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Hydrological modeling of a small agricultural watershed using the SWAT model: The case of the Zaiane River, Algeria

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Sustainable water resource management requires a good understanding of the elements of water balance. However, measuring many of these elements in the field is difficult, and the use of modeling tools is essential. The main objective of this study was to develop a monthly hydrological model to calculate the water balance of a small agricultural watershed (Oued Zaiane) and evaluate the capacity and effectiveness of the model. We opted for a methodology based on combining the free geographic information system QGIS with the agro-hydrological model Soil and Water Assessment Tool (SWAT) to perform geospatial analyses and simulate hydrological functions at a watershed scale. The model calibration phase was conducted using the SWAT-CUP tool with an adjustment algorithm (SUFI2) to optimize the sensitivity and uncertainty analysis parameters. The model was run from 2013 to 2020 with a calibration period of 2015 to 2019. The results obtained after calibration showed a satisfactory simulation after evaluating the model's performance using the following statistical coefficients: coefficient of determination (R^2) and Nash–Sutcliffe efficiency coefficient (NSE). The monthly calibration of the flow rate yielded good values for coefficients such as R^2=0.78 and NSE=0.55, confirming SWAT as an effective tool for simulating the hydrology of agricultural watersheds.

KEY WORDS: Hydrological modeling, SWAT, GIS, Watershed, Oued Zaiane

Introduction

Acquiring expertise in water resource management is essential for ensuring the quality of life of our planet and contributing to the sustainable development of our society. In this context, a watershed is used as the basic geographical unit for effective management of available water resources (Taleb et al., 2019).

Watershed-based water management is currently being implemented in Algeria. This approach integrates all activities at the watershed level, both quantitatively and qualitatively, for rational management of water resources.

Knowledge of how water resources evolve over time at the watershed level is essential to implement better strategies for managing and planning this important resource. Hydrological modeling is a decision-making tool that can anticipate these changes (Andro, 2019).

Hydrological modeling of watersheds and the simulation of their components play a fundamental role in solving water resource, environmental, and social problems (Ghoraba, 2015).

The role of a hydrological model is to represent the water balance and its components at the basin scale, such as precipitation, evapotranspiration, and infiltration, and to assess water resource management (Parra et al., 2018).

In recent years, several hydrological models have been developed worldwide to simulate watershed hydrological functions (Pereira et al., 2016). Among these models is the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998).

The SWAT model is widely used worldwide at different scales and under different environmental conditions, making it an effective tool for assessing water resource and pollution issues. (Gassman et al., 2007). SWAT has also been applied in several studies in Algeria (Yebdri et al., 2007; Mendas et al., 2008; Zettam et al., 2017; Hallouz et al., 2018; Otmane et al., 2019; Mami et al., 2021).

To this end, a hydrological modeling study was conducted using the SWAT model. In addition, this study analyzes the following elements: spatial representation of determining factors, such as soil, topography, meteorology, and land use, using a geographic information system (GIS); simulation of the water cycle to represent the elements of the water balance at the watershed scale; and calibration of flow with the selection of calibration parameters and evaluation of the model performance.

Consequently, the main objective of this study was to propose a modeling methodology to provide a simulated scenario for small agricultural watersheds.

Material and methods

Study area

The area covered by this study was located between latitudes 36°20'30″ "N and 36°17'30"N and longitudes 3°56'30"E and 4°5'0"″ E. The northern part of the Oued Zaiane sub-basin constitutes the upper-western part of the Soummam watershed (Fig. 1).

The study area forms an excellent agricultural basin as it is located on the El Asnam Plateau in the Wilaya of Bouira in northern Algeria, 100 km from the capital city.

Oued Zaiane is the main wadi that drains the basin and originates in the Tagudite Mountains of the Daïra Bordj Okhriss. The most important tributaries are the Oued Khemis, Oued Okhriss, and Oued Moukhtar, the latter of which was monitored by a hydrometric station (El Asnam).

The basin covers an area of 37 km² and has a 45 km perimeter. The altitudes ranged from 402 m to 596 m (Fig. 1). The climate is hot and dry from May to September and cold and rainy from October to April. The average annual rainfall was 303 mm at El Asnam station for the period 2014–2021.

The basin is located above the Miocene-Quaternary aquifer of the El Asnam Plateau, where the geological formations can be summarized from the most recent to the oldest as follows: Quaternary: Terraces: Marly eluvium, gravel, and Lower Miocene (Aquitanian): gravel, reddish sandy clay, and conglomerates.

Description of the SWAT model

The Soil and Water Assessment Tool (SWAT) is a continuous-time conceptual model and decision-making tool designed to help water resource managers assess, mobilize, and manage water supplies at the watershed level (Arnold et al., 1998). The SWAT is an agro-hydrological model developed in the early 1990s in the United States. Department of Agriculture Agricultural Research Service (USDA-ARS). In the SWAT model, watersheds are first divided into sub-basins and then into hydrological response units (HRUs) that contain land use, topography, and soil-type characteristics (Abbaspour et al., 2015). The hydrological cycle simulated by SWAT was based on the water balance equation, as follows:

$$SW_t = SW_0 + \sum (R_{day(i)} - Q_{surf(i)} - E_{a(i)} - w_{seep(i)} - Q_{gw(i)}) \quad (1)$$

where

SW_t – is the final soil water content [mm],
SW_0 – is the initial soil water content on day i [mm],
t – is time in [days],
$R_{day(i)}$ – is the precipitation on day i [mm],
$Q_{surf(i)}$ – is the surface runoff on day i [mm],
$E_{a(i)}$ – is the evapotranspiration on day i [mm],
$w_{seep(i)}$ – is the amount of water entering the vadose zone from the soil profile on day i [mm],
$Q_{gw(i)}$ – is the amount of return flow on day i [mm], (Neitsch et al., 2005).

