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Assessment of runoff variability under various factors using SWAT model in a Tunisian semi-arid watershed

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Abstract

This research aims to establish a correlation between prolonged shifts in precipitation patterns and runoff and to delineate spatial surface runoff distribution within the Wadi Rmel watershed using the Soil and Water Assessment Tool (SWAT) model. The calibration and validation processes reveal good agreement between measured and simulated flows with a monthly time step. Significantly, the Nash-Sutcliffe Efficiency (NSE) values of 0.61 and 0.83, accompanied by the coefficient of determination (R^2) values of 0.66 and 0.85 for calibration and validation, respectively. It clearly indicates a strong agreement between the observed and simulated streamflow data. Subsequently, an exploration of the spatiotemporal variability of runoff underscores the synchronous relationship between runoff and monthly and annual precipitation fluctuations between 2000 and 2020. The values of R^2 were 0.7 and 0.79 for monthly and annual studies, respectively, confirming a strong correlation between the two cited variables. Additionally, anthropogenic impacts, particularly Soil and Water Conservation (SWC) measures, were investigated. A high R^2 coefficients (0.91 for linear relationship) were obtained and showed the high relation between SWC and runoff. In fact, the combination of SWC techniques, vegetation cover, topography and precipitation led to a reduction of 44% of surface runoff, during 2015-2020. Spatially, higher runoff occurred in central and eastern parts due to agriculture and hilly terrain, while forested areas and gentle slopes exhibited lower runoff. In conclusion, this study underscores the model's utility in characterizing arid catchment surface runoff. Its capacity to simulate and assess runoff enriches water resource management comprehension in such contexts.

Keywords: Streamflow; Surface runoff; Rainfall; SWAT; Arid condition

1. Introduction

Water Scarcity is a looming threat to life in developing countries in the 21st century. Water is the essence of life, and its scarcity [1], caused by the rising population and its mismanagement, represents a significant challenge to human survival and development. While the world faces numerous environmental concerns, water scarcity emerges as a pressing issue, particularly in developing countries. On the other hand, this problem can also be largely explained by hydrometeorological phenomena, such as the irregular distribution of precipitation and soil water content [2]. Therefore, it is important to understand the hydrological reactions of the catchment. Understanding the behaviour and responses of the watersheds requires the use of hydrological models [3]. These models were created and employed as mathematical representations of hydrological processes, aiming to enhance comprehension of how natural and anthropogenic disturbances affect hydrological features [4]. The study of streamflow modelling holds great importance for various aspects of water resource management and understanding hydrological processes [5]. Moreover, it is important to investigate the relationship between rainfall and runoff under various climate conditions [6]. Worldwide

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several hydrological models were used to understand the complex rainfall-runoff reactions in watersheds. In the context of a globally warming climate, it is evident that human activities have emerged as the primary catalyst for alterations in annual runoff patterns [7]. This underscores the significant role that human actions, such as land use changes, urbanization, and water management practices, play in shaping hydrological dynamics, even against the environment of broader climatic shifts. Recognizing the dominance of human influence in driving these changes highlights the need for sustainable water resource management strategies that consider both climate-related factors and anthropogenic interventions. The data indicates a notable inverse relationship between the extent of runoff and the areas designated for terracing, the land formed as a result of check dam implementation, and the establishment of Land use Land cover (LULC) [8]. This suggests that as these measures expand, there is a corresponding reduction in runoff levels. According to the objectives of this study, many hydrological models have been developed.

In this study, the Soil and Water Assessment Tool (SWAT) [9, 10] was chosen. SWAT was described as a sophisticated method [11, 4, 12] for evaluating the effects of water resource management strategies in the most difficult watersheds. This study focus on parameter uncertainty analysis for streamflow simulation using the SWAT model links with the SUFI-2 algorithm on monthly time steps in the Wadi Rmel watershed, Northeast of Tunisia. The method combines SWAT-CUP's capabilities with the SUFI-2 algorithm, effectively integrating their strengths to achieve more reliable results in hydrological modelling and analysis. The main objectives of this work were

- To evaluate the potential of the SWAT to simulate runoff in a semi-arid watershed,
- To identify the significant parameters affecting streamflow using SUFI-2 algorithm,
- To assess long-term changes impact of rainfall on runoff, and
- To study the spatial variability of surface runoff.

2. Material and methods

2.1. Description of Study Area

The Wadi Rmel watershed is located in Northeastern Tunisia, for the most part in the Zaghouan governorate, with a small area belonging to the Nabeul governorate and another to the Ben Arous governorate (Figure 1). Wadi Rmel is situated approximately 80 km to the south of Tunis and spans across an area measuring 675 Km^2. The Rmel Dam, constructed in 1998, serves as the outlet of this watershed. This studied watershed is under the influence of a Mediterranean climate caused by the effect of the sea and a continental climate influenced by the region's mountain ranges.

