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Sediment yield estimation using a semi-quantitative model and GIS-remote sensing data*

M. Mahmoodabadi

Department of Soil Science, Agriculture Faculty, Shahid Bahonar University of Kerman, Kerman, Iran

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A b s t r a c t. This study applies the MPSIAC semi-quantitative model along with geographical information system and remote sensing techniques to estimate sediment yield in a semi-arid region in central Iran. Nine data layers of the model were generated from Landsat ETM$^+$ imagery, adapted regional maps and field surveys. The GIS was applied to integrate the layers together and generate the sediment yield map. The results showed a range of sediment yield from 263.3 to 496.9 t km^{-2} year^{-1} with an average of 356.4 t km^{-2} year^{-1}. However, it seems that descriptions of the model are sometimes too broad for making reliable scoring. Nevertheless, this model is generally less data demanding and provides an efficient way to estimate sediment yield in ungauged basins. It was found that hills are the most sensitive land types to sediment yield in the region.

K e y w o r d s: soil erosion, MPSIAC model, satellite data, semi-arid region

INTRODUCTION

Soil erosion is one of the most significant forms of land degradation (Erskine *et al*., 2002) and a severe eco-environmental problem (Pan *et al*., 2006) in the world. There is an increasing interest in improving water resource development, watershed management, land use and productivity (Daroussin and King, 2001). Erosion decreases soil quality and crop production, declines on-site land value, and causes off-site environmental damage. In order to protect lands from further degradation and make mitigation measures effective, it is essential to assess erosion hazard severity. Sediment yield data and appropriate prediction tools are fundamental requirements for planning and managing water resource development schemes (Haregeweyn *et al*., 2005). Recently, many process-based and empirical models are proposed to describe and predict soil erosion by water, and associated sediment yield. Since most process-based erosion models, in general, are not well tested and require many input parameters, the empirical prediction models continue to play an important role in soil conservation planning. Physically-based models and also the more complex conceptual models, while having other merits, are not particularly appropriate for estimating basin sediment yield since many of these models focus only on a limited number of erosion and sediment transporting processes (Merritt *et al*., 2003). In contrast, empirical models are used due to their simple structure and ease of application (Amore *et al*., 2004). However, these kinds of models are often based on multiple correlations performed on site-specific empirical data, limiting their application to the specific site of origin. Due to the complexity of sediment yield models, many researchers have tried to overcome these limitations by producing numerical values to describe catchment characteristics. Often, these models are a combination of descriptive and quantitative procedures that describe a drainage basin and result in a quantitative or sometimes qualitative estimate of sediment yield in a basin. Therefore, these models can be classified in general as semi-quantitative. The low data requirements and the fact that practically all significant erosion processes are considered makes semi-quantitative models especially suited for estimating off-site effects of soil erosion (de Vente and Poesen, 2005).

The universal soil loss equation (USLE) is the most widely used empirical model (Wischmeier and Smith, 1965). In different parts of the world, USLE (Erskine *et al*., 2002; Lee, 2004) and revised USLE (Renard, 1997) has

Corresponding author's e-mail: mahmoodabadi@mail.uk.ac.ir
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been used by some researchers. Some other models have been applied for estimating erosion severity and sediment yield in sub-catchment area for which hydrometric data is not available. In this regard, the semi-quantitative models benefit from a more quantitative description of factors used to characterize the basin. Probably the most well known semi-quantitative model was developed by the Pacific South-west Inter-Agency Committee (PSIAC, 1968) for application in arid and semi-arid areas in the south western US (de Vente and Poesen, 2005) and is believed to be appropriate for the same environmental conditions in Iran (Tangestani, 2006). Unlike USLE and its different versions, the PSIAC model can be applied to estimate total annual sediment yield (Woida and Clark, 2001; Mahmoodabadi *et al*., 2005), and not just that resulting from sheet and rill erosion. The PSIAC model was developed for watersheds bigger than 30 km^2, however its application in smaller catchments had also good results (Tangestani, 2006). This model is factor-based and consists of a rating technique that characterizes a drainage basin in terms of sensitivity to erosion, possibilities for sediment transport and floodplain storage, the protective role of vegeta- tion, and the influence of human land use practices (PSIAC, 1968). The procedure considers nine factors that depend on sur- face geology, soils, climate, runoff, topography, ground cover, land use, channel erosion, and upland erosion (Table 1). After summation of the individual scores, the sediment yield rating index can be determined and converted into an esti- mated sediment yield. A modified version of PSIAC was presented by Johnson and Gebhardt (1982) who produced a numerical basis for calculating the score rating for indi- vidual factors to reduce the subjectivity of the assessment, so called the modified PSIAC method (MPSIAC). In Iran, some studies have been conducted to evaluate the semi- quantitative PSIAC model and its modified version and to test its accuracy in estimation of sediment yields (Mahmooda- badi *et al*., 2005; Tangestani, 2006). The results of these stu- dies indicate that the model represents better estimation in comparison to other existing models.

