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(RESEARCH ARTICLE)

Hydrological modelling using SWAT in a Complex Semi-Arid Watershed

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Abstract

Hydrological models have emerged as essential tools for examining the hydrological processes of complex watersheds addressing various environmental and water resource issues. This study focuses on modeling the hydrology of the Merguellil watershed in central Tunisia using the Soil and Water Assessment Tool (SWAT). The SWAT model is a physical modeling tool developed to forecast hydrological processes and is well-documented as an effective tool for resource water management. The primary objective of this research is to evaluate the SWAT model's performance in simulating monthly hydrological processes within the Merguellil watershed in central semi-arid Tunisia. Calibration of the model was conducted from 2002 to 2011, followed by a validation from 2012 to 2017. Sensitivity analysis identified key parameters, including Curve Number, Slope Length, and effective hydraulic conductivity, as the most sensitive. The findings demonstrate that the model exhibits satisfactory performance according to goodness-of-fit criteria during both the calibration and validation phases. The Nash–Sutcliffe Efficiency (NSE) were 0.65 and 0.41, respectively, for calibration and validation periods. The coefficient of determination (R^2) and Kling-Gupta efficiency (KGE) are both equal to 0.7, the RMSE-observations standard deviation ratio (RSR) is less than or equal to 0.6, for calibration. The Percent Bias (PBIAS) indicates that the model overestimates the discharges by +23.5% during the calibration period. In addition, the runoff in Merguellil watershed demonstrated a notable spatio-temporal variability, significantly influenced by the complexity and heterogeneity of its environment.

Keywords: Hydrological modeling; Calibration; Runoff; SWAT model; Tunisia

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1. Introduction

Hydrological modeling is crucial for understanding the fundamental principles of the hydrological cycle, enabling effective management of water resources. Rainfall-runoff modeling has become essential for comprehending and managing water resources across various regions [1,2]. These models offer valuable insights into how catchments respond hydrologically to precipitation. Further, modeling hydrological processes needs interdisciplinary approaches.

In recent years, numerous hydrological models have been developed to investigate alternative management strategies for water resources, assess the impacts of land use and climate change, control floods, and project different potential scenarios [3,4]. There are several agro-hydrological models that differ in their conception. Among the available hydrological models, the Soil and Water Assessment Tool (SWAT) stands out for its robust and polyvalent capabilities [5]. As a distributed hydrological model, SWAT is commonly used to simulate the impacts of human activities, such as changes in land use [6,7], as well as natural measures like erosion [8] and extreme precipitation events affecting water

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quantity and quality [9]. It has been used also to simulate many hydrological processes, including surface runoff, evapotranspiration, land use changes, and water resource management scenarios [6,10–12]. This model offers various modules, including daily and sub-daily runoff modules, enabling users to conduct a thorough and precise assessment of hydrology within a watershed [13]. The SWAT model is incorporated with GIS-based interfaces, allowing for consistent integration. Additionally, it can be easily connected to tools for sensitivity, calibration, and uncertainty analysis such as SWAT-CUP [14].

Arid and semi-arid regions, like Northern Africa, face significant water shortages. Projections indicate that the semi-arid regions of Tunisia, already recognized for their insufficient water resources, will face even greater water scarcity in the future [15]. Merguellil watershed is located in central Tunisia, in a semi-arid context. It suffers from several water management issues as numerous Mediterranean basins. It consists of two geographically contrasting entities. The upstream section, which corresponds to the El Haouareb dam watershed, is mountainous and represents heterogeneous geomorphology. The downstream section is situated in the Kairouan plain, which is extensively irrigated from the Kairouan aquifer [16]. This study focuses on the upstream part of the watershed.

Consequently, the most appropriate model for this study is one that incorporates hydrological processes while accounting for the spatial variability and complexity of the watershed. The Soil and Water Assessment Tool (SWAT) has been selected to recognize its ability to accurately simulate complex and heterogeneous hydrological processes.

The objective of this study is to assess the performance of the SWAT model in a semi-arid Mediterranean watershed situated in central Tunisia, focusing on its ability to simulate hydrological processes and the spatial distribution of runoff in the catchment from 2002 to 2017.

