



Assessment of soil erosion risk in a semi-arid climate watershed using SWAT model: case of Tata basin, South-East of Morocco

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Abstract

Increased sedimentation is the main problem that affects dam efficiency by reducing storage capacity. Planning for dam construction and maintenance requires design strategies that heavily depend on integrated basin models, properly identifying principal sediment origins within the watershed and qualifying the sediment production rate. In this research work, the physically-based watershed SWAT model, defined as the Soil and Water Assessment Tool, was used to estimate the rate of sediment production for future dams in the Tata basin, located in southeast Morocco. The model was calibrated and tested for uncertainty by the employment of the algorithm Sequential Uncertainty Fitting-2. The outputs were used for assessing critical sediment source areas. Calibration and validation of the model were performed by monthly data. The values for Nash–Sutcliffe efficiency coefficient, Percent bias coefficient and determination coefficient (R^2), respectively, during the calibration period 1990–1998 (0.96, –13% and 0.96) and the validation period 1999–2006 (0.77, +11% and 0.93) indicate the accordance with the results obtained for the measured flow and the simulated flow values. The annual sediment yield of the Tata basin extends from 0 to 11 t/ha/y with a mean of 2.3 t/ha/y. The spatial distribution of these sediments varies from upstream to downstream. The downstream basin generated more sediment to the river per unit area, though it was less than the total amount of the basin for the upstream area. This variation is influenced by the increased downstream surface runoff and also by other characteristics of the basin such as slope and lithology. The low erosion places correspond to areas with lithological formations that are more resistant to erosion.

Keywords Erosion · Sediment yield · SWAT model · Tata basin · Morocco

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Introduction

Sedimentation is a major environmental concern associated with soil erosion (Mosbahi et al. 2013; Mallick et al. 2014). It is extensively known due to the impact it has on the quality of water resources, reduction in reservoir capacity, and poor agricultural yield through nutrient loss (Cai et al. 2012; Yan et al. 2013). The quantity of sediment produced and transported within drainage basins is a result of the combined action of topography, soil texture, climate change, geology, and land use (Asres and Awulachew 2010; Tram et al. 2021). Existing studies point out the internal link of the production and the transportation of sediment to synergistic forces of land use and climate (Bussi et al. 2016; Tram et al. 2021). To reliably predict the quality of sediment transport from ground soils to watercourses and rivers, both for the identification of areas with erosion problems and to suggest the best management practices to decrease erosional impacts, a modeling approach is often used (Yesuf et al. 2015). The watershed soil erosion models can represent fluvial transport related to the separation, transport, and deposition of soil particles caused by rainfall and surface flow throughout the catchment area (e.g., Lee et al. 2013; Mosbahi et al. 2013; Mallick et al. 2014; Tram et al. 2021).

Recently there has been a rise in the development and use of these models (Yang and Wang 2010). The Soil and Water Assessment Tool model (SWAT) is one of the extensively utilized models (e.g., Arnold et al. 1998; Akoko et al. 2021). This model is widely used as it is an ongoing, semi-distributed model created to identify critical areas of erosion that supply high quantities of sediments as well as simulating hydrologic processes within a vast spectrum and state of the environment (Arnold et al. 1993; Gassman et al. 2007). It is also used as an integrated basin model to provide useful planning strategies (Rickson 2014).

Several studies have shown that SWAT is capable of modeling data-lacking and ungauged watersheds with reasonable accuracy (e.g., Arnold et al. 2012; Mallick et al. 2014; Mosbahi et al. 2013; Nyeko 2015; Havrylenko et al. 2016; Kondo et al. 2021; Tang et al. 2021). Only a few studies have employed this model in Morocco (cf. Briak et al. 2016; Boufala et al. 2019; Markhi et al. 2019). In this context, this study aims to use the SWAT model to (1) assess spatial distributions of soil erosion and sediment transport for the Tata basin, where there are limitations in terms of data availability, and (2) evaluate the potential sediment yield entering a future dam reservoir. The specific study objectives are to calibrate, validate, and perform an uncertainty analysis of the SWAT model for the Tata basin and identify critical areas of erosion. A feasibility study of this development allowed us to calculate the

infiltrated water volume at groundwater level (1.9 Mm^3), which corresponds to tenfold the infiltrated volume without a dam. It would therefore be reasonable to calculate the sediment load entering this dam reservoir through mathematical modelling using SWAT software. This calculation makes it possible to define the lifetime of this dam and its profitability in terms of integrated water management.

Study area

Tata basin is a hydrographic system situated in the mountain chain of the Anti-Atlas, in the province of Tata in the southeastern part of the Kingdom of Morocco, between Lambert coordinates X (200,000 and 280,000) and Y (290,000 and 360,000) (Fig. 1a). The basin area is 1912.75 km^2 . The sources for the primary stream of the basin are located approximately 2000 m in the Anti-Atlas Mountains. The basin has a sub-desert and continental climate. The annual average rainfall is low (less than 150 mm) and the average summer temperature is higher than $32 \text{ }^\circ\text{C}$. The gap between the average temperatures varies considerably large across the seasons ($19 \text{ }^\circ\text{C}$ in winter and $30 \text{ }^\circ\text{C}$ in summer). The wet season goes from the beginning of October to March, and the period of the dry season is from April to the end of September. Around 18 affluent streams, distributed on both sides of the valley, are significantly involved in the flow of the Tata River. Rain provides most of the water for the Tata River with very poor contribution during the springtime (less than $1 \text{ m}^3/\text{s}$). The monthly flow of the Tata River is extremely changing due to the high variability of precipitation in the Tata River (Fig. 1b) (Echogdali et al. 2018a, 2021). Construction of a dam has been proposed, just upstream of Tata city, to limit the impact of floods (Echogdali et al. 2018a, b, 2022; Ikirri et al. 2021), and to allow for a gradual recharge of the alluvial groundwater downstream.

Methods and materials

SWAT model description

The SWAT model is a semi-distributed hydrological model operating at an uninterrupted time move (Arnold et al. 2012). This model was built for the simulation of change effects in the practices of watershed management, on the hydrology of surface water and groundwater, pollution expanse, water erosion, and sediment transportation (Taylor et al. 2016). It involves two kinds of functional units, namely Hydrologic Response Unit (HRU) and Sub-basin (Neitsch et al. 2011). The first unit, HRU, is spatial of the homogeneous property of slope, land use, and soil, in every sub-basin (Arnold et al. 2012). The second unit partially points out regions comprising the major spring

