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### Research Article

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## Assessment of the SWAT model in simulating watersheds in arid regions: Case study of the Yarmouk River Basin (Jordan)

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Abstract: The Soil and Water Assessment Tool (SWAT) was used to simulate monthly runoff in the Yarmouk River Basin (YRB). The objectives were to assess the performance of this model in simulating the hydrological responses in arid watersheds then utilized to study the impact of YRB agricultural development project on transport of sediments in the YRB. Nine and three years of input data, namely from 2005 to 2013, were used to calibrate the model, whereas data from 2014 to 2015 were used for model validation. Time series plots as well as statistical measures, including the coefficient of determination  $(R^2)$  and the Nash–Sutcliffe coefficient of efficiency (NSE) that range between 0 to 1 and  $-\infty$  to 1, respectively, between observed and simulated monthly runoff values were used to verify the SWAT simulation capability for the YRB. The SWAT model satisfactorily predicted mean monthly runoff values in the calibration and validation periods, as indicated by  $R^2 = 0.95$  and NSE = 0.96 and  $R^2 =$ 0.91 and NSE = 0.63, respectively. The study confirmed the positive impact of soil conservation measures implemented in the YRB development project and confirmed that contouring can reduce soil loss from 15 to 44% during the study period. This study showed that the SWAT model was capable of simulating hydrologic components in the drylands of Jordan.

Keywords: soil and water assessment tool, Yarmouk watershed, watershed management, arid regions, hydrological model

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### 1 Introduction

Mathematical models play an important role in supporting land use planning with the aim of enhancing sustainable water quantity and quality management [1]. They are based on the water balance equation of the main components of the water cycle and incorporate physical and geomorphological watershed characteristics. Hydrological models are useful tools for managers, water resources planners, and academics in helping to understand complex hydrological and water quality processes at the watershed scale and as support tools for decisionmaking. Currently, hydrological models are used to forecast floods and droughts and for irrigation management, and monthly simulated discharges help to anticipate the effects of various land uses and soil management practices on water resources, sediment yield, and water quality [2,3]. To achieve these functions, the model must demonstrate that it can correctly simulate the hydrological processes and predict the hydrological responses of the studied watershed, such as floods, droughts, soil erosion, and water quality [4]. Among the various mathematical models currently used, the Soil and Water Assessment Tool (SWAT) has still been receiving considerable attention [4,5].

Researchers from the United States Department of Agriculture have developed, tested, and validated the SWAT model with adequate results for many watersheds in America [6,7]. Early works by American researchers have shown that the performance of the SWAT is satisfactory for various watershed types and sizes with  $R^2$ values ranging from 0.55 to 0.96, such as in the Seco Creek Basin in Texas (size of 114 km<sup>2</sup>) [6], Lower Colorado River Basin (8,927 km<sup>2</sup>) [8], Goodwin Creek watershed in Mississippi (21.31 km<sup>2</sup>) [9], Greenhill watersheds in Indiana (113 km<sup>2</sup>) [10], Rio Bravo Basin (598,538 km<sup>2</sup>) [11], and Ariel Creek watershed in Pennsylvania (39.5 km<sup>2</sup>) [12]. Since then, the model has been subjected to progressive improvements and modifications [13-15] to accommodate its application

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under various climate, data availability, and topographic conditions.

Model application in arid and semiarid regions is challenging owing to changes in the relative implications of various hydrological processes to runoff and water quality parameters compared to those in humid areas and owing to limited access to accurate data and reliable monitoring systems [16,17]. To simulate a watershed, the basic hydrology of the region must first be understood and then presented in mathematical relationships that reflect the actual hydrological conditions of the area. Currently, the SWAT is used to assess various objectives in watersheds worldwide. Gassman et al. presented a comprehensive overview for more than 250 cases of SWAT applications worldwide [18]. Moriasi et al. have used the model to assess the influence of agricultural management practices [19]; others have used it to identify sources of pollution and its fate [16,20], evaluate the impacts of climate change [21], evaluate the impact of dams on water balance [22,23], and measure the hydrology and sediment transfer in various catchments [24–26]. These model applications cover watersheds worldwide, including humid areas such as Northern Europe and Canada to a large extent [27,28], and arid countries such as southeast Africa [3], southern Australia [29], China [30], India [31], Pakistan [32], Iran [33], and Mediterranean coastal basin countries, i.e., Spain, France, Italy, Tunisia, and Algeria, to a limited extent [34-38].