Any model for computing soil erosion and sediment yield must deal with a large number of variables. The GIS allows simpler and faster data and parameter management. Therefore, GIS is a useful tool for sediment yield studies. Applications of GIS and remote sensing techniques in erosion and sediment yield assessment have been developed recently (Lee, 2004). The combined use of remote sensing, GIS and erosion models has been shown to be an effective approach for estimating the severity and spatial distribution of erosion. Clark (1999) compared the sediment yield of the PSIAC model and the observed data in two basins of New Mexico. The results indicated that applying the GIS, the differences between predicted and observed values were 11-14%, while without using the GIS these differences rose to 30%. Woida *et al*. (2001) developed a GIS-based application to analyze the PSIAC factors in a distributed manner at a 30 m resolution. It was found that this captured better the variability of the watershed characteristics and provided better estimates than without the use of the distributed data. So, applying the GIS and remote sensing would improve the prediction of sediment yield.

The purpose of this study was to assess the MPSIAC semi-quantitative model using GIS and remote sensing for erosion and sediment yield prediction.

MATERIALS AND METHODS

The study was performed in the Golabad watershed which is located between 51° 56’ and 52° 14’ E and 33° 01’ and 33° 22’ N with an area of 582.7 km^2 in a semi-arid region

T a b l e 1. MPSIAC factor ratings (Johnson and Gebhardt, 1982)

MPSIAC factor	Equation and description
Surface geology	$Y_1=X_1$, where X_1 is a geology erosion index based on rock type, hardness, fracturing and weathering from geological reports (hard massive rock has an index of one and marine shale, mudstone or siltstone has an index of 10)
Soils	$Y_2=16.67X_2$, where X_2 is the USLE soil erodibility factor values determined by procedures of Wischmier and Smith (1978)
Climate	$Y_3=0.2X_3$, where X_3 is 2 year, 6 h precipitation amount in mm determined from weather records
Runoff	$Y_4=0.2X_4$, where X_4 is the sum of yearly runoff volume in mm times 0.03 and of yearly peak stream flow in m^3 sec^{-1} km^{-2} times 50
Topography	$Y_5=0.33X_5$, where X_5 is slope steepness in percent
Ground cover	$Y_6=0.2X_6$, where X_6 is bare ground in percent
Land use	$Y_7= 20-0.2X_7$, where X_7 is canopy cover in percent
Upland erosion	$Y_8=0.25X_8$, where X_8 is the Soil Surface Factor (SSF) determined by procedures described in Bureau of Land Management (BLM), Manual 7317
Channel erosion	$Y_9=16.67X_9$, where X_9 is the SSF gully rating associated with X_8

in central Iran (Fig. 1). The elevation of this region varies from 1 653 to 2 947 m a.s.l. and the average precipitation is about 170 mm year^{-1}. Rangeland is the dominant land use in the watershed, while due to specific climate conditions, land use, and high grazing rate, there is poor vegetative cover in the watershed. Based on soil taxonomy, the common soil orders are Aridisols and Entisols. This is as a result of unfavourable conditions of soil development such as limited soil formation and considerable soil erosion rate. Consequently, in some parts, in addition to the ochric, also the calcic horizon can be observed at soil surface. The texture of studied soils ranges from clay loam to sandy loam with considerable amount of gravel (32%). The organic matter content is between 0.25-0.43% and $CaCO_3$ varies from 11 to 46%. These conditions lead to high erodibility of soils, since it is influenced by soil properties such as organic matter, particles dispersibility, and aggregate stability (Dexter and Czyż, 2000; Igwe, 2000; Igwe and Udegbunam, 2008).

