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Multi-Site Calibration and Validation of SWAT Model for Hydrologic Modeling and Soil Erosion Estimation: A Case Study in El Grou Watershed, Morocco

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ABSTRACT
Water management is one of the critical challenges facing humanity due to increasing demand and limited resources resulting from the rapid growth of population, urban planning, agricultural and industrial sectors. Hydrological modeling is one of the key solutions used by researchers for estimating and monitoring the spatial and temporal variability of water resources in a watershed. This paper aims to evaluate the Soil & Water Assessment Tool (SWAT) performances and simulates the water cycle components of El Grou watershed (3504 km^2), one of the main basins in the landscape hydrology of Morocco. It points to the need for developmrent of better model input data sets in Africa which are unlimted available when they are crucial for a detailed study of water resources. The model was built under ArcSWAT, and all other processes such as sensitivity analysis, calibration (10 years) and validation (4 years) were done with SWAT-CUP software using the SUFI-2 algorithm. The coefficient of determination (R^2), the Nash–Sutcliffe efficiency (NSE) and the square error (RSR) were used to evaluate model performances. The results show that calibration and validation are considered very good, with R^2 and NSE >0.81 and RSR <0.5. The hydrological regime of the El Grou watershed points out a predominance of evapotranspiration (75%). Moreover, soil erosion estimation for the period (2000–2015) indicates a low to medium potential of soil erosion with an average of 11.3 t/ha/year.

Keywords: Hydrological modeling, soil erosion, spatial calibration, SWAT model, El Grou watershed, SWAT-CUP, SUFI-2

INTRODUCTION

The geographical location of Morocco gives a climatic specificity to this country, which is a transition zone between the Mediterranean climate and a semi-arid to the Saharan climate in the south. The country is characterized by a spatio-temporal irregularity of precipitation with long periods of drought and consequently a decrease in available water resources pressed by a strong demographic growth accompanied by the development of agricultural and industrial sectors. For this reason, scientific research comes to give the answers to the problems related to the sustainable management of this vital resource through numerous studies carried out with hydrological models at the scale of the main Moroccan watersheds (Fadil et al., 2011; Bouslihim et al., 2021; Choukri et al., 2019; Bouslihim et al., 2019). Hydrological models are considered indispensable tools for estimating the spatial variability of water resources (Liu et al., 2008; Coron et al., 2012; Pahl-Wostl et al., 2013; Sheffield et al., 2014). However, some models are hyperparameterized and require data from several different sources, which are sometimes inaccessible or unavailable, like the SWAT model (Schuol and Abbaspour 2006).

The main objective of this paper is to evaluate the performance of the SWAT model, with the challenge to overcome the limitation of data input unavailability by using different sources. The developed model represents the hydrological functioning of El Grou watershed and generates the water balance with all its components.

MATERIALS AND METHODS

Study Area

The El Grou watershed covers an area of 3504 km^2 (Fig. 1). The study area is limited to the north by the Bouregreg watershed, to the east and south by the Oued Oum Er Rbia watershed, and to the west by the Korifla watershed. The altitude varies between 109 m and 1606 m. The El Grou watershed is characterized by a semi-arid climate with an average annual rainfall of 416 mm (2000- 2015), and an average temperature varies between 23°C and 13°C.

Description of the SWAT model

The Soil and Water Assessment Tool (SWAT) model is a continuous, semi-distributed, physical, hydro-agricultural model developed to assess the effects of agricultural practices on watershed regimes in terms of quantity and quality (G. Arnold et al., 2012). In SWAT, the watershed is divided into several hydrological response units (HRUs) based on slope, pedology, and land use (Neitsch et al., 2011).

The SWAT model simulates the entire hydrologic cycle through an equation that presents the water balance in a watershed (Neitsch et al., 2011).

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

where: t is time step (days),
SW_t and SW_0 are final and initial soil water content (mm), and
R_{day}, Q_{surf}, E_T, Q_{gw} et W_{seep} are respectively, are the daily amounts of precipitation (mm), surface runoff (mm), evapotranspiration (mm), return flow (mm), and water entering the vadose zone from the soil profile (mm).

