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SWAT model application for sediment yield modeling and parameters analysis in Wadi K'sob (northeast Algeria)

Noureddine MAREF*, Djelloul BAAHMED, Kader BEMMOUSSAT, Zakaria MAHFOUD

A comprehension of the erosion processes and sediment transport in the watershed is essential for the sustainable management of the water resources and soil fertility. In this study, the Soil and Water Assessment Tool (SWAT) model was applied to demonstrate its ability to modeling the suspended sediment yield in the Wadi K'sob basin located in the northeast of Algeria. The data used to set up the SWAT model are the Digital Elevation Model (DEM), land use, soil types and weather data. The results obtained after calibration oscillating between good and satisfactory where (NSE=0.67 and R^2=0.73) in the first calibration period and (NSE=0.65 b and R^2=0.67) in the second period. In the validation, the performance of the SWAT model was very good (NSE =0.78 and R^2 =0.79) in the first period while in the second period the prediction of the model was satisfactory (NSE=0.52 and R^2=0.54). In addition, the validation process revealed that some parameters are stable and related on watershed characteristics while other unstable parameters depend on soil properties especially soil permeability and soil erodibility.

KEY WORDS: Sediment yield, Modeling, SWAT, Model parameters, Performance

Introduction

The sediment transport in Algerian watershed is dominated by suspended sediment (Probst and Amiotte-Suchet, 1992) that making it the largest source of sediment transported to the dams (Toumi and Remini, 2020). These reservoirs are strongly affected by the siltation phenomenon which reduces the water storage capacity and the useful life of certain dams (Remini and Hallouche, 2007). In Algeria, the silting of dams in exploitation is increasing year by year. It was 32 Mm^3 $year^{-1}$ in 2000 (Remini and Hallouche, 2004), it increased to 45 Mm^3 $year^{-1}$ in 2006 (Remini and Hallouche, 2007). The siltation rate rose to 65 Mm^3 $year^{-1}$ in 2017 which represents about 0.75% of the annual loss of dam capacity (Remini, 2017).
In addition, the water erosion and sediment transport represent the first factor that reduces the fertility of agricultural land (Xiong et al., 2024), by leaching nitrogen that concentrates in surface water and leads to its pollution (Siman and Velisková, 2020, Kováčová, 2022, Kováčová, 2023).
The sediment transported in streams is usually estimated at the gauging station using in situ measurements of suspended sediment concentration (Achite and Ouillon, 2007). However, it is impossible to apply these measurements in ungauged watersheds, which makes it difficult to quantify the volume of sediment deposited in dams. Therefore, the lack of sediment transport observations leads then to develop several hydrological models (Achite and Ouillon, 2007).
Nevertheless, application of these models usually requires different physiographic factors such as topography, soils characteristics and land use (Lisitisyna and Aleksandrova, 1972). Recent advances in Geographic Information System (GIS) tools and remote sensing technologies have overcome many difficulties and limitations in running these models (Khanchoul et al., 2020).
In this context, several models have been developed, in order to predict sediment transport and erosion processes at the basin scale. These include the Water Erosion Prediction Project (WEPP), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) and Soil and Water Assessment Tool (SWAT).
Indeed, Soil and Water Assessment Tool (SWAT) model was applied for erosion modeling in many parts of the world, including semi-arid watersheds (Mosbahi et al., 2012). SWAT model was tested in several watersheds across Africa, especially in the west Africa (Mosbahi et al., 2012). For exemple, SWAT was applied in Keleta watershed (central Ethiopia) by Tibebe and Bewket (2010), Fadi et al. (2011) used SWAT in the Bouregreg basin (Morocco) and Bouraoui et al., (2005) in the Medjerda catchment in Tunisia.
In Algeria, the SWAT model was applied, in a number of studies, to predict sediment transport and silting of dams

such as Hallouz et al., (2018), Zettam et al., (2017), Kateb et al., (2019) and Khanchoul et al., (2020).

SWAT is widely used to predict water balance and sediment loss (Premanand et al., 2018), it can also simulate the movement of nutrients and pesticides in the watershed (Arnold et al., 2012).

Thus, the principal advantage of SWAT is that it can assess the impact of land management practices on quantity and quality of water in large complex watershed with varying soils, land use and management conditions (Premanand et al., 2018, Khanchoul et al., 2020). This model requires several input data, which consists of the Digital Elevation Model (DEM), land-use, soil types and meteorological data (Shivhare et al., 2018). In recent years, the SWAT model has been implemented in the geographical information system platforms (QGIS and ArcGIS) that allow the extraction of spatially distributed parameters of elevation, land use and soil types.