In this study, integrated land and water irrigation system (ILWIS) by Westen and Farifteh (1997) academic version 3, was used to construct different digital layers and databases. Besides, remote sensing data were derived from enhanced thematic mapper plus (ETM^+) data of the Landsat satellite. The input data to the model were prepared by means of maps *eg* topography, geology, land use, *etc*., reports and field reconnaissance. Land capability and resources map (scale of 1:250 000) of the watershed was selected as the base map (Fig. 2). As shown in this map, mountains (1-2, 1-3, 1-4), hills (2-1, 2-2, 2-4), plateau (3-1, 3-2, 3-4) and alluvial fans (8-1, 8-2) are four dominant land types in the region. In order to check the boundaries of the map units, ETM^+ data were used. Different combinations of 7 bands were constructed to obtain the best colour composite map on the basis of the least correlation. According to correlation matrix, a colour composite image created by bands of 1, 5, and 7, had the most useful information for our purposes. After digitizing the land capability map as a base map, it was crossed to the colour composite map of the satellite imagery. Due to some deviations of boundaries, the base map was adapted using colour composite and topography maps. This modified version map of land units is shown in Fig. 3.

To apply the MPSIAC model, the nine input layers were created based on the descriptions given in Table 1. In order to run the model in the GIS framework, each layer was digitised and scored, individually. The sediment yield rating index map was prepared by integrating these nine layers. Annual sediment yield was calculated using the following equation (Johnson and Gebhardt, 1982):

$$S_y = 0.253e^{(0.036R)}, \quad (1)$$

where: S_y is the sediment yield (t ha^{-1}), assuming a sediment volume-weight of 1.360 kg m^{-3}, *e* is the base of natural logarithms, and *R* (sediment yield rating index) is the sum of MPSIAC factors.

RESULTS AND DISCUSSION

Table 2 shows nine scored-layers for different land types and the land units. The present watershed has diverse geology structures, while most parts of the basin are formed of quaternary deposits with high sensitivity to erosion. By soil sampling and field experiments, the erodibility factor in USLE for each land unit was determined and then the soil layer was obtained. Erodibility was assessed by the USLE *K* factor. The soil-erodibility factor (*K*) is the rate of soil loss

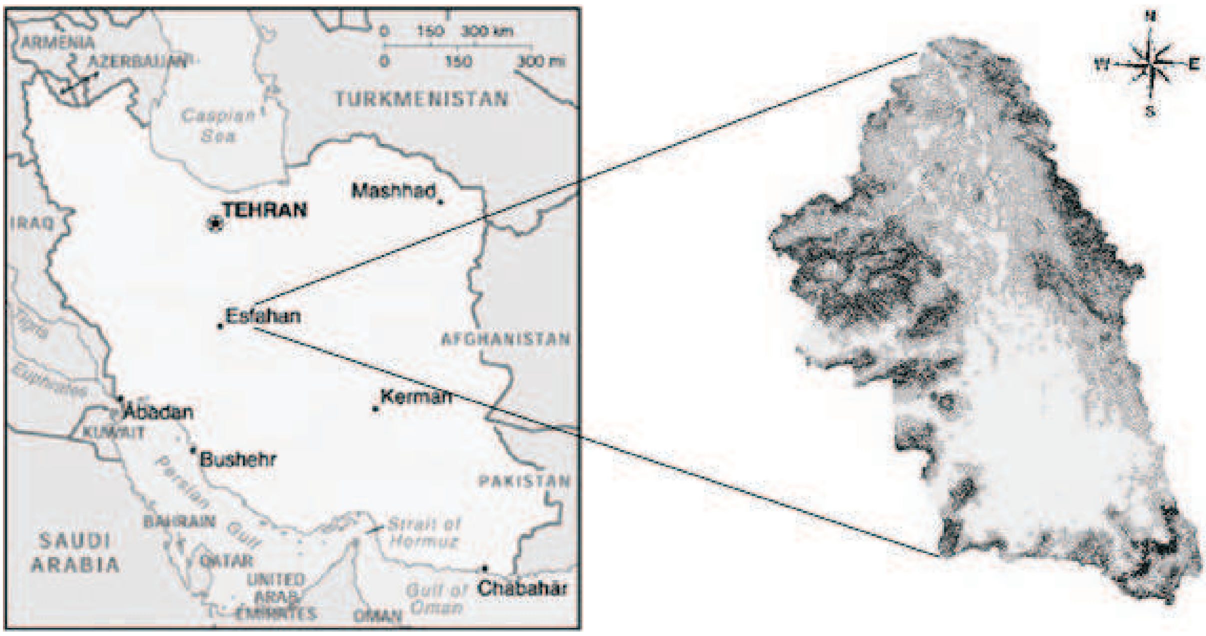

Fig. 1. Location of the Golabad watershed in Iran.