SWAT input datasets

The SWAT model requires different spatio-temporal data types, such as climatic data (precipitation, temperature max/min), spatial data (topography, pedology and land use) and hydrological data. The data used in the study are described below:

Slope (Fig. 2a) was developed from the ASTER-GDEM global digital elevation model (DEM) with a spatial resolution of 30 m (Hirt et al., 2010). The hydro-rainfall station Ras El

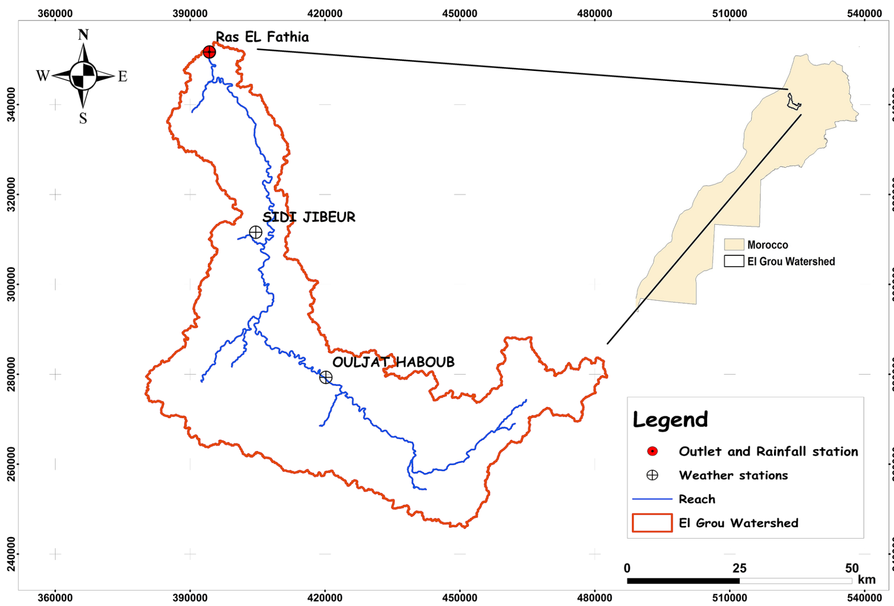

Fig. 1. Location map of El Grou Watershed

Fathia was used as an outlet (x = 394300 m, y = 351700 m). On the basis of topography, the watershed was delineated and divided into 16 sub-basins.

The soil map (Fig. 2b) was extracted from the Harmonized World Soil Database (HWSD) of the Food and Agriculture Organization of the United Nations (FAO), at a scale of 1:5,000,000 (Nachtergaele et al., 2010). It consists of a map layer associated with an attribute table that presents the characteristics of different soil types, such as available water capacity (AWC), organic carbon, soil texture, soil depth. According to the FAO classification, the studied watershed comprises four different types of soil units: Luvisols (84.7%), Vertisols (7.35%), Planosols (6.79%) and Calcisols (1.16%).

The land use map (Fig. 2c) was extracted from Landsat 8 TM imagery (Jia et al., 2014) with a resolution of 30 m using supervised classification in the ArcGIS program and considering five classes. In general, it can be noticed that the pasture covers about half of the total area (54.98%), followed by agriculture (26.91%) and forest (12.22%).

Meteorological and hydrological data: daily precipitation and flow data were obtained from the Hydraulic Basin Agency of Bouregreg and Chaouia (ABHBC) for three stations, Ras El Fathia, Sidi Jibeur, and Ouljat Haboub) (Fig. 1). Other climatic data (maximum and minimum temperature, relative humidity, wind speed, solar radiation) were obtained from two global meteorological databases: the first is the Climate Forecast System Reanalysis (CFSR) from the U.S. National Center for Environmental Prediction (NCEP) for the period (01/01/2000 to 31/07/2014) (Saha et al., 2010). The second database used was obtained from the Prediction of Worldwide Energy Resources (POWER) Project at the NASA Langley Research Center (LaRC) for the period (01/08/2014 to 31/12/2015) (power.larc.nasa.gov; Stackhouse 2006).

