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Combined impacts of climate and land use scenarios on sediment loads in small agricultural watershed in Tunisia

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Abstract

This study investigates the impact of conservation practices, specifically mulching and terracing, on soil erosion in the Kamech watershed (2.6 km^2) situated in the Cap Bon region of northeastern Tunisia, under both current and future climate scenarios. Utilizing the Soil and Water Assessment Tool (SWAT) model, the research evaluates the effectiveness of these Best Management Practices (BMPs) in reducing soil loss, revealing significant reductions of 1.5 t ha^{-1} yr^{-1} for mulching and 2 t ha^{-1} yr^{-1} for terracing. The findings indicate that these practices play a crucial role in enhancing soil conservation amidst climate change challenges, including altered precipitation patterns and increased temperatures. Additionally, the study highlights a notable decline in average monthly rainfall projected for the period 2051 to 2100 under the RCP8.5 scenario, further emphasizing the importance of implementing effective soil management strategies. This paper indicates that both methods, mulching and terracing, significantly contribute to reducing soil erosion under future scenarios (2051-2100). Their implementation proves essential for effective soil conservation, helping to mitigate the impacts of climate change and maintain soil health in the Kamech watershed. The results contribute to a better understanding of BMP performance in addressing soil erosion, water quality, and hydrological responses in the face of evolving environmental conditions.

By enhancing our understanding of these interactions, this research aims to provide valuable insights for sustainable watershed management, particularly in regions prone to water scarcity and land degradation.

Keywords: Climate variability; BPM; Soil erosion; SWAT model; Tunisia

1. Introduction

Water resources management is a complex challenge involving intricate processes at both surface and subsurface levels, as well as their interconnected systems [1, 2]. The hydrological characteristics within these water systems vary significantly across time and space, which complicates the management process and adds to the difficulty of effectively addressing the needs and challenges of water resources [3, 4]. This variability, combined with the interdependent nature of hydrological systems, renders water resource management a highly demanding and intricate task. In fact, land degradation has emerged as a critical global environmental issue, posing significant challenges for ecosystems and human societies alike [5]. The ongoing degradation of land leads to the loss of soil fertility, reduced agricultural productivity, and the depletion of vital natural resources. Across the globe, the depletion of these essential resources,

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such as water, fertile soil, and vegetation, is one of the most pressing problems confronting humanity. This decline not only threatens food security but also exacerbates climate change and biodiversity loss, further intensifying the environmental crisis [6, 7].

Human-induced environmental changes are significantly altering geomorphic processes across various regions of the world, leading to both increases and decreases in sediment delivery [8, 9]. These changes, driven by factors such as land use, deforestation, and climate change, can disrupt natural sediment transport systems, resulting in complex and variable impacts on sediment dynamics. The consequences of these shifts in sediment delivery can affect ecosystems, water quality, and landform stability [10].

Climate change and land use alterations significantly impact watershed hydrology and water quality. Studies using various models and scenarios consistently show that these changes lead to increased surface runoff, streamflow, and peak discharge volumes [11]. Climate change generally results in higher precipitation and temperature, affecting evapotranspiration and groundwater recharge [12, 13]. On the other hand, land use changes, particularly urbanization and deforestation, intensify surface runoff and alter nutrient loads [14-17]. The combined effects of climate and land use changes often produce more substantial impacts than either factor alone, emphasizing the need to consider both in watershed management and planning [15, 17]. These changes can have significant implications for water resources, necessitating the development of mitigation and adaptation strategies to enhance watershed resilience [14]. Recent studies have investigated the combined impacts of climate change and land use scenarios on sediment loads in various watersheds. Climate change is projected to decrease annual water supply and sediment inflow to reservoirs in Morocco [18] and Thailand [19], while increasing both in Vietnam [20]. Land use changes generally led to decreased sediment loads, except in Vietnam where deforestation increased sediment yield. The combined effects of climate and land use changes resulted in overall reductions in sediment loads in Morocco and Thailand, but increases in Vietnam. In Poland, precipitation changes had the most significant impact on sediment loads, while temperature and land use changes slightly decreased them [21]. These studies highlight the importance of considering both climate and land use changes in watershed management plans to address future water availability and sediment-related challenges.

A modeling approach is a widely utilized and effective method for predicting runoff and soil erosion in the context of global environmental changes, as highlighted in the review by Li and Fang (2016) [22]. Such models allow researchers to simulate various scenarios and assess the potential impacts of climate change, land use shifts, and other human-induced alterations on hydrological and geomorphological processes. By providing valuable insights into future trends, modeling serves as a crucial tool for informed decision-making in water and land resource management.