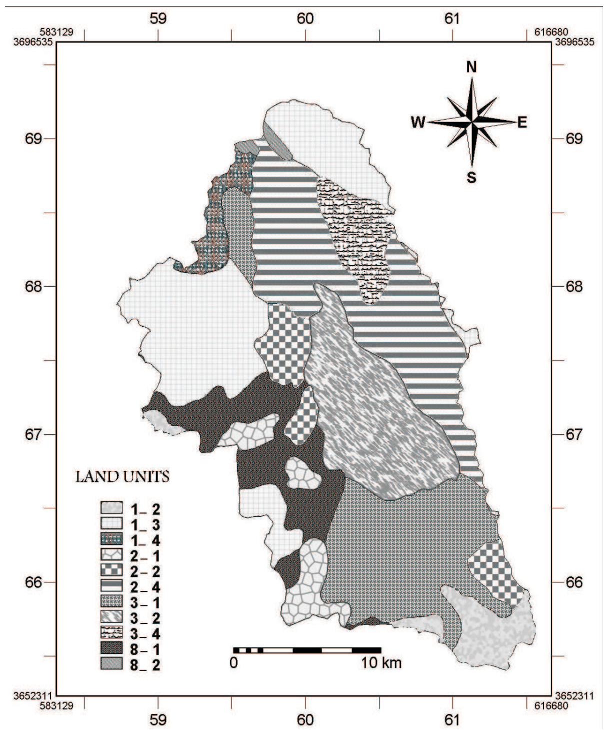

Fig. 2. Land capability and resources map of the Golabad watershed. The dominant land types are mountains: 1-2, 1-3, 1-4 land units; hills: 2-1, 2-2, 2-4 land units; plateau: 3-1, 3-2, 3-4 land units; and alluvial fans: 8-1, 8-2 land units.

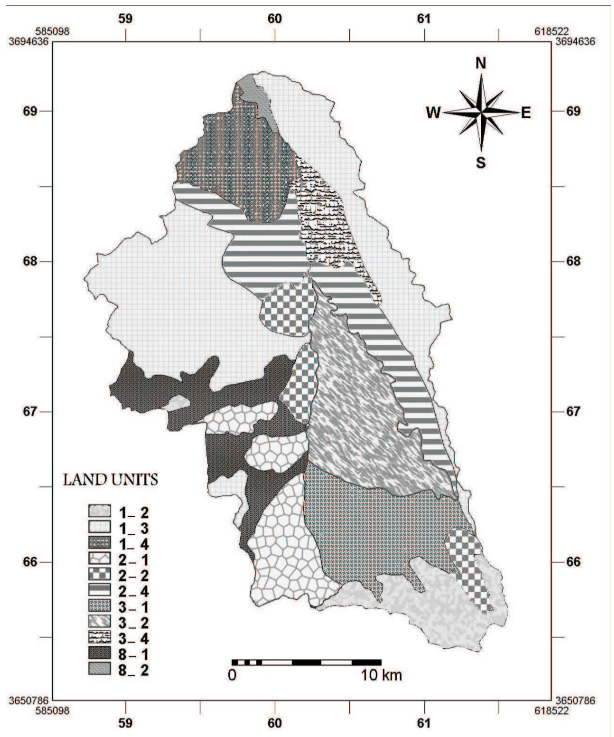

Fig. 3. Adapted land units map of the Golabad watershed. Explanation as in Fig. 1.

