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Climate change impacts on the hydrological behaviour of watershed in northeastern Tunisia (Oued El Abid watershed)

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Abstract

Climate change significantly impacts watershed hydrology, altering water supplies, natural disasters, and eco-hydrologic processes. These effects vary geographically, with some regions facing severe droughts while others experience increased precipitation and flooding. Climate change influences atmospheric evaporation demand, precipitation patterns, vegetation composition, streamflow characteristics, and groundwater dynamics. The temperature increases and rainfall changes in some watersheds can lead to increased potential evapotranspiration and decreased streamflow and soil water. Flood frequency analyses indicate an overall increasing trend in the latter half of the 21st century.

The Oued El Abid catchment area, as like all catchments in northern Tunisia, is likely to be subject to major climatic and hydrological variations as a result of climate change. Advanced hydrological modelling using the HBV-Light model was set up to simulate current conditions and future scenarios based on Afric-Cordex climate models. The model demonstrates robust performance, achieving Nash-Sutcliffe Efficiency (NSE) values of 0.71 in calibration (1972-1992), and 0.66 in validation from 1993-2001.

This climate change has a direct effect on the hydrological projections, which reveal significant changes, with annual flow reductions ranging from 35% to 43%, with more severe impacts under the RCP8.5 scenario for 2069-2099. Spring and summer seasons are particularly vulnerable, showing flow decreases of up to 68% and over 40%, respectively, extreme monthly variability is projected, reaching 88% reduction in July under RCP8.5.

This research provides important results for water resource managers, highlighting the necessity of long-term planning and sustainable water management practices in the face of climate change.

Keywords: Afric-Cordex models; Climate change; Future projections; HBV-Light model; Northern Tunisia

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1. Introduction

Climate change significantly impacts hydrology by altering the hydrological cycle, leading to more intense and frequent extreme precipitation events. Climate change results in decreased precipitation, increased temperatures, reduced surface runoff, groundwater, and water yield, ultimately leading to a decline in annual flow and potential water scarcity.

Climate change significantly impacts watershed hydrology, affecting various aspects such as temperature, precipitation patterns, evaporation, and stream flow characteristics [1]. These changes can lead to water shortages, altered land use, and degraded water quality in Mediterranean ecosystems [2].

Watershed modeling tools are crucial for assessing impacts and developing mitigation strategies [3]. Combined climate and land use changes can intensify the water cycle, increase surface runoff and stream discharge, and introduce seasonal variations in watershed systems [4]. Understanding these dynamic changes is essential for developing effective mitigation and adaptation strategies.

Climate change poses significant threats to water resources in Tunisia, particularly in arid and semi-arid regions. Rising temperatures and decreasing precipitation are expected to exacerbate water scarcity [5, 6].

The Medjerda River Basin, shared between Tunisia and Algeria, is projected to face increased water demands and shortages by 2050, affecting vital sectors and groundwater storage [7].

The Cap Bon region in Tunisia faces significant challenges in water resource management due to increasing demand from agriculture, tourism, and domestic use [8]. The area's water footprint is predominantly green (85%), with blue water accounting for 15% [9].

Groundwater resources are under pressure from overexploitation, leading to marine intrusion in coastal aquifers [10]. Modeling studies have shown that continued pumping could result in drawdowns of 4-5 meters below sea level within 14 years, reversing the hydraulic gradient [11]. To address these issues, researchers recommend integrated water resource management, considering water not only as an economic resource but also as an essential environmental component [8]. Improved strategies for water resources development and management are crucial to protect surface and groundwater from quality and quantity deterioration [11].

The aim of this article is therefore to analyse the impact of climate change on the hydrology of the Oued Abid catchment in Cap-Bon, north-east Tunisia. After analysing historical data for the region, hydrological modelling is performed using HBV hydrological model.

The future precipitation and temperature were collected from the outputs of the CCMA-CanESM2, CSIRO-RCA4, NOAA-RCA4, ICHEC-REMO2009, MIROC-RCA4, MPI-REMO2009, ensemble models of the Coordinated Regional Climate Downscaling Experiment (Cordex-Africa). The bias correction was carried out using the Distribution Mapping for Precipitation and temperature method (DM). These data were introduced to HBV hydrological model to assess the impact of climate change on the future hydrological response of the Oued El Abid Catchment, under two Representative Concentration Pathway (RCP) RCP 4.5 and RCP 8.5.

2. Material and method

2.1. Study area and database

The Cap Bon region, situated in the northeast of Tunisia, spans approximately 2840 km², which is about 1.8% of the country's total area [8]. The study area is located in North-East Tunisia (36° 27′N, 10° 44′ E), the study area occupied 2.825 km².