Model Setup

Generally, a total period of 16 years (2000 to 2015) was used over three periods. Two years were reserved for model initialization (warm-up), the following ten years were used formodel calibration (2002–2011) and four years for validation (2012–2015). The SUFI-2 (Sequential Uncertainty Fitting) method implemented in the SWAT-CUP program developed by Abbaspour et al. (2004) was used to identify sensitive parameters for model calibration. Similar studies in the same climate condition allowed optimizing the parameters used for calibration (Fadil et al., 2011, Bouslihim et al., 2021, Brouziyne et al., 2017, Markhi et al., 2019, Bouslihim et al., 2019, Milewski et al., 2020). T-stat and p-value were used to select the sensitive parameters to be calibrated (G. Arnold et al., 2012). The range of optimal values of these parameters is presented in Table 1.

Three statistical indicators for evaluating SWAT performance were used : Nash-Sutcliffe (NSE) (Nash and Sutcliffe 1970), coefficient of determination R^2 (Krause et al., 2005), and the ratio of the root mean square error to the standard deviation of measured data (RSR) (Legates and McCabe 1999) (Table 2). The choice of the best model performance should consider the two indicators for uncertainty estimation: the p-factor, which should be close to 1, and the lowest possible r-factor tends to 0 (G. Arnold et al., 2012), and is also based on the performance classification proposed by Moriasi et al. (2007).

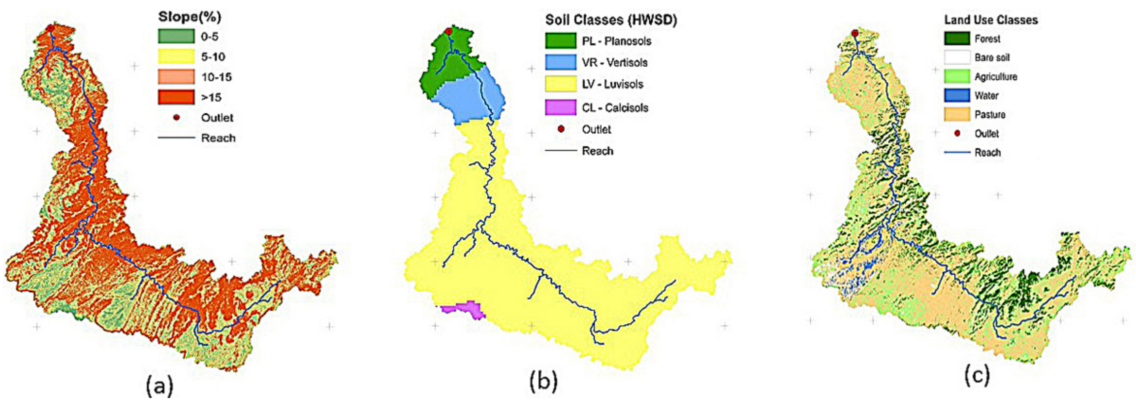

Fig. 2. Spatial data input of El Grou watershed. (a) Slope map; (b) Soil map; (c) Land use map

Table 1. The sensitive parameters used for the El Grou basin with a range of the optimal value

SWAT Parameters	Unit	Description	Initial range value	Method
CN2	-	Curve number condition for moisture condition II	(-0.4, 0.4)	R
ALPHA_BF	days	Baseflow alpla factor	(0, 1)	V
ESCO	-	Soil evaporation compensation factor	(0, 1)	V
EPCO	-	Plant uptake compensation factor	(0, 1)	R
SOL_AWC	mm H_2O/mm Soil	Available water capacity of the soil	(-0.5, 0.5)	R
SOL_K	mm/h	Saturated hydraulic conductivity at the first soil layer	(-0.25, 0.25)	R
SOL_BD	g/cm^3	Moist bulk density	(-0.5, 0.5)	R
SOL_ALB	-	Moist soil albedo	(-0.4, 0.4)	R
SLSUBBSN	m	Average slope length	(-0.3, 0.4)	R
HRU_SLP	m/m	Average slope steepness	(-0.3, 0.3)	R
CH_N2	-	Manning's n value for main channel	(0.01, 0.3)	V
CH_K2	mm/h	Effective hydraulic conductivity	(0, 150)	R
GWQMN	mm	Threshold depth of water in shallow aquifer for base flow	(-1000, 1000)	A
RCHRG_DP	-	Deep aquifer percolation fraction	(0.1, 0.9)	V
GW_REVAP	-	Groundwater «revap» coefficient	(0.02, 0.4)	V

Note: R – means the existing parameter value is multiplied by (1+ a given value), V – means an existing parameter value is to be replaced by a given value, A – means the existing parameter value is to be added by a given value.