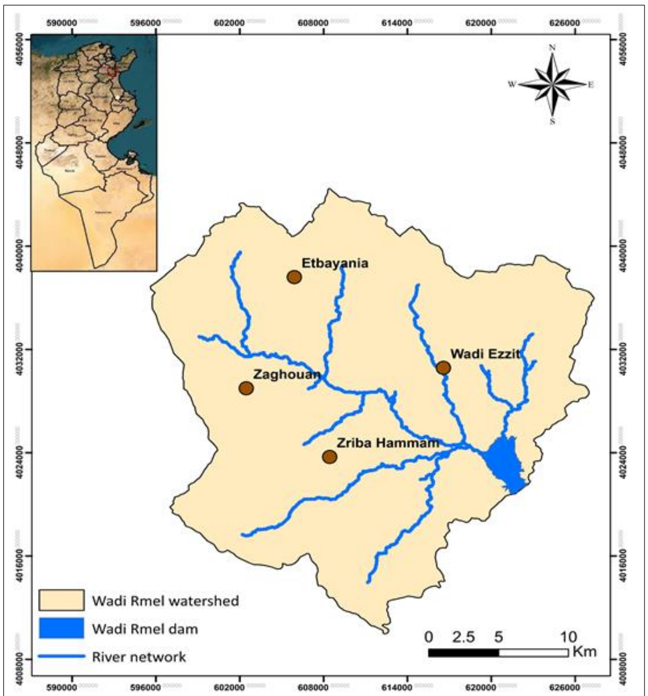


Figure 1 Location map of the study area

The climate within the study area exhibits a range from sub-humid to upper semi-arid conditions, particularly in the northern and northwestern parts, where the mountain ranges are located, to lower semi-arid in the South of the basin. A moderate semi-arid climate defines the central portion of the basin. The yearly mean precipitation falls within the range of 350 to 600mm [13]. Rainfall is primarily concentrated in the winter season. The average annual temperature hovers around 18.5 °C.

2.2. Data collection

In order to accomplish the study's mentioned purpose, a collection of input data was prepared. A Digital Elevation Model (DEM), featuring a spatial resolution of 30 meters by 30 meters, was acquired from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/). The utilization of this DEM allowed for the identification of both the main watershed and its sub-watersheds, as well as the delineation of drainage surfaces. Additionally, it facilitated the establishment of the stream network and the identification of the longest reaches within it, all based on elevation data. Slope classes within the study area were derived from the DEM data. These slope classes hold significant importance as inputs for the SWAT (Soil and Water Assessment Tool) model. They play a crucial role in generating Hydrological Response Units (HRUs) within the model's framework.

Land Use/Land Cover (LULC) is a pivotal input parameter for the SWAT model, significantly influencing the hydrological responses of a studied watershed. The distribution and characteristics of different LULC types directly impact various hydrological processes. To do this, a set of Landsat imagery was downloaded from the USGS Earth Explorer website, with a spatial resolution of 30 meters. Subsequently, a supervised classification process was applied to create LULC maps for the research region. A study and assessment of the change in LULC has been conducted every five years, starting from the year 2000. Simultaneously, a series of SWC maps were developed on the same dates, with a five-year interval, starting from the year 2000. In this case, the maps depicting changes in LULC and the SWC techniques will be utilized to assess the influence of these changes on runoff within the studied watershed. The soil map is a crucial component used to characterize the properties and distribution of soils within a study area. It provides essential data for modeling various hydrological processes. In this case, a soil map and database were obtained from Laboratory analysis of the Chemical and physical characteristics of soil samples. Daily meteorological data as well as daily flow data at the gauging stations were gathered from several departments of the Minister of Agriculture, Hydraulic Resources, and Maritime Fishing, Tunisia, for the years 2000 to 2020.

2.3. Model setup

SWAT is a hydrological model, is characterized as a semi-distributed modeling tool. It considers the watershed as a collection of sub-watersheds, each with its unique characteristics and hydrological response [14]. SWAT employs Digital Elevation Model (DEM) data to partition the watershed into several sub-basins, each of which encompasses the main channel and numerous Hydrological Response Units (HRUs). HRUs constitute the smallest compact units within the watershed, delineated based on their uniform attributes encompassing slope, land use and soil type characteristics [15] (Figure 2).

In this research, the process of simulating streamflow was carried out through the utilization of observed data [16]. This simulation was conducted using the Sequential Uncertainty Fitting (SUFI-2) approach [17, 18] (Figure 2). The application of this algorithm was executed using the open-source software SWAT-CUP [19, 20]. The p-factor and r-factor serve as metrics to evaluate the efficacy of model simulation and uncertainty evaluation.

In this research, a set of twenty-two parameters was chosen for sensitivity analysis. From this set, six parameters were identified as the most sensitive ones for the calibration and validation processes of the model [21]. To facilitate these processes, the streamflow data was divided into two distinct periods. Firstly, a warm-up period was incorporated to initialize the model variables and obtain reliable starting values. This warm-up period spanned from 2000 to 2001. Subsequently, the calibration phase utilized data from the period between 2001 and 2014. Finally, the last six years of available data (from 2015 to 2020) were dedicated to the validation of the model's performance [22]. The subsequent stage involved the assessment of the SWAT model's performance. This evaluation was conducted to appraise the concordance between the simulated data and the observed data for both the calibration and validation periods, as outlined in the work by Sao et al. [23].

