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RESEARCH ARTICLE

ASSESSMENT OF SEDIMENT YIELD USING SWAT MODEL: CASE STUDY OF KEBIR WATERSHED, NORTHEAST OF ALGERIA

Kamel Khanchoul[a*], Amina Amamra[b], Bachir Saaidia[c]

[a]Department of Geology, Laboratory of Soils and Sustainable Development, Badji Mokhtar University-Annaba, P.O. Box 12, Annaba, Algeria.
[b]Department of Biology, Laboratory of Soils and Sustainable Development, Badji Mokhtar University-Annaba, P.O. Box 12, Annaba, Algeria.
[c]Department of Geology, Laboratory of Water Resources and Sustainable Development, Badji Mokhtar University-Annaba, P.O. Box 12, Annaba, Algeria.
Corresponding author email: kamel.khanchoul@univ-annaba.dz; kam.khanchoul@gmail.com

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ABSTRACT

Erosion is identified as one of the most significant threats to land in increasing rates of soil loss and reservoir sedimentation. An integrated approach therefore requires sediment assessment for identification of its sources for efficient watershed management. The present study is aimed to examine the spatial and temporal sediment yield distribution potential and to identify the critical erosion prone zones within Kebir watershed, Algeria using Soil and Water Assessment Tool interfaced in GIS for the period from 1982 to 2014. The model is calibrated by adjusting sensitive parameters and validation is done using observed data from 1982 to 1998. The model performance checked by the coefficient of determination (0.76), Nash–Sutcliffe coefficient (0.75) and relative error (+8.19%) suggests that the model has performed satisfactorily for sediment yield prediction. The simulated outputs of the model show that the 33-year period of sediment load production is estimated to be 19.24x10^6 tons and a mean annual sediment yield of 856.14 T/km^2/yr. Temporally, sixty-four percent (50%) of sediment yield generated in the watershed occurs in five months of the winter and fall seasons. The most erosion vulnerable sub-basins that could have a significant impact on the sediment yield of the reservoirs are identified. Based on this, sub-basin 16, 14, 13, 11 and 8 are found to be the most erosion sensitive areas that could have a significant contribution, of 50%, to the increment of sediment yield. Best management practices are highly recommended for the land sustainability because of the high sediment supply to the dams.

KEYWORDS

SWAT application, erosion, sediment yield, sustainability, watershed.

1. INTRODUCTION

Soil erosion and sedimentation by water involves the processes of detachment, transportation, and deposition of sediment by raindrop impact and flowing water (Wischmeier and Smith, 1978; Julien, 1998). The major forces originate from raindrop impact and runoff. The mechanisms of soil erosion take place where water from areas of sheet flow runs together under certain conditions and forms small rills that produce small channels (Jung et al., 2017). The concentration of flow into rills and gullies causes erosion of soil and weak lithological formations, and much material can be transported within these channels. Soil erosion may not be noticeable on exposed soil surfaces, even where the raindrops are eroding large quantities of sediment; however, erosion can be dramatic where concentrated flows create extensive rill and gully systems (Kim, 2006).

Accelerated soil and water loss caused by human activities and natural factors are seriously threatening land resources, water resources and ecological environment. The studies of soil erosion and sediment migration are very important and significance because soil erosion is a main component of source pollution, it is one of the basic work to calculate the sediment yield and the sediment transport (Gassman et al., 2007). The assessment of soil erosion and sedimentation requires a basic understanding of the spatial patterns, rates and processes of soil erosion and sediment transport at the watershed scale. However, spatial data are often scarce; thus, the ability to model the spatial patterns of sediment delivery and to identify the source areas of sediment is very limited (Haregeweyn et al., 2013).

