Journal of Hydrology: Regional Studies 63 (2026) 103027

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Enhancing groundwater resources through managed aquifer recharge: A SWAT application in arid southeastern Tunisia

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ARTICLE INFO

Keywords:
Soil and Water Assessment Tool (SWAT) model
Arid regions
Water Harvesting Techniques (WHTs)
Gabion structures
Recharge wells
Managed Aquifer Recharge (MAR)

ABSTRACT

Study region: The Triassic aquifer of Sahel el Ababsa in the Jeffara plain, southeastern Tunisia, lies in an arid region facing growing water scarcity due to climate and land-use pressures.
Study focus: This study applied the Soil and Water Assessment Tool (SWAT) to simulate hydrological processes and evaluate the impact of Managed Aquifer Recharge (MAR) structures, including traditional Water Harvesting Techniques (WHTs), on groundwater recharge. Two SWAT models were developed for the pre-implementation (1971–1990) and post-implementation (1991–2020) phases of the Tunisian Strategy for Water and Soil Conservation (SWSC). Model calibration using observed discharge and potential evapotranspiration (PET) showed satisfactory performance (R^2 = 0.72, NSE = 0.63 for discharge; R^2 = 0.79, NSE = 0.72 for PET) with validation also satisfactory (R^2 = 0.69 and NSE = 0.62 for discharge; R^2 = 0.82 and NSE = 0.75 for PET).
New hydrological insights: SWAT successfully reproduced groundwater recharge under natural conditions, consistent with previous studies in southern Tunisia, and quantified the additional recharge induced by MAR structures. Results demonstrate that rainwater-based MAR significantly enhances aquifer recharge and confirm SWAT's suitability for simulating water balance in arid environments. The water balance shifted from 74 % Actual Evaporation (ET), 5 % recharge, and 21 % outflow before SWSC to 82 % ET, 7.2 % recharge (including recharge wells), and 13 % outflow after SWSC implementation. In the calibrated Koutine watershed, WHTs induce an estimated + 5 % increase in groundwater recharge.

Abbreviations: MAR, Managed Aquifer Recharge; SWAT, Soil and Water Assessment Tool; SWSC, Strategy for Water and Soil Conservation; PET, Potential Evapotranspiration; SDP, Seawater Desalination Plant; CN, Curve Number; WHT, Water Harvesting Techniques; SCS, Soil Conservation Service; IRA, Institut des Régions Arides; LU, Land Use; DEM, Digital Elevation Model; CULT, Cereal cultivation; STPP, Plain rangelands; OLVM, Mountain rangelands; URBN, urban zone; STPJ, Mountain rangelands.; MBEH, Minéraux Bruts d'Erosion Hydrique, Regosols; PEEH, Peu Evolués d'Erosion Hydrique, Regosols; PEAH, Peu Evolués d'Apport Hydrique, Fluvisols; ISOH, Isohumiques Bruns Calcaires Tronqués, Xerosols; JESR, soil on the terraces of Jessour; STAB, Soil on the terraces of Tabias; R^2, coefficient of determination; NSE, Nash–Sutcliffe efficiency.

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https://doi.org/10.1016/j.ejrh.2025.103027
Received 23 September 2025; Received in revised form 3 December 2025; Accepted 6 December 2025
Available online 12 December 2025

1. Introduction

Drought and water scarcity in arid regions, exacerbated by low and highly variable rainfall, rapid population growth, and increased demand for water resources, present a significant challenge to sustainable development (Dai, 2011; Sheffield et al., 2012). To address this issue, innovative solutions such as WHTs are essential (Rockström and Falkenmark, 2015; Piemontese et al., 2020). These methods, which capture and store surface runoff, can improve water availability for agriculture, recharge groundwater, and reduce soil erosion, offering a practical and cost-effective strategy for enhancing water security and resilience in these vulnerable areas.

Despite their recognized potential, WHTs remain underrepresented in large-scale hydrological modeling studies, especially in arid and semi-arid regions where they could offer the most benefits (Li et al., 2000; Oweis and Hachum, 2006; Tamagnone et al., 2020). Existing literature often focuses on small-scale, site-specific case studies or on individual techniques without assessing their cumulative hydrological impact at watershed or aquifer scale (Rockström et al., 2003; Abdelkareem et al., 2023; Calderón et al., 2024). Moreover, many studies tend to overlook quantitatively assessing the contribution of WHTs to groundwater recharge using physically based models, or evaluating the long-term sustainability of WHTs under varying climatic and land use scenarios (Calianno et al., 2023; Abd-Elaty et al., 2024). There is a critical need to bridge this gap by evaluating the effectiveness of such MAR techniques within a spatially explicit, process-based modeling framework that allows the quantification of groundwater recharge and other key hydrological processes. By simulating the impact of MAR techniques on groundwater recharge over multi-decadal periods and comparing historical and contemporary land use scenarios, this research aims to contribute to a broader understanding of how traditional WHTs and other MAR techniques, such as recharge wells and gabions, which are already implemented in the region, can be integrated into sustainable water strategies in Tunisia.

For centuries, the need to collect surface water and to limit sediments' transportation, was imposed in the South of Tunisia in order to face water scarcity. People, well adapted to these conditions, invented traditional runoff WHTs called *Jessour* and *Tabias*. The *Jessour* system (singular *Jessr*), shown in Fig. 1, consists of several units called Jessr, hydraulic units installed at the talwegs of valleys, mountainous and gentle slope areas. The Jessr is used to allow the retention of runoff water and sediments, to create rich agricultural areas, to conserve the vegetation cover, and to enhance the aquifer recharge. The Jessr is composed of three components: The Impluvium or catchment which is the area used to collect the rainwater, the terrace, and the dyke (El Amami, 1982, 1984; Ouessar, 2007; Ouessar et al., 2009; Castelli et al., 2019; Calianno et al., 2020). *Tabias* are similar to the *jessour,* except that they are essentially situated on gentle slopes, in the piedmont surfaces where the slope does not exceed 3 % and where the soil is relatively deep. (El Amami, 1982, 1984; Ouessar, 2007).

Other MAR techniques are already widely used in the Tunisian arid and semiarid zones, particularly through groundwater recharge structures such as *gabion check dams* constructed across wadis. Each structure typically spans the width of the wadi bed, with a height of 2–3 m. These structures collect runoff water, promoting infiltration and reducing flooding by slowing down the runoff rate (Ouessar, 2007). *Floodwater harvesting* systems built in gabions collect and divert all or part of the floodwater to neighboring fields (Ouessar, 2007). Such interventions enhance aquifer recharge and provide natural irrigation for agricultural lands (Ouessar and Yahyaoui, 2000; Ouessar, 2007; Ouessar et al., 2009; Castelli et al., 2019; Calianno et al., 2020).

Recharge wells are another MAR technique, mainly applied to calcareous aquifers with low permeability. They demonstrate high efficiency in replenishing groundwater, often observable during field visits. A recharge well consists of an inner long tube reaching the water table or a permeable layer, and an outer tube at the surface that secures the gravel filter (Ouessar and Yahyaoui, 2000; Yahyaoui

Fig. 1. The Jessour WHT. Photo of M. Ben Zaied, Koutine 2023.

et al., 2002; Ouessar, 2007). These MAR interventions, relying on rainwater and runoff, provide a sustainable strategy to enhance groundwater availability and support agriculture in arid regions.

MAR techniques play a crucial role in enhancing groundwater recharge in arid regions, where water scarcity is a major challenge, and their impact can be effectively assessed using hydrological models. The Soil and Water Assessment Tool (SWAT) is a basin-scale model developed by (Arnold et al., 1998). It is physically based, continuous-time model operating on a daily time step and capable of long-term simulation (Arnold et al., 1998). SWAT is a widely used hydrological model designed 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 (Arnold et al., 1998; Gassman et al., 2007).

The SWAT model has been widely applied worldwide to simulate water balance, water quality, sediment transport, and climate impacts at scales ranging from small watersheds to entire continents (Neitsch et al., 2005; Schuol et al., 2008; Gassman et al., 2007; Abbaspour et al., 2015; Akoko et al., 2021). In Tunisia, SWAT has been used to investigate hydrological processes and environmental issues such as water quality (Bouraoui et al., 2005; Othman et al., 2021), soil erosion (Mosbahi et al., 2012; Jarray et al., 2023), and sediment transport (Ben Salah and Abida, 2016). Specific adaptations of the model were also developed to better represent local conditions, notably SWAT-WH, which integrated water harvesting systems into the Wadi Koutine watershed (Ouessar, 2007; Ouessar et al., 2009), and SWAT-WH2, which further incorporated different WHTs by modifying the "potholes" option (Abdelli, 2017).

While these applications demonstrate the versatility of SWAT, most studies in Tunisia have focused on individual practices or single catchments. The combined effects of traditional WHTs (Jessour and Tabia), gabion structures, and modern MAR interventions (recharge wells) on groundwater recharge remain poorly quantified, particularly at the watershed scale.

This study addresses these gaps by quantitatively assessing, for the first time in Tunisia, the contribution of both traditional and modern MAR systems to groundwater recharge under arid conditions. It applies a process-based, spatially distributed SWAT model to the Koutine, Gattar, and Médenine watersheds in southeastern Tunisia, which play a key role in recharging the Triassic aquifer of Sahel El Ababsa in the Jeffara plain.

At the national level, the Tunisian government has launched the first Strategy for the Water and Soils Conservation (SWSC) for the period 1990–2004. Since then, the WHTs subsequently expanded rapidly.

The present study aims to simulate the main hydrological processes and quantify the water balance components in these watersheds, with a specific focus on groundwater recharge. The objectives are (i) to **assess** recharge dynamics and water balance components under pre- and post-SWSC conditions, and (ii) to determine the relative contribution of each MAR intervention to total groundwater recharge, thereby providing quantitative insights for sustainable water management in arid Tunisia.

A comprehensive climatic, hydrologic, geologic, soil, and land cover database was developed to calibrate and validate the model. The calibrated SWAT model was subsequently employed to analyze recharge dynamics before and after the implementation of WHTs

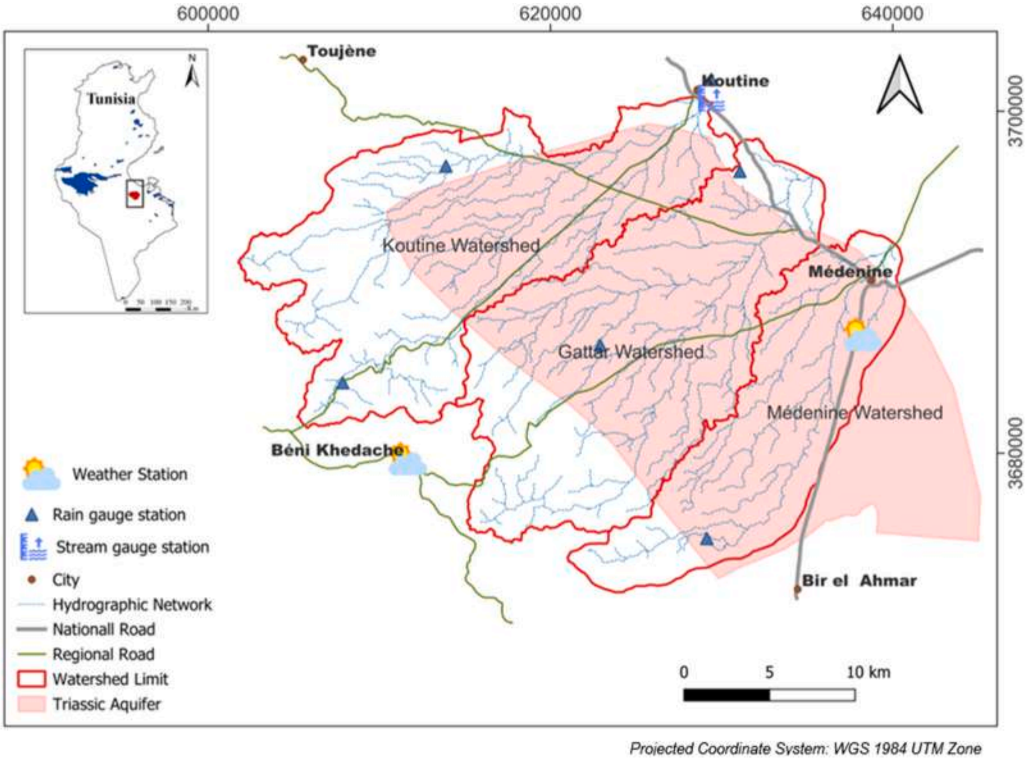

Fig. 2. Study area location.

and other MAR techniques, and to quantify their contribution to aquifer recharge. This study advances understanding of the role of MAR in enhancing groundwater resources in arid and semi-arid regions, while providing a methodological framework applicable to similar contexts for integrated water resources management.

2. Methodology

2.1. Study area overview

The study site encompasses the Koutine, Gattar, and Médenine (also known as Hjar) watersheds, located to the west of Médenine city, in the southeastern region of Tunisia. These watersheds contribute to the recharge of the Triassic aquifer, which serves as a main source of drinking water for the cities of Médenine and Tataouine, the latter located in the adjacent governorate of Tataouine (Hadded et al., 2025). The entire study area falls within the coastal plain of Jeffara, in the Médenine governorate. Given the limited precipitation in the region, groundwater resources are the primary water supply. The Triassic aquifer covers an area of 650 km^2, with the majority of its extent located within the Médenine governorate. A smaller portion, approximately 5 % of the total area, extends into the southern part of the Tataouine governorate. Fig. 2 illustrates the study area location.