In this study, distinct objective functions were employed for the calibration and validation processes performance evaluation. The Nash-Sutcliffe efficiency coefficient (NSE), widely recognized as an efficient criterion for evaluating hydrological model performance, was chosen as the objective function for both calibration and validation processes in this case. Additionally, several other model performance metrics, such as coefficient of determination (R^2), and other relevant indicators, were computed to comprehensively assess the hydrological models' performance. These statistics provided a comprehensive evaluation of how well the models replicated the observed data and helped to gain a more comprehensive understanding of their effectiveness.

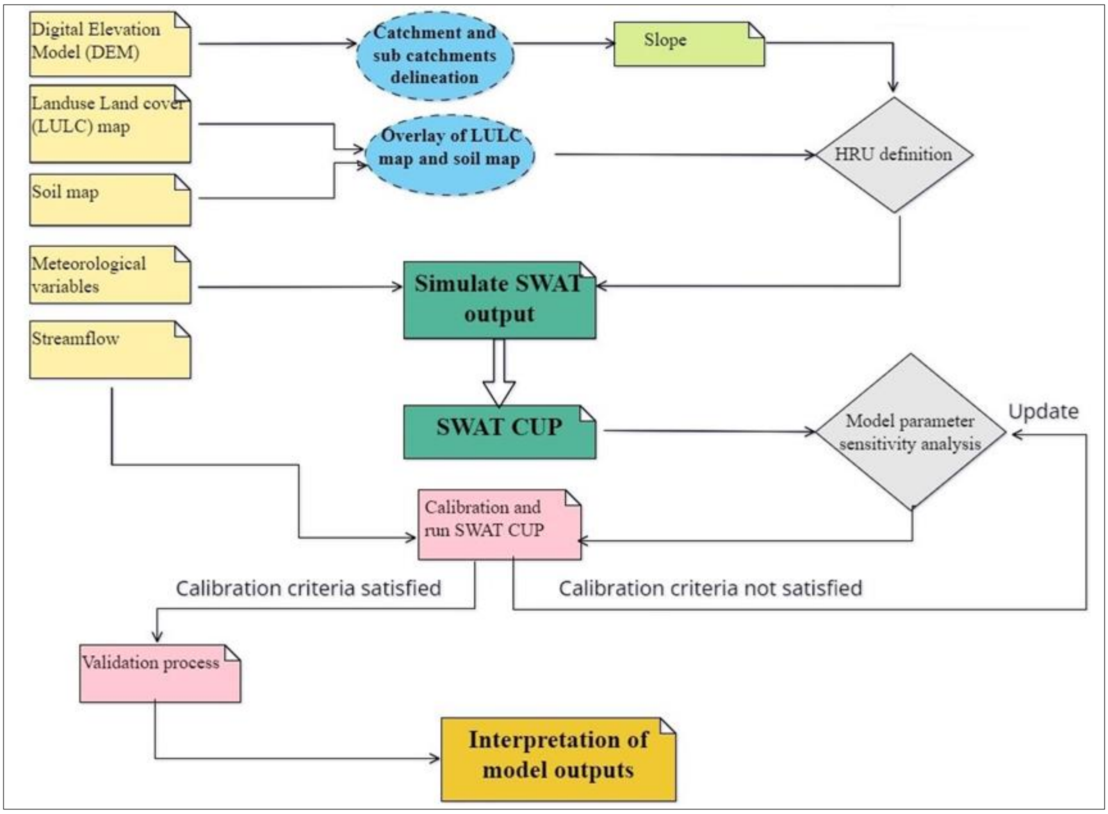


Figure 2 Flow chart of how the SWAT model works

3. Results

3.1. Monthly simulation

The SWAT-CUP model, employing the SUFI-2 algorithm, was utilized to conduct sensitivity analysis for streamflow simulation. In fact, this method is regarded as easily implementable. Moreover, the sensitivity analysis was used to identify the most sensitive parameters in the Wadi Rmel watershed. Finally, the parameters that significantly impacted streamflow simulation were identified and ranked based on p-value and t-stat [19]. In this study and according to the statistical ranking output, a total of 22 parameters were classified as sensitive due to their significant impact on the streamflow simulation. For the monthly assessment [24], a set of six most sensitive parameters were chosen (Table 1). These parameters were then employed for the procedures of calibrating and validating the model.

Table 1 Monthly most sensitive parameters of the Wadi Rmel watershed [24]

Parameter Name	Description	t-Stat	P-Value	Rank
CN2.mgt	SCS runoff curve number	17.628	0.000	1
SOL_AWC.sol	Available water capacity of the soil layer	15.787	0.000	2
USLE_K.sol	USLE soil erodibility factor	-2.890	0.002	3
USLE_P.mgt	USLE support practice factor	2.850	0.005	4
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium	2.570	0.010	5
GW_DELAY.gw	Groundwater delay	2.570	0.011	6

