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Modelling water-harvesting systems in the arid south of Tunisia using SWAT

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Abstract

In many arid countries, runoff water-harvesting systems support the livelihood of the rural population. Little is known, however, about the effect of these systems on the water balance components of arid watersheds. The objective of this study was to adapt and evaluate the GIS-based watershed model SWAT (Soil Water Assessment Tool) for simulating the main hydrologic processes in arid environments. The model was applied to the 270-km^2 watershed of *wadi* Koutine in southeast Tunisia, which receives about 200 mm annual rain. The main adjustment for adapting the model to this dry Mediterranean environment was the inclusion of water-harvesting techniques and a modification of the crop growth processes. The adjusted version of the model was named SWAT-WH. Model evaluation was performed based on 38 runoff events recorded at the Koutine station between 1973 and 1985. The model predicted that the average annual watershed rainfall of the 12-year evaluation period (209 mm) was split into ET (72%), groundwater recharge (22%) and outflow (6%). The evaluation coefficients for calibration and validation were, respectively, R^2 (coefficient of determination) 0.77 and 0.76; E (Nash-Sutcliffe coefficient) 0.73 and 0.43; and MAE (Mean Absolute Error) 2.6 mm and 3.0 mm, indicating that the model could reproduce the observed events reasonably well. Discrepancies remained mainly due to uncertainties in the observed rainfall and runoff data. Recommendations for future research include the installation of additional rainfall and runoff gauges with continuous data logging and the collection of more field data to refine the input parameters (soil and land use). In addition, crop growth and yield monitoring is needed for a proper evaluation of the crop growth submodel, to allow the economic assessment of the different water uses in the watershed.

1 Introduction

Water management is the most critical issue in dry areas as it impacts the livelihood of people and the productivity of the land and the society in general. For thousands of years, inhabitants of the dry areas have constructed water-harvesting systems that helped them cope with water scarcity (El Amami, 1984; Boers, 1994; Oweis et al., 2004). These systems were built to capture surface runoff from sparsely covered, rocky mountain slopes or to divert occasional *wadi* flow to fields for crop production. Despite the long and successful history of these systems, little is known about their effect on the hydrological processes in these dry areas.

The 272-km^2 Koutine watershed in southeast Tunisia is a typical example of a southern Mediterranean dryland watershed. Water-harvesting systems were traditionally developed by rural communities in the upstream mountain areas. However, water-harvesting systems gradually expanded to the foothills of the mountains, especially during the last three decades.

During the relatively wet period 1973–1985, the average annual rainfall over the watershed of 209 mm produced an average runoff of 12 mm/yr, which flooded the downstream rangelands in the coastal plain (*sebkhas*) (Fersi, 1985). Transmission losses through the wide *wadi* bed are also serving as a source of recharge for the region's aquifers. However, in dry years (e.g., 1981/1982), no runoff reached the downstream areas.

Derouiche (1997) assessed the recharge of the 725-km^2 Zeuss-Koutine aquifer, which covers most of the *wadi* Koutine watershed, using biannual and annual groundwater level observations in 28 piezometers and boreholes and the finite difference groundwater flow model MULTIC (Djebbi, 1992). Lateral inflow from the upstream aquifer in the south (Grès de Trias) (30 l/s) and direct recharge in the Matmata mountains (4 l/s) were assumed constant and were estimated by calibration, whereas recharge from the remainder of the soils was assumed negligible. For the period 1974/1975 to 1984/1985, average annual groundwater recharge from *wadis* and the Matmata mountains (upper boundary of the model) was computed to be equal to 301 l/s. This would be equal to 13.1 mm over the area of the aquifer and 6.1% of the average annual rainfall for this period in the *wadi* Koutine watershed.

Watershed models can provide further insights in the distribution and uses of the water in these arid watersheds. Although there are many watershed models around (Singh and Woolhiser, 2002; Borah and Bera, 2004), few of them can be easily applied to simulate the highly spatially and temporally variable processes in arid watersheds with water-harvesting practices. The Soil and Water Assessment Tool (SWAT), developed by Arnold et al. (1998), was selected for application in south-eastern Tunisia, because (1) it simulates all water balance components at various temporal scales (daily and long-term); (2) it has a GIS interface that allows easy representation of different spatially variable data and processes; and (3) it has a wide development and users' community with open access to the model documentation and source code.

Applications of SWAT in watersheds in humid regions have been abundantly published in the literature (e.g., Srinivasan et al., 1993; Srinivasan and Arnold, 1994; Cho et al., 1995; Bingner et al., 1997; Arnold et al., 1999; Santhi et al., 2001; Kaur et al., 2003). However, applications of SWAT in dry environments are still relatively limited. In Tunisia, Bouraoui et al. (2005) applied SWAT to an 8000-km^2 basin of the Medjerda river located in a semi-arid to sub-humid bioclimate (297–1056 mm annual rainfall) in the northwest of the country to study the potential hydrological and water quality (nitrate) impacts of land management scenarios. They found that the model was able to represent the hydrological cycle even though some discrepancies were observed, due to a lack of sufficient rainfall data but also due to the fact that reservoirs (dams) were not simulated. In Morocco, Chaponniere (2005) applied SWAT for the representation of the hydrological functioning of a semi-arid mountain watershed. She studied two theoretical scenarios on the potential effects of changing the partitioning between rainfall and snow on the outflow. She pointed out that one of the reasons of the poor functioning of the model was the fact that the local water-spreading systems (*seguias*), which have an important effect on the water routes inside the watershed, were not represented in the model. She recommended the integration of these systems for any further analysis of the water balance. Conan et al. (2003) applied SWAT (version 99.2) to demonstrate the impact of groundwater withdrawals on the hydrological behaviour of the Upper Guadiana catchment located in a semi arid area (400–500 mm rainfall) of central Spain. They found that although the model is well adapted to describing the changes from wetlands to drylands due to human interventions, it did not properly represent all the details of the discharge history. They recommended including additional rainfall data and reservoir operating information to enable better representation of the hydrological functioning of the watershed. To evaluate the effect of different land uses and management practices on surface and soil water flow in a small arid catchment in northern Syria, Bruggeman and Van der Meijden (2005) adapted SWAT by introducing a number of adjustments to the model including growth and dormancy of olives and winter crops, the effect of grazing on leaf area index (LAI), the change of Curve Number (CN) during the growing season, and the use of the irrigation from reach option to represent the runoff harvesting practices widely used in typical dry environments of North Africa and West Asia.

The overall objective of this paper is to adapt and evaluate SWAT for simulating the main hydrologic processes in arid Mediterranean environments. The specific objectives are to (i) develop a methodology to represent water-harvesting systems in SWAT; (ii) adjust the crop model parameters and processes to represent Mediterranean arid cropping systems; and (iii) evaluate the new SWAT-WH version in a 270-km^2 dryland watershed in southeast Tunisia using 38 storm events.

2 Materials and methods

2.1 Study area

The study watershed, *wadi* Koutine, is located in the *Jeffara* region in southeast Tunisia. It lies in the upper arid bioclimate region (Floret and Pontanier, 1982). The rainfall regime is of Mediterranean type with the rainy season extending from September to April. The average annual rainfall ranges from 160 mm in Médenine (1900–2004) in the *Jeffara* plain to 235 mm at Béni Khédache (1969–2003) in the Matmata mountains. The average annual temperature is 20°C, the coldest month is December (mean minimum daily temperature 7°C) and the warmest month is July (mean maximum daily temperature 37°C).