Simulation models, such as the Soil and Water Assessment Tool (SWAT) [23], have gained widespread acceptance as effective surrogate measures to quantify the impacts of various combined change's scenarios. The SWAT model [24, 25] offers a robust framework to assess the effects of land management strategies on water, sediment, and nutrient flows. Numerous studies in the published literature demonstrate its versatility and effectiveness in various environmental settings, providing valuable insights for sustainable watershed management and conservation planning.

The primary objectives of this study are to evaluate the performance of the SWAT model in simulating runoff and sediment dynamics in a semi-arid Mediterranean watershed located in the northern region of Tunisia. Additionally, the study aims to quantify the impact of Best Management Practices (BMPs) on soil erosion under current and future (2051-2100) condition. By evaluating these interactions, the research aims to offer critical insights into the future challenges posed by environmental changes in regions vulnerable to land degradation.

2. Material and Methods

2.1. Study area

The Kamech watershed, situated on the Cap Bon peninsula in northeastern Tunisia, is a small yet hydrologically and environmentally significant catchment area (Figure 1). Spanning approximately 2.63 Km^2, it exemplifies the characteristics of Mediterranean semi-arid regions. The watershed is located in rolling hills, with elevations between 53 and 149 m. The terrain features both steep and gentle slopes, affecting water and sediment movement. Despite its modest size, the Kamech Watershed plays a crucial role in local water management and maintaining ecological balance, making it a valuable area for investigating the impacts of hydrological processes, climate variability, and land use changes in Mediterranean semi-arid environments. This region has a Mediterranean climate, marked by hot, dry summers and mild, wet winters. Annual rainfall ranges from 450 to 600 mm, primarily falling between October and March. Precipitation is irregular, resulting in drought periods followed by intense storms.

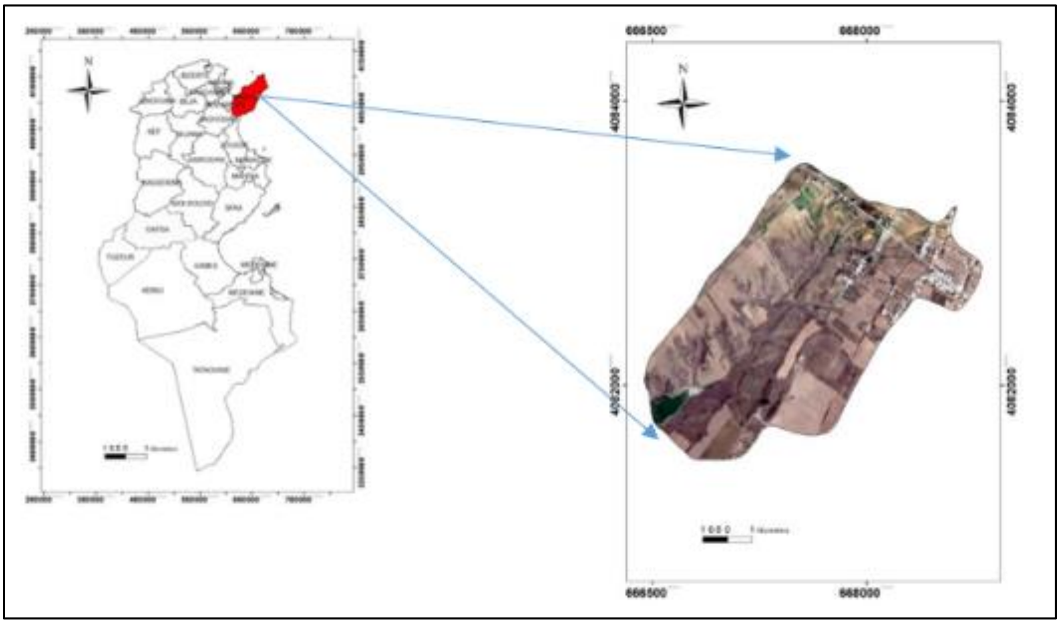


Figure 1 Location map of Kamech Watershed

The watershed has become a focal point for research on hydrological modeling, sustainable land use practices, and environmental impacts. Studies conducted here provide essential insights into addressing water scarcity and optimizing water use in agriculture, a key sector for Tunisia's economy. However, the Kamech Watershed is particularly vulnerable to challenges such as erosion, excessive runoff, and frequent drought conditions, which threaten both its natural resources and agricultural productivity. Its landscape consists of a mix of agricultural land and natural vegetation, including olive groves, cereal crops, and patches of native scrubland. This diverse land use not only supports agricultural activities but also contributes to the ecological health of the area, providing habitats for various species and playing a vital role in maintaining the watershed's hydrological balance. Finally, this watershed is crucial for understanding the interaction between climate variability and land-use practices in a semi-arid Mediterranean context, making it an important area for environmental research and sustainable development.