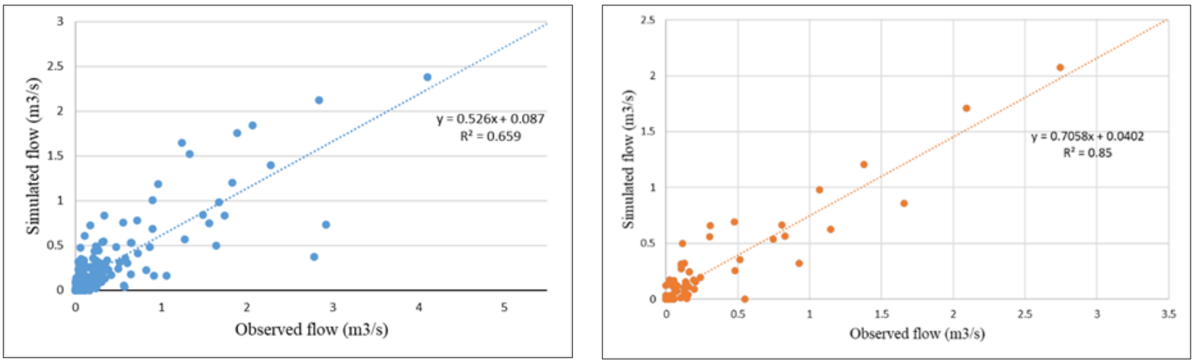
These findings emphasize that the parameters identified as most sensitive are associated with surface runoff, groundwater dynamics, and soil properties. These parameters hold substantial influence over the simulation of streamflow. In the Wadi Rmel watershed (Table 1), the curve number (CN2) was identified as the first most sensitive parameter. In fact, the sensitivity of this parameter in relation to streamflow simulation is depending on a variety of factors, including soil attributes such as type, texture, and permeability, as well as the characteristics of land use within the area. The calibration and validation procedures were carried out utilizing the SUFI-2 algorithm and involved the application of streamflow data collected at the gauging station within the studied watershed from the years 2000 to 2020. For the calibration process, the streamflow data spanning fourteen years, from 2001 to 2014, were employed, while the validation was conducted using data of six years, ranging from 2015 to 2020. The initial year, 2000-2001, was considered as a warm-up period. In model evaluation, the results of calibration and validation statistical parameters for monthly simulation were depicted in Table 2 [24].

Table *2* Summary of statistics for calibration, validation processes for monthly step in the Wadi Rmel watershed

Process	**NSE**	**R^2**
Calibration (2001-2014)	0.61	0.66
Validation (2015-2020)	0.83	0.85

For the monthly simulation, the value of the performance indicator was 0.61 for NSE for the calibration process. A very good correlation was obtained during the validation period with NSE equal to 0.83 (Table 2).

Furthermore, Figure 3 displays the correlation graphs comparing observed and simulated data. During the calibration and validation periods, the R^2 values were calculated to be 0.66 and 0.85, respectively. These values signify a very good correlation between the observed and simulated streamflow data.



(a) (b)

Figure 3 Correlation performance of (a) calibration and (b) validation for Wadi Rmel watershed

Consequently, the statistical metrics showed a very good concordance between the observed and simulated streamflow data, spanning both the calibration and validation periods.

In conclusion, the SWAT model demonstrate a strong concordance between measured and simulated flows when utilizing a monthly time step for both the calibration and validation procedures.

3.2. Long-term changes in precipitation and runoff

This part of this research aims to assess the long-term variations in runoff and rainfall and to find a relationship between these two components in the Wadi Rmel watershed from 2001 to 2020. In the Mediterranean climate of Northeast Tunisia, the monthly and annual rainfall variations have a notable impact on the runoff pattern. These variations are distinctly reflected in the way runoff behaves over time. In fact, rainfall fluctuations were responsible for the changes observed in surface runoff that contributed to losses.

In this context, a good relationship between runoff coefficient and monthly precipitation was demonstrated with a satisfactory coefficient of determination (R^2) equal to 0.7 (Figure 4). In this study, the maximum runoff condition was occurred when monthly precipitation was equal to 0.5 mm. Equally, the minimum runoff condition was occurred when monthly precipitation was 2.5 mm (Figure 5).