RESULTS AND DISCUSSIONS

Model calibration and validation

Generally, one-point calibration (principal outlet) will often not yield satisfactory results for the watersheds characterized by a large area (Abbaspour et al., 2018). For this, the authors chose to proceed by a multi-site calibration, which is often applied in several studies (Cao et al., 2003; Santhi et al., 2008; Zhang et al., 2008). Therefore, the calibration of the SWAT model on the El Grou watershed was carried out by comparing the measured and simulated during the calibration and validation periods. The performance indices of the model obtained by the SUFI-2 method are presented in Table 3.

According to the performance indices, the model gives excellent results with NSE, R^2 and RSR values of 0.80, 0.80 and 0.45, respectively. Furthermore, the same tendency was observed for the validation period with an NSE, R^2 and RSR value of 0.82, 0.82 and 0.43, respectively. On the other hand, the r-factor and p-factor are suitable for both periods. Generally, according to Moriasi et al. (2007), the calibration and validation results are qualified as very good.

The simulated flows at Ras El Fathia station are very well adjusted to the observed flows, which demonstrates that the model has well reproduced the dynamics of flows, except during the peaks where the simulated flows are underestimated in November 2002, February 2009 and 2010 corresponding to intense floods (Fig. 3).

Water Balance Components

The average annual water balance was calculated in the SWAT model with all its components mentioned in equation 1. The result of the water balance simulated in the El Grou watershed by the SWAT model (Fig. 4) indicates that the annual average of precipitation is 416.7 mm mm, of

Table 2. Performance measurements of recommended statistics used for streamflow simulation (D. N. Moriasi et al., 2007)

Performance rating	NSE	R²	RSR
Unsatisfactory	NSE ≤ 0.5	R² < 0.50	RSR > 0.7
Satisfactory	0.5 < NSE ≤ 0.65	0.50 < R² <0.70	0.6 < RSR ≤ 0.7
Good	0.65 < NSE ≤ 0.75	0.70 < R² <0.80	0.5 < RSR ≤ 0.6
Very good	0.75 < NSE ≤ 1	>0.80	0.5 < RSR ≤ 0

Table 3. Calibration performance indices at Ras El Fathia station

Parameter	Calibration (2000–2011)	Validation (2012–2015)
p-factor	0.63	0.65
r-factor	0.51	0.70
R^2	0.80	0.82
NSE	0.80	0.82
RSR	0.45	0.43

which 315.4 mm is evaporated. Thus, the average annual runoff is about 50 mm, and groundwater contributes to the river runoff with 30.55 mm while 3.26 mm are infiltrated to the deep aquifer. The results show a predominance of the evapotranspiration component; in fact, 75% of annual precipitation is evaporated. The same tendencies are obtained in other studies under similar conditions realized to estimate the water balance in different watersheds of Morocco. Fadil et al. (2011) found a predominance of evapotranspiration component with 70% between 1989–1997 and 81% between 1998–2005 in the Bouregreg watershed. Lamia et al. (2020) found that evapotranspiration contributes with 54% to the water balance of the Ouergha watershed in northwest Morocco. Boufala et al. (2019), in the upper Sebou watershed, found similar evapotranspiration contribution value of 69% in the basin water balance. All these results show that evapotranspiration contributes the most to the hydrological cycle in the areas characterized by an arid to semi-arid climate.

Estimation of soil erosion

The SWAT model estimates sediment yield with the Modified Universal Soil Loss Equation (MUSLE) at the level of the created sub-watersheds and the generated HRUs (G. Arnold et al., 2012).