A runoff gauging station was established by the hydrological service of the Ministry of Agriculture (DGRE) in 1971 at the crossing point between *wadi* Koutine and the main road linking Médenine and Gabès (Fersi, 1985). The watershed upstream from the runoff station covers an area of 272 km^2 and stretches from an elevation of 690 m above sea level (a.s.l.) in the Matmata mountains to 100 m a.s.l. at Koutine village and then extends into the saline depression of Sebkha Oum Zessar before ending in the Mediterranean (Gulf of Gabès) (Fig. 1).

In addition to the presence of shallow aquifers (less than 50 m deep) as underflow groundwater beneath the main *wadi*s of the watershed (Hallouf, Nagab, Koutine), the study watershed covers partially the sandstone Triassic aquifer (*Grès de Trias*) (in the upstream part) and the Zeuss Koutine aquifer (in the middle and downstream parts). The first one provides the freshest groundwater of the region (salinity less than 1 g/l), which is mainly used for irrigation and drinking water salinity adjustment (mixing with more saline water), while the second one is the main source of water supply for the province of Médenine (Ouessar and Yahyaoui, 2006).

The land use of the study area is dominated by sparsely covered, degraded steppes. Cropped sites, mainly for growing olives, are found on terraces behind water-harvesting structures. Two types of water-harvesting techniques are practiced by the local farmers: *jessour* and *tabias* (Ouessar et al., 2006).

Jessour are mainly found in the mountainous areas of the watershed. This system is an ancient water-harvesting technique widely spread in the region of the Matmata mountains. *Jessour* are constructed in the inter-mountain and hill water courses to intercept runoff and sediments. *Jessour* is the plural of a *jessr* which is a hydraulic unit made of three main components: a dike (it is locally called also *tabia*) in the form of a small earth embankment with a spillway made of stones, a terrace which represents the cropping area, and an impluvium which is the runoff catchment area (El Amami, 1984) (Fig. 2).

Tabias are essentially situated in the piedmont areas in the middle of the watershed on gentle slopes. The *tabia* is formed by a principal embankment of 50 to 150-m situated along contour lines with lateral bunds of about 30 m long at the ends. The *tabia* gains its water directly from its impluvium or by the diversion of *wadi* runoff. Water is captured until it reaches a height of 20 to 30 cm, after which it is diverted (flow over), either by a spillway or at the upper ends of the lateral bunds (Alaya et al., 1993) (Fig. 2).

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* cover the tributaries (*thalwegs*), and receive runoff from the mountains (mountain rangeland). The *tabias* receive the runoff from their impluviums and/or the spillover from the upstream *jessour* if they are installed on the same tributary. The outflow from the *jessour* and *tabias* flows into the reach.

2.2 SWAT model

SWAT is a physically-based 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 (Neitsch et al., 2002). Spatial variability of soil, land use and management practices are accounted for by discretization of the watershed into subbasins based on the topography and stream network. Each subbasin consists of multiple Hydrologic Response Units (HRUs) representing unique combinations of soil and land cover properties.

The climatic variables consist of precipitation, maximum and minimum air temperature, solar radiation, wind speed, and relative humidity. SWAT includes also the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climatic data or to fill in gaps in measured records. There are three options for estimating reference evapotranspiration (PET): Hargreaves (Hargreaves and Samani, 1985), Priestley-Taylor (Priestley and Taylor, 1972), and Penman-Monteith (Monteith, 1977; Allen, 1986). Considering the availability of data for the study area, the PET was calculated by the Hargreaves method. Potential soil water evaporation is estimated as a function of PET and the plant's LAI and plant water transpiration is simulated as a linear function of PET and LAI.

SWAT provides two methods for estimating surface runoff volume: the SCS curve number procedure (SCS, 1972) and the Green and Ampt (1911) infiltration method. Because of the lack of long-term rainfall intensity data at the watershed level as required by the latter method, the SCS CN method was selected for runoff computation. It calculates the runoff for a given rainfall depth and CN. It is an empirical formula based on several years of rainfall and runoff data obtained from a variety of combinations of soil, land use, topography and climate across the US. The CN is related to the land use and the soil hydrologic group. The method is widely used, not only in the US, but also in other countries (Ponce and Hawkins, 1996).

SWAT defines percolation as the water that drains through the root zone into the aquifer. Downward flow occurs when the field capacity of a soil layer is exceeded. The downward flow rate is governed by the saturated hydraulic conductivity (K_s) of the soil layer. Lateral subsurface flow in the soil profile is calculated simultaneously with percolation. A kinematic storage routing method, which is based on slope, slope length, and saturated hydraulic conductivity is used to predict lateral flow in each soil layer. Lateral flow occurs when the storage in any layer exceeds field capacity and is a function of lateral flow travel time (days) and the difference between soil water content and field capacity (Neitsch et al., 2002).

The lateral flow and surface runoff of all HRUs are summed for each subbasin and then routed through the stream network. Transmission losses are computed as a function of the hydraulic conductivity of the channel bed (K_{chan}), channel width and length, and flow duration, following the procedure of Lane (1983). SWAT routes the stream flow through the channel network using the variable storage routing method or the Muskingum river routing method. Both methods are variations of the kinematic wave model as detailed by Chow et al. (1988).

The crop growth and biomass production module uses a simplified form of the EPIC crop model (Williams et al., 1984). The model uses Monteith's approach to estimate the potential biomass accumulation (Monteith, 1977), coupled with water, temperature and nutrient stress adjustments. SWAT simulates also erosion and water quality processes but these are not considered in this application.

Considering the above processes, the water balance of the watershed can be expressed as follows:

$$\Delta \mathrm{SW} = P - Q_{\mathrm{SURF}} - ET - W_{\mathrm{SEEP}} - Q_{\mathrm{GW}}$$

where ΔSW is the soil water content change, P is the precipitation, QSURF is the surface runoff out of the watershed, ET is the evapotranspiration, WSEEP is the percolation from the soil profile, and QGW are the transmission losses from the streams. All parameters are expressed in (mm) over the watershed area.

2.3 Model modifications

The SWAT code was modified to simulate the collection of runoff water behind the water-harvesting structures (*jessour* and *tabias*) by bringing the surface runoff and lateral flow generated in the subbasin back to the water-harvesting HRUs in the subbasin (Fig. 3). SWAT's irrigation-from-reach option was used to allow the entry of input data for controlling the amount of water harvested by the different HRUs. This option allows the user to specify the fraction of the runoff water (FLOWFR) and a maximum height of the water impoundment on each HRU (DIVMAX), as illustrated in Fig. 4. First the water is distributed to all *jessour* HRUs and secondly to the *tabia* units, which are generally located downstream from the *jessour*. Finally the remainder of the runoff flows downstream. If the total water harvested by the HRU exceeds the field capacity of the soil profile, it will become percolation. This is different from the SWAT irrigation operation, which limits the water application to what can be stored in the soil profile. The lateral flow of the *jessour* and *tabias* was assumed zero (flat terraces).