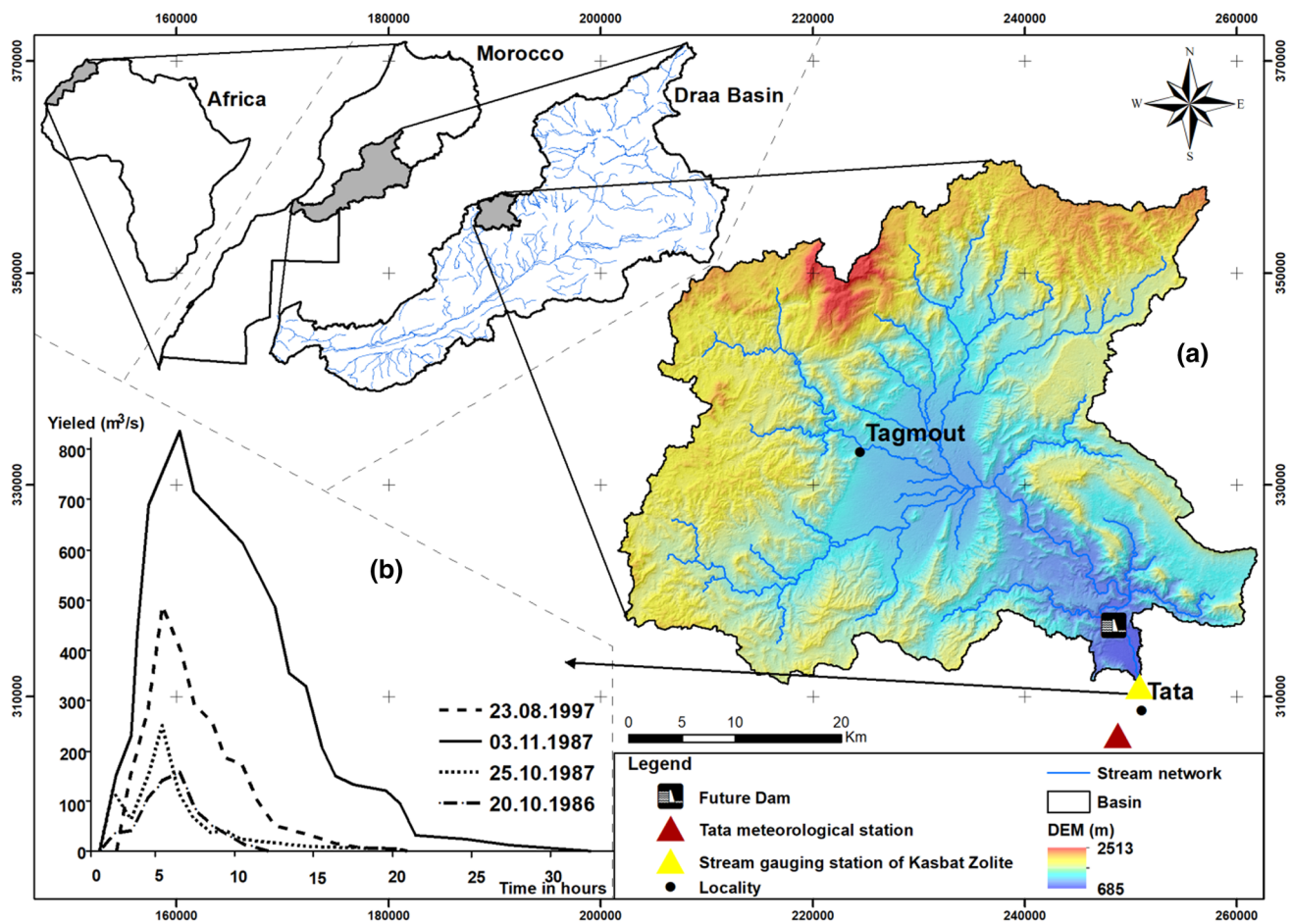


Fig. 1 Geographic location of Tata basin a Digital elevation model (DEM) b Flow hydrograph of Tata basin

and the area contributing to it, composing one or many HRUs (Vigiak et al. 2017). The model forecast each HRU hydrology, from the equation of the water balance, taking into account daily rainfall, surface runoff, percolation, lateral flow, irrigation, and evapotranspiration (Neitsch et al. 2005). The simulation of the land phase is done based on the water balance equation as shown below (Neitsch et al. 2005):

$$SW_t = SW_o + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})i \tag{1}$$

SW_t represents the water content in the soil (mm), SW_o the water available for plants (mm), Q_{surf} stands for the surface run-off (mm), R_{day} for precipitation (mm), E_a for evapotranspiration (mm), W_{seep} for percolation (mm), and t for the time (days).

The water phase in the water cycle portrays the path of water in the riverbed through the method of variable storage coefficient (Williams 1969) or Muskingum routine (Linsley and Kohler 1958). In SWAT, sediment yield

is evaluated with empirical Modified Universal Soil Loss Equation (MUSLE) for every HRU (Williams 1975a):

$$Sed = 11.8(Q_{surf} \times q_{peak} \times Area_{hru})^{0.56} \times K_{USLE} \times C_{USLE} P_{USLE} \times L_{USLE} \times C_{FRG} \tag{2}$$

Sed represents sedimentation yield on a given day (t), Q_{surf} is the volume of surface run-off (mm/ha), q_{peak} is the peak run-off rate (m^3/s), $Area_{hru}$ for the HRU area (ha), K_{USLE} stands for the universal soil loss equation (USLE) factor of soil erodibility, C_{USLE} for USLE cover and management factor, P_{USLE} for USLE support practice factor, L_{USLE} for USLE topographic factor, and C_{FRG} stands for coarse fragment factor.

Soil and Water Assessment Tool Calibration and Uncertainty Procedures (SWAT-CUP) is an independent operation containing five different automated calibration procedures among which we have validated and performed sensitivity analysis functionalities, in addition to visualization of results (Abbaspour et al. 2007). The employment of the SWAT-CUP model requires ArcSWAT output files (Abbaspour 2011).

Several algorithm procedures are developed for SWAT-CUP simulations. During the study, Sequential Uncertainty Fitting-2 (SUFI) calibration algorithm was used because it is frequently applied for hydrological calibration of catchment areas (Abbaspour et al. 2007).

The simulated streamflow and the measured monthly flow values for the Tata River were compared to perform calibration and validation (Moriassi et al. 2007). The simulation period for which the model was run is from May 1st, 1985 to October 2006 with the first 5 years, from 1985 to 1989, as a warm-up period, 9 years of streamflow data (1990–1998) were used for the calibration, whereas the last 8 years (1999–2006) was used for the validation.

The accordance between measured and simulated flows was assessed using the determination coefficient (R^2), the Nash–Sutcliffe efficiency coefficient (NSE), and the Percent bias coefficient (PBIAS). The equations used to calculate these coefficients are the following:

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (3)$$

$$PBIAS = \frac{\sum_{i=1}^n (O_i - S_i)}{\sum_{i=1}^n O_i} \times 100 \quad (4)$$

where O_i is the observed variable, S_i the simulated variable, and \bar{O} mean observed variable.

NSE shows to what extent the graph of the observation against the simulation fits the 1:1 line (Nash and Sutcliffe 1970). The PBIAS measures the average simulated values trend to be greater or lesser than the observations (Gupta et al. 1999).

Input data used in SWAT

SWAT demand two kinds of input data: spatial and temporal data (Halefom et al. 2017; Boufala et al. 2019). Land use map, soil map, and slope map (Digital Elevation Model–DEM) are included in the spatial data. Hydrological

data (streamflow and sediment yield) and climate data (solar radiation, relative humidity, air temperature, precipitation, and wind speed) are included in the temporal data. See Table 1 for the details of the databases.

Hydro-meteorological data

The principal input data for the hydrological process in SWAT is climate data. For that, daily precipitation, maximal and minimal air temperature, wind speed, solar radiation, and relative air humidity, data from the meteorological station were used. The daily flow data from the Kasbah Zolite stream gauging station was used to evaluate the performance of the SWAT simulation. These meteorological and hydrological data covered 22 years from May 1985 to October 2006. The Hydraulic Basin Agency of Souss Massa (Agadir, Morocco) provided those data.