2.2. SWAT model

In this study, the SWAT model (Soil and Water Assessment Tool) was employed to assess sediment load and investigate the effects of land use and climate change on the water erosion process. The United States Department of Agriculture (USDA), created the extensive hydrological model, to forecast the effects of land management techniques on water, sediment, and agricultural chemical yields over extended periods of time in large, complicated watersheds [26]. SWAT is a spatially distributed physical model, it guarantees the Simulation of the hydrological cycle, plant growth, soil erosion, and nutrient transport through mathematical equations based on physical laws [26]. Furthermore, the ease of integrating GIS data into the SWAT model is a significant advantage when studying regions with limited data availability [27]. This makes it an effective method for application in the Kamech watershed. Based on the water balance equation SWAT simulates the hydrological cycle. However, the sedimentation is computed using the Modified soil loss equation [26]:

$$E = 11.8 \times (Qsurf \times qpeak \times area)^{0.56} \times K \times C \times P \times LS \times CFRG$$

where Qsurf is the volume of surface runoff [mm], qpeak is the peak run-off rate [m^3 s−1], AreaHRU is the area of HRU [ha]. P is the practice support factor, K is the soil erodibility factor and depends on the type of soil, C is the factor and crop management factor, L and S factors indicate the length and steepness of the slope, respectively. The course fragment factor is CFRG.

2.3. Dataset used for SWAT implementation

To ensure a reliable simulation, several types of data about the watershed, land use, soil qualities, and climate conditions must be prepared meticulously (table1). First of all, the borders of the watershed are established and topographic features such as slope, stream networks, and sub-basin delineations are computed using a high-resolution digital elevation model (DEM) with a resolution of 30 m. The land use map that identifies the different land cover is generated using a Landsat image. This satellite imagery is processed by QGIS within a supervised classification method. However, the soil data was obtained from in-site sample collection. The soil properties (soil texture, water content, and organic matter component), were determined using normal laboratory procedures. The combination of the previous three inputs allows to the model to generate the hydrologic response units (HRU) within a homogeneous combinations. The Multiple HRU Method was utilized after fixing the thresholds of 10% for all of the three datasets (landuse, soil and slope classes). Finally, climatic parameters with a daily time step were included, covering the period from 1995 to 2007. These data were collected from the hill lake climatic station. Moreover, a resampling procedure was used to harmonize all of the input maps.

Table 1 Swat inputs for Kamech watershed

input	Description
Digital elevation model	Cell size 30 m Shutter Radar
Land use/ Land cover	Cell size 30m
Soil	In-site collected data/laboratory analyses
Weather Data (daily time-step)	Daily (1995-2007) from the Kamech hill lake climatic station
Flow data	Monthly (1995-2007) calculated by a reservoir hydrological balance
Erosion	Yearly sediment yield calculated by bathymetric measurement at the Kamech Hill lake

2.4. Implementation of SWAT under global change scenarios

To implement the SWAT model under global change scenarios, it is essential to integrate future climate projections, land use changes, and other environmental factors. These scenarios, including shifts in land use and climate change, have a significant influence on watershed hydrology, sediment transport, and water quality. For simulating these consequences and evaluating probable future risks and management alternatives, SWAT is a very useful tool. Global climate models (GCMs) and Representative Concentration Pathways (RCPs) from the IPCC (Intergovernmental Panel on Climate Change) are commonly used in climate change projections. RCP2.6 (low emissions), RCP4.5 (mid emissions), and RCP8.5 (high emissions) are typical scenarios (Gassman 2007). These "trajectories" (or pathways) show the future atmospheric greenhouse gas concentrations, and then forecast their impact on temperature and rainfall.

In this study, the RCP8.5 scenario was selected to simulate the worst-case future climate conditions. This methodology gives local and regional authorities projected land-use plans or scenarios to attenuate the impacts of the increasing water scarcity. In fact, this allows for the analysis of how watershed behavior is affected by future climate and land-use scenarios [25]. However, it is very important to avoid bias in the projected future data by using a bias correction method [28]. In this case, and in order to align the model projections' distribution with the observed distributions, the quantile mapping method was used.

In fact, temperature and precipitation data for the RCP 8.5 scenarios were collected from CORDEX Africa. Using a basic mean strategy, a Multi-Model Ensemble (MME) approach was employed to handle the uncertainty of several models. Data of daily rainfall and maximum and minimum temperature was prepared to run SWAT for projection scenarios from 2025 to 2100.