The region experiences an arid climate, with an average annual rainfall of about 180 mm, occurring over roughly 30 days each year. The average annual temperature is 22.9 ºC, and reference evaporation rates are notably high. The water balance in the region is consistently negative throughout the year. Rainfall in the study area is characterized by sporadic and torrential events, with low average amounts and significant spatiotemporal variability (Hadded et al., 2013, 2022, 2025).

Despite the arid climate, the study site is characterized by a dense network of wadis, all originating from the highlands of the Tunisian Dahar and draining either directly into the Mediterranean Sea or into salt depressions and lagoons. Intermittent rivers in arid regions play a crucial role in supporting local ecosystems, but their flow can be unpredictable, with dry periods potentially lasting months or even years, which challenges both biodiversity and water resource management (Hadded et al., 2013, 2022, 2025). However, during periods of flow, these rivers present a valuable opportunity to enhance agriculture and groundwater recharge, providing essential water for farming, wildlife, and communities.

The watersheds are drained by a network of wadis. These wadis serve as the principal drainage features within the study area and were explicitly included in the SWAT model to reflect local hydrological processes. The total area of the watersheds spans 1281 km^2, with the Koutine watershed covering 343 km^2, the Gattar watershed covering 380 km^2, and the Médenine watershed covering 558 km^2. The Triassic aquifer of Sahel El Ababsa, predominantly composed of sandstone, is primarily found in the region of Médenine-Bir Lahmer and El Mzar. Its northern boundary is defined by the Upper Permian outcrops of Djebel Tébaga in Médenine, while to the south, it is limited by the reliefs of Djebel Rahach in the Kirchaou region. To the west, the aquifer is bounded by the outcrops of the Dahar mountains, and to the east, it is constrained by the Médenine fault, which brings the aquifer into contact with the neighboring Jeffara aquifers (Gaubi, 1995). The Triassic sandstone outcrops in the piedmont areas and the wadis in the Sahel El Ababsa region are considered the primary recharge zones for this aquifer (Gaubi, 1995; Trabelsi, 2009).

2.2. Modelling framework

SWAT divides the watershed into smaller sub-watersheds and Hydrologic Response Units (HRUs) with their unique attributes. HRUs are lumped land areas within the subbasin that are comprised of unique land cover, soil, and management combinations. Simulation of the hydrology of a watershed can be separated into two major divisions: the land phase and the water or routing phase of the hydrologic cycle (Neitsch et al., 2002, 2005). A trend that has paralleled the historical development of SWAT is the creation of various Geographic Information System (GIS) tools to support the input of topographic, land use, soil, and other digital data into SWAT (Gassman et al., 2007). These interfaces make it easier to assess the impact of various watersheds and water management scenarios and to assess water quality (Janjić, Tadić, 2023; Krysanova and Arnold, 2008; Dile et al., 2016). The development of spatial databases, GIS, and advances in distributed hydrological modelling led to enormous progress in detailed, spatially distributed analysis of hydrological systems and water resources (Olivera et al., 2006; Glavan and Pintar, 2012; Umugwaneza et al., 2022). The spatially distributed data (GIS input) needed for the SWAT interface include the Digital Elevation Model (DEM), soil data, land use and stream network layers.

The mathematical equation of the SWAT is based on the water balance equation, which is expressed as:

$$\Delta SW = P - Q_{SURF} + ET + W_{SEEP} + Q_{GW} \quad (1)$$

where Δ_{SW} is the change in soil water content, P is the precipitation, Q_{SURF} is the surface runoff out of the watershed, ET is the evapotranspiration, W_{SEEP} is the percolation from the soil profile and Q_{GW} represent the transmission losses from the streams. All parameters are expressed in (mm) over the watershed area.

SWAT provides two methods for estimating surface runoff: the SCS Curve Number (CN) procedure (USDA Soil Conservation Service, 1972) and the Green & Ampt infiltration method (Green and Ampt, 1911). The SCS CN method was selected for runoff computation in the present model. The SCS runoff equation is an empirical model that was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types (Rallison and Miller, 1982). The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions. Typical curve numbers for moisture condition II (CN2) are listed for various land covers and soil types by the SCS Engineering Division (SCS, 1986).

To show the SWAT modeling response to LU changes, especially before and after the first Tunisian SWSC was implemented between

1990 and 2004, two SWAT models were constructed with a daily time step. The first model, representing the state before the SWSC (1971–1990), was used for calibration, while the second model (1990–2020) was used for validation. This separation was chosen to consider the two periods pre- and post-SWSC and based on the availability of observed runoff data.

2.3. SWAT input data

2.3.1. Climate data

In order to have a representative distribution of rainfall for the entire study area, 9 rain gauges' stations are considered: Beni khadech, Zammour, Halg Ejmel, Haraboub, Koutine, Loudayet, Ksar el Hallouf, Ksar Jedid and Ourgigin. Other climate data were obtained from the three nearest weather stations of the region which are the weather stations of Médenine, Beni Khedache and El Fje

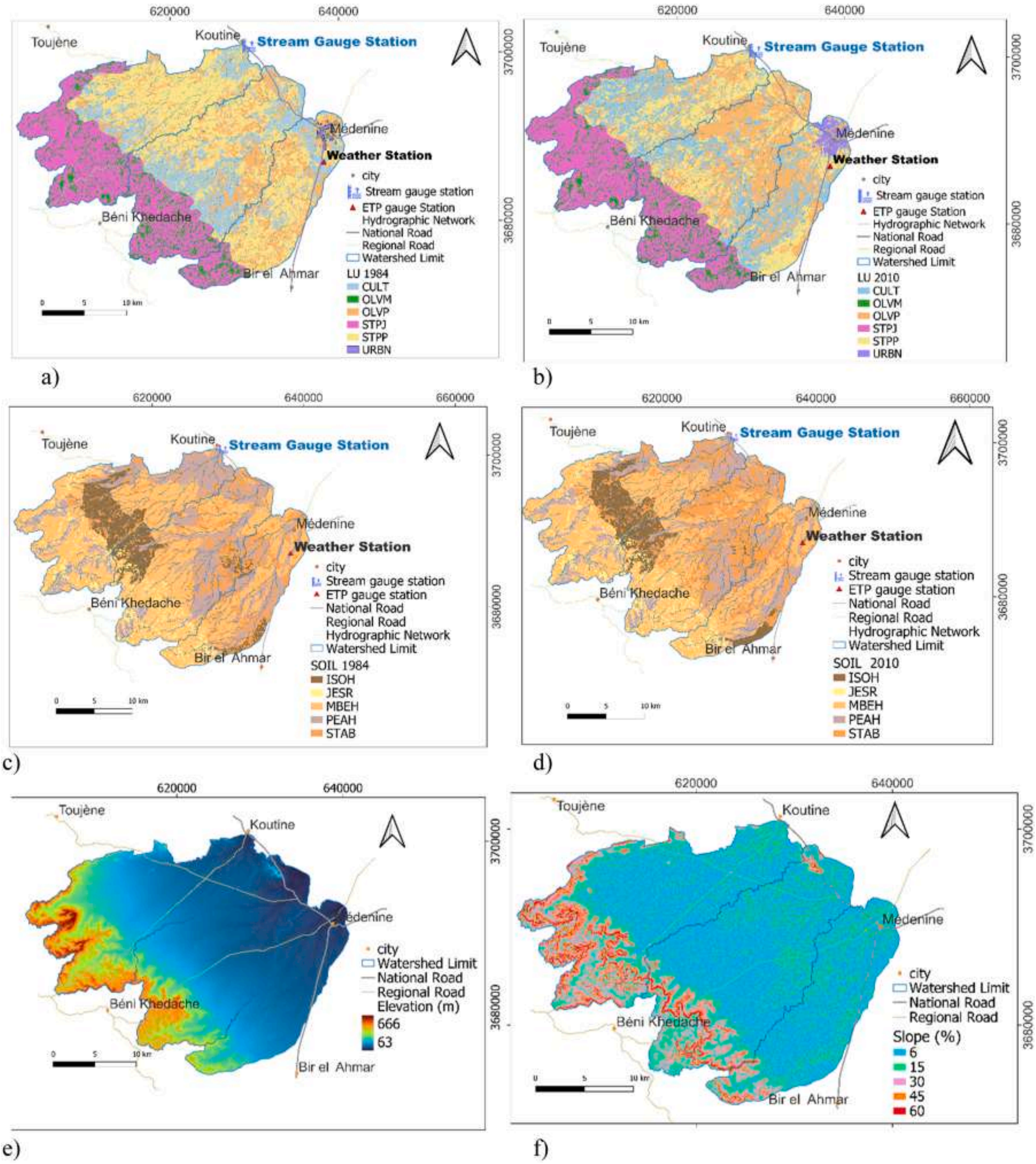

Fig. 3. Land Use map for the year 1984 (a) and for the year 2010 (b), processed by Essifi (2023) from Landsat TM images; Soil map for the year c) 1984 and d) 2010 and Study area elevation map (e) and slope map (f).

(IRA). The locations of the weather and rain gauge stations are shown in Fig. 2. Data from these stations were used for streamflow prediction and calibration purposes. The climatic variables used in SWAT modelling consist of precipitation, maximum and minimum air temperature, solar radiation, wind speed, and relative humidity. All variables were collected from the weather stations and the rain gauges of the studied region, except the solar radiation. The solar radiation data used in this study were sourced from the ERA5-Land database, available on the Copernicus Climate Data Store platform (CDS, 2023). SWAT includes the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climatic data or to fill in gaps in measured records. For this study, the weather generator was only used to fill missing climatic records. Daily PET records are collected from the weather station of Médenine to aid in the calibration procedure.

2.3.2. The land use and curve number data

The study area is primarily characterized by sparsely vegetated and degraded steppes. Agricultural lands are mainly dedicated to olive cultivation (*Olea europaea*), grown on terraces reinforced by water-harvesting structures. Cereals, such as barley (*Hordeum vulgare*) and durum wheat (*Triticum durum*), are cultivated intermittently during wet years. The rangelands, classified as arid, consist of a diverse mix of grasses and low-growing shrubs, providing limited but essential grazing resources (Ouessar, 2007; Ouessar et al., 2009).

Further refining the classification of natural vegetation, (Ouessar, 2007) and (Ouessar et al., 2009) distinguished between mountain and plain vegetation types, highlighting their distinct phenological characteristics and grazing practices. They categorized, so, land use into specific classes, which remain applicable in the present study. These classes include: **CULT**: Cereal cultivation, **OLVM**: Olive orchards on mountainous terraces (*jessour*), **OLVP**: Olive orchards on plains (*tabias*), **STPJ**: Mountain rangelands, and **STPP**: Plain rangelands (Ouessar, 2007; Ouessar et al., 2009). Their spatial distribution in the present study area is illustrated in Fig. 3. To determine the CN, (Ouessar, 2007) and (Ouessar et al., 2009) referenced the SCS table (SCS, 1986), based on soil hydrologic groups and land use. In the present work, the CN values adopted are those proposed by (Ouessar et al., 2009), ensuring consistency with previous studies in the region. Additionally, a small area was added to represent the urban zone in the city of Médenine: **URBN**.

The objective of this work is to show the SWAT modeling response to LU change, especially before and after the first Tunisian SWSC (1990–2004). For this purpose, two LU maps were prepared from Landsat TM imagery (USGS, 2021) acquired on September 22, 1984, and May 9, 2010 with 30-meter spatial resolution. The images were processed by Essifi (2023, unpublished data) using supervised classification with the CART algorithm implemented in Google Earth Engine. The training data were derived from the land use map of (Ouessar et al., 2009). Post-classification processing included GIS-based geoprocessing techniques such as pixel smoothing and clumping. Class recognition was validated against ground truth data.

2.3.3. The soil data

Soil classes were obtained from the soil map of the Jeffara region (Taamallah, 2003). However, the soil map does not identify the soils accumulated behind the water-harvesting units. Therefore, a modification of this map was done by (Ouessar, 2007) and (Ouessar et al., 2009). The soil map was modified to take into account sediments deposited behind the water-harvesting units. 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 (Ouessar, 2007; Ouessar et al., 2009). In addition to the soil textural properties, SWAT model requires different physicochemical properties such as available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. The texture and organic matter of all encountered soils were determined by (Ouessar, 2007) and (Ouessar et al., 2009) using standard laboratory analysis. Both the water characteristics calculator and the measured field, capacity and wilting point, of the jessour and tabias'soils were used to define the missing characteristics of the soil (Ouessar, 2007; Ouessar et al., 2009). In summary, (Ouessar, 2007) and (Ouessar et al., 2009) identified eight type of soil, they provided their characteristics and they are: **MBEH** (Minéraux Bruts d'Erosion Hydrique, Regosols); **PEEH** (Peu Evolués d'Erosion Hydrique, Regosols); **PEAH** (Peu Evolués d'Apport Hydrique, Fluvisols); **CRCG** (Calcimagnésiques sur Rendzine Calcalire, Rendzinas); **ISOH** (Isohumiques Bruns Calcaires Tronqués, Xerosols); **AFFL** (outcropping); **JESR** (soil on the terraces of Jessour) and **STAB** (Soil on the terraces of Tabias) (Ouessar, 2007; Ouessar et al., 2009); only 5 classes are used in this study.

