Volume CSIEA (12). Published November, 01, 2017
www.jnsciences.org
E-ISSN 2286-5314

JOURNAL OF NEW SCIENCES
WWW.JNSCIENCES.ORG

Hydrological modelling of stream flows in the Rmel watershed using SWAT model

Conférence Scientifique Internationale sur l'Environnement et l'Agriculture

T. HERMASSI*[1], M. KHADHRAOUI[1], H. HABAIEB[1]

[1] National Institute for Rural Engineering, Water and Forests-Tunisia University of Carthage

*Corresponding author: taoufikhermassi@yahoo.com

Abstract - Tunisia is characterized by a semi-arid climate over more than 90% of its territory with irregular and high spatial variability of rainfall. This constitutes a major constraint limiting agriculture development which depends on the availability of water resources. The assessment and the effective management of water resources in a territory require then extensive knowledge of involved hydrological processes as well as their temporal and spatial scales.

This paper discusses the issue of mobilization and hydrological functioning of the Rmel watershed to get an efficient management of water resources in case of scarcity or extreme events using modelling tool.

This watershed (675 km^2) is situated in North-East Tunisia with average annual rainfall of 420 mm and was equipped in 1998 with a dam. Data on rainfall collected at 12 rainfall stations during the period 1998-2013 are analyzed and used to build a coherent series of monthly rainfalls. In a second step, rainfall-runoff modelling using SWAT Model was used to estimate runoff and water budget of the dam. The Nash criterion is about 85% for calibration and validation. For the tow scenarios with an increase of the annual crops and farmland areas, we noticed that the watershed response was affected in the same way, causing an overestimation of water budget and especially the runoff peaks.

The use of the model to make prediction of stream flow using downscaled climatic data from ARPEGE for the period 2060-2080 was discussed. For SWAT model, the estimated stream flow shows a tendency to increase the runoff process explained by the increase of the rainfall intensity.

We noted that the implementation of SWAT model is able to represent efficiently the actual hydrologic runoff phenomenon and to predict watershed hydrological behaviour in the future. Thus, this work could be considered as a new tool decision support that can contribute to better management of natural resources in semi-arid environment.

Keywords: Hydrogical modeling, streamflow, Rmel watershed, Tunisia, climate change.

1. Introduction

Tunisia is a southern Mediterranean country; it is characterized by a spatio-temporal variability of rainfall with a marked contrast of hydro-climatic conditions: a humid climate in the North West to a structural deficit in the Southeast. Aware of these issues, Tunisia began an extensive program of mobilization of water resources, with a partial interconnection of hydraulic structures, in order to satisfy a growing water demand for the demographic development.

Tunisia also has the reputation of being prone to very high erosion risk. Indeed, water erosion is a complex phenomenon threatening water and soil resources of the country. The physical and climatic characteristics of Tunisia are favourable for triggering the water erosion phenomenon. On the other hand, water erosion in Tunisia has been accelerated by socio-economic conditions by crops subsidies agriculture manifested by a great change in the land cover.

Land cover change seriously affects water resources. As the most direct expression of the interaction between human activities and the natural environment, land cover affects the condition of water resources and agricultural economic growth, thereby affecting the process of watershed hydrology and water resource cycles.

Recently, SWAT model has been applied to study climate change scenarios, for vulnerable situation of water availability, specifically, in the regions where more prolonged droughts and more frequent and more intensive floods will occur. In this study the impacts of climate change on stream flow and water resources management using data from the Rmel watershed which is located in the north-eastern of Tunisia to test the effectiveness of the proposed methodology above using downscaled GCM climate predictors in the SWAT hydrological model for water resources predictions, taking into account the evolution of land cover scenarios. Thus, the objective of this study is to improve the efficiency of future water assessment in a climate change context. The output of this study can then be used as an input for further decision support for water resources planning in the watershed.

2. Material and methods

2.1. Study area

The Rmel watershed Rmel is located on the north-eastern of Tunisia. Its stream length is 46 km, with a drainage area of 675 km^2. It is characterized by a maximum altitude at Zaghouan mountain of 1295 m.a.sl. and a minimum altitude at the outlet of 30 m.a.sl..