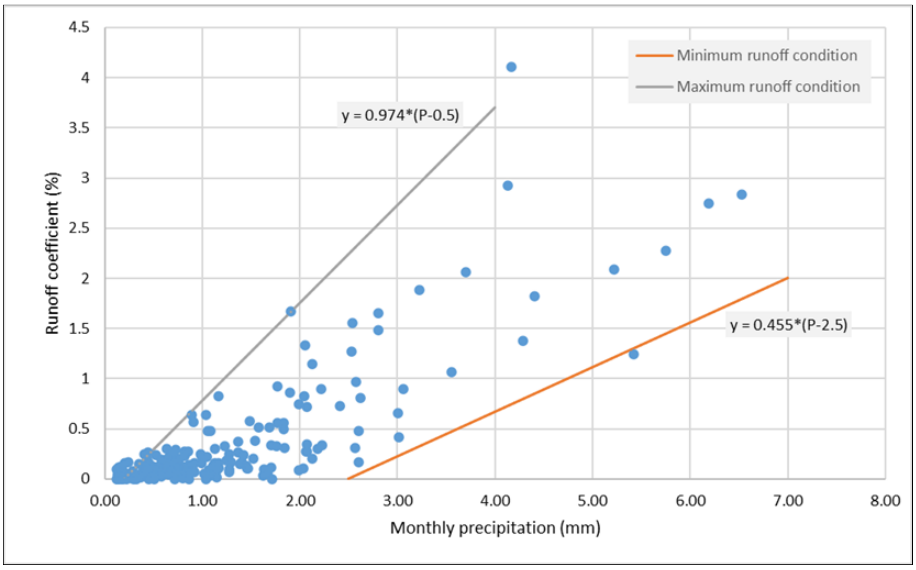


Figure 3 Relationship between runoff coefficient and monthly precipitation

Figure 5 illustrates the annual changes in rainfall and simulated runoff over time, offering insights into the dynamic behavior of these components across the years. The temporal variability of runoff corresponds closely to variations in rainfall, exhibiting a pronounced peak during years of high precipitation. This relationship is particularly evident during two notable instances of increased rainfall in 2003 and 2011, which align with peaks in the runoff levels (Figure 5). Conversely, the years with the lowest recorded rainfall (2000, 2001, and 2017) also show decreased concentrations of runoff. This graphical representation effectively captures the shifting patterns of runoff in response to rainfall and the passage of time. Therefore, it is evident that runoff displays analogous fluctuations reflects the changes in precipitation in the studied area.

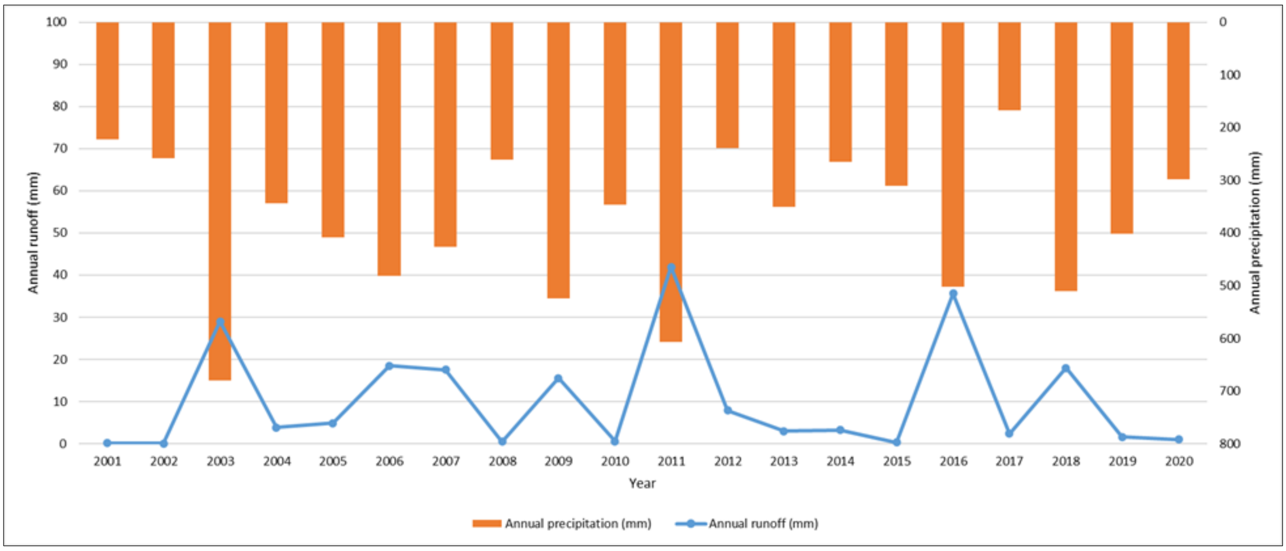


Figure 4 Long-term variations in runoff and rainfall

Understanding the relationships between annual runoff and precipitation is essential for effective water resource management, flood prediction and environmental conservation. In this context, a robust and significant relationship between runoff coefficient and annual precipitation was proved (Figure 6) with a coefficient of determination (R^2) equal to 0.79. In this hydrological study, the maximum runoff condition was occurred when annual precipitation levels reached a substantial 150 mm. During this event, the land's capacity to absorb water was exceeded, resulting in a significant increase in surface runoff. Conversely, the minimum runoff condition was occurred when annual precipitation levels were relatively lower, around 370 mm. These findings underscore the critical relationship between precipitation levels and runoff, illustrating how variations in rainfall can greatly influence the dynamics of water movement within a given area (Figure 6).