Spatial data

Digital elevation model (DEM)

A DEM of the Tata basin was utilized to represent the relief of the study area (Fig. 1a), which was extracted from the ASTER-GDEM data (Global Digital Elevation Model from the ASTER) with a spatial resolution of 30 by 30 m. The DEM was integrated into the SWAT model and used to delineate the sub-basins. DEM was used to derive topographic parameters such as slope, length of slope for the sub-basins.

Land use map

Land use map is used in ArcSWAT to divide the sub-watersheds into small units (Boufala et al. 2019). A land use map was created from an overseen classification of Sentinel-2 satellite imagery using Envi 5.3 software (Fig. 2a). The classification showed 4 different categories: Bare soil (96.34%), Watercourses (2.62%), Agricultural (0.84%) and Urban (0.20%).

Table 1 Sources and descriptions of data used for the Tata River basin

Data type	Resolution	Description
DEM	30×30 m	The ASTER-GDEM data (Global Digital Elevation Model), USGS earth explorer
Land use data	10×10 m	Land use classification collected from Sentinel-2 images, taken on June 08, 2016, from ESA
Soils data	1/1 500 000	Soil map collected from the National Institute of Agronomic Research in Morocco HWSD (Harmonized World Soil Database) by FAO (Food and Agriculture Organization)
Weather data	Daily	Daily precipitation, maximum and minimum air temperature, relative air humidity, wind speed, and solar radiation data collected at Tata meteorological station
Streamflow data	Daily	Daily streamflows measured at Kasbat Zolite Stream gauging station

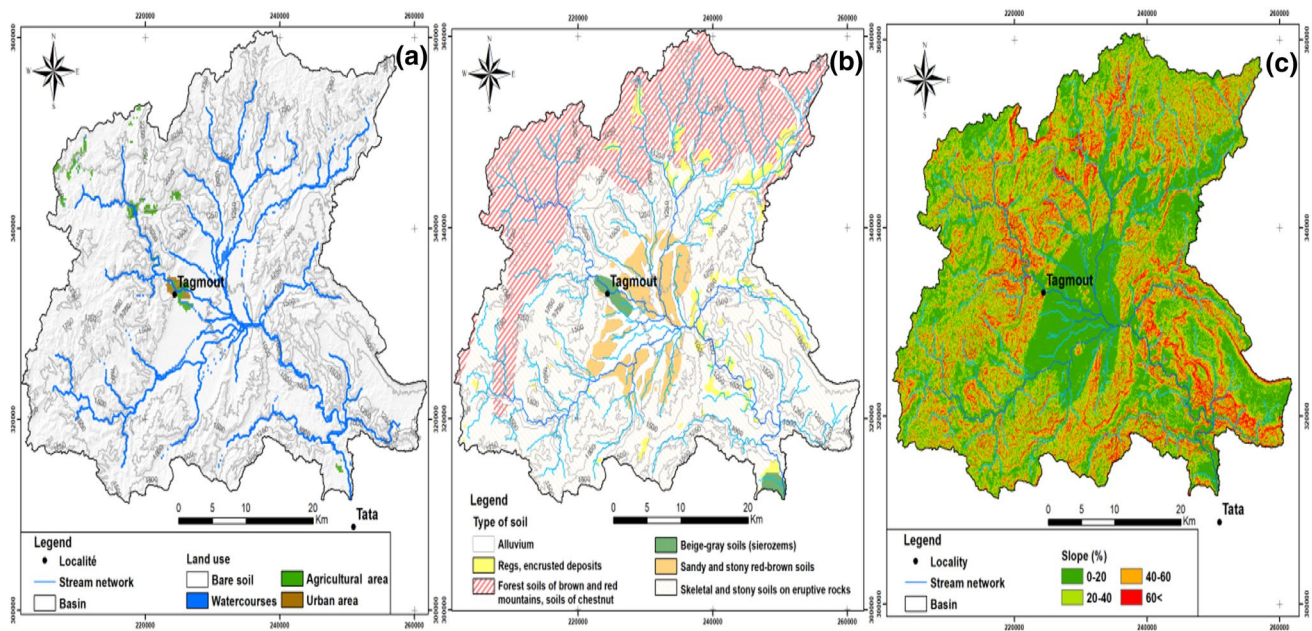


Fig. 2 Thematic maps used to discretize HRUs in Tata basin **a** Land use **b** Soil **c** Slope map

Soil map

Soil map was produced by the National Institute for Agromomic Research (Rabat, Morocco). Besides, we used the Harmonized World Soil Database (HWSD) developed by the Food and Agriculture Organization (FAO). This database consists of a digital map layer coupled to an attribute table containing the main characteristics of the soil types (Nachtergaele and Velthuisen 2009). HWSD provides all of the information describing the physical and chemical properties of the soil, such as texture, depth, hydraulic conductivity (Ksat), saturated hydraulic conductivity (SOL_K), and soil hydrologic group (HYDGRP), which play a large role in determining the movement of water and air within the HRU (Fig. 2b). The classes fall into 3 main categories, skeletal and stony soils on eruptive rocks (52.58%), forest and chestnut soils (28.64%), and sandy and stony red-brown soils (5.05%).

Slope map

The slope map, the drainage plan of the catchment area, slopes, the lengths of the stream, and the widths of the rivers into the catchment area were derived from the ASTER DEM (Chaemiso et al. 2016). The spatial distributions of slope classes in the Tata basin showed 4 classes: 0–20% (39.50%), 20–40% (32.72%), 40–60% (18.52%) and > 60% (9.26%). As the slope increases, sediment transport accelerates downstream (Fig. 2c).

Delineation of sub-basins and HRU definition

The basin has been divided into 33 sub-basins (Fig. 3). To avoid landscape heterogeneity, the sub-basins were also subdivided into 218 HRUs using 10% as the threshold for the physical parameter, namely land use, type of soil, and slope (cf. Her et al. 2015).

Sensitivity analysis

SWAT input parameters are based on processes and ought to be kept within a realistic range of uncertainty. The first thing to do before starting a calibration is to determine the parameters that are more sensitive for a given basin or sub-basin (Arnold et al. 2012). The process of determining the change of rate in model output relative to the change of rate in model input defines the analysis of sensitivity. The identification and understanding of the influence of parameters are essential to reduce their number in the calibration phase (Holvoet et al. 2005). The capacity of the model to sufficiently simulate streamflow and sediment rate generally depends on the accurate calibration of parameters (Xu et al. 2009).

The SWAT Hydrological input parameters were chosen based on the authors' knowledge (environmental, geomorphological, topographical, and geological reasons) of the basin. The sensitivity analysis of SWAT parameters has been related by Malagò et al. (2015) and Abbaspour et al. (2007). The results found 11 important parameters in the Tata basin (Table 2).

