Adaptation and Evaluation of SWAT Model for Application in an Arid Watershed in southeast Tunisia

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Abstract

In the arid regions of Tunisia, huge efforts are being made in water harvesting and soil conservation. A growing need for the assessment of their impact is felt. Due to the complexity of the processes at the watershed level, recourse to modeling is inevitable. In this framework, the objective of this paper is to adapt and evaluate the ArcView SWAT model for application in the assessment of the hydrological impact of water harvesting works. Some adjustments were made to the SWAT code to adapt the model to the processes in this arid environment. The model was calibrated and validated using 34 daily runoff events for the Oum-Zessar watershed upstream of Koutine (270-km^2). Evaluation of the hydrologic goodness-of-fit of the model based on the observed and simulated daily runoff data gave reasonable results . The model efficiency (Nash-Sutcliffe coefficient) was 0.26 for the calibration period (1975-1979) and 0.83 (1980-1992) for the validation period. The evaluation was affected by uncertainties in the data and poor rain gauge coverage and further study is needed. Watershed modeling is a time-consuming task, even more so because of the scarcity of data. Nevertheless, the model is very attractive for application, considering the gradual generalization and widening of the scope of the use of digital data layers and spatial decision support systems by the various end users (agriculture, environment, planning, etc.).

Introduction

During the last two decades, the Tunisian government has engaged in a vast program for the conservation and mobilization of natural resources (Min. Agr., 1990a, 1990b). In the Jeffara region (southeastern part of Tunisia), which encompasses the study site, huge works for soil and water conservation (water harvesting) and rangelands rehabilitation have been implemented. Although the immediate effects are visible, their efficiency in both the short and the long term need to be assessed and evaluated in details (De Graaff and Ouessar, 2002; Sghaier and Genin, 2003).

Models can be used to evaluate the complex interacting processes at the watershed level. By simplifying and simulating natural processes, models have become efficient tools for analyzing the impacts of land use changes and the development of best management practices (Borah and Bera, 2004). In parallel, geo-information technology has offered appropriate tools for data collection from the earth-surface, information extraction, data manipulation and visualization (Sharifi, 2002).

The objective of this paper is to adapt and evaluate the use of ArcView SWAT (Soil Water Assessment Tool) model (Neitsch et al., 2002; Diluzio et al., 2002) for the assessment of hydrological impacts of water-harvesting works in an arid watershed in southeast Tunisia.

Materials and Methods

Study Site

The application was carried out for the watershed Wadi Oum Zessar, which covers around 336 km^2 (Fig. 1). The watershed is located in southeastern Tunisia and has an arid Mediterranean bioclimate with an annual rainfall ranging between 150 and 230 mm. The watershed starts at the Matmata mountain range (Kef Ennsoura) and ends in the Mediterranean Sea. It has three main tributaries: Wadi Nagab, Wadi Moggar and Wadi Hallouf. The hydraulic history of this watershed is very ancient and rich, as witnessed by the remains of a dam built in the Roman era near the village of Koutine, and the ancient terraces encountered in the hills of Wadi Nagab. At present, the upstream area is terraced with *jessour,* which are ancient water-harvesting techniques constructed in the form of small earthen retention dams with spillways typical for the mountains of southeast Tunisia (El Amami, 1984; Ben Mechlia and Ouessar, 2004). The intermediate zones incorporate *tabias,* similar to *jessour* but encountered mainly on the foothills and the flat areas (Alaya et al., 1993), and floodwater diversion structures. In the beds of the main *wadi*, several gabion check dams were built for the recharge of the Zeuss-Koutine aquifer. Detailed descriptions of the area are found in Ouessar et al. (1999) and Mahdhi et al. (2000).