The Rmel watershed dam was built in 1998 with an average capacity of 22 million m^3. This reservoir is designed mainly for the irrigation of tow public irrigated perimeters Zaghouan (500 ha) and Bouficha (5900 ha). The stored/distributed volume for irrigation depends on the water availability at the dam.

Since 1998 the study area was monitored by hydrological equipments for surface runoff.

The climate is classified as semi-arid according to the UNEP aridity index (UNEP, 1992). So, the watershed is subjected to a double influence: Mediterranean, by the effect of the sea and continental under the influence of mountain prevailing in the region. It is characterized by a great spatial and temporal variability generating very random water availably. Therefore, the mean air temperature is about 20°C and the mean annual precipitation is about 470 mm (decreasing from West to East).

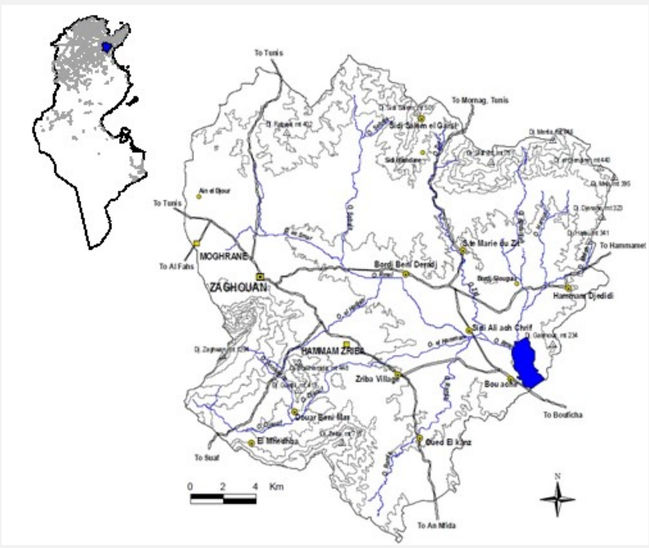

Figure 1. Rmel watershed location.

In addition to the dam, 22 hill lakes were built on the Rmel watershed. The majority of these hill lakes are intended for the agricultural holding, for the protection and groundwater recharge.

This watershed is bounded by mountains like Jebel Jenaini (400 ma.s.l), Jebel Merlia (646 ma.s.l), Jebel Zouaouine (477 ma.s.l), Jebel Keffa (349 ma.s.l), Jebel Zaghouan (1295 ma.s.l), Jebel Naoura (534 ma.s.l), Jebel Mdeker (464 ma.s.l) and Jebel Abid (311 ma.s.l).

The upper mountainous area of the Rmel watershed is covered with forest and grassland. The middle and downstream plain areas, which are covered with arable land, are an important part of the agricultural activities and which are occupied by annual crops of cereals, vegetables, olive trees and orchards.

2.2. Hydrolgical Modeling

Distributed hydrological models, such as the SWAT (Soil and Water Assessment Tool) model, are large-scale basin models that have been widely used recently. As a typical distributed hydrological model, the SWAT model is globally used because the input variables can be easily obtained, it has high computational efficiency, it provides long-term watershed simulation, and it is open sourced.

SWAT model is a continuous-time; semi physically based hydrologic model operating on a daily time step and is designed to predict impacts of land management practices on water, sediment and agricultural yields (Arnold et al., 2012).

In SWAT model, the catchment is divided into multiple sub-watersheds based, which are then further subdivided into hydrologic response units (HRUs). The water balance for each HRU is represented by the following equation:

Equation 1:

$$SW_t = SW_0 + \sum P_i - \mathrm{Q_{sup.i}} - Q_{lat.i} - \mathrm{ET_i} - \mathrm{Q_{sub.i}})$$

where SW_t: the final water content of the soil (mm); SW_0: the initial soil water content (mm); P_i: the pluvial precipitation (mm); Q_{supi}: the surface runoff (mm); $Q_{lat\ i}$: the lateral flow (mm); ET_i: the evapotranspiration (mm); and $Q_{sub\ i}$: the groundwater flow (mm).

