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International Journal Water Sciences and Environment Technologies
Vol. (vi), Issue 1, April 2021, pp. 114-123
ISSN Online: 1737-9350; ISSN Print: 1737-6688, Open Access
www.jiste.org
Scientific Press International Limited

Erosion Potential Method (Gavrilović Method): Methodological improvements and application in Toudgha River catchment, southeast of Morocco.

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Abstract

In the central high Atlas of Morocco, water erosion is the most important problem among soil degradation factors. It is a dynamic and complex phenomenon, linked to natural and anthropic factors which are difficult to control in time and space. Land degradation has visible impacts on the environment and hinders economic and social development. The consequences of erosion in high Atlas watersheds are costly for the Moroccan economy. The Erosion Potential Method also known as Gavrilović method is a valuable instrument for the estimation of the mean annual sediment yield at the watershed scale. The goal of this paper was to demonstrate its applicability in Toudgha River catchment located in the southeast flank of high Atlas Mountains. Urban areas which are adjacent to the rivers and flood plains are the most vulnerable areas to the water erosion (Tamttatoucht, Tizgui and harat al yamine villages) as they contain large number of population and agriculture economic resources. Thus the local officials of Tinghir city should recognize these prone areas to flooding in order to prevent and mitigate the impact of erosion. The main focus is given on the EPM modification and to provide an annual assessment for the catchment using GIS tools applied in this area as example. This study is the first to assess soil loss due to water erosion in Toudgha River and present the results in a map model. The method is intended for the quantification of erosion processes by estimation of erosion intensity; identify high risk areas and transportation of erosion sediment by river network.

Key Words*:* Erosion Potential Method, Toudgha River catchment, GIS, central high Atlas, water erosion risk, Morocco.

Méthode d'érosion potentielle (méthode du Gavrilović) : Méthodologie et application au bassin versant de la rivière du Toudgha, sud-est du Maroc

Résumé

Dans le Haut Atlas central du Maroc, l'érosion hydrique est le principal facteur de dégradation des sols. Il s'agit d'un phénomène dynamique et complexe, lié à des facteurs naturels et anthropiques difficiles à contrôler dans le temps et l'espace. La dégradation des sols a des impacts visibles sur l'environnement et sur le développement économique et social. La méthode d'érosion potentielle, également connue sous le nom de méthode Gavrilović, est une approche pour l'estimation de la production annuelle moyenne de sédiments à l'échelle d'un bassin hydrographique. L'objectif de cet article était de démontrer son applicabilité dans le bassin versant de la rivière du Toudgha, situé sur le flanc sud-est de massif du haut Atlas central. Les zones urbaines adjacentes aux rivières et aux plaines inondables sont les plus vulnérables à l'érosion hydrique (villages de Tamttatoucht, Tizgui et harat al yamine) car elles contiennent un grand nombre de ressources économiques liées à la population et à l'agriculture. Les autorités locales de la ville de Tinghir devraient donc reconnaître ces zones vulnerables aux inondations afin de prévenir et d'atténuer l'impact de l'érosion. L'objectif est mis sur la modification de l'EPM et sur l'évaluation annuelle du bassin versant à l'aide d'outils SIG appliqués dans cette zone à titre d'exemple. Cette étude est la première à évaluer la perte de sol due à l'érosion hydrique dans la rivière du Toudgha et à présenter les résultats dans un modèle cartographique. La méthode est destinée à la quantification des processus d'érosion par l'estimation de l'intensité de l'érosion ; à l'identification des zones à haut risque et au transport des sédiments d'érosion par le réseau fluvial.

Mots Clés : Méthode d'érosion potentielle, bassin versant du Toudgha, SIG, Haut Atlas central, risque hydrique, Maroc

INTRODUCTION

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In recent years, many methods for erosion intensity and sediment production assessment and estimate have been developed. The necessity for better model performance lead to the more frequent application of the method sensitivity in order to decrease errors that arise from the model concept. Soil erosion due to surface water is one of the most important land degradation problem and a critical environmental hazard worldwide [12]. Human development and the inappropriate land utilization have accelerated the soil erosion at many locations on the earth's surface [3] [24] [34] As a result, every year millions of tons of sediment are produced around the world, and the water erosion is responsible for more than 56% of this sediment volume [9].