The SWAT Model

The SWAT is a physically-based, watershed-scale model developed by Arnold et al. (1998). It is a continuous time model that operates on a daily time step to estimate the effects of land and water management and pollutant releases in stream systems in large complex watersheds with varying soils, land use and management conditions over long periods of time. The SWAT includes the ability to model the entire process of the hydrologic cycle, including rainfall, evapotranspiration, water withdrawals, and ground water recharge. SWAT allows for the creation of multiple Hydrologic Response Units (HRUs), which are separate, unique combinations of soil and land cover properties within subbasins, thus representing local variation. Another attractive feature of the SWAT,
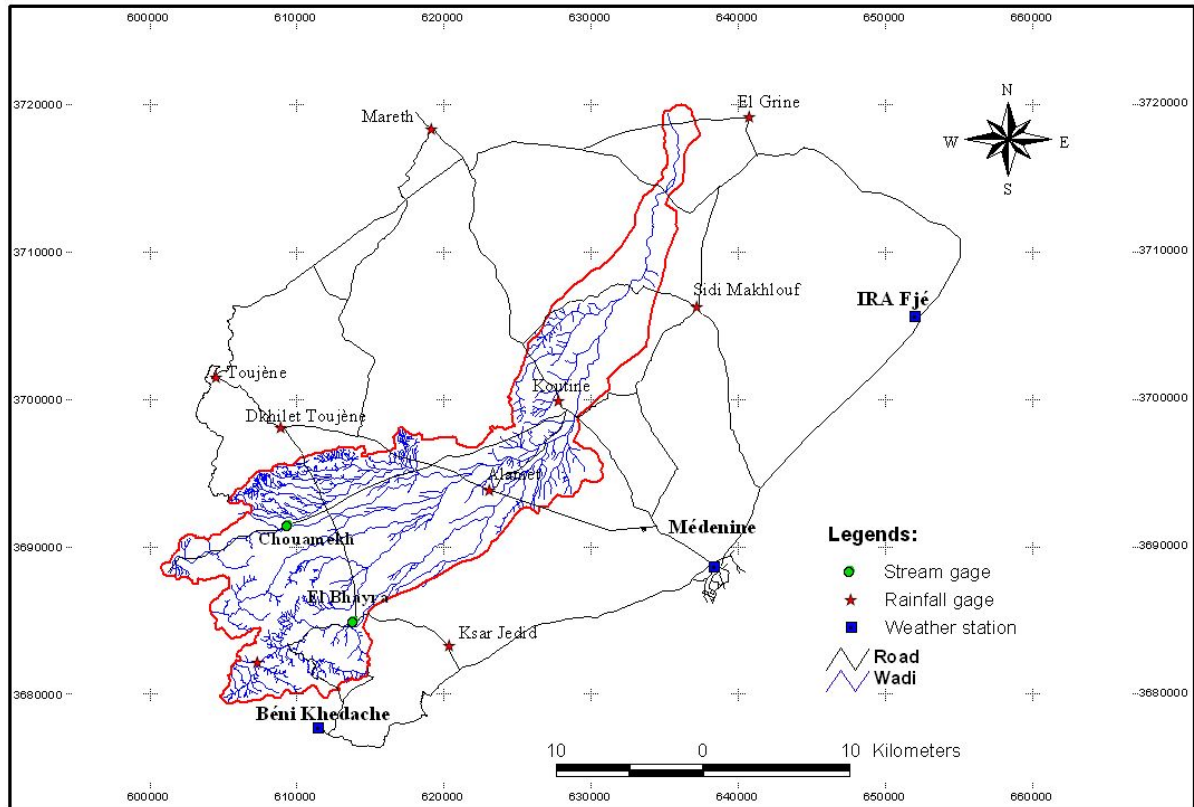
Fig. 1. The study watershed and the monitoring network.

facilitated by the addition of the GIS interface, is the ability to easily alter input parameters such as land cover, soil distribution, and climate data. The subbasin components of the model can be grouped into eight major divisions; hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management (Neitsch et al., 2002).