2. Material and methods

2.1. Study area

The Merguellil watershed, located in central Tunisia, has been the subject of numerous research studies that have detailed the study area and the main issues related to water management [17,18]. It encompasses an area of 1200 km^2 extending up to the El Houareb dam (**Figure 1**). The watershed is characterized by a complex and mountainous geomorphology, with altitude varying from 1200 m to 200 m. Specifically, 33% of the area are between 200 m and 400 m, 36% between 400 m and 600 m, 20% between 600 m and 800 m, and 11% exceeds 800 m [19]. The terrain features both steep and gentle slopes, which significantly influences the hydrological process in the watershed. In fact, 70% of the watershed's surface has slopes of less than 7%, while slopes higher than 15% account 10% of the watershed area [16]. The topography of the Merguellil watershed is regarded as rugged. It is situated within a Mediterranean semi-arid climate, characterized by considerable seasonal fluctuations. The watershed lies also in a climatic transition zone influenced by the Mediterranean climate from the north and the hot and arid pre-Saharan region in the south [20]. The Merguellil watershed exhibits spatial and temporal variability in rainfall, with an average annual precipitation of around 300 mm. Consequently, it demonstrates a precipitation gradient of 20 mm per 100 m of altitude [21]. This variability in rainfall, combined with high intensities, leads to significant spatial and temporal fluctuations in hydrological processes.

Moreover, land use and soil types in the Merguellil watershed are diverse and heterogeneous, reflecting the complexity of the ecosystem. The Merguellil watershed plays an important role in the region because it recharges the aquifer of the Kairouan plain, which has the greatest potential for agricultural development in Tunisia [19]. It is an important region for studying the impacts of hydrological processes, climate variability, and land use change within Mediterranean semi-arid environments. Further, this watershed was significantly altered by anthropogenic activities. It is considered a focal point for research on hydrological modeling and on ungauged water-scarce areas. Indeed, it is crucial to understand the interaction between climate variability, geomorphological complexity, and the heterogeneity of land use and soils in a semi-arid Mediterranean context.