The impacts of soil erosion include decrease of effective root depth, nutrient and water imbalance in the root zone, also has led to the decrease in soil quality that results in loss of fertile top soil cover and a reduction in agricultural production. It also delivers millions of tons of sediment into reservoirs and lakes, causes damages to the dams facilities, and results in high economic costs by affecting the water quality [24] [30]. Thus, soil erosion is being considered as one of the major threats to global economic and environmental sustainability. Some temporally invariable parameters such as lithology, size of watershed, and variable factors such as climate, hydrology, ground cover, and land use also affect the sediment yield [17] [33] Note that soil erosion and sediment yield from agricultural or highly degraded forest areas is typically higher than that from uncultivated areas. Cultivated areas can act as both a source and a pathway for transporting nutrients [21].

Many studies have shown that human activity is the major cause of recent changes in the land use [3]. Also in non-residential areas biophysical conditions of the land, such as lithology, soil characteristics, hydrology, topography, and ground cover largely determine the spatial pattern of the land use and its temporal changes [10] [28].The analysis presented in this paper refers to the application of the Gavrilović method (Erosion Potential Method), an empirical and semi-quantitative method that can estimate the amount of sediment production and sediment transport in Toudgha River watershed in Morocco as well as the erosion intensity and indicate the areas potentially threatened by erosion.

Each parameter was discussed individually in relation to its effect upon the method results, and ranked into categories depending on their influence. The reason of the analysis was to explore the constraints of the Gavrilović method and the method response to changes deriving from each individual parameter in reason to provide a better understanding of the EPM method, the weight and the contribution of each parameter in the overall method. The parameters that could potentially be used in future research, for method calibration and modification in catchments with different characteristics.

There are a variety of methodologies and models that can be applied to erosion sediment production assessment [16] [7]. The limit of application behind them differs; each model integrates different scientific technics and modeling approaches. Water erosion models differ in the output informations they provide (erosion sediment production, high risk areas erosion intensity and sediment transportation) but also in terms of complexity, the process considered and the data required for model calibration and model application [7].

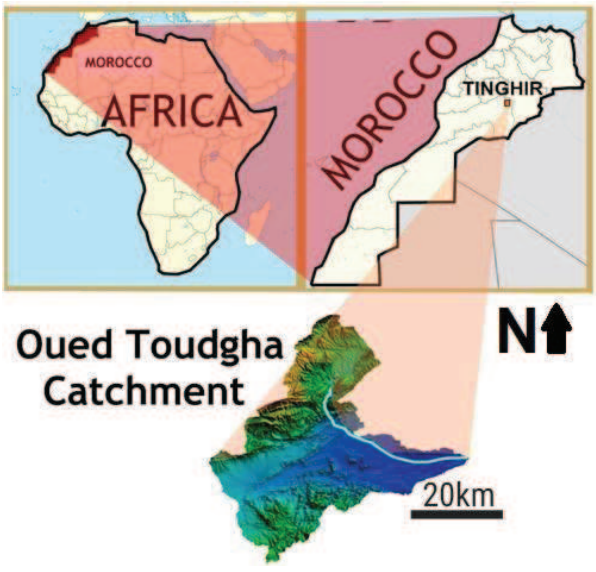

Figure 1. Geographic setting of the study area of Toudgha river catchment.

The Toudgha river watershed is located to the west part of the large Ziz-Ghris basin, which corresponds to a Mesozoic tectonic depression [15]. It is bordered in the north by the reliefs of the central high Atlas and in the south by those of the Anti-Atlas chain.

The basin is mainly occupied by a principal river called (Oued Toudgha) in Figure 1, which drains the southern part of the central High Atlas chain. This basin is monitored by the hydrological station of Tamtattoucht, located upstream of the Toudgha gorges for 20Km to the North and the second one of Ait Bouijane station is about 40km to the South of the first. Toudgha River feeds the Tinghir region palm grove, and then crosses the Tinjdad palm grove.to finally join the Ziz basin hydrographic network.

The Toudgha valley appears larger in the downstream part, while it becomes more entrenched to the upstream region. This allows us to subdivide the basin into three domains based on the overall relief presented in Figure 2 below : 1/ a high mountain domain which includes high reliefs constitute by carbonate facies of liassic age; 2/ a second intermediate domain characterized by quite important reliefs corresponding to the hills of the upper cretaceous period, but with less elevation than the previous ones; 3/ a downstream domain characterized by altitudinal depressions (small basins) and ending with the flat zone (quaternary deposit).