In this study, the SWAT model was applied using QGIS software, a free geographic information system, with the QSWAT plugin.

QSWAT, an open-source GIS interface for the SWAT model, was developed on a QGIS platform. This interface allows the preparation of the SWAT model inputs, followed by the execution of simulations. It also allows for the visualization of the outputs. (Dile et al., 2016).

Sensitivity analysis

The purpose of the sensitivity analysis approach is to assess the impact of changes in the input parameters on the simulation results. (Kateb et al., 2019). The SWAT calibration and uncertainty procedure (SWAT-CUP) tool (Abbaspour et al., 2007) is a platform that contains several methods for calibrating and analyzing SWAT model uncertainty (Andro, 2019). The uncertainty estimation procedures were based on Bayesian (Taleb et al., 2021) and on-site methods (GLUE (Beven and Binley, 1992), ParaSol (van Griensven et al., 2006), and SUFI-2 (Abbaspour et al., 2007)).

In this study, the SUFI-2 (Sequential Uncertainty Fitting) method was used to identify the most sensitive parameters for calibrating the model.

Model performance evaluation

To evaluate the performance of the model, we first visually compared the graph showing the results of variables such as simulated flow and observed flow data, and then proceeded to use statistical indices such as the Nash-Sutcliffe (NSE) (Nash and Sutcliffe, 1970), which is a normalized statistical index that can determine the relative magnitude between residual variances and measured data (Moriasi et al., 2007). The Nash-Sutcliffe coefficient evaluates the degree of fit between the observed and simulated data. It ranges from 0.5 to 1; the higher the NSE is above 0.5, the more satisfactory the results. The coefficient of determination, R^2, is the square of the linear correlation coefficient.

(R) between predicted and measured values. It ranged from 0 to 1, and when its value exceeded 0.5, calibration results were considered satisfactory. The two coefficients are calculated using the following equations:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Oi-Si)^2}{\sum_{i=1}^{n}(Oi-\bar{O})^2} \quad (2)$$

$$R^2 = \frac{\sum_{i=1}^{n}(Oi-\bar{O})(Si-\bar{S})}{[(\sum_{i=1}^{n}(Oi-\bar{O})^2]^{0.5}[(\sum_{i=1}^{n}(Si-\bar{S})^2]^{0.5}} \quad (3)$$

where

Oi – is the observed values,
Si – is the simulated values,
$\bar{O}$ – is the average of the observed values,
$\bar{S}$ – is the average of the simulated values;
n – is the number of observations.

By comparing NSE and R^2, we found that the interpretation of NSE model performance involves

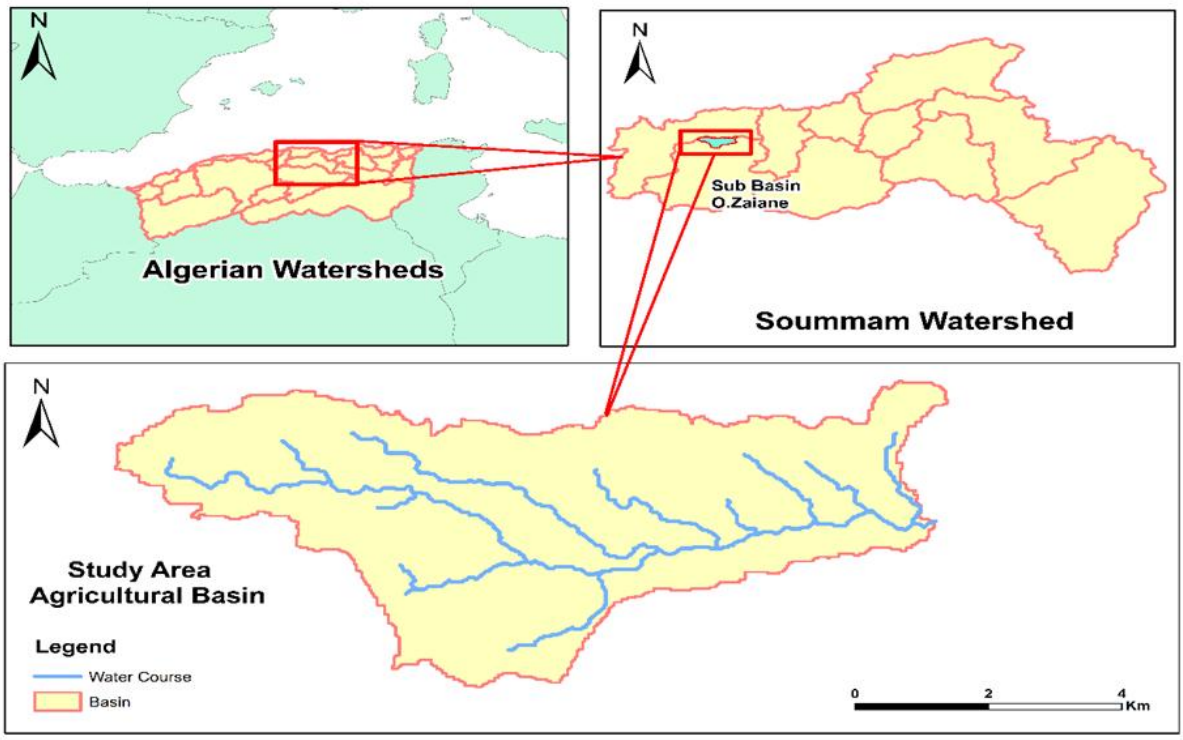


Fig. 1. Geographic location of the study area.

reproducing the values observed individually, whereas R^2 does not reproduce these values (Green et al., 2006).