In this case the objectives may be to reduce the peak rate of runoff for minimizing soil erosion and sediment yield. Hence, the modeling of runoff, soil erosion and sediment yield are essential for sustainable development. Furthermore, the reliable estimates of runoff and sediment yield for inaccessible and ungauged areas are tedious and time consuming by conventional methods. Therefore, it is desirable that some suitable methods and techniques are evolved for quantifying the hydrological parameters from all parts of the watersheds (Jain et al., 2010; Khanchoul et al., 2014; Khanchoul and Khanchoul, 2019). Due to the importance of studies on erosion by water, there are several mathematical models that

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consider factors of anthropic and natural order, the estimates of sediment yield, among other hydrological parameters. Modeling is, therefore, an effective way to develop the required knowledge regarding the hydrological changes and their consequences in future (Mahzari et al., 2016). The SWAT (Soil and Water Assessment Tool) is a mathematical model of public domain, developed in the early 90s, which is a physically based distributed hydrological model, to predict the effect of management decisions on water, sediment, nutrient and pesticide yields with reasonable accuracy on a large, ungauged river basins on a daily time step (Chandra et al., 2014).

In recent years, the study of soil erosion and hydrological processes is more common by using the remote sensing, geographic information system technology and the Universal Soil Loss Equation (USLE) model, where some of the popular models are identified as the Modified USLE (MUSLE) and the Revised USLE (Benchettouh et al., 2017; Abdo and Salloum, 2017; Djoukbala et al., 2018). ANSWERS (Area Non-point Source Watershed Environment Response Simulation), AGNPS (Agriculture Non-point Pollution Source), WEPP (Water Erosion Prediction Programme) are few among the models (Beasley, 1980; De Roo et al., 2007; (Abdelwahab et al. 2018; Chia and Mbajiorgu 2019; Akbari et al., 2015; Gelder et al., 2018). These models had been evaluated under different conditions from different researchers in different parts of the world. Nevertheless, the applicability of the different models has revealed that SWAT model is more accurate and more powerful, especially in watersheds where datasets of sediment concentrations and stream flows are unavailable (Zalaki-Badil et al., 2017).

Several studies have shown the robustness of the SWAT model in predicting sediment yields at different watersheds. Recently, the model has been widely applied for the simulation of runoff, sediment yield and total phosphorus losses from watersheds in different geographical locations, with varying conditions and management practices (Spruill et al., 2000; White and Chaubery, 2005; Gassman et al., 2007; Parajuli et al., 2007). However, few studies have been on the applicability of the SWAT model in Algeria, particularly in the northeastern part of the country. Some researchers have applied the model to simulate the more parameters including the runoff, silt and diffuse source nitrogen (N) and phosphorus (P) pollution loading of seven hydrological stations of Poyang Lake Basin (Ma et al., 2015; Liu and Jiang, 2019). In other studies, researchers have applied the model to simulate water quantity and water quality under the land use scenarios through the SWAT model in Changjiang River basin (Liu et al., 2015). Chaâbane Ben Salah and Abida have presented an application of the model SWAT to simulate daily and monthly water and sediment fluxes in the Wadi Hatab watershed (Salah and Abida, 2016).

Over the last few years, this model has been used throughout the northwest of Algeria. Moreover, it has attracted attention from few researchers despite its effectiveness and feasibility in different types of watersheds. A group researchers have applied SWAT to predict streamflow and sediment transport through a small agricultural watershed of Wadi Harraza, Chellif basin (Hallouz et al., 2018). Other researchers have conducted simulations by SWAT to quantify sediment yield at Beni Haroun reservoir and to identify the vulnerable areas to erosion in order to reduce dam silting (Kaleb et al., 2019).

The watershed of Kebir Wadi is the subject of some works in the field of erosion by water but few concerning the siltation of Mexa dam located at the basin hydrometric gauging station. The Kebir watershed is undergoing high sediment transport into the reservoir and there are unavailable bathymetric measurements and suspended sediment estimations, after the dam construction in 1999, that are supplied by the National Agency for Dams and Transfers (ANBT). By applying the SWAT model, which is not widely used in this part of Algeria, the objectives of this study are: (1) to evaluate the contribution of the different factors of the basin to surface water; (2) to evaluate the sediment yields, identify and prioritize vulnerable sub-basins within the watershed in order to apply the management of the watershed, and also to protect the existed reservoirs from sediment silting and ensure water self-sufficiency.