The second modification was the adjustment of the crop model parameters and processes to represent Mediterranean arid cropping systems. The initialization of the heat unit accumulation was changed to allow the perennials and annual crops to grow during the Mediterranean hydrologic year from fall to summer. The dormancy period was removed because the crops in the watershed do not become dormant. Furthermore, as olives are permanently green, the shedding of leaves for trees, present in the model, was removed. SWAT allows the user to specify a change in CN for selected tillage practices, but this option did not function in SWAT2000; this was corrected. The modified SWAT model is referred to as SWAT-WH.

2.4 Model parameterization

SWAT was applied to the entire 272-km^2 large study watershed upstream from Koutine. We used a 12-year runoff record (1973/1974 till 1984/1985) available for the runoff station of Koutine (Fersi, 1985) for model testing and evaluation.

2.4.1 Topography and watershed configuration

A 30-m DEM was generated from available topographic maps of the area (scales of 1:50 000; 1:100 000 and 1:200 000), from a SPOT stereo pair and from the stream network digitized from a multi-spectral (XS) SPOT image, using the TOPOGRIDTOOL routine. The main channel network was created by the ArcView SWAT interface from the DEM, using a threshold upstream drainage area, which defines the head of a main channel, of 100 ha. Some of the generated stream channels were removed to match the actual occurrence of the streams as observed on the SPOT image. Especially in the upstream areas the channels are completely covered by cascades of *jessour*. A few subbasins were subdivided, through the manual addition of outlets, to ensure the connection between runoff generating areas and the different cropped areas that harvest this runoff. Then, 35 subbasins were obtained.

The main transmission losses are expected to take place at the level of the main reaches (*wadis*). A value of 70 mm/h, corresponding to the average effective hydraulic conductivity of a channel with sand and gravel and low silt content (Lane, 1983), was used. This value is also close to the average measured value (91 mm/h) found by Osterkamp et al. (1995) in the United Arab Emirates for similar *wadi* bed properties as in the study watershed. The recharge from the *wadis* in the upstream subbasins that are completely covered with *jessour*, as well as from the tributaries in the subbasins, was assumed negligible (K_{chan}=0 mm/h).

2.4.2 Climate

Daily precipitation data are needed when using the SCS curve number method to model surface runoff. The daily rainfall data, recorded and published by the hydrological service of the Water Resources Directorate in the Ministry of Agriculture (DGRE, 1968–1985), were collected from the 7 stations (Koutine, Allamet, Toujène Dkhilet, Ksar Hallouf, Ksar Jedid, Béni Khédache and Médenine) in and around the watershed (Fig. 1). SWAT allocates the nearest rain gauge to each subbasin. Due to some missing records, the rain gauge allocation is different for the first 3 years of the 12-year evaluation period.

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 computed for use by the weather generator to fill in missing data.

2.4.3 Soils

Soil classes were obtained from the soil map (at 1:200 000 scale) of the Jeffara region produced by Taamallah (2003), based on a visual interpretation of a Spot multi-spectral (XS) image of 1998 and field investigations. Texture of 31 representative profiles was determined using the sieve-pipette method (Gee and Bauder, 1986) and organic matter by the method of Walkley and Black (1934).

The soil map was modified to take into account the soils built up behind the water-harvesting units as deposited sediments. The boundaries of the soil units were adjusted based on a supervised and unsupervised classification of the Spot XS image of 1991 and additional field investigations using a handheld Global Positioning System (GPS). Three classes were added: the deep "artificial" soils formed as small terraces behind the water-harvesting structures by the deposition of sediment (JESR: soils behind *jessour*, TABS: soils behind *tabias*) and the calcareous outcroppings on the mountains, as part of the Matmata cuesta, in the upstream parts of the watershed where the soil is almost nonexistent (AFFL).

For the soils on the terraces (JESR and TABS) of the water-harvesting structures, measured available water capacity (AWC), bulk density (BD) and saturated hydraulic conductivity (K_{soil}) (Maati, 2001) were used. AWC was determined from the difference in soil-water content at −33 kPa and −1500 kPa using pressure chambers (Soil moisture Equipment, Santa Barbara CA, USA). The BD was measured using 100−cm^3 cores and K_{soil} was obtained from infiltration experiments using a double ring with an inner diameter of 28 cm and an outer diameter of 53 cm. As it is frequently done in watershed modelling where the soil properties are not fully available (e.g., Heuvelmans et al., 2004; Bouraoui et al., 2005), the missing water characteristics of the remaining soils were derived by means of the calculator of Saxton (2005). A summary of the soil characteristics is given in Table 1.

2.4.4 Land use and CN

A land use map of the study area based on a semi-supervised classification of the Spot XS image of 1991 (Zerrim, 2004) was adjusted by adding the different soil and water management practices (*jessour* and *tabias*), with the help of a visual interpretation of the Spot XS image of 1998 and aerial photos (missions of 1975, 1990), in addition to field checks and GPS surveys.

The main land uses in the watershed are rangelands, fruit trees and cereals. Fruit trees, mainly olives, (*Olea Europaea*), are found on the *jessour* and *tabias* only. Cereals (barley, *Hordeum vulgare,* and wheat, *Triticum durum*) are grown episodically during wet years. The natural vegetation (ranges) was divided into two classes: mountain and plain, because of their different phenology and grazing practices.

The soil hydrologic group and CN values were selected based on the SCS tables (SCS, 1986). Because of their shallowness, most soils were identified as group D soils. The rangelands were considered arid rangelands made of herbaceous-mixture of grass and low growing brush (SCS, 1986), while the cereals were considered small grains in straight rows and bare soils during fallow. The olives are grown on flat terraces, with a CN of 30.

To allow a change in CN when the crops and rangelands have developed a protective ground cover, a tillage operation with zero depth and zero mixing was used. For the rangelands and cereals, the CN was set for three periods as a function of the growing cycles and management operations, and included planting, grazing, harvesting (Table 2).

2.4.5 Crop growth and management parameters

The crop parameters (potential heat units, base and optimal temperatures, length of the growing season, leaf area development parameters) for the relevant crops in the SWAT database were checked and adjusted to obtain the general growth and water use patterns as observed in the study area. Although, for this study, the testing of the crop input and output data focused on the effects of the soil water balance rather than on the actual crop yields, some adjustments were made as described below.

Olive trees are the dominant fruit trees cropped in the area. It was assumed that the olive trees have matured but kept growing normally by pruning the tree after harvest in December. The values of the radiation use efficiency and the harvest indices were adjusted to obtain biomass and yield production figures close to the average values found in the literature (Labras, 1996; Fleskens et al., 2005) and field knowledge.

The characteristics of the US southwest rangelands were used with minor adjustments (biomass production, grazing pattern, base and optimal growth temperature) based on research work undertaken in the arid regions of Tunisia (Floret and Pontanier, 1982; Neffati, 1994; Ouled Belgacem, 2006). The rangelands are generally grazed around the year by various animals like sheep, goat and camel.

After the first significant rains, which fall between October and November, the farmers plant barley and occasionally wheat and legumes. Following harvest in May, the stubble of cereals is completely grazed by the animals and only negligible amounts of residues are left. The cereal crop parameters suggested by Bruggeman and Van der Meijden (2005) for the Khanasser Valley (Syria) were adopted because of similar climatic dryland conditions.