Methodology

Preparation of input data for the SWAT model

The preparation of SWAT inputs is a crucial step for the success of this model. This process began with the preparation of a digital terrain model (DTM) (Fig. 2) produced using a global digital elevation map (ASTER GDEM). This was then used to delineate the watershed and sub-basins, the hydrographic network, and to derive the slope map.

For the land cover and land use (LULC) map, we used the Global Land Cover extract from ESRI, which is based on Sentinel-2 images with a high resolution of 10 m and updated until 2023. After geoprocessing, we obtained a land-cover map with seven classes (Fig. 3), where the agriculture (AGRL) class dominated the largest basin area.

Next, we prepared a soil map (Fig. 4) based on data from the global soil maps of the Food and Agriculture Organization (FAO) and United Nations Educational, Scientific, and Cultural Organization (UNESCO), which yielded the following three soil classes:

- Lc48-2a: This class is dominated by medium-textured chromic Luvisols, with an association of chromic and vertic Cambisols: flat to undulating, which is the largest class in our basin with an area of more than 21 km².
- Ne52-2a: Medium-textured euritic Nitosols dominate, with an association of calcareous fluvisols: flat to undulating. This is the second-largest class, with an area of over 17 km².
- Lo38-bc: Hilly to rugged ortic Luvisols dominate this class, with associations of calcareous cambisols and highly dissected mountainous lithosols. It is the smallest class in the basin with an area of approximately 0.5 km².

Daily precipitation data were obtained from the El Asnam station of the National Water Resources Agency, located at (4° 2'24.74″ "E, 36°18'45.00"″ N), at an altitude of 434 m. The Minimum and maximum temperatures, solar radiation, relative humidity, and wind speed were obtained from the National Aeronautics and National Aeronautics and NASA websites. The data were integrated into the SWAT climate database after creating a weather generator for the study area. The El Asnam hydrometric station, located at the same coordinates as the rain gauge station (4° 2'24.74 °E, 36°18'45.00″ N) at an altitude of 434 m, measured the flow rates from 2014 to 2019.

Delimitation of the watershed

The first step was to delimit the basin using a digital terrain model (DTM) with free QGIS software and the QSWAT plugin, which provided the hydrographic network and divided the basin into 20 subbasins (Fig. 5). The soil, slope, and land use maps were merged to create hydrologic response units (HRUs) in each sub-basin. Twenty HRUs were identified in this basin.

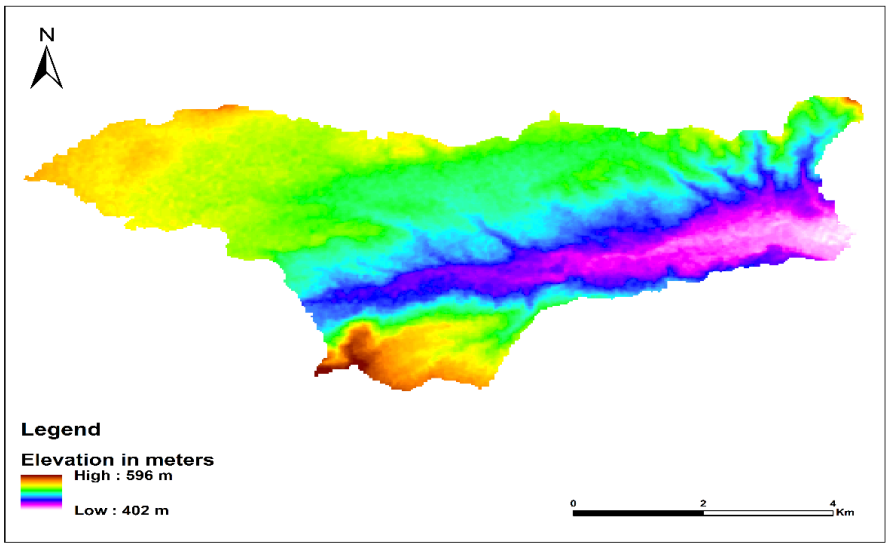


Fig. 2. Digital Elevation Model of the study area.

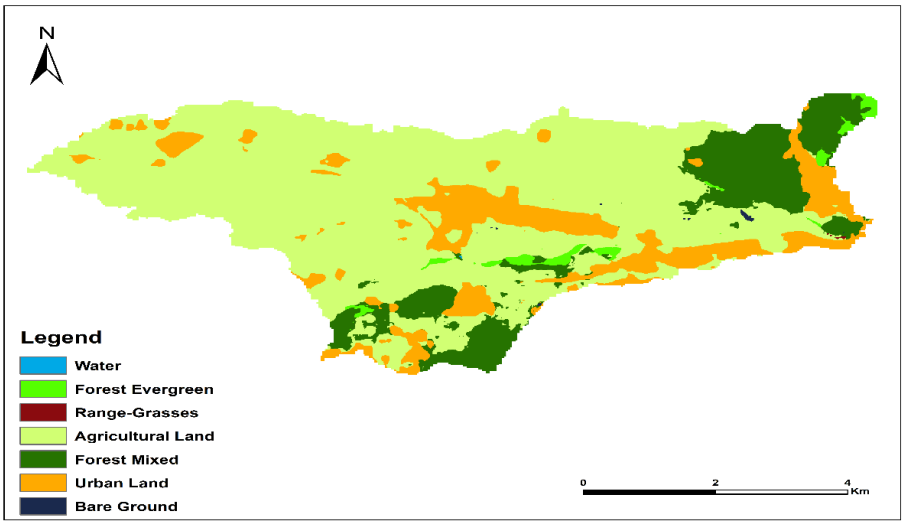


Fig. 3. Land use map of the study area.