In SWAT model and for the daily time step, the surface runoff is computed by the the Soil Conservation Service method (SCS) curve number (CN) method (USDA-SCS, 1972). The Runoff is then routed through the channel network using the variable storage routing method (Williams, 1969). The surface runoff was calculated by

Equation 2:

$$Q_{surf} = \frac{(R_{day} - \mathrm{I_a})^2}{(R_{day} - \mathrm{I_a} + S)}$$

Where, Q_{surf}: the accumulated runoff or rainfall excess (mm), R_{day}: the daily rainfall depth (mm), I_a: the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm) and S: the soil water retention parameter (mm). Hence, runoff occurs when $R_{day}>I_a$.

The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content, it is adjusted based on the antecedent rainfall. The retention parameter is defined as:

Equation 3:

$$S = 25.4.(\frac{1000}{CN} - 10)$$

Where CN: the curve number of the day which is an empirical parameter used in hydrology for predicting direct runoff or infiltration from excess rainfall. CN is controlled by the soil type, the soil hydrological condition, vegetation cover, land use and treatment, and the antecedent moisture condition.

2.3 Input data

The required input data for SWAT model include DEM (Digital Elevation Model), land use/cover, soil type, and hydrometeorology.

The DEM data were obtained from the Aster (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM (Global Digital Elevation Model) grid with a resolution of 30 m was used as topographical input to define the watershed boundary, river network, sub-basins, and to derive slope-related parameters.

Land use data were obtained from the agricultural map the scale 1/50000 (Ministry of Agriculture, 2000).

Soil data were obtained from the agricultural map the scale 1/50000 (Ministry of Agriculture, 2000).

Precipitation: Daily rainfall data of five rain gauge stations (Rmel dam, Oued Ezzit, Zaghouan, Mograne and Sbaihia). The data were collected from the Water Resources Directorate of the Ministry of Agriculture. It is noted that the study area is an agriculure use on most part by a wheat (52%), followed by a pasture and forest area were representing 18 % and 16 % respectively.

Meteorological data such as relative humidity, air temperature, solar radiation and wind speed were provided by the National Centers for Environmental Prediction (NCEP) for the period 1998-2013.

Hydrological data from 1998 to 2013 of the Rmel watershed measured at the Rmel dam gauging station were collected from the Dams Directorate of the Ministry of Agriculture. The Location of the gauging station is shown in Figure 1.

3. Results and Discussion

According to the Rmel watershed hydrographical network, the watershed was divided into 43 subbasins. On the basis of the sub basin, land use data and a soil type map were input into the SWAT model, with a set basin slope rating. The threshold values were set at 10%, and the Rmel watershed was divided into 122 hydrological response units (HRUs). After meteorological data and other database files were input to the model, the watershed hydrological simulation process was achieved.

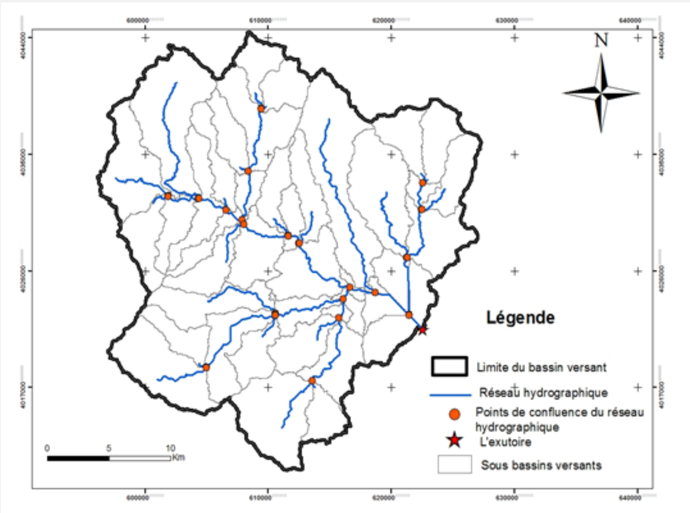

Figure 2. Subdivision into sub watershed of Rmel watershed

3.1. Sensitivity analysis

The main objective of the sensitivity analysis is to study the behaviour of model parameters to reduce their number for the calibration procedure (Refsgaard, 1997). Since the parameters are not independent, the equifinality problem (Beven, 2001) can be limited if only a minimum of parameters affecting the production and transfer functions are retained at the hydrological unit scale.

