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Application of the modified universal soil loss equation (MUSLE) in prediction of sediment yield (Case study: Kengir Watershed, Iran)

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Abstract Modified Universal Soil Loss Equation (MUSLE) application study is undertaken in order to estimate the sediment yield of the Kengir watershed in Iyvan City, Ilam Province, Iran. The runoff factor of MUSLE is computed using the measured values of runoff and peak rate of runoff at outlet of the watershed. Topographic factor (LS) and crop management factor (C) are determined using geographic information system (GIS) and field-based survey of land use/land cover. The conservation practice factor (P) is obtained from the literature. Sediment yield at the outlet of the study watershed is simulated for six storm events spread over the year 2000 and validated with the measured values. The high coefficient of determination value (0.99) indicates that MUSLE model sediment yield predictions are satisfactory for practical purposes.

Keywords MUSLE · Sediment yield · Kengir watershed · Iyvan · Storm event

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Introduction

Soil erosion is an important item of consideration in the planning of watershed development works. It reduces not only the storage capacity of the downstream reservoirs but also deteriorates the productivity of the watershed. Accurate estimation of sediment-transport rates, in general, depends on an accurate a priori estimation of overland flows. Thus, any errors in the estimation of overland flows would be magnified through grossly inaccurate erosion estimations (Clarke 1994). Globally, more than 50% of pasturelands and about 80% of agricultural lands suffer from soil erosion (Pimentel et al. 1995). It is reported (Dudal 1981) that, worldwide, about 6,000,000 ha of fertile land is being lost every year due to just soil erosion and related factors. At this rate, it is estimated that currently about 1,964.4 Mha of total land area has already been degraded (UNEP 1997). Of this, about 1,903 and 548.3 Mha are affected with water and wind erosion problems, respectively.

Land degradation by soil erosion is a serious problem in Iran with an estimated soil loss of $2{,}500 \times 10^6$ t year^{-1}, and about 94% of arable lands and permanent rangelands are in the process of degradation (FAO/UNEP 1994; Masoudi et al. 2006). In terms of erosion, Iranian soils are under a serious risk due to hilly topography, soil conditions facilitating water erosion (i.e., low organic matter, poor plant coverage due to arid, and semiarid climate), and inappropriate agricultural practices (i.e., excessive soil tillage and cultivation of steep lands). This widespread problem threatens the sustainability of watershed which is the main surface source of drinking water for Iyvan city, Iran. Water and soil losses are the main reasons for sediment entering the reservoir, and these processes potentially reduce water quality. Soil erosion in this area strongly influences the ecological health of the city.

Therefore, it became necessary to quantify soil erosion more extensively, with the aim of providing a tool for planning soil conservation strategies on watershed basis. The formulation of proper watershed management programs for sustainable development requires information on watershed sediment yield. Due to the complexity of the variables involved in erosion modeling, it became difficult to measure and to predict the sediment yield in precise manner. Among available soil erosion and sediment yield models, the universal soil loss equation (USLE), the revised version of it (RUSLE), and its modified version (MUSLE) are used in hydrology and environmental engineering for computing the amount of potential soil erosion and sediment yield (Mishra et al. 2006). The USLE (Wischmeier and Smith 1978) was developed for estimation of the annual soil loss from small plots of an average length of 22 m, its application for individual storm events and large areas leads to large errors (Hann et al. 1996; Kinnell 2005), but its accuracy increases if it is coupled with a hydrological rainfall-excess model (Novotny and Olem 1994). In the USLE model, there is no direct consideration of runoff, although erosion depends on sediment being discharged with flow and varies with runoff and sediment concentration (Kinnell 2005). It has been observed that delivery ratios to determine sediment yield from soil loss equation can be predicted accurately but that vary considerably. The reason for this may be due to the variation in rainfall distribution over time from year to year. As a result of uncertainty in the delivery ratio, Williams and Berndt (1977) proposed MUSLE with the replacement of the rainfall factor with a runoff factor. Particularly, this model is intended to estimate the sediment yield on a single storm basis for the outlet of the watershed based on runoff characteristics, as the best indicator for sediment yield prediction (ASCE 1970; Williams 1975a, b; Hrissanthou 2005). MUSLE increases sediment yield prediction accuracy and also, it eliminates the need for delivery ratios. The MUSLE has been used previously by many researchers (Banasik and Walling 1996; Kinnell and Risse 1998; Tripathi et al. 2001; Sadeghi and Mizuyama 2007) and, in some cases, subjected to different modifications. The sediment yield model like MUSLE is easier to apply because the output data for this model can be determined at the watershed outlet (Pandey et al. 2009).