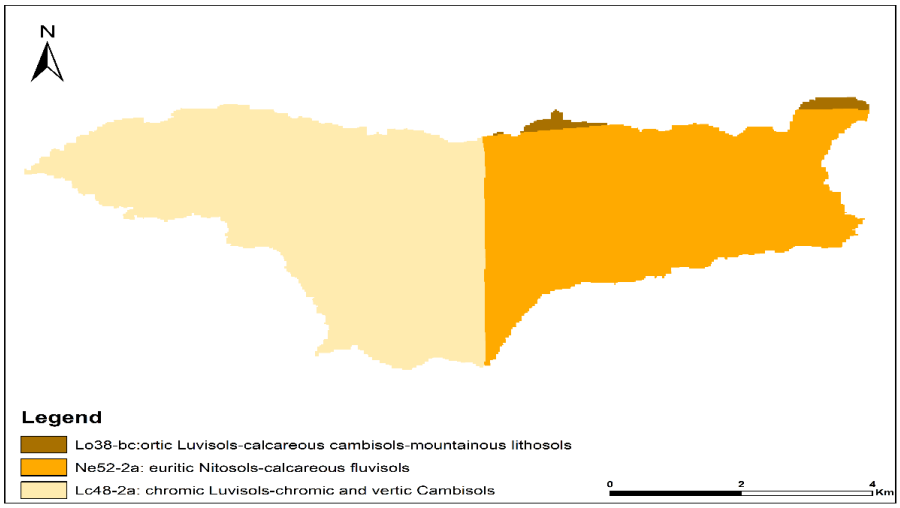


Fig. 4. Soil map of the study area.

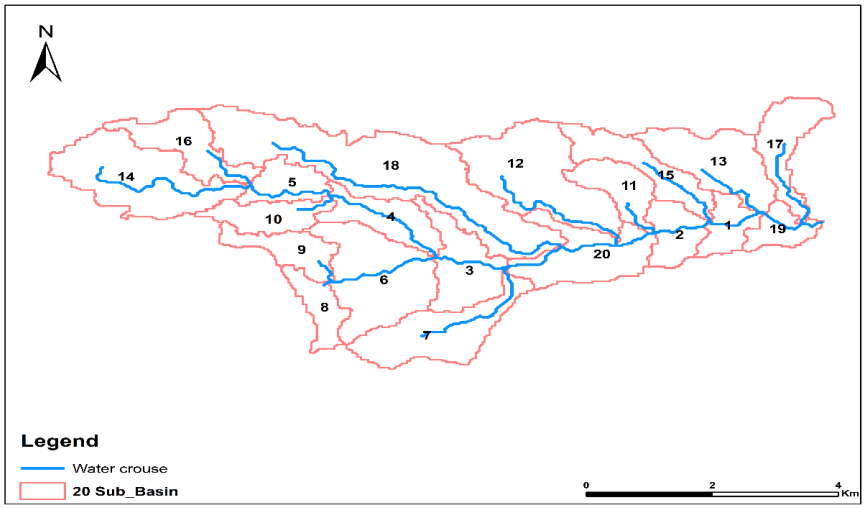


Fig. 5. Map of sub-basins and hydrographic network.

Results and discussions

Basin water balance

Diagnosing the water situation in our basin requires conducting an in-depth analysis of the water balance and studying its various components to fully understand the hydrological functioning of the model.

(Fig. 6) shows the water balance simulated by the SWAT model for the period 2013–2020. The annual precipitation was 586.8 mm year^{-1}, surface runoff was 135.28 mm year^{-1}, potential evapotranspiration was 1700.8 mm year^{-1}, and water percolation to shallow aquifers was 286.78 mm year^{-1}. However, recharge to deep aquifers (confined aquifers) that pass through an impermeable layer was 14.34 mm year^{-1}.

According to the results of the SWAT model, in terms of groundwater resource management in our study area, there is significant water percolation into the shallow aquifers or the Miocene-Quaternary unconfined aquifer of the El Asnam Plateau that covers our agricultural basin, while the average thickness of Quaternary alluvium is 10–60 m, which allows for good recharge of wells and boreholes for farmers in the region through increased flow rates.

Basin water balance spatialization of results obtained by SWAT

Using the free geographic information system QGIS, we spatialized our SWAT model results by developing thematic maps for various components of water balance. Spatialization allowed us to analyze the results across the entire basin of the study area.

To this end, we started with a map of the different flows in the hydrographic network of the study area.

The flow rate in our study area varied between 0.01 and 0.45 m^3 s^{-1} (Fig.7), with the highest values (0.18–0.45 m^3 s^{-1}) found downstream in the basin, specifically in the main wadi of our basin, Oued Zaiane. In contrast, the flow values decreased in the upstream part of the basin and small tributaries of the wadis.

