surface water sources such as reservoirs, dams, and direct river-water extraction.

2.2. Modeling Approach

2.2.1. Hydrological Modeling

Data and Sources

The effects of climate change on streamflow in the Siliana watershed were simulated using the 2012 version of the Soil and Water Assessment Tool (SWAT) [20], which necessitates a diversity of information related to meteorology, land use, and crop management.

The SWAT input data used in this research, including the available data, sources, and spatial resolutions, are provided in Table 1. Figure 2 illustrates the methodological approach employed in this research.

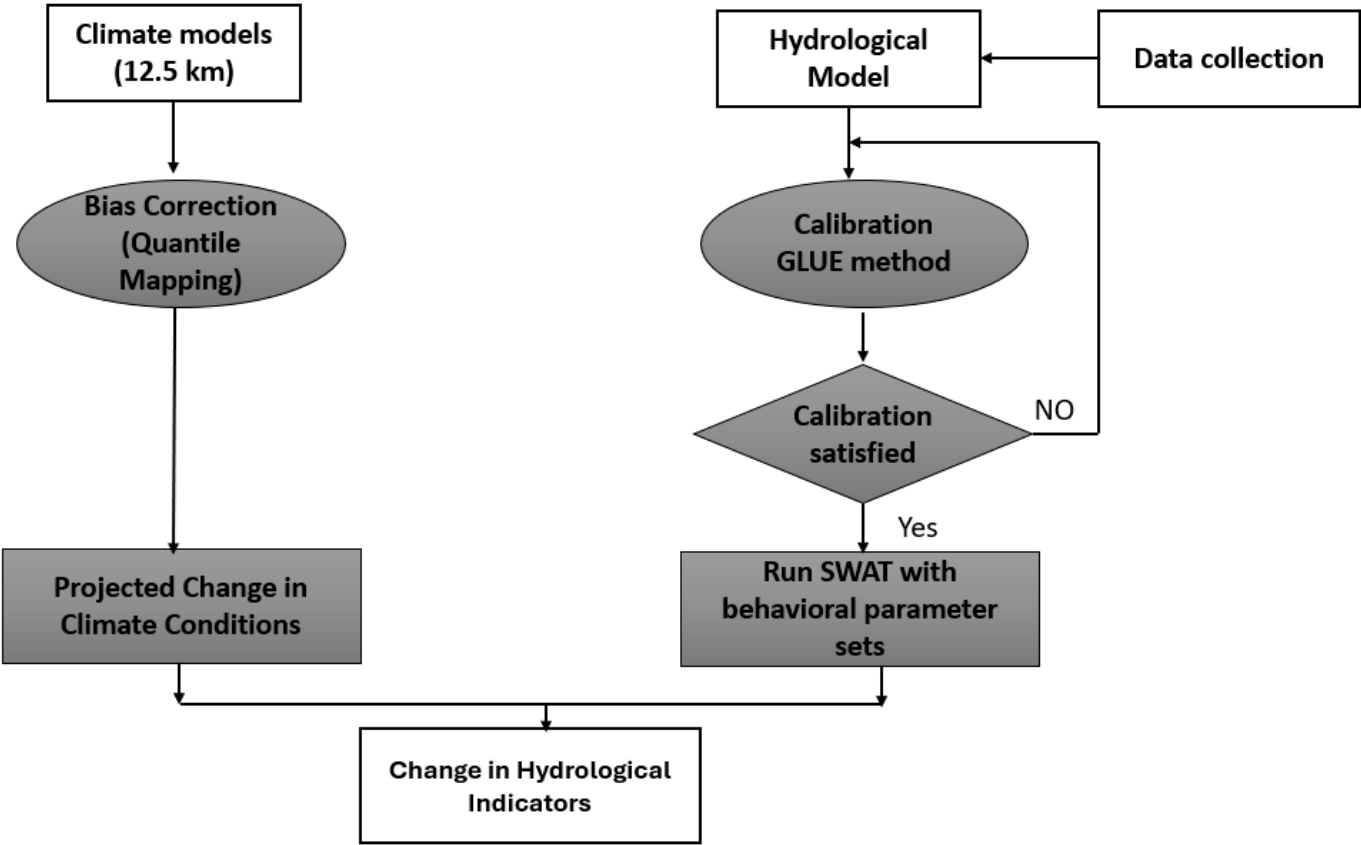


Figure 2. Flowchart representing the methodological strategy of this study.

Table 1. Data collected for implementing SWAT in our study.

Available Data	Resolution/Scale	Source
Precipitation	Daily (1979–2005)	Five stations (Lakhouet, Siliana, Makther, Elgantra, and Lakhmes). Source: General Directorate of Water Resources (Tunisia)
Temperature	Daily (1979–2005)	Siliana station. Source: National Meteorological Institute (Tunisia)
Solar radiation, wind humidity	Daily (1979–2005)	Nine climatic stations (SWAT). Source: http://swat.tamu.edu/ (accessed on 1 December 2019)
Digital elevation model	30 m	Shuttle Radar Topography Mission (SRTM) of USGS (http://srtm.csi.cgiar.org/) (accessed on 1 December 2019)
Soil map	1.50,000	Agricultural map
Land-use map	1.5000	Agricultural map; Land-use database (SWAT model crop database)
Discharge	Monthly (1987–2005)	General Directorate of Dams and Major Hydraulic Structures

2.2.2. Climate Modeling

A thorough understanding of drought conditions in a region necessitates examining not only historical and current droughts but also projecting future drought scenarios [21]. Therefore, both historical and future periods were included in this study.

Four different climate model combinations were utilized to generate daily climate estimates for precipitation as well as minimum and maximum temperatures: four GCMs with varying resolutions and four RCMs from EURO-CORDEX, each with a resolution of 12.5 km × 12.5 km. (Table 2). We used the same locations as the observation stations for the downloaded data. The output runs of these models for representative emission pathways RCP4.5 and RCP8.5 were downloaded from the Earth System Grid Federation (ESGF) website (<https://cordex.org/data-access/esgf/>) (accessed on 15 October 2021). Our study used 27 years of data from historical simulation runs (1979–2005) for reference purposes. The future climate is depicted by 27 years from 2046 to 2072. All climate data are provided with a 12.5 km spatial resolution. The GCM-RCM combinations from CORDEX make these data appropriate for evaluating uncertainties associated with selecting climate models and RCP scenarios in regional studies. These climate models were selected based on various factors, including their ability to accurately replicate rainfall and temperature patterns in the Mediterranean region, as demonstrated in several studies [4–6,22]. Additionally, they were chosen based on their spatial resolution [23], their application in a number of other hydrological studies [13], and their performance in studies for the north African and Mediterranean regions [6,7].

Table 2. GCM-RCM combinations utilized from EURO-CORDEX.

Institute	Global Climate Model	Regional Climate Model
CLMcom	CNRM-CERFACS-CNRM-CM5	CCLM4-8-17
GERICS	NCC-NorESM1-M	REMO2015
KNMI	ICHEC-EC-EARTH	RACMO22E
MPI-CSC	MPI-M-MPI-ESM-LR	REMO2009

To address the uncertainty brought on by various GCMs and RCMs, a multi-model ensemble (MME) using a simple mean technique was employed. The MME approach is widely used in climate research to enhance the robustness and reliability of projections [24,25]. It operates under the premise that no single model can fully capture the complexity of climate systems. By combining the outputs from multiple models, MME reduces uncertainties and provides a more comprehensive picture of potential climate outcomes. The key idea behind the MME is that each climate model has different strengths, weaknesses, and inherent biases. The MME approach relies on the concept that various models possess distinct strengths and weaknesses and that aggregating their predictions

can yield more reliable and precise forecasts. By averaging or combining multiple models, the ensemble approach mitigates model-specific errors and provides a more reliable estimate of future climatic conditions. MME methods are particularly useful when assessing future climate projections, hydrological impacts, or extreme weather events. In climate modeling, this method is used to improve the accuracy of future projections by integrating the outputs of multiple models. This is achieved by combining the outputs of multiple GCMs and RCMs to form an ensemble of predictions. In this research, each model is given an equal weight when combining projections.

$$M = \frac{1}{N} \sum_{i=1}^N X_i \quad (1)$$

where M is the models ensemble mean, N is the number of models, and X_i is the output from the i -th model.