In the present work, the adopted soil map was obtained by merging the official agricultural map of Médenine with the OLVM and OLVP classes from the LU map, to implement agricultural activities taking place on the Jessour and Tabias for the years 1984 and 2010, before and after the SWSC strategy. The resulting two soil map are distributed as follows in the Fig. 3.

2.3.4. The digital elevation model

The DEM for the study area was obtained from the SRTM (Shuttle Radar Topography Mission) with 30-meter resolution (USGS / NASA, 2000). It was used to derive slope and elevation attributes of the study area, which are presented in Fig. 3. The minimum elevation in study area is 63 m; the maximum one is about 660 m and the mean one is 230 m. The study area is a plain where most of the slopes are below 6 %.

The main channel network, which defines subbasin separation, was created using the TauDEM tool (Tarboton, 2005) integrated in the SWAT model. This tool extracts hydrologic information from the DEM. Based on this, 71 subbasins were delineated. Three manually defined outlets represent the final points of the hydrographic network for the three watersheds. The DEM was used to delineate watersheds and extract drainage patterns. Subbasin parameters, such as area, elevation, slope, slope length, and stream characteristics (slope, length, depth, and width) were derived from the DEM.

2.4. Calibration and validation limitations

The study area presents data limitations; in fact, there is only one streamflow gauging station at the outlet of the Koutine watershed, while the other watersheds lack any stations. Consequently, the calibration was performed using the Koutine watershed as a reference, and the optimized parameters were subsequently extended to the Gattar and Médenine watersheds, assuming similar hydrological behavior and climatic conditions.

The calibration relied solely on streamflow data from the Koutine station, while PET observations were used only as an independent verification step. To evaluate the robustness of the extended model, the comparison between simulated and observed PET values (measured at the Médenine meteorological station in the Médenine watershed using a Piche Evaporimeter) was used as an independent verification step. This additional check helped assess the model's ability to reproduce regional evapotranspiration dynamics and ensure overall water balance consistency across the three watersheds model.

The runoff gauging station "Koutine Cassis GP1" 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). It uses a float-type limnograph. The location of the Stream flow gauge station is shown in Fig. 2. (Fersi, 1985) provided data for 38 runoff events occurring from September 1973 to April 1985. For each event, he reported the runoff depth (mm), peak flow, and event duration (hours), along with an isohyet map based on daily rainfall data. Of the 38 events, a total of 66 daily records were used. The two largest runoff events occurred on December 12–13, 1973, and March 4–5, 1979. Only seven records showed runoff exceeding 5 mm (10 % of the total), with maximum values of 42 mm in 1979 and 30 mm in 1973. The discharge data were also reported in m^3 /s in the official annual reports of the DGRE. In addition, these reports include measurements collected in 1990, 1992, and eight additional measurements in 1995.

Flow records reveal significant variability and scarcity, posing a major challenge for calibration in arid environments with intermittent wadis. Of the total measurements, 41 entries (59 %) recorded flows below 1 m^3 /s, 15 records (22 %) ranged between 1 and 5 m^3 /s, 9 records (13 %) fell between 5 and 20 m^3 /s, and only 4 records (6 %) exceeded 20 m^3 /s. The highest recorded flow was 131 m^3 /s in 1979, during an event that peaked at 1475 m^3 /s. This uneven distribution of data, dominated by low-flow conditions with a few extreme events, complicates model calibration and increases uncertainty. Fig. 4 gives a clear idea of the scarcity, weakness, and irregularity of the observations, highlighting the challenges of the calibration process and the importance of complementary PET-based verification.

2.5. Integrating management operations in SWAT modelling

Agricultural practices are mainly recorded in the HRU management file (.mgt), which includes data on crop activities (planting, harvesting), irrigation, fertilizer and pesticide applications, and tillage operations. This file is divided into two sections: one defining initial conditions and constant management practices, and the other outlining the schedule of management operations throughout the simulation (Arnold et al., 2012). Table 1 gives the LU, the year, the month and the starting day when operations take place. It also provides the management operation and The SCS curve number for the operation (CNOP). The CN can be updated during plant, tillage, and harvest/kill operations. Once a CNOP value is defined, it replaces CN2 from that operation onward for moisture condition II. For the irrigation operation, the timing is scheduled, and the details are provided in the next section.

2.6. Modelling the impact of WHTs on groundwater recharge

Various methods have been developed to quantify groundwater recharge, including both direct measurements and indirect approaches. Hydrological modeling is also widely used to estimate recharge, particularly in data-scarce regions, as it allows for spatially and temporally distributed assessments under different scenarios. However, all these approaches carry inherent uncertainties related

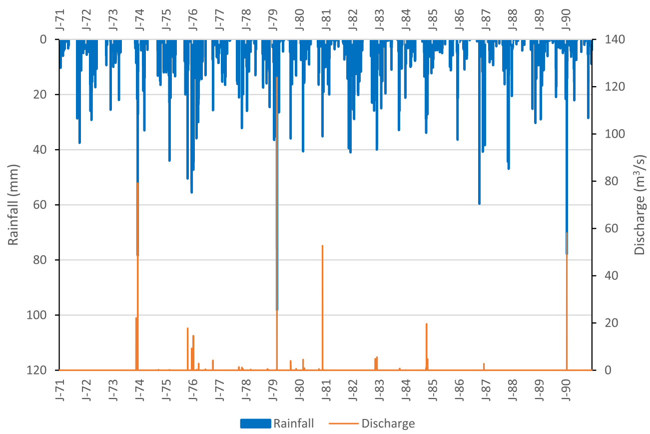

Fig. 4. Average annual rainfall observed at all stations (mm) Vs observed Discharge (m^3/s) for the calibration period (1971–1990).

Table 1
Management operations considered in the SWAT model.

LU	YEAR	MONTH	DAY	MGT_OPERATION	CNOP
CULT	1	1	1	tillage operation	84
CULT	1	5	1	tillage operation	91
CULT	1	11	1	tillage operation	87
CULT	1	6	1	harvest and kill operation	91
CULT	1	12	1	planting/beginning of growing season	87
CULT	1	12	1	auto fertilization initialization	87
OLVM	1	1	1	tillage operation	30
OLVM	1	5	1	tillage operation	30
OLVM	1	12	15	harvest only operation	30
OLVM	Scheduled	Scheduled	Scheduled	irrigation operation	30
OLVP	1	1	1	tillage operation	30
OLVP	1	5	1	tillage operation	30
OLVP	1	12	15	harvest only operation	30
OLVP	Scheduled	Scheduled	Scheduled	irrigation operation	30
STPJ	1	7	1	grazing operation	84
STPP	1	7	1	grazing operation	87

to data availability, parameter estimation, and the natural heterogeneity of soils and aquifers. The recharge estimates presented in this study should therefore be considered indicative rather than absolute. No direct measurements of groundwater recharge are available, and recharge was not used as a calibration target. Furthermore, only a single gauging station exists in the Koutine watershed, and discharge observations are limited in time. As a result, the uncertainty of the simulated recharge cannot be directly quantified. In the future, installing flowmeters in the recharge wells of the study area could provide direct measurements of infiltration, enabling a more accurate calibration of recharge and a quantitative assessment of its uncertainty. Despite these limitations, the model provides a first-order assessment of potential groundwater replenishment and the relative impact of water-harvesting techniques under current conditions.

The simulation of WHTs in the SWAT model follows the approach described by (Ouessar, 2007) and (Ouessar et al., 2009). In this setup, specific HRUs were defined to represent the main types of WHTs used in the study area (Jessour and Tabias) based on their associated land use (OLVM and OLVP) and soil characteristics (JESR and STAB).

The irrigation-from-reach option in SWAT was used to simulate the redirection of runoff from the main channel toward the WHTs HRUs. The parameter FLOWFR defines the proportion of the runoff that is diverted to these HRUs, representing the harvesting efficiency of each system. The parameter DIVMAX was used to control the maximum height of water that can be impounded, accounting for physical barriers such as dikes, spillways, and slope (Ouessar, 2007; Ouessar et al., 2009). In the present study, the values of FLOWFR and DIVMAX are the same as those calibrated by (Ouessar, 2007) and (Ouessar et al., 2009) based on local rainfall patterns, land use, and WHTs design. A conceptual schematic (Fig. 5) has been added to illustrate how FLOWFR and DIVMAX emulate the field processes of water harvesting and infiltration in Jessour and Tabia structures. The model ensures realistic simulation of water distribution across these HRUs. Any excess water flows downstream and may be subject to transmission losses in the main reach (wadi).

Since the wadis are intermittent and runoff events are rare, a historical irrigation schedule was introduced to identify potential

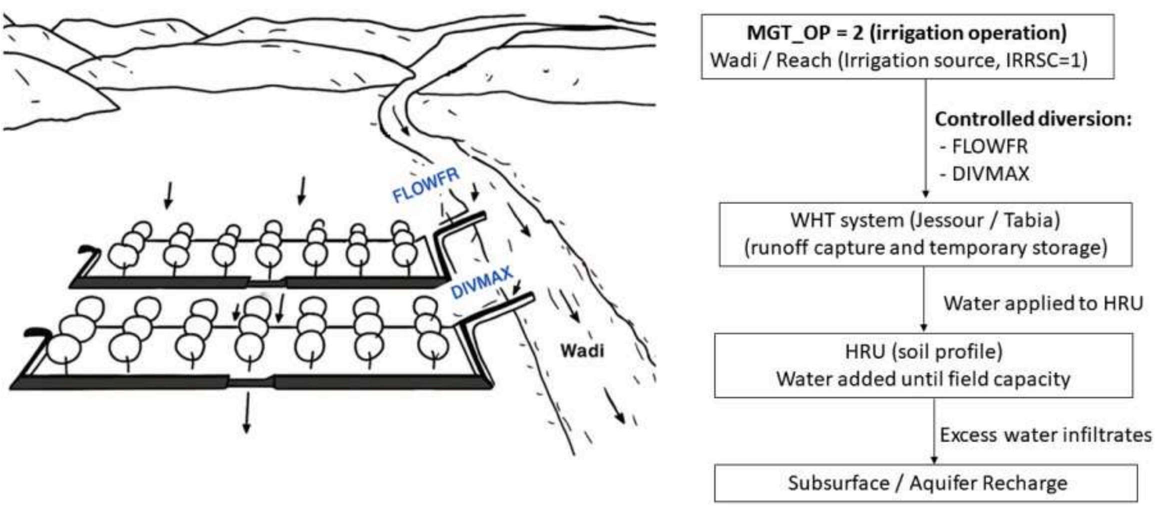

Fig. 5. Conceptual diagram of WHTs representation in SWAT (adapted from Ouessar et al. 2007). DIVMAX: maximum diversion equals the spillway height of the water harvesting unit, FLOWFR: Flow fraction.

water-harvesting periods, based on significant rainfall events during the entire simulation period (1971–2020). This schedule was divided into two phases: 1971–1990 for calibration, representing pre-SWSC conditions, and 1991–2020 for validation, corresponding to post-SWSC conditions. The schedule defines potential irrigation timing, while actual water application is controlled by **MGT_OP = 2 in SWAT**, meaning irrigation is applied only when water is available and limited to what is needed to fill the soil profile to field capacity. This approach ensures realistic simulation, reflecting temporal variability in rainfall and hydrological constraints of intermittent wadis.

For the post-SWSC model (1991–2020), the same method: irrigation-from-reach option in SWAT (MGT_OP = 2**)**, using the FLOWFR and DIVMAX parameters as applied for Jessour and Tabias, was additionally employed to simulate gabion structures implemented during this strategy. Gabion locations were digitized from a 2012 satellite image (Google Earth Pro, 2012) and HRUs containing gabions were identified by overlaying HRU shapefiles with digitized gabion shapefiles.

On the other hand, during the post-SWSC simulation, recharge wells were represented as reservoirs, accurately reflecting their actual locations. The original QSWATRef2012 Access database was modified by adjusting the minimum and maximum reservoir input parameters**,** including the reservoir surface area, the volume of water required to fill the reservoir, and the hydraulic conductivity of the reservoir bottom, to ensure consistency between the recharge well characteristics and the model inputs. For calibration, an estimation of the potential recharge per well in the Oum Zessar arid area, Tunisia, was considered, which reported an average of approximately 98,000 m^3 /year per well for the Triassic aquifer (Carletti et al., 2019). Accordingly, the reservoir parameters in the present model were tuned to reproduce this average annual recharge for each well. In total, 13 recharge wells were incorporated into the model as part of the SWSC strategy.

2.7. Model performance evaluation criteria

For the evaluation of model performance, two statistical criteria were employed: The Nash–Sutcliffe efficiency (NSE), which measures the overall accuracy of the model by comparing the observed and simulated values; and the coefficient of determination (R^2), which quantifies the proportion of variance in the observed data that is explained by the model, providing a measure of its predictive power (Krause et al., 2005).

The “R^2” is defined as:

$$R^2 = \left(\sum_{i=1}^{n} (O_i - \overline{O}).(P_i - \overline{P}) \Big/ \sqrt{\sum_{i=1}^{n} (O_i - \overline{O})^2} . \sqrt{\sum_{i=1}^{n} (P_i - \overline{P})^2} \right)^2 \tag{2}$$

with “O” observed and “P” predicted values. The range of “R^2” lies between 0 and 1. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation.