This considerable flow of Oued Zaiane provides farmers with the opportunity to irrigate neighboring agricultural plots (Fig. 8).

In terms of water resource management in an agricultural basin, we should also focus on the components of the water balance that are related to irrigation management. This has enabled us to propose the spatialization of three parameters through the development of three thematic maps as a decision-making tool to facilitate the work of managers and decision-makers in the agricultural water sector in the Wilaya of Bouira.

The soil moisture in our basin ranged from 176.26 to 116.92 mm per year (Fig. 9), with the highest values of 117.12–176.26 mm located downstream of the basin, whereas the lowest values of less than 117.12 mm were upstream of the study area. This information on soil moisture provides essential insights into how to manage agricultural water distribution in the study area and how to choose the types of crops to be distributed across the agricultural plots covering the surface area of the basin.

Most of the basin's surface has evapotranspiration between 140.95 and 163.84 mm per year (Fig. 10), except for small parts of the upper and southern parts of the basin, which have values of less than 140.95 mm per year.

Potential evapotranspiration varied between 1699.6 and 1702.5 mm per year (Fig. 11), in most of our study area and decreased slightly in the southern downstream part of the basin, where the main river flows.

Model calibration

Sensitivity analysis results

The sensitivity analysis stage is necessary before beginning the calibration procedures (Abdelkbir et al., 2023). The results of the calibration parameter values and their definitions are listed in Table 1. The GW-DELAY

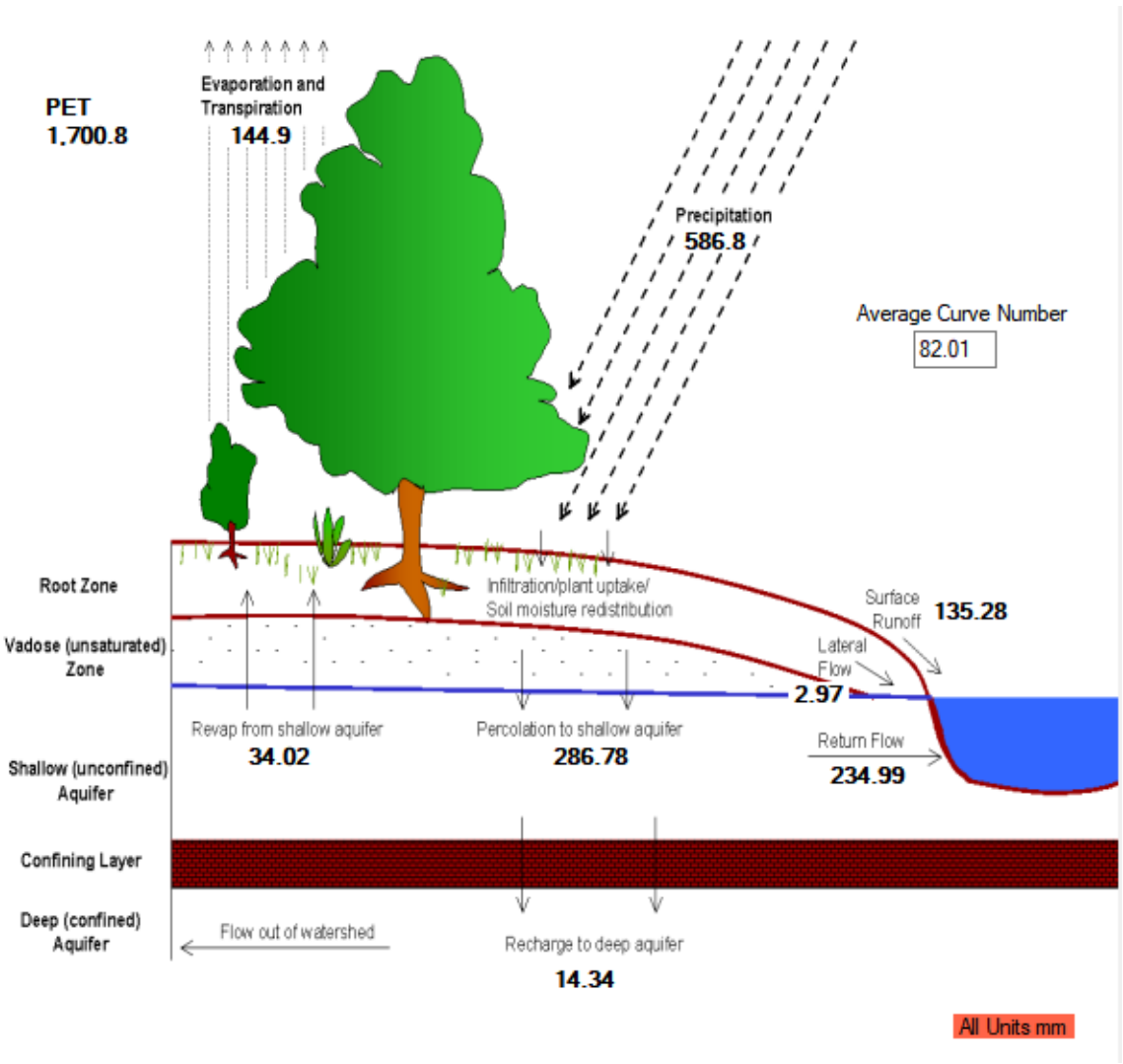


Fig. 6. Diagram of the basin's water balance.