As described previously, the water-harvesting systems are controlled by two parameters. The value of DIVMAX was set to 0.25 m for the *jessour* and 0.15 m for the *tabias*, based on reported spillway dimensions and pounded water level in the terraces of these water-harvesting systems (El Amami, 1984; Chahbani, 1990; Alaya et al., 1993; Ennabli, 1993; Ben Mechlia and Ouessar, 2004) and field knowledge. Considering that not all runoff water is captured by the water-harvesting systems, the FLOWFR of *jessour* and *tabias* were set to 0.90 and 0.95, respectively.

2.5 Model evaluation

2.5.1 Sensitivity analysis

A parameter sensitivity analysis was conducted to evaluate the effect of changes in the baseline model parameter values, as presented in the previous section, on the water balance components and to identify which parameters have the most effect on the outflow of Koutine watershed. The parameters selected in this study for sensitivity analysis were based on the model description and other published SWAT applications. In a study on the long term land use effects in the semi-arid Upper Guadiana river basin (Spain), Conan et al. (2003) found that the water yield in the stream is sensitive to CN, AWC, K_{soil}, and aquifer properties. As far as surface runoff is concerned and according to various authors (e.g. Heuvelmans et al., 2004; Chu and Shirmohammadi, 2004), the most sensitive parameters in SWAT are CN, AWC, K_{soil} and K_{chan}. For our specific case, we added DIVMAX and FLOWFR which are the parameters used to represent the water-harvesting systems. Thus, a total of six input parameters were evaluated.

The relative sensitivity index (RSI) (Lenhart et al., 2002) was computed as follows:

$$RSI = \frac{(y_1 - y_0)/y_0}{(x_1 - x_0)/x_0}$$

where x_0 is the initial value of the parameter (baseline parameters) and y_0 is the corresponding output, x_1 is the tested value of the parameter and y_1 is the corresponding output. The sign of the index shows if the model reacts co-directionally to the input parameter change, i.e. if an increase of the parameter generates an increase of the output and vice versa. A value of RSI near zero indicates that the output is not sensitive to the parameter under study. A value of RSI significantly different from zero shows high degree of sensitivity. Because of the linear nature of this analysis, no parameter interaction is captured.

The tested values of the parameters were their estimated upper and lower limits. Based on field knowledge, the DIVMAX was changed up and down by 20% while the FLOWFR was varied by 5%. The soils in the watershed are dominated by sandy loam textures, which have an expected AWC range of 6 to 12% (e.g., Allen et al., 1998). However, because the total storage capacity of the soils is also affected by their depth, which involves another uncertainty, this parameter was varied with a 50% range. The changes for the K_{soil} were similar. For the K_{chan}, we used the range given by Lane (1983) and Osterkamp et al. (1995) (30 to 180 mm/h) for typical dry channels. As the CN values in the watershed are relatively high, the range was 5% up and 10% down.

The model was run by changing one parameter at a time in the same direction for all HRUs or subbasins. The main water balance components ET, PERC, TLOSS, and FLOW_OUT at Koutine station, and their respective RSI were computed. A total of twelve runs were performed.

2.5.2 Calibration and validation

As the SWAT model contains many difficult to measure or non-measurable parameters, especially at the watershed scale, the most sensitive parameters, as identified in the sensitivity analysis, were adjusted based on the 12-year runoff record reported by Fersi (1985). The model parameters were adjusted manually by trial and error using the statistical indicators presented below but also by considering the representativeness of the observed runoff events and the estimated recharge of the study area (Derouiche, 1997).

Fersi (1985) mentioned that 39 runoff events were recorded during the period from September 1973 up to April 1985, but he provided data for 38 events only. For each runoff event, he reported: the runoff depth (mm), the time to peak, the duration of the event (hours) and provided an isohyet map, based on the daily rainfall data from the 6 rainfall stations in and around the watershed. He also reported the daily runoff amounts for these events on a calendar-day basis (0 to 24 h). After 1979, rainfall in Koutine, Allamat, Béni Khédache was recorded by a rainfall recorder. For this period, Fersi (1985) provided hyetographs for 6 events but with the rainfall averaged for the three stations. A few inconsistencies were noticed between the rainfall event totals on the isohyets maps of Fersi (1985) and the totals for the reported runoff period obtained from the daily rainfall data reported by DGRE (1968–1985). Apparently, the daily rainfall (8 a.m. to 8 a.m.) was not always consistently recorded on the correct day. After cross checking between the above data sources and INM (1979–1985), daily rainfall amounts of one or two stations were moved one day backwards or forwards for a few events, based on the occurrence and spatial distribution of the rain at the 6 rain gauges in and around the watershed and the nearby Medenine station (Fig. 1).

Due to the fact that a better rainfall coverage was available for the period September 1978 to August 1985 (6 stations) than for the period September 1973 to August 1978 (4 to 6 stations), the 21 runoff events of the 1978–1985 period were used for calibration and the other 17 events (1973–1978) were used for validation. Although the validation results may, therefore, not be optimal, this would provide a more robust model parameterization.

Graphical and statistical measures were used to evaluate the model performance based on the above mentioned measured data. The statistical criteria used to evaluate the hydrologic goodness-of-fit were the coefficient of determination (R^2) and the model efficiency or Nash-Sutcliffe coefficient (E) (Nash and Sutcliffe, 1970). The coefficient of determination is an index of the degree of linear association between the observed and the simulated values, but it is highly affected by the good matching records of high values. The Nash-Sutcliffe coefficient indicates how well the plot of observed versus simulated data is close to 1:1 line. It is the most often used coefficient in SWAT calibrations (Gassman et al., 2007). The optimal value of the model efficiency is 1. It is calculated as follows:

$$E = 1 - \frac{\sum_{i=1}^{n} (Oi - Pi)^2}{\sum_{i=1}^{n} (Oi - \overline{O})^2}$$

In addition, we used also the mean absolute error (MAE) index which is a statistical estimator to show how much the model over or under-estimates the observations. It writes as:

$$\text{MAE}=\left(\sum_{1}^{n} |O_i - P_i|\right)/n$$

where O_i is the observed value, P_i is the predicted value, O is the average value and n is the number of observed values.

To capture some of the uncertainty in the parameter values, two additional runs were performed: one with the combination of the extreme parameter value settings that would result in maximum outflow from the watershed and one with the combination that would result in minimum outflow (Table 3). The simulated extreme runoff was compared with the observed watershed runoff.

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3 Results and discussion

3.1 Sensitivity analysis

The results of the sensitivity analysis tests at the watershed level are given in Table 4. The simulations with the base parameter set for the 1973–1985 period resulted in the following distribution of the incoming precipitation (209 mm/yr average) for the watershed: 72% evapotranspiration, 19% percolation, 6% outflow from the watershed and 3% transmission losses through the *wadi* bed. The computed water balance components were most sensitive to CN and FLOWFR, and to a lesser extent to AWC and K_{chan}. Because the CN controls the first step in the water routing cycle by the subdivision of the rainfall into runoff and infiltration, it had a major impact on all the water balance components.

The relative sensitivity of the simulated average annual flow out of the watershed to a change in the CN was 7.54 for a 5% increase and 6.77 for a 10% decrease in the CN values. These were far higher than the relative sensitivities to the FLOWFR, which were −0.85 and −0.91, respectively. Interestingly, the simulated FLOW_OUT was much less sensitive to the height of the harvested water on the *jessour* and *tabias* (DIVMAX) than to the fraction of runoff water harvested, with a relative sensitivity of −0.34 for a 20% increase and 0.22 for a 20% decrease in the value of DIVMAX. The lower sensitivity to an increase in DIVMAX, as compared to a decrease, indicated that not all events filled the water-harvesting structures up to their capacity.