SWAT-CUP was developed mainly for SWAT calibration, validation, and uncertainty analysis. They integrated the continuous uncertainty matching algorithms.

The parameter sensitivity analysis, calibration, verification, and uncertainty analysis can be performed by comparing the results of the SWAT model to those of the SWAT-CUP. Based on the SWAT-CUP program, the SUFI-2 algorithm (Sequential Uncertainty Fitting algorithm) was chosen for the sensitivity analysis of the model parameters.

Based on the Rmel watershed situation, 8 parameters were chosen, are shown in Table 1.

Table 1. Calibrated parameter values for Rmel Watershed

Parameter	Influence object	Sensitivity ranking
CN2	Surface runoff	1
GW DELAY	Groundwater process	2
ALPHA BF	Base flow	3
SURLAG	Surface runoff	4
ESCO	Soil evaporation	5
GW REVAP	Groundwater process	6
ALPHA BNK	Stream runoff	7
SOL AWC	Soil moisture	8

For the surface runoff model calibration, the performance of the simulation was assessed based on the Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970).
Equation 4:

$$NSE = 1 - \frac{\frac{1}{N}\sum\left(Q_{sim}(t) - Q_{obs}(t)\right)^2}{\sum\left(Q_{obs}(t) - \overline{Q}_{obs}(t)\right)^2}$$

3.2. Analysis of the Simulation Results

The available data was divided into two periods, the first period (September 99 to August 2006) was chosen for calibration and the second period (September 2006 to August 2013) was chosen for validation. The comparison of simulated and measured monthly runoff shows that the results are fairly accurate at Rmel watershed.
For the calibration period, the result shows that the Nash criterion is of the order of 85. The correlation coefficient was also greater than 0.66 with a general aver estimation of peaks about 5%. The simulation results of the calibration period are acceptable. It should be noted that the model simulate some peak runoff that are note well performed relating to the quality of observed runoff. But, in general, it is clear that the model was indicated a very close agreement between observed and simulated results.

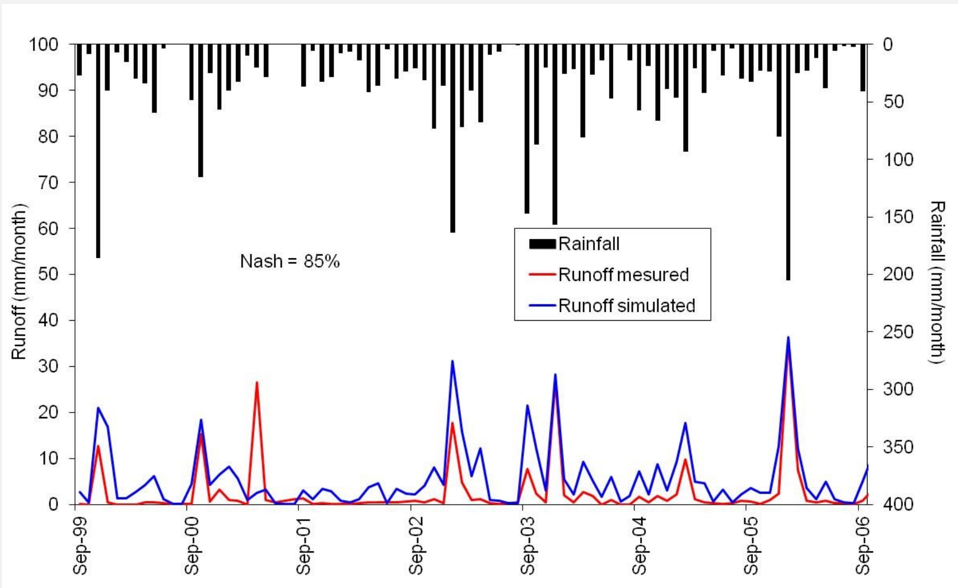

Figure 3. Comparison of the observed and simulated discharges for the Rmel watershed during the calibration period (1999-2006).