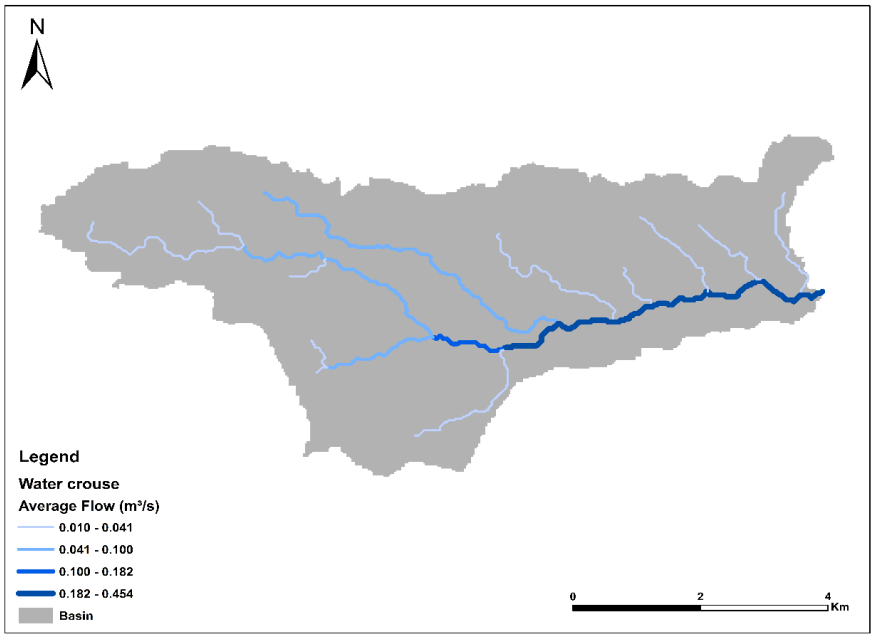


Fig. 7. Map of average monthly flow for the period 2013–2020.

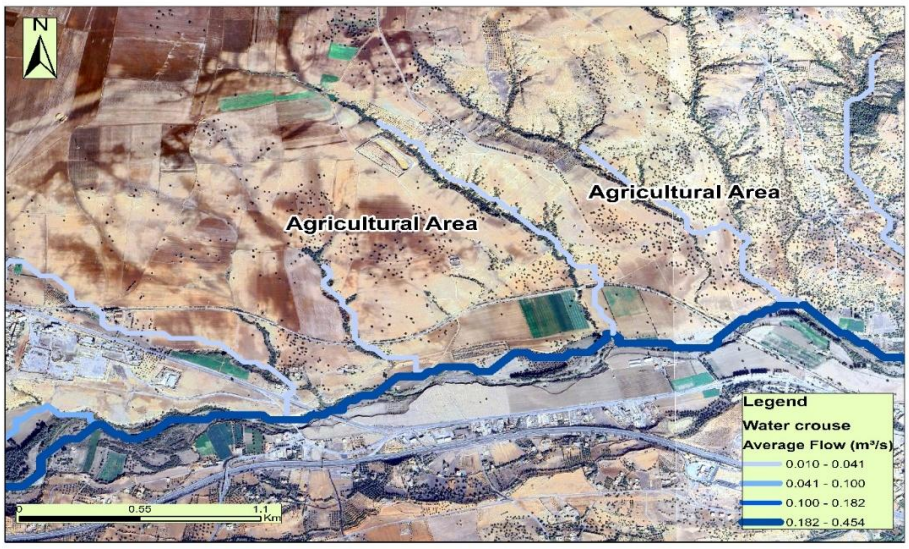


Fig. 8. Satellite image of agricultural land near Oued Zaiane.

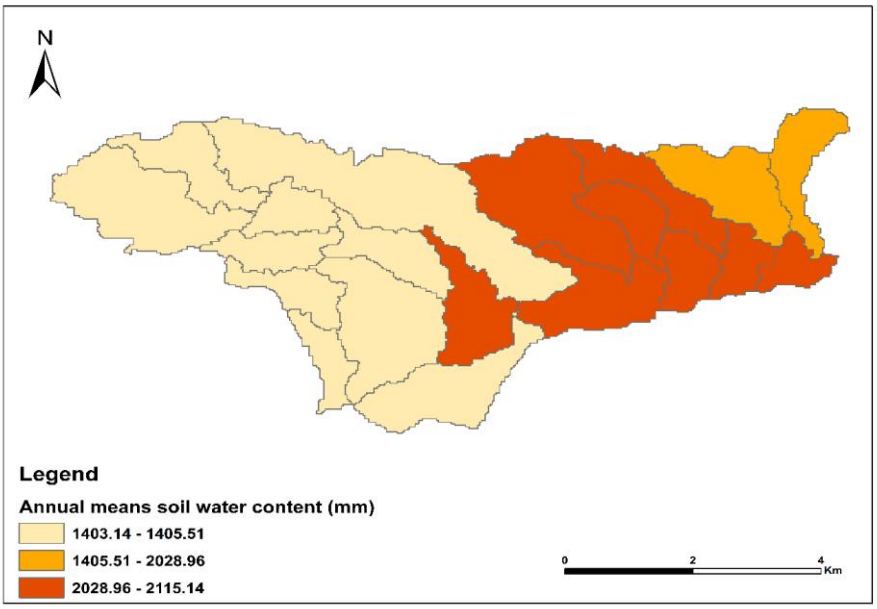


Fig. 9. Map of average annual soil moisture for the period (2013–2020).