To address any residual bias in these climate predictions and ensure accuracy at the watershed scale for hydrological modeling, bias-correction (BC) procedures were employed. In this study, future precipitation and temperature data were corrected for bias using the quantile mapping (QM) method. QM has been demonstrated to be more effective than other BC techniques that only adjust mean or variance, making it suitable for analyzing extremes [26], hydrological modeling [27], and water quality assessments [28]. The effectiveness of BC may vary depending on the area. Chen et al. [29], for example, examined the performance of BC in ten river basins across North America. They noted that incorporating bias-corrected variables into hydrological modeling introduces an additional layer of uncertainty to the already uncertain climate data. Teng et al. [30] employed two conceptual lumped daily rainfall–runoff models and compared four BC methods across eight watersheds in southeastern Australia. Yang et al. [31] assessed distribution-based scaling against the delta change method across several river basins in Sweden using the HBV model. Regardless of the hydrological model used, distribution-based BC methods such as QM were deemed more effective than those based on mean and variance corrections in these studies. This was consistent with research that directly compared how BC affected hydroclimatic variables [32,33].

In the basic QM method, the cumulative distribution function (CDF) of the simulated time series is matched to the CDF of the observation time series. Both parametric and non-parametric methods, based on empirical distributions, were developed in the literature [34]. However, Gudmundsson et al. [35] found that non-parametric transformations are preferable to parametric distribution-derived transformations, as non-parametric methods are more effective in systematically reducing biases. A disadvantage of these methods is that a purely empirical approach is prone to either overfitting or underfitting, particularly with small sample sizes in observations. In simulations, the uncertainty from fitting is generally smaller than the uncertainty arising from the models and scenarios themselves.

2.2.3. SWAT Model Setup Simulation and Validation

Model Setup and Simulation

The SWAT model, developed by Arnold et al. [20], is a continuous, spatial, and daily time-step and semi-distributed hydrological model [36]. It was initially intended to evaluate the climate change impacts on and land management strategies for watershed hydrology in vast, complicated watersheds over a long period of time [20]. Although developed and calibrated in a distinct climatic zone, it has been successfully applied in a number of locations worldwide, including the Mediterranean [2–7]. Furthermore, a lot of testing and calibration has been performed to make sure the model is trustworthy in predicting water stress and vegetation response under different circumstances. Previous studies have used SWAT to evaluate the consequences of climate change scenarios and look at adaptive management techniques to lessen the effects of climate change [6,7]. However, it is crucial to remember that the model precision and capacity to simulate different future scenarios depend on the availability and quality of the input data, including climate projections, land

management techniques, and hypotheses about how hydrological processes may change in response to climate change.

On a watershed scale, SWAT simulates a number of characteristics, including stream-flow, sediment loss transport, and nutrient flow. By creating a digital basin for discharge simulation, the SWAT employs a digital elevation model (DEM). The watershed is then divided into distinct sub-basins, which are then further subdivided into hydrologic response units (HRUs) depending on a range of factors, including land use, soil characteristics, terrain, and management strategies. The SCS Curve Number (SCS-CN) approach or the Green and Ampt infiltration equation are two methods SWAT uses to model various hydrologic processes, including surface runoff. The Priestley–Taylor and Penman–Monteith methods, among others, are alternate procedures that SWAT uses to simulate evapotranspiration.

The Generalized Likelihood Uncertainty Estimation (GLUE) approach [37] was used to estimate uncertainty and calibrate the SWAT model parameters for the Siliana catchment, as has been done in other studies [38–40]. The GLUE method operates on the idea that there is not just one perfect set of parameters to describe a watershed's hydrology. Instead, many different sets of parameters can be valid. This concept is known as equifinality [41]. In the GLUE method, the model is run using a range of parameter values that are randomly picked from their possible ranges. The performance of the model is then checked against actual observations using a likelihood function. By setting a threshold for this function, we can identify which parameter sets are acceptable. The uncertainty in the model's predictions is then assessed based on the results from these acceptable simulations. Calibration was carried out from 1995 to 2005. The simulations closely match the trend and variability of the measured discharge, though they slightly overestimate peak flows. Out of over 6000 GLUE runs, 77% of the behavioral simulations had a Nash coefficient greater than 0.5. Additionally, 67.7% of the observed discharge fell within the 95PPU. The r-factor, indicating the thickness of the 95PPU, is 1. More information about the model set-up and calibration were outlined in El Ghouli et al. [41].

The current study's primary goal was to assess the hydrological implications of climate change while only considering uncertainty related to climate models. Hence, hydrological parameter uncertainty was not taken into consideration. The parameter set that best suited the NS criteria in the study of El Ghouli et al. [41] was therefore chosen as the reference parameter set. SWAT was then compelled to act by an ensemble of four climate model projections for the reference and future eras.

2.2.4. Hydrologic Indicators

Changes in watershed flow regimes between the reference and future periods can be assessed using a wide range of current hydrologic indicators [42,43]. However, no single set of hydrologic indicators is specifically recommended for studying the effects of climate change. The selection of indicators depends on the study's objectives, the available data, and the hydrological characteristics of the location. These indicators should capture the range of hydrologic processes related to watershed flow responses, such as water balance, frequency, timing, and flow magnitude. In this study, a comprehensive set of indicators was evaluated.

The N-day minima and maxima approach was examined as the first indicator in this study. It refers to the minimum and maximum flows recorded over a continuous N-day period. This method is essential for understanding variability and extremes in hydrological events. By analyzing different durations (N days), both short-term and long-term hydrological events can be characterized. Shorter durations are generally associated with high-flow occurrences or flash floods, whereas longer durations could signify prolonged wet or dry spells. In our study, we analyzed 1-day, 30-day, and 90-day minima and maxima. For dry days, we set a threshold of 0 mm, excluding small amounts of rainfall from consideration.

The Flow Duration Curve (FDC) was used as another hydrologic indicator, illustrating the proportion of time that a daily or monthly streamflow is exceeded during a specific period [44]. Extreme events can be identified from the FDC as high flows (Q10) and low

flows ($>Q_{70}$) from different segments of the curve. These extreme events are crucial for various hydrological services, as they help predict both the frequency of flood flows and severe rainfall events or storms. Low flows, however, must be modeled locally, as they are influenced by several local factors, including soil characteristics, geology, regional climate patterns, and aquifer hydraulic properties.

The study used the FDC method to explore in greater detail the changes in extreme flows by analyzing 27 years of daily discharge simulations.

Many studies use drought indicators to measure a region's dryness. These indicators offer a numerical assessment of climatic conditions by accounting for drought intensity, duration, and severity. Drought indicators have two main functions: monitoring and early warning as well as evaluating the vulnerability of various systems to drought. Vicente-Serrano et al. [45] proposed a climatic drought index: The SPEI is derived from variations in the water balance resulting from climatic factors (precipitation minus potential evapotranspiration).

The variables used to calculate SPEI in this study were the difference between precipitation (P) and potential evapotranspiration (PET) simulated by SWAT model using the Penman–Monteith method:

$$Di = Pi - PETi \quad (2)$$

where Di is the monthly difference (mm/month) for month i ; Pi is the total monthly precipitation (mm/month); and $PETi$ is the total monthly potential evapotranspiration (mm/month).

