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ORIGINAL ARTICLE

Hydrological modeling of the watershed of a RAMSAR site using the SWAT model (Ichkeul National Park—Tunisia of the extreme north)

Ayser Ben Saad[1] · **Moufida Ben M'barek-Jemai**[1] · **Nabiha Ben M'barek**[2] · **Safa Mezza**[1]

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Abstract

The semi-distributed SWAT model is widely used at the watershed scale. The objective of this study is to evaluate the capacity of the SWAT model to simulate the water balance components of the uncontrolled part of the Ichkeul watershed. This is done to predict the future flow out and impacts of urban facilities and climate change on the Ichkeul ecosystem. In addition, the risk of losing this strategic asset must be minimized. Various climatic (precipitation, temperature, wind speed, relative humidity, and solar radiation) morphological (DEM) and thematic data were used to feed the model. Through the SUFI-2 algorithm, SWAT-CUP performs the sensitivity and uncertainty analysis operation. For the time intervals of 2015–2017 and 2018–2019, the model was calibrated and validated by comparing simulated flows with observed flows at the Ecluse-Sidi Hassoun station located downstream of the study area. The quality of the daily simulated liquid flow predictions was evaluated using a performance evaluator (R^2, NSE, PBIAS, P-factor, and R-factor). For the calibration and validation periods, NSE, PBIAS, P-factor, and R-factor were 0.87 and 0.93, -6.7 and 6.8, 0.97 and 0.95, 1.17 and 1.11, and finally 0.88 and 0.94 for R^2. These findings demonstrate a good match between the measured outflow and the simulation. SWAT predicts outflows effectively. Thus, the outflow from the uncontrolled part of the Ichkeul watershed may be predicted using this model.

Keywords Hydrological modeling · Ichkeul watershed · Calibration · Validation · SWAT · SWAT-CUP

Introduction

The climate of Tunisia is quite erratic and ranges from arid to semi-arid. Drought is one of the most concerning effects of this variability (Henia 1987). Drought can be defined as a temporal imbalance of water availability consisting of persistent lower-than-average precipitation of uncertain frequency, duration, and unpredictable severity (Pereira et al. 2002). The need to construct hydraulic systems has always been motivated by a lack of water supply. Hydraulic action has always been intended to permanently store extra water in rainy years (in dams and aquifers) so that it can be used in dry years (ITES 2014). These hydraulic works are constructed on the main wadis at the level of the Ichkeul watershed and stop practically all of the freshwater inflow to the lake. Climate change theory increased water demand, and the building of dams on the wadis of Sejnane, Joumine, Melah, Ghezela, and Tine are all factors that have considerably worsened the overall status of the National Park of Ichkeul. All these factors have caused an ecological and hydrological imbalance in this aquatic ecosystem. By executive order n°80–1608 on December 18, 1980, the Ichkeul National Park was created. The lake and marshes of Ichkeul have long been acknowledged as one of the four most important wetlands of the western Mediterranean basin, together with Donana in Spain, the Camargue in France, and El Kala in Algeria. It is also one of the few locations in the world to be included in three international agreements. It is the last large freshwater lake in North Africa. In 1979, the Ichkeul National Park was included in the UNESCO list of World Natural Heritage sites. After that, the indigenous population

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✉ Ayser Ben Saad
aysar1@outlook.fr

Moufida Ben M'barek-Jemai
benmbarek_moufida@hotmail.fr

Nabiha Ben M'barek
nabiha_2003@yahoo.fr

Safa Mezza
safamezza683@gmail.com

[1] Department of Earth Science, University of Bizerte-FSB, University of Carthage, 7120 Bizerte, Tunisia

[2] National Environmental Protection Agency (ANPE), Tunis, Tunisia

of the park and the human initiatives related to conservation had already prompted it to be included in the list of UNESCO biosphere reserves in 1977. Finally, the convention of RAMSAR in 1980, gave the lake and the marshes of Ichkeul the status of the wetland of international importance as a place of wintering for thousands of migratory water birds, among which some species are threatened (ANPE: National Agency for Environmental Protection 1994). The Ichkeul National Park is characterized by a very particular hydrological system based on the seasonal alternation of water levels and salinity. During the winter, the Ichkeul lake is fed by freshwater from its catchment area and flows into the Bizerte Lake via the Tinja wadi, but during the summer, the current reverses and the lake receives marine flows. Ichkeul's aquatic ecosystem (lake and marshes) attracts hundreds of thousands of migrating birds like ducks, coots, greylag geese… Due to a shortage of fresh water over the winter, the grass fields are naturally and swiftly harmed by the salinization of the lake waters. As a result of this dire condition, the number of birds wintering in Ichkeul has plummeted, owing to a scarcity of food and fresh water for this avifauna. Detailed characterization and modeling of the study area can provide insight into the effects of climate change and hydraulic facilities on the hydrological environment of the Ichkeul. Modeling hydrological behavior is essential to address problems related to water resource management, land use planning, or any of the various aspects of hydrological risk. Several hydrological models of watersheds are available in the literature, each with its unique set of characteristics and field of use. The Hydrologic Simulation Package Fortran (HSPF) (Holtan and Lopez 1971), the European Hydrological System (EHS) (Abbott et al. 1986), the Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998), and the Hydrologic Engineering Centre Hydrologic Modeling System (HEC-HMS; HEC 2000) are the most widely used watershed-scale models.

Because runoff is a resolution feature for hydrologic models, a model that can simulate runoff realistically is needed to estimate the flow value. According to Pereira et al. (2016), SWAT, one of these models, is the most effective at reproducing watershed hydrologic functioning on many occasions. Numerous studies show the successful application of the SWAT model around the world (Abbaspour 2007; Grusson 2015; Sisay et al. 2017; Kumar et al. 2018; Hosseini and Khaleghi 2020; Muthee et al. 2022; Tarekegn et al. 2022). The most common use of the SWAT model is to perform water balances. The model has been successfully used to simulate outflows from watersheds with sizes ranging from 122 to 246 Km^2 (Arnold and Allen 1999). But also, according to Arnold and Allen (1999), conducting the overall water balance on watersheds ranging in size from 2,253 to 304,620 Km^2 gives very satisfactory results. Even at the continental scale, this model has proven performance (Schuol et al. 2008; Abbaspour et al. 2015). Once the model has been chosen, its ability to represent reality must be evaluated. This is most often done by comparing the simulated results with observations. In this study, using a daily time step, the capacity of the SWAT model to reproduce the flow observed at the outlet of the uncontrolled part of the Ichkeul watershed will be tested to have an idea of the water resources of the area of interest, to determine the need for the freshwater of the Ichkeul lake, and then later, to model its salinity and quantify the sediments to establish guarantees for its survival.

Material and methods

Description of the study area

The Lake Ichkeul watershed is an exoreic basin located in the extreme north of Tunisia (9°30'N, 37°00'S) (Fig. 1). It has an area of about 2232 Km^2 with an overall slope of SW-NE with altitudes ranging from 1 to 714 m. Administratively, the basin extends over three governorates of northern Tunisia that are Bizerte, Beja, and Manouba, and reveals the delegations of Bizerte, Tinja, Mateur, Ghezela, Hechachna, Sejnane, Joumine, Tebourba, El Battane, Beja, Medjez El Bab, and Nefza. The watershed of Ichkeul belongs to the hydrological unit of northern Tunisia Nefza-Ichkeul, according to the subdivision of the Tunisian territory into hydrological basins. The Nefza-Ichkeul complex covers an area of 4865 Km^2. Its average annual liquid contribution is estimated at 860 Mm^3. The abundant surface waters of the watershed and their chemical qualities make this region a true water tower of the Tunisian territory (Ben Mammou 2006). This region has a fairly uniform Mediterranean climate; it is a warm temperate zone between the polar front and the trade wind front. Winter is frequently the wettest time of year. It is globally included between the isohyets 600 and 900 mm and, consequently, it belongs to the humid to the subhumid bioclimatic stage with a typically Mediterranean climate. The main rivers that cross the watershed of Ichkeul are Sejnane, Joumine, Tine, Melah, and Ghezela. As such, five dams have been installed on these wadis that are; the dams of Joumine (1983), Ghezela (1984), Sejnane (1994), Melah (2014), and Tine (2015). These dams form a sort of belt that subdivides the Ichkeul watershed into two almost equal parts in terms of area. The first part is controlled by the dams and the second part is not controlled. The downstream part shelters the national park of Ichkeul, placed in the plain of Mateur, 25 km southwest of Bizerte.