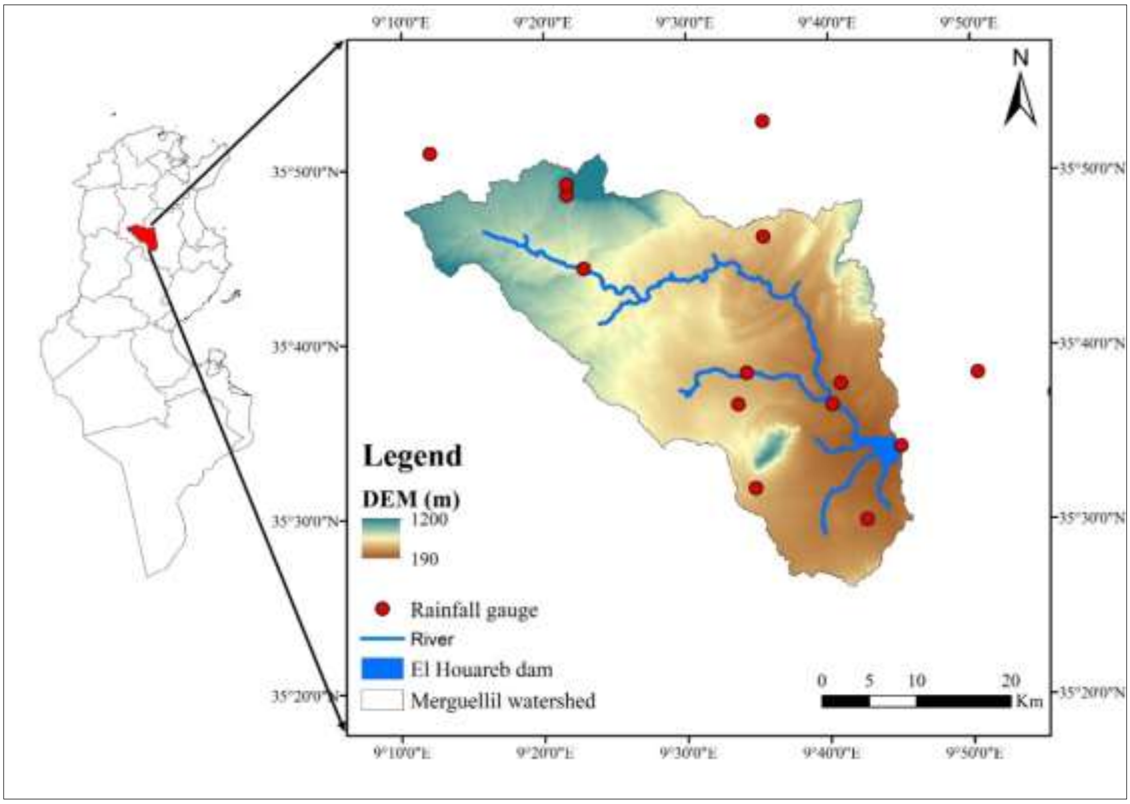


Figure 1 Location of Merguellil watershed

2.2. Description of SWAT model

Soil and Water Assessment Tool (SWAT) is a semi-distributed agro-hydrological model that can operate on a daily or hourly time scale and over long periods [22]. This continuous physical model is designed to predict and quantify the impacts of land management practices and climate on water resources, sediment transport, and the yields of agricultural chemicals in vast and complicated watersheds. SWAT divided a watershed into subbasins linked by a stream network and further delineates these subbasins into Hydrologic Response Units (HRUs), each characterized by distinct combinations of soil and land cover. The hydrologic cycle, simulated by SWAT, is based on the water balance equation [23]:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

Where SW_t and SW_0 are the final and initial soil water content respectively (mm), t is the time in days, R_{day} is amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm) and Q_{gw} is the amount of return flow on day i (mm).

2.3. Model input data

As a physically based, distributed parameter watershed model, SWAT demands extensive geospatial input data to simulate watershed dynamics effectively. The main geospatial input data contains a digital elevation model (DEM), land use map, soil properties and climate data (Figure 2). The datasets listed below were collected for the Merguellil watershed study. A Digital Elevation Model (DEM) with a high spatial resolution of 30 m was used to delineate subbasins. The land use map used in this study was generated from Sentinel-2 satellite imagery (with high spatial resolution of 10 m), employing a supervised classification method. The soil map and their physical properties (including texture, available water capacity, bulk density, saturated conductivity, organic carbon and soil albedo,) were obtained from on-site data collection and laboratory analyses. Daily climate data (precipitation and streamflow) from 2002 to 2017 were provided by Tunisian regional administrations and collected from weather stations. HRUs were delineated within each subbasin by setting threshold values of 10% for land use, soil, and slope (Figure 2).