Data Sources and Parameter Selection

The SWAT has a database with default crop and soil parameters for US applications. These parameters were adjusted and tested for the study area conditions. A summary of the data for this model application is presented below, details can be found in Ouessar (2005).

Topography and watershed configuration

The subbasin delineation is obtained from a digital elevation model (DEM). A 30-m DEM was generated by the interpolation of digitized contour lines and altitude points, obtained from the available topographic maps of the area. Where no topographic data were available, the contour lines were taken from a 30-m DEM obtained from a SPOT stereo pair (26/05/1998 and 31/05/1998).

The threshold area for the generation of streams in the GIS interface was set at 100 ha. The subbasins, which are automatically generated based on the confluence of streams, were adjusted by manual editing, considering the location of the different water-harvesting practices.

Plate 1. Cereals and halophytes in the downstream area of Oum Zessar watershed.

Climate

Daily precipitation data are needed by the SWAT when the curve number (CN) method is selected to model surface runoff. The daily rainfall measurements were collected from ten stations in and around the watershed (Fig. 1). Missing records were replaced with data from the nearest stations (Ouessar, 2005).

Daily values of maximum and minimum temperature were obtained from the weather stations of Médenine, Béni Khédache and El Fjè (IRA). The monthly average daily minimum and maximum temperatures and standard deviations of these stations were also computed for use by the weather generator in case of missing data. Considering the availability of data, potential evapotranspiration was calculated by the Hargreaves method.

Soils

A soil map (1:200,000 scale) of the Jeffara region was produced by Taamallah (2003). The texture and organic matter of all soils were determined by the analysis of 31 representative profiles. Modification of this map was made for this modeling study. The boundaries of the soil units were adjusted based on a supervised and unsupervised classification of the SPOT

multispectral image of 1998 and additional field investigations using a Global Positioning System (GPS). Three classes were added: the 'artificial' soils formed behind the water-harvesting structures by the deposition of sediment (JESR: soils behind *jessour*, TABS: soils behind *tabias*) and the outcroppings of Matmata mountains (AFFL).

For the soils on the terraces of the water-harvesting structures (JESR and STAB), the available soil water capacity, bulk density, and saturated hydraulic conductivity were measured (Maati, 2001). The characteristics of the remaining soils were computed from their texture with the Soil Water Characteristics calculator (Saxton, 2005). This calculator estimates the water holding characteristics by regression equations derived from different datasets available in the US (Saxton et al., 1986).

Land use and Curve Number

The land use map of the study area was based on a map of the natural vegetation prepared for the Jeffara region by Hanafi et al. (2003) and a semi-supervised classification of the SPOT XS image of 1991 undertaken by Zerrim (2004). In addition, field checks were conducted. The land use map represented the situation before the large scale implementation of water harvesting works. The following classes were distinguished:
- Fruit trees (mainly olives) on *jessour*,
- Fruit trees (mainly olives) on *tabias*,
- Episodic winter cereals (mainly barley) (Plate 1),
- Rangelands in the mountains,
- Rangelands in the plains,
- Halophytes in the saline depression (Sabkhah Oum Zessar) at the outlet of the watershed.

The runoff CN was selected from a standard table (USDA-NRCS, 1986) based on the land use and the soil hydrologic group (Table 1). The USDA-NRCS (1996) classified soils into four hydrologic groups (A to D) based on the infiltration characteristics of the soils. To classify the soils of the study area into the four soil hydrologic groups, the USDA-NRCS (1996) guidelines were used.

The rangeland and pasture vegetation was classified as desert shrubs (USDA-NRCS, 1986), while the cereals were considered small grains in straight rows and bare soil during fallow. The olives are grown on flat terraces.

Table 1. Soil hydrological groups and runoff curve number values.