As expected, the AWC had an important effect on ET and PERC. A 50% increase in the AWC (assumed to represent a change in soil depth as well as in water holding capacity), increased the ET from 72 to 78% of the total rainfall and reduced the percolation from 19 to 12%. A 50% reduction of the AWC reduced the ET from 72 to 58% of the rainfall and increased the percolation from 19 to 33%. As the K_{soil} values in the watershed are relatively high, it was found not to be a sensitive parameter. The FLOWFR, and to a less extent the DIVMAX, also affected percolation because these parameters control the amount of water captured by the water-harvesting systems, with downwards drainage mainly occurring from the relatively shallow soils (1 m) of the *tabias*.

3.2 Calibration and validation

The results of the base run indicated that for high rainfall events in the upstream areas runoff was generally underestimated by the model, whereas for events with high rainfall in the mid- and downstream areas runoff was overestimated. As FLOW_OUT is most sensitive to the CN, adjustments were made to the CN as shown in Table 2. To reduce the runoff in the mid- and downstream area, the CN of the cereals and the rangelands in the plain was reduced. However, the reduction of the CN is constrained by the shallowness of the majority of the soils covered by these land uses. These shallow soils fill up quickly, with the remainder of the rain turning in to runoff, lateral flow and percolation. The CN of the mountain rangelands on the soils in the downstream areas (ISOH, PEAH) were assumed to have similar CNs as the plain rangelands on these soils. For the mountain rangelands on the shallow soils (MBEH, CRCG), which are mainly found on the sloping lands in the upstream and midstream areas, the CN was increased by 2 points. Because the area occupied by *jessour* seemed to be somewhat overestimated, the DIVMAX of *jessour* was reduced from 0.25 to 0.22 m, which also increased the runoff from the upstream areas. The FLOWFR of the *tabias*, which capture a large part of the runoff of the upstream areas, was reduced from 95 to 90%.

The R^2 of the 21 calibrated runoff events was 0.77 and the Nash-Sutcliffe coefficient was 0.73. A graphical representation of the observed versus simulated outflow of the recorded events at Koutine station is presented in Fig. 5. As can be seen, the calibrated events (Sep. 1978–Aug. 1985) fitted the observed events reasonably well. For the 17 validation events, the fit was not as good, an R^2 of 0.76 and an E of 0.43 were obtained. The validation period clearly suffered from the absence of the Koutine and Allamet rain gauges, which cover most of the downstream and midstream areas. In their absence, the rain was interpolated from the remaining four rain gauges plus the Médenine station. The Koutine gauge became operational in September 1975 and the Allamet gauge in September 1976. Most of the events before this date were overestimated.

It is important to note that 50% of the total runoff of the 12-year period is produced by two events. The largest event, which occurred in March 1979 (calibration period), had an area-weighted rainfall of 166 mm over the watershed and an observed runoff of 42 mm. This event was estimated quite well by the model (47 mm). The second largest event, on December 1973 (validation period), which received 91 mm rain and 30 mm runoff, was clearly underestimated (12 mm) and did not even fall inside the boundaries of the extreme parameter sets. This was most likely at least partly due to absence of both the Koutine and the Allamet rain gauges.

The runoff coefficients of the 38 events ranged between 0.0002 (December 1983) and 0.62 (June 1976). The first event occurred towards the end of a dry month with 3 consecutive days of rain observed at all 6 gauges. The observed rainfall for this 3-day event was 56 mm, but the maximum daily rain for any of the 6 gauges did not exceed 31 mm (upstream). The observed runoff was 0.009 mm, whereas SWAT simulated 0.5 mm runoff. The event of June 1976 consisted of a sole 13 mm in Béni Khedache (upstream), which, very surprisingly, resulted in 0.29 mm runoff over two days in Koutine. As expected this event also fell outside the uncertainty bounds of the extreme parameter sets. Some rain was observed in Medenine on the day before the runoff, so it is likely that not all rain that fell on the watershed during this event was captured by the rain gauge network or by their observers. Clearly, the highly variable spatial distribution of the rainfall, which frequently occurs in dry regions, induces problems. For the same area weighted average rainfall over the watershed we can obtain contrasting responses. As expected, better model fits were generally obtained for high and uniformly distributed rainfall events (e.g. March 1979).

Except for the varying distributions of the rainfall over the watershed, and the somewhat inadequate coverage of the rain gauges, differences in the intensity of the rainfall also affected the observed rainfall-runoff relations in the watershed. The highest reported 30-min maximum intensity (76 mm/h), which is the reported average of the Béni Khedache, Allamet and Koutine rain gauges (Fersi, 1985), was recorded for a 23-mm rainfall event on 15 October 1984. This event produced indeed high runoff (7 mm). During the same month (29 October 1984), the reported maximum 30-min intensity of a seemingly similar rainfall event (27 mm) was only 24 mm/h. As expected, this event produced much less runoff (1.6 mm) than the previous event. The SWAT simulations of these events were affected by the different initial soil moisture conditions and by the spatial distribution of the rainfall. The first event, which occurred mainly in the midstream areas (Allamet and Toujène Edkhila) had a simulated runoff of 2.2 mm, whereas the second event, which covered the complete watershed had a simulated runoff of 4.6 mm.

As can also be seen in Fig. 5, almost all calibrated events fitted between the minimum and maximum bounds obtained with the extreme parameter sets. However, three of the observed events (24/11/79, 13/12/73, 20/11/80) had higher observed runoff than the maximum simulated runoff and one event (19/10/84) had lower than the minimum. As discussed previously, it is very likely that these events suffered from inadequate representation of the spatial distribution of the precipitation by the rain gauges and measurement inaccuracies.

Although the performance indicators are relatively low, the calibrated model captured the average annual runoff for the watershed quite well. The calibrated model predicted an average annual flow out of the watershed of 12 mm which is similar as the 11.9 mm computed from the runoff observations presented by Fersi (1985). Although Fersi (1985) mentioned only one runoff event not being recorded, it is likely that some more events may not have been recorded as well. In addition to the observed events, the model predicted runoff rates of more than 0.01 mm/d for about 40 daily events during the 12-year period. However, the model behaved similar to the observed record (i.e., no runoff) for the remaining records (253 rain days).

3.3 Water balance components

For the calibrated parameter set, the model predicted that the average annual rainfall of the 12-year evaluation period over the area of the watershed (209 mm), mainly goes to ET (150 mm, 72%), then to percolation (39 mm, 19%), to stream flow at the outlet of the watershed (12 mm, 6%) and to transmission losses (6 mm, 3%).