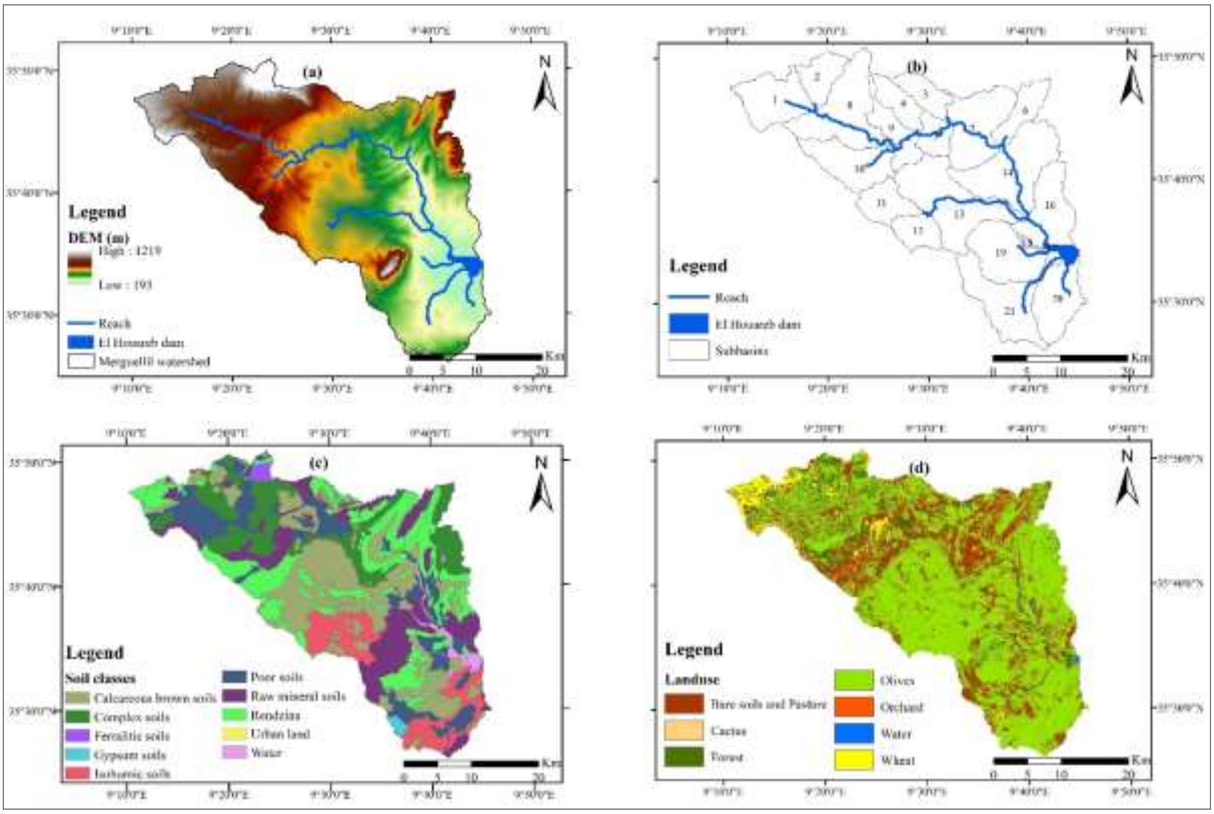


Figure 2 (a) 30 m Digital Elevation Model (DEM), (b) sub-basins of Merguellil watershed, (c) Soil classes and (d) Landuse

3. Results and discussion

3.1. Sensitivity analysis

The delineation of the Merguellil watershed has led to the identification of 21 sub-basins. Further, these sub-basins have been subdivided into hydrological response units (HRUs), which are the basic spatial units of the SWAT model. This subdivision led to 452 HRUs. These HRUs allow for a more accurate representation of each sub-basin by considering the heterogeneity of the landscape in terms of land use, soil types, and slopes [24].

Calibration, sensitivity analysis, and validation are crucial and interdependent steps to minimize prediction uncertainty. For this purpose, we used SWAT-CUP, a tool developed for uncertainty analysis and calibration [25]. More specifically, in this study, we used the SUFI-II algorithm (Sequential Uncertainty Fitting algorithm), a sequential uncertainty fitting algorithm that classifies parameters into specific intervals [26].

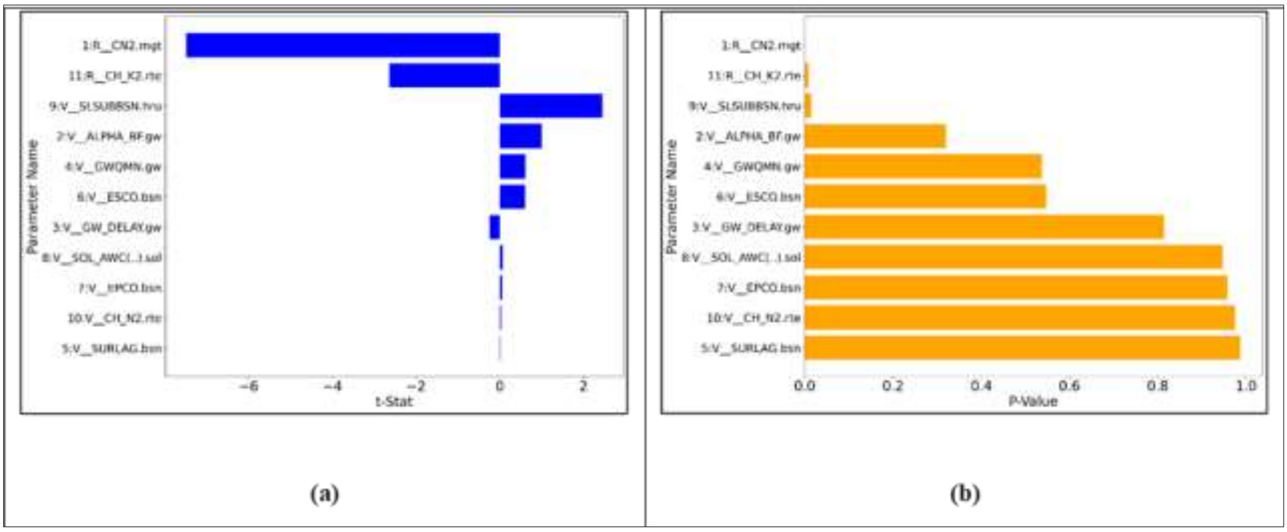
Before calibration, it is crucial to reduce the number of sensitive parameters that have a significant impact on the model simulations. To achieve this, a sensitivity analysis was conducted for the Merguellil watershed. Calibration was carried out using monthly discharge data for the period 2002 to 2011. The monthly discharges measured at the same station were used for the hydrological validation of the model for the period 2012 to 2017. In total, 11 parameters were selected for calibration, as detailed in **Table 1**. A precise adjustment of the intervals of the selected parameters mentioned above was performed.