The Cap Bon has a semi-arid Mediterranean climate with warm season, proven by the study of [12], showed that this study area has a semi-arid climate with an average annual precipitation of 600 mm and temperature show a significant warming trend in annual temperature, with magnitudes equal to 0.065 and 0.045 °C/year. The annual reference evapotranspiration exceeds 1100 mm.

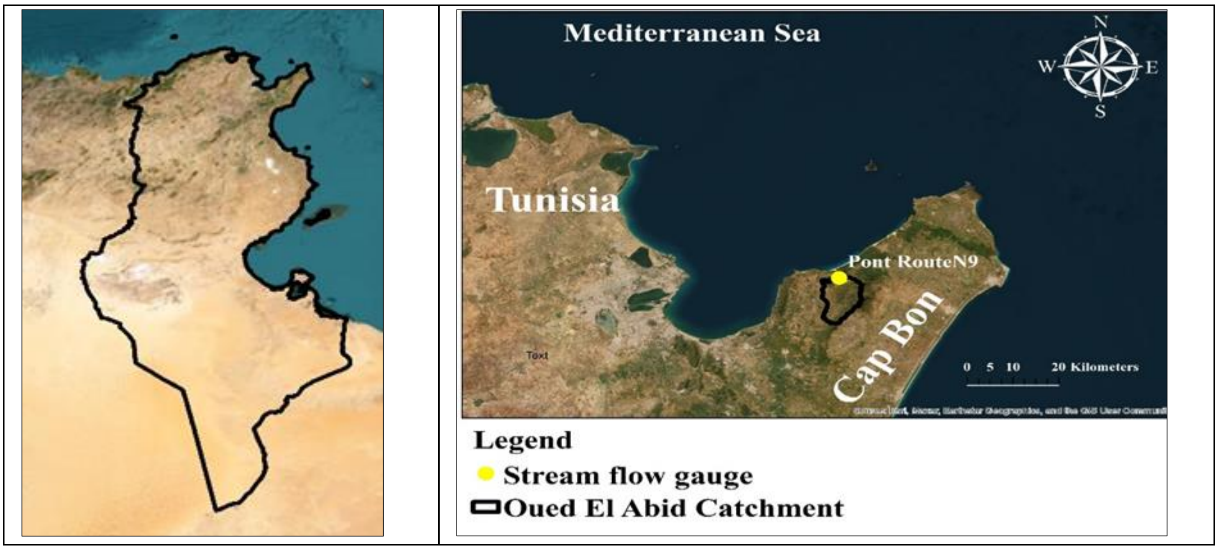


Figure 1 Location map of Oued El Abid Catchment

To achieve the objective of our study a set of climatic data (precipitation and temperature) were collected from INM (National Meteorological Institute), available on a daily scale during the observed period from 1971-2001.

The hydrometric data used in this study correspond to Pont Route gauging station (Figure1), which was collected from the General Direction of Water Resources, available on a daily scale during the observed period 1971-2001, the characteristics of Oued El Abid catchment are presented as following in the Table 1.

Table 1 The characteristics of Oued El Abid catchment

Catchment	Station name	Longitude (DD)	Latitude (DD)	Altitude (m)	Area (Km2)	Period of observation
Oued El Abid	Pont Route N9	10.66	36.86	10	81	1971-2001

DD: Decimal degree

To evaluate future flow projections for the Oued El Abid watershed, a multi-model ensemble (MME) method was applied using six regional climate models from the Afric-Cordex project (CCMA-CanESM2, CSIRO-RCA4, NOAA-RCA4, ICHEC-REMO2009, MIROC-RCA4, MPI-REMO2009) with 50km resolution, and corrected by distribution mapping (DM) method for the precipitation and temperature. This method consists of averaging the outputs from these six models to reduce individual model uncertainties and achieve more accurate projections.

2.2. HBV model

For the hydrological modelling of the Oued El Abid Catchment, the Hydrologiska Byråns Vattenbalansavdelning HBV-Light model (Figure 2), developed by the Swedish Meteorological and Hydrological Institute (SMHI) [13], is used.

The HBV-Light hydrological model, illustrats its four main routines. The Snow routine handles snowfall and melting processes using parameters like TT and CFMAX. Below this, the Soil routine is depicted as layered soil sections, modelling infiltration and evapotranspiration with parameters such as FC and BETA. The Groundwater routine is represented by subsurface reservoirs, simulating underground water storage and flow using parameters including K0, K1, K2, and PERC.

Finally, the Routing routine is shown at the watershed outlet, employing the MAXBAS parameter to convert runoff into streamflow. This representation demonstrates how the HBV-Light model simulates the entire hydrological cycle, from precipitation input to final outflow, by integrating key hydrological processes across different components of the watershed.