The “NSE” is defined as:

$$NSE = 1 - \left(\sum_{i=1}^{n} (O_i - P_i)^2 \Big/ \sum_{i=1}^{n} (O_i - \overline{O})^2 \right) \tag{3}$$

The range of “NSE” lies between 1.0 (perfect fit) and $-\infty$. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model.

According to Moriasi et al. (2007, 2015), model performance related to streamflow daily simulation is considered satisfactory when NSE $\geq$ 0.5 and $R^2 \geq$ 0.6.

2.8. Sensitivity analysis, calibration, and validation

Since the Koutine watershed is the only subbasin with a runoff gauging station, and because the study area is relatively small (1.281 km^2) with fairly uniform physical characteristics, the calibration and validation were performed on this watershed. After calibration, the optimized parameters were applied to the entire study area, which includes the three watersheds of Koutine, Gattar, and Médenine.

The SWAT model was developed on a daily time step using intermittent observed discharge data from 1973 to 1996. Specifically, discharge data from 1973 to 1990 were used to calibrate the first Koutine model, representing the pre-SWSC period, with a simulation period from 1971 to 1990. The remaining observations were used to validate the second model, representing the post-SWSC period, with a simulation period from 1991 to 2020.

Uncertainty analysis was conducted using the Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour et al., 2004, 2007). Accurate model parameterization, a key component of calibration, requires a deep understanding of the hydrological processes within the studied system. Proper parameterization improves calibration efficiency, enhances model accuracy, and reduces prediction uncertainty. To determine appropriate parameter ranges under arid conditions, an initial manual calibration was performed. This step allowed the assessment of parameter sensitivity and their impact on the water balance. The final parameter selection was achieved after multiple calibration trials with adjustments to parameterization.

The SUFI-2 algorithm in the SWAT-CUP software package was used for model calibration, validation, sensitivity, and uncertainty analysis. Based on a Bayesian framework, SUFI2 quantifies the uncertainties through sequential and fitting processes. It considers parameter uncertainty from various sources, including input data, model structure, and measured data (Xue et al., 2013). The p-factor, the percentage of observed data bracketed by 95 % prediction uncertainty (95PPU), is used to quantify the degree of all uncertainties. The 95PPU is calculated at the 2.5 % and 97.5 % levels of the cumulative distribution of output variables using Latin hypercube sampling method (Abbaspour et al., 2004, 2007). The r-factor measures the average thickness of the 95PPU band relative to observed data variability. For streamflow, a p-factor > 0.7–0.75 indicates good calibration. Ideally, a p-factor of 1 and r-factor of 0 indicate a perfect fit (Abbaspour et al., 2004, 2007; Abbaspour, 2015; Abbaspour et al., 2018). Further model performance is assessed using R^2 and NSE. To allow comparison with previous recharge studies, an extensive set of parameters affecting the water balance was considered. A total of 24 parameters were taken into account, which are:

The parameter range was selected based on a detailed study and field recognition under arid conditions for some parameters, ensuring careful analysis from the beginning. Additionally, for other parameters, the ranges were tested through sensitivity analyses by performing manual calibrations to define its boundary limits.

Interestingly, some fixed choices in the SWAT model were made based on the initial field and hydrogeological reconnaissance of the study area. Specifically, setting Surface runoff lag time (SURLAG) = 1 means that the surface runoff generated in a subbasin is transferred directly to the outlet on the same day, without any delay or attenuation. The maximum value for the threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN) was assigned to cancel return flow, since no return flow occurs in the study case. Similarly, the maximum value for the parameter initial depth of water in the deep aquifer (DEEPST) and the minimum value for the initial depth of water in the shallow aquifer (SHALLST) were set to represent the absence of a shallow aquifer and the presence of a deep one. By assigning the maximum value to DEEPST.gw, the model indicates that the simulated groundwater reservoir, the Triassic Aquifer of Sahel El Ababsa, is deep, with no shallow aquifer present. This setup accurately reflects the hydrogeological conditions of the study area, where only a deep aquifer serves as the primary groundwater source. Consequently, only 20 parameters were left for calibration (Table 2).

3. Results

3.1. Land use distribution in the study area and main changes

The Triassic aquifer of Sahel El Ababsa is recharged by the three watersheds of Koutine, Gattar, and Médenine. Table 3 provides the representation of each LU as a percentage of the total study area for each LU map (1984 and 2010). A comparative analysis of the two LU maps generated in this study reveals the following key changes associated with the implementation of the SWSC: the area covered by OLVP increased by nearly 40 %, CULT areas expanded by approximately 13 %, while OLVM areas remained largely unchanged.

3.2. Soil distribution in the study area and main changes

Initially, the Koutine, Gattar, and Médenine watersheds contained 14 % ISOH soil, 11 % STAB soil, 7 % JESR soil, 45 % MBEH soil, and 23 % PEAH soil. In the second soil map, significant changes appear, particularly in the STAB soil, which represents 16 % of the study area, and the PEAH soil, which covers 20 % as shown in Table 4. These changes are consistent with the evolution of land use, especially the expansion of *tabias* and *jessour*. Indeed, soils under tabias (STAB) and jessour (JESR) have distinct hydrological and

Table 2
Considered parameters for calibration.

Parameters	Parameters Description
GW_REVAP.gw	Groundwater "revap" coefficient.
SOL_AWC(.).sol	Available water capacity of the soil layer.
SLSUBBSN.hru	Average slope length.
EVRCH.bsn	Reach evaporation adjustment factor.
SOL_Z(.).sol	Depth from soil surface to bottom of layer.
OV_N.hru	Manning's "n" value for overland flow.
GW_DELAY.gw	Groundwater delay
EPCO.hru	Plant uptake compensation factor.
CN2.mgt	Manning's "n" value for the main channel
REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur
SOL_K(.).sol	Saturated hydraulic conductivity
CANMX.hru	Max canopy storage
HRU_SLP.hru	Average slope steepness
FFCB.bsn	Initial soil water storage expressed as a fraction of field capacity water content
ESCO.hru	Soil evaporation compensation factor
RCHRG_DP.gw	Deep aquifer percolation fraction
CH_N2.rte	Effective hydraulic conductivity in main channel alluvium
ALPHA_BF.gw	Baseflow alpha factor
TRNSRCH.bsn	Fraction of transmission losses from main channel that enter deep aquifer
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium
GWQMN.gw	Treshold depth of water in the shallow aquifer required for return flow to occur
SHALLST.gw	Initial depth of water in the shallow aquifer
DEEPST.gw	Initial depth of water in the deep aquifer
SURLAG.bsn	Surface runoff lag time

Table 3
Evolution of the Land Use for the years 1984 and 2010.

Value	LULC Classes	SWAT code	Area (%)		Changes
			1984	2010	(%)
1	Cereal cultivation	CULT	17.4	19.5	+ 13
2	Olive orchards on mountainous terraces	OLVM	6.8	6.8	-
3	Olive orchards on plains	OLVP	20.3	28.9	+ 43
4	Mountain rangelands	STPJ	24.3	24.3	-
5	Plain rangelands	STPP	30.9	19.0	-39
6	Urban build up land use	URBN	0.3	1.5	+ 20

Table 4
Evolution of the Soils for the years 1984 and 2010.

Value	Soil Classes	SWAT code	Area (%)		Changes
			1984	2010	(%)
1	Isohumiques Bruns Calcaires Tronqués, Xerosols	ISOH	14	14	-
2	soil on the terraces of Jessour	JESR	7	7	-
3	Minéraux Bruts d'Erosion Hydrique, Regosols	MBEH	45	43	-11
4	Peu Evolués d'Apport Hydrique, Fluvisols	PEAH	23	20	-17
5	Soil on the terraces of Tabias	STAB	11	16	+ 46

physical properties, and their distribution shifts with the development of these WHTs.

3.3. HRUs distribution in the study area and main changes

The model built for the first phase (1971–1990) and for the entire study area (3 watersheds) includes 1096 HRUs, while the second model for the same area and for the period 1991–2020 includes 1144 HRUs. Fig. 6 shows the distribution of land use and soils for all HRUs in both models. It should be noted that the HRU definition in both models was based on the filtering method, using thresholds of 10 % for land use, soil, and slope.

3.4. Sensitivity analysis results of the Koutine watershed

A total of 20 hydrological parameters were considered in calibration using SWAT-CUP, as detailed in Table 5, which presents the parameters, their adjusted values, and the overall sensitivity results. It should be noted that the sensitivities given above are estimates of the average changes in the objective function resulting from changes in each parameter, while all other parameters are changing. This gives relative sensitivities based on linear approximations and, hence, only provides partial information about the sensitivity of the objective function to model parameters. In this analysis, the larger, in absolute value, the value of t-stat, and the smaller the p-value, the more sensitive the parameter (Abbaspour et al., 2004, 2007).

As mentioned in the previous section, a preliminary manual calibration was conducted to determine realistic parameter ranges under arid conditions and to constrain variation intervals according to field observations and literature data. This procedure allowed for a better definition of the parameter space and ensured physically meaningful ranges before applying the SUFI-2 algorithm. Consequently, the parameter ranges were well constrained, which explains the low t-statistic values and high p-values (~0.99) observed in Table 5. These values indicate a stable and robust calibration, with limited parameter uncertainty, rather than a lack of model sensitivity. The final parameter set achieved a consistent representation of watershed processes and produced a satisfactory

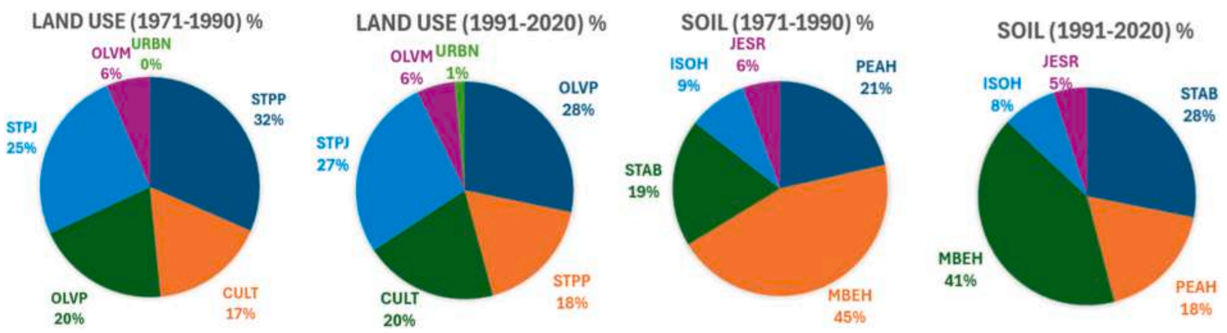

Fig. 6. Distribution of land use and soils in the two SWAT models.

Table 5
Sensitive parameters for daily flow and global sensitivity results.

Parameter name	Min_value	Max_value	Fitted_value	t-Stat	p-Value
V_GW_REVAP.gw	0	0.2	0.1374	0.000039354	0.999968617
R_SOL_AWC(.).sol	-0.5	0.3	0.2448	-0.000065028	0.999948142
R_SLSUBBSN.hru	-0.3	0.3	0.1326	-0.000113763	0.999909278
V_EVRCH.bsn	0.5	1	0.9055	0.000410606	0.999672556
R_SOL_Z(.).sol	-0.5	0.5	0.4430	0.000734141	0.999414549
V_OV_N.hru	0.01	0.03	0.0133	0.000778395	0.999379258
V_GW_DELAY.gw	0	12	5.0520	0.000935929	0.99925363
V_EPCO.hru	0.8	1	0.8886	0.00101854	0.99918775
R_CN2.mgt	-0.2	0.2	0.1056	-0.001301634	0.998961993
V_REVAPMN.gw	10	1000	361.4500	-0.001541961	0.998770341
R_SOL_K(.).sol	-0.5	0.5	-0.2690	-0.001615813	0.998711447
V_CANMX.hru	0	10	5.2300	-0.001821861	0.998547131
R_HRU_SLP.hru	-0.3	0.3	0.1146	-0.002421808	0.998068696
V_FFCB.bsn	0	0.3	0.0993	0.002820773	0.997750536
V_ESCO.hru	0	1	0.9810	0.003047795	0.997569495
V_RCHRG_DP.gw	0.2	1	0.2824	0.00351347	0.997198138
V_CH_N2.rte	0.025	0.033	0.0317	0.006951807	0.994456224
V_ALPHA_BF.gw	0.001	0.3	0.0312	-0.008813802	0.992971395
V_TRNSRCH.bsn	0.5	1	0.8275	0.010461238	0.991657684
V_CH_K2.rte	50	100	92.6500	0.033396428	0.973372487

* **V:** the existing parameter value is to be replaced by a given value and **R:** an existing parameter value is multiplied by (1 + a given value).