SWAT model

The SWAT (Soil and Water Assessment Tool) model is a continuous-time, semi-distributed, process-based river

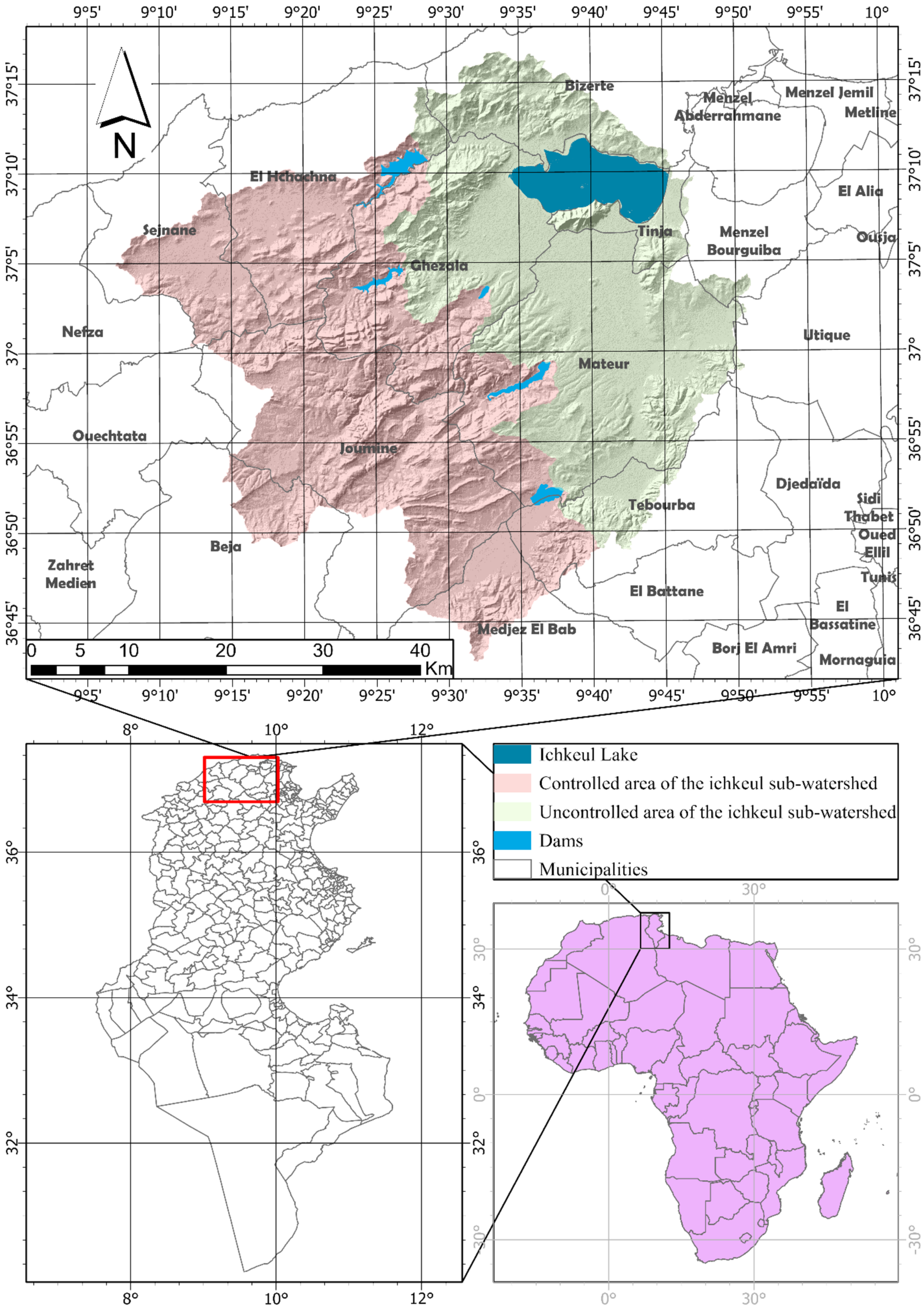

Fig. 1 Location map of the study area

basin model (Arnold et al. 2012). SWAT was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use, and management conditions over long periods (Neitsch et al. 2002). SWAT is a model whose process representation is complex and based on physical representation. Differentiating hydro system components is possible in a variety of ways. It is a semi-distributed model allowing a discretization of space based on the topographic reality. Despite its complex representation of hydrological processes, the computational resources required to run it are moderate, allowing its use on large temporal and spatial scales (Grusson 2015). SWAT analyzes the entire watershed, subdividing it first into sub-watersheds and then into several sections called hydrologic response units (HRUs). Each HRU has specific land use, soil, and slope characteristics. HRUs have been used to describe spatial heterogeneity in land use, soil type, and slope class in a watershed. The hydrological cycle simulated by SWAT is based on the water balance equation Eq. 1.

$$\mathbf{SW}_t = \mathbf{SW}_0 + \sum_{i=1}^{t}(\boldsymbol{R}_{\mathbf{day}} - \boldsymbol{Q}_{\mathbf{surf}} - \boldsymbol{E}_a - \boldsymbol{W}_{\mathbf{sweep}} - \boldsymbol{W}_{\mathbf{gw}}) \tag{1}$$

where SW_t is the final water content in (mm), t is time in a day, R_{day} is the precipitation amount on specific days i (mm), Q_{surf} is the runoff amount on specific days i (mm), E_a is evapotranspiration amount on a day i (mm), W_{sweep} is the amount of water percolated into the vadose zones on a day i (mm), and W_{gw} is the return amount of flow on a day i (mm).Two methods can be employed to separate precipitation into runoff and infiltrated water in SWAT: the SCS curves (USDA 1972) or the Green and Ampt curves (Green and Ampt 1911). The first technique determines runoff water amounts based on soil moisture content. Based on matric potential and hydraulic conductivity, the second technique calculates the amount of infiltrated water, but it requires sub-daily precipitation data, which is less common. Therefore, the SCS curve number method was used in this work to calculate the amount of water available for runoff The number of the SCS curve is described using Eqs. 2 and 3:

$$\boldsymbol{Q}_{\mathbf{surf}} = \frac{(\boldsymbol{R}_{\mathbf{day}} - 0.2\boldsymbol{S})^2}{(\boldsymbol{R}_{\mathbf{day}} - 0.8\boldsymbol{S})} \tag{2}$$

$$\boldsymbol{S} = 25.4\left(\frac{1000}{\boldsymbol{CN}} - 10\right) \tag{3}$$

where Q_{surf} is the depth of runoff in (mm), R_{day} precipitation (mm), S is maximum potential retention and, CN is the curve number.

The curve number depends on the soil, the soil use and the slope, and the soil moisture content. For each pair of soil/soil use, three NCs are determined: NC1 in dry conditions, NC2 in medium moisture conditions, and NC3 in wet conditions.