HRU[a]	Land use	Soil[b]	Hydrologic group	Slope (%)	Area (%)	Curve Number		
Halophyte rangelands (STPH)[c]						Oct-Feb	Mar-Jun	Jul-Sep
1	STPH	HALO	A	1.2	1.3	55	77	63
2	STPH	HYDR	A	1.2	1.2	55	77	63
3	STPH	ISOH	C	1.2	0.2	81	90	85
Mountain rangelands (STPJ)[c]						Oct-Feb	Mar-Jun	Jul-Sep
4	STPJ	MBEH	D	7.8	20.7	88	86	96
5	STPJ	CRGY	C	2.5	0.7	85	81	90
6	STPJ	ISOH	C	4.2	4.9	85	81	90
7	STPJ	CRCG	D	3.1	3.0	88	86	96
8	STPJ	PEAH	A	3.3	2.5	63	55	77
9	STPJ	AFFL	D	9.8	3.4	98[d]	98[d]	98[d]
10	STPJ	HALO	A	1.2	0.3	63	55	77
Rangelands of the plain (STPP)[c]						Oct-Feb	Mar-Jun	Jul-Sep
11	STPP	ISOH	C	3.5	6.4	85	81	90
12	STPP	PEEH	C	9.1	3.2	85	81	90
13	STPP	CRCG	D	7.8	6.5	88	86	96
14	STPP	PEAH	A	7.4	4.3	63	55	77
15	STPP	MBEH	D	3.4	0.1	85	86	96
16	STPP	ISHM	B	¤	¤	77	72	85
Cereals (CULT)						Nov-Dec	Jan-Apr	May-Oct
17	CULT	CRGY	C	1.2	0.2	88	84	91
18	CULT	HALO	A	1.2	2.8	72	65	77
19	CULT	ISOH	C	4.7	3.8	88	84	91
20	CULT	PEEH	C	3.9	0.2	88	84	91
21	CULT	CRCG	D	7.1	2.4	91	88	94
22	CULT	PEAH	A	5.1	1.2	72	65	77
Olives in the mountains and plains (OLVM, OLVP)[e]						Jan-Apr	May-Dec	
23	OLVM	JESR	A	6.9	23.7	30	30	
24	OLVP	STAB	B	7.8	7.0	30	30	

[a] Hydrologic Response Unit
[b] HALO: halomorphes (Solonchak, Solonetz); HYDR: hydromorphes (Gleysols); ISOH: isohumiques bruns calcaires tronqués (Calcic Xerosols); MBEH: minéraux bruts d'érosion hydrique (Regosols); CRGY: calcimagnésiques sur rendzine gypseuse (Gypsisols); CRCG: calcimagnésiques sur rendzine calcaire (Rendzinas); PEAH: Peu évolués d'apport hydrique (Fluvisols); AFFL: outcropping; PEEH: peu évolués d'érosion hydrique (Regosols); JESR: soil on the terraces of *jessour*; STAB: Soil on the terraces of *tabias*.
[c] For rangelands in the study area (Ouled Belgacem, 2004, Pers. Com.):
Oct-Feb: 10-25% cover (poor); Mar-Jun: 25-50% cover (fair); Jul-Sep: < 10% cover (very poor).
[d] Adjusted for slope.
[e] Olives are grown on flat areas (terraces).

Crop parameters and management

To change the CN because of the changes in cover during the growth of the vegetation, a tillage operation with zero mixing depth and zero efficiency was added to the tillage database. Olives are planted on the terraces of *jessour* and *tabia*. The olives are harvested in December.

The planting date of cereals was set to November 15 and the harvest and kill date was May 15. To change the CN after the crop has fully emerged, a tillage operation was applied on January 1. The stubble of barley is grazed by the animals. Thus, almost no residues are left for enriching the soil. Therefore, the harvest index was set at 0.95.