2. Study Area

The Kebir watershed is located in the northeast of Algeria. This watershed of 681 km^2 is distinguished at its outlet by Mexa reservoir with a capacity of 47 million cubic meters (Figure 1). The watershed has also two reservoirs constructed upstream from the Mexa dam and which are the Bougous reservoir built in 2012 with a capacity of 27 million cubic meters and Barbara reservoir located in Tunisia with a capacity of 74 million cubic meters (Amamra and Khanchoul, 2019). The climate is Mediterranean, with a mean annual rainfall equal to 637 mm. The precipitation data sets have shown that there are rainfall events greater than 30 mm/day during an average of 4 to 5 days/year from November to May during the 20-year period. Local temperatures vary between 28°C and 31°C with a mean annual temperature of 18°C (Boukhrissa et al., 2013).

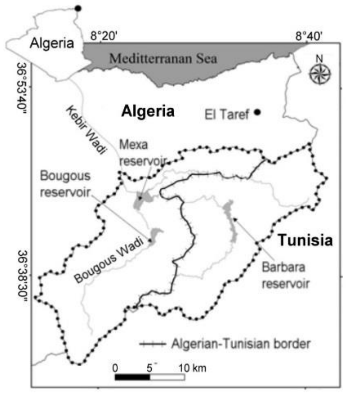

Figure 1: Location map of Kebir watershed.

The watershed is mainly composed of weathered Oligocene sandstone and clay rocks that represent as much as 45% of Kebir basin area. The rest of the lithologic formations are constituted of Mio-Pliocene conglomerate and clay, Cretaceous marl and marly limestone (Khanchoul et al., 2012). Land use is characterized by intense forest associated with sparse shrubs and grasslands that occupy 43% of the basin area. Dense forests of Oak cork and Zen oak are diffused in the south area of the basin and west of Bougous on poorly developed soils (Figure 1). Shrubs (Oleo-lentiscus and Erica europa) with an open canopy, covering 19% of the Kebir area, are damaged by livestock and fires during the summer season. Most of the agricultural land is cropland and pasture and tends to be especially in the northeast part of the study area.

3. Materials and Methods

The SWAT model has several interfaces like ARCSWAT version 2012, which is used to enter the different types of data needed to make a simulation in the model (Kateb et al., 2019). For this study, three types of data namely spatial geomorphological such as Digital Elevation Model, land use and soil types, meteorological and hydrological (Hydrologic Response Unit) data are collected. The model divides the watershed into sub-watersheds and those into hydrological response units (HRU's) generate by slope classes, soil type classes and land cover.

3.1 Spatial data collection and analysis

3.1.1 The digital elevation model (DEM)

Digital Elevation Model (DEM) is a valuable tool for the topographic parameterization, particularly for erosion and drainage analyses, hillslope hydrology and watersheds (Pandey et al., 2016). In addition, USGS Digital elevation model (DEM) is an array of regularly spaced elevation values referenced horizontally either to a Universal Transverse Mercator (UTM) projection or to a geographic coordinate system.

DEM used in SWAT model, obtained from ASTER Global Digital Elevation Version 2 Model with a resolution of 30 m, to delineate the watershed and its sub-basins, delineate the location of watercourses and to create the slope classes map using Arcgis 10.4 software. Sub-basin cutting is done taking into consideration the automatic cutting (Figure 2).

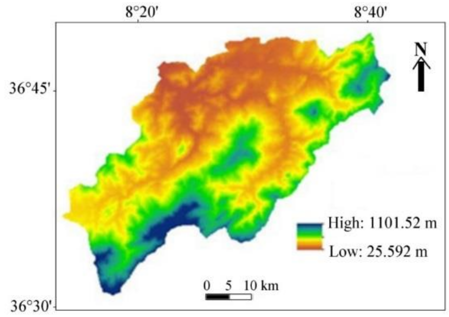

Figure 2: Digital elevation model of the Kebir watershed.

3.1.2 Hydro-meteorological data

Meteorological data including daily precipitation between 1982 and 2014 from three meteorological stations, maximum and minimum air temperature, relative humidity, wind speed, and solar radiation are provided by the National Agency of Hydraulic Resources and Global Weather Data for SWAT. The meteorological data used by SWAT have specific structures. These data, after having been collected, have been transformed into a dBASE file for the different types of meteorological data inputs as shown in table 1.

Table 1: Data format inputs for rainfall, temperature and solar radiation.