The most sensitive parameters contribute more significantly to SWAT model uncertainty than less sensitive parameters, especially if these sensitive parameters are not properly calibrated. Therefore, sensitivity analysis is the essential first step in model calibration. However, it is not always possible to calibrate all sensitive parameters in ungauged watersheds. In our study, all soil-related parameters (whether collected in the field or analyzed in the laboratory), as well as certain meteorological parameters (precipitation from the rain gauge), were excluded from the calibration processes. Indeed, measured parameters have a relatively minor impact in hydrological uncertainty modeling, as noted by [26–28].

Table 1 Parameters used in calibration of the Merguellil watershed

Parameter name	Definition	Intervals
CN2	SCS runoff curve number	[-0.3-0.1]
CH_K2	Effective hydraulic conductivity in main channel alluvium	[100-500]
EPCO	Plant uptake compensation factor	[0.3-1]
CH_N2	Manning's "n" value for the main channel	[-0.01-0.3]
GW_DELAY	Groundwater delay (days)	[0-500]
ESCO	Soil evaporation compensation factor	[0.5-1]
SOL_AWC	Available water capacity of the soil layer	[0.25-1]
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	[1000-5000]
ALPHA_BF	Baseflow alpha factor (days)	[0.4-1]
SURLAG	Surface runoff lag time	[10-24]
SLSUBBSN	Average slope length	[80-150]

The parameters are classified according to their sensitivity levels, as assessed by the global analysis conducted with SWAT-CUP, using t-stat and p-value. The most sensitive parameters are those for which the p-value is less than 0.05. According to this statistical analysis and for a monthly time step, three parameters have been identified as the most sensitive: SCS runoff curve number (CN2), effective hydraulic conductivity in main channel alluvium (CH_K2), and average slope length (SLSUBBSN) (Figure 3).



(a) (b)

Figure 3 Sensitivity analysis results

3.2. Calibration and validation of SWAT model

Figure 4 and

Figure 5 present comparisons between the monthly measured discharges at the monthly simulated discharges at the El Houareb dam, which is the outlet for Merguellil watershed, for calibration and validation, respectively.