This diversified relief includes rugged terrain in the northern, north-western (High Atlas) and south-western parts (Anti-Atlas which corresponds to the northwest front of the Craton West African). Plateaus are located in the central part in particular, in the pre-African furrow, while the plains are covered by sedimentary terrains of Quaternary deposits which are the Tafilalt plain, oasis of Goulmima, Ferkla and Ghelil.

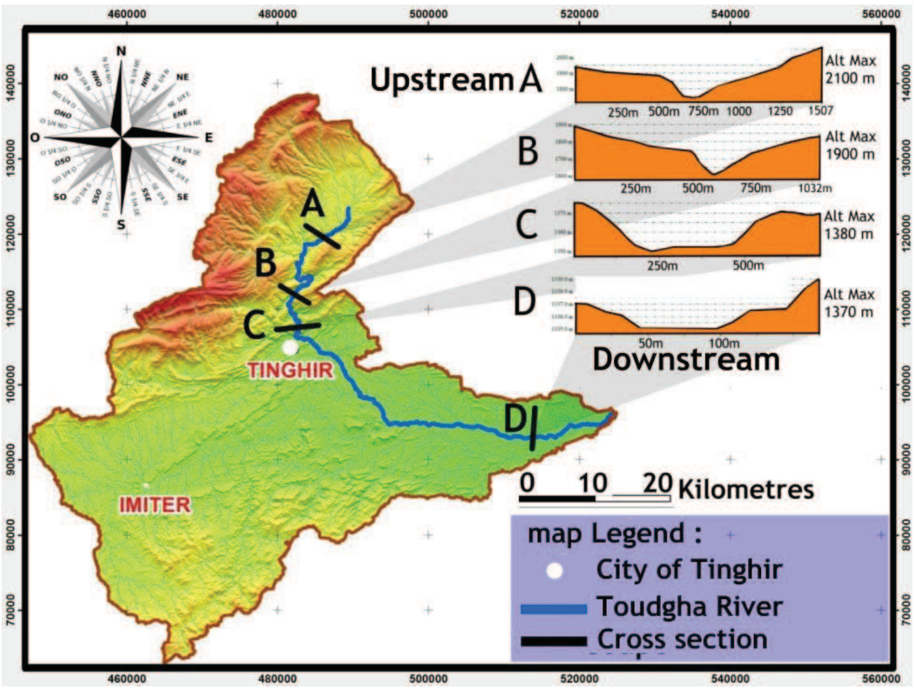

Figure 2. Cross sections showing the evolution of the river bed width of Toudgha River from upstream to downstream.

From the previous descriptions we confirm that the lateral borders of Toudgha river floodplain are essentially formed by permeable to semi-permeable soils and materials (sandstone, conglomerate ,less consolidated limestone, clay and silt) these lithological compositions will leads to the infiltration of rainfall to deep layers (high porosity), this circulation of water will contribute to the increase of vulnerability and the instability of these areas especially the river banks and flood plain areas that will make it easier to result in water erosion discharge and sediment transportation during flood events.

MATÉRIALS AND MÉTHODES

The first step to predict erosion and its severity on Toudgha river catchment is finding the methodology to apply. The restrictions of scale applicability of a method, and type of erosion the method deals with, has already covered within past researches [7] [2]. The accessibility of the data is often the crucial factor in the process of a model which is why this criterion is considered as the most relevant factor in proposed and applied methodology in this area.

Till the present, there has not been a model that considers all these processes together and can be applied on the catchments with the area of 30 km² or more with satisfying results [7]. Spatial heterogeneity, natural complexity and the lack of available data are the main reasons that increase the error rate of a model results. The first step, after the preliminary research, geographic and lithological informations gathering about the area, knowing the limit of application of the method, the research aims and goals for the area of interest has been defined, is to compose the primary list of existing erosion models as to be a first step in the process of appropriate method selection.

Different erosion models have been applied to evaluate soil erosion rates. Modeling is widely used in erosion studies [4]. There are different classifications of erosion models. They are divided into empirical and process based models. USLE [31], RUSLE [23], MUSLE [14]. and modified versions of these models are examples of empirical models. Papers applying these models were published in the international database of Web of Science.Examples of process-based erosion models: LISEM [11] MMF [20] [25] WATER/SEDEM [22], SWAT [29] and EUROSEM [19].