Regarding evapotranspiration, the SWAT model uses potential evapotranspiration to calculate evapotranspiration. Potential evapotranspiration is defined as the maximum evaporation potential for reference vegetation. Three methods that are included in the model are used to determine it: Penman–Monteith (Monteith 1965), Priestley-Taylor (Priestley and Taylor 1972), and Hargreaves (Hargreaves et al. 1985). The Penman–Monteith method requires solar radiation, air temperature, wind speed, and relative humidity. The Priestley-Taylor method requires radiation, air temperature, and relative humidity, whereas the Hargreaves method requires only air temperature. Therefore, given the availability of climate data for the study area, the Hargreaves method was used. The potential evapotranspiration was calculated by Eq. 4.

$$\boldsymbol{E}_0 = \frac{0.0023\boldsymbol{H}_0\left(\boldsymbol{T}_{\mathbf{max}} - \boldsymbol{T}_{\mathbf{min}}\right)^{0.5}(\boldsymbol{T}_{\boldsymbol{av}} + 17.8)}{\boldsymbol{L}_{\boldsymbol{v}}} \tag{4}$$

where E_0 is potential evapotranspiration ($\mathrm{mm.d}^{-1}$), L_v is the latent heat of vaporization of water ($\mathrm{MJ.kg}^{-1}$), H_0 is the extra-terrestrial radiation ($\mathrm{MJ.m}^{-2}.\ \mathrm{d}^{-1}$), and T_{max}, T_{min}, and T_{av} are, respectively, the maximum, minimum, and average temperatures of the day (°C).

Model input

In this study, the meteorological data used for the SWAT model are precipitation, minimum and maximum air temperature, relative humidity, wind speed, and solar radiation. In addition, the spatial data required are the digital elevation model (DEM), land cover, and soil data (Fig. 2a, b).

Digital elevation model (DEM)

The definition of sub-watersheds in a SWAT project is derived from the definition of the river network, which is based on the topography. The resolution of a digital terrain model, which is raster data consisting of a network of cells or pixels containing elevation values, affects the definition of the hydrographic network and the delimitation of the watershed. For this work, a DEM with a resolution of 12.5 × 12.5 m was downloaded from https://search.asf.alaska.edu/.

Land use/land cover

The Sentinel-2A satellite image, which has a spatial resolution of 20 m, was processed to produce the land cover data. The year of observation is 2016. To identify the land

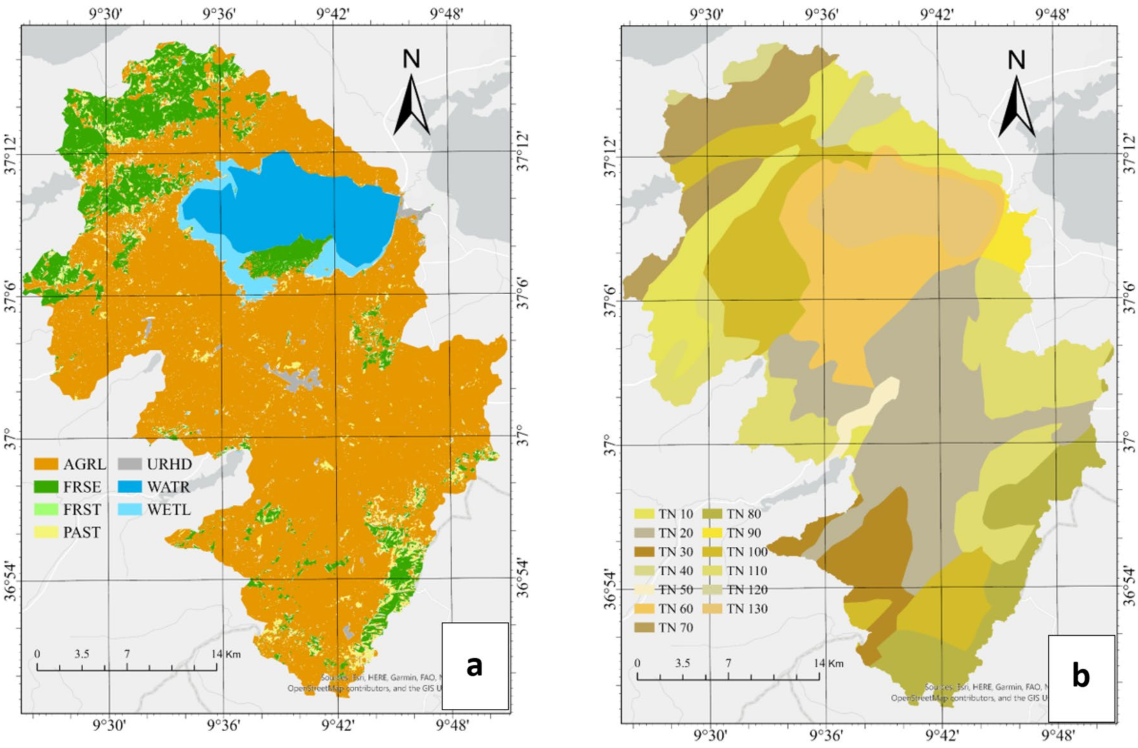

Fig. 2 Land use map **a** and Soil map **b** of the uncontrolled part of the Ichkeul watershed

use, an unsupervised classification is then performed. In the attributing table, each land cover in the SWAT model is represented by a four-letter code. Seven land cover classes were identified and reclassified to match the SWAT database. The dominant classes are cropland 69.4% and forest 12.7%. Lake Ichkeul covers an area of about 13% of the area of interest, while urbanized areas represent only 0.008% of the uncontrolled part of the watershed (Fig. 2a).

Soil data is a crucial component of any hydrological model. The region's soil map was taken from the SOTWIS-Tunisia map (version 1.0), produced by ISRIC, FAO, and UNEP, under the direction of the International Union of Soil Sciences (IUSS). Twelve soil units were identified in the study area and used in the model. These units are presented in Fig. 2b.

Weather data/daily flow

Daily climate data have been provided by the National Institute of Meteorology (INM), the Regional Commissioner for Agricultural Development of Bizerte (CRDAB), and the Directorate General of Dams and Large Hydraulic Works (DG-BGTH). The meteorological data used in this study are daily precipitation, minimum and maximum temperatures, relative humidity, wind speed, and solar radiation for the period between 2007 and 2019. These data are generated in the following stations: Sidi Ahmed, Tinja, Mateur, Battan, Sejnane, Ghezela, Melah, and Joumine (Fig. 3). The data on outflow comes from the station Ecluse-Sidi Hassoun, which is situated downstream of the Ichkeul watershed. The National Environmental Protection Agency (ANPE) records this data three times a day. Dam outflow data, also provided by DG-BGTH, is used to make the necessary corrections to the outflows recorded by the above station.

The lock of Tinja, built in the late 1980s on the wadi Tinja, controls the exchange of water between Lake Ichkeul and the lagoon of Bizerte. Since 2015, Lock management is completely absent to avoid inaccurate outflow measurements.