	A- Rainfall	
Name	Format	Definition
DATE	(mm/dd/yyyy)	Date when measure has been taken
Rainfall	Floating point (f5.1)	Daily rainfall
	B- Temperature (3 fields)	
Name	Format	Definition
DATE	(mm/dd/yyyy)	Date when measure has been taken
MAX	Floating point flottant (f5.1)	Daily maximum temperature (°C)
MIN	Floating point (f5.1)	Daily minimum temperature (°C)
	C- Solar radiation (2 fields)	
Nom	Format	Definition
DATE	(mm/dd/yyyy)	Date when measure has been taken
SLR	Floating point (f5.3)	Daily solar radiation

This same format is used for the wind speed (m/s) and relative humidity (%). Moreover, the use of table 2 remains the same for the location of the air temperature station. However, for the tables of location of the wind, solar radiation and relative humidity stations, the elevation must simply be removed (Yvio, 2008).

Table 2: Table of spatial location of the rainfall station.

Name	Format	Definition
ID	Integer number	Identification number
Name	String max 8 characters	Name of station
LAT	Floating point	Latitude in decimal degree
LONG	Floating point	Longitude decimal degree
ELEVATION	Integer number	Elevation of stations corresponding to rainfall data (m)

Then the hydraulic response unit analysis is done for the spatial input data and the weather/meteorological data table. For the weather generator/ synoptic station all the required values are computed both manually and using helping software such as Hydraccess. Daily discharge outflow data for the Kebir watershed are provided by the Algerian National Agency for Dams and Transfers (ANBT).

3.1.3 Cartographic data

The slope, land use, and soil types are reclassified according to the nomenclature of SWAT. Slope map has been created using DEM and Arcgis 10.4. The land use map is extracted from remote sensing of LANDSAT 8 satellite imagery. LANDSAT 8 satellite imagery is imported from the USGS database. Using supervised classification by ERDAS software and the manipulation by Arcgis software of the spectral band of the LANDSAT 8 ETM satellite image. The newest satellite in the Landsat series offers to scientists a clearer view with better spatial resolution, providing thus moderate spatial resolution, global, synoptic, and repetitive coverage of the Earth's land surfaces (Parece et al., 2014; Kateb et al., 2019).

The land use and soil type maps and tabular databases are used to conduct the realization of the sediment yield model. The mapping of the used soil types, at a 1:500,000 scale and 1:200,000, are developed by the Tunisian Ministry of Agriculture, soil division (1973) and the Geographic Office of the Army (1948). The existing soil types of the basin are Luvisols, Calcisols, Vertisols. Figure 3 shows the distribution of land use, slopes and soil types in the study area.

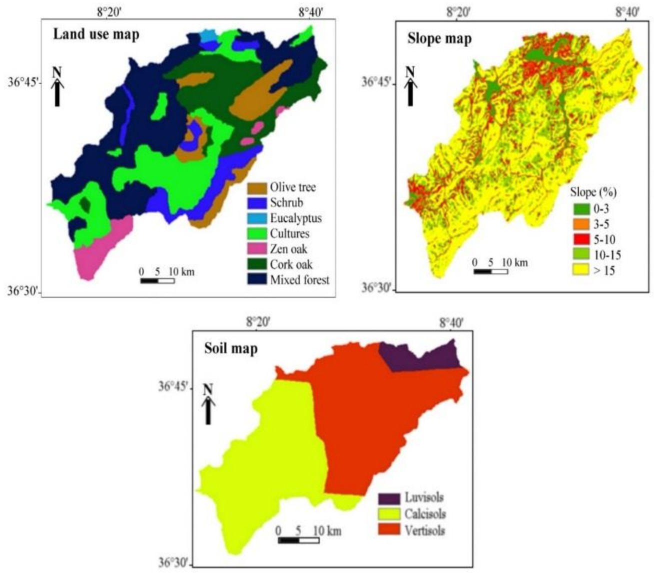

Figure 3: Maps showing slopes, land use and soil types of the Kebir watershed used in SWAT.

The Luvisols occupy the flat or slightly inclined landscapes under climatic regimes ranging from cool temperate to the warm Mediterranean type. The mixed mineralogy, the high nutrient content and the good drainage of these soils make them suitable for agriculture (cereals) and which are present in 10% of the total of the basin area. Based on the Food and Agriculture Organization (FAO) classification system, Calcisols are characterized by a displaced layer of calcium carbonate. These soils represent 43% of the surface of the basin. The Vertisols are soils rich in clay, which undergo significant vertical cracks during the dry seasons. Typically found under grassland and sloping landscapes, they are suited for use as pastures. They present 50% of the basin area.