Hikaru et al. (2000) demonstrated successful application of USLE to mountainous forests in Japan. Cambazoglu and Gogus (2004) estimated sediment yield using MUSLE and USLE in the Western Black Sea region of Turkey. Tripathi et al. (2001) estimated sediment yield from a small watershed of India using MUSLE and GIS, and the estimated values were very close to the observed values of sediment yield. From the literature, it is evident that very limited information on application of the MUSLE model is available for Iranian watersheds especially for Zagros mountain range in western Iran. In Iran, especially at Zagros mountain range, topographic conditions, soil conditions, rainfall pattern, and cultivation practices are entirely different from those in other parts of the world.

Keeping this in mind, the present investigation was taken up to assess the applicability of the MUSLE for the Kengir watershed of Iyvan, Ilam province, Iran , where there is difficulty in identifying suitable models for estimation of soil erosion and sediment yield at the watershed scale in addition to the problems of irregular and discontinuous runoff and sediment data collection.

Description of the study area

The study area lies between 46° 17′ 11″ and 46° 27′ 35″ E longitude and 33° 41′ 14″ to 33° 50′ 57″N latitude with elevation ranging from 995 to 2,555 m above mean sea level (Fig. 1). The geographical area of the watershed is approximately 41,368 ha. The mean annual precipitation of the watershed, based on the data collected for the period 1976–2005 at Iyvan climatologic station located in the central part of the watershed, is some 674 mm of which 90% falls between late October and early April. The watershed is governed by the dry and cold Mediterranean climate, mainly covered by agricultural areas in mid- and downstream and forest in the upstream areas and also rangeland in downstream areas. The minimum and maximum temperatures vary from −3.1 to 32.4°C. The mean relative humidity varies from a minimum of 19% in September to a maximum of 55% in the month of January. Erosion problem is prevalent in the study area due to rolling topography and improper agricultural management practices. The watershed is equipped with a hydrometric station at the main outlet, where the water level is recorded continuously, whereas sediment sampling is only occasional.

Methodology

In the present study, MUSLE is used to estimate sediment yield from the Kengir watershed. Runoff factor is a major input into the MUSLE model. It is computed using the runoff and peak runoff rates measured at the outlet of the study watershed. The sediment yields estimated by MUSLE for different events during the year 2000 are compared with the observed sediment yield data collected from the stream gauging station located at the outlet of the watershed. The model performance is evaluated on the basis of test criteria recommended by the ASCE Task Committee (1993) and graphical performances criteria suggested by Haan et al. (1982).