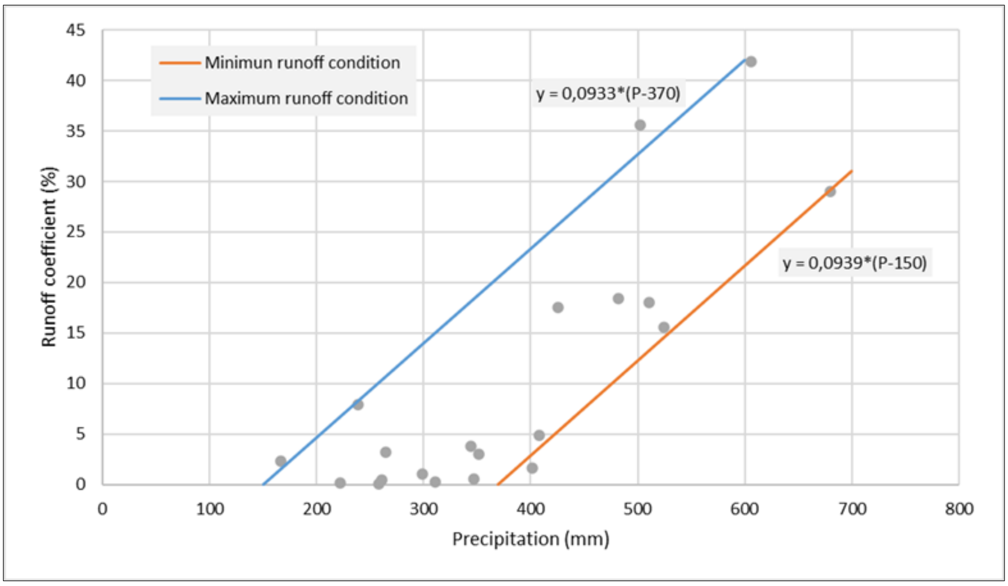


Figure 5 Relationship between runoff coefficient and annual precipitation

Between the years 2000 and 2020, an interesting pattern emerged in this hydrological analysis (Figure 6). Despite experiencing annual rainfall consistently above the mean annual rate, the annual runoff coefficient remained at 10%. This phenomenon can be attributed to the efficiency of a combination of various anti-runoff factors within the study area.

3.3. Spatial distribution of surface runoff

Surface runoff has exhibited notable variations both across different subbasins and over various years. This dynamic behavior underscores the complex relationship between multiple factors that influence the movement of water across the landscape. Understanding these nuanced variations in surface runoff, both across years and subbasins, is essential for efficient water resource management. It emphasizes the need for comprehensive hydrological assessments that consider the complicated interactions between natural and anthropogenic elements shaping surface runoff dynamics. This study shows that there is an important correlation between SWC techniques, vegetation cover and surface runoff over the years.

Various types of vegetation can help decrease surface runoff. The effectiveness of vegetation in reducing runoff depends on several factors, including the type of vegetation, its root structure, canopy density, and the climate and soil conditions. In fact, one of the most significant alteration affecting runoff was the change in LULC. Indeed, olive orchards and pasture classes registered the most significant land use change. The analysis indicates an important decline of 46% in rangelands between 2000 and 2020. Moreover, percentages of areas occupied by forest and garigue were decreasing in the last two decades. From 2000 to 2020, area of olives was increasing from 14% to 21% of the total area.

In general, the change in treated areas with SWC techniques was accompanied by an increase of areas occupied by orchard, olive trees and wheat crops. The scatter plot illustrating the relationship between the surface runoff within the watershed and the extent of terraced areas during the period from 2005 to 2020 provides clear evidence of the sustained influence of terracing practices in diminishing surface runoff. This influence is substantiated by a robust coefficient of determination (R^2 = 0.91 for the linear relationship and 0.99 for the quadratic relationship) (Figure 7). Indeed, this positive correlation emphasizes the success of the chosen SWC strategies and their harmonious integration with land use practices, resulting in a meaningful reduction in surface runoff and its associated environmental benefits. It underscores how these SWC measures, when properly situated and combined with appropriate land use practices, have successfully mitigated surface runoff.

By optimizing the implementation of SWC techniques, including carefully managing slopes and strategically implementing vegetation, the synergy of these efforts has contributed to minimizing surface runoff. During the interval from 2005 to 2010, an increase of 5.6% in areas subjected to SWC management coincided with a notable decline of 3% in surface runoff. In fact, this reduction of runoff was accompanied by an augmentation of olive trees, by around 16% and a reduction of 13% of pasture areas. In contrast, during the subsequent period spanning from 2010 to 2015, the rate of change in treated areas was more modest at 2.27%, yet it yielded a substantial reduction of 25.7% in surface runoff. This reduction is may be also explained by the continued expansion of olive trees (5%) and diminishing of rangelands by about 4%.

This robust pattern underscores the significant role played by vegetation cover, particularly trees, in conjunction with SWC techniques. It is noteworthy that this specific decade, encompassing the years from 2005 to 2015, witnessed a distinct shift in land use dynamics marked by an increase in olive tree cultivation and a concurrent decrease in pasture areas. Consequently, the reduction in surface runoff observed during this period can be attributed to the combined influence of SWC techniques and these alterations in land use practices. This synergy underscores the multifaceted nature of the reduction in surface runoff observed during this timeframe.

During the period from 2015 to 2020, there was a perceptible decline in the annual average precipitation when contrasted with earlier periods. This decrease in rainfall added to the challenges faced by the region. According to this meteorological shift, the expanse of pasture areas continued its diminishing trend, further altering the landscape. In this evolving environmental context, a notable transformation occurred the agricultural landscape. Olive trees expanded, and they were intercropped with wheat crops, which happened to be the domains most treated by SWC measures. The strategic deployment of these techniques also persisted, with ongoing implementation in areas well-suited for their application. This concerted effort and adaptability in response to changing conditions yielded a remarkable outcome. A substantial reduction of 44% in annual surface runoff was observed. This achievement underscored the effectiveness of both agricultural diversification and the continued implementation of SWC techniques in reducing surface runoff (Figure 7). In consequence, the positive impact of combined strategies can be pronounced over a long period.