3.2 Hydrological modelling

The first spatial discretization unit is the sub-watershed, obtained by dividing the basin into sub-basins from the Digital Surface Model by creation of sub-basin outlets. By setting the minimum drainage area for the formation of a watercourse, we define with precision the hydrographic network that we want to model. The division into sub-basins is dependent on the hydrographic network since at each confluence, two outlets are placed and each outlet corresponds to a sub-watershed area (Figure 4A). The sub-basins are indeed hydrological basins and have only one outlet. This step makes it possible to define the overall resolution of the model realization. The obtained Raster sub-watersheds are then converted to vector ones as shapefile (Figure 4B).

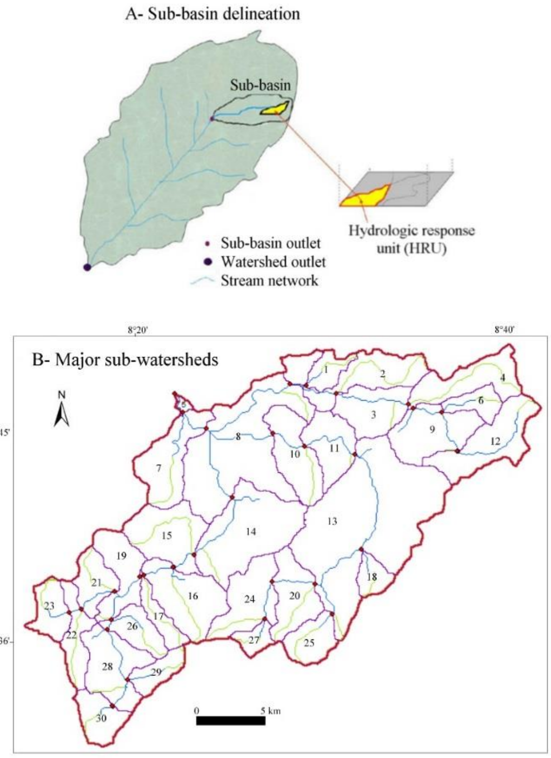

Figure 4: Kebir watershed delineation and subdivision of sub-watersheds.

In applying the SWAT model, the study area is first divided into sub-basins based on the DEM connected through stream channels, and then these sub-basins are further divided into hydrologic response units (HRUs). Each HRU, consisting of unique land use, management, topographical, and soil characteristics, is an independent unit of the SWAT model and does not interact with the other HRUs. Simulation of the watershed hydrology is separated into a land phase, which controls the amount of water and sediment loadings to the main channel in each sub-basin, and an in-stream or routing phase, which is the movement of water, sediment through the channel network of the watershed to the outlet (Arnold et al., 2012). The HRUs are obtained by superimposing each of these data and then by grouping the zones together having similar physical characteristics (Figure 5). Thus, the construction of the SWAT model is based on the concept of HRU, with a geographical area having the same soil, land use and slope classes.

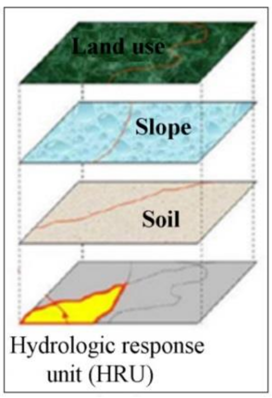

Figure 5: URH delineation approach developed by Grusson, 2016.

In addition, the SWAT model is based on the water balance in the soil profile, and the processes simulated that include infiltration, surface runoff, evapotranspiration, base flow, and percolation (Zhang et al., 2019). Some of the advantages of the Swat model include: modeling of ungauged catchments, prediction of relative impacts of scenarios such as changes in management practices, climate and vegetation on water quality, quantity or other variables (Jain et al., 2010). This provides a useful tool to fill in missing daily data in the observed records. The hydrological cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW + \sum_{t=1}^{t} (R_i - Q_i - ET_i - P_i - Qr_i)$$

Where: SW_t is the final water content available for plants in the soil (mm); SW is the initial soil water content (mm); R_i is the amount of precipitation on day i (mm);

Q_i is the amount of surface runoff on day i (mm); ET_i is the amount of evapotranspiration on day i (mm); P_i is the amount of percolation and bypass existing the soil profile bottom on day i (mm); Qr_i is the amount of return flow on day i (mm); t is the duration in days.