The figure 3 shows that the high spikes of the simulated hydrograph are close to the high peaks of the observed hydrograph, except for the lowest discharges peaks, the forms of the two hydrographs are quite close to one another, the simulated volume is always over-estimated compared to the volume observed. It is noted that in the calibration period that the April 2001 event is not well simulated by the model since the rainfall calculated by the Thiessen method smoothed this value which is not representative of the whole watershed which probably concerned mainly the downstream part of the watershed only. By eliminating this event the Nash criterion increase to 89% and the correlation between the simulated and observed discharge is about 81%.
For the validation period, the result shows that the Nash criterion is of the order of 84% (figure 4). The correlation coefficient was also greater than 0.65 with a general aver estimation of peaks about 15%.
The figure 4 shows the validation result of the SWAT model at the Rmel watershed for the period September 2006 to August 2013:

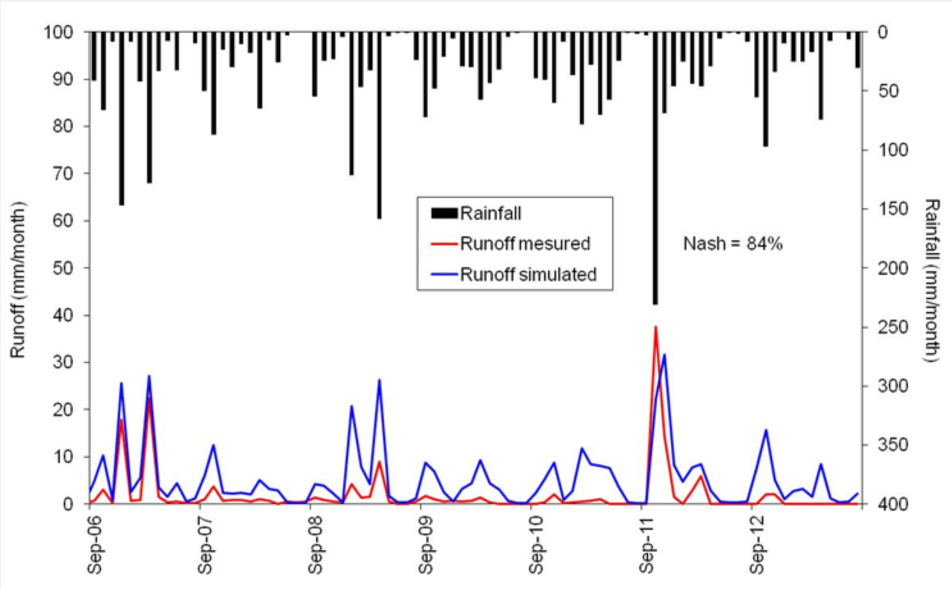

Figure 4. Comparison of the observed and simulated discharges for the Rmel watershed during the validation period (2006-2013).

The high peaks of the simulated hydrograph are close to the high peaks the observed hydrograph but there is always an overestimated by the model. This overestimation of the runoff is accompanied by the corresponding volumes.

3.3. Land use change scenarios

After calibration, the SWAT model was used to test several scenarios on land use in order to determine their impacts on runoff. This evaluation is made by comparing the scenarios discharge at the outlet with the reference observed current discharge.
The scenarios was chosen based on the increase in the annual crops and agricultural land area depends on the surfaces of pasture and forests, in fact with climate change and increasing subsistence needs, land uses tend to change their vocation to meet the needs of farmers.
In order to study the hydrological response of the SWAT model to the land use changes, the cereals surfaces increase from 52% to 70% and then to 86% depend on the rangelands (17%) and forests (16%). The figure 5 shows the simulation for the first scenario and the second scenario.