SWAT divides the watershed into sub-watersheds connected by a stream network. Then each sub-basin is further subdivided into several Hydrologic Response Units (HRUs), where each HRU contains the same land use, soil characteristics and slope classes (Neitsch et al., 2005; Worqlul et al., 2018). HRU represents the basic simulation unit on which the SWAT model estimates the sediment yield with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977).

However, SWAT is characterized by a large number of parameters (Sane et al., 2020) where the successful application of this model depends on the calibration of sensitive parameters (Duan et al., 1992). In this context, several calibration programs have been developed for SWAT model, such as SWAT-CUP and R-SWAT. Although, SWAT-CUP is recognized as the most popular software used for SWAT model calibration procedure (Pandey et al., 2021), it has some disadvantages which are the update problems and difficulty in operation (Ozdemir et al., 2018). One alternative of SWAT-CUP is R-SWAT which is an open source program written in R language. It has been developed for automatic calibration of SWAT model. This program contains several calibration and sensitivity analysis algorithms, among them, Generalized Likelihood Uncertainty Estimation (GLUE) is a practical method, easy to implement and widely used in hydrology (Pandey et al., 2021).

In this study, SWAT model was chosen for sediment yield modeling as well as to test its performance in Wadi K'sob basin using R-SWAT code. The Wadi K'sob was selected for this study because of its contribution to the silting up of the K'sob dam.

Material and methods

Study watershed

The Wadi K'sob is part of the large Chott el Hodna watershed (Fig. 1). It is limited in the north and northwest by the mountain range of Bibans, in the south and southwest by the Hodna Mountains and in the east by the high plains of Sétif (Zeroual, 2016). The geographical location of the basin is between 35°55'10.46" N and

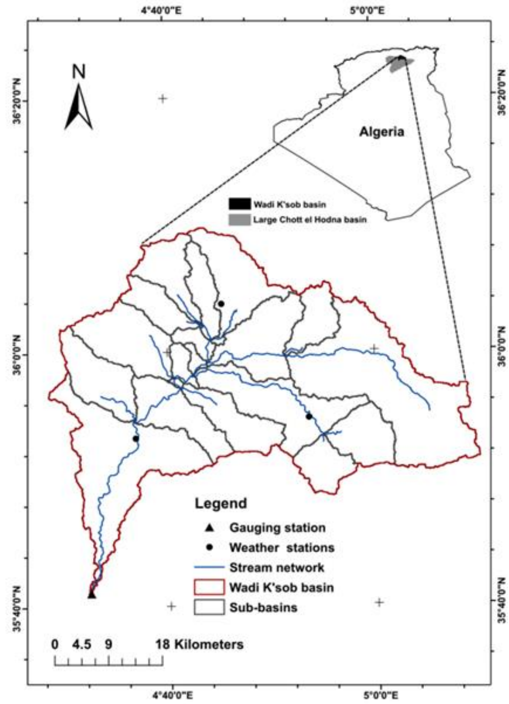

Fig. 1. Geographical position of the study watershed.

36°9'26.26'' N, and 4°27'56.84'' E and 5°10°40.51'' E. The total drainage area of the basin is approximately 1539 km^2. The length of its main channel is 93.4 km. The elevation of the watershed ranges from 428 m to 1869 m (Fig. 5). Slopes within the catchment vary between 2.9% and 57%, whereas the average slope of the main channel is 1.5%. The Wadi K'sob arises at an altitude of 1620 m and then flows in a northeast to southwest direction of the basin and finally empties into the K'sob dam at 454 m.

The climate of the study catchment is Mediterranean, characterized by high temperature and low rainfall with an irregular rainfall pattern in time and space. The Mediterranean climate is identified by the strong change between seasons (Aboumaria et al., 2009).

Mean annual precipitation is around 574 mm year^{-1} (2002–2014), mostly concentrated in autumn (October to November), winter (December to February) and spring (March to May) while the dry period extends from June to September. As for the average annual potential evapotranspiration, it is about 792 mm. This value is approximately 37% higher than the average annual rainfall. The temperature ranges from -2°C to 36°C and mean annual temperature is 14°C. July is the hottest month while the coldest month is January.

Mean annual discharge recorded at the gauging station (Fig. 1) for the period (2004–2014) was 1.18 m^3 s^{-1}.

In terms of sediment transport, the Wadi K'sob basin has a specific degradation of about 474 t Km^{-2} year^{-1} which corresponds to 0.73 Mt year^{-1} of sediments transported to the K'sob Dam. Demmak (1982) estimated the specific degradation of Wadi K'sob basin for the period (1972–1979) at 344 t Km^{-2} year^{-1} which means that erosion activity in this basin has accelerated in recent years.