3. Results

3.1. Erosion spatial distribution

The delineation of the Kamech watershed using the ArcSWAT interface generated 9 sub-basins and 360 HRUs. The multiple HRU method was used to separate the HRUs; this technique allows for the collection of more spatial information. Various studies demonstrate how the multiple HRU approach can improve the accuracy of models for watersheds with high geographic variability, especially when simulating processes like fertilizer and sediment transport [29].

Sensitivity analysis identifies the most important input parameters influencing the output variables, such as streamflow, sediment yield, nutrient loading, and crop yield, and plays a critical role in comprehending the behavior of the model [30]. For this purpose, the SWAT-CUP tool is used [31].

The result of the sensitivity study shows that 6 parameters were the most sensitive: CN, Sol_K, ALPHA_BF, RCHRG_DP, HRU_SLP and GW_DELAY. In conclusion, it is important to notice that the hydrological behavior of Kamech is globally impacted by the runoff, groundwater and infiltration process and the topography.

Using the SWAT model, a map depicting the spatial distribution of erosion results was generated following the calibration and validation processes (Figure 2).

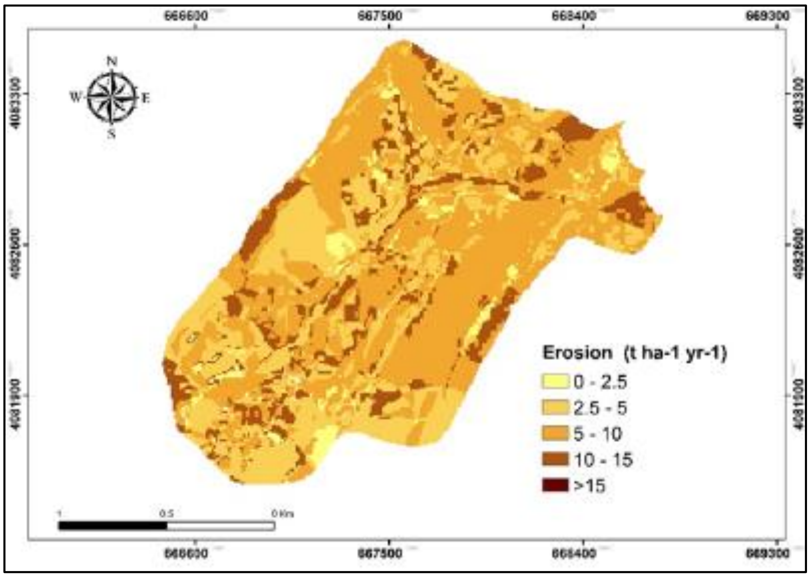


Figure 2 Spatial Soil loss classes distribution

The average annual erosion rate identified is 9.5 t ha^{-1} yr^{-1}. The highest erosion rates, exceeding 15 t ha^{-1} yr^{-1}, occur in areas with slopes greater than 15% and on plots cultivated with annual crops. The clayey nature of the soils in the Kamech basin makes them inherently prone to detachment, especially with the absence of anti-erosion management techniques.