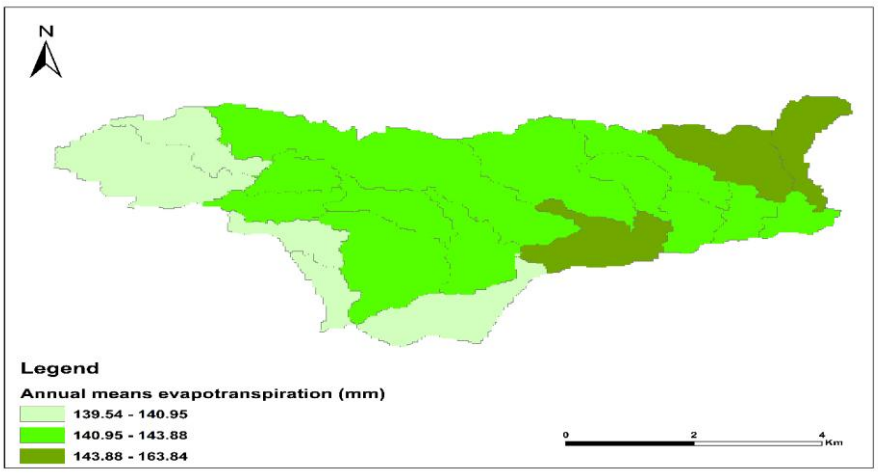


Fig. 10. Evapotranspiration map for the period (2013–2020).

parameter, which determines the delay in the time it takes for water to leave the soil and enter the shallow aquifer, has increased, given the impermeable geological formations found in the study area and the high piezometric level of the Quaternary aquifer

Flow calibration results

The objective of the model calibration was to reduce the uncertainty between the simulated and observed values. After calibrating the four most sensitive parameters (Table 1), the flow was calibrated using the monthly averages measured at EL Asnam station from 2015 to 2019.
The results of the statistical indices obtained show that the coefficient of determination R^2 has a value of 0.78, and the Nash-Sutcliffe coefficient NSE is 0.55, which exceeds 0.5. Therefore, the results were satisfactory, indicating an excellent model performance. The calibration results for the observed and simulated monthly flows are shown in (Fig. 12).

Discussions

Flow calibration was performed monthly between 2015 and 2019. The results show that the model performed well in terms of its ability to reproduce the hydrological functions of the basin. However, a comparison with similar studies in Algeria shows that the model is well adapted to the local climate, as demonstrated by the study by Zettam et al. (2020) in Algeria in the semi-arid Tafna basin shows an NSE between 0.42 and 0.75 and an R^2 between 0.25 and 0.84, while Bougamouza and Remini (2022) in the Oued El Abiod watershed in the Biskra region found NSE between 0.53 and 0.56 and R^2 between 0.72 and 0.78, and Abdelkbir et al. (2023) in the Bouhamdane watershed found NSE values between 0.68 and 0.76 and R^2 values between 0.78 and 0.89. Mebarki et al. (2024) found NSE values between 0.69 and 0.79 and R^2 values between 0.86 and 0.93 in the upper watershed of the Mina
River (northwestern Algeria), even in the Maghreb country of Choukri et al. (2019) in Morocco in

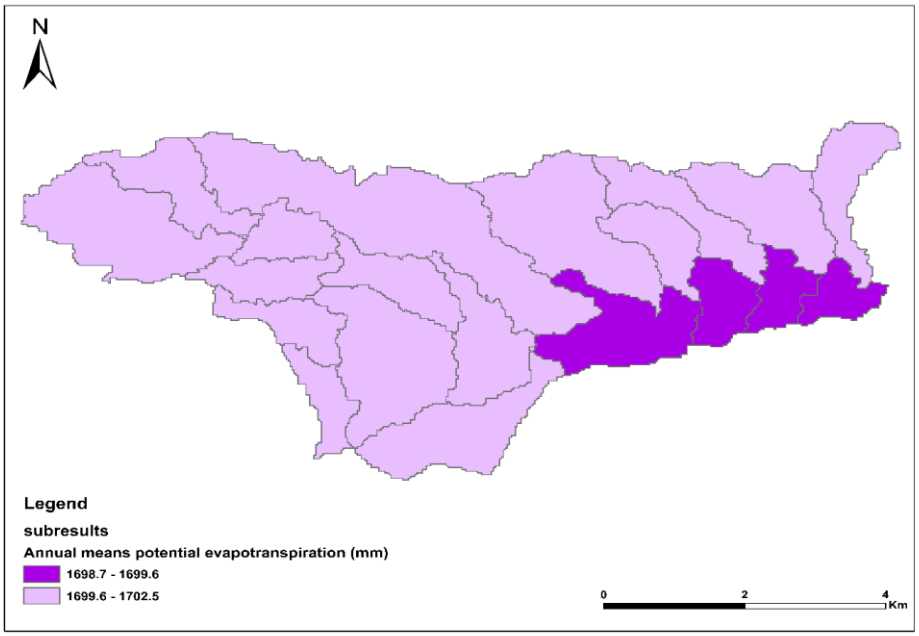


Fig. 11. Potential evapotranspiration map for the period (2013–2020).