The monthly distribution of runoff and sediment yield in

Wadi K'sob is shown in Fig. 2. It reveals an irregular flow regime of this Wadi with a remarkable variability of the sediment yield. Thus, sediment yield is not closely related to water discharge, especially in January and May. Although, these two months are considered rainy months, they are the least productive of runoff while producing more sediments. This means that there are other factors influencing soil loss such as low vegetation cover, the vulnerability of the soil to erosion due to high temperatures and the high intensity of rainfall (Demmak, 1982).

Land use map (Fig. 3) shows that most of the catchment is under natural vegetation cover composed of scrub/shrub (55.81%), crops (22.68%) and trees (3.95%). The rest consists of crops (22.68%), built area (10.97 %), and bare ground (6.29%).

The soil map of the Wadi K'sob basin presented in Fig. 4, shows that there are six (6) classes of soil types in this basin, the details of their nomenclatures according to the FAO–UNESCO classification are given in Table 1.

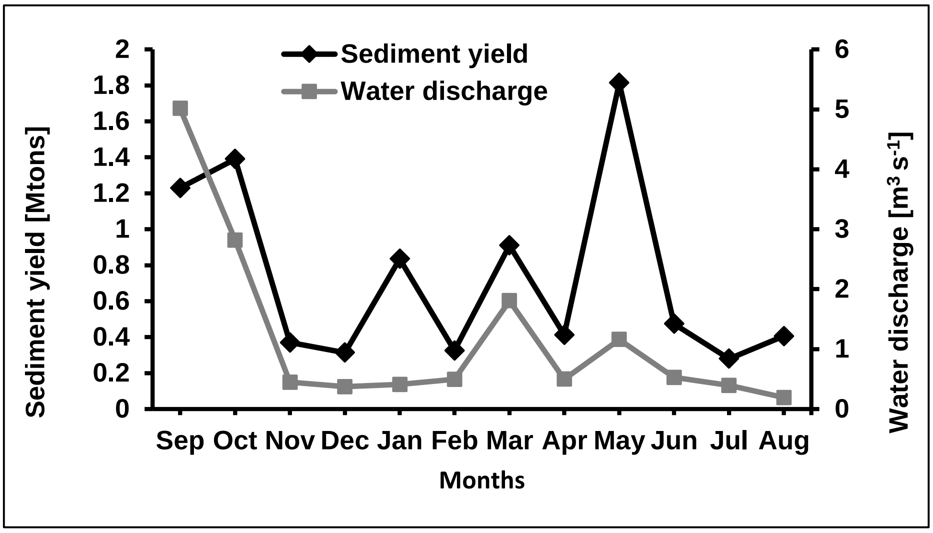

Fig. 2. Monthly distribution of sediment yield and water discherge in Wadi K'sob watershed.

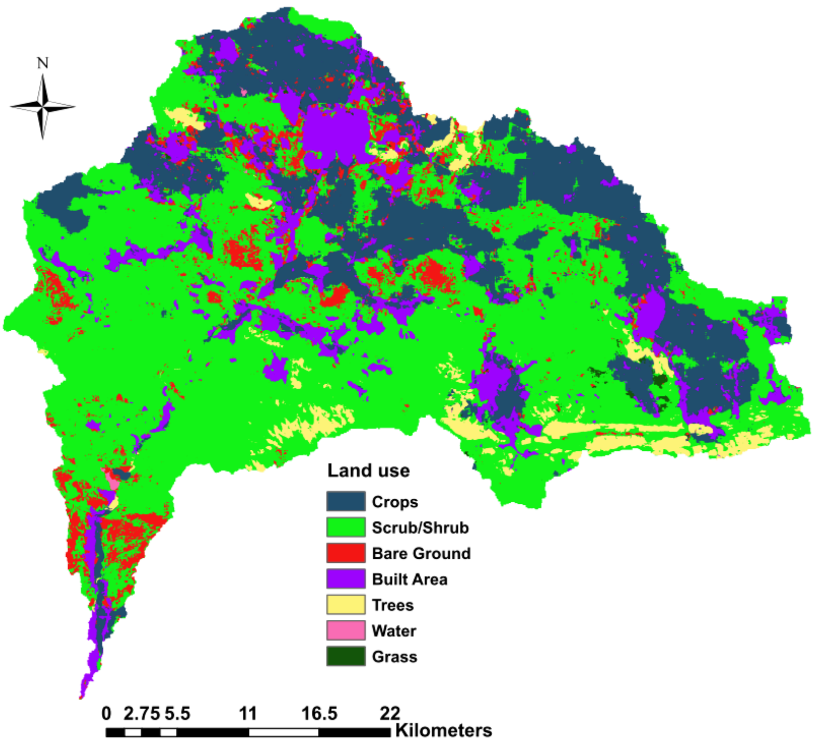

Fig. 3. Land use map of the Wadi K'sob basin.