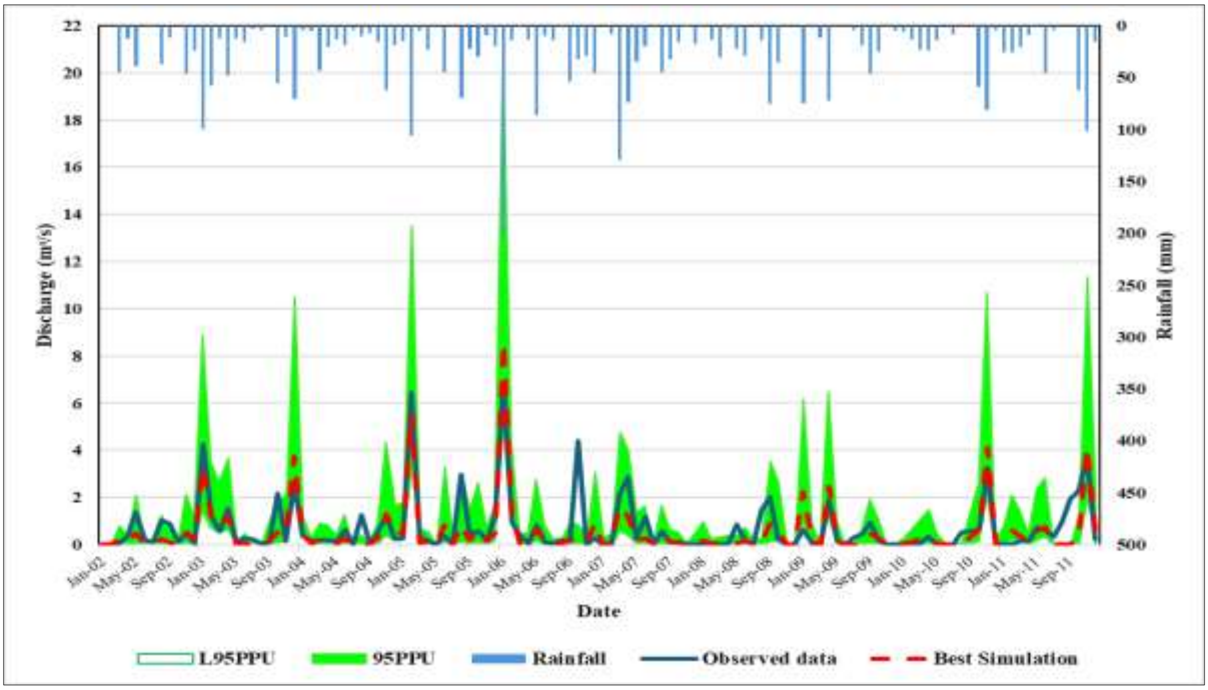


Figure 4 Comparison of the monthly runoff observed and simulated for the calibration period (2002-2011)

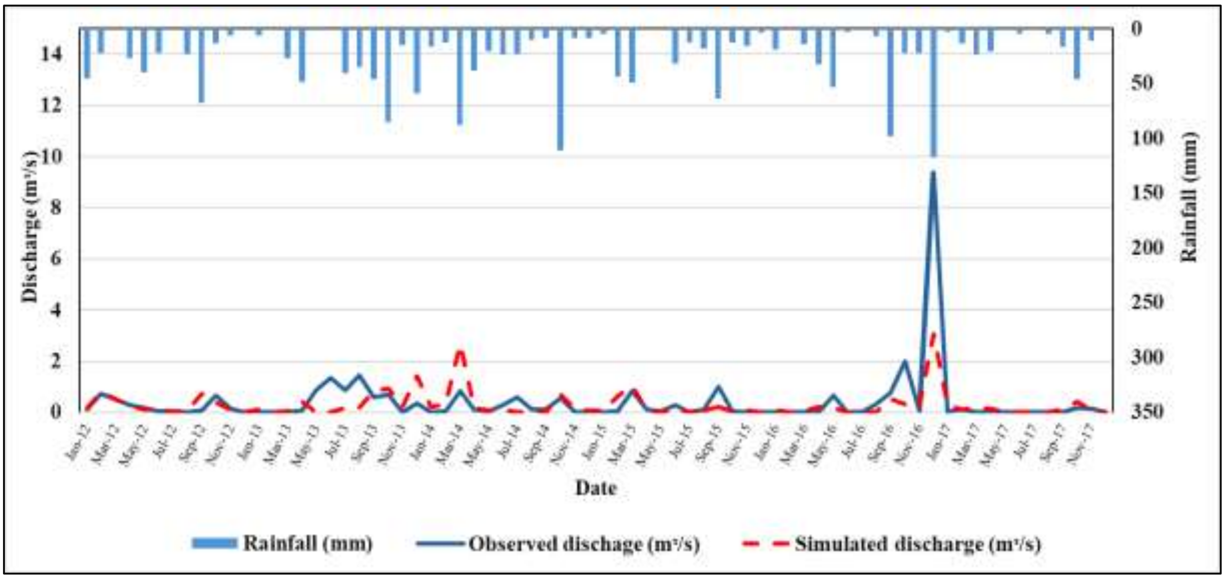


Figure 5 Comparison of the monthly runoff observed and simulated for the validation period (2012-2017)