Fig. 3 Delineated sub-basins of the Tata basin

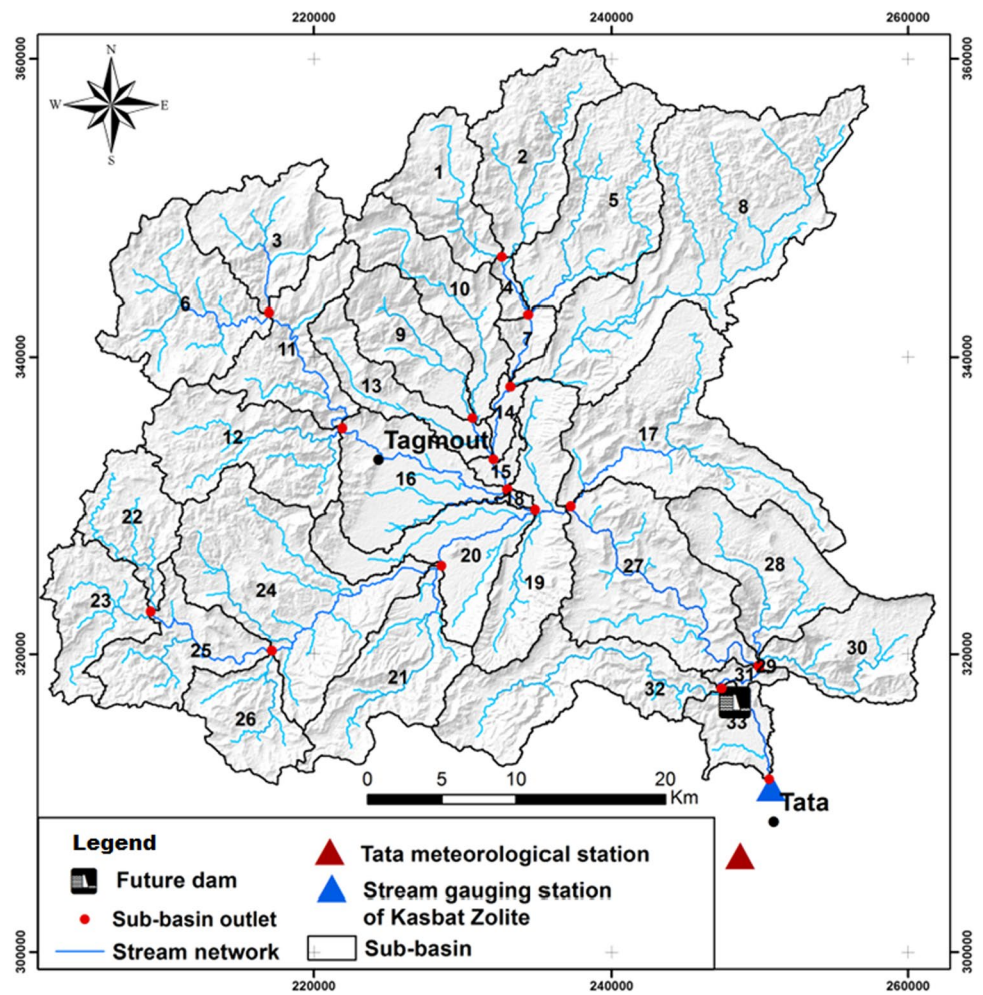


Table 2 Sensitive parameters and fitted values after calibration using SUFI-2

Parameter name	Description	Rank	Adjusted value	Min value	Max value	Range
r_CN2.mgt	Curve number	1	0.17756	0.17499	0.179886	39–92
r_EPCO.hru	Plant uptake compensation factor	2	0.019266	0.011923	0.031503	0.81–0.96
r_OV_N.hru	Manning’s ‘n’ value for overland flow	3	3.584584	3.264844	3.652408	0.01–0.15
r_SOL_BD.sol	Moist bulk density	4	0.012938	0	0.039809	1.3–1.83
v_ALPHA_BF.gw	Base flow alpha factor	5	0.973035	0.970711	0.976909	–
v_CH_K2.rte	Channel effective hydraulic conductivity	6	2.286209	2.135731	8.15484	–
v_CH_N2.rte	Manning’s ‘n’ value for main channel	7	0.042591	0.040147	0.045897	–
v_DEP_IMP.hru	Depth to impervious layer for modeling perched water tables	8	3151.363281	2916.91284	3240.29273	–
v_GW_DELAY.gw	Groundwater delay time	9	29.256178	28.637705	31.386473	–
v_GW_REVAP.gw	Groundwater revap co-efficient	10	0.139277	0.137979	0.148361	–
v_SURLAG.bsn	Surface runoff lag coefficient	11	9.816657	8.247377	10.04084	–

v: Means the existing parameter value is to be replaced by the fitted parameter value

r: Means an existing parameter value is multiplied by (1 + fitted parameter value)

Calibration and validation

The better action to parameterize a model for a given set of the local condition is the calibration. For this work, the calibration was carefully applied to the SWAT model by using the SUFI-2 method to reduce the uncertainty and to provide the best representation of hydrologic and sediment transport processes in the Tata basin. During the calibration, we checked different model components to ensure that reasonable predictions were made in the study area. The validation of a model is a process that demonstrates the capability of a given model to properly and satisfactorily reproduce observations. Validation consists of running the model with the optimal parameters resulting from the calibration and comparing simulated values to observed (Arnold et al. 2012). In this case, the validation of the SWAT model was performed during the 8 years (1999–2006) after the calibration (1990–1998) by comparing the observed and simulated streamflow values.

Results and discussion

Model calibration and validation

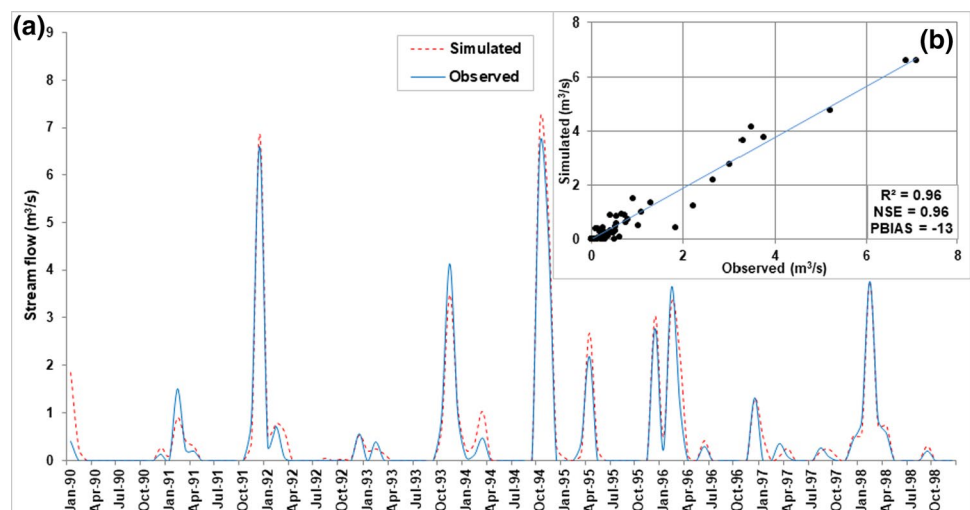
Model calibration results indicate a good match between the simulated monthly discharge and the observed Tata River (Fig. 4a). Following the SWAT model, recommended performance assessment criteria (Moriassi et al. 2007), the calibration allowed us to reproduce streamflow with a coefficient of $NSE=0.96$, $R^2=0.96$, and $PBIAS=-13\%$ (Fig. 4b), which is evaluated as very good simulation. Fitting quality indices were satisfactory for the monthly period of calibration. In another study of a semi-arid river in the Sbaihia basin in Tunisia, Khelifa et al. (2017) found the coefficient of NSE to be 0.89 and the R^2 to be 0.89. Gyamfi et al. (2016)

reported $NSE=0.88$, $R^2=0.89$ and $PBIAS=-11.49\%$ for the monthly flow calibration in the Olifants basin in South Africa. Therefore, the calibrated SWAT model can be used successfully to predict the volume of inflow into the potential dam for the Tata basin.