Estimation of erosion was run over 16 years (2000 to 2015) after model calibration and validation. The results show that the amounts of sediment transported through the sub-basins vary between 8.39 and 19.97 t/ha/year with an average erosion rate of 11.3 t/ha/year, which indicates a rate above the average soil tolerance threshold (7/t/ha/year) (Meyer and Wischmeier 1969) (Fig. 5).

The spatial variability of erosion shows that 85% of the basin area has moderate losses that vary between 10 and 15 t/ha/year, while low losses between 5 and 10 t/ha/year correspond to 13%. The rates higher than 15 t/ha/y present only 2% of the basin's total area and concern two sub-basins 1 and 6, respectively (Table 4).

The results obtained are close to those found by Moussebbih et al. (2019) in the Bouregreg watershed (a nearby watershed) with an average erosion value of 13.81 t/ha/year by applying the empirical model RUSLE (Revised Universal Soil Loss Equation) to estimate the erosion rate. However, Markhi et al. (2019), in the N'fis watershed of the High Atlas watershed, found higher erosion rate values of 141 t/ha/year, which was explained by a topography characterized by steep slopes and high erosive rainfall. On the other hand, Bouslihim (2020) found lower erosion rate values that did not exceed 0.5 t/ha/year.

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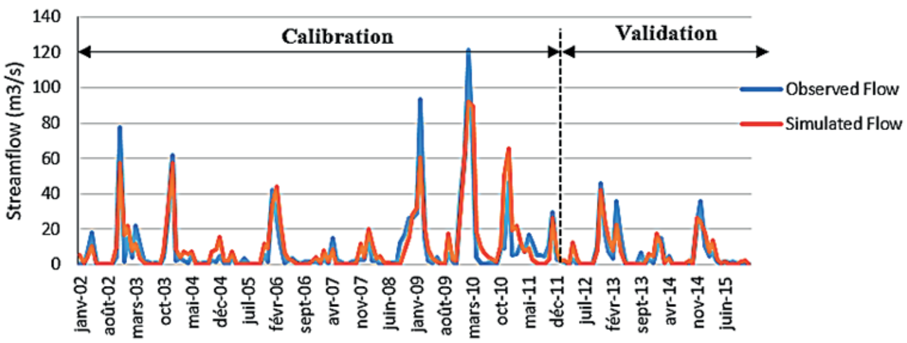

Fig. 3. Comparison between observed and simulated monthly flow at Ras El Fathia station