Two statistics, known as the P-factor and R-factor, are used to quantify the calibration performance or goodness of fit after each iteration. The P-factor indicates model accuracy and ranges from 0 to 1, representing the percentage of measured data that falls within the 95PPU band. Consequently, (1 - P-factor) reflects the model error. The R-factor measures the average thickness of the 95PPU in relation to the standard deviation of the measured data, indicating model uncertainty. It can vary from 0 to a relatively high value, with an R-factor around 1 being ideal, as it matches the standard deviation of the observations. Together, these two factors provide a comprehensive assessment of the calibrated model's performance. A P-factor close to 1 and an R-factor near 0 signify that the calibrated model closely aligns with the measurements. For river discharge, the P-factor should be at least 0.7, while the R-factor should not exceed 1.5 [29]. Consequently, simulation results for a monthly time step showed that the estimated P-factor for calibration is 0.71, meaning that 71% of the observed discharges are included in the 95PPU during the calibration period from 2002 to 2011. In contrast, the R-factor, which assesses the thickness of the 95PPU envelope, is 1.26 for the same period. These results appear to be acceptable for the Merguellil watershed. This indicates that the model effectively represents the hydrological processes within the watershed, providing reliable predictions for water discharge.

In addition, the performance criteria for calibration and validation for a monthly time step are presented in Table 2. The Nash–Sutcliffe Efficiency (NSE) was used as the objective function. Other performance criteria were also considered, including the coefficient of determination (R^2), Percent bias (PBIAS), the RMSE-observations standard deviation ratio (RSR), as well as the Root-mean-squared error (RMSE), Mean Absolute Error (MAE), and Kling-Gupta efficiency (KGE).

Results indicate that all performance criteria (Table 2) for the calibration period are relatively satisfactory: the coefficient of determination (R^2) and Kling-Gupta efficiency (KGE) are both equal to 0.7, the RMSE-observations standard deviation ratio (RSR) is less than or equal to 0.6, and the Nash–Sutcliffe Efficiency (NSE) is 0.65 [9,30]. Thus, the performance criteria reveal a satisfactory agreement between the measured and simulated discharges, for a monthly time step. Additionally, the Percent bias (PBIAS) indicates that the model overestimates the discharges by +23.5% during the calibration period from 2002 to 2011.

However, the model performance is relatively lower for the validation period, with an NSE equal to 0.41, for a monthly time step (Table 2). This is due to the low observed discharges during the validation period from 2012 to 2017. In fact, the measured discharges are generally below 2 m^3/s, except in December 2016, when a discharge of 9.36 m^3/s was recorded with a precipitation of 117 mm (

Figure 5). The model does not perform as well in dry years.

Table 2 SWAT model performance criteria for calibration and validation

	NSE	RMSE	RSR	PBIAS	MAE	R^2	KGE
Calibration	0.65	0.70	0.59	23.5%	0.63	0.7	0.7
Validation	0.41	0.88	0.76	26.1%	0.34	0.5	0.32

3.3. Spatial runoff distribution

Figure 6 illustrates the spatial variability of simulated runoff in the Merguellil watershed between 2002 and 2017. It is noted that runoff in the Merguellil watershed is significantly influenced by the complexity and heterogeneity of its environment. Topographical variations, diverse soil classes, land use change, and divers climatic conditions affect all runoff behavior. Indeed, the topography of the Merguellil catchment is varied, with areas of hills and plateaus. This topographical diversity leads to significant differences in streamflow. In areas with steep slopes (upstream of the catchment), surface runoff is higher, while in flatter areas (downstream of the catchment), infiltration is enhanced, reducing surface runoff. Furthermore, the watershed includes various soil classes, ranging from clay soils to sandy soils, each with distinct water properties. Clay soils, for instance, have a high-water retention capacity, which can increase runoff, while sandy soils allow for faster infiltration but also generate increased runoff during intense rainfall. Moreover, land use plays a crucial role in the hydrological cycle. Protected areas with dense vegetation can intercept rainfall, reduce runoff, and promote infiltration. In contrast, bare soil can increase runoff, especially during rainfall events.

Finally, the watershed is marked by high variability in rainfall [31–33]. It is characterized by prolonged drought periods followed by intense rainfall. These seasonal variations can lead to very different hydrological responses, with flash floods occurring during rainfall events that take place in spring (from February to May) and autumn (from September and October) [34], while dry periods can result in a significant decrease in runoff. Additionally, the configuration of rivers and streams in the Merguellil watershed is complex. The interactions between various streams, hills, and flat areas contribute to an uneven distribution of runoff. In fact, hydrological networks can act as collection areas for runoff water, leading to very different hydrological responses within the watershed.