Three types of rangeland vegetation have been considered; the mountain ranges, the plain ranges and the halophytes ranges found in the saline depression at the outlet of the study watershed. We used the US southwest rangelands characteristics with some adjustments based on information from studies undertaken in the arid regions of Tunisia (Floret et Pontanier, 1982; Ouled Belgacem, 2006). The rangelands are generally grazed around the year by various animals (sheep, goat and camel). However, intensive grazing of the saline depression takes place during the winter as it is the favorite rangeland area of camels during that period.

Representation of Water-Harvesting Practices in SWAT

During rainfall events, the runoff that is generated at the level of the impluviums (catchments) runs onto the terraces of the *jessour* and *tabias*. Part of the runoff water will form temporary ponds with a depth equal to the height of the spillway. It will infiltrate into the soil slowly after the runoff event. The *jessour* are found along the tributaries (talwegs), they receive runoff from the mountain rangelands. The *tabias* receive the runoff generated on their impluviums and the outflow from the *jessour* if they are installed on the same tributary. The outflow from the *jessour* and *tabias* flows into the reach and continues towards the outlet.

The SWAT considers that the runoff coming out of any HRU flows directly to the reach. To harvest the runoff water behind the jessour and old tabias, an option "irrigation from surface runoff" was added to the model code. To control the amount of water to be applied to the HRU this option used the same parameters as those of the "irrigation from reach" option. The model allows the user to specify a fraction of the runoff (FLOWFR) and a maximum height of water to be put on the HRU (DIVMAX). The value of DIVMAX was set as the equivalent spillway height, which was estimated based on field knowledge. The flow fraction was assumed to be 100%. The SWAT subsequently applies this amount as irrigation by filling up the soil of the HRU to field capacity. In reality, the soils could fill up to saturation. Therefore, the model code was changed to allow irrigation application up to saturated moisture content (SAT). If the total water exceeds the field capacity of the soil profile, it will become percolation and lateral flow. The lateral flow of the *jessour* and *tabias* was assumed zero.

Model Evaluation

For the evaluation of the SWAT model application to the study area, runoff events (total daily volumes), recorded at the Koutine station during the period 1975 to 1992 (DRE, 1975-1992; Fersi, 1985; Ayadi, 1992) were used. The hydrometric Koutine station was installed by the

Hydrological Service of the Ministry of Agriculture (DRE) in 1974. A battery of scales were installed in a cross section on the *wadi* close to the village of Koutine and monitored by an observer who lives nearby. During flooding, the observer made notes of the time and the height of the water in the *wadi*. The data were converted to flow based on a calibration curve (Fersi, 1985). The area upstream of Koutine station covered 270 km^2.

The runoff events recorded in the annual reports of the DRE were checked first. Records with anomalies (runoff without rainfall, very low rainfall with high runoff, etc.) were discarded. For the daily rainfall data, some events in 1975/76 and 1990 had a shift of one day; these were adjusted accordingly. A total of 34 days were retained: 18 days (Oct 75 - Nov 79) were used for calibration and the remaining 16 days for validation. The model was calibrated by changing the values of the representative dike height (DIVMAX) of the *tabia* and *jessour* within reasonable limits.