The model performance, defined as the goodness of fit between the observed and predicted sediment yield, is quantitatively evaluated using the Nash-Sutcliffe efficiency coefficient (NSE) and the coefficient of determination (R^2). R^2 ranges from 0 to 1, and typically values greater than 0.5 are considered acceptable (Garbrecht et al., 2003).

4. Results and Discussion

4.1 Model calibration and validation

For the creation of the present project, SWAT model is used in combination with a Geographic Information System (GIS). ARCSWAT is the module allowing the interaction between the Open Source model and the GIS software. It is used in its most recent version ARCSWAT 2012. The hydrological modeling of the watershed is performed using the ARCSWAT 2012 software interface. The model has divided the watershed into 30 sub-basins and subsequently 1526 HRUs (hydrological response units). They are generated by the combination of climate data, plant cover, soil types and slope.

The data being integrated into the model is therefore ready for simulation. Several options are then available to the user. The first step consists in defining the period of time over which the simulation will be performed in relation to the monthly sediment transport measurements in the Kebir basin from 1982 to 1998 at the basin outlet, in order to be able to establish the validation of the simulated model. Then the user can choose the time step of data output (daily, weekly or monthly). A monthly step is initially chosen.

Output files are generated with each new SWAT simulation. The file summarizing the processes on the basin "output.std" allows the user to see at each time step the values of precipitation, runoff, infiltration, evaporation and evapotranspiration, recharge of the aquifer. Another file "output.sbs" presents the same parameters previously mentioned but detailing them at HRU level. A third detail concerns the "output.bsb", the values of the processes at the scale of the sub-watershed.

Finally, the last "output.rch" shows the values of the parameters concerning the water in the river. These files are output in the form of delimited text files and in the form of an "Access" database. An improvement in the simulation is observed during the calibration phase. The model is calibrated on 5 parameters; it is focused on the soil and slope parameters which have an essential impact on the simulations (Table 3). At this stage, a large number of simulations and calibration tests are being carried out in order to best correlate the observed and simulated sediment loads as it is seen in Figure 7.

Table 3: Values of the calibrated parameters in SWAT.

Parameters	Description of the parameters (min – max)	Calibrated parameters
SPCON	Linear parameters for calculating the channel sediment rooting: 0,0001 – 0,01	0.001
SPEXP	Exponent parameter for calculating the channel sediment rooting: 1 – 1,5	1.00
USLE_K	USLE equation for soil erodibility factor: 0 – 0,65	0.35
USLE_P	Conservation practice factor: 0 – 1	0.50
SLSUBBSN	Mean length of slopes: 10 – 150	90

4.2 Annual and seasonal variation of sediment yield

The simulations show high sediment yields in the wet period than in the dry period. It is important to note that this comparison of the observed and simulated sediment yield is made at the outlet of the basin for the period from January 1982 to December 1998.

Visually, the simulated and observed sediment yields have been computed at a monthly scale. Thus, the calculation of sediment yields show that the amount of the observed annual sediment yield and very close to that simulated by the SWAT model (Figure 6). The calibration of the model has given a Nash-Sutcliffe efficiency coefficient of 0.75, indicating a good calibration of the model. Furthermore, the observed annual sediment yield production is equal to 12.20 x 10^6 tons and that of simulated sediment yield is estimated to be 13.20 x 10^6 tons. We note that the estimation error is only + 8.19%; leading to slight overestimation.

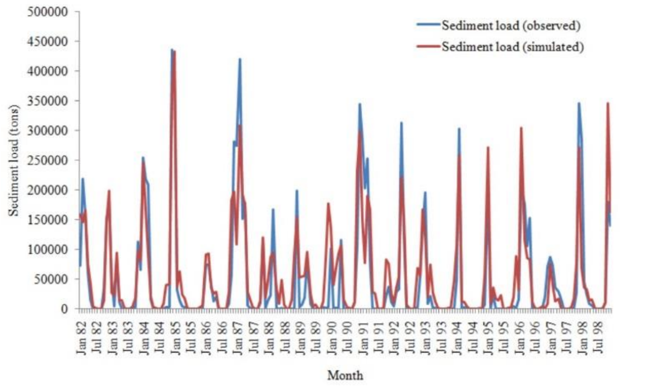

Figure 6: Observed and simulated sediment yield in the Kebir watershed (period January 1982 to December 1998).