The results showed rather high average annual groundwater recharge rates (22% of the average annual rainfall) compared to the 6.1% computed by Derouiche (1997). However, it is difficult to make the comparison as the basic hypothesis and the application scale are different. As there are some underflow aquifers (shallow aquifers), not all of the percolation from the soils, computed by SWAT, may end up in the deep aquifer from where Derouiche (1997) calibrated and computed the recharge. Also, Derouiche (1997) assumed that all boundary conditions (outflow to the *sebkha* and the inflow from the other aquifers) were fixed and did not vary with time and that the only varying parameter was the recharge through the *wadi* beds. However, this may not always be the case. Studies in similar arid environments reported annual recharge rates ranging from 3 to 15% of the precipitation. For example, Osterkamp et al. (1994, 1995) reported a total average annual recharge of 3% of the rain (180 mm) in California, and 7% of the rain (130 mm) in Oman (Al Ain), whereas Barnes et al. (1994) found that the transmission losses and percolation represented 15% of the rain (278 mm) in an arid region of Australia.

The water balance components of the different land uses in the watershed are presented in Table 5. The highest rates of percolation are produced at the level of the water-harvesting units (OLVP and OLVM). However, the olives of the mountains collected more runoff (almost three times) than those of the plains. In fact, the sloppy area (mountains rangelands) produced surface runoff double of the piedmont and flat area (plain rangelands). This explains to some extent also the settlement and cropping pattern of the watersheds in the dry areas, where the farmers started upstream and gradually moved downstream.

4 Conclusions

The GIS-based model SWAT (version 2000) was adapted and evaluated for water balance assessments in arid watersheds with water-harvestings systems. The main changes were the redistribution of runoff water within a subbasin to represent different water-harvesting systems (*jessour* and *tabias*), and adjustments of the crop growth processes to simulate cereals and olive production in Mediterranean environments. We denoted the adapted model as SWAT-WH (SWAT for Water Harvesting). The model was evaluated for the 272-km^2 Koutine watershed in southeast Tunisia, using 38 runoff events recorded between 1973 and 1985.

The runoff record provided a prime example of the highly variable behaviour of arid watersheds, with runoff coefficients for the 38 events varying between less than 1% and 62%. However, these rainfall-runoff relations were affected by the low density of the rain gauge network and possible measurement inaccuracies. A reasonable representation of the majority of these events could be obtained with SWAT-WH through calibration of the CN, the FLOWFR, and DIXMAX.

The runoff process is also affected by the rainfall intensities, which is not directly captured by the CN method. Although SWAT can also use the Green-Ampt method for runoff calculations, the required detailed breakpoint rainfall data are not available for the study site. Despite the limitations of the CN method, it is still widely used because of lack of rainfall intensity data. Therefore, better CN estimates are needed through the monitoring of rainfall and runoff at small, relatively uniform watersheds. However, it is important that any future monitoring efforts include continuous measurements, such that comparisons between the CN and other runoff and infiltration models can be made.

Although SWAT-WH allows a reasonable representation of the water balance components of the different soil and land uses at the subbasin level, it does not allow the representation of spatial variability at this level. Therefore, to evaluate the long term hydrologic impact and the dynamics of the water-harvesting structures, SWAT-WH could be coupled with a cell-based routing model at the subbasin level.

A disadvantage of SWAT is that it forces all precipitation that does not runoff to enter the soil profile. With the predominating shallow and sandy textured soils in the watershed, this resulted in the simulation of high percolation rates. However, it is likely that part of the water is stored in small surface depressions and ponds and in some soils also in the upper, cracked parts of the bedrock, from which it is extracted by the roots of the olive trees and the native rangeland vegetation. Therefore, not all of the computed percolation may contribute to groundwater recharge. Thus, a more accurate estimation of groundwater recharge would require a pounding routine, as well as detailed monitoring of water movement in the vadose zone. Another groundwater recharge process simulated by SWAT is the transmission loss from the stream. However, these results are difficult to evaluate because of a general scarcity of field observations. Thus, successive *wadi* flow stations, as suggested by Shentis et al. (1999), should be installed at selected sections of the main *wadi* network to allow a better computation of the transmission losses and hydraulic conductivity of the channel bed. These data could also be useful for groundwater flow and other model applications (e.g. MODFLOW).

An important asset of SWAT is that it also simulates crop production and management processes, thus, allowing the estimation of water productivity and economic evaluation of alternative water management scenarios. This is especially opportune for the allocation of scarce water resources in the dry areas. However, crop growth and production studies are needed to develop local crop growth parameters and to evaluate the crop growth model for these arid environments.

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Table 1. Summary of the soil properties.

Soil*	Depth	Clay	Silt	Sand	BD	AWC	K	OC
	cm	%	%	%	mg/m^3	% (vol)	mm/h	%
AFFL	0–10	13	12	75	1.5	12	18	0.24
CRCG	0–20	10	9	81	1.6	10	29	0.28
MBEH	0–20	13	11	75	1.5	12	18	0.24
PEEH	0–20	11	11	78	1.6	12	24	0.29
ISOH	0–10	7	4	89	1.7	9	53	0.22
	10–40	9	7	84	1.6	10	37	0.18
STAB	0–7.5	19	17	64	1.5	15	120	0.70
	7.5–100	15	10	75	1.6	12	120	0.36
PEAH	0–70	10	15	75	1.6	12	28	0.12
	70–140	3	19	78	1.8	12	84	0.15
	140–200	16	17	67	1.5	13	11	0.19
JESR	0–7.5	15	21	64	1.4	18	60	1.02
	7.5–52.5	17	19	64	1.5	18	60	0.51
	52.5–200	14	14	72	1.7	14	17	0.28

AWC: available water capacity; BD: bulk density; K: Hydraulic conductivity; OC: organic carbon.

AFFL: *Outcropping*; CRCG: *calcimagnésiques sur rendzine calcalire* (Rendzinas); ISOH: *iso-humiques bruns calcaires tronqués* (Calcic Xerosols); JESR: *soil on the terraces of jessour*; MBEH: *minéraux bruts d'érosion hydrique* (Regosols); PEAH: *Peu évolués d'apport hydrique* (Fluvisols); PEEH: *peu évolués d'érosion hydrique* (Regosols); STAB: Soil on the terraces of *tabias.*

*– in French: French classification (CPCS, 1967) (Taamallah, 2003);
– between parentheses in English: FAO classification (FAO, 1989).

Table 2. Soil hydrological groups and base and final runoff curve number values, with the final values that were adjusted in the calibration right of the dash.

Landuse[1]	Soil[2]	Area (%)[3]	HYDGRP	Curve Number		
Mountain rangelands[4]				Oct–Nov	Dec–June	July–Sep
STPJ	AFFL	4.4	D	97	97	97
STPJ	CRCG	0.8	D	93/95	89/91	97
STPJ[1]	MBEH	26.3	D	93/95	89/91	97
STPJ	ISOH	3.9	D	93/86	89/84	97/95
STPJ	PEAH	0.1	A	80/63	71/55	84/77
Plain rangelands[2]				Oct–Nov	Dec–June	July–Sep
STPP	CRCG	9.5	D	93/92	89	97
STPP	MBEH	0.2	D	93/92	89	97
STPP	PEEH	3.9	D	93/92	89	97
STPP	ISOH	6.9	D	93/86	89/84	97/94
STPP	PEAH	5.5	A	80/61	71/55	84/77
Cereals				Nov–Dec	Jan–Apr	May–Oct
CULT	CRCG	3.6	D	91	89/88	94
CULT	PEEH	0.1	D	91	89/88	94
CULT	ISOH	3.4	D	91	89/84	94/91
CULT	PEAH	0.8	A	72/63	67/60	77
Olives				Jan-Dec		
OLVM	JESR	22	A	30		
OLVP	STAB	8.6	B	30		

[1] CULT: Cereals; OLVM: Olives of the mountains (*jessour*); OLVP: Olives of plains (*tabias*); STPJ: Rangelands of the mountains; STPP: Rangelands of the plains.