The difference Di offers a straightforward measure of water surplus or deficit for the month under analysis. Subsequently, it is considered that D follows log-logistic distribution following Singh et al. [46]:

$$f(D) = \frac{\beta}{\alpha} \left(\frac{D - \gamma}{\alpha} \right)^{\beta-1} * \left(1 + \left(\frac{D - \gamma}{\alpha} \right)^{\beta} \right)^{-2} \quad (3)$$

where α , β , and γ represent the scale, shape, and origin parameters, respectively, for D values within the specified range ($\gamma < D < \infty$).

Parameters of the log-logistic distribution can be obtained following different procedures. Among them, the Probability-Weighted Moments (PWMs) procedure is a robust and easy approach [46]. The PWMs of order s are calculated as follows:

$$w_s = \frac{1}{N} \sum_{i=1}^N (1 - F_i)^s D_i \quad (4)$$

where F_i is a plotting position estimator; it represents the Landwehr empirical probability used by various researches [47,48] and is calculated as follows:

$$F_i = \frac{i - 0.35}{N} \quad (5)$$

where i is the range of observations arranged in increasing order, and N is the number of data points.

The parameters of the log-logistic distribution are then obtained as follows:

$$\beta = (2w_1 - w_0) / (6w_1 - w_0 - 36w_2) \quad (6)$$

$$\alpha = \frac{(w_0 - 2w_1)\beta}{\Gamma\left(1 + \frac{1}{\beta}\right)\Gamma\left(1 - \frac{1}{\beta}\right)} \quad (7)$$

$$\gamma = w_0 - \alpha\Gamma\left(1 + \frac{1}{\beta}\right)\Gamma\left(1 - \frac{1}{\beta}\right) \quad (8)$$

The cumulative probability distribution function of the D series, adhering to the log-logistic distribution, is expressed as follows Vicente-Serrano et al. [45]:

$$F(D) = \left[1 + \left(\frac{\alpha}{D - \gamma} \right)^\beta \right]^{-1} \quad (9)$$

Using $F(D)$, the SPEI can be readily derived by standardizing the values of $F(D)$, and this represents the frequency factor characteristic of the normal distribution [49,50].

$$\text{SPEI} = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3} \quad (10)$$

where

$$W = \sqrt{-2\ln(P)}, \quad (11)$$

for $P \leq 0.5$, where P represents the probability of surpassing a specified D value:

$$P = 1 - F(D) \quad (12)$$

If $P > 0.5$, it is substituted with $1 - P$, thereby reversing the sign of the resulting SPEI. The constants involved are $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$.

The SPEI indicator can characterize drought events by detailing their severity, duration, intensity, probability, and return period, offering insights into drought exposure. The previously mentioned SPEI calculation method incorporates both temperature and precipitation data, enabling it to account for temperature variability when assessing drought severity. A drought event is defined as a period with negative SPEI values [51]. To assess the drought's length and severity, a threshold must be set. The SPEI remains consistently negative throughout the drought duration (DD), which starts when the SPEI reaches -1 and ends when it turns positive. Drought severity is calculated as the sum of SPEI values over the duration, as outlined in Equation (12).

$$S = -\sum_{i=1}^{DD} \text{SPEI}_i \quad (13)$$

The intensity (I) of drought refers to the severity of drought conditions, typically quantified by the relationship between drought severity and its duration. It is a measure of how severe the moisture deficit is over a specific period. The formula used to calculate drought intensity was regarded as the proportion of drought severity to its duration.

$$I = \frac{S}{DD} \quad (14)$$

Other features of drought were assessed using the SPEI classification method proposed by McKee et al. [52], as presented in Table 3.

Table 3. Classification of SPEI by McKee et al. [52].

SPEI Values	
+2	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.0 to −1.49	Moderately dry
−1.5 to −1.99	Severely dry
−2 and less	Extremely dry

In this study, we chose to use daily time intervals for analyzing flow extremes and monthly time steps for projected change in the water balance indicator and drought analysis.

3. Results

3.1. Climate Models Evaluation

The results, which show how the climate model data were evaluated against local climate observations of monthly precipitation and temperature for the reference period (1979–2005) in the Siliana watershed, are presented in Figure 3. The results show that most of the measured precipitation falls within the climate model projected range between the 25th and 75th percentiles. This demonstrates their ability to accurately reproduce the volume, monthly variability, and seasonality of real precipitation.

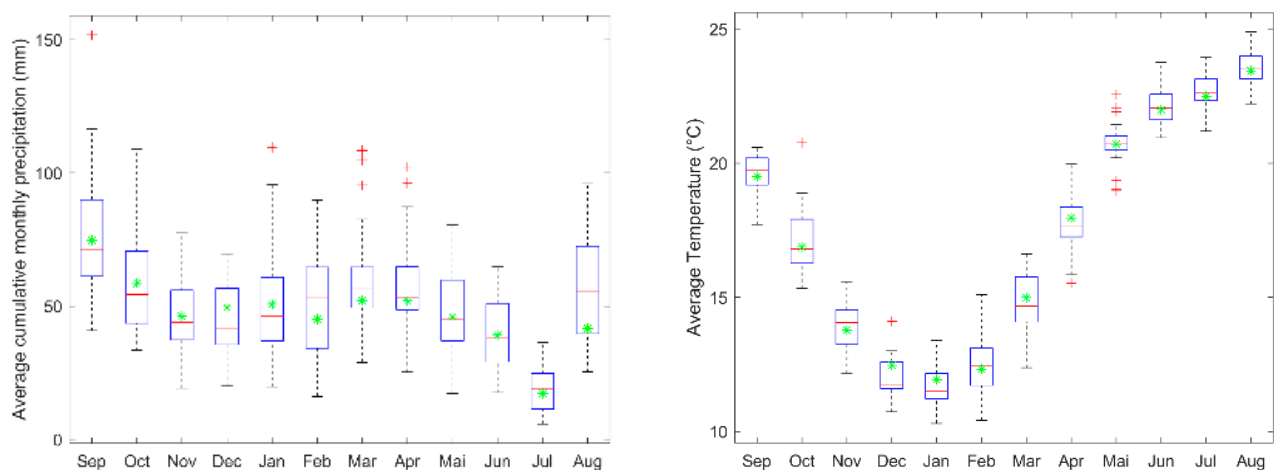


Figure 3. Comparison of observed data with climate model ensemble predictions for monthly precipitation and temperature in the Siliana watershed. The boxplots represent the predictions from the climate model ensemble, with the central line indicating the median and the edges of the box denoting the 25th and 75th percentiles. The green dots signify the observed data. The red + signs represent the outliers.

The average annual recorded and simulated precipitation amounts are 580 mm and 540 mm, respectively. Additionally, the selected climate models effectively capture the amplitude and monthly variation of temperature during the reference period (Figure 3).

3.2. Projected Changes in Water Balance Indicators

Projected changes in the water balance indicator for the future period (2046–2072) were assessed by calculating the average relative deviation in monthly cumulative precipitation, monthly evapotranspiration, and monthly soil water content as well as the absolute change in monthly temperature compared to the reference period (1979–2005) using the climate multi-model ensemble (Figure 4).

Precipitation is expected to diminish by an average of -60% and -68% for the two scenarios of RCP4.5 and RCP8.5, respectively, in summer (JJA); -26% and -33% in autumn (SON); -20% and -24% in spring (MAM); and a slight increase in both scenarios in winter by 16% . Annually, this average projected decrease is likely to range between -25% and -30% , leading to an average cumulative annual precipitation between 454 and 426 mm in the 2070s in comparison to the reference mean value of 580 mm.

Temperature is expected to increase in the future scenario in comparison to the reference period. Temperature increase is likely to be greater in summer than in winter, with a monthly average increase by $3\text{ }^{\circ}\text{C}$ and $5\text{ }^{\circ}\text{C}$ according to scenarios RCP4.5 and RCP8.5, respectively. The projected pattern in climatic condition changes in the Siliana watershed agree with their wider trends over the Mediterranean basin as reported by numerous

studies [53–56]. In a study conducted in northern Tunisia, Dakhlaoui et al. [57] found that precipitation is projected to decrease by 8% under RCP4.5 and by 15% under RCP8.5 from 2040 to 2070 and will decline by -16% under RCP4.5 and -26% under RCP8.5 between 2070 and 2100.