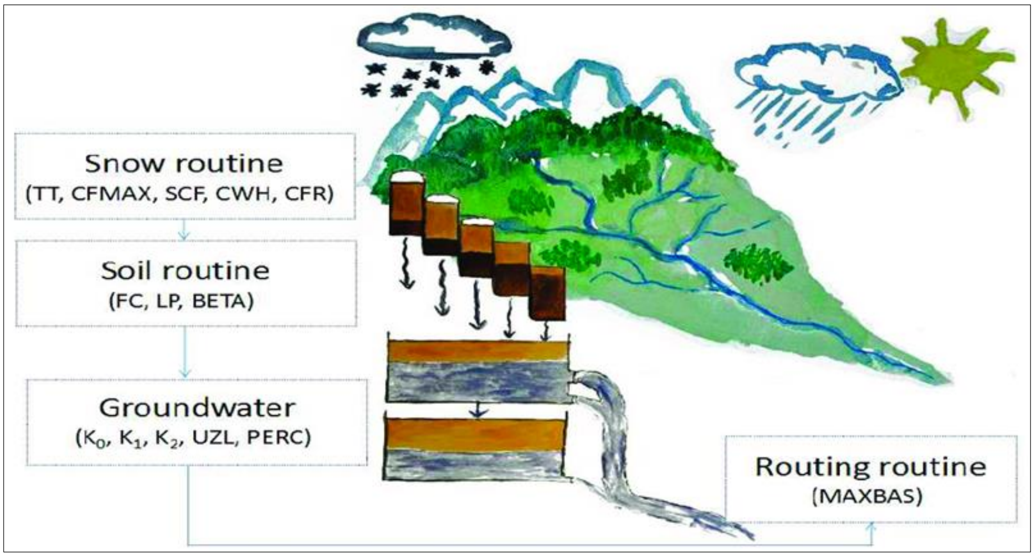


Figure 2 Schematic structure of HBV-light model [14]

This conceptual tool, applied to simulate daily flows, requires three main input parameters: precipitation, temperature, and potential evapotranspiration (ETP) at a daily time step. For potential evapotranspiration (ETP), the Oudin method [15] was applied, which considers the daily average air temperature and solar radiation and depends on the latitude and the 365 days of the year. It is defined by the following equation Eq1:

$$PE = \frac{\mathrm{ReTa+5}}{\gamma\rho * 100}, \mathrm{Ta} + 5 > 0, \mathrm{PE} = 0 \text{ ………….Eq 1}$$

Where:
PE: Potential Evapotranspiration (mm day^{-1}) ;
Re: Solar radiation, depending on latitude and Julian day (MJ m^{-2} day^{-1});
Ta: Daily average temperature (°C);
γ: Latent heat flux (2.45 MJ kg^{-1});
ρ: Water density (kg m^{-3}).

The model's efficiency, based on the Nash-Sutcliffe criterion [16], is defined by the following equation:

$$\mathrm{Nash} = 1 - \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs} - \bar{Q}_{obs})^2} \text{ ……………. Eq2}$$

With:

Q_{obs} Observed flows; Q_{sim} Simulated flows; $\bar{Q}_{obs}$ Observed mean flows, and n number of observations.

In this study, the HBV model was calibrated over the period 1972-1992 and validated over the period 1993-2001.

3. Results

3.1. Climate Projection for the Oued El Abid watershed

3.1.1. Rainfall projections

Under the RCP4.5 scenario (Table 2), annual precipitation is projected to decrease by 7% in the medium term (2039-2069) and 5% in the long term (2069-2099). March will have significant reductions of up to 34% by the end of the century.

About the RCP8.5 scenario (Table 2), annual rainfall will decrease more drastically, with a 10% reduction in the medium term and 17% in the long term. March and April will show an important decrease of about 30% and 41% respectively by 2099.

Table 2 Changes in annual and monthly rainfall projections for the Oued El Abid watershed (%)

	RCP4,5		**RCP8,5**	
	(2039-2069)	**(2069-2099)**	**(2039-2069)**	**(2069-2099)**
Annual	-7%	-5%	-10%	-17%
January	-17%	-18%	-16%	-15%
February	7%	15%	-9%	-6%
March	-27%	-34%	-28%	-33%
April	-23%	-19%	-22%	-41%
May	-8%	-11%	-3%	-26%
June	33%	74%	48%	29%
July	70%	77%	17%	30%
August	-35%	-18%	-20%	-25%
September	-14%	0%	-8%	-17%
October	-2%	16%	8%	1%
November	-2%	-9%	-19%	-20%
December	8%	-4%	-2%	-19%

Rainfall projections reveal significant changes across seasons under the RCP4.5 and RCP8.5 scenarios (Figure 3).