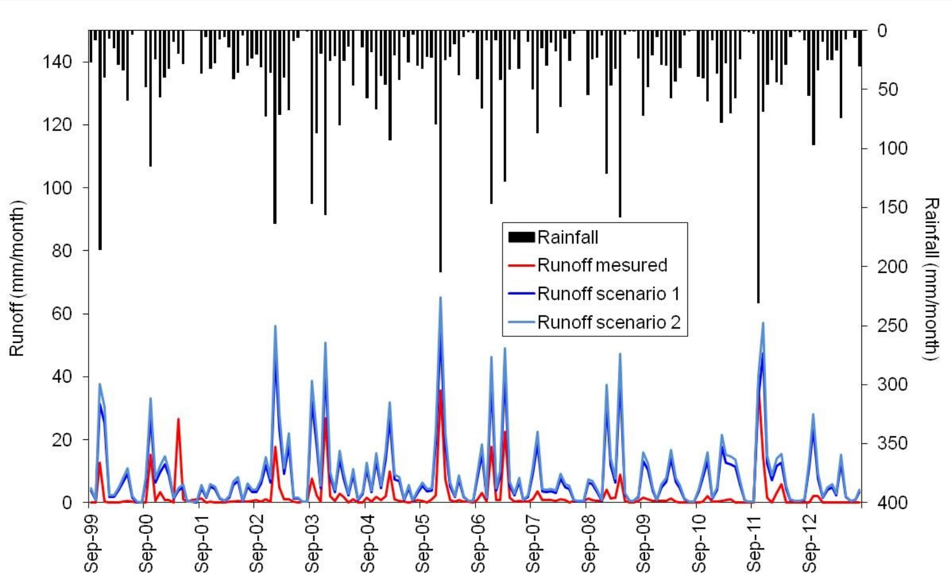

Figure 5. Comparison of the observed and simulated discharges for the tow scenarios at the Rmel watershed.

For both scenarios, the increase in the area of annual crops and agricultural land similarly affects the hydrological response of the watershed, causing the overestimation of flows from the current state, especially at the peaks of the discharge, the first scenario causes an over estimation about 150% and the second about 180%. These changers of land use promote the runoff especially during the autumn and just before plowing, by reducing the vegetation cover and the development of a thin crust, which greatly reduces the infiltration process especially for the events characterized by high intensities.

3.4. Climate change scenario

In order to understand the hydrological behaviour of the Rmel watershed in the context of climate change, the scenario was carried out using the data from ARPEGE model of Météo-France for the period 2070-2100. Indeed, the period 2070-2100 will be marked by an increase in water requirements, but it is also marked by a decreasing rainfall and increasing temperatures that will aggravate the future situation. Based on the assumption of future climate change scenarios, the SWAT model was used to estimate runoff in the Rmel watershed on a monthly scale for the future periods. This simulation is carried out with the aim of having hydrological forecasts for the period 2070-2100 based on daily climatic data (rainfall, maximum and minimum temperature) provided from ARPEGE results at the Mograne station.

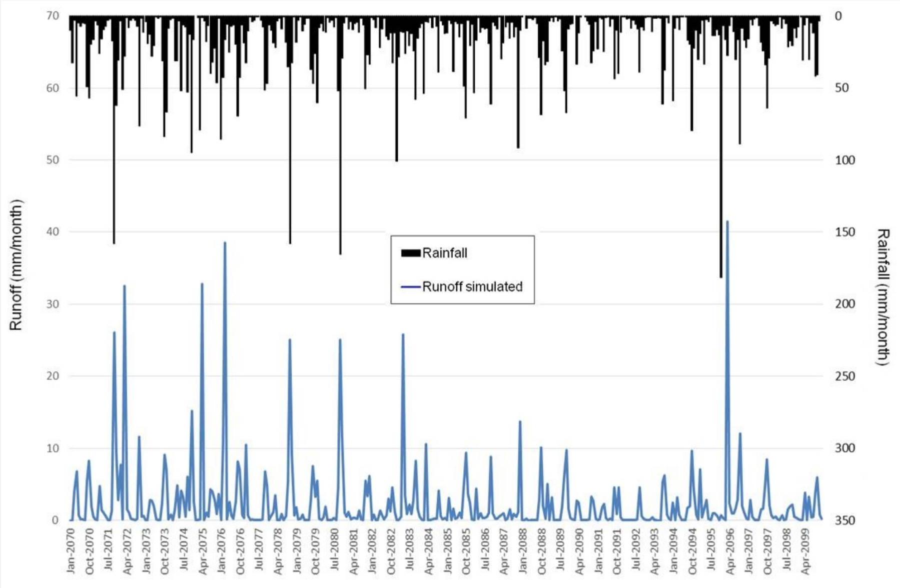

Figure 6 : Simulated discharge using SWAT model for the period 2070-2100 at Rmel watershed.