Table 1. Results of the sensitivity analysis performed by SWAT-CUP

Parameters	Definitions	Calibratedvalue	Default value
CN2mgt	Initial SCS runoff curve number for moisture condition II	0	-0.20–0.20
GW.DELAY.gw	er rechargedelay	24 days	30–450 days
ALPHA.BF.gw	Evaporation coefficient from the groundwater table	0.5 day^{-1}	0–1 day^{-1}
Gwqmn	Minimum water level required for water transfer fromshallow aquifer to watercourse	1 mm	0–2 mm

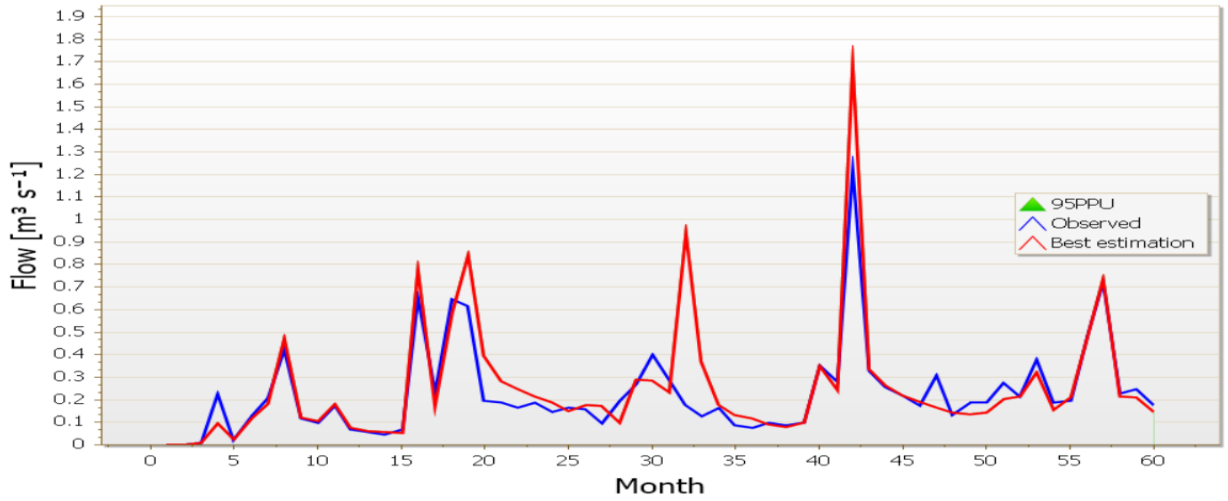


Fig. 12. Monthly calibration of observed and simulated flows at hydrometric stations.

the Telta watershed in the western Rif, the results were also positive, with NSE between 0.61 and 0.82 and R^2 between 0.64 and 0.83. Ait M'barek et al. (2019), in a case study in the El Grou watershed in Morocco, found NSE between 0.80 and 0.82 and R^2 between 0.80 and 0.82, while El Harche et al. (2021) demonstrated better calibration in the Telta watershed in Tunisia, with NSE and R^2 values of 0.97 and 0.99, respectively. Mosbahi et al. (2015), in a semi-arid watershed, presented a very good result with NSE=0.78 and R^2=0.85, in Mediterranean Europe, Dechmi et al. (2012) in the irrigated Del Reguero watershed in Spain, where NSE is between 0.80 and 0.90, in Asia, Dlamini et al. (2017) in the Bernam basin in Malaysia, the monthly calibration results for the indices R^2 between 0.62 and 0.67, and NSE between 0.61 and 0.62, in North America, Zare et al. (2022) in the Saskatchewan basin in southern Canada, the NSE varies between 0.42 and 0.76, while in South America, Troin et al. (2012) in the subtropical lake watershed: Laguna Mar Chiquita, Argentina, the NSE value is between 0.71 and 0.86.

Based on the satisfactory results of the model performance evaluation, we recommend the use of the SWAT model to simulate the hydrological behavior of small agricultural watersheds similar to those in our study area.

Conclusion

In this study, the SWAT model was applied to a small agricultural watershed that was drained mainly by Zaiane river for the period from 2013 to 2020. The watershed was divided into 20 (HRU) hydrological response units that combined soil, topography, and land use data in order to attempt to reproduce the hydrological functioning of the basin by extracting the water balance and simulating the flows of the main part of the basin. Model calibration is an essential step in evaluating its performance and simulation capacity in the study area, which has specific regional climate characteristics. The sensitivity and uncertainty analyses were based on the selection of four parameters, three of which were related to the characteristics of groundwater and aquifers that play a major role in the region's agricultural life and one parameter related to surface runoff, which was the subject of this simulation.

The results of the calibration of simulated monthly flows with observed flow data from the El Asnam hydrometric station, which belongs to the National Water Resources Agency, from 2015 to 2019, showed excellent model performance with satisfactory values for the statistical indices used in the model evaluation, such as the coefficient of determination R^2 with a value of 0.78, and the Nash-Sutcliffe coefficient NSE=0.55.

The spatialization of the results of some components of the water balance also allowed us to analyze the water situation in the study area and find ways to improve water resource management in the basin, which is predominantly agricultural. To this end, we propose several recommendations to help decision-makers in the water resource sector, particularly water mobilization and agricultural hydraulic services, and implement appropriate water resource management in this region, notably by encouraging and facilitating authorizations for farmers to drill shallow boreholes because of the good recharge rates of shallow aquifers in the region.

Exploiting the flow of Oued Zaiane, which is not captured by a dam or a hillside reservoir, is very close to agricultural plots. Therefore, it is important to divert the water of the Oued Bouhlou to a small rural dam to store as much water flowing in this Oued as possible. Based on the good results of the SWAT model, we propose covering all major wadis with weather and automatic hydrometric stations to measure flow rates and cover a larger area of watersheds in the future.

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