The SWAT model is considered a practical and effective tool to improve water quality in land use planning. SWAT applications may include several processes, including surface runoff, evapotranspiration, irrigation and drainage, sediment transport, groundwater flow, crop growth and harvesting, nutrients yield, pesticides yield, and water flow, as well as the long term effects of different agricultural management practices [2,3]. The SWAT model has been widely applied to watersheds with moderate to high precipitation conditions and vegetation cover. However, to date, this model has not been thoroughly tested in arid and semiarid environments with long dry periods, short rainy seasons, and climate conditions that are characteristic of Jordan [18,39].

Jordan is an arid to semiarid country that suffers from both water shortages and increasing demand for water due to rapid population growth. It is considered among the poorest countries in the world with regard to water resources [40]. Its climate is mostly arid; over 91% of the total area of Jordan receives less than 200 mm of rainfall per year, 7% is considered semiarid land with an annual rainfall ranging from 200 to 300 mm, and approximately 2% of the land area, which is located in the northwestern

highlands, has an annual precipitation of 300 mm up to 600 mm. The rapid increase in population due to refugee flux, farming, and industrial development has placed heavy demands on water resources [31,41].

Arid and semiarid environments in Jordan are described by high temperature, sporadic and low average rainfall, and high intensity rain storms that result in a large amount of runoff, peak discharge, and erosion. Accelerated land degradation, which increases the risk of flooding in the valley (offsite impact), is being observed in Jordan [42]. Therefore, there is a need to test and validate the SWAT model in such an environment in order for it to be used for land and water management purposes.

Data availability is a considerable challenge for applying hydrological models in data scarce conditions. Most model applications correspond to case studies from humid countries with wide data availability, unlike the data scarcity typically encountered in developing countries [43]. Therefore, we tested the SWAT in a semiarid environment with data scarce, i.e., only one runoff station. The main objectives of this research were to test the SWAT's applicability in arid and semiarid environments and to identify the most significant parameters affecting the hydrological response of the Yarmouk River Basin (YRB).

## 2 Materials and methods

The SWAT model was adopted to simulate the Yarmouk River flow just before it enters the Jordan River (Figure 1), and thus represented the total river discharge of this river basin. Water allocation of the Yarmouk River flow has been the subject of intense political negotiations between Israel and Jordan and between Syria and Jordan since the 1950s. Accurate prediction of the Yarmouk River flow is necessary for all parties to help water managers and decision makers to better assess water allocation and management within their countries.

#### 2.1 Study area

The YRB is located in the northern part of Jordan, and the Yarmouk River marks the natural border between Syria and Jordan. The basin on the Jordan side is located between 32°20′N to 32°45′N and 35°42′E to 36°23′E and covers a region of around 1,426 km² (Figure 1). The YRB is one of the most important basins in Jordan because of its

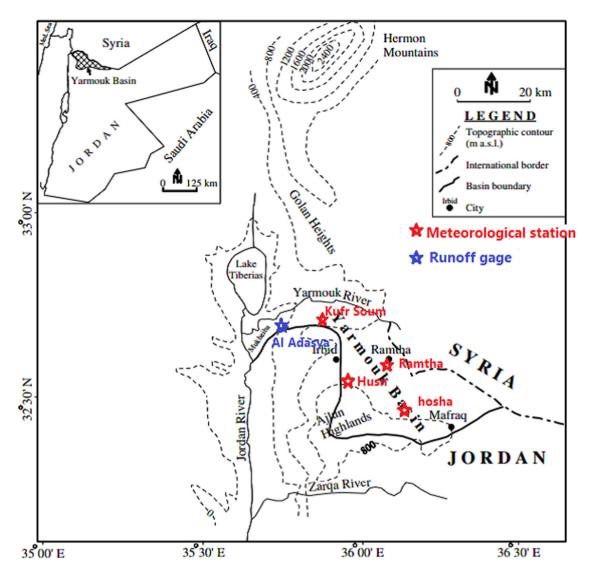


Figure 1: Location of the Yarmouk River Basin (YRB), meteorological stations, and Runoff gage station showing the basin's principal physiographic features.

large contribution to the annual water budget of the country. It receives most of its flow from the surrounding mountain areas, namely, the Ajloun Mountains in Jordan and Golan Heights in Syria. The Jordan River represents its western boundary (Figure 1). The Yarmouk River begins at Jabal Al-Arab in Syria and drains to the west to reach the Jordan River just south of Lake Tiberias. Syria and Jordan signed a bilateral treaty to share the Yarmouk River flow in 1987. In 2006, a major dam (Al-Wehda Dam) was built on the Yarmouk River to supply Jordan with around 110 million cubic meters (MCM) of potable water per year. However, a significant part of the flow of the Yarmouk River is diverted upstream by Syria, thereby decreasing the proposed share of water according to treaties and agreements to nearly one-third. In this study, we have not included the dam operation in our simulation