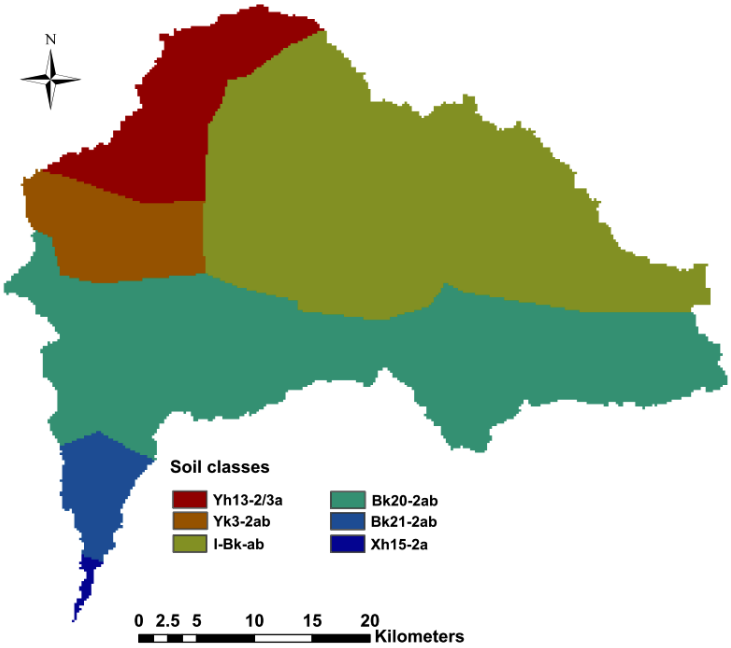

Fig. 4. Soil map of the Wadi K'sob basin.

Table 1. Area ratio and nomenclature of different soil types

Soil code	Nomenclature	Lithology	Area ratio [%]
I-Bk-ab	Lithosols	Clayey marl	41.64
Bk20-2ab	Calcic Cambisols	Cretaceous crystalline limestone	37.61
Yh13-2/3a	Haplic Yermosols	Neogene clayey marl	32
Yk3-2ab	Calcic Yermosols	Dolomite, granite	10
BK21-2ab	Calcic Cambisols	Cretaceous limestone and marl	7
Xh15-2a	Haplic Xerosols	Sand in Precambrian	3.43

Model description

SWAT is a semi-distributed, physically based model and continuous in time (Neitsch et al., 2005; Arnold et al., 2012). This model is an open source code developed by the United States Department of Agriculture–Agricultural Research Service (USDA–ARS) (Arnold et al., 2012). SWAT can be applied to catchments of various sizes with daily, monthly, and yearly time step (Douglas-Mankin et al., 2010; Gassman et al., 2014; Krysanova and White, 2015). The current versions of SWAT are SWAT2012 and SWAT+. In this work, we used SWAT 2012 implemented in QSWAT which is an interface in the QGIS. The important components of the hydrological cycle are described in SWAT by the water balance equation (Neitsch et al., 2005):

$$SW_t = SW_0 + \sum_{i=1}^{i=t}(R_{day} - Q_{surf} - ET - W_{perc} - Q_{gw}) \qquad (1)$$

where
SW_t – final soil water content on day i,
SW_0 – initial soil water content on day i [mm],
t – time [days],
R_{day} – precipitation on day i [mm],
Q_{surf} – surface runoff on day i [mm],
ET – evapotranspiration on day i [mm],
W_{perc} – percolation on day i [mm],
Q_{gw} – return flow on day i [mm].

Erosion and sediment yield are estimated by Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977):

$$Sed = 11.8(Q_{surf} \times q_p \times area_{HRU})^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG \qquad (2)$$

where
Sed – sediment yield [tons],
Q_{surf} – surface runoff volume [mm ha^{-1}],
q_p – peak runoff rate [m^3 s^{-1}],
$area_{HRU}$ – hydrologic response unit area [ha],
$KUSLE$ – soil erodibility factor,
$CUSLE$ – cover and management factor,
$PUSLE$ – support practice factor,
$LSUSLE$ – topographic factor,
$CFRG$ – coarse fragment factor.