In winter, rainfall is expected to decrease, with reductions of 2% to 4% under RCP4.5 and more substantial declines of 9% to 14% under RCP8.5. Spring shows a severe reduction in rainfall, with decreases of 22% to 24% under RCP4.5 and an even greater reduction of 21% to 34% under RCP8.5. Summer rainfall shows a decrease of 5% for the medium term under RCP4.5, but an increase of 18% in the long term, while RCP8.5 shows a medium-term increase of 3% and a long-term decrease of 4%. In autumn, rainfall is projected to decline by 6% to 12% under RCP8.5 for the long term.

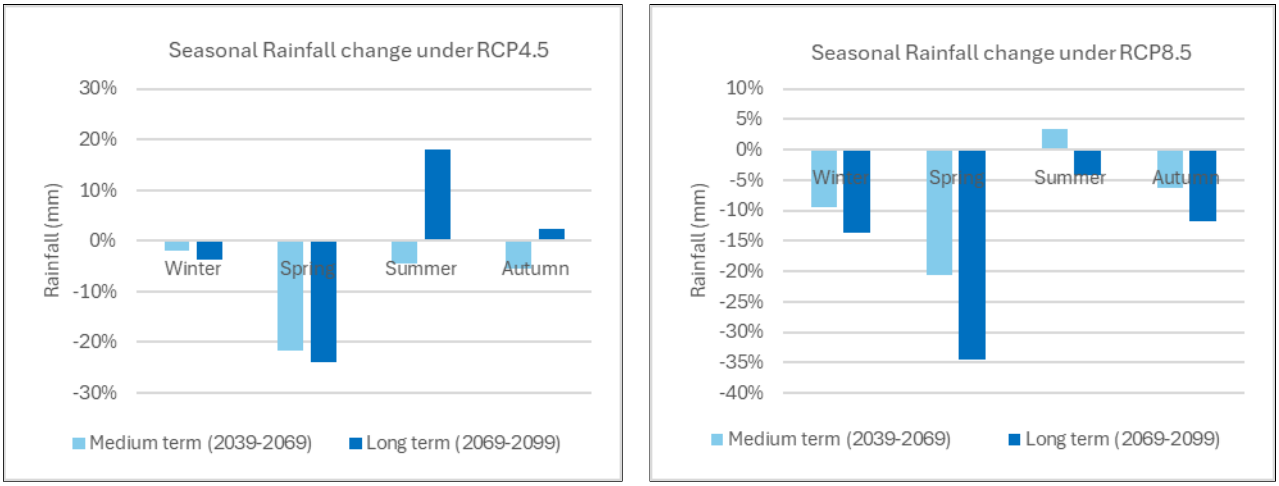


Figure 3 Seasonal rainfall projection for the Oued El Abid basin under RCP4.5 and RCP8.5

The results indicate a general trend of decreasing rainfall, particularly in winter and spring, with RCP8.5 predicting more pronounced reductions. Summer and autumn show variability, with some increases in the medium term but decreases in the long term, especially under RCP8.5.

3.1.2. Temperature projections

Under the RCP4.5 scenario (Table 3), the Oued El Abid catchment is expected to have a moderate temperature increase, with annual warming of 0.08 °C in the medium term (2039-2069) and 0.10 °C in the long term (2069-2099). Winter months, especially January and February, will be warmer, with increases up to 0.15 °C by the end of the century.

For the RCP8.5 scenario (Table 3), the trigger is more significant, with annual temperatures increasing by 0.11 °C in the medium term and up to 0.19 °C in the long term. Winter months, with January and February, warm up to 0.26 °C.

Even summer months, June and August will face notable increases, with temperatures rising by up to 0.15 °C by 2099.

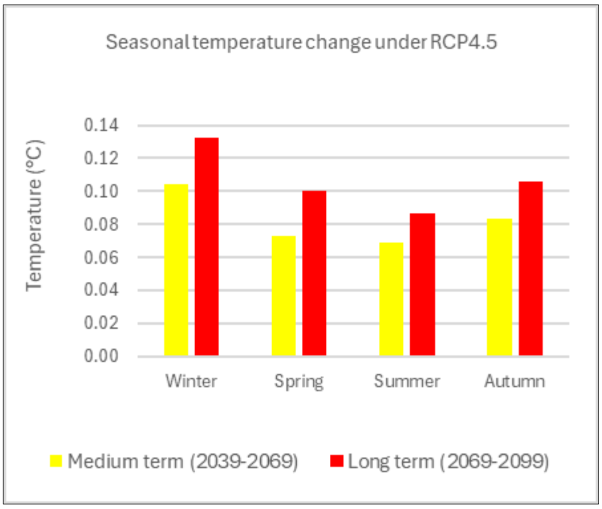
Table 3 Changes in annual and monthly temperature projections for the Oued El Abid watershed (°C)