The validation (1999–2006) of the module shows that the observed streamflow values are slightly lower compared to the simulated values at peak flow for December 2002, September 2003, and December 2004 (Fig. 5a). There are numerous reasons for the slight-over and under-prediction of the streamflow. For example, poor performance has been noted in the case of inadequate representations of precipitation due to the lack of rainfall stations (Bouraoui et al. 2005; Cao et al. 2006), the variability of other climatic parameters such as the atmospheric temperature and the solar radiation (Shirmohammadi et al. 2006) and data inaccuracy (Harmel et al. 2006). Data processing can also contribute to the uncertainty of measured data due to missing data, assumptions for estimating missing data, and errors in the management and data input. But it is most likely to be associated with errors in observed data.

According to the model performance indicators recommended for a given monthly period (Moriassi et al. 2007), the period of validation evinces that the achieved model is quite appropriate between simulated and observed monthly streamflow in the Tata basin with an NSE coefficient in order of 0.77, PBIAS on the order of +11% and 0.93 for R^2 (Fig. 5b). Other research in semi-arid regions of Morocco have also found similar results for monthly flow validation with $NSE=0.88$ and $R^2=0.91$ in the R'dom basin in North-Western Morocco (Brouziyne et al. 2018) and $NSE=0.89$, $R^2=0.90$ in the Tleta basin in North Morocco (Choukri et al. 2019). Although the calibration results show a better match than the validation results, the good agreement between simulation and observation in the validation phase indicates that the SWAT model was adequately calibrated and provides

Fig. 4 **a** Observed and simulated monthly streamflow **b** Correlation of observed and simulated monthly streamflow during the calibration phase (1990–1998)



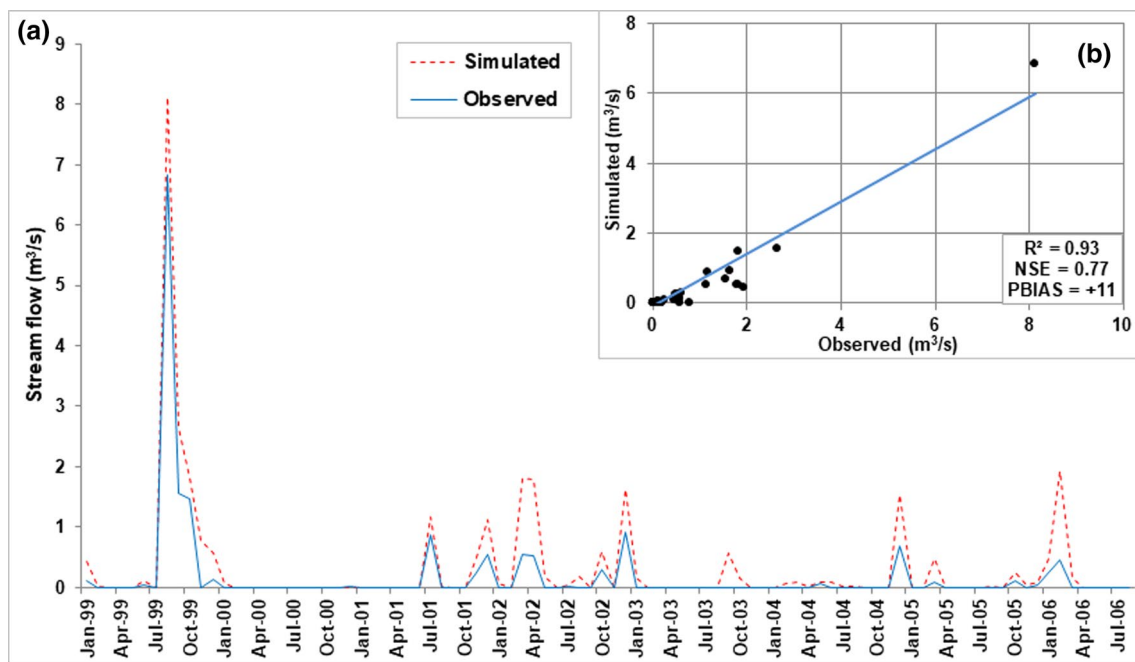


Fig. 5 **a** Observed and simulated monthly streamflow **b** Correlation of observed and simulated monthly streamflow during the validation phase (1999–2006)

confidence for further assessment of streamflow hydrologic response of the Tata basin.

Evapotranspiration

The SWAT model estimates evapotranspiration by the Penman–Monteith method (PMM). Of all the 11 parameters, curve number (CN2), plant uptake compensation factor (EPCO), and moist bulk density (SOL_BD) are the most sensitive factors for the simulation of evapotranspiration. The evapotranspiration (Fig. 6a) varied between 60 and 600 mm, it is around 120 mm over the entire basin except for sub-basins 4, 14, 18, and 31 (200–600 mm), which are characterized by small surfaces. Evapotranspiration comes from the transpiration and evaporation of water from the plant canopy. In the study area, the reduction of agricultural land, plant surfaces, and forests has led to a drop in evapotranspiration over the entire basin. Pan et al. (2021) showed that as transpiration and evaporation of water trapped by plant leaves increases, the amount of evapotranspiration increases. Similarly, Stancalie et al. (2010) found that evapotranspiration is about 100 mm lower on bare soil surface than on covered soil.

Surface runoff

A gradient of surface runoff can be distinctly observed from upstream to downstream in Fig. 6b. In the upstream part of the basin, the surface runoff is mainly reduced, while runoff

increases in many downstream sub-basins. Runoff was calculated based on parameters classified by sensitivity analysis, namely curve number (CN2), plant uptake compensation factor (EPCO), baseflow alpha-factor (ALPHA_BF), channel effective hydraulic conductivity (CH_K2), manning's 'n' value for the main channel (CH_N2) and surface runoff lag coefficient (SURLAG). The CN2 factor, which controls the runoff process, appears as the most sensitive parameter. It is sensitive for both the simulation of surface runoff and evapotranspiration. At the sub-basin scale, annual surface runoff varied between 0 and 7.149 mm. The highest runoff rates are located in sub-basins 18, 20, and 33, downstream of Tagmout village due to the type of land use, slope, and type of soil. Runoff is average in the western and eastern parts of the city of Tagmout and the central part of the basin. This is due to the type of land use, which shows land consisting of bare soil, occupying most of the study area (96.34%), the geological formation represented by limestone, and the degree of slope, which can exceed 30% in certain areas promoting surface runoff. Zhao et al. (2004) showed that there is a strong relationship between runoff volume and land cover, where high runoff volume was observed due to vegetation removal and urbanization. As a result, surface runoff occurs more easily under these conditions. This is consistent with the results of Pan et al. (2021), who showed that reduced vegetation cover reduces evapotranspiration, soil water content and increases surface runoff and water yield. On the other hand, low rates are observed in the northwestern part of the basin at sub-basins 1, 2, 3, 5, and 6. Even if the ground