According to Scoccimarro et al. [58], nearly all Mediterranean basins are likely to experience more extreme precipitation, with an increase of up to 30% in winter and a decrease of up to 20% in summer. In both the RCP4.5 and RCP8.5 scenarios, there is a clear trend toward reduced future discharge compared to the reference scenario (Figure 4). In the Siliana watershed, the projected decrease in reference monthly flow is expected to range from -36.5% to -63% during the wet season (October to April) and from -57.7% to -79% during the dry season (May to September) under the RCP4.5 and RCP8.5 scenarios, respectively. The average annual discharge is forecasted to decline by 44% under RCP4.5 and 69% under RCP8.5.

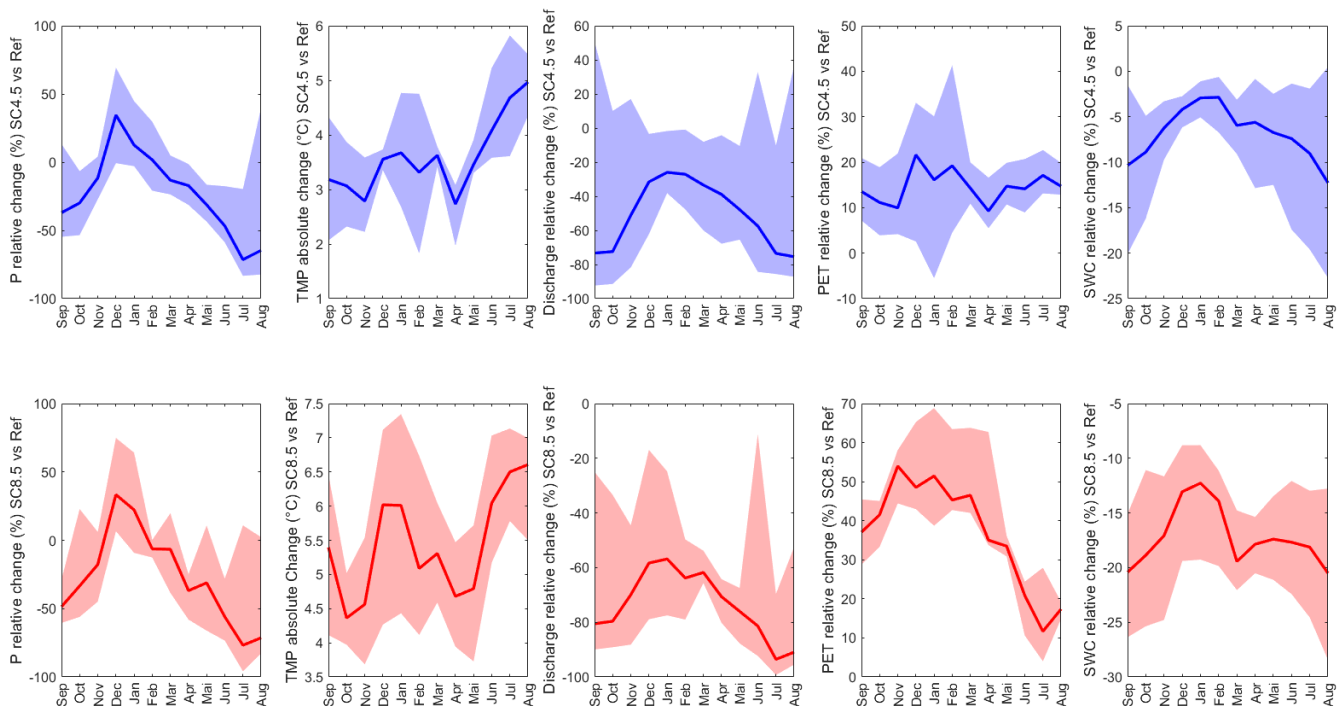


Figure 4. Anticipated change in water balance indicators (P, TMP, discharge, SWC, and PET) for the Siliana watershed. The blue and red shaded regions depict the uncertainty in the climate models, while the blue and red lines represent the ensemble mean for the climate models under RCP4.5 and RCP8.5, respectively.

For potential evapotranspiration, the models project increases of 14.5% and 45% during the wet season and 14.8% and 23.3% during the dry season under the RCP4.5 and RCP8.5 scenarios, respectively, compared to the reference scenario.

Soil water content is expected to reduce. The decrease will vary between -5.2% and -16.1% in the wet season and between -9.2% and -18.8% in the dry season under the RCP4.5 and RCP8.5 scenarios.

3.3. Flow Extremes Magnitude and Frequency

To study flow extremes, FDCs for the Siliana watershed were constructed based on 27-year daily discharge simulations. From these FDCs, high flows (with flow percentile above 70%) and low flows (with flow percentile below 10%) were extracted, with their associated frequency, duration, and their projected deviation, with respect to reference values, as well as their associated uncertainty reconstructed using climate model ensembles.

The results in Figure 5 show that the average deviation of high flows decreases by 6% under RCP4.5 and increases by 2% under RCP8.5. The maximum high flow peaks are $44 \text{ m}^3/\text{s}$ during the reference period, $48 \text{ m}^3/\text{s}$ under RCP4.5, and $52 \text{ m}^3/\text{s}$ under RCP8.5. While the high flow peak is projected to increase in the future, the duration of these high flows is expected to shorten, indicating more intense but shorter flood events. On average, high-flow duration decreases by 64% under RCP4.5 and by 60% under RCP8.5. The maximum duration of high flows is 8 days in the reference period, dropping to 5 days under RCP4.5 and 4 days under RCP8.5.