The peak runoff rate (q_p) is given by following equation:

$$q_p = \frac{\propto \times q \times A}{360 \times t_c} \quad (3)$$

where

t_c – concentration time [hours],
q – runoff [mm],
A – HRU area [ha],
α – dimensionless parameter that expresses the proportion of total rainfall that occurs during t_c.

SWAT model inputs

SWAT model requires several data, such as DEM, land use, soil properties and daily weather data. DEM was obtained from the USGS website (https://earthexplorer.usgs.gov/) in Shuttle Radar Topography Mission (SRTM) format with a spatial resolution of 30 m. DEM is used to generate other input data, such as terrain slope, drainage network and sub-catchments boundaries.

Soil map was used to determine soil properties in the study watershed (Fig. 4). It was produced by FAO–UNESCO global soil map (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/). For soil data, six (6) different soil types can be identified in the Wadi K'sob watershed (Fig. 4). Further, land use layer includes seven (7) classes (Fig. 3). It was downloaded from this link: https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2.

The weather data necessary to run the model includes daily precipitation, air temperature (minimum and maximum), solar radiation, wind speed and relative humidity. The weather data of three (3) meteorological stations (Fig. 1) for the period 2002–2014 were provided by the National Office of Meteorology (*Office National de la Météorologie: ONM*).

Simulation steps

The various stages of SWAT execution are described as following:

1. Initially, the outlet is select to delimit the study catchment which is divided into sub-basins using DEM (Fig. 5) and those into Hydrological Response Units (HRUs). Each HRU has the same land use, soil type and slope classes.
2. Next, we insert the existing meteorological data (precipitation, air temperature (minimum and maximum), solar radiation, wind speed and relative humidity).
3. Finally, we run the SWAT model and visualize the results.

The basin under study was divided into nineteen (19) sub-basins and twenty four (24) Hydrological Response Units (HRUs) were created as indicated in Fig. 5.

Model calibration and validation

Calibration and validation of the hydrological model are essential procedures that confirm the predictive capacity of the model (Xue et al., 2018). The calibration process aims to adjust the values of one or more parameters to obtain better modeling results (Almeida et al., 2018). The sensitivity analysis allows to detect and classify parameters that have significant impact on model performance (Saltelli et al., 2000; Sane et al., 2020).

However, the validation is an operation that confirms the reliability of the calibrated models (Lin et al., 2019). In this phase, we run the model with calibrated parameters and compare between simulated and observed data for another period not used in the calibration (Arnold et al., 2012; Pereira et al., 2014).

For this study, the calibration process was performed

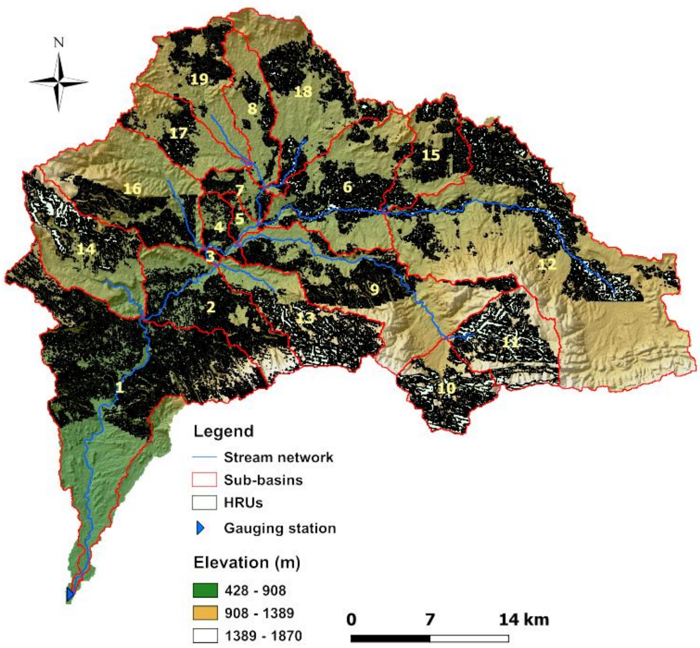

Fig. 5. Study catchment DEM includes the sub-basins and HRUs.

automatically by the R-SWAT software. R-SWAT is an open source code developed by Dr. Tam Nguyen (department of hydrogeology. Helmholtz centre of Environmental Research –UFZ, Germany). This program is intended for parallel parameter sensitivity, calibration and uncertainty analysis. Thus, the GLUE algorithm was used as the iterative method for calibration process and thirteen (13) parameters were identified by the sensitivity analysis as shown in Table 2.