T a b l e 2. Scores for the nine input layers of different land units

Land type	Land unit	Surface geology	Soils	Climate	Runoff	Topography	Ground cover	Land use	Upland erosion	Channel erosion
Mountain	1-2	5.4	7.33	3.97	0.60	9.79	6.98	17.2	11.8	11.69
	1-3	5.2	3.33	3.97	2.41	9.18	8.32	16.2	13.8	11.69
	1-4	4.7	3.33	3.97	1.53	4.17	10.90	17.3	13.8	11.69
Hill	2-1	7.3	4.83	3.97	0.67	5.04	8.91	15.0	19.5	16.70
	2-2	7.2	5.33	3.97	0.68	4.52	11.00	15.6	14.3	13.36
	2-4	6.4	6.17	3.97	1.50	4.51	11.50	16.6	17.0	15.03
Plateau	3-1	8.4	5.50	3.97	0.55	0.94	10.10	15.8	10.5	10.02
	3-2	8.2	3.67	3.97	0.26	1.29	11.00	15.7	11.0	10.02
	3-4	6.3	3.83	3.97	2.36	3.23	13.90	18.0	13.3	13.36
Alluvial fan	8-1	8.4	4.67	3.97	1.10	2.57	8.11	14.3	11.3	11.69
	8-2	6.9	4.67	3.97	0.21	3.69	13.80	16.5	11.3	11.69
Min		4.7	3.33	3.97	0.21	0.94	6.98	14.3	10.5	10.02
Max		8.4	7.33	3.97	2.41	9.79	13.90	18.0	19.5	16.70
Average		6.8	4.79	3.97	1.08	4.45	10.40	16.2	13.4	12.45

per rainfall erosion index unit plot. Division of the subsequent K-factor with the factor 7.59 will yield K values expressed in SI units of t ha h ha^{-1} MJ^{-1} mm^{-1} (Renard *et al.*, 1997). Determined erodibility of the soils ranged from 0.026-0.058 in SI units indicating some differences in the surface soil properties.

A sediment yield rating (R) layer was prepared by integrating the nine layers of the model. Table 3 shows estimated sediment yield values for different land units. The values of R varied from 65.07 to 82.71 with an average of 73.5. As shown in Table 3, this rating was the least for plateaus (land units 3-2 and 3-1), while hills (2-4 and 2-1 land units) had the highest value ratings. Using Eq. (1), the sediment yield values were calculated for different land units. According to Table 3, estimated sediment yield ranged from 263.3 to 496.9 with an average of 356.4 t km^{-1} $year^{-1}$. In spite of low annual precipitation, this range appears to be quite high, while other studies in Iran or other countries resulted in similar or even higher vales of sediment yield. Erskine *et al.* (2002) studied the sedimentation of dams in small sandstone drainage basins near Sydney, Australia. Their result indicated that cultivated basins produce an average sediment yield of 7.1 t ha^{-1} $year^{-1}$ whereas grazed pasture and forest/wood land basins export averages of only 3.3 and 3.1 t ha^{-1} $year^{-1}$, respectively. Nevertheless, these yields were high by Australian standards. In Iran, based on 20 years data of 120 sedimentology stations, Jalalian *et al.* (1994) reported a sediment yield of 348 t km^{-2} $year^{-1}$, with maximum value of 750 t km^{-2} $year^{-1}$. In addition, the Consulting Company of Jamab (1999), using data of 360 sedimentology stations, estimated the range of sediment yield from 1.58 to 3 025 t km^{-2} $year^{-1}$. The study of Arabkhedri *et al.* (2005) resulted in an average of sediment yield of 214 t km^{-2} $year^{-1}$ indicating an erosion rate of 6 t ha^{-1} $year^{-1}$. In a recent comprehensive research which has been done by the SCWMRI (2007) and covered the whole territory of Iran, the rate of soil erosion 6.2 t ha^{-1} $year^{-1}$ has been reported. Our results indicated that land units 2-4 and 2-1 (hills) had the highest sediment yield. This high sediment yield appeared to be partly due to upland erosion and channel erosion in the watershed (Table 2). In addition, vegetation cover in the region is scattered, which influences the sediment yield. Vegetative covers have the ability to reduce flow velocity, which reduces the erosive force of runoff (Pan and Shangguan, 2005). In addition, the soil structure under vegetative cover is improved, with a higher infiltration rate and plant roots reinforcing the soil body. In general, vegetation reduces runoff due to canopy interception and higher infiltration rate associated with improved soil structure (Pan *et al.*, 2006).