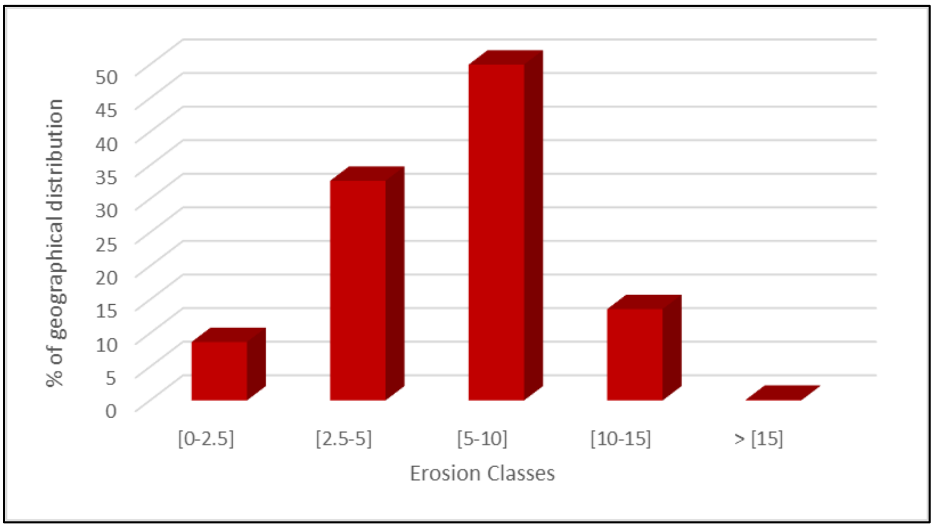
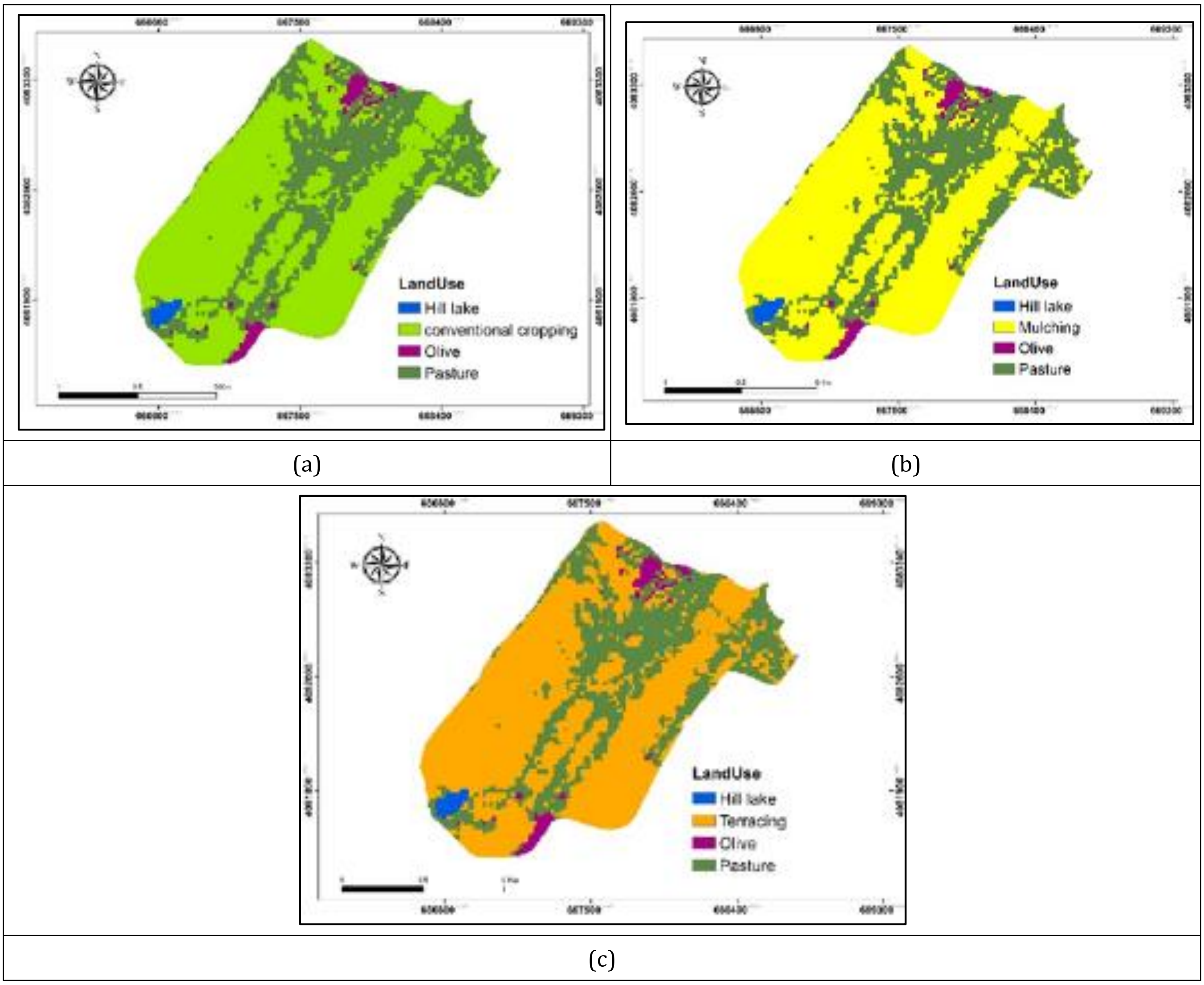


Figure 3 Classes of soil loss distribution

The results reveal five erosion classes, ranging from less than 2.5 t ha^{-1} yr^{-1} to more than 15 t ha^{-1} yr^{-1} (Figure 3). The predominant class is the medium category, which encompasses erosion rates between 5 and 10 t ha^{-1} yr^{-1}, accounting for 83% of the total study area. Indeed, this basin is heavily influenced by human activities such as agriculture and grazing. The Kamech watershed consists of clay-loam and sandy-loam soils, characterized by a high concentration of carbonate materials. The texture of these soils renders them moderately erodible and especially vulnerable to water erosion, particularly in sloped areas. Moreover, the low amount of organic matter diminishes water storage capacity, exacerbating the impacts of drought and heavy rainfall events.