The future change in the precipitation regime modifies the frequency and the amplitude of certain classes of daily precipitation, in fact, it is noted that the high peaks of discharge will slightly increase during the period 2070-2100 despite the decrease of rainfall; the result is due to the emergence of increasingly important intensities.
Measures to be undertaken for mitigation and adaptation due to climate change require further study of future hydrological behaviour to address the reduction of water resources but also the relationship with other factors that influence the watershed hydrology such as land use management.
The calibration, validation and simulation results show that the SWAT model satisfactorily reproduces the measured discharges in the Rmel watershed for the first period 1999-2006 and a less satisfactory for the second period 2006-2013. The statistical coefficients (Nash criterion) show a good fit of the model for the calibration and validation periods. The model has strong applicability; it can be used to simulate the monthly runoff process in this watershed.
The results take into account the difficulty of the model to reproduce the dynamics of the discharge: overestimated peaks flow and volume over the two periods. On the other hand, the water balance showed that the model respected globally the orders of magnitude of the volumes of water at the reservoir. These errors are within the acceptable range for the study purpose of assessing the long-term effects.
Thus, we can conclude from the calibration-validation phase that the model has managed to reproduce the current hydrological behaviour in a sufficiently reliable way.
The future climate change assumption is based on the results of downscaling of regional climate predictions. As the future climate is uncertain, many other factors will affect hydrology and water resources, in addition to rainfall and land use changes.

4. Conclusion

The implementation of SWAT model is able to represent efficiently the current hydrologic runoff phenomenon and to predict watershed hydrological behaviour in the future. Considering two land use scenarios may occur for future hydrologic changes that needs calibrated and validated watershed model. The land use scenario is presented as a scenario that should be reached to mitigate the impacts of climate change. The outputs for this scenario are compared with current land use scenario.
The hydrological model applied is the SWAT model, for its implementation, we have prepared a database (DEM, land use map and soil types, climate data). Due to the limitations, there were some errors in the simulation.

The estimation of inputs for a possible climate change shows a tendency to increase the runoff process. It should be noted that the implementation of the SWAT model on a Tunisian watershed area is long and laborious because of the enormous mass of parameters that must be provided and the lack of data and that there are certain points to be explored in the future, such as the water erosion study.

5. Références

Arnold JG, Moriasi DN, Gassman PW., Abbaspour KC., White MJ, Srinivasan R, Santhi C, Harmel RD, Griensven A,Van-Liew MW. Van Kannan N, Jha MK. (2012) SWAT: model use, calibration, and validation. 2012 American Society of Agricultural and Biological Engineers ISSN 2151-0032. Vol. 55(4): 1491-1508.

Beven K (2001) How far can we go in distributed hydrological modelling? Hydrology and Earth System Sciences, 5(1), 1-12.

Refsgaard JC (1997) Validation and Intercomparison of Different Updating Procedures for Real-Time Forecasting. Hydrology Research IWA Publishing 1997, 28 (2) 65-84.

Ministry of Agriculture (2000) Cartes agricoles régionales des gouvernorats de Zaghouan Ben Arous et Nabeul. Commissariats de Développement Agricoles Régionales-Ministère de l'agriculture-Tunisie.

Nash J, Sutcliffe JV (1970) River flow forecasting through conceptual models part I—A discussion of principles. J Hydrol 1970; vol. 10, no. 3, pp. 282–290.

UNEP (1992) World Atlas of Desertification. UNEP, Geneve.

USDA-SCS (1972) National engineering handbook, Section 4, Hydrology. USDA-Soil Conservation Service. Washington, DC.

Williams JR, Kannan N, Wang X, Santhi C, Arnold JG (2012) Evolution of the SCS runoff curve number method and its application to continuous runoff simulation, Journal of Hydrologic Engineering, vol. 17, n°. 11, pp. 1221–1229, 2012. DOI: 10.1061/(ASCE)HE.1943- 5584.0000529.