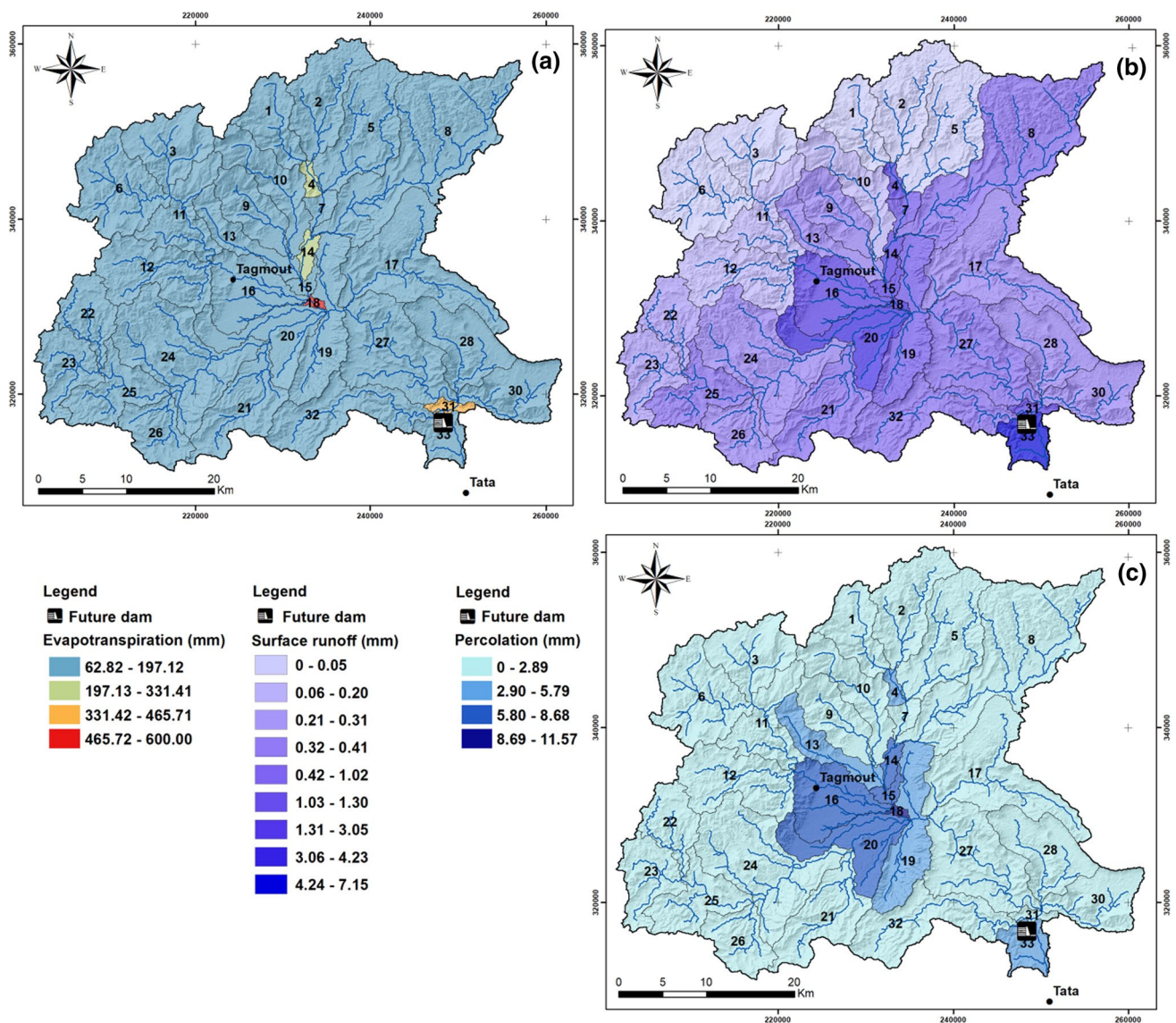


Fig. 6 Map showing **a** evapotranspiration (mm) **b** surface runoff (mm) **c** percolation (mm) for every sub-basin (1990–2006)

seems not to be very permeable, the geological formations, in particular ignimbrite, gabbro and conglomerate are quite weathered and fissured allowing water to infiltrate. Ignimbrite and gabbro can indeed be highly fractured under the effect of local or regional tectonics (Cavazos-Álvarez et al. 2020; Okudaira et al. 2015). The tectonic deformation thus favors infiltration through joints and faults (Antonellini and Mollema 2019).

Percolation

Percolation indicates a vertical flow of water into the alluvial layer. It depends on precipitation, land use, soil type, lithological structure, and relief. Figure 6c shows the spatial distribution of the yearly average percolation

rate in the Tata basin. The rate of percolation ranged from 0 to 11.57 mm. The highest values (5.80 to 11.57 mm) were located in the Tagmout alluvial plain (sub-basins: 14, 15, 16, 18, and 20), which consists of alluvial formations, regs, and encrusted deposits. These formations have a very high permeability that is favorable for percolation. For moderately permeable formations, the average percolation rate ranges from 2.90 to 5.79 mm (sub-basins: 4, 13, 19, and 33). For moderately permeable formations, the average percolation rate ranges from 2.90 to 5.79 mm (sub-basins: 4, 13, 19, and 33). A lower infiltration rate, which was observed elsewhere, is due to topographic conditions. These areas have higher relative relief and hence, the slopes are steeper as shown in Fig. 1a. These are also areas where water availability is low due to a

sparse hydrographic network. To have significant infiltration amounts, it is indeed necessary to have enough water.

The area around Tagmout village is characterized by a relatively important runoff, but also by an important infiltration. This seeming paradox is due to the geomorphology and hydrography of this alluvial plain. It is a water assembly area from the hydrographic network. The 3 main tributaries of the basin gather here and make it possible to have conducive conditions to water flow, in contrast to the watershed periphery. This potential availability of water allows a portion to infiltrate and increases the percolation rate of the area. Moreover, it is an inhabited zone. The villagers' activities have made it possible to develop vegetation, although sparse, which slows down water flow and favors infiltration.

Spatial distribution of erosion

The SWAT model simulation shows that the range of sediment yield delivered by the different spatial units of the Tata basin varies from negligible erosion to more than 11 t/ha/y (Fig. 7a). A comparison of the analysis of the sediment yield on the Tata basin with other studies carried out in the same mountain chain (Anti-Atlas) shows that the average sediment yield obtained in this study (2.3 t/ha/y) is in close agreement with the estimate established by Elmouden et al. (2017) for the Souss-Massa basin, which is 2.5 t/ha/y. Compared to other semi-arid regions in the Middle East and North Africa (MENA) region, these values seem to be much lower than the average of 5.18 t/ha/y obtained by Bouguerra

et al. (2016) for the Boumessaoud basin in Algeria, 6.10 t/ha/y obtained by Elahcene et al. (2013) for the Bellah basin in Algeria, 7.50 t/ha/y calculated by Snoussi (1988) for the Sebou basin in Morocco and 3.73 t/ha/y by Haida et al. (1996) for the Tensift basin in Morocco.