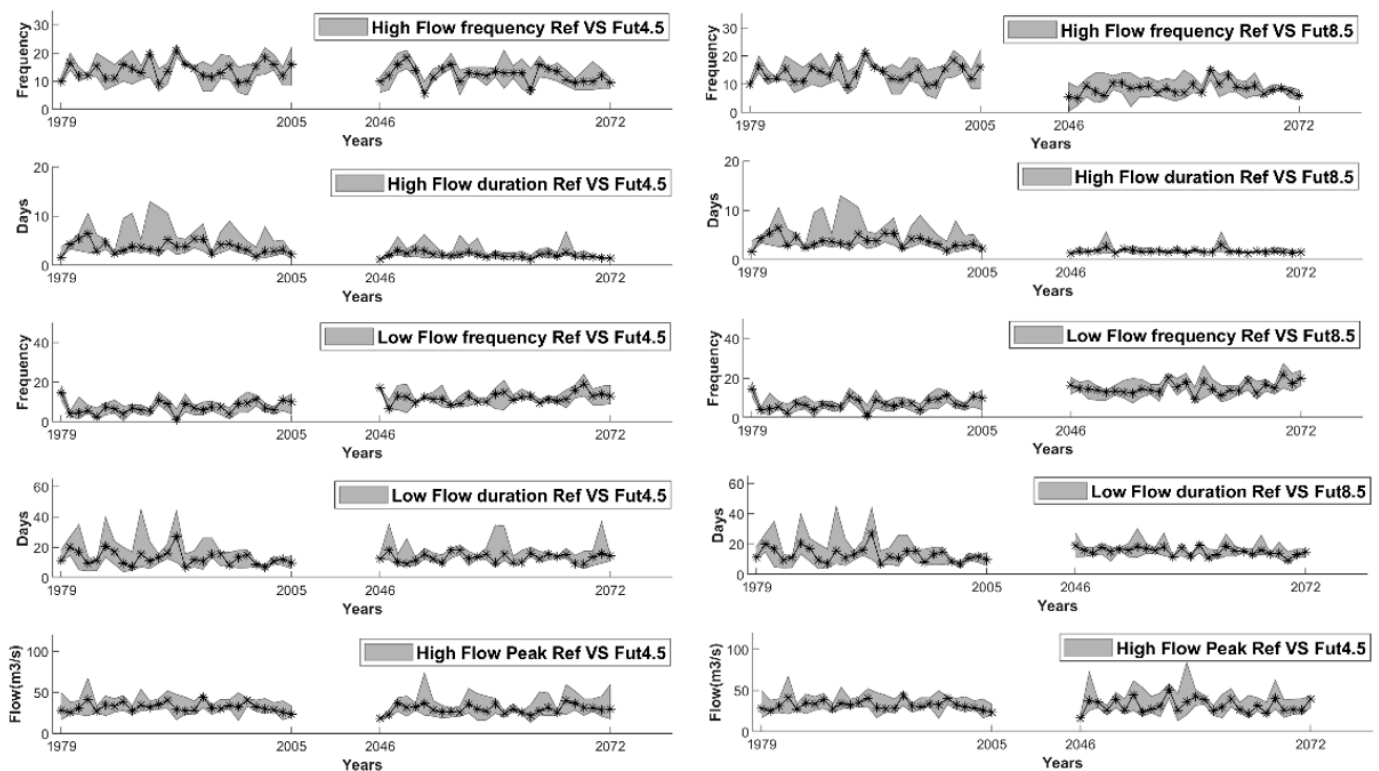


Figure 5. Projected hydrological indicators: high-flow frequency, high-flow duration, low-flow frequency, low-flow duration, and high flow under RCP4.5 (left) and RCP8.5 (right) versus reference indicators. The shaded gray area refers to CME uncertainty, and the black line with black stars refers to the CME mean.

Results show also that uncertainty in both projected scenarios decreased across various hydrological indicators, indicating that climate models predict similar future simulations and exhibit a consistent tendency to forecast the magnitude and frequency of flow extremes.

The high-flow frequency based on daily simulations will decrease in two projected scenarios. Results show that average deviation between reference and future scenarios will decrease by -11% under RCP4.5 and will decrease by -37% under RCP8.5. The frequency of low flows is expected to rise in both projected scenarios, with an average increase of 69% under RCP4.5 and 110% under RCP8.5. The duration of low flows, which is around 14 days during the reference period, is projected to be 15 days under both RCP4.5 and RCP8.5. In conclusion, we can infer that low-flow frequency will become higher for the whole year and will sustain for a longer time period, which may result in more severe hydrological droughts in the Siliana watershed.

These results are similar to the findings of Piras et al. [59], who projected an increase in low-flow days in the Rio Mannu Basin (Italy) due to a projected change in climate. Similar trends for low-flow conditions in the Merguellil watershed in Tunisia were also projected by Abouabdillah et al. [60]. Results suggest, therefore, that drier conditions

with notable reduction in average extremes in annual flow are likely to occur in the future period in the Siliana watershed. A reduction in high-flow duration is crucial for maintaining a healthy ecosystem and can adversely affect water availability for dams and water conservation structures.

3.4. Magnitude of Flow Extremes Duration

As projections indicate an increase in low flows in the Siliana watershed, particularly during droughts, we employed the N-day minima and maxima approach to examine changes in the magnitudes of flow extremes over various time-slice durations. These changes were derived from moving averages of daily SWAT simulations for each climate model, covering both reference and future periods. In this analysis, we specifically focused on annual maximum and minimum flow magnitudes for consecutive durations of 30 and 90 days.

The results, depicted in Figure 6, illuminate the shifts in flow magnitudes for the Siliana watershed.

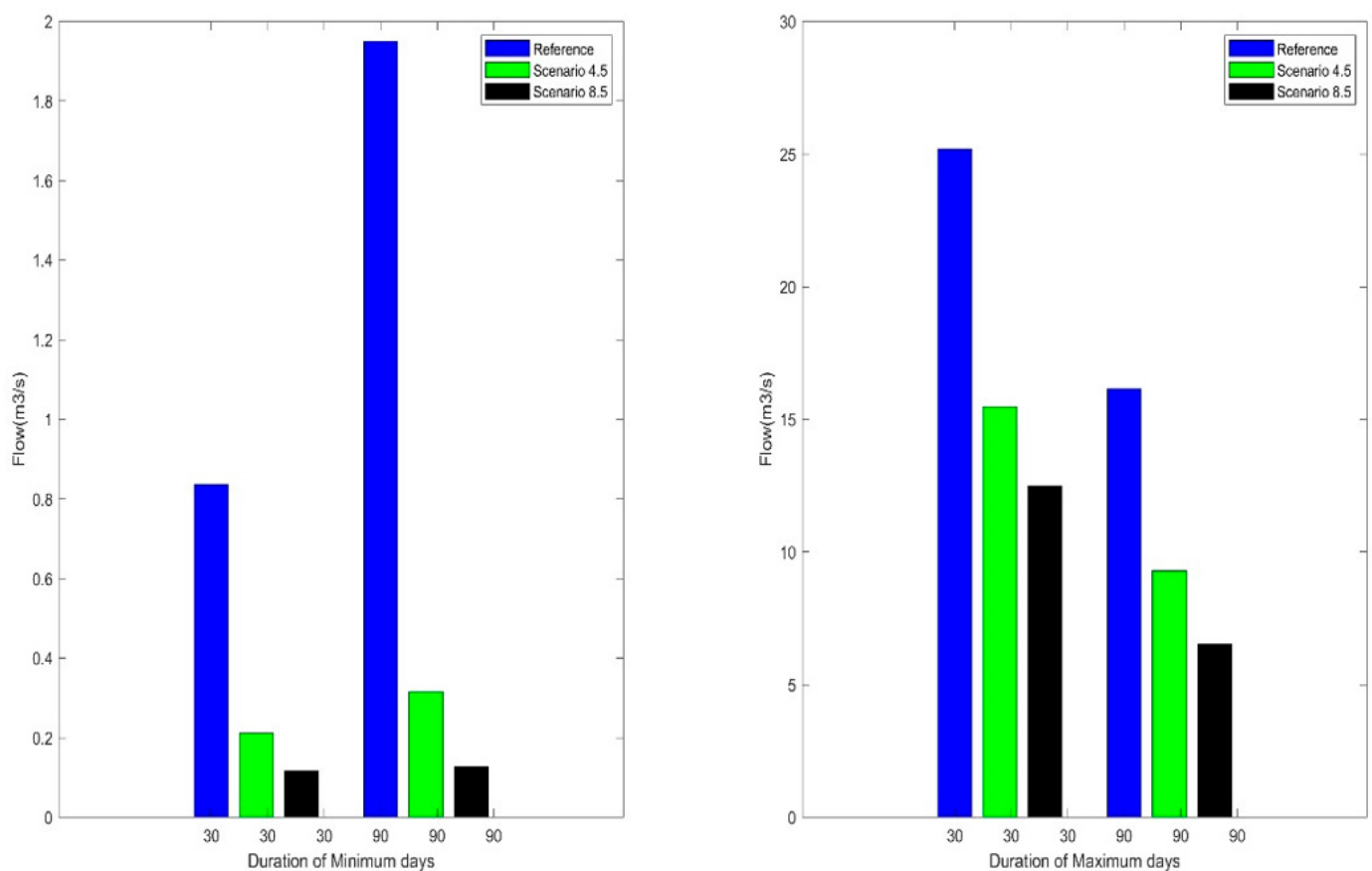


Figure 6. Changes in minimum (left) and maximum (right) flow extremes for various time durations for the Siliana watershed. Bars are for the climate models' ensemble mean, with blue color for the reference period, green color for the RCP4.5 scenario, and black color for the RCP8.5 scenario.