The EPM was developed by Gavrilovic based on field research conducted in the Morava River Catchment area in Serbia and has been applied worldwide in areas threatened by water-induced erosion processes [1]. The erosion model presented in this article which is presented in Figure 3 is based on the EPM and was used to provide three results: the erosion coefficient Z (Equation (1)), the total annual volume of detached soil Wa (m3/year) (Equation (2)) and the actual sediment yield Gy map (Equation (4)) which is applied for the first time in Toudgha river catchment.

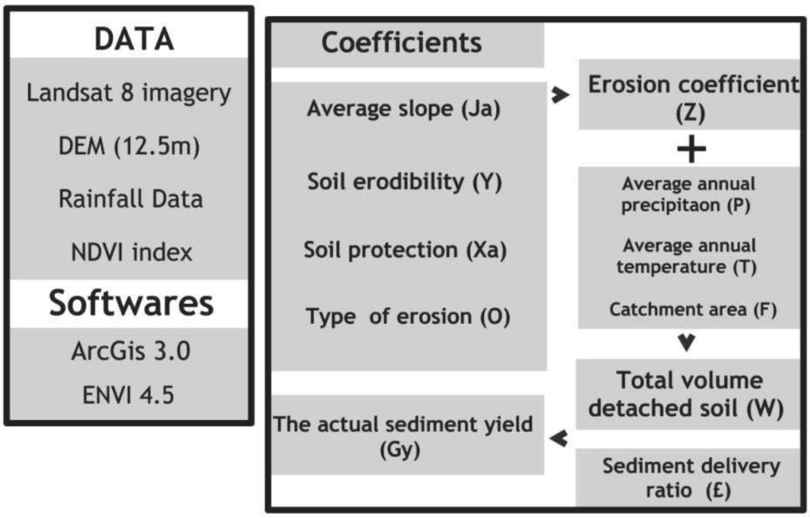

Figure 3. Flow chart of the adopted model based on the EPM.

(Equation (1)) $Z=Y*Xa*(\phi+\sqrt{Ja})$ (the erosion coefficient)

Where (Y) is the soil erodibility coefficient, (Xa) is the soil protection coefficient; (ϕ) is the coefficient of type and extent of erosion, (Ja) is the average slope of the study area (%). The erosion coefficient (Z) is the only method output that shows both numerical and descriptive information about the area susceptibility to erosion processes.

(Equation (2)) $Wa = T*Pa*p*Z1.5*F$ (the total annual volume of detached soil)

Where T is the temperature coefficient calculated by using (Equation (3)), Pa is the average annual precipitation (mm) and F is the study area (km2). Temperature coefficient is calculated using Equation (3):

(Equation (3)) $T = \sqrt{[(T0/10) + 0.1]}$ T0 is the average annual temperature (° C).

(Equation (4)) $Gy = £ * Wa$ (the actual sediment yield)

Where £ is the sediment delivery ratio and can be calculated using the modified (Equation (5)) proposed by Lazarevic [7]:

(Equation (5)) $£ = [\sqrt{(O*z)} / (lp + 10)] * Dd$ (the sediment delivery ratio)

Where O is the perimeter of the study area (km), z is the mean difference in the elevation of the study area (km), lp is the length of the principal waterway (km) and Dd is the drainage density (km/km2)

(Equation (6)) $Dd = (lp+la)/F = L/F$ (the drainage density)

Where la is the cumulative length of the secondary waterways (km) and L is the cumulated length of the principal and secondary waterways (km). The soil protection coefficient, soil erodibility coefficient, and coefficient of type and extent of erosion are determined using tables that provide descriptive and numerical evaluations for these parameters.

The average annual precipitations Pa was obtained from the Ziz ghris Agency data, and the average annual temperature T was extracted using the band number B10 of landsat 8 Oli/Tirs analysis under GIS software, with an average temperature of 12 months of the year 2019 (by calculating the average of 12 values extracted from 12 bands of Landsat 8 oli/Tirs (Band10)).

In present work, firstly the Landsat 8 OLI/TIRS C1 Level-1 satellite image has been downloaded from www.earth explorer.usgs.gov, covering the complete study area acquired on 2019/02/19.