The Kebir watershed shows a variation between 0 to 433,100 tons/km^2 (Figure 7). The simulations show that the largest quantities are recorded in January 1985 with 433,100 tons, November 1998 with 346,300 tons, February 1987 with 308,500 tons, December 1990 (299,100 tons), and February 1996 (304,000 tons). These five months have contributed with almost 13% of the total annual sediment load.

Moreover, the observed and simulated mean annual sediment yield during the study period of 1982-1998 are 920.62 T/km^2/year and 996.01 T/km^2/year respectively. Nevertheless, the accepted SWAT simulated model for the period after the dam construction (period 1999-2014) is equal to 6.04x10^6 tons, with a mean annual sediment yield of 608.08 T/ km^2/year. It should be noted that this simulation is done without considering the siltation of the three dams where bathymetric data are not available. In fact, this estimation via modeling is a first attempt which requires in the future the acquisition of other data on the silting up of dams and the introduction of other physical parameters to be able to carry out the estimation of the soil loss in the watershed.

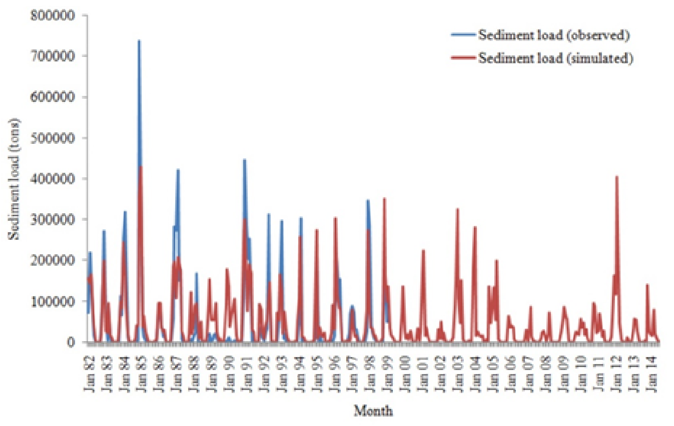

Figure 7: Observed and simulated sediment yield in the Kebir watershed for the period (January1982- July 2014).

The results obtained from the monthly simulation from 1982 to 2014 show that it is possible to identify the major erosion zones in the Kebir watershed. Based on the annual sediment yield in each sub-basin, we find that among the 30 sub-basins, there are the basins: 16, 14, 13, 11 and 8 which are identified as the most affected by water erosion (high and very high classes). They occupy 50% of the basin area, or 330 km^2 (Figure 8). They are spread out at the southeast and northeast parts. These environments are represented by steep to very steep slopes, generally exceeding 25%. There is also sandy clay series with cultivated soils, degraded mixed forest and shrubs which promote erosive dynamics.

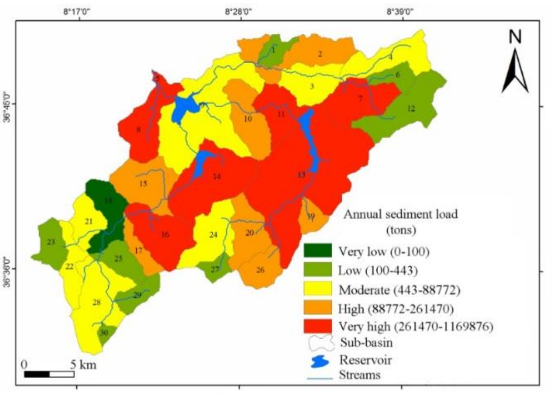

Figure 8: Spatial distribution of sediment yields in the sub-basins of the Kebir Wadi.