Model setup

The SWAT software is a single executable file (.exe) that runs the model equations and generates output files. Arc SWAT is an ESRI-ArcGIS software module that allows users to import and create input files for the SWAT model and facilitates model configuration by leading users through a step-by-step process. This procedure starts with the import of georeferenced layers like topography, watershed boundaries, land use, soil characteristics, and so on, and ends with the calibration and validation step. The overall workflow of the SWAT model and SWAT-CUP is shown in Fig. 4. The required spatial data were projected into the same projection

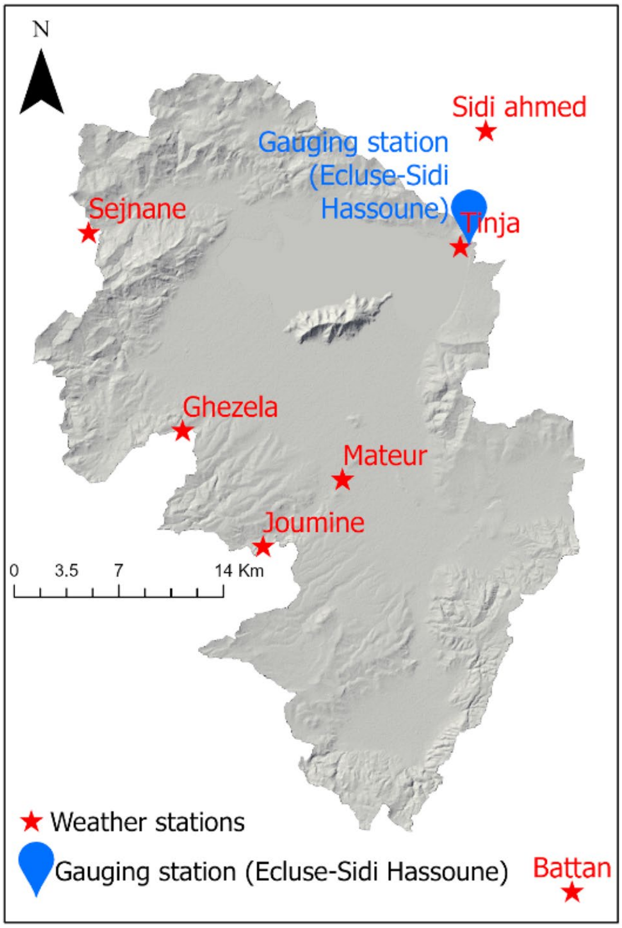

Fig. 3 Location of the meteorological stations and the flow-out measurement station

system, WGS 1984 UTM zone 32 N, using ArcGIS version 10.3.

Manual pre-definition of the stream network and sub-watersheds

Drainage networks are a fundamental condition for watershed delineation and an indispensable component in hydrological modeling. Therefore, reasonable and accurate watershed delineation is a precondition for runoff, sediment transport, water quality simulation, and basin resource management (Billen et al. 2005). The stream network process usually starts by allocating flow directions for each DEM cell, then analyzes the flow accumulation, and finally selects those cells that have a total higher threshold of flow accumulation than a defined value (Meisels et al. 1995). Many factors, including the DEM spatial resolution, the calculated algorithm, and the physical characteristics of the basin, can directly affect the accuracy of drainage networks derived from DEM data (Li and Wong 2010; Ariza-Villaverde et al. 2015). The automatic method of delineating the hydrographic network and sub-watersheds at the plain level is imprecise. Following the discovery of numerous errors following the execution of the process of automatic generation of the hydrographic network as well as the automatic delimitation of the sub-watershed areas, the decision was made to predefine manually the hydrographic network and the sub-catchment areas of the study zone. This error was primarily due to the weak variation of the slope at the level of the plain of Mateur, so the decision was made to predefine manually the hydrographic network and the sub-catchment areas of the study zone. The “Pre-defined streams and watersheds” function of the SWAT model allow users to import pre-defined watershed boundaries and streams (Luo et al. 2011). Each defined river has to fill in the following eight fields (Table 1): "FID," "shape," "ARCID," "GRID_CODE," "FROM_NODE," "TO_NODE," "Subbasin," and "SubbasinR," while the defined watersheds have to fill in just four fields, which are respectively (Table 2): "FID," "shape," "GRID_CODE," and "subbasin". The streams and sub-basins datasets were imported using the "Predefined streams and watersheds" function after they were defined. The uncontrolled part of the Ichkeul watershed was divided into 13 sub-basins (Fig. 5 and Tables 1 and 2).

HRUs

In SWAT, a watershed is divided into multiple sub-watersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, topographical, and soil characteristics (Arnold et al. 2012). The objective of the HRU definition was to reduce the heterogeneities due to climate, soil types, topography, and geology that influence hydrologic response (Sisay et al. 2017). With the combinations and the reclassifications of slope class, land use, and soil data, a total of 206 HRUs were defined. The hydrologic cycle is climate driven and provides moisture and energy inputs, such as daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity, that control the water balance (Arnold et al. 2012).

Model execution

The hydrologic cycle is climate driven and provides moisture and energy inputs, such as daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity, that control the water balance (Arnold et al. 2012). SWAT reads those observed data directly from the input files and generates this data at runtime to start the simulation. The climate data was prepared for the period 2013–2019. The

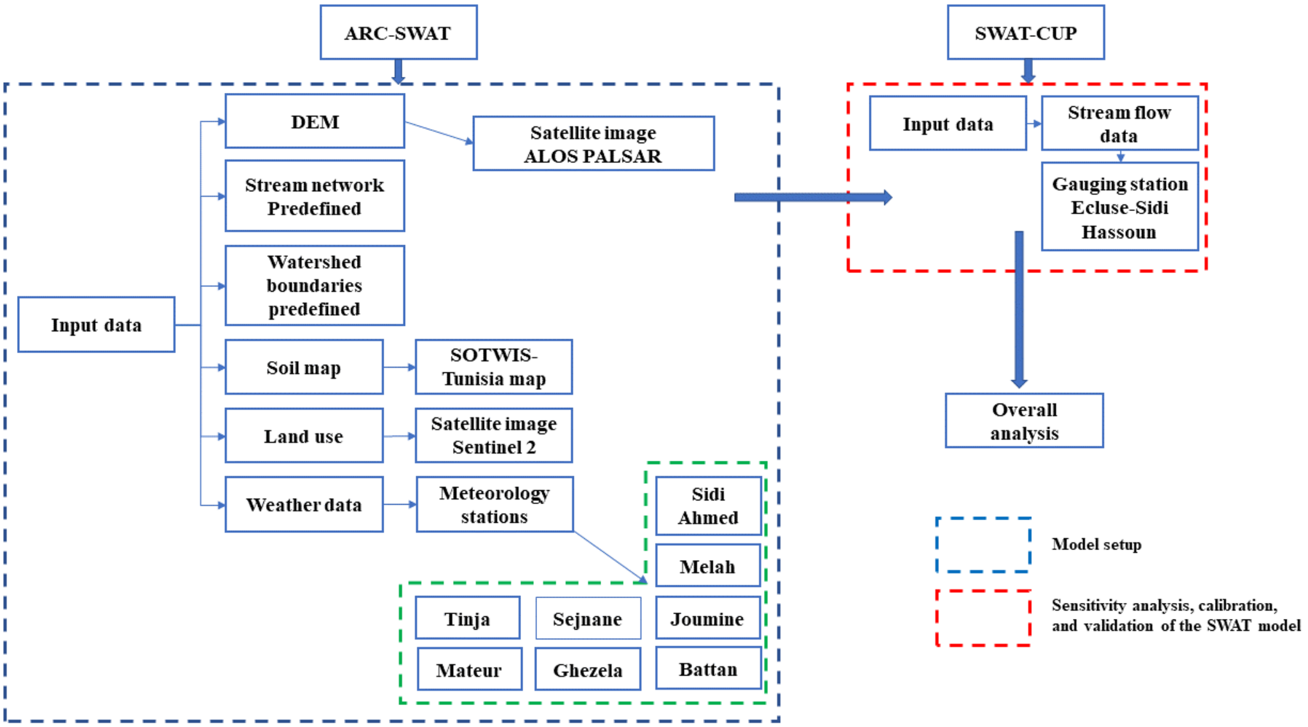

Fig. 4 Detailed methodological framework

Table 1 Attribute table of the predefined hydrographic network of the uncontrolled part of the Ichkeul watershed

FID	Shape	ARCID	GRID_CODE	FROM_ NODE	TO_NODE	Subbasin	SubbasinR
1	Polyline	1	1	1	2	1	2
2	Polyline	2	2	2	6	2	6
3	Polyline	3	3	3	5	3	5
4	Polyline	4	4	4	5	4	5
5	Polyline	5	5	5	6	5	6
6	Polyline	6	6	6	7	6	7
7	Polyline	7	7	7	0	7	0
8	Polyline	8	8	8	7	8	7
9	Polyline	9	9	9	8	9	8
10	Polyline	10	10	10	8	10	8
11	Polyline	11	11	11	10	11	10
12	Polyline	12	12	12	10	12	10
13	Polyline	13	13	13	12	13	12

SWAT model was run to simulate the different hydrological components which are canopy storage, surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, water redistribution in the soil profile, return flow, and infiltration recharge from surface water bodies, ponds, and tributary channels.