When comparing the reference period to the future period, a significant decline is observed in both the maximum and minimum flow magnitudes for different time durations. This decline is particularly pronounced for low flows, with the impact becoming more substantial as the flow duration increases (Figure 6). The 30-day minimum flow is projected to decrease by -74.8% and -86.1% in RCP4.5 and RCP8.5, respectively. The 90-day minimum flow is anticipated to decrease by -83.8% and 93.5% in RCP4.5 and RCP8.5, respectively.

For maximum flows, although the reduction is less intense compared to minimum flows, the most substantial decline in annual peak flow is anticipated for the 90-day

duration, with a reduction of 59.6% under RCP8.5. The changes in the magnitude of annual flow extremes durations align with the projected alterations in extreme flow magnitude and frequency, indicating a future characterized by drier conditions and a notable reduction in average annual flow extremes in Siliana watersheds.

The maximum and minimum flows play a crucial role in maintaining a healthy ecosystem and can adversely affect water availability for dams as well as their operational efficiency. For instance, the volume and timing of water releases from the Siliana dam for irrigation may be affected and may need to be adjusted in light of the expected decrease in annual flows. These factors are crucial not only for the effective management of water resources, including the operation of dams and drought and flood protection, but also for agriculture and the domestic and industrial sectors [61].

3.5. Timing of Flow Extremes

To investigate potential changes in the timing trends of annual flow extremes between the reference and future periods due to climatic changes in the Siliana watersheds, we performed an analysis that involved identifying the average Julian date of annual minimum and maximum flows over a 1-day duration, as forecasted by climate models. For example, in the reference scenario, the annual minimum flow for a single day in the Siliana watershed typically takes place from early June to late August. However, under future conditions, the same hydrological indicator is expected to shift, occurring between the beginning of June and late September for RCP4.5 and between the beginning of May and late September for RCP8.5. Furthermore, the variability in the Julian date of flow extremes in the future is likely to be as extensive as observed in the reference period, as indicated by the MME uncertainty (Figure 7).

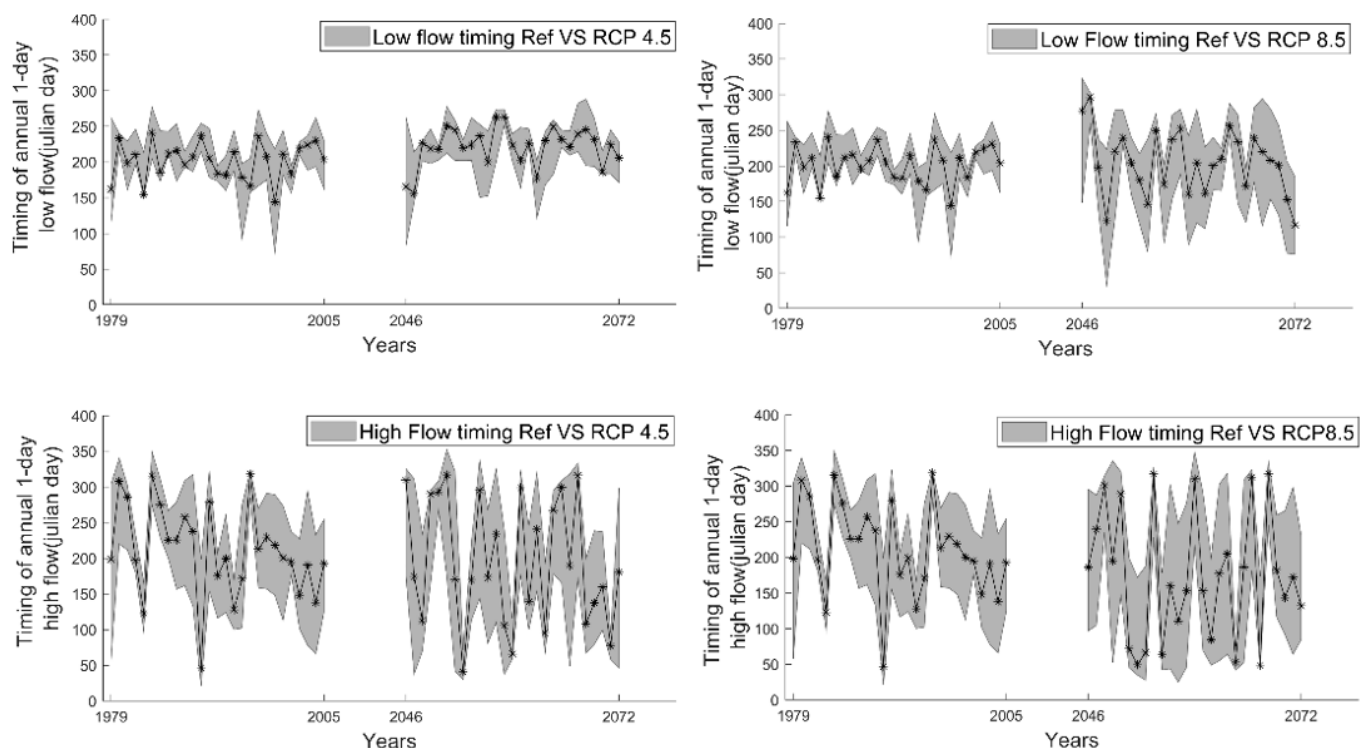


Figure 7. Variations in the yearly timing of 1-day minimum and maximum average annual flows for the Siliana watersheds. The shaded gray area illustrates the range of climate ensemble models in Julian days, while the black line with black stars signifies the average of the climate ensemble.

Notably, the largest uncertainty was recorded for the timing of annual 1-day maximum flows, both in the reference and future periods, aligning with the considerable uncertainty associated with projections of high flows. This uncertainty underscores the challenges in

precisely predicting the timing of extreme flow events, an aspect crucial for understanding and managing the impacts of hydrological changes in the Siliana watershed.

3.6. Drought Duration, Severity and Intensity

To evaluate the impact of drought and identify various characteristics such as duration, intensity, and severity, we utilized the meteorological drought indicator SPEI, which was calculated using daily data averaged over 12 months (Figure 8).