3.2. Application of Best management farming practice (BMP)

The implementation of conservation practices plays a significant role in reducing soil erosion [32, 33]. Based on the functions of these practices, a proposed approach aims to simulate their impacts on soil detachment caused by runoff using the SWAT model. In this paper, the selected practices for simulation include soil cover through mulching and the application of terracing (Figure 4).



(a) (b) (c)

Figure 4 Land use scenarios for the best management farming practice (a) conventional farming (b) Mulching (c) terracing

The application of mulching is materialized by to the slowing of runoff by reducing the CN (curve number) and increasing soil roughness, as well as improving infiltration. Mulching reduces both sheet and rill erosion by intercepting raindrops and decreasing their kinetic energy. According to Neitsch et al. (2009) [26], the CN was reduced by 8, and the OVN-Manning roughness coefficient was reduced by 10%. To simulate the terracing, the USLE_P values were modified according to the recommendations of Roose (1999). The value of the parameter (SLSUBBSN), representing the slope length, was also reduced by 50% [26]. These two farming practices were applied to the HRUs with annual crops.

According to the SWAT model, implementing conservation practices in the Kamech watershed has a substantial impact on reducing soil erosion. These practices not only mitigate erosion but also contribute to effective soil conservation management. By promoting sustainable land use and protecting soil health, these measures enhance the watershed's resilience against environmental changes and improve overall land productivity. In fact, the erosion rates resulting from both scenarios were significantly reduced. The calculated rates are 2 t/ha/year for terracing and 1.5 t/ha/year for mulching, representing reductions of 70% and 75%, respectively.

3.3. Climate change study in Kamech

Before utilizing the Cordex climatic data, all necessary bias corrections were applied, and an analysis of the monthly predicted information was conducted to identify the future climatic trends in the Kamech watershed. Since the RCP8.5 scenario shows a continuous rise of the atmospheric gas concentrations, this will unluckily worsen water scarcity, affect agricultural output, and increase vulnerability to extreme weather events like floods and droughts. Climate models indicate an overall decline in the Mediterranean region's total annual precipitation under the RCP 8.5 scenario including northern Tunisia.

Using RCP8.5, the monthly average precipitation (pcp) was studied for the long-term period, between 2051 and 2100. In fact, figure (5) demonstrates a significant decline in precipitation by the end of the century. Compared to historical averages (1961-1990), this reduction is anticipated to be between 8 and 20% by the end of the 21st century (2051-2100) (Figure 5). The decrease is explained by the general drying tendency that warming scenarios predict for the Mediterranean region [34].

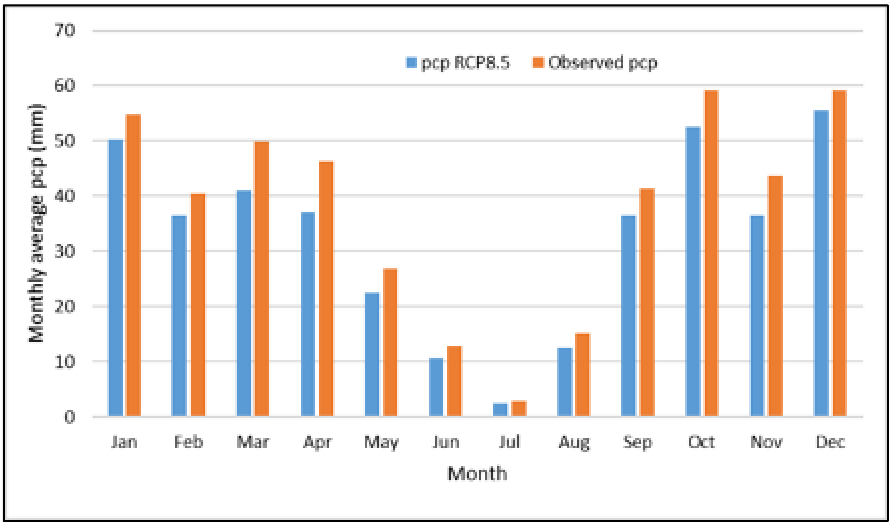


Figure 5 Comparison between observed and predicted monthly average (2051-2100) precipitation

On the other hand, this study indicates that the maximum and minimum monthly temperature will rise under the RCP8.5 scenario. Additionally, evapotranspiration is expected to increase, further decreasing soil moisture and intensifying the effects of reduced rainfall. This could particularly affect agricultural productivity of the watershed characterized by rain-fed agricultural system, which relies heavily on winter rains. According to Evans (2009), the (MENA) region, which includes the North Africa zone is predicted to see mean temperatures rise by 1.4°C between 2045 and 2054, and by 4°C between 2090 and 2099 [35].