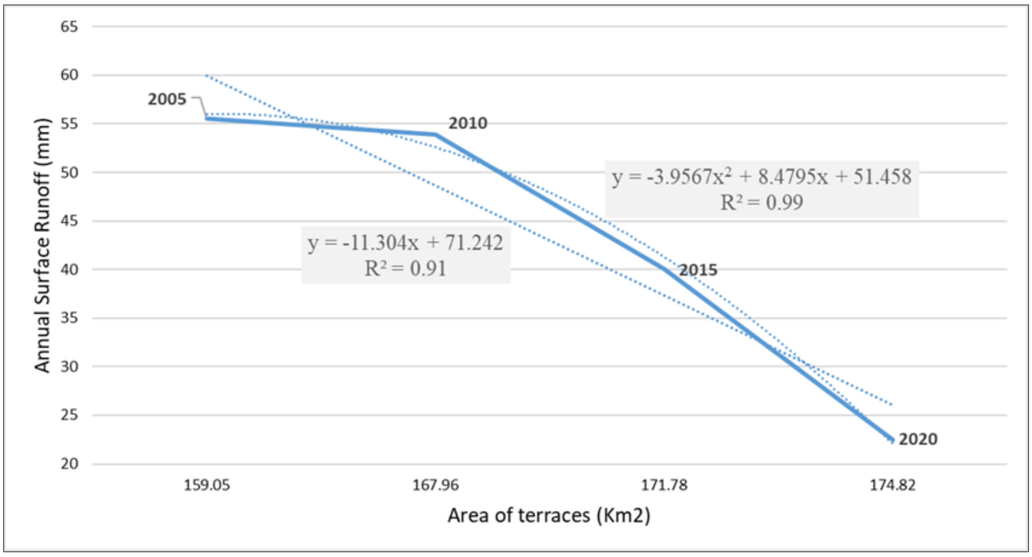


Figure 6 Watershed's annual surface runoff versus the area of terraces (x) between 2005 and 2020

Therefore, a close connection exists between surface runoff and SWC measures. In fact, the inherent synergy between surface runoff and SWC techniques underscores their integral role in sustainable water management and land conservation. The successful implementation of SWC practices positively influences the hydrological cycle, channeling surface runoff towards a more balanced interaction with the landscape. The spatial distribution of surface runoff is a multifaceted phenomenon, shaped by a combination of natural factors such as topography, soil characteristics, vegetation cover, and climate patterns, as well as anthropogenic alterations like land use changes and urbanization. Predicting and forecasting the spatial distribution of runoff sources holds paramount significance in the realm of watershed management and exploitation.

The estimation of the spatial distribution of surface runoff has been carried out through the utilization of the SWAT model. As evident from Figure 8, surface runoff exhibited a concentration in the central and eastern regions of the watershed. Notably, subbasin 14 exhibited a maximum annual average surface runoff exceeding 300 mm (Figure 8). In fact, this area was distinguished by its low slope and the prevalence of wheat cultivation. Moreover, surface runoff, between 200 and 300 mm, exhibits a pronounced tendency to concentrate primarily within areas designated for agriculture such as subbasins 13, 18 and 23 (Figure 8). These agricultural zones are identifiable by their distinct features, such as a limited presence of dense vegetation cover and a prevailing cultivation of wheat crops. Furthermore, a parallel pattern is observed where surface runoff also converges within urbanized localities (subbasin 15), reflecting the intricate interplay between land development and water movement dynamics (Figure 8). On the other hand, subbasins 2, 5, 10 and 11, located in the center of the watershed, with a very moderate slope, less than 50 m, and they were presented with a surface runoff of less than 100 m. This attitude was explained by the important presence of olive trees (Figure 8).