[2]AFFL: Outcropping; CRCG: *calcimagnésiques sur rendzine calcalire* (Rendzinas); ISOH: *isohumiques bruns calcaires tronqués* (Calcic Xerosols); JESR: *soil on the terraces of jessour; MBEH: minéraux bruts d'érosion hydrique* (Regosols); PEAH: *Peu évolués d'apport hydrique* (Fluvisols); PEEH: *peu évolués d'érosion hydrique* (Regosols); STAB: Soil on the terraces of *tabias.*

[3]As percentage of the watershed total area.

[4] For rangelands in the study area (Ouled Belgacem, 2004, personal communication):

– Mar–Jun: 25–50% cover,

– Oct–Nov: 10–25% cover,

– Jul–Sep: <10% cover.

Table 3. Parameters values for extreme (minimum and maximum) watershed runoff, with percent changes relative to the calibrated parameter values.

	Minimum scenario	Maximum scenario
K_{chan} (mm/h)	180	30
DIVMAX	+20%	−20%
FLOWFR	+5%	−5%
K_{soil}	+50%	−50%
AWC	+50%	−50%
CN	+5%	−10%

Table 4. The water balance components, expressed as a percentage of the precipitation over the watershed, and their relative sensitivities (RSI) to selected model parameters for the 1973–1985 evaluation period.

	RSI				Water balance components (%)			
	ET	PERC	TLOSS	FLOW_OUT	ET	PERC	TLOSS	FLOW_OUT
Base scenario	–	–	–	–	72.2	18.8	2.8	6.0
K_{chan}=180	0.00	0.00	0.31	−0.15	72.2	18.8	4.2	4.6
K_{chan}=30	0.00	0.00	0.73	−0.35	72.2	18.8	1.7	7.2
DIVMAX+20%	0.00	0.09	−0.10	−0.22	72.2	19.1	2.8	5.7
DIVMAX-20%	0.00	0.11	−0.01	−0.34	72.2	18.4	2.9	6.4
FLOWFR+5%	0.07	0.43	−2.69	−0.85	72.4	19.2	2.5	5.8
FLOWFR-5%	0.06	0.35	−1.79	−0.91	71.9	18.5	3.1	6.3
K_{soil}+50%	0.00	−0.01	0.02	0.01	72.2	18.7	2.9	6.0
K_{soil}-50%	0.00	−0.01	0.02	0.00	72.1	18.9	2.8	6.0
AWCc+50%	0.21	−0.74	−0.19	−0.20	79.7	11.9	2.6	5.4
AWC-50%	0.39	−1.51	0.01	−0.04	57.9	33.0	2.8	6.1
CN+5%	−0.45	−1.65	7.94	6.77	70.5	17.3	4.0	8.0
CN-10%	0.67	−6.43	9.40	7.54	69.7	24.9	1.5	3.7

Input parameters: DIVMAX: Maximum level of the pounded water on the water-harvesting fields; AWC: Available water capacity; K_{soil}: Soil hydraulic conductivity (mm/h); CN: Curve number; K_{chan}: hydraulic conductivity of the stream channel bottoms (mm/h); FLOWFR: fraction of runoff flow diverted to water-harvesting systems. Model outputs: ET: Evapotranspiration; PERC: Percolation; TLOSS: transmission losses; FLOW_OUT: stream flow at the watershed outlet.

Table 5. Evapotranspiration (ET) and percolation (PERC) from the different landuses.

Landuse	CULT	STPP	STPJ	OLVP	OLVM
PRECIP (mm)	209	209	209	209	209
Harvested water (mm)	0	0	0	44	156
ET (mm)	114	117	93	187	277
PERC (mm)	21	23	13	66	88
Runoff and lateral flow (mm)	75	69	103	0	0

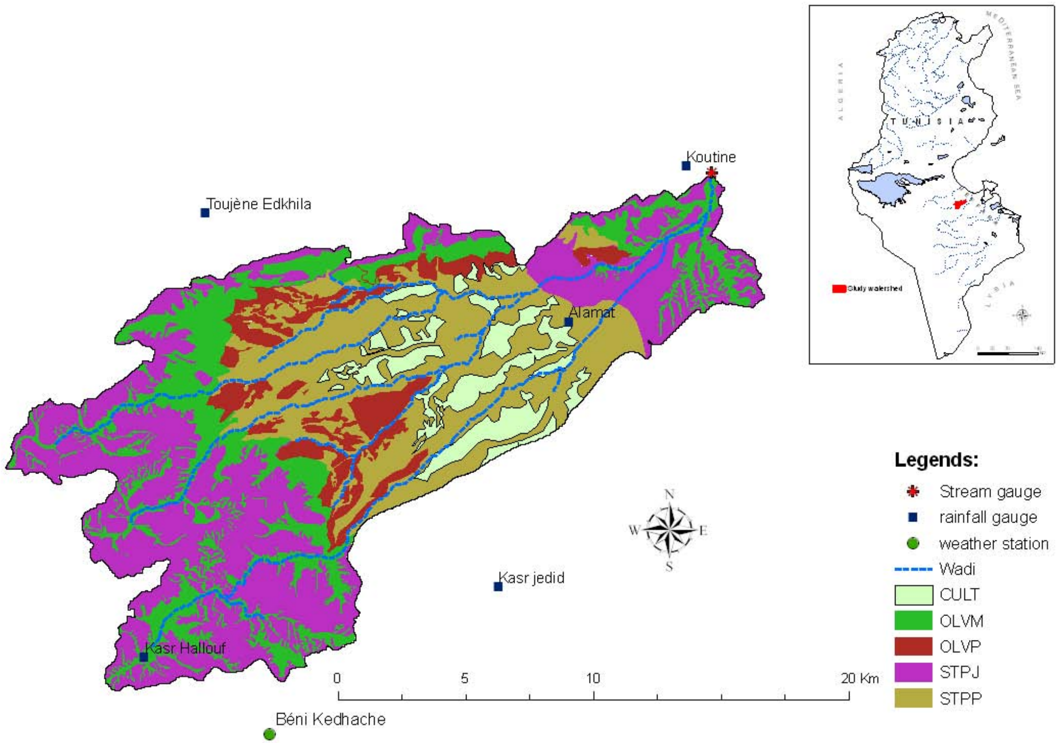

Fig. 1. Study watershed location and monitoring network (OLVM: Olives of the mountains (*jessour*); OLVP: Olives of plains (*tabias*); STPJ: Rangelands of the mountains; STPP: Rangelands of the plains; CULT: Cereals).