Sensitivity analysis, calibration, and validation of the SWAT model

The first step in the calibration and validation process in SWAT is the determination of the most sensitive parameters for a given watershed or subwatershed (Arnold et al. 2012).

Table 2 Attribute table of the predefined sub-basins of the uncontrolled part of the Ichkeul watershed

FID	Shape	GRIDCODE	Subbasin
1	Polygon	1	1
2	Polygon	2	2
3	Polygon	3	3
4	Polygon	4	4
5	Polygon	5	5
6	Polygon	6	6
7	Polygon	7	7
8	Polygon	8	8
9	Polygon	9	9
10	Polygon	10	10
11	Polygon	11	11
12	Polygon	12	12
13	Polygon	13	13

It is necessary to identify key parameters and the parameter precision required for calibration (Ma et al. 2000). The user determines which variables to adjust based on sensitivity analysis. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters) (Arnold et al. 2012). The second step is calibration. Calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty (Arnold et al. 2012). Model calibration is performed by carefully selecting the values of the model input parameters already identified during the sensitivity step and comparing the observed data with the model predictions (in this case the outflow). The final step is validation. Model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations, although “sufficiently accurate” can vary based on project goals (Refsgaard 1997).

The calibration of the model can be done in two different ways. Calibration can be accomplished manually or using autocalibration tools in SWAT (Van Griensven and Bauwens 2003; Van Liew et al. 2005) or SWAT-CUP (Abbaspour 2007). The present study is based on the autocalibration method via the SWAT-CUP software.

SWAT-CUP links five algorithms, used for sensitivity analysis, calibration, and validation of the SWAT model. These algorithms are the Sequential Uncertainty Fitting Algorithm (SUFI-2), the Particle Swarm Optimization (PSO), the Markov Chain Monte Carlo (MCMC), the

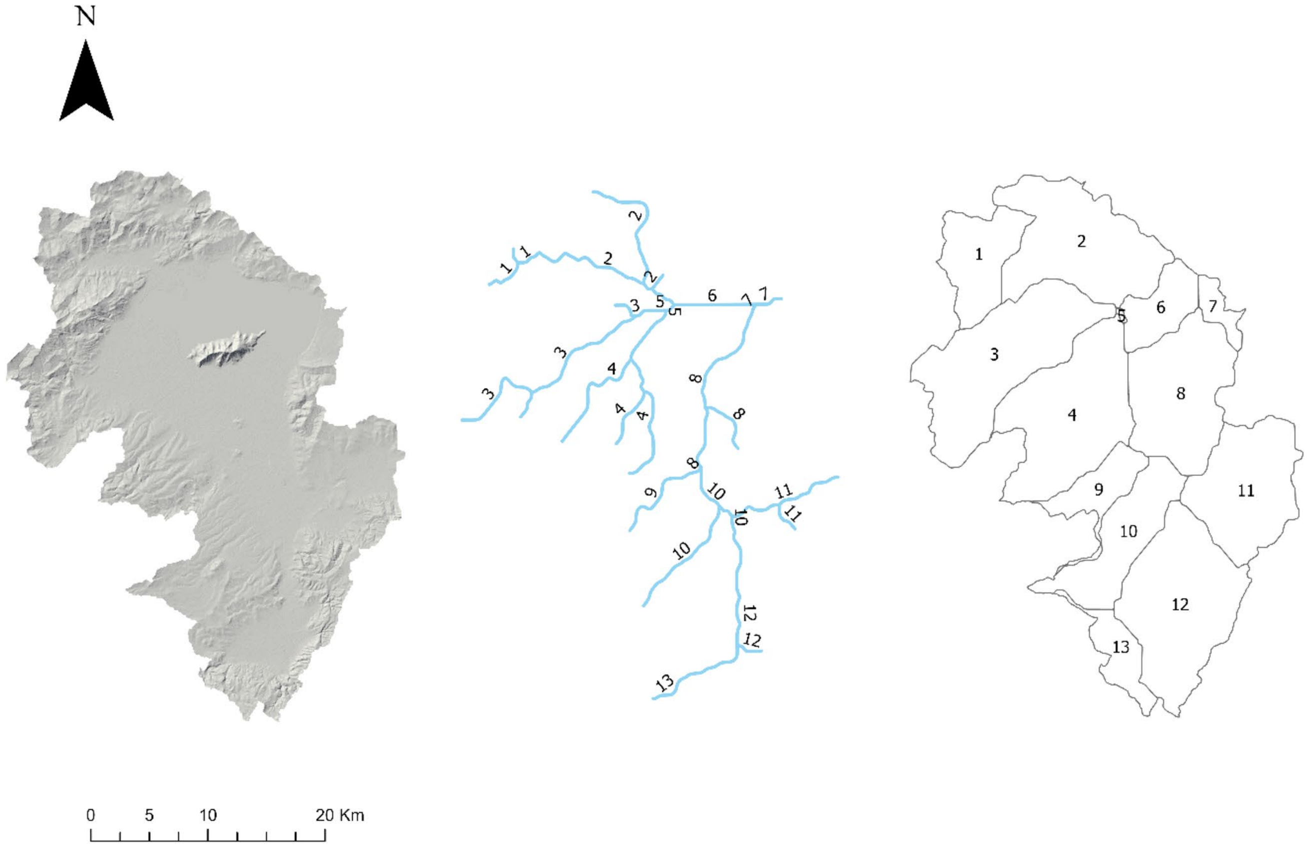

Fig. 5 Summary map of the delimitation steps of the studied territories (from the DEM to the definition of the sub-watersheds)

Generalized Likelihood Uncertainty Estimation (GLUE), and finally the Parameter Solution (Parasol). The SUFI-2 algorithm has been used to perform the calibration and validation sensitivity analysis processes.

It is recommended to evaluate the performance of a model graphically and by statistical criteria (Moriasi et al. 2007). Krause et al. (2005) recommend a combination of different effectiveness criteria for scientifically sound model calibration and validation. In the present study, the coefficient of determination (R^2), the Nash and Sutcliffe model efficiency coefficient (NSE) (Nash and Sutcliffe 1970), and the percentage bias (PBAIS) are the statistical criteria that were used to evaluate the performance of the SWAT model. NSE, PBIAS, and R^2 are calculated by Eqs. 5, 6, and 7, respectively:

$$\mathbf{NSE} = 1 - \frac{\sum_{i=1}^{n}(\mathbf{Oi} - \mathbf{Pi})^2}{\sum_{i=1}^{n}(\mathbf{Oi} - \mathbf{Oavr})^2} \tag{5}$$

$$\mathbf{PBIAS} = \frac{\sum_{i=1}^{n}(\mathbf{Oi} - \mathbf{Pi}) * 100}{\sum_{i=1}^{n}\mathbf{Oi}} \tag{7}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}(\mathbf{Oi} - \mathbf{Oavr})(\mathbf{Pi} - \mathbf{Pavr})}{\sum_{\mathrm{i}=1}^{n}(\mathbf{Oi} - \mathbf{Oavr})^2\sum_{i=1}^{n}(\mathbf{Pi} - \mathbf{Pavr})^2}\right)^2 \tag{8}$$

In addition to the evaluation criteria listed above, Abbaspour (2007) suggest the use of two additional measures, known as the P-factor and R-factor. The P-factor is the percentage of the measured data bracketed by the 95PPU and the R-factor, is a measure of the quality of the calibration and indicates the thickness of the 95PPU. The combination of the P-factor and R-factor together indicates the strength of the model calibration and uncertainty assessment, as these are intimately linked (Arnold et al. 2012).