According to our simulated results in Fig. 7a, the downstream basin supplied more sediment to the river per unit area (11 t/ha/y), whereas the erosion in the upstream basin is lower compared to the average for the total basin. Sediment loss depends on the local influence of many factors. The extreme sediment yield occurred in sub-basin 33 (11 t/ha/y), which corresponds to the highest runoff zone reaching 7.14 mm and thus, participating in the process of uprooting soil particles. In addition, the dominance of bare soil shows the sensitivity of this basin to erosion. In less covered areas, the soil is bare and more affected by erosion (Hughes et al. 2015). This basin corresponds also to areas with a low covered rate, weak slopes, and especially having recent lithological formations, which are easily transportable by rivers (regs, encrusted deposits, and alluvial alternating clay) (Fig. 7b). Medium risk areas show erosion rates ranging from 1.58 to 2.45 t/ha/y. The latter occupy sub-basins 8, 9, 16, 17, 24, 25, and 26. The lowest values are recorded in sub-basins 1, 2, 3, 5 and 6 (0 to 0.14 t/ha/y). Their low values are caused by the presence of consolidated conglomerate, sandstone, and dolerite. Hard rock provides considerable protection against erosional processes and this makes their erosion by surface water very difficult. The different soil types induce

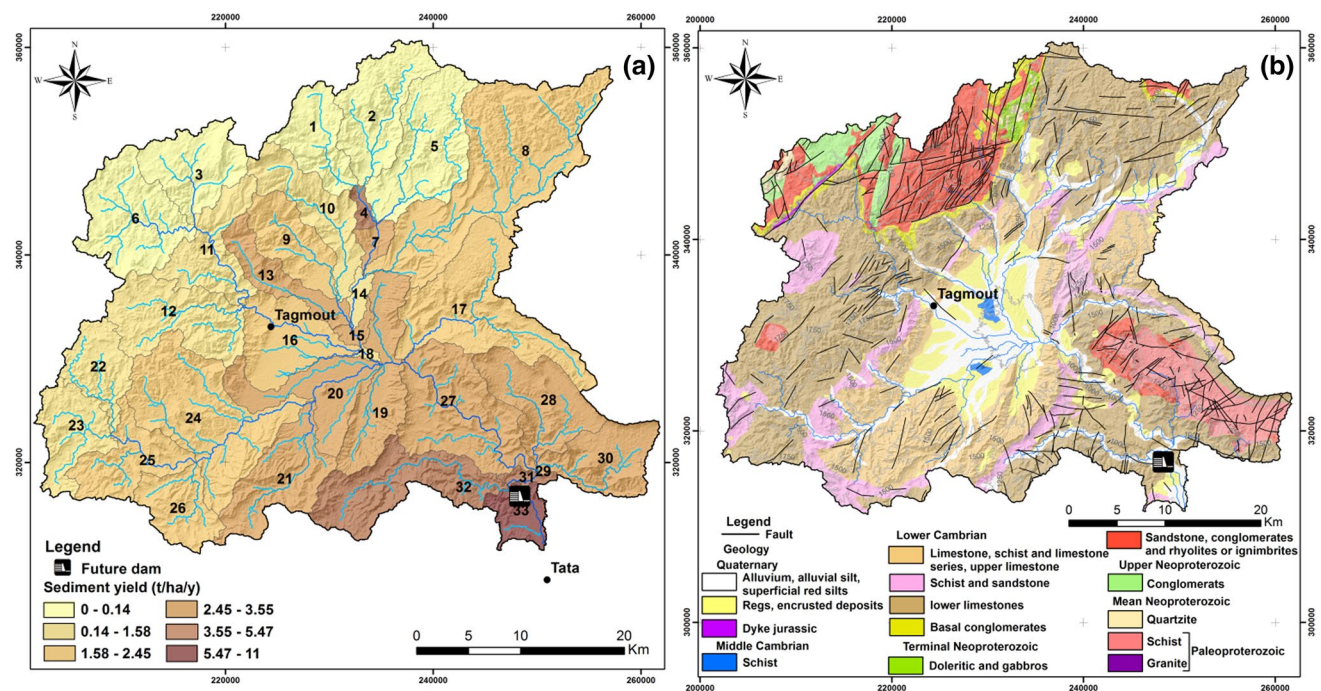


Fig. 7 a Distribution of Sediment yield of the Tata basin b Geological map of Tata basin

different characteristics on runoff and sediment loss. The spatial distribution of the soil type upstream of the basin consists essentially of a forest type soil with increased forest biomass that could better protect soils against erosion during rainy episodes (Zuazo and Pleguezuelo 2008), while the downstream part is formed by sierozem soils, a type of soil contributed to a higher rate of erosion high, which concur with what was found by Toubal et al. (2018).

In general, runoff and erosion increase significantly from upstream to downstream, the highest values occurring mainly on bare soils accentuated by topography. Sediment loss is influenced by both runoff rates and soil properties (Benchettouh et al. 2017; Mapes and Pricope 2020; Nehai et al. 2021). Several similar studies carried out in semi-arid regions have shown that sediment losses are much greater on bare soils due to increased runoff (Hughes et al. 2015; Benchettouh et al. 2017; Nehai et al. 2021).

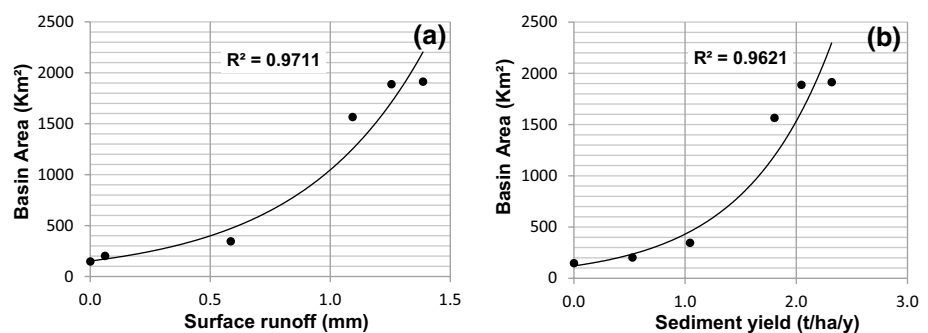
The slopes are very steep in the south-eastern (sub-basins 28 and 30) and southern (sub-basin 32) portions of the basin (Fig. 7a). There are a few areas with a slope above 40% in the central part of the basin but take place more often at the edges. The slope affects significantly the transport capacity of sediment, for instance, the slope has a significant effect on sediment transport capacity, e.g. slope with higher friction and therefore the great capacity of transport is generally at a steeper gradient (Wei et al. 2017). Thus, steep slope areas are usually more susceptible to erosion. The results of our study show that the sediment yield in sub-basins with slopes greater than 40% was between 2.45 and 4.47 t/ha/y. The loss in soil rises generally with the steepness of the slope on uncultivated soils (Ziadat and Taimah 2013). Topography largely influences the mechanism of erosion and several factors must be taken into consideration to judge the role of this factor (Battany and Grismer 2000). Thus, its effect is more amplified depending on the type of land use, plant cover, and erosion prevention practices (Battany and Grismer 2000). The variation in land cover also corresponds to the pedological variation. This variation in soil characteristics is an indicator of erosion. In the study area, the considerable presence of bare soil and the lack of forest cover in high slope areas can contribute to the sediment outflow from

these sub-basins. These are also areas where skeletal soils are present, indicating a high susceptibility to water erosion.

This result shows that surface runoff is not the only factor that plays an important role in the movement of soil particles, but the loss of sediments is strongly conditioned by other factors, such as topography, land use category, and soil type. In general, no work has been done in these mountainous regions to assess the ability of the SWAT model to predict surface runoff, evapotranspiration, percolation, and sediment loss. There are gaps in hydrological modeling in the Tata Basin due to little or no observational data to validate the results. The presence of a single weather station allows the SWAT model to simulate sediment loss; this limited number of stations affects the accuracy of the simulation, even if the validation results are reasonable. Consequently, the improvement of these data will increase the reliability of this model (cf. Panagopoulos et al. 2011; Polanco et al. 2017; Zhang et al. 2021; Rumph Frederiksen and Molina-Navarro 2021).