due to the fact that most of the river flow were allowed to pass downstream for irrigation and domestic uses. Currently, Jordan utilizes 290 MCM/year of water from both the Jordan River and Yarmouk River and diverts it to the King Abdullah Canal to be utilized for the irrigation of crops in the Jordan Valley and for domestic uses in the capital of Amman. The Yarmouk River is considered the largest tributary of the Jordan River and joins it below Lake Tiberius; its largest width is 9 m and its depth is approximately 1.5 m. The annual average historic flow was estimated to be 450 to 500 MCM in the 1950s, but it has decreased sharply to approximately 83 to 99 MCM at present owing to the construction of a series of infrastructures and diversion structures upstream by Syrian entities. However, the river has a low baseflow that currently ranges between 0.5 and 5 m<sup>3</sup>/s and is prone to

irregular flooding that results in high flood flow during winter [44]. The measured runoff values for the watershed were obtained at the Adassia outlet (AD0033), at which a permanent measuring station for the Yarmouk River has been built by the Jordan Ministry of Water and Irrigation.

### 2.2 Hydrological model data

YRB drains into a narrow and shallow perennial wadi of approximately 60 km long, forming the border between Jordan and Syria, and is considered the largest tributary for the lower Jordan River. The mean annual historic flow of Yarmouk river is estimated at 450–550 MCM up to the 1950s, declining currently to about 90 MCM due to the construction dams and diversion units upstream in the Syrian side. The predominant climate in the watershed is Mediterranean subtropical where summer months are dry and hot and winters have moderate temperatures and are rainy. The annual average rainfall ranges from 106 mm in the southern Jordanian Badia to 486 mm in the northern west (Golan Heights). Average maximum and minimum temperatures range from 30–13°C in the Jordan Valley to 18–5°C in the highlands.

The prediction accuracy of hydrological models, such as the SWAT, depends on the quality and accuracy of input data and how well they describe the actual characteristics of the watershed. A wide range of input data are required by the SWAT, including the digital elevation model (DEM), land use, land cover data, and soil and climatic data. The DEM is one of the main inputs of the SWAT model; it represents the elevation at any point in a given area at a specific spatial resolution. A global DEM at 30 m resolution was used to delineate the boundary of the watershed and analyze the drainage patterns of the land surface terrain. The DEM was built using 1 arc-second (approximately 30 m) resolution from the advanced space borne thermal emission and reflection fadiometer. Onedegree tiles covering the study area were downloaded from USGS Earth Explorer website (http://earthexplorer. usgs.gov/) and then processed using tools within ArcGIS 10.2.1 (©1999-2013 Esri Inc.) into voids sink and mosaicked DEM. Terrain and stream network parameters, such as slope gradient, length, channel slope, and width, were obtained from the DEM.

Land use is an important factor that affects surface erosion, runoff, and evapotranspiration processes in a watershed during simulation. A land use map of the study area was obtained from the Jordan Ministry of Water and Irrigations and contained 19 land use classes

that were more detailed than would be needed for application in the SWAT. We redefined the land use map to conform to the generic land cover of the SWAT and confined the land cover into four classes, namely, urban, rangeland, bare soil, and agriculture, as shown in Figure 2. The land uses seemed to conform well to the visual observations of the watershed, where the range land, bare soil, and agricultural land represented approximately 30% each and urban areas represented 10% of the watershed. We also prepared the soil textural classes and soil physicochemical properties, which were required by the SWAT model, using a soil map. The soil map and the weighted average properties for two layers were adopted from the Digital Soil Map of the World version 3.6, which was available at the Food and Agriculture Organization [45]. Four soil classes were identified for the YRB, including clay 51%, clay 40%, clay loam, and loam soils (Figure 3). The shallow layer depth was 300 mm, while the total soil profile depth was 1,000 mm with an average porosity of 0.5. These extracted data contained the soil texture,

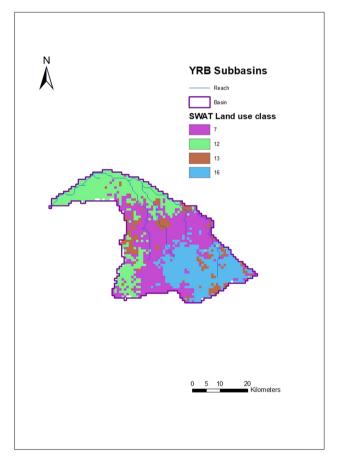


Figure 2: Map showing the land use within the YRB according to the Soil and Water Assessment Tool (SWAT) model classes. URBN, RNGB, BARR, AGRL represent urban, range, bare, and agricultural land, respectively.

available water content, hydraulic conductivity, bulk density, and organic carbon content for each type of soil.