The zones of moderate sediment yield production are well developed in the northeast and southeast parts distinguished by the sub-basins of numbers 9, 4, 3, 28, 24, 22, and 21. These sub-basins are characterized by a predominance of clays and marly limestone supporting mostly Cork oak, Zen oak and oleo-lentisk forests and shrubs. The slopes of these environments vary between 5 to 10%. The surfaces occupied by this class is equal to 15% (90 km^2) of the basin area. The low to very low sediment yield distribution concerns the rest of sub-basins such as 30, 29, 25, 21, 12, and 6. They are mainly located in the northwestern, northeastern and southern parts of the basin. These environments are developed on gentle slopes less than 5% and occupy 35% (245 km^2) of the basin area.

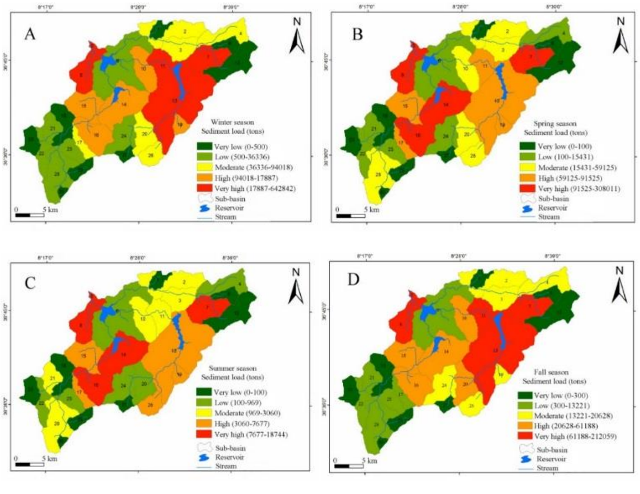

Figure 9: Seasonal variation of sediment yields in the sub-basins according to seasons. A- Winter; B- Spring; C- Summer; D- Fall.

The seasonal variation in the watershed shows a significant sediment yield affecting 50% of the surface of the basin during the winter and fall seasons. The sub-basins 7, 8, 11, and 13 have the highest sediment yields; this essentially depends on the climatic characteristics as storm events (Figure 9). The spring and summer seasons are characterized by a decrease in sediment yield where sub-basins 13, 11, 10, which had high sediment production in winter and in autumn, have received less sediment supply in spring and summer; therefore a very strong to strong change in class.

The sediment yield in summer is not significant but it presents a spatial distribution largely analogous to the spring season. We notice in this spring season a dense to fairly dense, covering forest, protective of their own soil by an underbrush and herbaceous canopy cover under forest, without being often grazed. This brings back to a situation of biostatic equilibrium, thus reducing the effect of morphogenic processes on the removal of soil particles.

5. Conclusion

The application of the semi-distributed model of SWAT model in the Kebir watershed is used for this research of spatial distribution of sediment transport to estimate sediment yield and erosion vulnerability in sub-basins. The model performance criterion used to evaluate the model result indicates that the model is robustness in performing the variability of sediment yield in both calibration and validation periods.

The transport of suspended matter varies greatly depending on hydro-climatic, topography, land cover, soil type factors. The simulated output of the model shows that sediment yield estimated at the outlet are equal to 996.01 T/km^2/year for the period 1982-1998 and 608.08 T/km^2/year for the period 1999-2014. The class of low to very low rates (less than 500 tons) constitutes less than 40% of the area of the basin area, knowing that these areas are located mainly in the downstream part of the basin where the low reliefs and plains dominate.

The sediment concentrations associated flows from the side slopes increase not only with slope gradient but also with slope length, particularly when slope gradients exceed 10%, producing thus the largest quantities of sediment (more than 90x10^3 tons). Slope angle has a clear positive effect controlling soil erodibility and erosion rates. In addition, the temporal distribution indicates that approximately 50% of sediment yield generated in the watershed occurs in winter and fall seasons due to the specific surface conditions of an area.

Furthermore, the simulation of sediment yield by the SWAT model are bringing useful information for targeted management and help involved stakeholders in water and soil conservation activities to choose the most appropriate practice for the study area. Besides this, policymakers are highly recommended to implement appropriate and careful management strategies such as fallow land, contour ploughing, soil bunds combined with trenches and trees on that erosion vulnerable sub-basins to maximize the design span life of the three reservoirs through reducing the sediment yield generated from the Kebir watershed.

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