3.4. Effect of BMP on water erosion under RCP8.5 scenario

The RCP 8.5 scenario predicts greater inter-annual rainfall variability, potentially resulting in some years being wetter or drier than others. This variability complicates agricultural planning and water resource management. Addressing these future challenges will necessitate the development of targeted strategies to mitigate water scarcity. Ben Slimane (2013) demonstrated through a sediment fingerprinting investigation that the primary source of sediment load is surface soil erosion rather than gully erosion. This finding highlights that conservation farming techniques would be more effective than gully remediation in mitigating erosion. To this end, the SWAT model was used to test two scenarios for a long-term horizon (2051-2100) employing Best Management Practices (BMPs), specifically mulching and terracing. These two techniques have demonstrated their effectiveness in reducing soil erosion in the current scenario.

To assess the impact of these techniques on soil erosion, two maps were created that illustrate the spatial distribution of soil erosion for the period from 2051 to 2100 (Figure 6). In fact, the visualisation of the geographical distribution of the erosion rate classes demonstrates the expansion of the low to moderate erosion with the disappearance of the high erosion class.

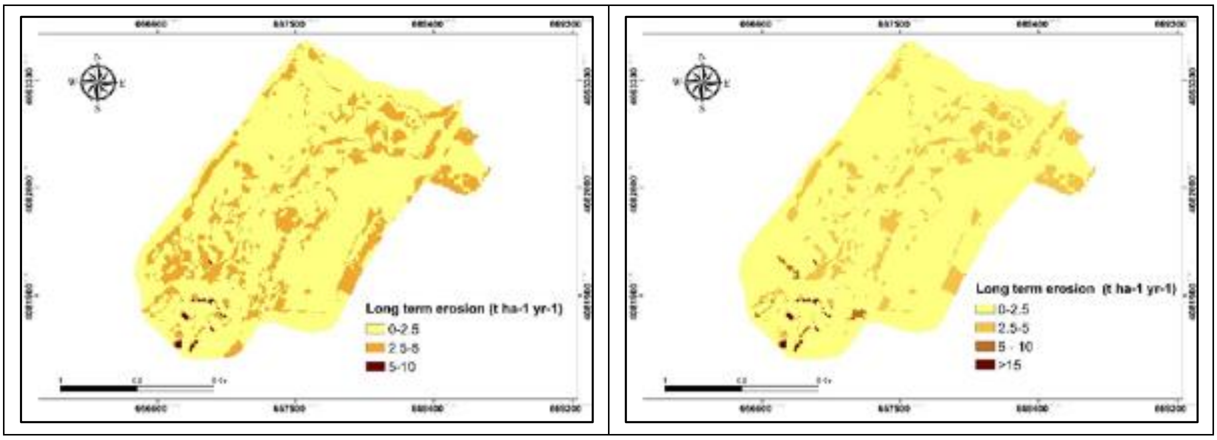


Figure 6 Erosion spatial distribution at long term (2051-2100): left using terracing techniques and right using mulching techniques

Over the long term (2051-2100), both terracing and mulching techniques have a considerable impact on reducing soil erosion, leading to a predominance of the erosion class ranging from 0 to 2.5 t ha^{-1} yr^{-1}. The results indicate erosion rates of 1 t ha^{-1} yr^{-1} for terracing and 1.3 t ha^{-1} yr^{-1} for mulching, as shown in Figure 6. This demonstrates the effectiveness of these practices in enhancing soil conservation and maintaining the ecological balance within the watershed.

It is important to note that the observed reduction in soil erosion is a result of a combination of factors, including the implementation of conservation management practices, a decrease in average precipitation, and an increase in temperature. These interconnected elements collectively contribute to the effectiveness of erosion reduction strategies in the watershed.

4. Discussion

Effective model calibration is essential for producing accurate outputs in hydrological predictions. Proper calibration ensures that the model parameters are aligned with observed data, which enhances the model's reliability and predictive capability. By fine-tuning the model to reflect the specific hydrological characteristics of the watershed, researchers can obtain more precise simulations of runoff, sediment transport, and other critical hydrological processes. This is particularly important in decision-making for water resource management and planning, as it enables stakeholders to develop informed strategies based on reliable predictions.

The quality of simulation outcomes is influenced by several factors, with the most critical being the quality of the input data. High-quality data is essential for ensuring accurate simulation performance, as it minimizes uncertainties and enhances the reliability of the model's predictions. When input data are precise and representative of the conditions within the watershed, the model can effectively capture the underlying hydrological processes, leading to more trustworthy results. Consequently, investing in robust data collection and management practices is vital for improving simulation quality and supporting effective water resource management strategies.