Quantitative assessments of the intensity of soil erosion and its spatial development have been extensively developed using erosion modeling at different levels of generalization, from small watershed to continental scales [13]. Currently, GIS tool and remote sensing are widely used to calculate the erosive soil loss. These systems allow large amounts of data to be processed and to help evaluate the amount of erosion at an acceptable accuracy at different levels of generalization. Advances in modern GIS technologies have allowed us to evaluate the erosion of unprecedentedly large basin and create cartographic models of soil erosion in Toudgha river catchment.

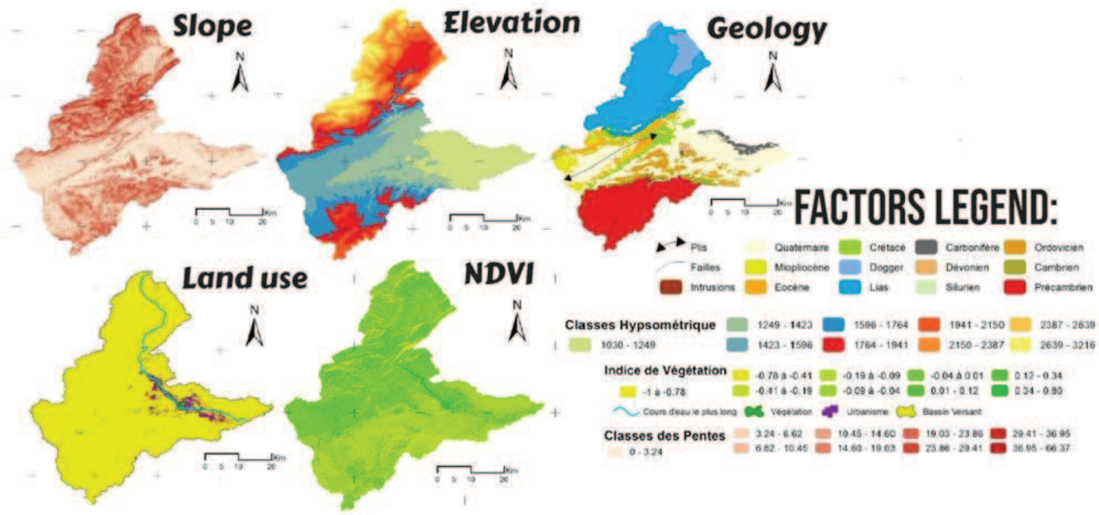

Figure 4. Preliminary factors integrated to calculate the EPM coefficients: land use, lithology, elevation, slope and NDVI.

RESULTS AND DISCUSSION

Erosion intensity and sediment production assessment:

Soil erodibility coefficient Y:

Soil erodibility presented in figure 5 is one of the most important factor integrated in erosion models. Its significance has been pointed by many scientists before such as [18] [5] [32].

This coefficient is based on soil type of Toudgha River catchment. For the purpose of uncertainty analysis, the map was derived based on the four Geological maps of Tinghir area with the scale 1:100 000 and evaluated according to the proposed tables for the Gavrilović method.

Soil protection coefficient Xa:

The equation using to measure the Xa parameter in Toudgha river catchment was:

$Xa = (XaNDVI-0.61)*(-1.25)$ **[6]**

$NDVI = (NIR-R)/(NIR+R)$ >> $XaNDVI = Min - 0.9\ NDVI < > Max + 0.6\ NDVI$

> $Xa = NDVI$ (values between -0.9 and +0.6)-0.61)*(-1.25)

Coefficient of type and extent of erosion ϕ:

This coefficient is a parameter integrated in our model calculation, which was obtained by using the equation below:

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$\Phi = \sqrt{R}/Q_{max}$ R = in our case it is the Band number 4 image in case of using (Landsat8 Oli/Tirs) images.
Qmax = value obtained from the attached MTL file (quantize_cal_max_band_4 = 65535)
> Qmax=65535

Average slope of the study area Ja:

The Alos palsar digital elevation model with a 12.5 * 12.5m cell size spatial resolution, from which the average slope of the study area (Ja factor) and mean difference in elevation (z) of the study area, The perimeter of the study area (O) the length of the principal waterway (Ip) and the drainage density (Dd) were extracted.