Daily outflow data from January 2013 to December 2017 were used during the calibration period and the remaining data from January 2018 to December 2019 were used to validate the model performance at the only gauging station (Ecluse-Sidi Hassoun). Data from the first 2 years (January 2013 to December 2015) were used as the "warm-up" period.

Results and discussion

The SWAT model was calibrated to a daily time scale. Data are available for the observation period (2015–2019), and they have been divided into calibration data (2015–2017) and validation data (2018–2019) (Fig.6 and 7). Uncertainty analysis is performed using the sequential uncertainty fitting (SUFI-2) algorithm (Abbaspour 2005).

Specification and parameter determination are two major steps in calibration (Sorooshain and Gupta 1995). Understanding the studied system's hydrological processes enables accurate parameterization of a model, which is a crucial step in its calibration. Correct parameterization can therefore result in model calibration that is quicker, more precise and has lower prediction uncertainty. Parameter sensitivities are determined by performing a multiple regression analysis, which regresses the parameters generated by Latin Hypercube against the objective function (Abbaspour 2007). To determine the relative significance of each parameter, a t-test and p-value are used. The most sensitive parameters in the calibration step are presented at the top of the rankings, that is, the highest value of the t-stat index module which represents the ratio of the parameter coefficient by the standard error; and the lower value of the "p-value" which is related to the rejection of the hypothesis that an addition in the value of the parameter provides a significant increase in the variable response (Abbaspour 2007). Six out of a total of nineteen parameters, in this study, were found to

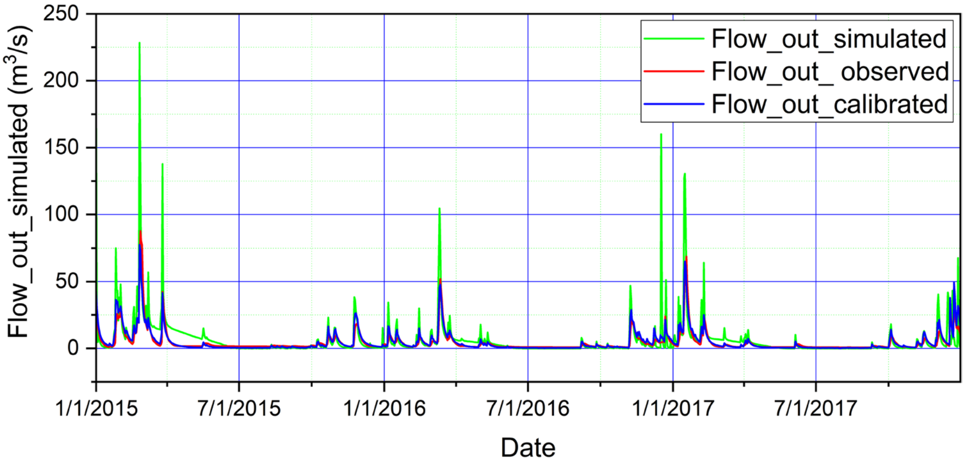

Fig. 6 Comparison of observed and simulated daily flows at the Ecluse-Sidi Hassoun station after the Calibration phase

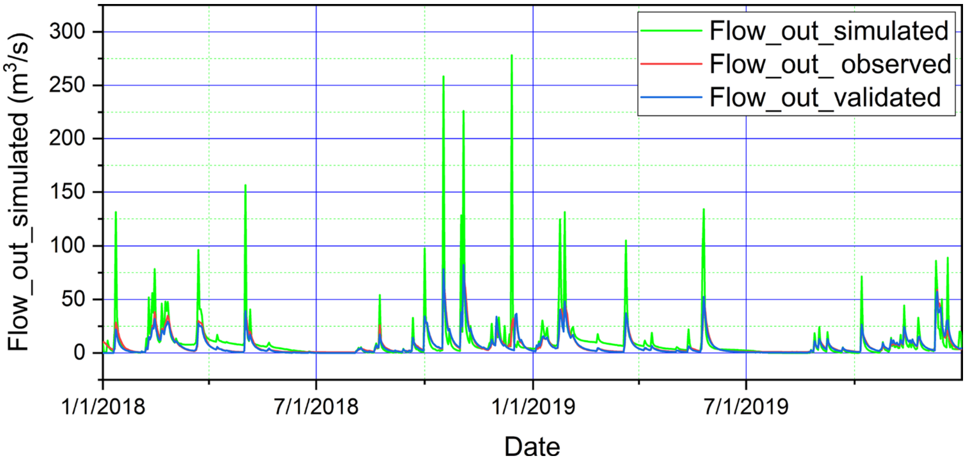

Fig. 7 Comparison of observed and simulated daily flows at the Ecluse-Sidi Hassoun station after the validation phase

Table 3 Result of the sensitivity analysis of the parameters chosen for the calibration phase

Parameter	T-Stat	*P*-value
SOL_BD	− 12.02	0.00
SOL_K	− 10.29	0.00
CN2	− 7.29	0.00
ALPHA_BF	− 5.54	0.00
GW_DELAY	2.55	0.01
CH_K1	2.10	0.04
CH_N1	1.47	0.14
RCHRG_DP	1.11	0.27
CH_N2	− 0.98	0.33
CH_K2	− 0.81	0.42
GW_REVAP	− 0.79	0.43
REVAPMN	0.55	0.59
OV_N	− 0.42	0.67
PLAPS	− 0.40	0.69
ALPHA_BNK	0.40	0.69
GWQMN	0.09	0.93
ESCO	0.01	0.99
SOL_AWC	0.00	1.00
TLAPS	0.00	1.00

SOL_BD Moist bulk density, *SOL_K* Saturated hydraulic conductivity, *CN2* initial SCS runoff curve number for moisture condition II, *ALPHA_BF* Base flow alpha factor, *GW_DELAY* groundwater delay, *CH_K* Effective hydraulic conductivity in tributary channel, *CH_N* Manning's "*n*" value for the tributary channels, *RCHRG_DP* Deep aquifer percolation fraction, *GW_REVAP* groundwater "revap" coefficient, *REVAPMN* Threshold water depth in the shallow aquifer for "revap", *OV_N* Manning's "*n*" value for overland flow, *PLAPS* Precipitation lapse rate, *ALPHA_BNK* Base flow alpha factor for bank storage, *GWQM* threshold depth for return flow of water in the shallow aquifer, *ESCO* soil evaporation compensation factor, *SOL_AWC* available water capacity of soil layer, *TLAPS* Temperature lapse rate

be sensitive. The parameters used in the sensitivity analysis are listed in Table 3, along with the sensitivity of each parameter. The sensitive parameters are Moist bulk density (SOL_BD), Saturated hydraulic conductivity (SOL_K), Initial SCS runoff curve number for moisture condition II (CN2), Base flow alpha factor (ALPHA_BF), Groundwater delay (GW_DELAY), and Effective hydraulic conductivity in the tributary channel (CH_K1).

Numerous methods have been used to calibrate and validate SWAT. Most published SWAT applications report both graphical and statistical hydrologic calibration results, especially for streamflow, and hydrologic validation results are also reported for a large percentage of the studies (Arnold et al. 2012). According to Coffey et al. (2004), there are close to 20 statistical tests that can be used to evaluate the predictions of SWAT. R^2, NSE, and PBIAS are the statistics that are most frequently used for calibration and validation. The R^2 obtained value for the calibration period (2015–2017) is 0.88, while the Nash–Sutcliffe efficiency (NSE) for the same period is 0.87. The percentage bias value (PBIAS) is − 6.7, as shown in Table 4. The outcome of the validation process (2018–2019) is an R^2 of 0.94, an NSE value of 0.93, and a PBIAS of 6.8% for the uncontrolled portion of the Ichkeul watershed.