The simulation results also indicate that sub-basins with high surface runoff increase downstream sediment yield as a larger surface runoff has a greater transport capacity (Fig. 8a). Total sediment yield increases even faster downstream, which is due to the cubic (approximate) relationship between sediment discharge and streamflow (Makaveev 1955). The increase in total sediment yield exceeds the increase of the Tata basin area (Fig. 8b). Therefore, specific sediment yield values increase downstream. It has been shown by de Vente and Poesen (2005) that the relation between the area of the basin and the yield of the sediment is divided into three or four groups. The specific sediment yield of the basins of Morocco and the largest basins of Tunisia represents the highest group, whereas the intermediate group is represented by Algeria and Spain and the lowest specific sediment yield is represented by Israel. This is not an easy way to explain the differences. However, the vegetal cover, the lithology, and the topography, or in other words the local environmental condition, which could be more favorable to erosion and sedimentation in basins of Morocco and Tunisia than the other basins, which are mentioned above, could be a plausible explanation. This positive

Fig. 8 Relationship between basin area increases **a** surface runoff increase **b** sediment yield increase



relationship between specific sediment yield and basin area (Fig. 8b) is characteristic for uncultivated basins or basins with limited cultivation such as the Tata basin, where agriculture accounts for less than 1% of the basin area (Fig. 2b).

Estimation of sediment inputs to the future dam

The yearly average contribution of sediments transported by the Tata River to a potential future dam was 66,000 tons from 1990 through 2006 (Fig. 9). The highest sediment load, approximately 711,000 tons, was recorded in 1999. This peak, ten times higher than the average, was because in the summer of 1999 there were 3 days of severe thunderstorms (24, 25, and 26 August 1999) with a cumulative precipitation of 104 mm during 72 h and rainfall of 76 mm in the first day (August 24). These unusual severe storms were followed by a second major rainfall event on October 9 and 10 (33 mm each day), though less anomalous than the August event. These two exceptional events increased the sediment load calculated by the MUSLE method.

The sediment yield was estimated using the MUSLE (de Vente and Poesen 2005) from rainfall and surface runoff (Arnold et al. 1998). The relationship between sediment

yield, surface runoff, and rainfall was evaluated by a sediment rating curve analysis (Fig. 10a, b). The results show that the sediment yield rate correlated better with runoff than rainfall, with R^2 of about 0.99 (Fig. 10) (ASCE 1970; Williams 1975a, b; Hrissanthou 2005).

To reduce the loss of sediments and their transport and to extend the life of this future dam, which is 80 years, several methods of combating the siltation of dams have been used, namely (Bracmort et al. 2006; Remini 2008; El Mahi et al. 2012; Elahcene et al. 2013; Guesri et al. 2020): (1) filter strips that reduce runoff, (2) raising the dam embankment, (3) reforestation, which allows reducing surface flow and rainfall erosivity and (4) stone bunds that reduce surface flow, sheet erosion, and slope length.

Conclusion

The hydrological model SWAT was successfully calibrated (1990–1998) and validated (1999–2006) using climatic conditions in this study. The monthly simulation values for R^2 , PBIAS and NSE were 0.96, -13% and 0.96 during the calibration period and were 0.93, +11% and 0.77 during

Fig. 9 Yearly sediment inputs to the future dam

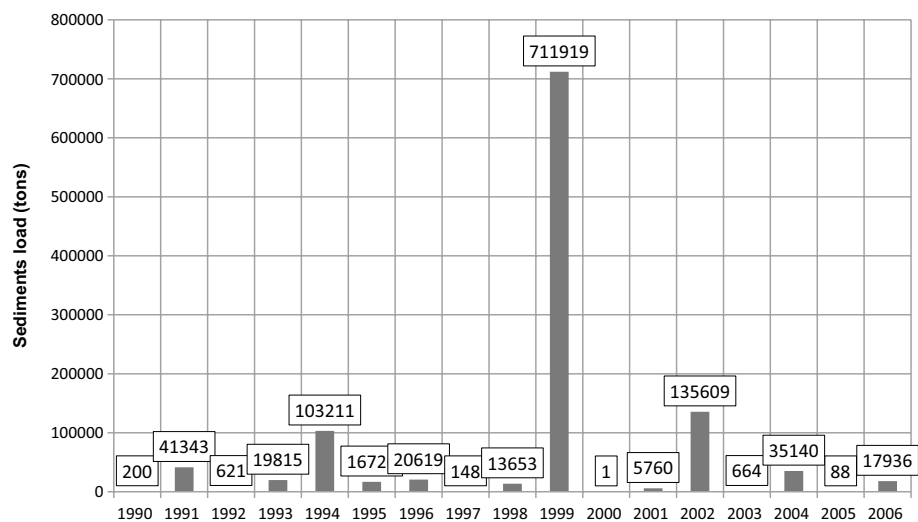
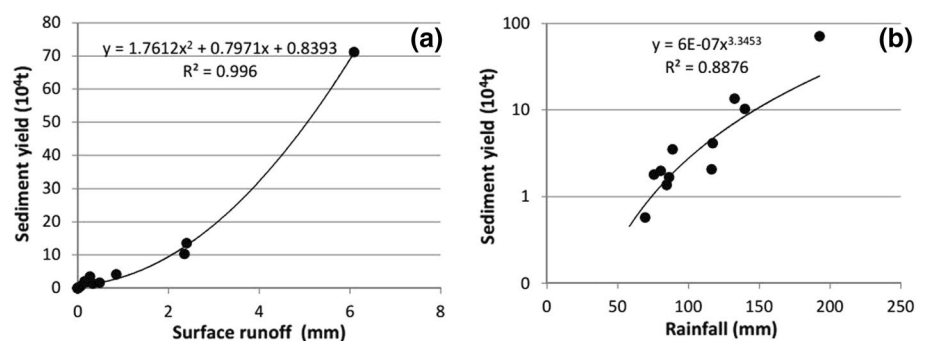


Fig. 10 Correlation of sediment yield with **a** surface runoff **b** rainfall



the validation period. The Tata basin has a sediment yield ranging from 0 to 11 t/ha/y and an average yield of 2.3 t/ha/y. This value is lower than for other Mediterranean areas. The downstream part of the basin where surface runoff increases are indicated by the model results as areas of critical sediment yield. This is due to the direct relationship between sediment yield and surface runoff. This work shows basin characteristics such as lithology, soil type, and slope influences sediment yield. According to these results, it was estimated that the average sediment load carried by the Tata River to a potential future dam site is about 66,000 t/y. Proper calibration of the SWAT model led to a perfect agreement between simulation and observation in the validation phase and provides confidence in the analysis of erosion and yield for the Tata basin and a future dam reservoir.

It can be deduced that the SWAT model is a reliable and accurate scientific method to provide a spatial distribution of erosion at the level of the Tata basin. These results can be exploited by decision-makers and managers to ensure sustainable management of natural resources and for soil management and conservation measures. Furthermore, installing a capping dam that will increase the artificial recharge of the alluvial aquifer of the Tata River, which makes it possible to overcome the scarcity of groundwater in the region.

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Code availability Available upon reasonable request.

Declarations

Conflict of interest The authors declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, "Assessment of soil erosion risk in a semi-arid climate watershed using SWAT model: Case of Tata basin, South-East of Morocco".

Ethical approval This article does not contain any studies involving human participants performed by any of the authors.

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