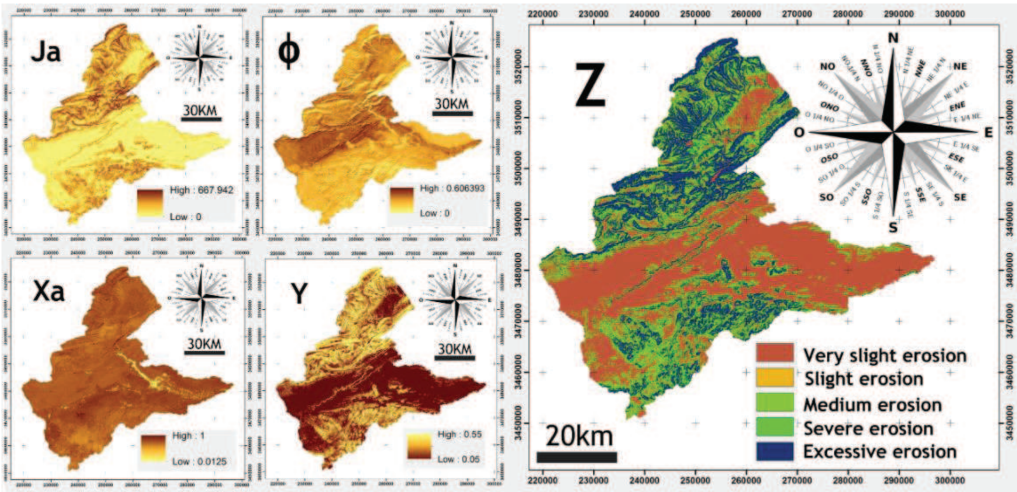


Figure 5. The coefficients maps used to elaborate the erosion coefficient Z map by the contribution of equation (1).

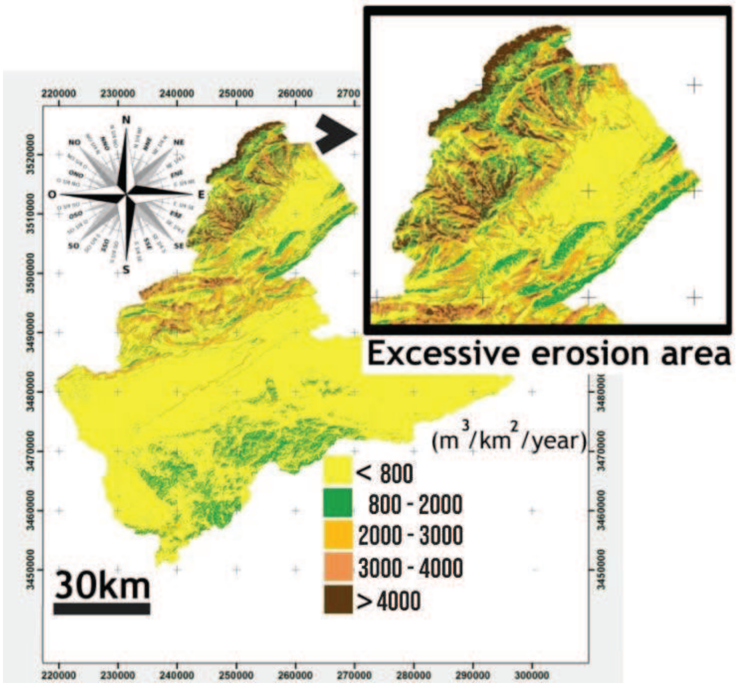
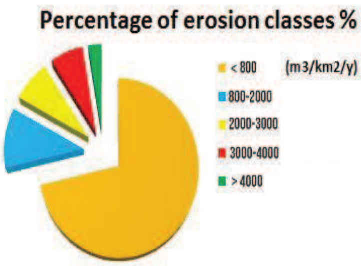


Figure 6. The Toudgha river catchment soil erosion map (Wa) showing the total annual volume of detached soil using EPM

Table 1. Distribution of soil loss classes in the catchment 'Area / percentages values'.