As science, technology, and society continue to advance, there is an increasing emphasis on the integrated management of vulnerable watersheds, particularly in addressing natural phenomena such as soil erosion. In this study, the SWAT model was applied to a small watershed covering an area of 2.6 km^2 to assess the long-term combined impacts of climate and land use changes on soil erosion over an extended period. This analysis seeks to address various questions which aim to deepen our understanding of the interactions between climate variability, land use practices, and their effects on soil erosion dynamics in similar environments.

In the Kamech watershed, the average actual erosion estimated by the SWAT model is 9.5 t ha^{-1} yr^{-1}, while the observed measurement is 12.34 t ha^{-1} yr^{-1}. The dominant erosion class falls within the low to medium range. The Kamech watershed experiences highly variable rainfall, with intense storms significantly affecting erosion processes. The surface runoff generated by these heavy rainfalls causes substantial sheet and rill erosion, particularly in areas with sparse vegetation. Additionally, the hilly topography, characterized by moderate to steep slopes, intensifies soil erosion in the watershed [36]. Given that the farming system in the Kamech watershed relies on conventional monoculture with minimal soil and water management practices, we evaluated the effect of two Best Management Practices (BMPs): mulching and terracing.

Additionally, we compared the impact of these practices on soil erosion with the baseline erosion results to assess their effectiveness in improving soil conservation under current conditions. In the second phase, we extended the study to evaluate their long-term impact on soil erosion for the horizon 2051-2100, providing insights into their potential effectiveness in future climate and management scenarios. The influence of these scenarios was incorporated into the SWAT model by adjusting several parameters to accurately simulate their effects.

The results indicate that both methods, mulching and terracing, significantly contribute to reducing soil erosion under the current scenario. These conservation practices have proven effective in mitigating erosion and promoting better soil management within the Kamech watershed. For this reason, two future scenarios were developed using terracing and mulching techniques over the long-term horizon (2051-2100) with the SWAT model. These scenarios aim to evaluate the potential impact of these conservation practices on soil erosion under future climate and conservation management conditions. Using RCP8.5 to study climate data, the results show a significant decrease in average monthly rainfall over the entire period from 2051 to 2100. Similar results were observed in a previous study conducted in the semi-arid region of Tunisia. Benrhouma et al. (2024) [29] found that the average monthly rainfall for the long term also showed a significant decline, aligning with the trends identified in our research. This further highlights the ongoing challenges related to water scarcity in semi-arid areas.

The application of mulching and terracing demonstrated a significant impact in reducing soil loss under both current and future conditions. These practices proved to be effective in mitigating erosion, enhancing soil conservation, and ensuring more sustainable land management in the Kamech watershed. Panagos et al. (2015) [37] found that terracing reduces soil erosion by 70% which alienate with our findings. In fact, these techniques improve the soil's capacity to absorb water and withstand erosion by preserving soil structure and increasing organic matter. BMPs stabilize riverbanks, increase water infiltration, and preserve soil fertility in addition to reducing sediment loss and promoting overall watershed health.

5. Conclusion

The Soil and Water Assessment Tool (SWAT) was applied to the Kamech watershed to assess, for the first time, the distinct and combined impacts of global change, specifically climate and land use changes, on runoff and erosion responses in northeastern Tunisia. The SWAT model was used with calibrated parameters throughout the reference period 1995-2007 to simulate three land use scenarios and the effect of climate change over the period 2051-2100. Throughout the reference period, the SWAT model accurately simulated water and sediment entering the reservoir downstream of the examined watershed. The simulated erosion rate was 9.5 t ha^{-1} yr^{-1} while the observed rate for the same period is 12.34 t ha^{-1} yr^{-1}. The dominant erosion class is the low to moderate class. The implementation of Best Management Practices (BMPs) has shown excellent results in reducing soil erosion under current conditions. Two farming practices were tested: mulching and terracing, which reduced soil loss by 1.5 and 2 t $ha^{-1}yr^{-1}$, respectively. These findings highlight the effectiveness of these techniques in enhancing soil conservation. The Kamech watershed is expected to face the impact of climate change with a decrease of the quantities of average precipitation and is expecting the rise of drought and aridity. Therefore, it is urgent to prioritize the application of BMP to prevent the deterioration of soil health. Coupling climate change scenario with BMP, is a good alternative to forecast a conservative strategy in a context of water scarcity. In this research, a significant reduction of soil erosion was observed in the studied watershed under the two identified techniques for long term horizon, 2051-2100. This method is invaluable for understanding the performance of Best Management Practices (BMPs), which are specifically designed to address soil erosion, water quality, and hydrological responses. It helps to assess their effectiveness in the context of climate change-related challenges, including altered precipitation patterns, rising temperatures, and extreme weather events.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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