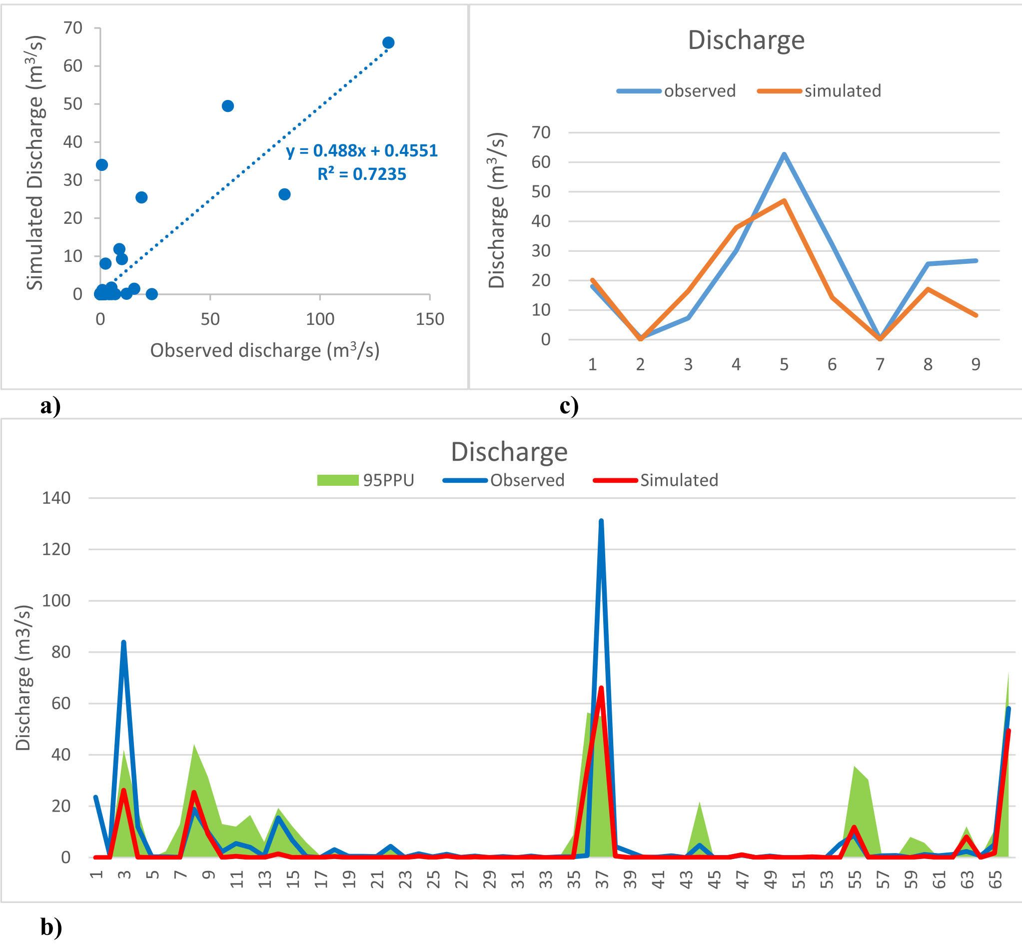

Fig. 7. Correlation diagram between simulated and observed data in the Koutine calibration model (a); Observed and Simulated daily discharge in the Koutine watershed for the calibration period (m^3/s) (b) an Observed and Simulated daily discharge in the Koutine watershed for the validation period (m^3/s).

agreement between simulated and observed discharges, confirming the reliability of the model configuration for arid hydrological conditions.

3.5. Evaluation of hydrological model performance in the Koutine watershed

As previously mentioned, the calibration was carried out on the model of the Koutine watershed, which is the only subbasin in the Médenine region equipped with a gauging station. The calibrated parameters were then extended to the entire study area, encompassing the three watersheds. Accordingly, a standalone model of the Koutine watershed was first constructed for calibration purposes. The simulation period for this calibration extends from 1971 to 1990, representing the pre-SWSC period.

Model performance was evaluated using R^2 and NSE. While higher values of these criteria were obtained, they did not fully capture the specific characteristics of the study area. Instead, the selected calibration result, although not yielding the highest statistical performance, provided a more realistic representation of the region's hydrological behavior. The resulting R^2 is 0.72, and the NSE is 0.63. A p-factor of 0.45 and r-factor of 0.43 are obtained.

The validation procedure using SWAT-CUP consists of comparing simulated outputs from the calibrated SWAT model with observed discharge data from a separate validation period. This process ensures the model's robustness and predictive capability. In this study, only nine discharge observations were available for validation (one in 1992 and eight in 1995) which limits the evaluation period but still allowed for a meaningful assessment. Model performance was evaluated using standard statistical indicators, including the R^2 and the NSE. The model achieved an R^2 of 0.69 and an NSE of 0.62, indicating satisfactory agreement (Legates and Mccabe, 1999; Moriasi et al., 2007). These results confirm that the model is reliable for simulating hydrological processes and suitable for further analysis. Fig. 7 shows the correlation between simulated and observed discharge during the calibration period, as well as the evolution of both series throughout the pre-SWSC and validation periods. The parameters calibrated at the Koutine watershed scale were then applied across the entire study area, which includes the three watersheds: Koutine, Gattar, and Médenine, each with a separate outlet.

Regarding the PET variable, available observations cover the period from March 1977 to December 2011. The meteorological station is located in the city of Médenine, within Subbasin 3, as shown in Fig. 2. The model covering the three watersheds was used to simulate PET. Using calibrated and fixed parameters, the model produced the following monthly PET simulation results. For the first model (1971–1990) the correlation between observed and simulated monthly PET is strong, with an R^2 of 0.79 and an NSE of 0.72. For the second model (1991–2020), the performance is better, with an R^2 of 0.82 and an NSE of 0.75. These results are illustrated in Fig. 8.

3.6. Study area water balance results

3.6.1. Water balance results of the pre-SWSC SWAT model (1971–1990)

The global water balance for the whole study area (three watersheds), based on an average precipitation of 194.5 mm yr^{-1} calculated over the 20-year calibration period (1971–1990), is distributed as follows: 74 % evaporation (ET), 5 % groundwater recharge, 21 % outflow. The calibrated parameters were then applied to the model for the period 1991–2020, corresponding to the post-SWSC implementation phase.

3.6.2. Water balance results of the post-SWSC SWAT Model (1991–2020) excluding Recharge Wells impact

For the 1991–2020 model, additional hydraulic structures were included to reflect the field conditions. Gabions were digitized from Google Earth Pro images and simulated using the irrigation option (MGT_OP = 2 option) in SWAT, similar to jessours and tabias. These structures modified the contributing and retention areas downstream. The digitized gabion structures cover a total area of approximately 360 ha, distributed as follows: 50 % in the Médenine watershed, 34 % in the Koutine, and 16 % in the Gattar.

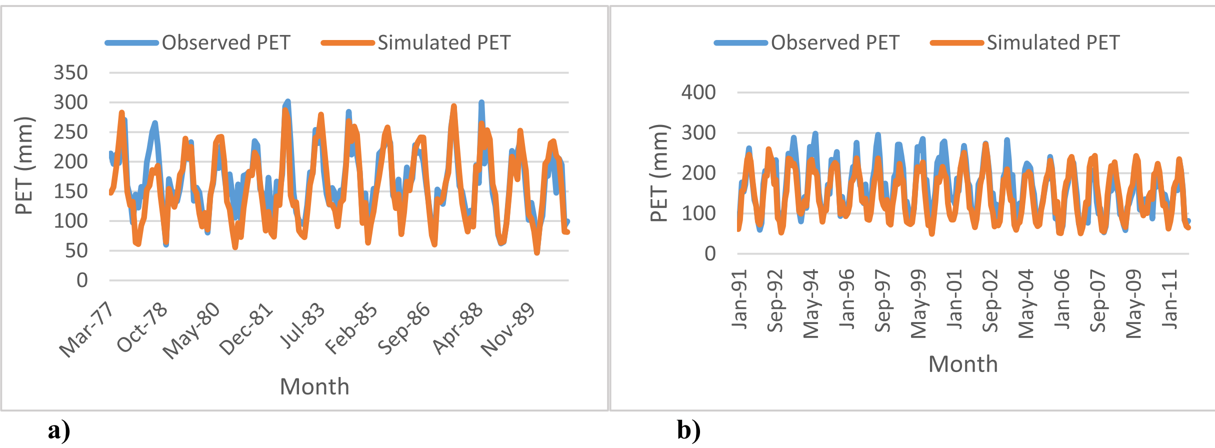

Fig. 8. Observed Vs Simulated PET during the pre (a) and post (b) SWSC period.

A total of 13 recharge wells were implemented during this SWSC strategy, distributed as follows: 10 in the Koutine watershed, 2 in Gattar, and 1 in Médenine. The reservoir seepage (output of the SWAT model) was considered as groundwater recharge in the present simulation. Since SWAT does not automatically include reservoir seepage in HRU water balance calculations, the corresponding recharge was manually added to the total water balance.

For the 1991–2020 period, the simulated global water balance for the three watersheds under an average annual precipitation of 174.9 mm yr^{-1} indicates: 82 % ET, 5 % groundwater recharge, and 13 % outflow. This result does not include recharge induced by the recharge wells. The average recharge simulated from the 13 recharge wells is 99,396 m^3 /year/well over the 30-year period.

Although land-use analysis revealed a 40 % expansion of OLVP areas after 1990, reflecting the rapid development of WHTs during the SWSC period, the simulated water balance for 1991–2020 shows a relative stability in recharge.

It is important to emphasize that these results exclude the contribution of recharge wells. This apparent stability in recharge could potentially be attributed to several interacting climatic and hydrological factors. Firstly, it is essential to acknowledge that the post-SWSC period experienced notable climatic changes, particularly during the last decades, characterized by an increase in temperature and a decrease in precipitation (Hadded et al., 2025). Specifically, the average annual precipitation decreased from 194.5 to 174.9 mm yr^{-1} , thus limiting the water available for recharge. Additionally, the increase in actual evaporation (from 74 % to 82 %) could have further limited the water available for infiltration and groundwater replenishment.

Conversely, the expansion of WHTs structures appears to have played a mitigating role, helping to maintain recharge levels despite these unfavorable climatic conditions. However, WHTs expansion may also have induced greater sediment deposition, reducing infiltration capacity while altering runoff dynamics. Overall, the apparent stability observed in the model results likely reflects a balance between the mitigating effects of WHTs expansion and climatic limitations, but does not include the additional recharge generated by the 13 recharge wells. Table 6 summarizes the water balance results from both SWAT models without accounting for well-induced recharge.

3.6.3. Water balance results of the post-SWSC SWAT Model (1991–2020) including Recharge Wells impact

Taking recharge wells into account, the present approach remains consistent with previous simulations, pending the availability of direct recharge measurements from these wells. The average flux simulated by SWAT is 99,396 m^3 /year/well, which closely agrees with the estimation reported by (Carletti et al., 2019) for the same Triassic aquifer in the Oum Zessar region (~98,000 m^3/year/well). The consistency between the simulated and reported values reinforces the reliability of the model setup and increases confidence in the representation of recharge wells in this study.

To express this discharge as a recharge depth (mm), it is necessary to normalize the volumes by the surface area of the subbasins hosting the recharge wells. As SWAT delineates the basin into subbasins, considering the area of each subbasin containing recharge wells allows spatial distribution of induced recharge. Based on the mean of the 13 recharge wells, the corresponding subbasin area is 669 ha, yielding an average induced recharge of 55 mm yr^{-1} over the 30-year simulation period. At the global scale of the aquifer, this represents an additional induced recharge of approximately 4 mm yr^{-1} over the same period.

When this contribution is integrated into the average water balance simulated by SWAT for the post-SWSC period (1991–2020), the groundwater recharge fraction increases from 5 % to about 7.2 % of total precipitation (under an average rainfall of 174.9 mm yr^{-1}), highlighting the impact of recharge wells at the aquifer scale. A more detailed assessment of recharge well performance, particularly during wet years, will be undertaken following the installation of flowmeters to measure the actual flow (infiltration) from the recharge wells into the aquifer.

3.6.4. Distribution of the main water balance components

The SWAT model enabled the visualization of key components of the water balance. Fig. 9, illustrates the spatial distribution across the entire study area of SURQ (mm), which represents the runoff depth, precipitation, PET, and ET, averaged over the two analyzed periods (before and after the implementation of the SWSC). The recharge will be discussed in the following section.

4. Discussion

Accurately quantifying the rate at which precipitation infiltrates the soil and percolates into deeper layers to recharge groundwater aquifers remains a significant challenge. This process is strongly influenced by the spatial and temporal distribution of rainfall, as well as by climatic, hydraulic, and pedological conditions. Although southern Tunisia is characterized by an arid climate, episodic rainfall events can still generate significant recharge. In many cases, rainwater accumulates in wadis, where localized infiltration through the riverbed allows for aquifer recharge. In such contexts, WHTs can significantly enhance recharge, particularly in well-managed areas.

Early studies attempted to estimate groundwater recharge using simple infiltration coefficients. For example, (Teissier, 1970)

Table 6
Simulated water balance using SWAT model without considering recharge wells.