The weather variables were obtained using the SWAT weather generator routine, namely, WXGEN. For the weather generator to successfully generate data for a specific watershed, certain weather parameters in each station in the watershed had to be calculated from the historic data and used as input to the weather generator. These parameters included the averages and extremes of monthly precipitation and temperature data and the averages of wind speed, relative humidity, and solar radiation, among other statistical parameters. Precipitation data series were used from five weather stations distributed over the Yarmouk watershed (Figure 1). These input data were calculated from the historic data series for the watershed using pcpSWAT, which was created by the SWAT user community.

The SWAT application involved partitioning the watershed into subbasins that were further subdivided into one or several homogeneous hydrological response units with relatively uniform combinations of land cover, soil, and

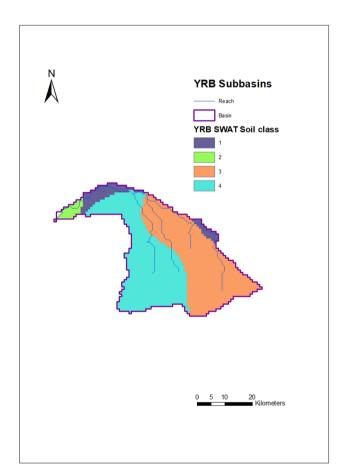


Figure 3: Map showing the soil types within the YRB based on the Food and Agriculture Organization soil map.

topography. The hydrological component of the SWAT model calculated the soil water balance at each time step depending on the daily amount of rainfall, evapotranspiration, runoff, and baseflow. The ArcSWAT interface was used for the setup and parameterization of the model. A DEM was imported into the SWAT model. A masking polygon (in grid format) was loaded into the model in order to extract the area of interest, delineate the boundary of the selected watershed, and digitize the stream networks. The spatial distributions of the 11 subbasins created in the YRB are shown in Figure 4.

#### 2.3 Model calibration and validation

Mathematical models have become one of the most important tools for watershed management, but they require careful calibration and validation before they can be used as a management tool. Calibration and validation processes reduce uncertainty and increase user confidence in model predictive ability.

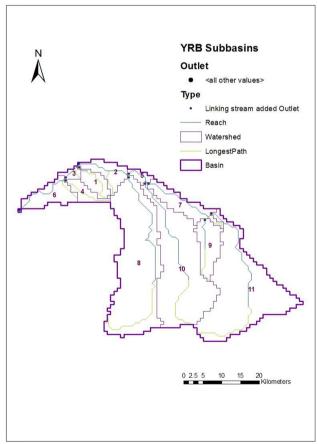


Figure 4: Spatial distribution of the 11 subbasins created in the YRB.

Model calibration and validation were performed using the streamflow records of two different data sets that contained 9 year, namely, from 1/1/2005 to 12/31/2013, and 2 year, namely, from 2014 to 2015, of hydrological data, respectively. These periods were selected and preferred based on the availability of recent data and because water flow record before 2005 has been used by other researchers for calibration of SWAT and other hydrological models. Using longer data set for model calibration generally improves the confidence in the model simulation and prediction. A multi-objective function was defined, which consisted of optimizing two different error metrics, including the Nash-Sutcliffe coefficient of efficiency [46] and coefficient of determination  $(R^2)$ . These functions were used to successfully calibrate and validate the SWAT model of the YRB watershed. During the calibration process, the model parameters were subjected to automatic adjustments with the calibration model SUFI-2 followed by manual calibration in order to obtain model results that better corresponded to the measured datasets. The model was then validated using 2 year of data from 1/1/2014 to 12/31/2015. Sensitivity analysis measures the response of an output variable to a change in the selected input parameter and how different parameters influence a predicted output; the greater the change in the output variable, the greater the sensitivity. In the sensitivity analysis, we identified the parameters that greatly influenced the predicted outputs and used them to calibrate the model.

Model calibration involves the modification of parameter values until the model-predicted output resembles the observed output, as measured by selected objective error functions [39]. The objective function for model calibration consists of a statistical test that minimizes the relative and average error or optimizes the NSE [15,27,37]. However, the calibrated parameters must be within the realistic ranges associated with the watershed in question [39]. Validation procedures consist of measuring the ability of the calibrated model to predict selected outputs using different data sets. Validation tests whether the model was calibrated only to a particular dataset or whether it represents the hydrological behavior of the watershed in general. If the objective function is not achieved for the validation dataset, calibration and/or model assumptions should be revisited.