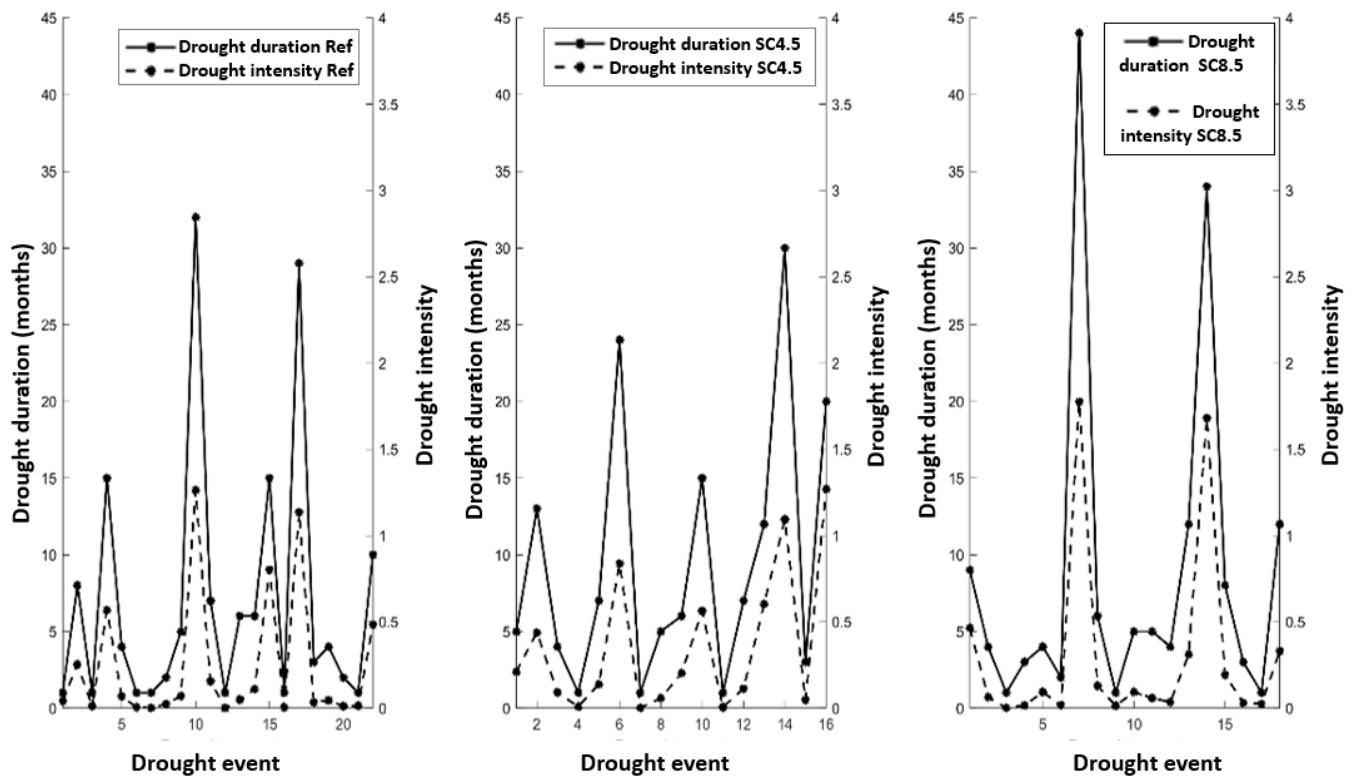


Figure 8. Drought duration and intensity in reference period (1979–2005) and future period (2046–2072) for different drought events.

The results indicate that both the duration and severity of drought are expected to rise. On average, the 27-year reference period recorded 22 events lasting 7 months with an intensity of 2. In contrast, under scenario 4.5, we anticipate 16 events with durations of 9.6 months, while scenario 8.5 predicts 16 events lasting 8.9 months, with intensities of 3.9 and 3.3, respectively. These findings suggest that the Siliana watershed will experience drier conditions. These findings demonstrate that it is projected that the Siliana watershed will experience drier conditions.

3.7. Spatial Variation of SPEI

The drought distribution in the Siliana watershed (Figure 9) shows both spatial and temporal variability. Drought conditions typically initiate in June, with July, August, October, and November being the driest months of the year. Notably, August is the month with the highest drought severity in both the reference and RCP8.5 scenarios.

In analyzing the spatial pattern based on the reference period, about 24% of the total surface area of the watershed experiences extreme drought, defined by SPEI values ranging from -1.5 to -2 . This extreme drought is mainly concentrated in the southwest and northern regions of the watershed. The remaining 76% of the total area experiences moderate drought conditions, with SPEI values between -1 and -1.5 .

In contrast, under the reference scenario, 15% of the total surface area experiences extreme drought, while the majority, 85%, encounters severe drought conditions. When

analyzed on an annual basis, the overall drought status for both scenarios is classified as normal.

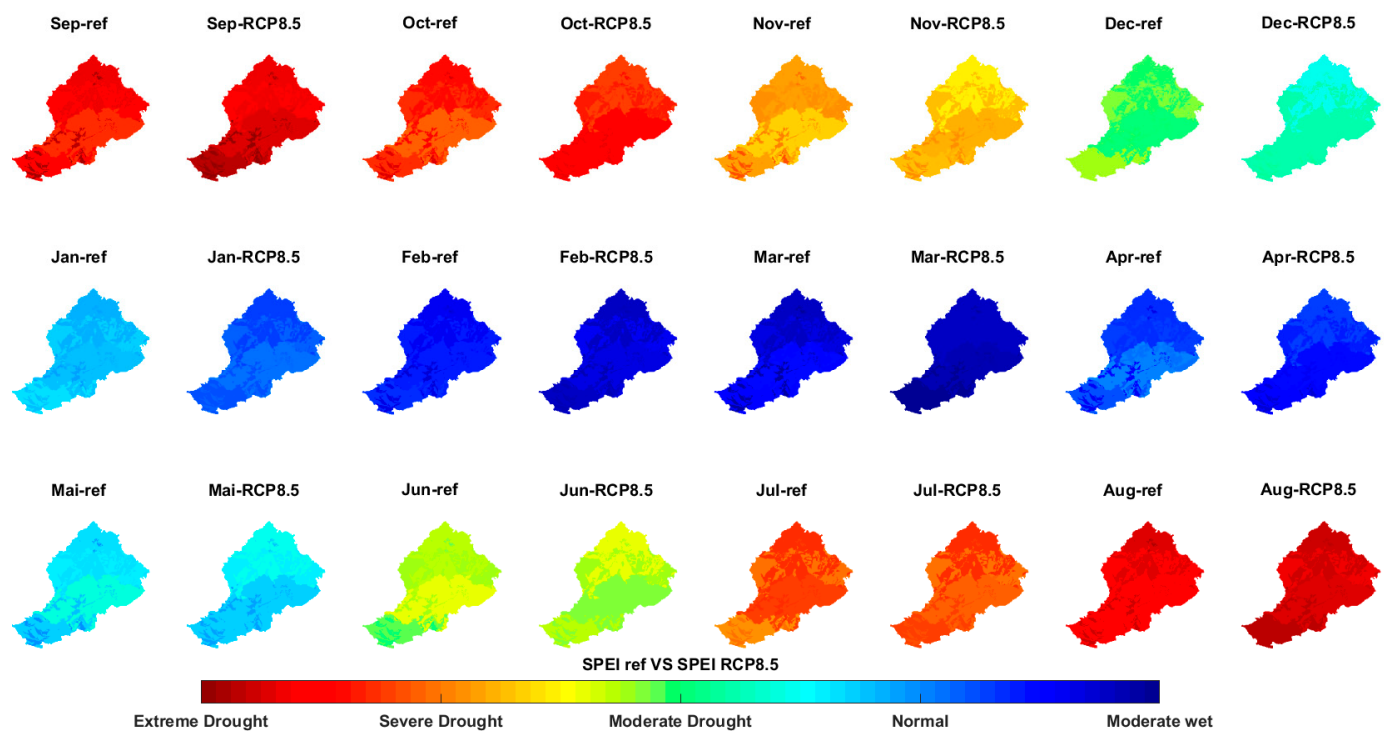


Figure 9. Spatial and temporal variation of SPEI values in the Siliana watershed.

This analysis offers valuable insights into the spatio-temporal dynamics of drought in the Siliana watershed, highlighting August as a crucial period for increased drought severity in both the reference and RCP8.5 scenarios.

4. Discussion

To create models that can predict the effects of climate change on watershed hydrology and various environmental factors, it is crucial to gather data from a variety of sources, including climatic data, land-use information, soil data, and recorded flow measurements. These models can then be utilized to inform water resource management based on the collected data. Improvements in the modeling of hydrological processes related to climate change are achieved when data from large-scale global climate models are downscaled to finer scales, resulting in predictions that are more applicable to local conditions. The quality of climatic data is a vital consideration in hydrologic model development, as low-quality data can introduce uncertainty into the models. Therefore, when implementing in this study the hydrological SWAT model, the quality of the climate data is of utmost importance. This study focused on the anticipated alterations in water balance metrics and climatic conditions from the reference period of 1979–2005 to the future timeframe of 2046–2072, based on the RCP4.5 and RCP8.5 emission scenarios. Numerous uncertainties may arise when translating climate change scenarios into their potential impacts on natural resources. To reduce this uncertainty, we used an ensemble set of downscaled climate scenarios to assess the impacts on the hydrology of the Siliana watershed. Using such an approach, the climate change signal varies across different GCM-RCM combinations. Despite this variability, all GCM-RCMs consistently portray a future climate characterized by higher temperatures, and nearly all climate models anticipate drier conditions ahead. Research shows variations in model projections for rainfall, while there is generally broad consensus on temperature increases [62]. In certain major river basins, including the Nile, Niger, Mississippi, and Amazon, precipitation projections show distinct trends [63]. Additionally,

it was noted that even a minor increase in global temperature can have a considerable effect on all components of the flow regime in almost all basins. However, this effect is frequently overshadowed by the uncertainty linked to GCMs, especially concerning rainfall.