	Pre-SWSC period (1971–1990)	Post-SWSC period (1991–2020)
ET (%)	74	82
Recharge (%)	5	5
Outflow (%)	21	13

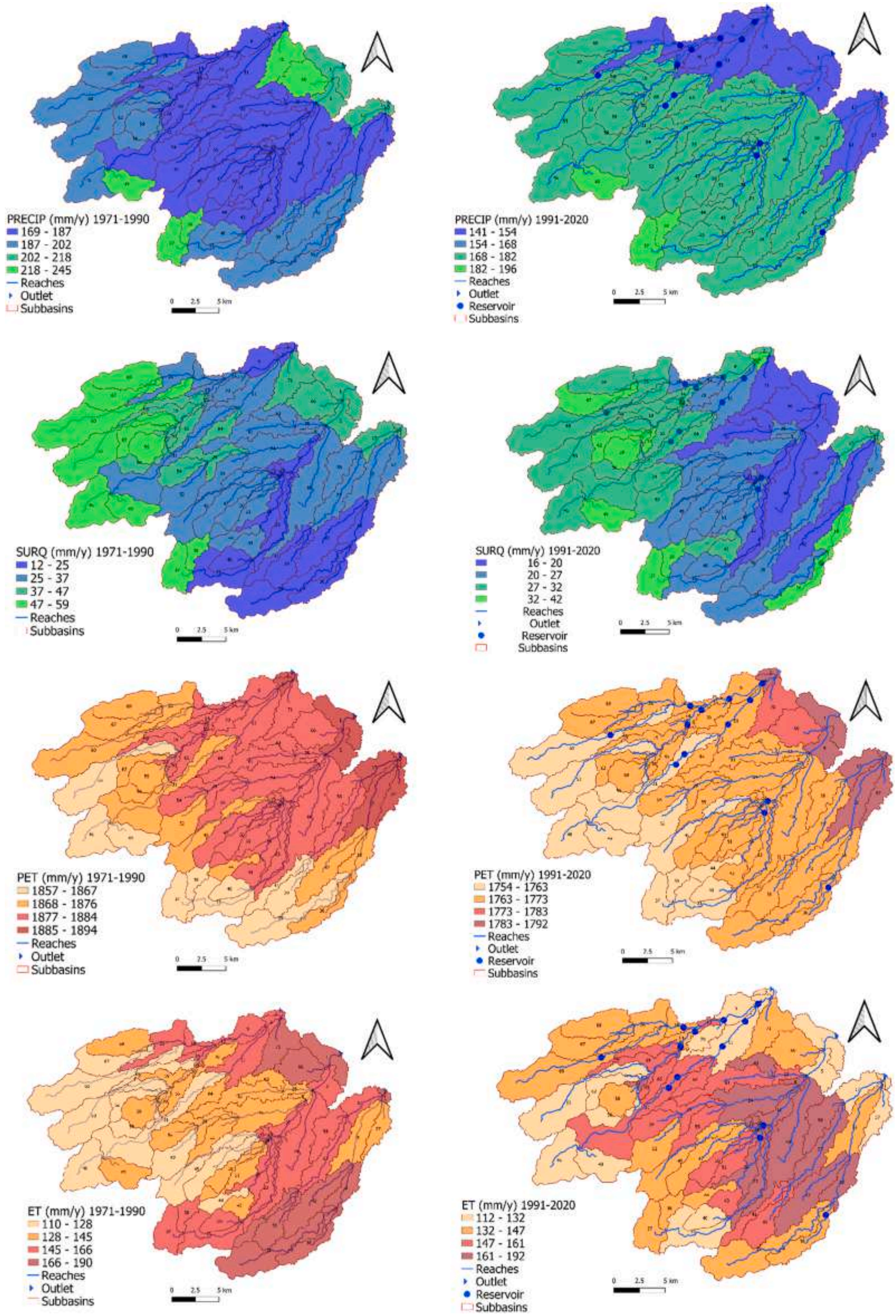

Fig. 9. Spatial distribution of PRECIP, SURQ, PET, and ET (mm yr^{-1}) before and after the implementation of the SWSC.

assumed an average annual rainfall of 200 mm and applied an infiltration coefficient of 10 % for the Dahar region (Teissier, 1970). Under these conditions, an infiltration coefficient of 5–10 % was applied to the Continental Intercalaire aquifer (UNESCO, 1972). Ben Baccar (1987) estimated direct rainfall infiltration with an average annual precipitation of 180 mm yr^{-1} and an infiltration coefficient of 5 % (Ben Baccar, 1987). Mansouri (1988), on the other hand, considered an average precipitation of approximately 100 mm yr^{-1} , assuming a 10 % infiltration coefficient (Mansouri, 1988). Similarly, Yahyaoui (1996) estimated an infiltration coefficient of 2.2 % for an average annual rainfall of 70 mm yr^{-1} (Yahyaoui, 1996).

However, it is crucial to discuss the recharge phenomenon. Groundwater recharge is composed of two main components: direct recharge and indirect recharge. Direct recharge occurs as rainfall infiltrates through the soil profile, whereas indirect recharge is primarily driven by surface runoff that infiltrates through fractures, joints, puddles, or through transmission losses during flood events in the wadi (Lerner et al., 1990; Maréchal et al., 2009). In arid regions, indirect recharge dominates, with the most significant recharge mechanism being infiltration from floods through the alluvial beds of ephemeral streams in wadi channels (Baba SY, 2005; Şorman et al., 1997). (Besbes, 2006) highlighted the important role of wadi floods in recharging aquifers in arid regions, noting that numerous studies on surface infiltration (transmission losses) show that, on average, 40–50 % of floodwater volumes infiltrate through the wadi bed (Besbes, 2006). Similarly, (OSS 2003a, 2003b) used infiltration coefficients of 2 % for direct recharge and 30 % of runoff for indirect recharge in its regional assessments of the Northern Sahara aquifers.

More recent studies in southeastern Tunisia reported recharge values that generally do not exceed 5–6 mm yr^{-1} . For example, Boughariou et al. (2016) estimated an average annual recharge of 5.5 mm yr^{-1} for the Sfax Aquifer System (southeastern Tunisia) (Boughariou et al., 2016). Similarly, in the Northern Gafsa Basin, recharge rates were estimated to not exceed 5.5 mm yr^{-1} (Mokadem et al., 2018a, 2018b). In the Jeffara of Médenine coastal aquifer system, (Hamzaoui et al., 2020) applied a direct recharge of 3 % of precipitation for model calibration, with an indirect recharge rate of 30 % of the runoff (Hamzaoui et al., 2020). For model calibration, a direct recharge equivalent to 2.4 % of total precipitation was applied, along with an indirect recharge through the wadi beds corresponding to 50 % of the runoff (Hadded et al., 2013; Hadded, 2015; Hadded et al., 2022, 2025).

In parallel with empirical coefficients, several studies have used runoff-based approaches. (Fersi, 1979) developed an empirical formula applicable to arid climates, linking runoff depth to rainfall and average watershed slope. Adjusted to experimental data points, Fersi's equation is expressed as follows (Fersi, 1979):

$$L_r = 0.017 \times P \times \sqrt{I_G} \tag{4}$$

Where Lr is the runoff depth (mm), P is the rainfall (mm) and I_G is the average watershed slope (m/km). (Fersi, 1976) found that runoff generally represents 4–6 % of annual precipitation in non-flood years and around 25 % in flood years (Fersi, 1976).

Mamou (1990) estimated that natural recharge in southern Tunisia varies between 2.5 % and 5 % of the average annual rainfall, with additional contributions equivalent to about 50 % of surface runoff (Mamou, 1990).

In our case study, this section discusses the recharge process within the Koutine watershed, which contains the only stream gauge station in the study area and was used for the calibration of the SWAT model. The available calibration period (1971–1990) is used, as it provides a greater number of observations, is sufficiently long to represent both dry and wet years, and ensures the most reliable simulation results.

An analysis of yearly recharge outputs generated by SWAT at the subbasin level (output.sub file) over the calibration period (1971–1990) revealed that SWAT-simulated recharge across subbasins ranged between 2 and 65 mm yr^{-1} , with an average value of 19.61 mm yr^{-1} , representing 10 % of the mean annual precipitation (195.5 mm yr^{-1}).

Further insights are obtained by examining the TLOSS (mm) output from the output.rch file, which represents indirect recharge through water loss in the oued beds. The TLOSS values ranged from 10 to 149 mm yr^{-1} across subbasins over the simulation period. The average TLOSS for all subbasins is 55 mm yr^{-1} , accounting for 28 % of the average SWAT precipitation (195.5 mm yr^{-1}).

It is important to note that SWAT employs the Thiessen Weighted Average Method to calculate precipitation in each subbasin. In this method, each weather station is assigned a specific area of influence, and the precipitation recorded at each station is weighted based on the proportion of its polygon that lies within each subbasin. Based on the arithmetic average precipitation over the 20-year period (134.2 mm yr^{-1}), the resulting recharge corresponds to approximately 41 %. These values are in close agreement with those reported in previous studies mentioned earlier in this section, which reinforces the consistency and reliability of the model results.

To assess the specific contribution of WHTs, the SWAT model was run without the irrigation option, which in this context simulates

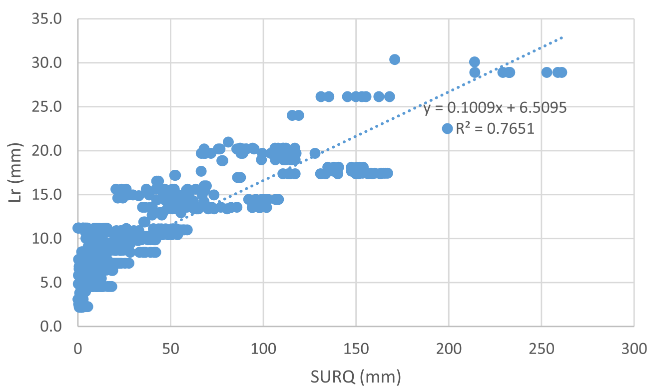

Fig. 10. Correlation between SWAT-simulated surface runoff depth (SURQ) and empirical runoff depth (Lr) calculated using the Fersi (1979) formula during the period 1971–1990.

the recharge induced by the WHTs jessour and Tabias. The results reflect the significance of these interventions: in fact, for the same average annual precipitation of 195.5 mm yr^{-1} , the recharge represents only 5 % of the rainfall. This result is well supported by all the studies previously mentioned in this section. This indicates that Jessour and Tabias contribute an additional 5 % recharge at the scale of the Koutine calibrated watershed.

To assess the reliability of SWAT's estimates against empirical approaches, we compared the model outputs with the Fersi formula, which is commonly applied in arid regions of southern Tunisia. For the entire Koutine watershed, using a mean annual precipitation of 195.5 mm yr^{-1} from SWAT and an average watershed slope (IG) of 11.1 m/km, the Fersi formula yields a runoff depth (Lr) of 10.7 mm yr^{-1} , corresponding to 5.5 % of the total precipitation. This runoff coefficient is very close to the range reported by (Fersi, 1976), between 4 % and 6 % of the average annual precipitation, thereby confirming the consistency of the model with empirical observations.

Fig. 10 shows the correlation between SURQ, the surface runoff depth simulated by SWAT, and Lr, the runoff depth calculated using the (Fersi, 1979) empirical formula. SURQ represents the amount of surface runoff generated in each HRU, expressed in millimeters, and is calculated using the SCS curve number method during the period 1971–1990. The figure demonstrates a strong correlation, with an R^2 of 0.76.

A more detailed analysis of HRU-level outputs (output.hru file) shows that for areas characterized by the STPP land use type, the average recharge across all subbasins and for the entire simulation period is 7.1 mm yr^{-1} . Since the STPP HRUs are distributed across all subbasins and SWAT uses the Thiessen method, the mean precipitation for this land use category is 188.9 mm yr^{-1} . Therefore, the recharge represents 4 % of this value. For the STPJ land use type, the mean precipitation is 203.4 mm yr^{-1} , while the recharge is 4 mm yr^{-1} , representing 2 % of precipitation.

Based on the Fersi formula, the corresponding Lr values are 10.3 mm yr^{-1} for STPP and 11.1 mm yr^{-1} for STPJ (both equivalent to about 5 % of the respective precipitation values). If 50 % of Lr is considered effective recharge, this results in 3 % of precipitation, which aligns closely with the recharge estimates produced by SWAT for STPP and STPJ (4 % and 2 %, respectively).

It is to note that the WHT structures are primarily located in the upstream areas, where they consist of jessour associated with the OLVM land use. In contrast, downstream areas are equipped with tabias, corresponding to the OLVP land use.

The recharge upstream, at the OLVM level, represents an average across all HRUs distributed over the upper sub-basins, with an average of 241.7 mm yr^{-1} , thus showing a recharge rate of 119 % of the estimated precipitation, which is 202.9 mm yr^{-1} .

The recharge downstream, at the OLVP level, represents an average across all HRUs distributed over the lower sub-basins, with an average of 304.5 mm yr^{-1} , thus showing a recharge rate of 161 % of the estimated precipitation, which is 188.5 mm yr^{-1} .

These results suggest that, in addition to direct rainfall, WHT systems efficiently capture and concentrate runoff from surrounding areas, thereby enhancing infiltration and resulting in recharge levels that exceed those expected from precipitation alone. The elevated recharge rates can be attributed to the cumulative effect of runoff being partially retained and redirected by the WHT structures, which increases the volume of water available for infiltration. These findings underscore the effectiveness of traditional WHT systems in boosting groundwater recharge, particularly in arid and semi-arid environments where maximizing water retention is essential.

5. Conclusions

This study assessed the impacts of land use change and MAR on groundwater resources in southeastern Tunisia using the SWAT model. By simulating two periods (pre-SWSC 1971–1990 and post-SWSC 1991–2020), the analysis highlighted the critical role of MAR techniques including traditional WHTs, gabions, and recharge wells, in enhancing groundwater recharge and improving water resource sustainability in arid environments.