	RCP4.5		**RCP8.5**	
	(2039-2069)	**(2069-2099)**	**(2039-2069)**	**(2069-2099)**
Annual	0.08	0.1	0.11	0.19
January	0.12	0.15	0.15	0.26
February	0.11	0.14	0.15	0.25
March	0.08	0.11	0.12	0.22
April	0.09	0.12	0.13	0.22
May	0.06	0.08	0.09	0.16
June	0.06	0.07	0.08	0.14
July	0.08	0.1	0.1	0.17
August	0.07	0.09	0.09	0.15
September	0.07	0.1	0.1	0.17
October	0.08	0.1	0.11	0.18
November	0.1	0.13	0.14	0.23
December	0.08	0.11	0.12	0.22

The results for the seasonal change in the temperature (Figure 4). For winter, the temperature rise is more pronounced under RCP8.5, with a medium-term increase of 0.14 °C and a long-term increase of 0.24 °C, compared to 0.10 °C and 0.13 °C under RCP4.5.

Spring temperatures also show a more substantial increase under RCP8.5, reaching 0.19 °C in the long term, compared to 0.10 °C under RCP4.5. In summer, the temperature increase is modest under both scenarios, the RCP8.5 scenario results in higher temperatures, with a long-term increase of 0.15 °C. Autumn temperatures show a similar trend, with a projected increase of 0.19 °C under RCP8.5 in the long term.

Overall, the RCP8.5 scenario predicts more significant temperature increases across all seasons, with the most pronounced changes occurring in the long term.



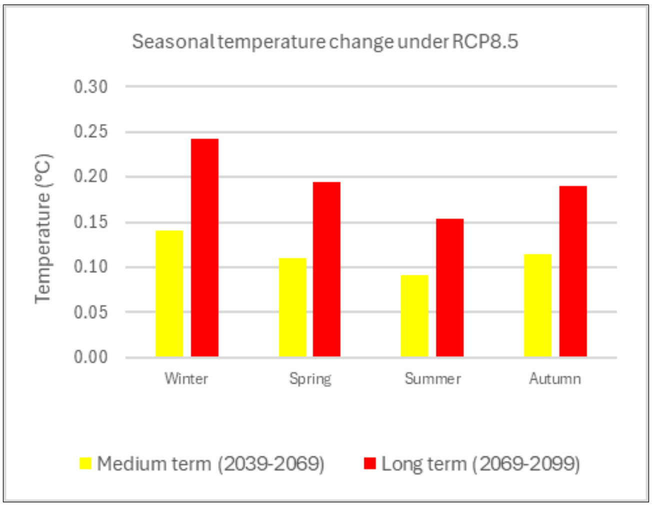


Figure 4 Seasonal temperature projection for the Oued El Abid basin under RCP4.5 and RCP8.5

3.2. Hydrological behaviour of the Oued El Abid catchment

3.2.1. HBV calibration

For the calibration period (1972-1992) (Figure 5), a good overall correspondence between observed (in blue) and simulated (in red) flows presented by an NSE criterion performance of 0.71, and about 0.72 for the coefficient of determination, the HBV-Light model captures the flow dynamics well, with peaks often coinciding with major rainfall events. The lowest flows appear to be correctly simulated, although some flood peaks are slightly underestimated or overestimated.