The R^2 statistic can range from 0 to 1, where 0 indicates no correlation and 1 represents perfect correlation, and it provides an estimate of how well the variance of observed values is replicated by the model predictions (Krause et al. 2005). A perfect fit between the simulated and observed data is indicated by an NSE value of 1 (Arnold et al. 2012). According to Gupta et al. (1999), the optimal value of PBIAS is 0. This means that smaller values of PBIAS indicate an accurate simulation of the model. This holds for the outcomes; R^2, NSE, and PBIAS are very close to the optimal limits defined above by the authors. The scatter plot (Figs. 8a, b, and 9) shows the strong correlation between the variables the model predicted and observed during the

Table 4 The values of the statistical evaluators of the simulation after the two phases of calibration and validation

Calibration					Validation				
P-factor	R-factor	R^2	NSE	PBIAS	P-factor	R-factor	R^2	NSE	PBIAS
0.97	1.17	0.88	0.87	− 6.7	0.95	1.11	0.94	0.93	6.8

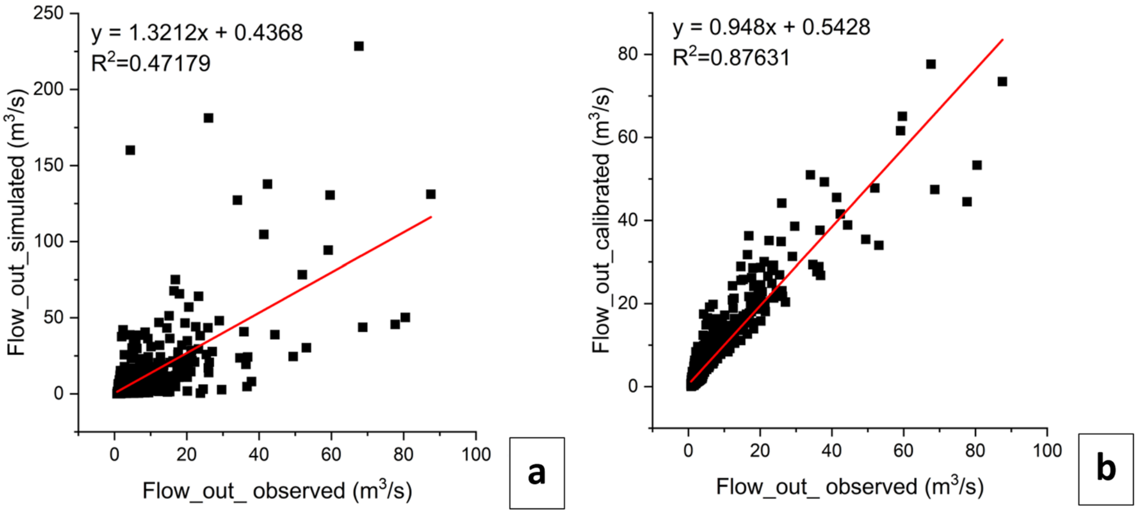

Fig. 8 Comparison of the simulated-observed **a** and calibrated-observed **b** daily flow at Ecluse-Sidi Hassoun station by linear regression before and after the calibration phase

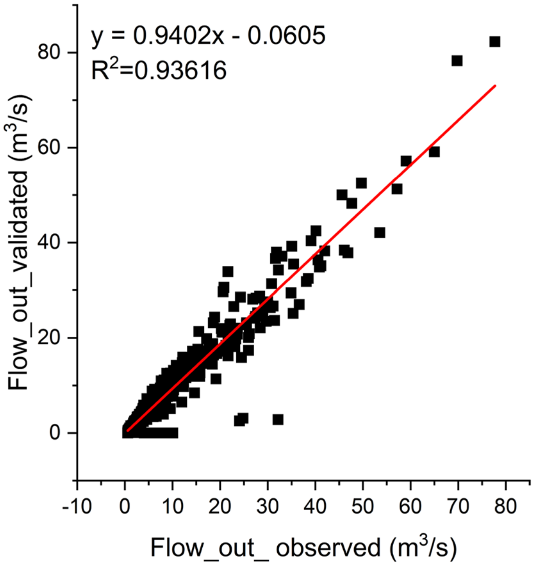

Fig. 9 Comparison of simulated and observed daily flow at the Ecluse-Sidi Hassoun station by linear regression after the validation phase

calibration and validation phases. These findings demonstrate the efficacy of the outflows predicted by SWAT. Studies that have been published by Santhi et al. (2001); Moriasi et al. (2007) and Van Liew et al. (2003) confirm the findings. When the Nash-Sutcliff efficiency (NSE) and coefficients of determination (R^2) are greater than 0.5 and the bias percentage is under 15%, calibration and validation are deemed to have been successful.

The R-factor and the P-factor should be measured, according to Abbaspour (2007), as they validate the accuracy of the uncertainty assessment and model calibration. A value of the P-factor close to 1 means that all observations are included in the prediction uncertainty. The R-factor should, in general, be less than 1.5 (Abbaspour 2007). After the adjustment phase, the values of the P and R factors for the calibration and validation period are (0.97, 1.17) and (0.95, 1.11), respectively (Table 4); these obtained values are within the limits of the P and R factors stated above.

Based on the statistical evaluations presented in Table 4, there appears to be a strong correlation between observed and simulated daily flows. Based on the results obtained, SWAT is capable of reproducing the observed daily outflow at the outlet of the study basin with a high level of accuracy.

Conclusion

To determine the need for the freshwater of Ichkeul lake, and then later, to model its salinity and quantify the sediments to establish guarantees for its survival, the SWAT model was applied. The model was then calibrated and validated on a daily basis by applying the SUFI-2 algorithm in

SWATCUP-2012 using historical stream flow recorded at the Ecluse-Sidi Hassoun station, located downstream of the Ichkeul watershed. 7 years (2013–2019) of datasets have been arranged for model setup, first 2 years (2013–2014) of data were kept as the warm-up period for the model. A sensitivity analysis is performed via SWAT-CUP to identify the most sensitive values and ranges of various hydrological parameters for the study area. In this study, six out of a total of nineteen parameters were found to be sensitive. Saturated hydraulic conductivity (SOL K), Initial SCS runoff curve number for moisture condition II (CN2), Base flow alpha factor (ALPHA BF), Groundwater delay (GW DELAY), and Effective hydraulic conductivity in the tributary channel (CH K1) are the sensitive parameters. Five statistical evaluators, Nash-Sutcliff efficiency (NSE), coefficient of determination (R^2), bias percentage (PBIAS), P-factor, and R-factor, were used to assess the performance of the models. During the calibration and validation periods, the R^2, NSE, and PBIAS values were 0.88, 0.94, 0.87, 0.93, -6.7, and 6.8, respectively. The P-factor and R-factor values during the calibration and validation period are 0.97, 0.95, -6.7, and 6.8, respectively. The result shows SWAT holds promise for use in the uncontrolled part of the Ichkeul watershed. It can be concluded that the outcome of the model indicated that there had been a good agreement between the simulated and observed flow. Therefore, the model is capable of reproducing the observed daily outflow at the outlet of the study basin with a high level of accuracy.

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Data availability I declare the availability of data for this journal.

References

Abbaspour KC (2005) Calibration of hydrologic models: when is a model calibrated? In: Zerger A, Argent RM (eds) Proceedings of the International Congress on Modelling and Simulation (MODSIM'05). Modelling and simulation society of Australia and New Zealand, Melbourne, pp 2449–2455

Abbaspour KC (2007) User manual for SWAT-CUP, SWAT calibration, and uncertainty analysis programs. Swiss Federal Institute of Aquatic Science and Technology, Eawag

Abbaspour KC, Vejdani M, Haghighat S (2015) SWATCUP calibration and uncertainty programs for SWAT. In: Proceedings of the International Congress on Modelling and Simulation.