The SWAT model was successfully calibrated and validated using limited but valuable data on streamflow and PET. Calibration results for discharge showed an R^2 of 0.72 and an NSE of 0.63, while validation yielded an R^2 of 0.69 and NSE of 0.62. For PET, the model achieved strong agreement with observations during the calibration period ($R^2 = 0.79$, NSE = 0.72), with moderate performance during validation ($R^2 = 0.82$, NSE = 0.75). These results confirm the robustness of SWAT in simulating hydrological processes in data-scarce arid regions.

The water balance for the entire study area during the pre-SWSC period (1971–1990), under an average annual precipitation of 194.5 mm yr^{-1} , was distributed as follows: 74 % ET, 5 % groundwater recharge, and 21 % surface outflow. In contrast, during the post-SWSC period (1991–2020), with a lower average annual precipitation of 174.9 mm yr^{-1} , the simulated water balance (without considering the impact of the recharge wells) was: 82 % for ET, groundwater recharge remained at 5 %, and surface outflow decreased to 13 %. When the effect of the recharge wells was included, groundwater recharge increased to 7.2 %.

Previous studies have estimated groundwater recharge using different approaches, but they consistently indicate that the recharge percentage ranges between 2.5 % and 10 % of annual precipitation. Additionally, average runoff rates have been evaluated at approximately 25 % of mean annual rainfall. To investigate the recharge process with precision in our study, we focused on the Koutine watershed, which contains the only available discharge observations in the region and was used as the calibration site for the SWAT model. Our analysis revealed that: The recharge during the pre-SWSC period, within the calibrated Koutine watershed, reached 10 % of average precipitation (19.6 mm yr^{-1}), aligning well with previous studies. Additionally, transmission losses (TLOSS), which represent indirect recharge through wadi beds, accounted for 41 % of precipitation, confirming their key role in arid-region recharge processes.

To isolate the effect of traditional WHTs, a SWAT model scenario excluding irrigation operations (which represent WHTs induced recharge) was compared with the full scenario. Results showed that recharge dropped to 5 % of precipitation in the absence of WHTs, indicating that these structures contributed an additional 5 % of recharge. At the land use level, the impact of WHTs was even more pronounced: HRUs under OLVP (tabias) and OLVM (jessour) land uses exhibited recharge rates of 161 % and 119 % of precipitation, respectively. This demonstrates the exceptional capacity of traditional WHT systems to concentrate and infiltrate runoff far beyond local rainfall inputs.

The strong correlation ($R^2 = 0.76$) between SWAT-simulated surface runoff (SURQ) and empirical estimates using Fersi's (1979) formula further confirms the model's accuracy in representing runoff behavior in arid Tunisia. Concerning the recharge wells MAR system, the average flux simulated by SWAT is estimated at 99,396 m^3 /year/well. This result is in close agreement with the estimation reported by previous studies for the same Triassic aquifer.

Overall, this study confirms the effectiveness of SWAT in simulating the complex interactions between climate, land use, and water management in arid regions. It also underlines the essential role of traditional WHTs and other MAR techniques such as gabion structures and recharge wells in enhancing groundwater recharge, especially in semi-arid and arid zones where water availability is a limiting factor for development. Traditional techniques like jessour and tabias, when well maintained and strategically implemented, provide a low-cost, nature-based solution to enhance resilience against water scarcity.

Despite these advances, the study remains constrained by limited hydrological observations (particularly for groundwater levels, wadi transmission losses, and recharge well monitoring) which introduces uncertainties that warrant future field-based validation.

Future research should aim to integrate climate change projections, socio-economic development scenarios, and more detailed field data into the modeling framework to support adaptive water resource management strategies. Additionally, exploring the long-term sustainability and sedimentation impacts of WHTs would further strengthen their integration into national water policies.

Beyond the local context, these findings demonstrate that a SWAT-based MAR assessment can be effectively applied at the national scale in Tunisia, which will be the focus of a forthcoming study. By simulating recharge induced by nature-based MAR systems under current and future climatic conditions, SWAT allows the evaluation of MAR effectiveness, identification of interventions most resilient to land use and climate variability, and quantification of groundwater response to different management scenarios. This provides decision-makers with concrete information to optimize MAR systems more broadly and allocate resources efficiently. Furthermore, the methodology is transferable to other arid and semi-arid regions in Africa, offering a framework to anticipate climate change impacts on groundwater resources and guide adaptive water management policies at larger scales. The ability of the model to operate effectively in data-scarce environments further emphasizes its relevance for scaling and planning resilient groundwater management across North Africa and the Sahel.

Author Contributions

Conceptualization, R.H., M.O. and F.A.; methodology, R.H., M.B.Z. and G.C.; software, R.H.; validation, R.H.; data curation, M.B.Z., M.O, F.A and B.E.; writing—original draft preparation, R.H.; writing—review and editing, R.H., G.C., and E.B.; management project, M.O., F.A., and M.B.Z.; All authors have read and agreed to the published version of the manuscript.

CRediT authorship contribution statement

Mohamed Ouessar: Project administration, Data curation, Conceptualization. **Elena Bresci:** Writing – review & editing. **Hadded Rym Rim:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Bouajila Essifi:** Data curation. **Fethi Abdelli:** Project administration, Data curation, Conceptualization. **Giulio Castelli:** Writing – review & editing, Methodology. **Mongi Ben Zaied:** Project administration, Methodology, Data curation.

Funding

This study was jointly funded by PRIMA project (SALAM-MED) from the European Union's Horizon 2020 Research and Innovation Program: no. 2131 and the Arid Regions Institute of Medenine IRA, Tunisia (Laboratory of Eremology and Combating Desertification: LR16IRA01).

Declaration of Competing Interest

The authors declare that they have no other competing interests.

Acknowledgments

We thank the officials of CRDA for providing the data necessary to complete this work. I also thank MO, FA and MBZ for their valuable advice.

Data availability

The data that has been used is confidential.

References

Abbaspour, K.C., 2015. SWAT-CUP: SWAT Calibration and Uncertainty Programs - A User Manual. Swiss Federal Institute of Aquatic Science and Technology (Eawag).

Abbaspour, K.C., Johnson, C.A., van Genuchten, M.Th, 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zone J. 3, 1340–1352. https://doi.org/10.2136/vzj2004.1340.

Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J., et al., 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. J. Hydrol. 333 (2), 413–430. https://doi.org/10.1016/j.jhydrol.2006.09.014.

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Kløve, B., 2015. A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model. J. Hydrol. 524, 733–752. https://doi.org/10.1016/j.jhydrol.2015.03.027.

Abbaspour, K.C., Vaghefi, S.A., Srinivasan, R., 2018. A guideline for successful calibration and uncertainty analysis for soil and water assessment: a review of papers from the 2016 International SWAT Conference. Water 6. ⟨https://www.mdpi.com/2073-4441/10/1/6⟩ (accessed 22 September 2025).

Abd-Elaty, I., Kuriqi, A., Ahmed, A., Ramadan, E.M., 2024. Enhanced groundwater availability through rainwater harvesting and managed aquifer recharge in arid regions. Appl. Water Sci. 14 (6), 121. https://doi.org/10.1007/s13201-024-02166-7.

Abdelkareem, M., Mansour, A.M., Akawy, A., 2023. Delineating the potential areas of rainwater harvesting in arid regions using remote sensing and GIS techniques. Water 15, 3592. https://doi.org/10.3390/w15203592 (accessed 21 September 2025).

Abdelli, F., 2017. Fonctionnement hydrologique pour l'aménagement d'un bassin versant aride moyennant l'adaptation du modèle SWAT: cas du bassin versant d'Oued Jir (Gabes). Phd, Institut National Agronomique de Tunisie. Ecole Doctorale Sciences et Techniques de l'Agronomie et de l'Environnement, 226pp.

Akoko, G., Le, T., Gomi, T., Kato, T., 2021. A review of SWAT model application in Africa. Water 13, 1313. https://doi.org/10.3390/w13091313.

Arnold, J., Srinivasan, R., Muttiah, R., Williams, J., 1998. Large area hydrologic modeling and asssement. PartI: Model development. J. Am. Water Resour. Assoc. 10 (34), 73–89.

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Neitsch, S.L., 2012. Soil & Water Assessment Tool: Input/Output Documentation. Version 2012. TR-439. Texas Water Resources Institute. ⟨https://swat.tamu.edu/documentation/⟩. Version 2012. TR-439.

Baba SY, M., 2005. Recharge et paléo-recharge du système aquifère du Sahara Septentrional. PhD (Thesis). Université de Tunis El Manar, p. 261 (Thesis).

Ben Baccar, B. 1987. Hydrogéologie des Matmatas. Direction générale des ressources en eau. Tunis, 70; 5 carte; 30cmpp. ⟨https://www.bibliotheque.nat.tn/KHNU/doc/SYRACUSE/690229/hydrogeologie-des-matmatas⟩ (accessed 21 September 2025).

Ben Salah, N.C., Abida, H., 2016. Runoff and sediment yield modeling using SWAT model: case of Wadi Hatab basin, central Tunisia. Arab. J. Geosci. 9 (11), 579. https://doi.org/10.1007/s12517-016-2607-3.

Besbes, M., 2006. Recharge des aquifères par les crues d'oueds. Front. Flood Res. / Le. Point De. la Rech. sur Les. crues 43–66.

Boughariou, E., Allouche, N., Jmal, I., Khanfir, H., Bouri, S. 2016. Impacts of climate change on water resources in arid and semi arid regions: case of Sfax region, Southeast Tunisia.

Bouraoui, F., Benabdallah, S., Jrad, A., Bidoglio, G., 2005. Application of the SWAT Model on the Medjerda River Basin (Tunisia). Phys. Chem. Earth Parts A/B/C. 30, 497–507. https://doi.org/10.1016/j.pce.2005.07.004.

Calderón, A.A., Escolar, D., Heider, G., Niborski, M.J., Jobbágy, E.G., Magliano, P.N., 2024. Rainwater harvesting technologies in arid plains of Argentina: small local strategies vs. large centralized projects. Front. Environ. Sci. 12. https://doi.org/10.3389/fenvs.2024.1486798.

Calianno, M., Fallot, J.-M., Ben Fraj, T., Ben Ouezdou, H., Reynard, E., Milano, M., Abbassi, M., et al., 2020. Benefits of water-harvesting systems (Jessour) on soil water retention in Southeast Tunisia. Water 12 (1), 295. https://doi.org/10.3390/w12010295.

Calianno, M., Ben Fraj, T., Fallot, J.-M., Abbassi, M., Ghram Messedi, A., Ben Ouezdou, H., Reynard, E., 2023. Upstream-Downstream Influence of Water Harvesting Techniques (Jessour) on Soil Water Retention in Southeast Tunisia. Water 15 (7), 1361. https://doi.org/10.3390/w15071361.

Carletti, A., Canu, S., Motroni, A., Ghiglieri, G., 2019. A combined methodology for estimating the potential natural aquifer recharge in an arid environment. Hydrol. Sci. J. 64 (14), 1727–1745. https://doi.org/10.1080/02626667.2019.1662422.

Castelli, G., Oliveira, L.A.A., Abdelli, F., Dhaou, H., Bresci, E., Ouessar, M., 2019. Effect of traditional check dams (*jessour*) on soil and olive trees water status in Tunisia. Sci. Total Environ. 690, 226–236. https://doi.org/10.1016/j.scitotenv.2019.06.514.

CDS, 2023. Copernicus Climate Change Service (C3S). ERA5-Land hourly data from 1950 to present. Copernic. Clim. Data Store (CDS). https://doi.org/10.24381/cds.e2161bac (accessed 21 September 2025).

Dai, A., 2011. Drought under global warming: a review. WIREs Clim. Change 2 (1), 45–65. https://doi.org/10.1002/wcc.81.

Dile, Y.T., Daggupati, P., George, C., Srinivasan, R., Arnold, J., 2016. Introducing a new open source GIS user interface for the SWAT model. Environ. Model. Softw. 85, 129–138. https://doi.org/10.1016/j.envsoft.2016.08.004.

El Amami, S., 1982. The traditional hydraulic structures in the Maghreb. ACSAD.

El Amami, S., 1984. Les aménagements hydrauliques traditionnels en Tunisie. Cent. De. Rech. En. Génie Rural (CRGR.

Fersi, M., 1976. Note sur le ruissellement de la plaine d'El Ababsa. DGRE.

Fersi, M., 1979. Estimation du ruissellement moyen annuel sur les bassins du Sud-Est, du Sud-Ouest et du Sahel Sud. Dir. G. éN.érale Des. Ressour. En. eau.

Fersi, M., 1985. Etude hydrologique d'oued Oum Zessar `a Koutine. Minist`ere De. l'Agric.

Gassman, P., Reyes, M., Green, C., Arnold, J., 2007. Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions, The. Trans. ASABE 50. https://doi.org/10.13031/2013.23637.

Gaubi, E. 1995. Synthèse hydrogéologique sur la nappe des Grès du Trias (Gouvernorats de Médenine et Tatouine). Rapport interne DGRE.

Glavan, M., Pintar, M. 2012. Strengths, Weaknesses, Opportunities and Threats of Catchment Modelling with Soil and Water Assessment Tool (SWAT) Model. https://doi.org/10.5772/34539.