## 2.4 Simulation of the impact of soil conservation measures

Following the calibration and validation of SWAT, the model was used to simulate the influence of soil

conservation measures including contouring, terracing, and/or combination of both measures on soil loss from YRB. The model simulations for sediments were carried out using sediment loss parameters commonly used in the YRB watershed. This was because measured sediment data was not available for the current watershed and therefore model-calibrated parameters were not available. The simulation was carried out to estimate the impact of the "YRB Agricultural Resources Development Project" that was carried out by the government of Jordan to improve agricultural practices at YRB. The Agricultural Resources Development Project in the YRB is one of the agricultural projects implemented by the Ministry of Agriculture in the north of the Kingdom covering an area of 1,230 km<sup>2</sup> and within a region with a population of more than 700 thousand people. The total cost of the project was 18.6 million dinars (26.25 million USD) funded by several international and Arab funding agencies, including the International Fund for Agricultural Development, the Abu Dhabi Fund for Development, and the OPEC Fund for Development, in addition to the contribution of the treasury and beneficiaries.

The project aims at improving food security and the income level of poor farmers within the project area by providing technical and financial support to farmers to establish soil and water protection measures and improving agricultural production (Figure 5). However, the impact of the soil and water conservation measures on the overall soil loss at YRB has not been carried out. We attempted in here to use SWAT in order to evaluate the impact of soil and water conservation measures carried out within YRB conservation project on the overall soil loss of the watershed. We simply varied the soil conservation factors such as contouring and land terracing in SWAT for the area of the subwatershed number 10, where those measures were implemented, and performed the simulation.

## 3 Results and discussion

### 3.1 Model calibration and validation

The uncalibrated SWAT model, which was based on default SWAT parameters from the YRB in 2005 to 2013, showed poor results when simulating monthly streamflow values. Baseflow values seemed to be underestimated in the uncalibrated run. The values of the measured flow rates were relatively smaller compared to simulated

values that ranged from 17 to 100 m<sup>3</sup>/s, and therefore, appear constant in some years. Nevertheless, the model seemed to respond to peak flows at the dates corresponding to actual peak flows, thereby resulting in a relatively acceptable simulation for some events.

The SWAT model parameters were calibrated using global sensitivity analysis, manual calibration methods, and auto-calibration methods in that order using 9 year of runoff data from 2005 to 2013. First, we determined the most significantly sensitive combination of parameters since these parameters had a large influence on runoff generation in the study area. In this step, we followed a logical order in the calibrated parameters owing to the existing correlations between the parameters and predicted outputs and parameter uncertainty. In addition, this step was necessary to reduce the number of parameters used in the model because over-parameterization can affect the efficiency of hydrological models [47,48]. Therefore, a preliminary sensitivity analysis was conducted to determine the most sensitive parameters based on researcher experience, data availability, and relevant literature, in addition to global sensitivity analysis of the candidate parameters. Sensitivity analysis was conducted using a Sequential Uncertainty Fitting Algorithm (SUFI-2) linked to the SWAT-CUP program. SUFI-2 is a powerful calibration sub-model that accounts for all sources of uncertainties in the model parameters and in the model input variables such as rainfall. It seeks to

bracket most of the measured data within a minimum uncertainty band, minimizing this uncertainty based on P and R factors. We examined the recommendations reported by previous studies involving hydrological modeling of other watersheds in Jordan, including the Zarga River watershed [49] and the modeling of the Jordanian side of the YRB for previous periods from 1972 to 1999 by [50]. We chose 12 parameters and subjected them to global sensitivity analysis in order to determine the most sensitive parameters affecting the river streamflow. The results of the global sensitivity analysis for the chosen calibrated parameters are shown in Table 1. These relative sensitivities estimated the average change in the NSE when the targeted parameter was changed while all other parameters remained constant. Parameters with a large t-test value and small p-test value were more sensitive than the other parameters [47]. The results were in agreement with several researchers who either created a multisite and multi-output sensitivity analysis for the model [26] or focused only on monthly streamflow prediction [51,52].

Model calibration was conducted using monthly values of streamflow. It was clear that the most sensitive parameter that controlled the flow partitioning into runoff and baseflow was the curve number (CN2), as shown in Table 1. As expected, CN2 was considered the most important parameter when modeling the hydrologic response using the SWAT model [15,53]. The second and third most sensitive parameters were the evaporation



Figure 5: Sample of soil conservation measure implemented within Yarmouk River Basin Development Project [58].