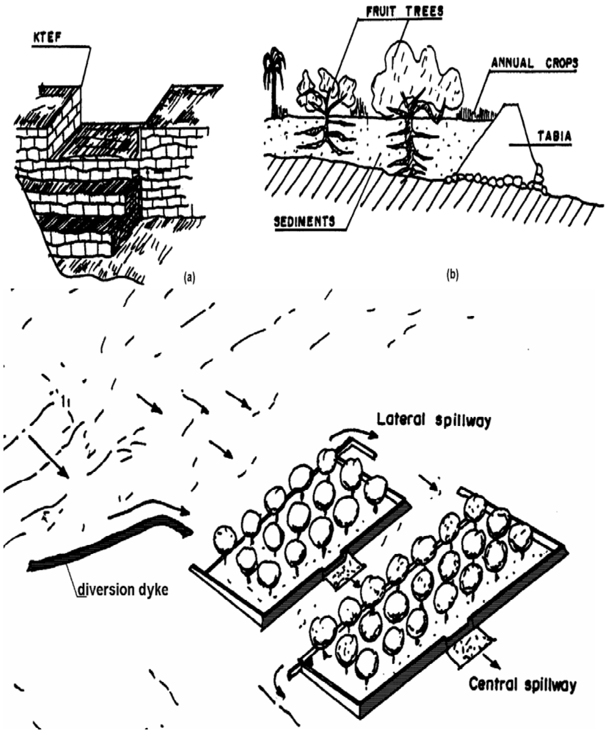

Fig. 2. Up: Scheme of the Jessr components (**a**): spillway, (**b**): side view (adapted from El Amami, 1984). Down: Scheme of a tabia with natural impluvium (adapted from Alaya et al., 1993).

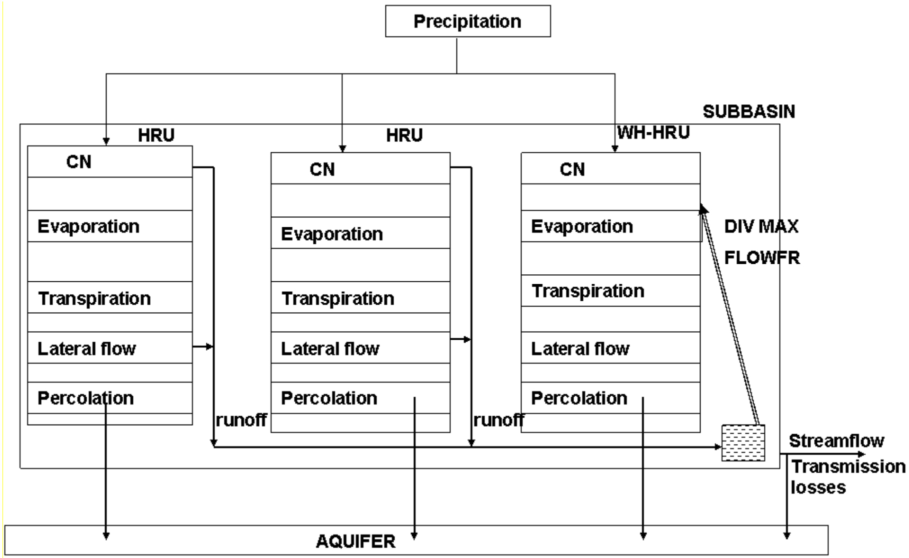

Fig. 3. SWAT water routing as applied in the study site (WH-HRU: water harvesting HRU, DIVMAX: maximum diversion (spillway height), FLOWFR: Flow fraction).

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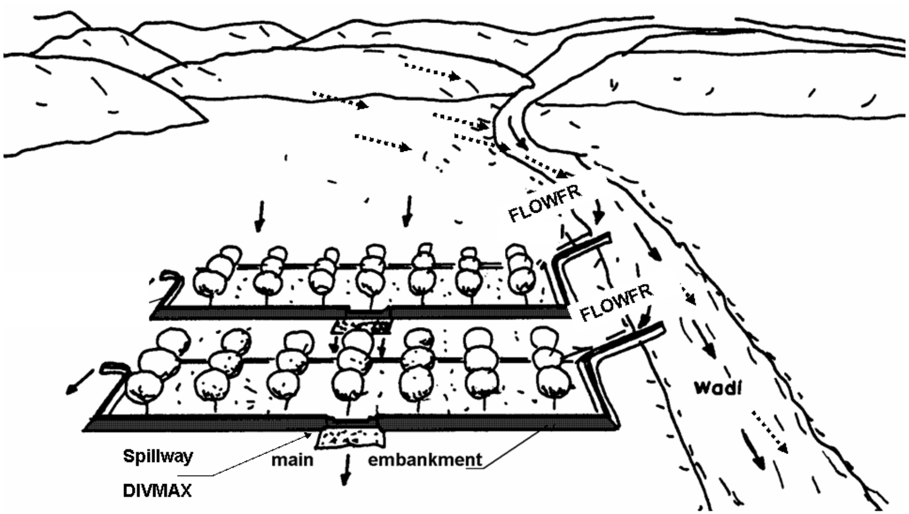

Fig. 4. Schematic representation of the runoff routing in SWAT (dashed lines) and SWAT-WH (full lines). DIVMAX: spillway height, FLOWFR: Flow fraction.

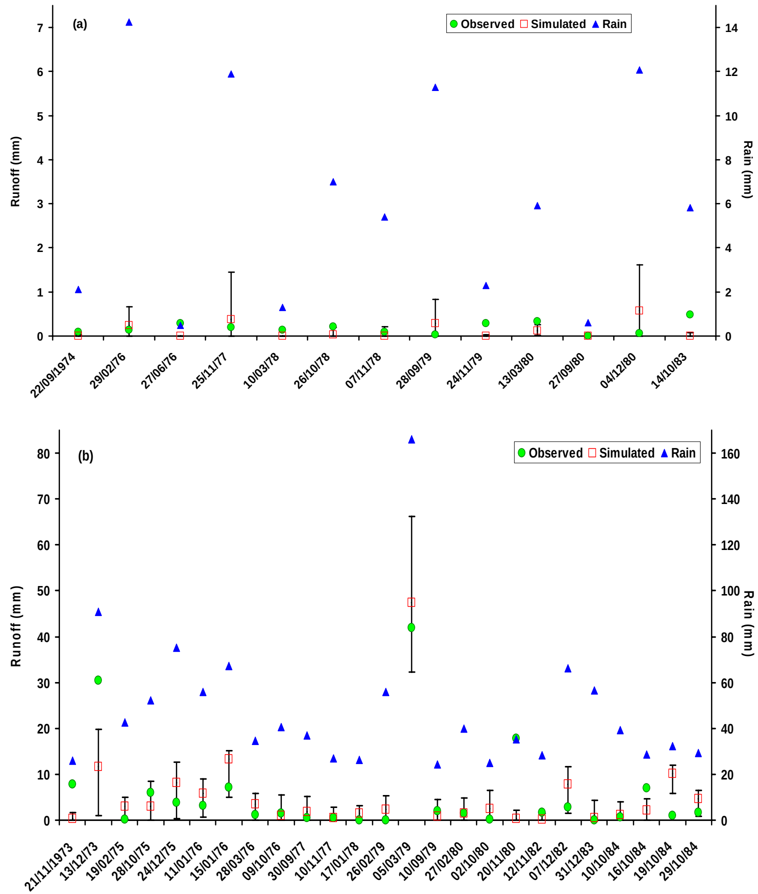

Fig. 5. Rainfall, observed and simulated runoff and the simulated minimum and maximum error bounds for events with less than 20 mm rain **(a)** and more than 20 mm rain **(b)**. The events after 1 September 1978 were calibrated.

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Modelling water-harvesting systems using SWAT

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