Graphical and statistical measures were used to evaluate the model performance based on the above data. Using a single goodness-of-fit measure for model evaluation is generally not sufficient (Chu and Shirmohammadi, 2004). Therefore, four statistical criteria were used to evaluate the hydrologic goodness-of-fit: the regression coefficient (r^2), the model efficiency or the Nash-Sutcliffe coefficient, R^2_{NS} (Nash and Sutcliffe, 1970), the standard error (STE) and the mean absolute error (MAE). The r^2 is an index of the degree of linear association between the observed and the simulated values. The Nash-Sutcliffe coefficient indicates how close the plot of observed versus simulated data is to the 1:1 line. It is calculated as follows
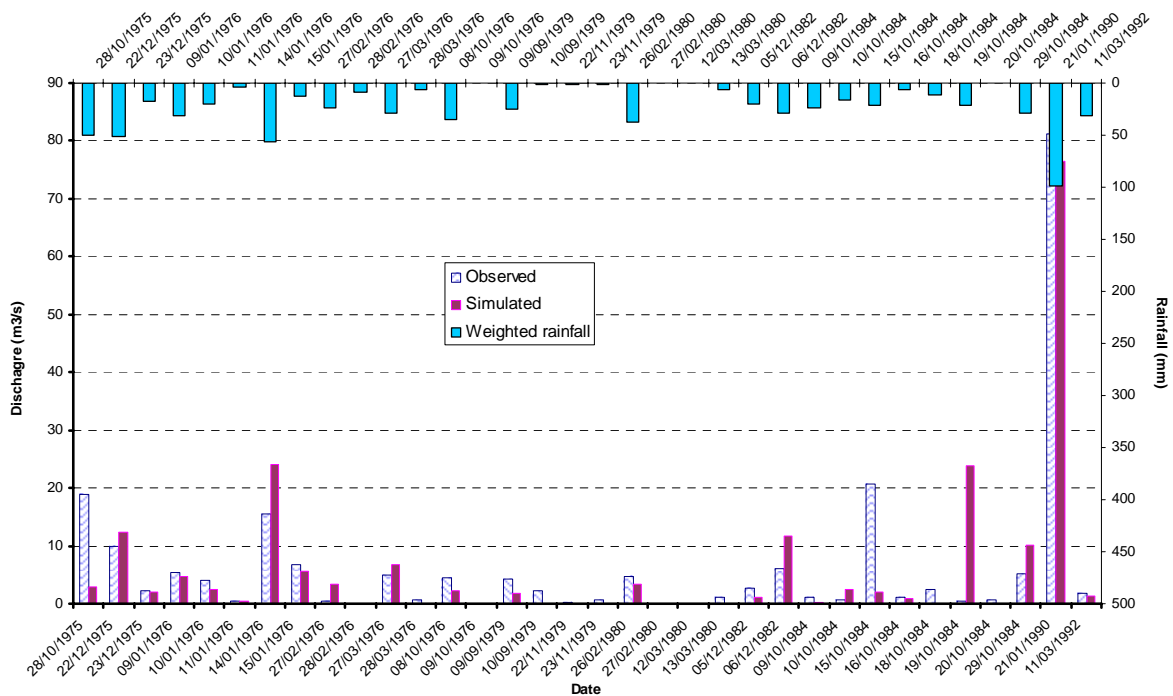

Fig. 2. Observed and simulated outflow during the evaluation period (1975-92).

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$$R_{NS}^2 = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(Oi - \overline{O})^2} \qquad [1]$$

where O_i is the measured value, P_i is the predicted value, $\overline{O}$ is the average observed value; and n is the number of observed values. The STE expresses the difference between the predicted values (P_i) and the observed data (O_i) as follows

$$STE = \sqrt{\left[\frac{1}{n(n-2)}\right]} \sqrt{\left[n\sum Pi^2 - (\sum Pi)^2 - \frac{\left[n\sum OiPi - (\sum Oi)(\sum Pi)\right]^2}{n\sum Oi^2 - (\sum Oi)^2}\right]}$$

$$[2]$$

Although the Mean Absolute Error (AME) tells nothing about over- or under-prediction, it is a deviance measure considered for assessing the agreement between observed values and predicted values. It is calculated as

$$MAE = \frac{1}{n}\sum |Oi - Pi| \qquad [3]$$

Results and Discussion

The calibrated values of DIVMAX were 0.20 and 0.25 m for *jessour* and *tabias*, respectively. The observed and the simulated outflow for the calibration and validation data sets are presented in Fig. 2. The plot shows a reasonable good match between the observed and the simulated values except for some events which occurred on consecutive days. The model performed well for some exceptional large rainfall events (1975, 1976, 1984, 1990), which had good rainfall covering the whole watershed. Nevertheless, some events were largely underestimated or overestimated. This could be expected considering that the runoff coefficients of the observed events varied from as low as 3% to as high as 70%. In addition, the spatial and temporal rainfall pattern in the area is never perfectly captured due to the low density of the rain-gauge network (6 stations for the area upstream of the runoff station).