Table 1: Sensitivity results within the acceptable ranges of the calibrated parameters using the Nash-Sutcliffe coefficient of efficiency

Parameter symbol	Parameter name	t-statistic	<i>p</i> -value
CN2	Curve number	-3.07236	0.003971
ESCO	Soil evaporation compensation factor	-2.59509	0.013478
SOL_AWC	Available water capacity of the soil	2.20549	0.033712
CANMX	Maximum canopy storage (mm H <sub>2</sub> O)	1.57589	0.123565
SOL_K	Saturated hydraulic conductivity	1.04423	0.303154
GW_REVAP	Groundwater evaporation coefficient	0.99911	0.324229
SOL_ZMX	Maximum rooting depth of the soil profile	0.84341	0.404421
REVAPMN	Threshold depth of water in the shallow aquifer	0.74806	0.459154
CH_K2	Effective hydraulic conductivity in the main channel alluvium	0.41730	0.678869
SOL_ALB	Moist soil albedo	-0.40015	0.691349
GW_DELAY	Groundwater delay	-0.34856	0.729395
EPCO	Plant uptake compensation factor	-0.16367	0.870879

compensation factor (ESCO), which governs soil evaporation calculations, and the available water capacity (SOL\_AWC), which measures the ability of the soil to store water, respectively. The fourth and fifth most sensitive parameters were CANMX, which is the maximum canopy storage (mm H<sub>2</sub>O), and saturated hydraulic conductivity (SOL K), which governs how much infiltrated water would ultimately percolate to the shallow aguifer. The other seven sensitive parameters were tuned so that the streamflow regime simulated the observed flow regime as much as possible. One of the most effective parameters in tuning was the groundwater delay time (GW\_DELAY), which measures how long it takes for baseflow water to move from the bottom of the root zone to the shallow aquifer and then appear again as return groundwater flow [54,55]. Large GW\_DELAY values smooth the release of groundwater over the year so that the model is able to capture the stream baseflow response through norainfall months from June to September. The effective hydraulic conductivity (CH\_K2), which controls the transmission losses to infiltration in the subbasin channels, was increased to 13.04 mm/h from its default value of 0 mm/h to reflect the consolidated high silt-clay nature of the bed of the channel. This adjustment of CH K2 allowed the simulated discharge peak flow to be lowered and smoothed while keeping the water cycle balance intact. The water cycle balance components after the calibration process was completed were believed to be in the appropriate range assuming that the model realistically simulated the processes.

The SWAT model contained a large number of parameters, and most of them were measured or estimated from the BASIN database. At first, manual calibration was conducted to achieve satisfactory results based on the total sum of measured versus simulated values in

order to achieve reasonable water balance quantities in the watershed. The steps were as follows: first, we adjusted the CN2 until a satisfactory runoff/precipitation ratio was achieved. Then, we adjusted the soil SOL\_AWC, ESCO, groundwater "revap" coefficient (GW\_REVAP), and threshold depth of the water in the shallow aguifer for revap to occur (REVAPMN) to achieve a satisfactory Evapotranspiration/precipitation ratio. The GW DELAY was then adjusted in order to make the observed flow regime as comparable as possible. Finally, the flow peaks were visually inspected and the unrealistic simulated high peaks were adjusted by increasing the CH\_K2 and the baseflow alpha factor (ALPHA\_BF), which were the most effective parameters for controlling the shape of the flood hydrograph. Parameters obtained from the manual calibration were checked against reasonable values for the watershed and then used as default parameters for the automated calibration. This process insured proper model performance and stability [56].

Manual calibrations were undertaken in order to understand the streamflow behavior depending on the most sensitive individual parameters, whereas automatic calibration was performed to achieve the optimal values for those parameters. The average monthly observed streamflow from 2006 to 2013 was 1.65 m<sup>3</sup>/s and the uncalibrated simulated streamflow was 6.16 m<sup>3</sup>/s, thereby indicating a poor water balance within the watershed. We conducted manual calibration for 9 year of input data from 1/1/2005 to 12/31/2013, which was followed by automatic calibration. In the automated procedure, parameters were iteratively adjusted within realistic uncertainty ranges to provide parameter sensitivity analysis and goodness-of-fit statistics. The automated calibration used the SUFI-2 procedure in the decision-making framework calibration, validation, sensitivity, and uncertainty analysis software SWAT-CUP which was developed by the Swiss Federal Institute of Aquatic Science and Technology [47]. The first year was used as a "warm-up" period that allowed the model to calculate values that became initial values for the subsequent period of interest. In the calibration process, the main criteria were to minimize the error between the simulated and observed mean monthly flows for the total calibration period at AL\_ADASYA station (AD0033) and to achieve the best relationship between the simulated and observed monthly flows in the calibration process. The top 12 significantly sensitive parameters that were used to calibrate the model as well as their initial and calibrated values are shown in Table 2.

Plots of the time series for the observed and simulated monthly streamflow as obtained by the SWAT-CUP 95PPU plot for the calibration and validation periods (2006–2013–2015) are shown in Figure 6. The measured and simulated monthly streamflow for the YRB at Al-Addasiya station are shown in Figure 7. During the calibration evaluation, the  $R^2$  value was 0.96, as indicated by the scatter plot for streamflow simulations against observed streamflow in Figure 7, while other measurements during the same period were a NSE of 0.95,  $R^2$  of 0.88.