Code	Classes (m3/km2/y)	Erosion Type	Area(km2)	%
1	<800	Very slight	1645.96	71.57
2	800-2000	Slight	251.31	10.93
3	2000-3000	Medium	180.27	7.84
4	3000-4000	Severe	158.42	6.89
5	>4000	excessive	63.56	2.76

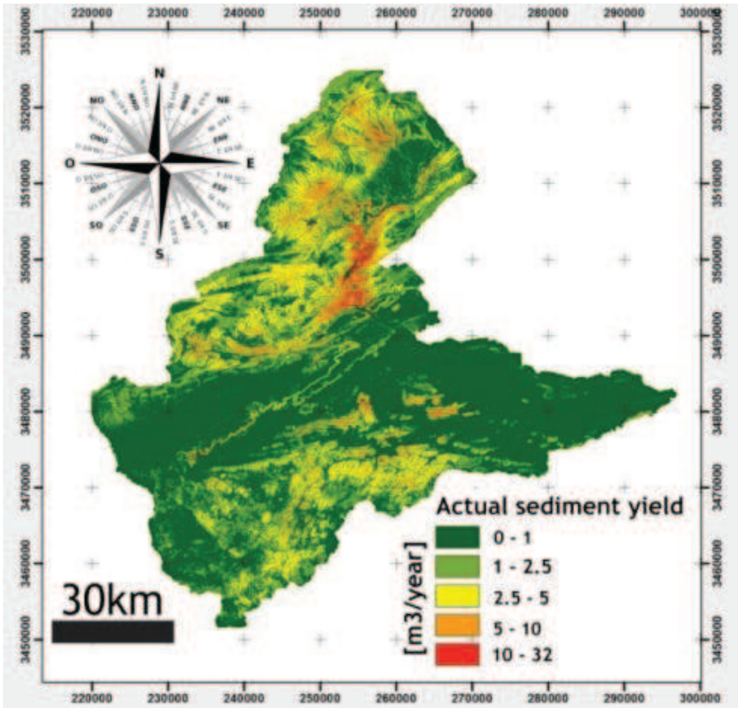


Figure 7. Actual sediment yield Gy of Toudgha river catchment.

The highest amounts of soil loss by applying the EPM model occurred in Toudgha river cathchmet is located in the extreme NW with an average of 4000 ($m^3/km^2/y$) this area constitute the highest value of rainfall /snowfall during the whole year, also its known by its lithological units (marle,dolomite,clay and limestone),the characteristics of this area (very steep slope and the very low vegetation cover) made it the source and the most area with high probability of occurrence of the hydric erosion risk and generally to be an area that produce all landslide types include falls, topples, translational slides, lateral spreads, and flows. Based on the spatio-temporal analysis of the potential losses of soil from water erosion within the whole parts and units of the area, we conclude the following results which are presented in Figure 6 and Table 1:

• There was a significant (71.57%) soil erosion rate occupied an area of 1645. 96 km^2 with an annual erosion of (< 800 m3/km2/year) on land located and characterized by area with very low slope even flat zone, urban area and by a high vegetation cover region as presented in Figure 6.

• There was a percentage of (7.84%) in soil erosion rate occupied an area of 180.27 km^2 with an annual erosion of (between 2000 - 3000 $m^3/km^2/year$) in the central part of the basin with medium slopes degrees in north part of the central high-Atlas Mountains.

• There was an average of (2%) in soil erosion rate occupied an area of 63.56 km^2 which is the most excessive erosion area with a minimum amount of 4000 $m^3/km^2/year$, at least three factors made this area a high risky zone in the whole basin which are the steep slopes, absence of vegetation cover and the important snowfall during the autumn season.

DISCUSSION

The model outputs are mainly based on the multiplication of the model parameters; thus, for example, when varying the Average erosion resistance of rocks (Soil erodibility coefficient Y), the model outcome total annual volume of detached soil Wa will vary proportionally. Not all parameters are included in the model through multiplication, examples of the average slope of the study area Ja, Average annual temperature T0, and Drainage density Dd Most of these parameters are categorized as high sensitivity, whereas those in the multiplication form are classified as very high-sensitivity factors.

The second thing that should be taken into consid¬eration during model modification in order to mitigate model errors and uncertainties is whether or not the average annual temperature is given a high enough significance in the model. The question is if the integration of T0 (annual temperature average in our case which was 32° for Tinghir region) in this way in the method restricts its use only within the areas of similar climate.