The calibration was done using daily sediment yield data corresponding to two (2) periods (10/10/2006 to 06/17/2007 and 10/29/2012 to 10/22/2013) and two (2) periods (06/18/2007 to 11/19/2007 and 10/23/2013 to 09/13/2014) of daily sediment yield were chosen as the validation periods. All these data were collected by the gauging station of the study watershed (Fig. 1) and provided by National Agency for Water Resources (*Agence Nationale des Ressources Hydrauliques: ANRH*).

The SWAT model's performance was evaluated for the calibration and validation periods using tow (2) objective functions, namely the Nash–Sutcliffe Efficiency (Nash and Sutcliffe, 1970) and coefficient of determination which are subject to the criteria given by Moriasi et al. (2007) and Thiemig et al. (2013), as shown in Table 3.

The Nash–Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2) are widely used to assess hydrological model performance (Buytaert and Beven, 2011; Ferraz et al., 2021).

4. Nash–Sutcliffe Efficiency (NSE)

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Y_O - Y_S)^2}{\sum_{i=1}^{n}(Y_O - \overline{Y_O})^2} \quad (4)$$

5. Coefficient of determination R^2

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Y_O - \bar{Y}_O)\times(Y_S - \bar{Y}_S)}{\sqrt{\sum_{i=1}^{n}(Y_O - \bar{Y}_O)^2}\times\sqrt{\sum_{i=1}^{n}(Y_S - \bar{Y}_S)^2}}\right]^2 \quad (5)$$

where

Y_o – observed values,

Y_s – simulated values,

$\bar{Y}_O$ – arithmetic mean of observed values,

$\bar{Y}_S$ – arithmetic mean of simulated values,

n – number total of observed and simulated values.

Table 2. Parameters selected for calibration process

Parameter	Definition	Range values	
		Min	Max
CN2.mgt	Initial Soil Conservation Service (SCS) runoff curve number	35	98
ALPHA_BF_D.gw	Base flow alpha factor [days]	0	1
CH_K2.rte	Effective hydraulic conductivity in main channel [mm h^{-1}]	0.01	500
ESCO.hru	Soil evaporation compensation factor	0	1
GW_DELAY.gw	Ground water delay [days]	0	500
SOL_K.sol	Soil saturated hydraulic conductivity [mm h^{-1}]	0	2000
SLSOIL.hru	Slope length for lateral subsurface flow [m]	0	150
USLE_K.sol	Soil erodability factor in USLE	0	0.65
CH_ERODMO.rte	Channel erodibility factor	0	1
OV_N.hru	Manning's "*n*" value for overland flow	0.01	30
SOL_AWC.sol	Available water capacity of the soil layer	0	1
SURLAG.bsn	Surface runoff lag time	0.02	24
GW_REVAP.gw	Groundwater "revap" coefficient	0.02	0.2

Table 3. SWAT model performance based on NSE and R^2 values and recommended criteria

Coefficient	Very Good	Good	Satisfactory	Unsatisfactory
NSE	0.75<NSE≤1	0.65<NSE≤0.75	0.50<NSE≤0.65	NSE≤0.50
R^2	R^2>0.80	0.70<R^2≤0.80	0.50<R^2≤0.70	R^2≤0.5

Results and discussion

The overall performance of the SWAT model in terms of predicting the sediment yield in Wadi K'sob is considered satisfactory or even good, as shown in Table 4, Fig. 6 and Fig. 7.

Based on the NSE and R^2 values, the performance of the model was good in the first calibration period (NSE=0.67 and R^2=0.73) and satisfactory in the second period (NSE=0.65 and R^2=0.67). However, the model prediction improved during the first validation period (NSE =0.78) indicating that the model performed very good, while R^2=0.79 indicates that its performance was good. In contrast, during the second validation period a decrease was observed for both (NSE=0.52) and (R^2=0.54) indicating a satisfactory performance of the model. The decrease in model performance may be related to the extended period used for simulation Table 4.

The graphical comparison between the observed (Obs _Sed) and simulated (Sim_ Sed) daily sediment yield (Fig. 6 and Fig. 7) shows a good agreement of the observed data compared to the simulated data, which indicates the accuracy of the model's prediction, whether for calibration or validation. The good performance of SWAT model is consistent with that found in Mediterranean Karstic watersheds (Nerantzaki et al., 2015). Thus, the SWAT model has proven its good performance in different types of watersheds and different climates such as: Jemma Subbasin of Upper Blue Nile in central Ethiopia (Zewde et al., 2024) and Mekong river basin in southeast Asia (Sok et al., 2020).