The results of the goodness of fit tests between the observed and the SWAT predicted outflow for the calibration and validation data sets is presented in Table 2. Reasonably correlations were obtained for these outflow data. However, better relations were obtained for the validation period than for the calibration period.

Table 2. Goodness-of-fit statistics for observed versus predicted outflow.

	Calibration (1975-79)	Validation (1980-92)	Whole period
r^2	0.46	0.83	0.80
R^2_{NS}	0.26	0.83	0.80
STE	4.06	8.39	6.42
MAE (mm)	0.68	0.21	0.26

r^2: coefficient of determination, R^2_{NS}: Nash-Sutcliffe coefficient, STE: Standard error, MAE: mean absolute error.

Taking into consideration the scarcity and uncertainty of the data in this typical arid environment, the above results showed that, even under dry conditions with coarse resolution of input information, the SWAT could simulate reasonably well the watershed runoff. The values of the performance indicators were similar to those reported for SWAT applications in other regions of the world, such as in the US (Srinivasan et al., 1998; Chu and Shirmohammadi, 2004), Germany (Fohrer et al., 2001), and India (Kaur et al., 2003).

Conclusions

The GIS-based model SWAT (version 2000) was adapted and evaluated in the watershed of Wadi Oum Zessar, located in the dry areas of southeast Tunisia. The input data were prepared from available data and information. The selection of parameter values was mainly based on the knowledge of the site, in addition to information available in the literature. To adapt the model to the specific conditions of the study area, the following adjustments were made to the SWAT code:

- To simulate the harvesting of runoff water by *jessour* and *tabias* an option was added to re-apply the surface runoff generated in the subbasin to selected HRUs in the subbasin. This option has similar parameters to regulate the amount of water applied to the HRU as the SWAT option "irrigation from reach".
- To simulate the infiltration of the pounded water in the soils of the *jessour* and *tabias*, the upper limit for irrigation was changed from field capacity to saturation.
- The dormancy period of annual crops was removed.
- The shedding of leaves for olive trees was removed.
- The functioning of the change of the runoff CN during tillage operations was corrected.

In addition, various SWAT options were used to simulate the watershed conditions. The representation of the new *tabias*, which receive water by diversion from the *wadi*, was simulated by using the SWAT option "irrigation from reach". The gabion check dams and recharge wells were modeled as reservoirs by choosing the appropriate input parameters for hydraulic conductivity and volume. The effect of the change in crop cover on surface runoff during the season was modeled by applying a tillage practice with zero mixing and depth to allow the change of the curve number.

Graphical and statistical measures were used to evaluate the model performance based on the

runoff data measured in the study area. Reasonable correlations were obtained for the outflow, although better relations were found for the validation than the calibration periods. Considering the scarcity and uncertainty of the data in this typical arid environment, SWAT could simulate reasonably well the watershed runoff even under dry conditions with relatively coarse resolution of input information.

The calibration and validation of the model for the study site was difficult because of the limited number of observed runoff events and the uncertainty of the observed data. Further work is needed to evaluate these events. It is recommended to improve the access and exchange of data between different concerned departments (agriculture, research, education, environment, meteorology) at local, sub-national, and national levels, especially for research and development purposes.

Although watershed modeling is very useful, it is a labor and time consuming task, especially the collection and preparation of input data (soil, land use, climate) and the selection of the parameter values. The scarcity and uncertainty of available data, typical for watersheds in the dry areas, complicated this task. Nevertheless, the model is very attractive for application, considering the gradual generalization and widening of the scope of the use of digital data layers and spatial decision support systems by different end-users (e.g., agriculture, environment, planning) in the country (Min. Agr., 2004; OSS, 2003).

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