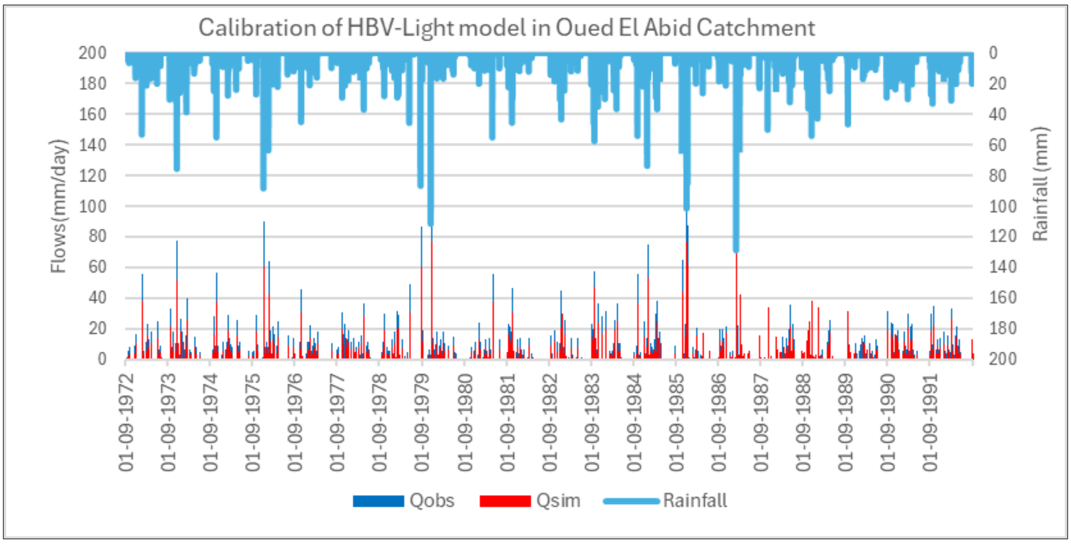


Figure 5 Calibration (1972-1992) of the HBV-Light model on the Oued El Abid Catchment

3.2.2. HBV validation

For the validation period (1993-2001) (Figure 6), the model continues to perform well with an NSE value of 0.66, and a higher estimation in terms of coefficient of determination achieves 0.66. The correspondence between observed and simulated flows remains good, which suggests that the calibrated model is robust and that its behaviour is consistent.

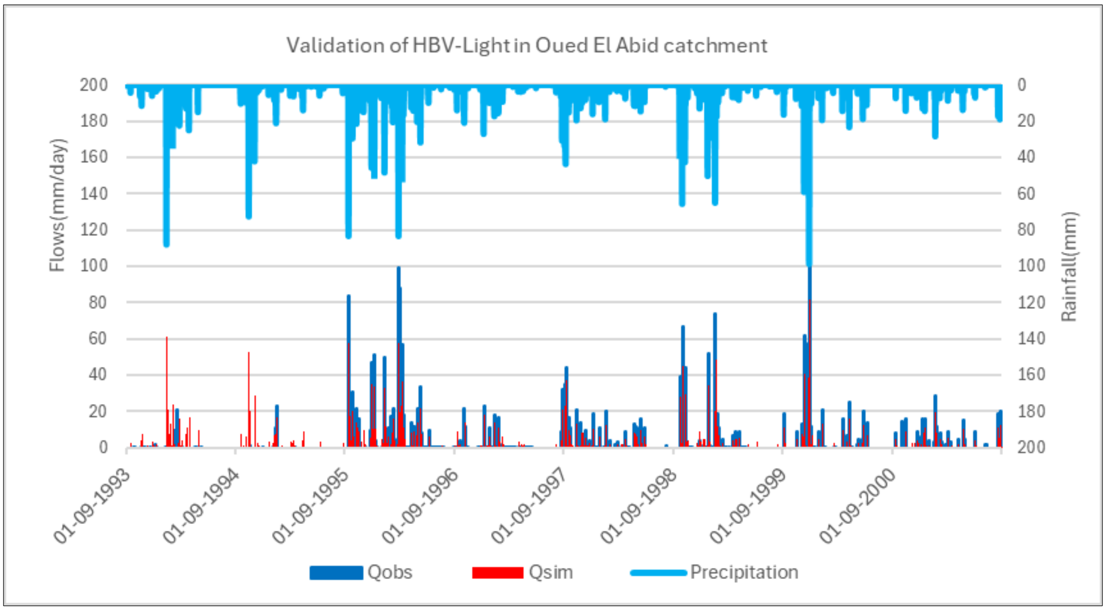


Figure 6 Validation (1993-2001) of HBV-Light model on the Oued El Abid Catchment

The HBV model appears to be well calibrated and validated for the Oued El Abid basin, reproducing observed hydrological dynamics satisfactorily for both low flows and flood events. The similar performance between the calibration and validation periods suggests that the model has a good capacity to simulate flows.

3.3. Flow projections for the Oued El Abid catchment

Projections of changes in flow show an alarming downward trend on all the time scales studied compared with the historical period (1971-2001).

On an annual scale (Table 4), there is a significant decrease ranging from 35% to 43% depending on the scenario, with a significant worsening for RCP8.5 in the long term (2069-2099).

The monthly analysis (Table 4) shows increased vulnerability, particularly in March, April, and May, where the falls exceed 60%. The summer months, particularly July, show considerable variability, with declines of up to 88% under RCP8.5, while December, January, and February will relatively be less affected, with declines of over 20%.

Table 4 Changes in annual and monthly flow projections for the Oued El Abid watershed (%)

	RCP4.5		**RCP8.5**	
	(2039-2069)	**(2069-2099)**	**(2039-2069)**	**(2069-2099)**
Annual	-38%	-35%	-40%	-43%
January	-36%	-35%	-34%	-30%
February	-29%	-22%	-44%	-39%
March	-61%	-69%	-64%	-63%
April	-63%	-57%	-59%	-74%
May	-66%	-67%	-55%	-67%
June	-31%	-13%	-30%	-21%
July	-49%	-42%	-88%	-55%
August	-57%	-42%	-43%	-47%
September	-45%	-33%	-40%	-46%

October	-30%	-11%	-21%	-26%
November	-20%	-28%	-38%	-38%
December	-21%	-33%	-32%	-44%

Seasonal variations (Figure 7) confirmed this downward trend, with spring being the most affected season, with flow reductions of up to 68%.