SWAT simulation seemed to underestimate river discharge for most months as shown in Figure 6. This is because SWAT most probably overestimated evapotranspiration in the watershed due to prolonged non-rainy days and evapotranspiration is mostly controlled by the soil moisture condition rather than climate parameters. It may also overestimate infiltration losses in such semiarid

watershed in which infiltration is predominantly controlled by soil surface conditions and formation of crust which are not important in humid watersheds and therefore not well-integrated in SWAT.

In the Model validation and during the validation period, the calibrated parameters were used and kept constant without any adjustment and used to simulate the monthly streamflow values for 24 months, from 1/1/ 2014 to 12/31/2015. The overall pattern of the simulated streamflow appeared to be in good agreement, as shown in Figure 6, with the observed streamflow values with an NSE value of 0.63 and  $R^2$  value of 0.91. In general, the SWAT model performed well during the verification period, which was similar to that in the calibration period. The peak streamflow in the YRB between September to November and between February to May 2015 was slightly underestimated, which affected the overall performance of the model. During the validation period, the mean simulated and observed flows were 2.10 and 4.76 m<sup>3</sup>/s with standard deviations of 4.89 and 10.05 m<sup>3</sup>/s, respectively. However, the simulated baseflow appeared to be highly correlated with the observed baseflow in both years.

A comparison of the model performance during the calibration and validation periods is shown in Table 3. Values of the objective functions  $R^2$  and NSE during the calibration and validation periods were reasonably close at 0.95 and 0.91 for  $R^2$  and 0.96 and 0.63 for the NSE, respectively. However, during the calibration years, the model overestimated the peak flow incidents and underestimated the baseflow, which resulted in an overall lower mean flow value of  $2.10 \, \text{m}^3/\text{s}$  compared to  $4.76 \, \text{m}^3/\text{s}$ .

**Table 2:** The calibrated parameters and their ranges under the pre-development conditions

Name of parameter (Unit)	Estimated value	Calibrated value	Realistic uncertainty range		Hydrologic process
			Min.	Max.	
Curve number	80.1	76	60	90	Runoff
Soil evaporation compensation factor (in)	0.7	0.742	0	1	Evaporation
Available water capacity of the soil (mm/mm)	0.098	0.27	0.07	0.18	Soil
Maximum canopy storage (mm)	0.186	0.910	0	2.5	Evaporation
Saturated hydraulic conductivity (mm/h)	0.910	1.925	0	2.000	Soil
Groundwater revap coefficient	0.12	0.1586	0.02	0.2	Groundwater
Maximum rooting depth of the soil profile (mm)	1,000	908.4	840	1,200	Soil
Threshold depth of water in the shallow aquifer (mm)	0.13	0.89	-1	1	Groundwater
Effective hydraulic conductivity in the main channel alluvium (mm/h)	0	13.0499	2	15	Channel
Moist soil albedo	0.21	0.0625	0	1	Soil
Groundwater delay (d)	365	418.5	300	500	Groundwater
Plant uptake compensation factor (in)	0.41	0.442	0	1	Evaporation

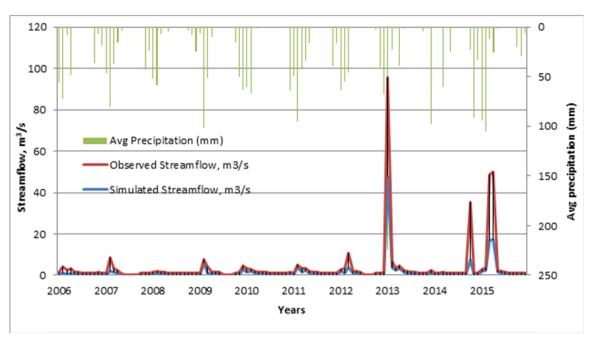


Figure 6: Measured and simulated monthly streamflow at Al-Addasiya station as well as the monthly observed precipitation during the calibration period (2006–2013) and validation period (2014–2015) using SWAT-CUP 95PPU plot output.

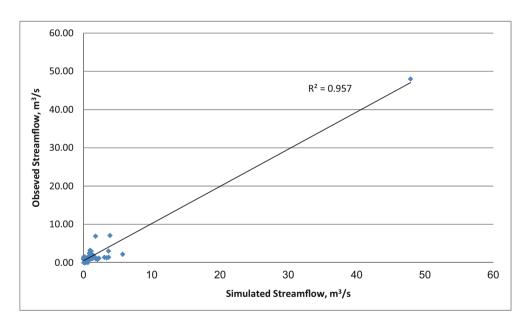


Figure 7: Scatter plot of the streamflow simulations against the observed streamflow during the calibration period (2006-2013).