The sediment yield map based on the MPSIAC model was generated through collapsing the total values into five classes based on the model tables (Fig. 4). Most of the watershed area is classified as areas with moderate to high sediment yields. Considering the fact that the soil formation rate

T a b l e 3. Sediment yield results of the MPSIAC model application

Land type	Land unit	Area (km^2)	Sediment yield (R)	Sediment yield (km^{-2} $year^{-1}$)
Mountain	1-2	36.4	74.68	372.1
	1-3	164.5	74.05	363.8
	1-4	41.4	71.32	329.7
Hill	2-1	47.4	81.90	482.6
	2-2	28.6	75.96	389.7
	2-4	65.5	82.73	497.2
Plateau	3-1	57.9	65.83	270.6
	3-2	68.0	65.04	263.0
	3-4	20.3	78.23	422.9
Alluvial fan	8-1	48.8	66.02	272.5
	8-2	3.9	72.67	346.2
Min		-	65.07	263.3
Max		-	82.71	496.9
Average		-	73.48	356.4

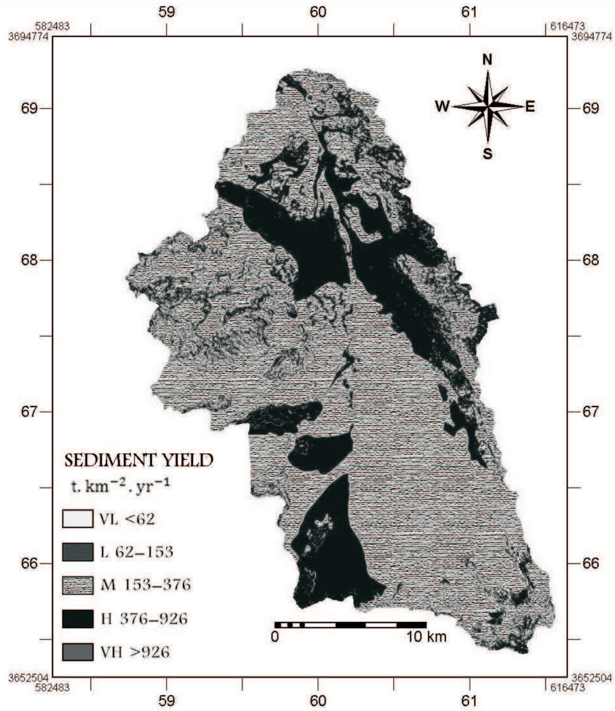

Fig. 4. Sediment yield map of the Golabad watershed: VL – very low, L – low, M – moderate, H – high, and VH – very high.

is very limited in this environment, obviously the high values of sediment yields could be problematic for a sustainable development system in this watershed. Therefore, some conservation and management practices are needed to be used in the hilly land units which have high sediment yields.

Usually, soil erosion and sediment yields cannot be estimated with high-levels of confidence, using the existing grey-box models, models with semi-quantitative estimating capabilities such as MPSIAC. Basin sediment yield is a product of all sediment producing and transport processes within a basin, which are rather difficult to model in arid environments due to intermittent stream flow, the discontinuity of flow, and highly irregular rainfall distributions (de Vente and Poesen, 2005). This leads to a necessity for calibration of a model outside the area for which the model is developed. Moreover, involving experienced and related experts during the rating of individual scores can minimize subjectivity of the scoring processes.

Until now it has not been possible to develop a model consisting of all components together, that could be used at the basin scale with reasonable results. The difficulties are due to a combination of natural complexity, spatial heterogeneity, and lack of available data (de Vente and Poesen, 2005). The PSIAC model focuses on sediment yield at a basin scale and off-site effects, as it does not specifically identify spatially distributed sources of sediments. In addition, the model specifically considers contribution of landslides, though only through observation of their occurrences. Thus, this model can be considered as a holistic sediment yield model, trying to include most erosion and sediment transport processes. It seems that descriptions of the PSIAC are sometimes too broad, which makes scoring difficult, and it results in poorer model performance. The model also has some extrapolation problems, especially when it relates to a score for measuring sediment yield. Nevertheless, this model is generally less data-demanding and it is an effort to represent available knowledge on sources of sediment and sediment transport, which certainly could be a useful tool supporting decision making processes in a sustainable watershed management system.

CONCLUSIONS

1.The estimations of the MPSIAC model showed that the sediment yield varied from 263.3 to 496.9 with an average of 356.4 t km^{-2} year^{-1}.

2. The results indicated that hills have the highest sensitivity to erosion and sediment yield.

3. Preliminary results of the applicability of this model showed it can be recommended for arid and semiarid watersheds with ungauged basins. However, there are still some uncertainties in the structure of the model, which can be only identified by retesting the model using the same procedure employed in its development under different environmental conditions.

4. Moreover, application of GIS and remote sensing indicated that these are helpful techniques to estimate sediment yields for better soil conservation practices in watersheds such as this. Hence, the combined use of remote sensing and GIS could be an effective approach for estimating the severity of erosion in ungauged watersheds of central Iran.

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