In the current study, projected precipitation tends to decrease and is associated with greater uncertainty, especially during wet periods. Compared to precipitation, temperature variations within the watershed are associated with uncertainties that are consistent during both wet and dry seasons in contrast to precipitation. This result is consistent with numerous studies carried out in the Mediterranean Basin [2,64,65] and, in particular, research conducted in Tunisia watersheds. For example, Moussa et al. [66] analyzed the anticipated changes in precipitation and temperature in the Siliana watershed using a set of seven combinations of GCMs and RCMs obtained from the EU-FP6 ENSEMBLES project. They found that precipitation is anticipated to decline during the winter months by 10% to 20%, whereas summer months are projected to experience changes ranging from an increase of 30% to a decrease of 20%. Meanwhile, autumn precipitation appears to remain comparable to the reference values. The average monthly temperature in the reference value will increase by a range of +0.9 to +5 °C.

Because of the high degree of uncertainty surrounding climate model projections, it is crucial to consider multi-model ensembles when determining long-term mean change projections and characterizing the uncertainty surrounding the implications of climate change. Nevertheless, the projected uncertainty ranges on hydrological properties could be considered as underestimated because the study disregarded the uncertainty of the hydrological model.

The results of the study are in line with previous research that has recommended using a multi-model ensemble approach to more accurately describe uncertainty and provide an efficient long-term ensemble mean projection [24,25]. However, it is essential to examine hydrologic indicators that can reflect the different aspects of a flow regime when assessing the impact of climate change on a specific region.

The future flow, SWC, and PET were investigated in the current study. A strong positive correlation coefficient of 0.68 and 0.72 exist between expected rainfall and flow under the 4.5 and 8.5 scenarios, respectively, proving that the Siliana watershed flow will be significantly impacted by reduced rainfall. In our study, it is projected that the average annual discharge will decrease by 44% under the RCP4.5 scenario and by 69% under the RCP8.5 scenario. Therefore, the study findings are consistent with previous research forecasts. For example, De Girolamo et al. [67] indicated that mean annual flow will decline by up to 39% compared to the historical period in a watershed in southern Italy.

Seasonal SWC is projected to decline between −5.2% and −16.1% during winter season and between −9.2% and −18.8% during summer season under the RCP4.5 and RCP8.5 scenarios, respectively (Figure 4). These findings are in line with the studies of Kovats et al. [68] and Niang et al. [69], who reported more a significant reduction in SWC during the summer season over southern Europe and north Africa.

The study findings are consistent with previous research. In Southern Europe and North Africa, the recharge of groundwater and the soil moisture content will consequently decline, especially during summer [68,69]. The study by Grillakis et al. [70] indicated a reduction in future soil moisture for Europe under RCP2.6 and RCP6.0 scenarios.

Evapotranspiration is also crucial for the water balance, particularly in the Mediterranean region, where it can account for as much as 90% of the annual rainfall [71]. Seasonally, it is anticipated that PET in the Siliana watershed will experience a significant increase, reaching up to 35% during the wet season under the RCP8.5 scenario. These study findings are consistent with previous predictions, including those made by Dakhlaoui et al. [57], who investigated PET projections in northern Tunisia. The results indicate an anticipated increase of 1.8% to 9.6% under the RCP4.5 scenario and 4.8% to 11% under the RCP8.5 scenario. These changes are predominantly forecasted for the summer months. Despite these PET variations, the study indicates that the impact on discharge is projected to be minimal, given the already low discharge levels during the summer.

Regarding significant alterations, anticipated changes in the Siliana watershed point towards a decrease in the frequency and magnitude of extreme flows in the future, as inferred from alterations in annual extreme flows. Water conservation initiatives and dam operations may be impacted by reductions in both the minimum and maximum flows on a yearly basis. For example, forthcoming decreases in annual flows may necessitate adjustments to the timing of water releases from the dams. The annual flow schedule is presented on a daily scale, facilitating a comprehensible and practical representation of annual flows. In terms of flow duration, the impact of lengthening the flow duration becomes more evident. The 90-day minimum is projected to undergo the most substantial reduction, with an average decrease of -59.6% . The results indicate a gradual decline in seasonal low flows, aligning with the extension of low duration. The extent of the reduction diminishes progressively with an increase in flow duration. The Siliana watershed area is supposed to experience a reduction in the occurrence and magnitude of severe flows in the future, reflecting the observed changes in annual flow extremes.

In a recent study, Blöschl et al. [72] highlighted that climate change in Europe has induced alterations in flood patterns, encompassing changes in magnitude, timing, and frequency. These researchers identified distinct regional patterns indicating both increases and decreases in river flood discharge across Europe over the last five decades, indicative of climate-induced shifts. In their study focused on the Candelaro Basin, including the Celone Sub-basin, Blöschl et al. [72] observed a negative rate of change in the mean annual flood discharge (the highest peak discharge recorded in each calendar year) per decade, ranging from -12 to -24% . The present study yielded similar findings, revealing a reduction in the 1-day maximum flow recorded over the past decades.

The findings clearly indicate a shift towards drier conditions, characterized by a general decrease in streamflow and an extension of the dry period. These conclusions are corroborated by several studies conducted in basins within the Mediterranean climate. Brouziyne et al. [24] identified an extension of the dry period in the future climate pattern, quantifying it to be approximately 10 days (2035–2050) in the Bouregreg Basin (Morocco). Abouabdillah et al. [53] forecasted a notable decline in annual maximum streamflow values across different durations in the Merguellil Basin (Tunisia) for both the near future (2010–2039) and the distant future (2070–2099). In the Koiliaris River (Greece), Nerantzaki et al. [73] noted a rise in the frequency of extremely low flows over time, coupled with a decrease in spring streamflow in both the near and far future. Fonseca and Santos [74] assessed a reduction in annual mean streamflow by 18–28% under future climate scenarios (2021–2100) in the Tamega River Basin (Portugal) relative to historical data from 1950 to 2015.

5. Conclusions

Robust projections about changes in river flow characteristics in the future are crucial for effective local and regional adaptation to the effects of climate changes in the hydrology of Mediterranean watersheds. In the present study, the impact of climate change on river flow characteristics in the Siliana Basin was analyzed using the hydrological SWAT model, which was driven by outputs from an ensemble of eight climate models. Changes in key hydrological variables related to watershed water balance, flow magnitudes, extremes, drought duration, and timing were examined between a reference period (1979–2005) and a future period (2046–2072), along with an assessment of their associated uncertainty. All projections indicated that the Siliana watershed is expected to experience hotter and drier conditions in the future. Future hydrological droughts may become more severe, as low-flow events are expected to occur more frequently, while the number of flow days is anticipated to decrease. However, the significant uncertainty associated with these projections highlights the importance of using a multi-model ensemble when estimating long-term mean changes and understanding the uncertainties related to climate change impacts. The calculated uncertainty ranges may be underestimated since the study did not account for the uncertainty in the hydrological model. Despite this uncertainty, assessments

indicate that climate change will adversely affect most hydrological indicators in the Siliana watershed. Therefore, future research should focus on conducting additional quantitative analyses of these effects, integrating uncertainties from both hydrological and climate models and taking into account the characteristics and physical properties of the watershed's flow regime. This approach is particularly crucial for developing effective climate change mitigation strategies in Mediterranean watersheds, where local variations in hydrological processes, meteorological conditions, and human impacts are present.

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