The model uncertainty is assessed by two factors, namely the *P*-factor and the *R*-factor (Shivhare et al., 2018). The *P*-factor is the percentage of observed data bracketed by the 95PPU band that represents a prediction uncertainty of 95% (Abbaspour et al., 2015). *R*-factor is the average thickness of the 95PPU band divided by standard deviation of the measured variable. The value of the *P*-factor is between 0% and 100% while that of the *R*-factor varies from 0 to infinity. If the *P*-factor is greater than 0.80, then observed values are of good quality (Singh et al., 2014), while the *R*-factor < 1.5 would be acceptable for perfect model simulation (Abbaspour et al., 2004, 2007).

In the present study, the P-factor values range from 0.84% to 0.90% indicating the use of good quality of the measured data. However, the R-factor values range from 1.39 to 1.70 which means there is less prediction accuracy in the results of the SWAT model, especially in the second period.

The calibration process showed that the values of certain

Table 4. Performance of the SWAT model after calibration and validation

Event	Nbr days	Period	NSE	Performan index	R^2	Performan index
10/10/2006 to 06/17/2007	251	Calibration	0.67	Good	0.73	Good
06/18/2007 to 11/19/2007	155	Validation	0.78	Very good	0.79	Good
10/29/2012 to 10/22/2013	359	Calibration	0.65	Satisfactory	0.67	Satisfactory
10/23/2013 to 09/13/2014	326	Validation	0.52	Satisfactory	0.54	Satisfactory

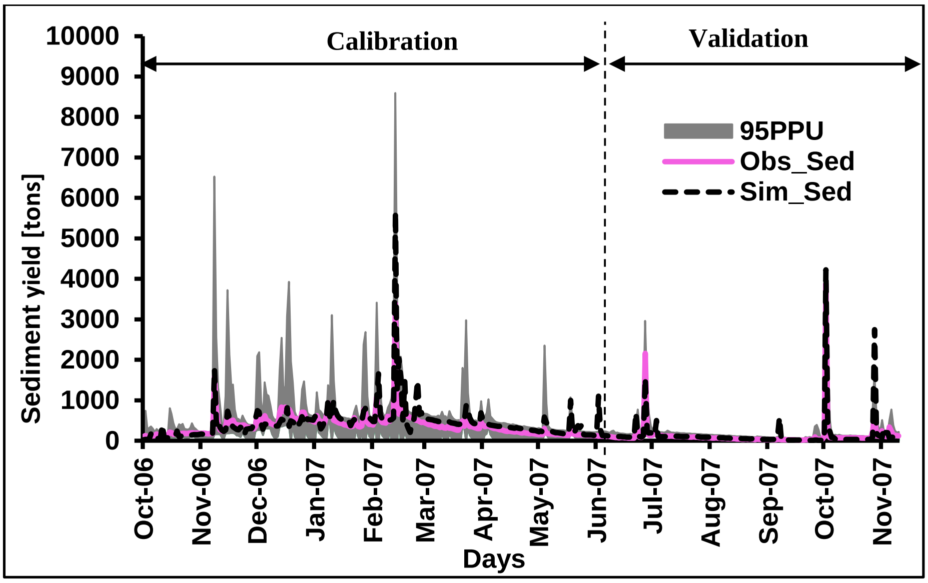

Fig. 6. Observed and simulated daily sediment yield for the first calibration and validation periods.