This spring reduction, combined with summer decreases of over 40%, could have major implications for the hydrological cycle, particularly in terms of aquifer recharge and water availability.

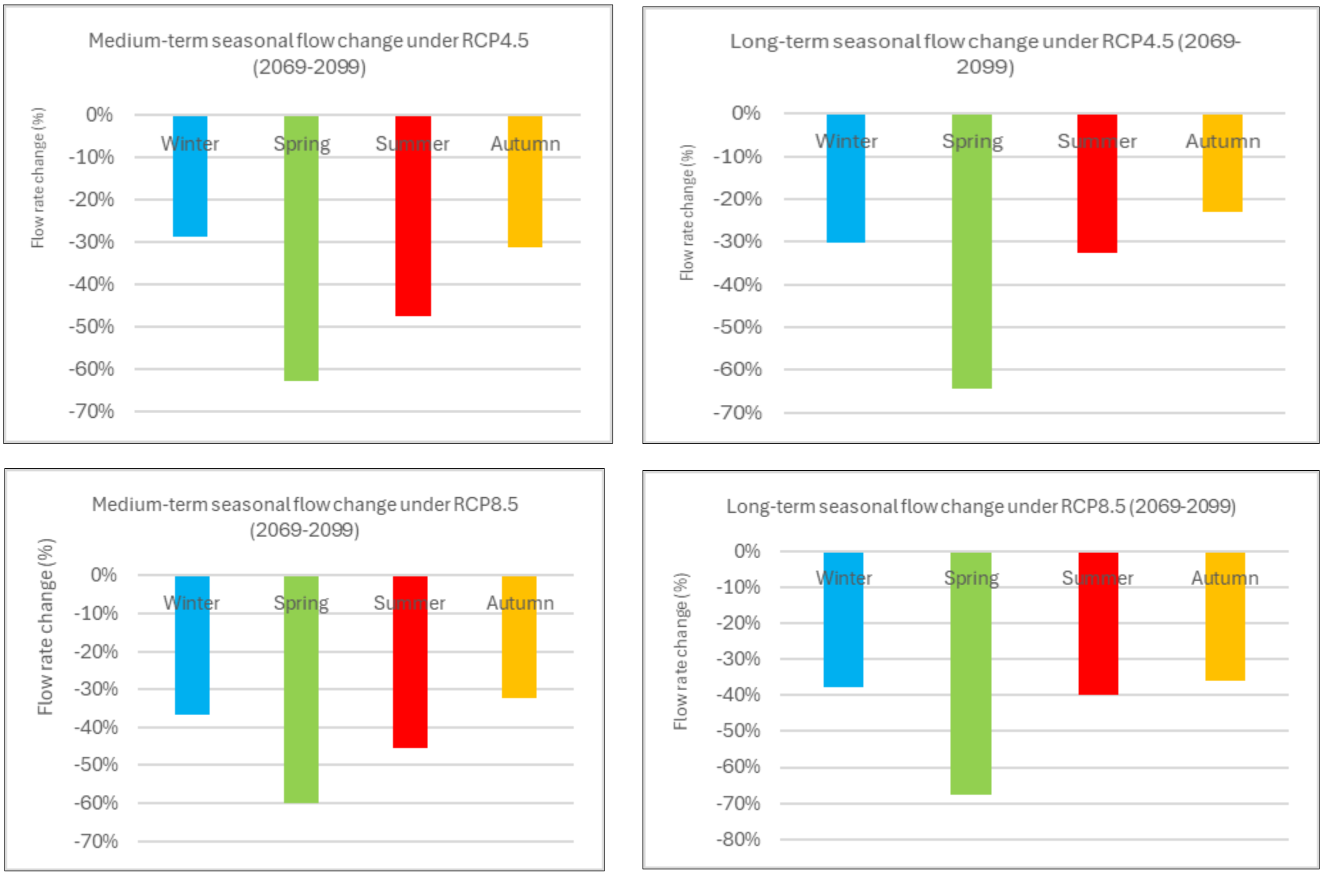


Figure 7 Seasonal flow projection for the Oued El Abid basin under RCP4.5 and RCP8.5

These results underline the urgent need for adaptive management of water resources, particularly for the critical spring and summer periods, and suggest that the impacts of climate change on flows could intensify over time, especially under the emissions scenario (RCP8.5).