Abbott MB, Bathurst JC, Cunge JA, O'connell PE, Rasmussen J (1986) An introduction to the European hydrological system—Systeme Hydrologique Europeen, "SHE", 2: structure of a physically-based, distributed modelling system

ANPE (1994) Rapport interne : Etude pour la sauvegarde du parc National de l'Ichkeul, 1ére partie : Collecte des données disponibles et analyse des études existantes : p 291

Ariza-Villaverde AB, Jiménez-Hornero FJ, De Ravé EG (2015) Influence of DEM resolution on drainage network extraction: a multifractal analysis. Geomorphology 241:243–254

Arnold JG, Allen PM (1999) Automated methods for estimating baseflow and groundwater recharge from stream flow records. J Amer Water Resour Assoc 35(2):411–424

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large-area hydrologic modeling and assessment: part I. Model development. J Am Water Resour Assoc 34(1):73–89

Arnold JG, Moriasi DN, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, Santhi C, Harmel RD, Van Griensven A, Van Liew MW, Kannan N (2012) SWAT: model use, calibration, and validation. Trans ASABE 55(4):1491–1508

Ben Mammou A (2006) Aménagements hydrauliques des bassins exoréiques de la Tunisie. Impact sur le flux sédimentaire et la stabilité du littoral, No 30 - Fluxes of small and medium-size Mediterranean rivers: impact on coastal areas. Trogir, March, April 2006

Billen G, Garnier J, Rousseau V (2005) Nutrient fluxes and water quality in the drainage network of the Scheldt basin over the last 50 years. Hydrobiologia 540:47–67

Coffey ME, Workman SR, Taraba JL, Fogle AW (2004) Statistical procedures for evaluating daily and monthly hydrologic model predictions. Trans ASAE 47(1):59–68

Green WH, Ampt GA (1911) Studies on soil physics: 1. The flow of air and water through soils. J Agric Sci 4(1):11–24

Grusson MY (2015) Modélisation de l'évolution hydroclimatique des flux et stocks d'eau verte et d'eau bleue du bassin versant de la Garonne [Thèse de doctorat]. Institut National Polytechnique de Toulouse (INP Toulouse), p 36

Gupta HV, Sorooshian S, Yapo PO (1999) Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J Hydrologic Eng 4(2):135

Hargreaves GL, Hargreaves GH, Riley JP (1985) Agricultural benefits for Senegal River basin. J Irrig Drain Eng 111(2):113–124

HEC (Hydrologic Engineering Center) (2000) Hydrologic Modeling System HEC-HMS. User's Manual, Version 2. Hydrologic Engineering Center; US Army Corps of Engineers, Davis

Henia L (1987) Climat et bilans de l'eau en Tunisie: essai de régionalisation climatique par les bilans hydriques

Holtan HN, Lopez NC (1971) USDAHL-70 model of watershed hydrology (No. 1435). Département de l'agriculture des États-Unis 87(1–2) :61–77

Hosseini SH, Khaleghi MR (2020) Application of SWAT model and SWAT-CUP software in simulation and analysis of sediment uncertainty in arid and semi-arid watersheds (case study: the Zoshk-Abardeh watershed). Model Earth Syst Environ 6:2003–2013. https://doi.org/10.1007/s40808-020-00846-2

ITES (2014) Tunisian Institute for Strategic Studie. Etude stratégique : Système hydraulique de la Tunisie a l'horizon 2030. Janvier, Tunis, Tunisia

Krause P, Boyle DP, Bäse F (2005) Comparaison de différents critères d'efficacité pour l'évaluation des modèles hydrologiques. Adv Geosci 5:89–97

Kumar N, Singh SK, Singh VG et al (2018) Investigation of impacts of land use/land cover change on water availability of Tons River Basin, Madhya Pradesh, India. Model Earth Syst Environ 4:295–310. https://doi.org/10.1007/s40808-018-0425-1

Li J, Wong DW (2010) Effects of DEM sources on hydrologic applications. Comput Environ Urban Syst 34:251–261

Luo Y, Baolin Su, Yuan J, Li H, Zhang Q (2011) GIS techniques for watershed delineation of SWAT model in plain polders. Procedia Environ Sci 10:2053p

Ma L, Ascough JC II, Ahuja LR, Shaffer MJ, Hanson JD, Rojas KW (2000) Root zone water quality model sensitivity analysis using monte carlo simulation. Trans ASAE 43(4):883–895

Meisels A, Raizman S, Karnieli A (1995) Skeletonizing a DEM into a drainage network. Comput Geosci 21:187–196

Monteith JL (1965) Evaporation and the environment. The state and movement of water in living organisms. In: 19th Symposia of the Society for Experimental Biology. Cambridge University Press, London, pp 205–234

Moriasi D, Arnold J, Van Liew M, Bingner R, Harmel R, Veith T (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE 50(3):885–900

Muthee SW, Kuria BT, Mundia CN et al (2022) Using SWAT to model the response of evapotranspiration and runoff to varying land uses and climatic conditions in the Muringato basin, Kenya. Model Earth Syst Environ. https://doi.org/10.1007/s40808-022-01579-0

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models: Part 1. A discussion of principles. J Hydrology 10(3):282–290

Neitsch SL, Arnold JG, Kiniry JR, Srinivasan R, Williams JR (2002) Soil and water assessment tool, user manual, version 2000. Grassland, Soil and Water Research Laboratory, Temple

Pereira LS, Cordery I, Iacovides I (2002) Coping with water scarcity. UNESCO IHP VI, Technical Documents in Hydrology No. 58, UNESCO, Paris, p 267

Pereira DR, Martinez MA, Pruski FF, da Silva DD (2016) Hydrological simulation in a basin of typical tropical climate and soil using the SWAT model part I: Calibration and validation tests. J Hydrol Reg Stud 7:14–37

Priestley CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large-scale parameters. Mon Weather Rev 100(2):81–92

Refsgaard JC (1997) Parameterisation, calibration, and validation of distributed hydrological models. J Hydrol 198(1):69–97

Santhi C, Arnold JG, Williams JR, Dugas WA, Srinivasan R, Hauck LM (2001) Validation of the SWAT model on a large river basin with point and nonpoint sources. J Am Water Resour Assoc 37(5):1169–1188

Schuol J, Abbaspour KC, Srinivasan R, Yang H (2008) Estimation of freshwater availability in the west African subcontinent using the SWAT hydrologic model. J Hydrol 352(1–2):30–49

Sisay E, Halefom A, Khare D et al (2017) Hydrological modelling of ungauged urban watershed using SWAT model. Model Earth Syst Environ 3:693–702. https://doi.org/10.1007/s40808-017-0328-6

Sorooshain S, Gupta VK (1995) Model calibration. In: Singh VP (ed) Computers models of watershed hydrology. Water Resources Publication, Highlands Ranch, pp 23–63

Tarekegn N, Abate B, Muluneh A et al (2022) Modeling the impact of climate change on the hydrology of Andasa watershed. Model Earth Syst Environ 8:103–119. https://doi.org/10.1007/s40808-020-01063-7

U.S. Department of Agriculture, Soil Conservation Service (1972) National Engineering Handbook. Hydrology Section 4. Chapters 4–10. Washington: USDA

Van Griensven A, Bauwens W (2003) Multiobjective autocalibration for semidistributed water quality models. Water Resour Res 39(12):1348–1356

Van Liew MW, Arnold JG, Bosch DD (2005) Problems and potential of autocalibrating a hydrologic model. Trans ASAE 48(3):1025–1040

Van Liew MW, Schneider JM, Garbrecht JD., 2003, octobre. Streamflow response of an agricultural watershed to seasonal changes in precipitation. In: Proceedings of the 1st interagency conference on research in the watersheds (ICRW), pp 27–30