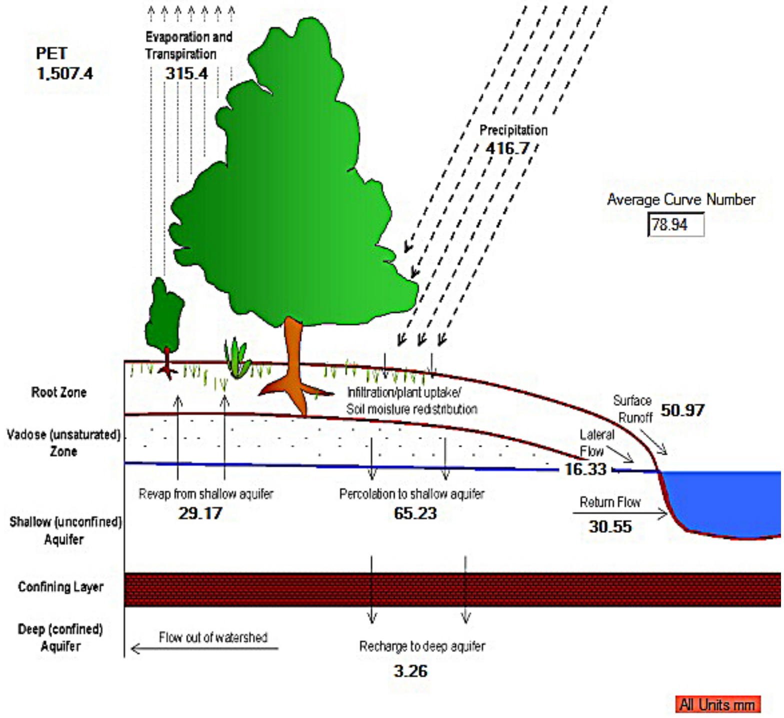

Fig. 4. Simulated annual average water balance of El Grou watershed

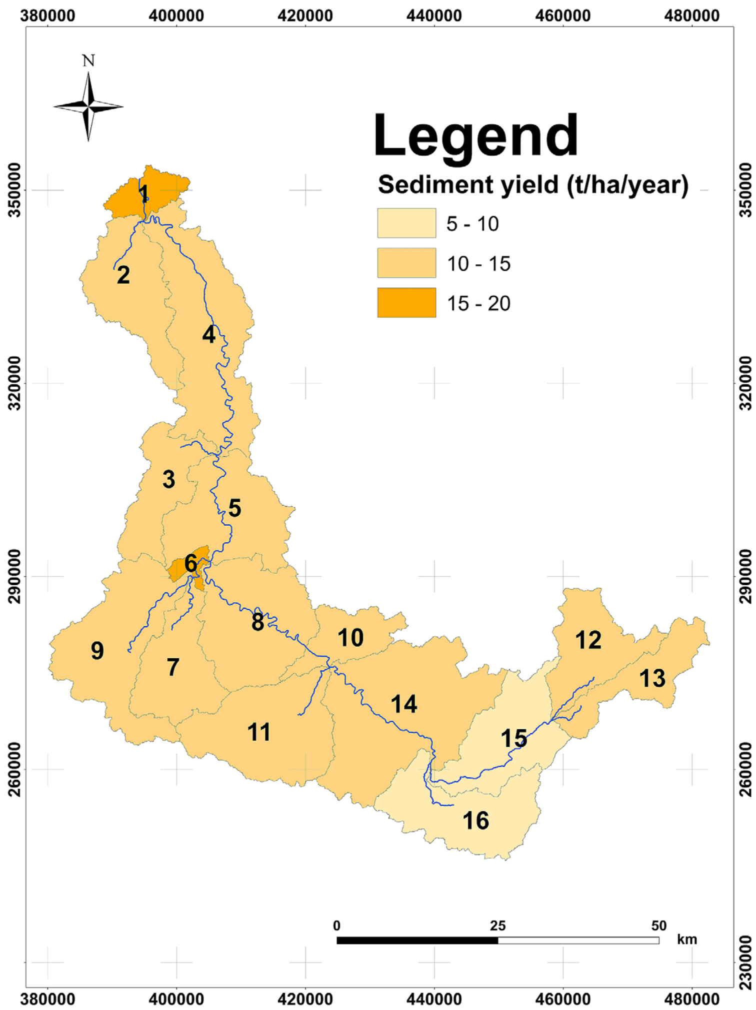

Fig. 5. Spatial distribution of the soil erosion rates by sub-basin

Table 4. Potential erosion risk classes of the El Grou watershed (Woldemariam et al., 2018)

Rate of erosion	Area (%)	Erosion risk
5–10	13%	Low
10–15	85%	Low medium
15–20	2%	Medium

soil resting on a predominantly impermeable bedrock (Cherrad 1997), with a moderate slope, also the basin is under the influence of contrasting stormy rainfall.

CONCLUSIONS

The SWAT model was used and successfully applied to the El Grou watershed to reproduce the hydrological functioning, estimate the erosion rate and provide decision-makers with a powerful and efficient water resources management tool. The results show very good model performances for different statistical indices (R^2, NSE and RSR) for both calibration and validation periods.

Based on the developed model, the average soil erosion is about 11.3 t/ha/year (2000–2015), wich indicates a potential low to medium risk of erosion, and this can be explained by soil nature, a topography with moderate slopes and stormy rainfall.

Therefore, the SWAT model could be an essential tool to guide all strategies related to water resources management, knowing that this work can be exploited in future studies to examine the effect of climate changes and anthropogenic dynamics on water resources and hydrological functioning of the watershed from a quantitative and qualitative point of view.

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