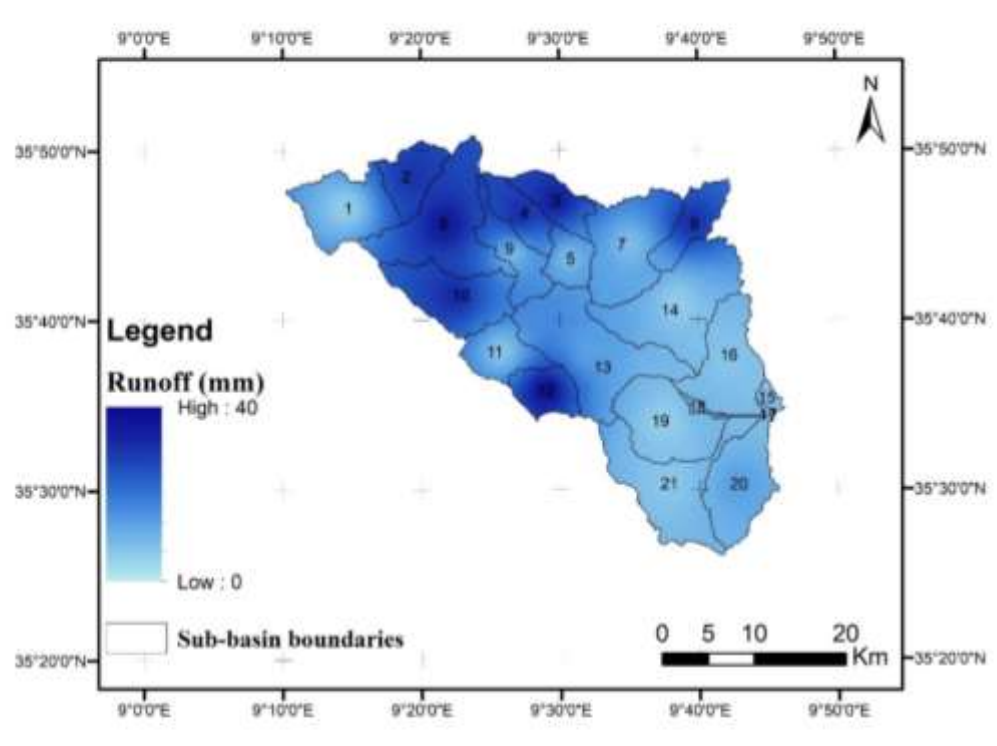


Figure 6 Spatial runoff distribution in Merguellil watershed between 2002 and 2017

4. Conclusion

The aim of this study is to assess the performance of the SWAT model, a physical and continuous modeling approach, in simulating monthly hydrological processes within the Merguellil watershed in semi-arid central Tunisia. A sensitivity analysis was conducted. Calibration and validation were performed using monthly streamflow data for the periods 2002 to 2011 and 2012 to 2017, respectively.

Results of the sensitivity analysis, based on t-stat and p-value, showed that the SCS runoff curve number (CN2), effective hydraulic conductivity in the main channel alluvium (CH_K2), and average slope length (SLSUBBSN) are the most sensitive parameters. In addition, Results indicate that all performance criteria for the calibration period are relatively satisfactory. The Nash–Sutcliffe Efficiency (NSE) were 0.65 and 0.41, respectively, for calibration and validation periods. The coefficient of determination (R^2) and Kling-Gupta efficiency (KGE) are both equal to 0.7, the RMSE-observations standard deviation ratio (RSR) is less than or equal to 0.6, for calibration. Indeed, the Percent bias (PBIAS) indicates that the model overestimates the discharges by +23.5% during the calibration period. Thus, the monthly simulated streamflow showed an acceptable agreement with the measured streamflow, demonstrating the model's effectiveness and its ability to simulate hydrological processes in the Merguellil watershed. Moreover, the runoff in Merguellil demonstrated significant spatio-temporal variability in runoff influenced by the complexity and heterogeneity of its environment. Topographical variations, diverse soil classes, land use change, and divers climatic conditions affect all runoff behavior.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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