Average slope length and gradient of the upper part of Toudgha River catchment have a great impact upon water erosion, runoff, and downslope sediment transport and as such represent study area topography .The impact of this parameter (Ja) upon a method outcome is high but according to its calculated values for sensitivity index I, Ja falls within parameters with lower high-sensitivity class values. All these parameters could potentially be used in future research where the need for its modification and method calibration presents for research areas with different characteristic (e.g. climate, geological, etc.) than those applied to nowadays.

[27] Indicated the dependence of parameter sensitivity ranking, for higher ranked parameters, on the variable, the location, and case study. They highlighted the need for the sensitivity analysis to be conducted on each new catchment study in order to select a subset of pa-rameters to be used for model calibration or/and uncertainty analysis. Overall, the most sensitive model parameters resulting from the conducted sensitivity analysis for Gavrilović method are also those considered significant in the scientific literature on erosion [26] [18].

Soil erodibility coefficient and soil protection coefficient Xa are considered very high-sensitive parameters with Xa being a high-sensitive parameter in relation to Wa model output. [8] Analyzed the effect of using different information sources for land use parameter Xa and noted significant deviation in model output values. Although, their analysis explores the parameter uncertainty in a model, it is also closely related to parameter sensitivity analysis since both analyses take into consideration the deviation in a parameter value, whether intentionally choosing the percentage for which its value will differ or choosing among various data whose deviation is defined by other external factors.

This research allows us, for the first time, to obtain quantitative data on the intensity of soil erosion in this area located in the south par of central high atlas of Morocco.

In addition, our research can also be considered a pilot project. The limitations associated with the sources of information, quality, and level of detail of the original data, as well as unresolved methodical objectives, are clearly visible as follows:

• Unfortunately, there is no national DEM with a high spatial resolution for Morocco; therefore, we used the global freely distributed DEM of Alos palsar 12.5m*12.5m, which does not have the highest spatial resolution among global freely distributed models. Our use of a more detailed terrain model as a result, the calculation of the LS factor from the used DEM may be underestimated;

• Due to the absence of erodibilty maps, we have used only the geological maps of the area (4maps) for producing Soil erodibility coefficient, with a scale of 1/100 000, this model greatly simplifies the spatial distribution of soil type hardness.

• The sparseness of the existing hydro meteorological stations (2 stations) in the study area also limits the spatial detail of erosion calculations by using a minimum data of rainfall data.

CONCLUSION

The Gavrilović method is a semi-quantitative method that enables assessment of erosion coefficient (intensity), total annual sediment production and actual sediment yield. During the research on the application of this method in Tinghir region and on the first time globally in the southeast of morocco, was noticed that the analysis using the modified formula for the sediment delivery ratio, that includes the drainage density as the ratio between the primary and secondary river length and catchment area, obtains results that correspond better to on-site measurements. From that, the recommendation to use modified formula for sediment delivery ratio in all future analysis including Gavrilović model was emphasized to avoid incorrect results indicating larger values for the actual sediment yield compared with those of the total annual volume of the detached soil (maximum interval between 4000 – 4500 m^3/km^2/year).

The data included in the model are subdivided into spatially variant and spatially invariant parameters. Soil erodibility coefficient is based on soil type in the area of interest and has been pointed as one of the most important parameters in erosion models. The model output erosion intensity, land cover map for the present area and the soil surface change were verified using Landsat imagery and visual survey in the field. All verifications revealed good results, and the high accuracy of the derived maps was confirmed. The research presented in this article has shown that the EPM model works well and can differentiate areas highly susceptible to erosion form those less so. However, for more specific and accurate analysis on model performance estimating the amount of soil loss, quantitative measurements are needed.

Despite its simplicity, EPM provides reliable sediment erosion estimates and, on the basis of the suggested modifications, it may prove to be an useful instrument for the assessment of the intensity of this phenomenon also in other parts. The modifications suggested for the application stage reflect more accurately the calibration approach followed by Gavrilovic in the definition of EPM parameters.

In summary, erosion occurred over all parts of the study area. The results showed that the central and southern parts of the watershed were lowly susceptible to erosion due to their hard and coherent lithological formations and the land cover variation, while the northern parts were more subjected to erosion due to less vegetation and steep slopes. Therefore, elaboration of erosion management plan to decrease the sediment production especially in the north parts of the Toudgha River is suggested. This study provided valuable information and demonstrated the usefulness of applying geospatial information in natural resources and soil conservation projects.

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