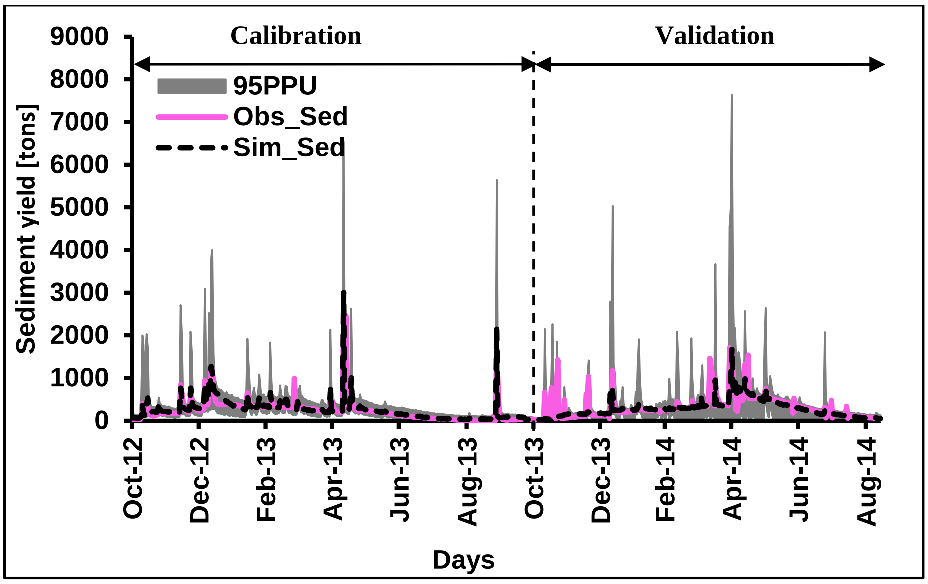

Fig. 7. Observed and simulated daily sediment yield for the second calibration and validation periods.

parameters were relatively stable in both calibration periods, such as CN2 (62.92 - 68.971), GW_REVAP (0.06 -0.071), OV_N (11.964 - 17.951), USLE_K (0.233 - 0.275), ESCO (0.363 - 0.376) and CH_K2 (69.982 - 77.258).

However, the values of other parameters were unstable, such as ALPHA_BF_D (0.156 - 0.942), GW_DELAY (42.907 - 121.085), SURLAG (5.959 - 15.19), SOL_AWC (0.009 - 0.849), CH_ERODMO (0.027 - 0.301), SLSOIL (8.253 - 34.05) and SOL_K (820.355 - 872.415).

Indeed, the stable parameters are related on the characteristics (topography, vegetation cover, land-use, etc.) of the study region. These parameters are responsible for channel routing (Pinto et al., 2013; Almeida et al., 2018; Koltsida et al., 2023). Nevertheless, the unstable parameters depend on soil properties, especially soil permeability and soil erodibility which vary with climatic conditions. Indeed, the soil erodibility can be affected by the dry and warm summer climate (Le Bissonnais et al., 2007). Furthermore, the concentration of rainfall, especially in autumn is one of the factors influencing the phenomenon of erosion (Ramos and Martínez-Casasnovas, 2008; Moussadek et al., 2011). Zewde et al. (2024) revealed that heavy rainfall associated with topographic instability, land use, vegetation cover and change in drainage network in a sub-catchment are the important factors that aggravate soil erosion.

Conclusion

The application of the SWAT model showed an acceptable performance in terms of simulating the daily sediment supply in the Wadi K'sob watershed. The prediction of model accuracy has been proven, whether for calibration or validation. Indeed, the first calibration period gave fairly high values of the objective functions where NSE=0.67 and R^2=0.73, which indicates that the performance of the SWAT model is good. However, during the second period, the values of NSE and R^2 decreased slightly (NSE=0.65 and R^2=0.67) indicating that the performance of the model is satisfactory. Regarding validation, the model prediction is between very good with NSE = 0.78 and good with R^2 = 0.79. On the other hand, the second validation period resulted in a decrease for both (NSE=0.52) and (R^2=0.54), indicating satisfactory performance of the SWAT model. We explain this to the extended simulation period.

The uncertainty analysis of the SWAT model using *P*-factor and *R*-factor indicating that the observed data are of good quality which is clearly evident from the *P* values which vary between 0.84% to 0.90%. However, the values of the *R*-factor vary from 1.39 to 1.70, which means that the results of the SWAT model are less accurate, especially in the second simulation period.

The process of calibrating the model parameters using the GLUE algorithm revealed that CN2, GW_REVAP, OV_N, USLE_K, ESCO and CH_K2 are parameters that remain relatively stable and do not change with changing simulation periods, which means that its parameters depend on the topography of the basin, plant cover, land use, etc. They are therefore responsible for channel routing. While the parameters ALPHA_BF_D, GW_DELAY, SURLAG, SOL_AWC, CH_ERODMO, SLSOIL and SOL_K which are linked to the permeability and erodibility of soils are unstable parameters and depend on climatic conditions.

Comparing our study with other studies using the SWAT model, we note the reliability of this model in terms of evaluating sediment yield in different types of watersheds and different climates, the Mediterranean basins are one of them.

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Noureddine Maref, Dr. (*corresponding author, e-mail: m.noure@yahoo.fr)
Djelloul Baahmed, Dr.
Kader Bemmoussat, Dr.
Zakaria Mahfoud, Dr.
Civil Engineering and Environmental Laboratory (LGCE)
University of Djillali Liabès
Faculty of Technology
Ben M'Hidi district, P.O.Box 89
22000, Sidi Bel Abbes
Algeria