Similar results were obtained by Zettam et al. who applied the SWAT to a large semiarid watershed in Algeria. They found that the NSE for eight stations ranged from 0.42 to 0.75, whereas the  $R^2$  values ranged from 0.25 to 0.84 [37]. White and Chaubey reported that the NSE and  $R^2$  values for monthly flow predictions ranged from 0.50 to 0.89 and from 0.41 to 0.91, respectively [26].

# 3.2 YRB agricultural resources development project

The impact of soil conservation measures carried out by the YRB development project on runoff and soil loss has been simulated with SWAT. Most of the conservation measures were carried out only in the subbasin 10 **DE GRUYTER** 

Table 3: Summary of the objective functions during the calibration and validation periods for the Yarmouk River Basin

Objective function	Calibration (2005-2013)	Validation (2014-2015)	
$R^2$	0.95	0.91	
NSE	0.96	0.63	
Simulated mean (m <sup>3</sup> /s)	1.21	2.10	
Observed mean (m <sup>3</sup> /s)	1.65	4.76	
Simulated Std Dev (m <sup>3</sup> /s)	4.89	4.89	
Observed Std Dev (m <sup>3</sup> /s)	4.87	10.05	

(Figure 4) with an area of 233 km<sup>2</sup> representing 20% of the watershed area. Therefore, we apply three soil conservation measures scenarios including contouring, terracing, and countering + terracing simultaneously for basin #10 only and the results are shown in Table 4. The influence of conservation measures on runoff was small, about 5% reduction in average, compared to soil loss and therefore was not detailed in Table 4.

Table 4 summarizes soil loss from YRB for several years with and without conservation measures. Soil loss from YRB varied largely along the years due to variations in rainfall depths and varied temporal rainfall distribution along the years. For control watershed, soil loss varied from 8.61 in 2007 to as high as 40,490 tons in the year 2013. The corresponding soil loss for the same two years with land contouring was 5.53 to 11,223 tons representing 21 and 44% reduction, respectively. In the case of terracing, the percent reductions in soil loss seemed to be higher in some years having low annual rainfall, i.e., 2006 and 2007, but lower for the years with high rainfall such as 2013. However, land management with both contouring and terracing did not further improve soil loss reduction compared to only contouring

Table 4: Summary of sediment loss in metric tons in YRB for various conservation measures for various years

Year	Control	Conservation measures				
	(metric tons)	Contouring (% reduction)	Terracing (% reduction)	Contouring and terracing (% reduction)		
2006	18.99	11.87 (21)	7.29 (34)	4.90 (41)		
2007	8.61	5.53 (21)	3.55 (35)	2.51 (43)		
2008	10.93	4.44 (15)	4.23 (15)	2.87 (18)		
2009	94.90	33.99 (16)	32.12 (16)	19.58 (20)		
2010	1718.03	363.48 (25)	483.69 (22)	290.77 (26)		
2011	4053.09	874.00 (37)	1128.51 (32)	677.55 (38)		
2012	1969.05	256.30 (33)	551.58 (27)	331.72 (31)		
2013	40489.69	5246.79 (44)	11223.13 (35)	6735.02 (41)		

or terracing, especially for wet years having high annual rainfall depth, i.e., 2009 to 2013. For dry years with low rainfall depth, i.e., 2006 to 2009, combined application of contouring and terracing seemed to be more effective and resulted in further decrease in soil loss compared to one practice only. Other studies have also reported the positive impact of contouring and terracing on sediment loss [57]. Using SWAT, they reported a 22% decrease in soil loss of an arid watershed in Tunisia with terracing.

### 4 Conclusions

The SWAT model was successfully calibrated and validated to simulate monthly runoff data in the YRB for a period of 12 years with an average NSE value of 0.8 and  $R^2$  value of 0.93. The YRB is a semiarid and complex watershed that contains a mix of urban, agricultural, and bare land with high temporal and areal rainfall variability and data scarcity. Runoff simulations during the calibration period showed high performance; however, during the validation process, its performance was generally lower conformed with similar studies in the literature. We used SWAT to study changes in soil erosion in the YRB as affected by various soil management practices including contouring and terracing which were implemented in YRB development project. Model application shows the positive impacts of soil conservation measures including contouring, terracing, and combination of those two measures on soil loss reduction from the watershed ranging from 15 to 44%. SWAT model proved to be a suitable tool for water flow prediction in large-scale watersheds and could be beneficial tool for water resource managers and planners in Jordan, in particular, and in other water-scarce countries in the region.

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