These flow projection results are consistent with the study by Dakhlaoui (2019) [17], who projected flow reductions of -57% under RCP 8.5 in the long-term using HBV-Light in the Oued El Abid basin.

4. Discussion

Climate change significantly impacts watershed hydrology by altering precipitation patterns, temperature, and water balance components, which can lead to reduced water availability and increased hydrological variability. The following sections detail these effects based on recent studies.

Studies indicate a trend of decreasing precipitation and increasing temperatures in various watersheds, such as the Walga–Darge watershed, where annual mean surface runoff is projected to decrease by up to 31.37% by 2080 [18]. In the Nagavali and Vamsadhara watersheds, projected changes in precipitation range from a decrease of 4.6% to an increase of 25.5%, significantly affecting streamflow and sediment yield [19].

In Tunisia, projections indicate a decrease in precipitation by approximately 10-12% in both dry and wet seasons, alongside an increase in temperature by about 1.8-2 °C [20]. Historical data analysis shows a trend of decreasing annual precipitation and increasing temperatures, which directly affects groundwater recharge and surface runoff [18].

The Gilgal Gibe watershed study highlights the importance of understanding hydrological responses to develop climate resilience strategies, revealing oscillating streamflow trends under different climate scenarios [21]. Integrated hydrologic modelling in data-sparse regions shows that climate change can lead to over 50% of watersheds becoming ecologically fragile, affecting both green and blue water sustainability [22].

The cumulative effects of climate change necessitate adaptive water management strategies to mitigate impacts on agricultural yields and water quality, as evidenced by the findings in the Nagavali and Vamsadhara watersheds [19]. While the studies emphasize the adverse effects of climate change on watershed hydrology, some researchers argue that adaptive management practices can help mitigate these impacts, suggesting a potential for resilience in water resource systems.

Climate change significantly impacts watershed hydrology in Tunisia, leading to alterations in water availability and quality. The Grombalia aquifer has experienced significant depletion due to climate change, with future projections indicating further reductions in groundwater levels due to increased evaporation and decreased recharge rates. Groundwater discharge to streams is expected to decline by over 34% by 2080, exacerbating water scarcity issues [18].

Climate change is projected to increase the frequency of droughts while decreasing high flow events, leading to severe water availability challenges [20].

The Medjerda watershed is particularly vulnerable to soil erosion, which is exacerbated by changing climatic conditions, impacting agricultural productivity and sustainability [23].

While these studies highlight the detrimental effects of climate change on watershed hydrology, it is essential to consider adaptive management strategies that could mitigate these impacts and enhance water resource sustainability in Tunisia.

5. Conclusion

The hydrological study of the Oued El Abid watershed, using the HBV-Light model, reveals a robust performance with NSEs of 0.71 in calibration and 0.66 in validation and good values in terms of coefficient of determination about 0.72 and 0.66 respectively for the two essential modelling steps, demonstrating its reliability in simulating hydrological dynamics.

Temperature projections indicate a moderate increase under the RCP4.5 scenario, with annual temperatures rising by 0.08 °C in the medium term (2039-2069) and 0.10 °C in the long term (2069-2099). Winter months, especially January and February, are expected to warm the most, with increases up to 0.15 °C by the end of the century. Under the RCP8.5 scenario, temperatures rise more significantly, with annual increases of 0.11 °C in the medium term and up to 0.19 °C in the long term, with winter months warming by up to 0.26 °C and summer months by up to 0.15 °C.

Rainfall projections reveal substantial changes, with reductions expected across seasons. Under the RCP4.5 scenario, annual precipitation is projected to decrease by 7% in the medium term and 5% in the long term, with March experiencing significant reductions of up to 34% by the end of the century. The RCP8.5 scenario predicts a more drastic decline, with annual rainfall decreasing by 10% in the medium term and 17% in the long term. March and April are expected to have substantial decreases of approximately 30% and 41%, respectively, by 2099.

The flow projections are alarming, showing annual decreases in flows of 35% to 43%, worsening under the RCP8.5 scenario (2069-2099). The decreases are particularly severe in spring (up to 68%) and summer (over 40%), with extreme monthly variability reaching 88% in July under RCP8.5.

Faced with this situation, there is an urgent need to adopt adaptive water resource management strategies. Recommendations include developing more efficient storage infrastructures, setting up early warning systems for water stress, encouraging artificial recharge of aquifers, strengthening water conservation policies, diversifying supply sources, and integrating these projections into long-term planning.

These measures, combined with investment in research to improve hydrological modelling, are essential to mitigate the impacts of climate change on the basin's hydrological regime and ensure sustainable management of water resources for northern Tunisia.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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