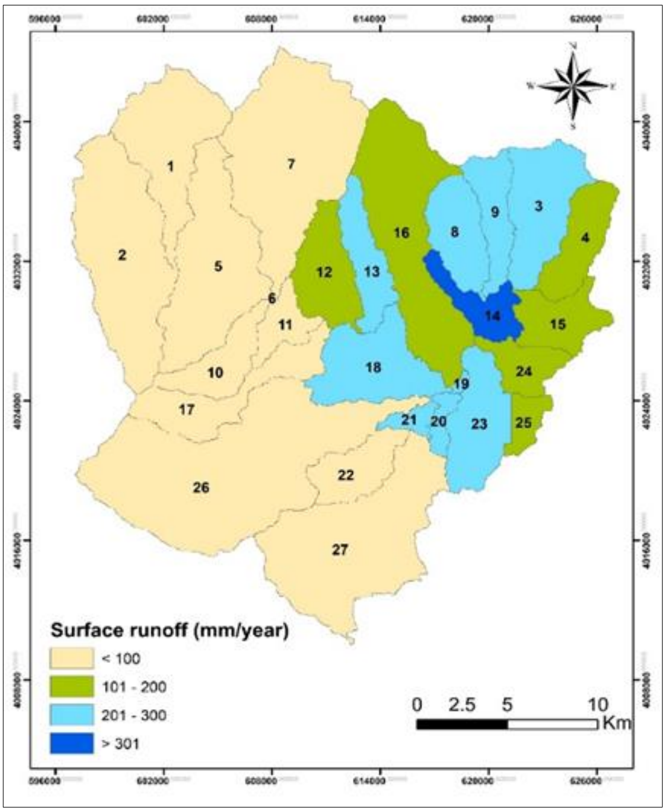


Figure 8 Spatial distribution of surface runoff

4. Discussion

In the realm of hydrological modeling, each step of the process exerts a substantial influence on predictive outcomes and the subsequent decision-making process. This research was undertaken with the primary aim of establishing a correlation between prolonged shifts in precipitation patterns and the resulting runoff dynamics. Concurrently, the study sought to delineate the spatial distribution of surface runoff within the Wadi Rmel watershed, utilizing the SWAT model. The model's efficacy was rigorously examined through both calibration and validation processes. Findings strongly indicate the model's proficiency in replicating authentic hydrological processes using NSE and R^2 indicators. Results of this research present that the model exhibited a notably strong concordance between observed and simulated flows with monthly time step. In fact, this result was consistent with similar research conducted worldwide [25, 26, 27]. In the subsequent phase, the spatio-temporal variability of runoff within the Wadi Rmel watershed was meticulously examined. The outcomes of this analysis revealed a close synchronization between variations in runoff and oscillations in regional precipitation patterns, particularly between the years 2000 and 2020. This synchronicity was most pronounced during notable precipitation events in 2003 and 2011, corresponding to observable peaks in runoff. Conversely, years characterized by limited precipitation such as 2000, 2001, and 2017 exhibited diminished runoff, further corroborating the interdependence of these two variables. The robustness of this relationship was quantitatively affirmed by an R^2 value of 0.79. This alignment between changes in runoff and fluctuations in precipitation patterns was pronounced in other different regions with different climate conditions such as in India [28, 29] and China [30, 31]. Another dimension of the study delved into the impact of anthropogenic interventions, specifically the implementation of SWC measures and land use changes. The impact of these techniques was evident, with a particularly pronounced reduction in surface runoff during the interval of 2015 to 2020. The discovery suggests that the implementation of Soil and Water Conservation (SWC) measures had a substantial and positive impact on curbing runoff when coupled with the cultivation of crops specifically chosen to minimize surface runoff. This synergy between SWC practices and the strategic choice of crops that are less prone to contributing to runoff has proven to be an effective strategy for managing and reducing the flow of water over the land surface. It underscores the importance of not only employing SWC techniques but also aligning them with appropriate land use practices to achieve optimal results in runoff reduction and overall watershed management. This outcome is in agreement with the study conducted by Li et al. [32] that investigated the impact of soil conservation measures on the reduction of runoff between 1972 and 1997. The result suggests that the soil conservation measures were responsible for 87% of the total reduction in runoff observed during that period. Indeed, Zhang et al., [33] affirm that terracing contributes to lower runoff coefficients. Spatially, the distribution of runoff exhibited distinct patterns: central and eastern portions of the watershed exhibited higher runoff, attributed to agricultural activities and hilly terrain while other parts with forested regions or with gentle slopes displayed comparatively lower runoff dynamics. In fact, steeper slopes generally lead to faster and more concentrated surface runoff, while flatter areas might experience slower and more dispersed flow. Pandi et al., [28] convey a similar notion in their findings, highlighting that surface runoff is diminished within mountainous-forested settings. On the other hand, the spatial variability observed within the Ib River watershed in India underscores the influential role of agriculture in shaping surface runoff patterns [29, 34]. It is suggested that the cultivation practices and land management associated with agriculture contribute significantly to altering the natural hydrological dynamics, leading to increased runoff in this area. To summarize, this study underscores the utility of the SWAT model as an adaptable and powerful tool for comprehending the spatiotemporal distribution of surface runoff within arid climatic conditions. The model's capacity to simulate and assess runoff patterns is a significant contribution to the understanding of water resource management in such environments. By shedding light on the complex dynamics of hydrological processes and the influence of anthropogenic interventions, this research contributes to the broader discourse on sustainable water management strategies.

5. Conclusion

Hydrological models were created and employed to create mathematical representations of hydrological processes. The purpose of this research was to establish a correlation between prolonged shifts in precipitation patterns and runoff, while also delineating the spatial distribution of surface runoff within the Wadi Rmel watershed through the utilization of the SWAT model. In fact, for both the calibration and validation processes, the model demonstrates good concordance between observed and simulated flows when using a monthly time step. These results underscore a robust alignment between the observed and simulated streamflow data, signifying the model's effectiveness in reproducing hydrological processes. For the next step, the spatio-temporal variability of runoff of the Wadi Rmel watershed was studied. This section presents that the variations in runoff closely mirror the oscillations in precipitation within the investigated region, between 2000 and 2020. Secondly, this study shows the important impact of anthropogenic interventions like the implementation of SWC techniques. The first finding presents that SWC techniques have an evident effect in reducing surface runoff over the years. Additionally, the spatial distribution within the Wadi Rmel watershed illustrates that surface runoff was notably elevated in the central and eastern sections due mainly to agricultural crops and hilly regions. Surface runoff shows a low average in zones with very moderate slopes and in areas occupied by trees.

In conclusion, this study highlights the effectiveness of the SWAT model as a valuable and useful tool for characterizing the spatiotemporal distribution of surface runoff within a catchment under arid climatic conditions. The model's capability in simulating and assessing runoff patterns contributes significantly to our understanding of water resource management in such environments. Overall, the presented outcomes aim to enhance our comprehension of the hydrological dynamics within the watershed. Thus, enriching the knowledge of decision-makers and regional planners within an ecosystem seems very essential.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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