Google Earth Pro, 2012. Google Earth Pro Satellite Image. ⟨https://earth.google.com⟩.

Green, W.H., Ampt, G.A., 1911. Studies on soil physics, 1. The flow of air and water through soils. J. Agric. Sci. 4, 11–24.

Hadded, R., 2015. ÉLABORATION D'UN SYSTÈME D'AIDE A LA DÉCISION POUR UNE GESTION DURABLE DES RESSOURCES EN EAU DANS LE BASSIN VERSANT DE ZEUSS KOUTINE. Inst. Natl. Agron. De. Tunis. 180. https://doi.org/10.13140/RG.2.2.10543.14242.

Hadded, R., Nouiri, I., Alshihabi, O., Maßmann, J., Huber, M., Laghouane, A., Yahiaoui, H., et al., 2013. A decision support system to manage the groundwater of the Zeuss Koutine aquifer using the WEAP-MODFLOW framework. Water Resour. Manag. 27. https://doi.org/10.1007/s11269-013-0266-7.

Hadded, R., Nouiri, I., Jamila, T., 2022. Assessment of climate change impact on the Zeuss–Koutine aquifer (Tunisia) using a WEAP-MODFLOW DSS. Arab. J. Geosci. 15. https://doi.org/10.1007/s12517-022-09840-7.

Hadded, R., Zaied, M., Elkmali, F., Castelli, G., Abdelli, F., Khabir, Z., Zaied, K., et al., 2025. A decision support system for managed aquifer recharge through non-conventional waters in the south of the Mediterranean. Resources 14, 63. https://doi.org/10.3390/resources14040063.

Hamzaoui, F., Zammouri, M., Ameur, M., Sy, M., Moncef, G., Bouhlila, R., 2020. Hydrogeochemical modeling for groundwater management in arid and semiarid regions using MODFLOW and MT3DMS: A case study of the Jeffara of Medenine coastal aquifer, South-Eastern Tunisia. Nat. Resour. Model. 33. https://doi.org/10.1111/nrm.12282.

Janjić, J., Tadić, 2023. Fields of Application of SWAT Hydrological Model—A Review. Earth 4, 331–344. https://doi.org/10.3390/earth4020018.

Jarray, F., Hermassi, T., Mechergui, M., Zucca, C., Le, Q.B., 2023. Long-Term Impact of Soil and Water Conservation Measures on Soil Erosion in a Tunisian Semi-Arid Watershed. Land 12 (8), 1537. https://doi.org/10.3390/land12081537 (accessed 21 September 2025).

Krause, P., Boyle, D., Bäse, F., 2005. Comparison of different efficiency criteria for hydrologic models. Adv. Geosci. 5. https://doi.org/10.5194/adgeo-5-89-2005.

Krysanova, V., Arnold, J., 2008. Advances in ecohydrological modelling with SWAT - A review. Hydrol. Sci. J. 53, 939–947. https://doi.org/10.1623/hysj.53.5.939.

Legates, D., Mccabe, G., 1999. Evaluating the use of "Goodness-of-Fit" measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35, 233–241. https://doi.org/10.1029/1998WR900018.

Lerner, D.N., Issar, A., Simmers, I., 1990. Groundwater Recharge: A Guide to Understanding and Estimating Natural Recharge. Heise, p. 828.

Li, F.-R., Cook, S., Geballe, G., Jr, W., 2000. Rainwater Harvesting Agriculture: An Integrated System for Water Management on Rainfed Land in China's Semiarid Areas. AMBIO A J. Hum. Environ. 29, 477. https://doi.org/10.1639/0044-7447(2000)029%255B0477:RHAAIS%255D2.0.CO;2.
Mamou, A. 1990. Caracteristiques, evaluation et gestion des ressources en eau du sud-tunisien. thesis, Paris 11. ⟨https://theses.fr/1990PA112380⟩ (accessed 21 September 2025).
Mansouri, R., 1988. Extrême sud tunisien. Etude hydrogéologique du continental intercalaire. Etude Tome 2.
Maréchal, J.-C., Murari, R., Riotte, J., Vouillamoz, J.-M., Mohan Kumar, M.S., Ruiz, L., Sekhar, M., et al., 2009. Indirect and direct recharges in a tropical forested watershed: Mule Hole, India. J. Hydrol. 364 (3-4), 272–284. https://doi.org/10.1016/j.jhydrol.2008.11.006.
Mokadem, N., Redhaounia, B., Besser, H., Ayadi, Y., Khelifi, F., Hamad, A., Hamed, Y., et al., 2018b. Impact of climate change on groundwater and the extinction of ancient "Foggara" and springs systems in arid lands in North Africa: a case study in Gafsa basin (Central of Tunisia). Eur. Mediterr. J. Environ. Integr. 3 (1), 28. https://doi.org/10.1007/s41207-018-0070-0.
Mokadem, N., Boughariou, E., Mudarra, M., Ben Brahim, F., Andreo, B., Hamed, Y., Bouri, S., 2018a. Mapping potential zones for groundwater recharge and its evaluation in arid environments using a GIS approach: Case study of North Gafsa Basin (Central Tunisia). J. Afr. Earth Sci. 141. https://doi.org/10.1016/j.jafrearsci.2018.02.007.
Moriasi, D., Arnold, J., Van Liew, M., Bingner, R., Harmel, R.D., Veith, T., 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Trans. ASABE 50. https://doi.org/10.13031/2013.23153.
Moriasi, D., Gitau, M., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Trans. ASABE (Am. Soc. Agric. Biol. Eng.) 58, 1763–1785. https://doi.org/10.13031/trans.58.10715.
Mosbahi, M., Benabdallah, S., Boussema, R., 2012. Assessment of soil erosion risk using SWAT model. Arab. J. Geosci. 6. https://doi.org/10.1007/s12517-012-0658-7.
Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., King, K.W., 2002. Soil and water assessment tool theoretical documentation: version 2000. Texas Water Resources Institute.
Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., King, K.W., 2005. Soil and water assessment tool theoretical documentation: version 2005. Texas Water Resources Institute.
Olivera, F., Valenzuela, M., Srinivasan, R., Choi, J., Cho, H., Koka, S., Agrawal, A., 2006. ArcGIS-SWAT: A Geodata Model and GIS Interface for SWAT. JAWRA J. Am. Water Resour. Assoc. 42, 295–309. https://doi.org/10.1111/j.1752-1688.2006.tb03839.x.
OSS, 2003b. Système Aquifère du Sahara Septentrional: Hydrogéologie, volume II | Bienvenue à l'Observatoire du Sahara et du Sahel. Rapport interne. Coupes. Planches. Annexes, Projet SASS. ⟨https://www.oss-online.org/fr/releases/OSS-SASS_HYDROGEOLOGIE⟩ (accessed 21 September 2025).
OSS, 2003a. Système Aquifère du Sahara Septentrional: Volume 4 Modèle mathématique. Rapp. Interne Et. Annex. Proj. SASS. ⟨https://www.oss-online.org/fr/publications/OSS-SASS-IV-MOD-MATH_fr⟩ (accessed 22 January 2025).
Othman, D.B., Megdiche, M.F., Gueddari, M., 2021. Assessment of Management Practices Impact on the Water Quality of the Béja River Watershed Using SWAT Model. In: Ksibi, M., Ghorbal, A., Chakraborty, S., Chaminé, H.I., Barbieri, M., Guerriero, G., Hentati, O., et al. (Eds.), Recent Advances in Environmental Science from the Euro-Mediterranean and Surrounding Regions, 2nd Edition. Springer International Publishing, Cham, pp. 535–543. https://doi.org/10.1007/978-3-030-51210-1_85.
Ouessar, M., 2007. Hydrological impacts of rainwater harvesting in wadi Oum Zessar watershed (Southern Tunisia). Ghent University. ⟨http://hdl.handle.net/1854/LU-822910⟩ (accessed 21 September 2025).
Ouessar, M., Yahyaoui, H., 2000. Abstraction and recharge impacts on the ground water in the arid regions of Tunisia: Case of Zeuss-Koutine water table. UNU Desert Ser. N. ° 2.
Ouessar, M., Bruggeman, A., Abdelli, F., Mohtar, R.H., Gabriels, D., Cornelis, W.M., 2009. Modelling water-harvesting systems in the arid south of Tunisia using SWAT. Hydrol. Earth Syst. Sci. 13 (10), 2003–2021. https://doi.org/10.5194/hess-13-2003-2009.
Oweis, T., Hachum, A., 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agric. Water Manag. 80 (1), 57–73. https://doi.org/10.1016/j.agwat.2005.07.004.
Piemontese, L., Castelli, G., Fetzer, I., Barron, J., Liniger, H., Harari, N., Bresci, E., et al., 2020. Estimating the global potential of water harvesting from successful case studies. Glob. Environ. Change 63, 102121. https://doi.org/10.1016/j.gloenvcha.2020.102121.
Rallison, R., Miller, N., 1982. Present Future SCS runoff Proced(accessed 21 September 2025).
Rockström, J., Falkenmark, M., 2015. Agriculture: Increase water harvesting in Africa. Nature 519 (7543), 283–285. https://doi.org/10.1038/519283a.
Rockström, J., Barron, J., Fox, P. 2003. Water productivity in rain-fed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems. pp. 145-162. https://doi.org/10.1079/9780851996691.0145.
Schuol, J., Abbaspour, K.C., Yang, H., Srinivasan, R., Zehnder, A.J.B., 2008. Modeling blue and green water availability in Africa. Water Resour. Res. 44 (7), 2007WR006609. https://doi.org/10.1029/2007WR006609.
SCS, 1986. Urban Hydrology for Small Watersheds. In: Technical Release, 55. Department of Agriculture, U.S.
Sharpley, A.N., Williams, J.R., 1990. EPIC – Erosion Productivity Impact Calculator. 1. Model Documentation. Technical Bulletin 1768. U.S. Department of Agriculture, Agricultural Research Service.
Sheffield, J., Wood, E.F., Roderick, M.L., 2012. Little change in global drought over the past 60 years. Nature 491 (7424), 435–438. https://doi.org/10.1038/nature11575.
Şorman, Ü., Abdulrazzak, M., Morel-Seytoux, H., 1997. Groundwater recharge estimation from ephemeral streams. Case study: Wadi Tabalah, Saudi Arabia. Hydrol. Process. 11, 1607–1619. https://doi.org/10.1002/(SICI)1099-1085(19971015)11:12%253C1607::AID-HYP490%253E3.0.CO;2-Q.
Taamallah, H., 2003. Carte pédologique de la Jeffara. Rapport interne, projet Jeffara. IRA/IRD.
Tamagnone, P., Cea, L., Comino, E., Rosso, M., 2020. Rainwater harvesting techniques to face water scarcity in african drylands: hydrological efficiency assessment. Water 12 (9), 2646. https://doi.org/10.3390/w12092646 (accessed 21 September 2025).
Tarboton, D., 2005. Hydrology Research Group-Terrain Analysis Using Digital Elevation Models (TauDEM) Version 5. https://hydrology.usu.edu/taudem/taudem5/ (accessed 21 September 2023.
Teissier, J.L. 1970. Note sur l'alimentation éventuelle de la nappe du Continental intercalaire à partir du plateau du Dahar en Tunisie (Région de Béni Kaddèche, Chenini, Douirat, Dehibat). Note, DGRE.
Trabelsi, R., 2009. Caracterisation hydrogeologique et geochimique du systeme aquifere de la djeffara (sud-est tunisien): modelisation et intrusion marine. PHD L'Éc. Natl. D. 'Ing. énieurs De. Sfax 220.
Umugwaneza, A., Chen, X., Liu, T., Mind'je, R., Uwineza, A., Kayumba, P.M., Uwamahoro, S., et al., 2022. Integrating a GIS-based approach and a SWAT model to identify potential suitable sites for rainwater harvesting in Rwanda. AQUA Water Infrastruct. Ecosyst. Soc. 71 (3), 415–432. https://doi.org/10.2166/aqua.2022.111.
UNESCO, 1972. Etude des ressources en eau du Sahara septentrional. In: Plaquette No, 5. UNESCO.
USDA Soil Conservation Service, V., 1972. National Engineering Handbook. Section 4 Hydrology, p. 734.
USGS, 2021. Landsat 4-5 Thematic Mapper Level-1, Collection 2 (Dataset). U.S. Geological Survey. ⟨https://www.usgs.gov/centers/eros/science/usgs-eros-archive-landsat-4-5-thematic-mapper-collection-2⟩.
USGS / NASA, 2000. Shuttle Radar Topography Mission (SRTM) Digital Elevation Data, 30 m resolution. U.S. Geological Survey. ⟨https://www2.jpl.nasa.gov/srtm/⟩ (accessed 23 October 2023).
Xue, C., Chen, B., Wu, H., 2013. Parameter Uncertainty Analysis of Surface Flow and Sediment Yield in the Huolin Basin, China. J. Hydrol. Eng. 19, 1224–1236. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000909.
Yahyaoui, H., 1996. Etude hydrogéologique des aquifères du Piémont Oriental et du flanc Occidental du Dahar (Régions de Remada et de Déhibat). Phd Fac. Sc. De. Tunis. 171.
Yahyaoui, H., Chaieb, H., Ouessar, M., 2002. Impact Des. Trav. De. Conserv. Des. eaux Et. Des. sols sur la Recharg. De. la nappe De. ZeussKouti.