Fig. 1 Location of study area
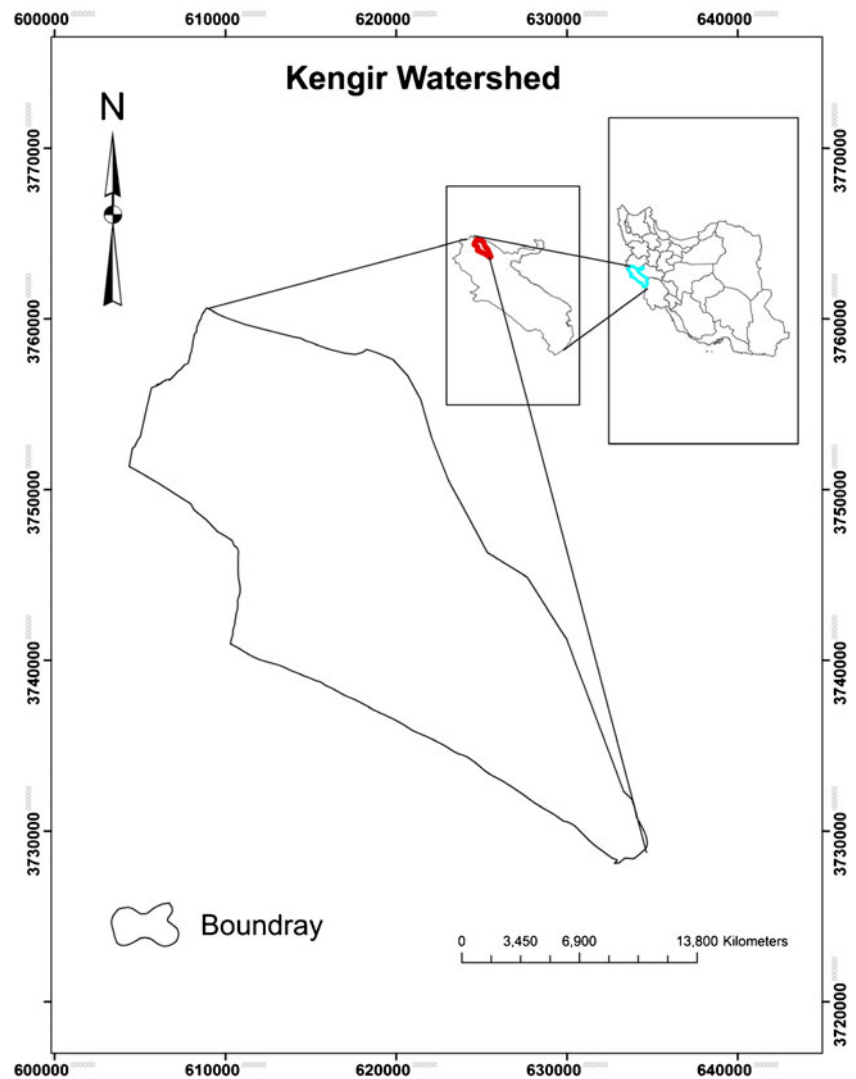
Estimation of sediment yield using MUSLE

Soil erosion is a hydrologically driven process on sediment being discharged with runoff (Kinnell 2005). By including the runoff as an independent factor in modeling erosion, MUSLE has an improved accuracy of soil erosion prediction over USLE and RUSLE (Williams 1975a, b; Williams and Berndt 1977; Erskine et al. 2002; Neitsch et al. 2005; Sadeghi et al. 2007). In general, MUSLE can be expressed as,

$$Y = 11.8 \left(Q q_{\mathrm{p}}\right)^{0.56} (K)(L)(S)(C)(P)$$

where, Y is sediment yield in tones; Q is volume of runoff in cubic meters; q_{p} is peak flow rate in cubic meters per second, and K is the soil erodibility factor, which is the erosion rate per unit of erosion index for specified soil in cultivated continuous fallow, having 9% slope and 22.13 m

length; LS is the slope length and gradient factor, which is the ratio of soil loss from the field slope length and gradient to that from 22.13 m length on the same soil type with a 9% slope; C is the cropping management factor defined as the ratio of soil loss from a field with a specified cropping and management to that from the fallow condition for which the factor K is evaluated; and finally, P is the erosion control practice factor, which is the ratio of soil loss with contouring, strip cropping, or terracing to that with straight row farming, up and down slope. The data about K, LS, C, and P are adopted from the literature (Arekhi and Kaur 2007).

Study storms

In order to apply the MUSLE model in the study watershed, six storm events are considered for which the flow discharge and sediment flux data are collected

through the development of hydrographs and sediment graphs, respectively. This is the total number of storms, which could be monitored during the wet season. The hyetographs associated with the storms are shown in Fig. 2, which are developed based on the discharge rating curve relation and through recording the water stage by limnigraph. The sediment concentration is sampled manually during the storm water flow at 30-min intervals using 1-L plastic bottle samplers, by the depth integration method (IWRRO Iranian Water Resources Research Organization 1996).The samples are then analyzed in the laboratory by the weighting method to determine the suspended sediment concentration. The measured hydrographs and sediment graphs are shown in Fig. 3. The amount of total sediment is then calculated based on the sediment concentration graph and in conjunction with the hydrographs. The characteristics of the selected six storm events are summarized in Table 1.

Development of model database for MUSLE

Runoff factor

The volume of runoff and peak flow rates are monitored at the outlet of the Kengir watershed, and the runoff factor is computed for all the individual rainfall events during study period, i.e., 2000.
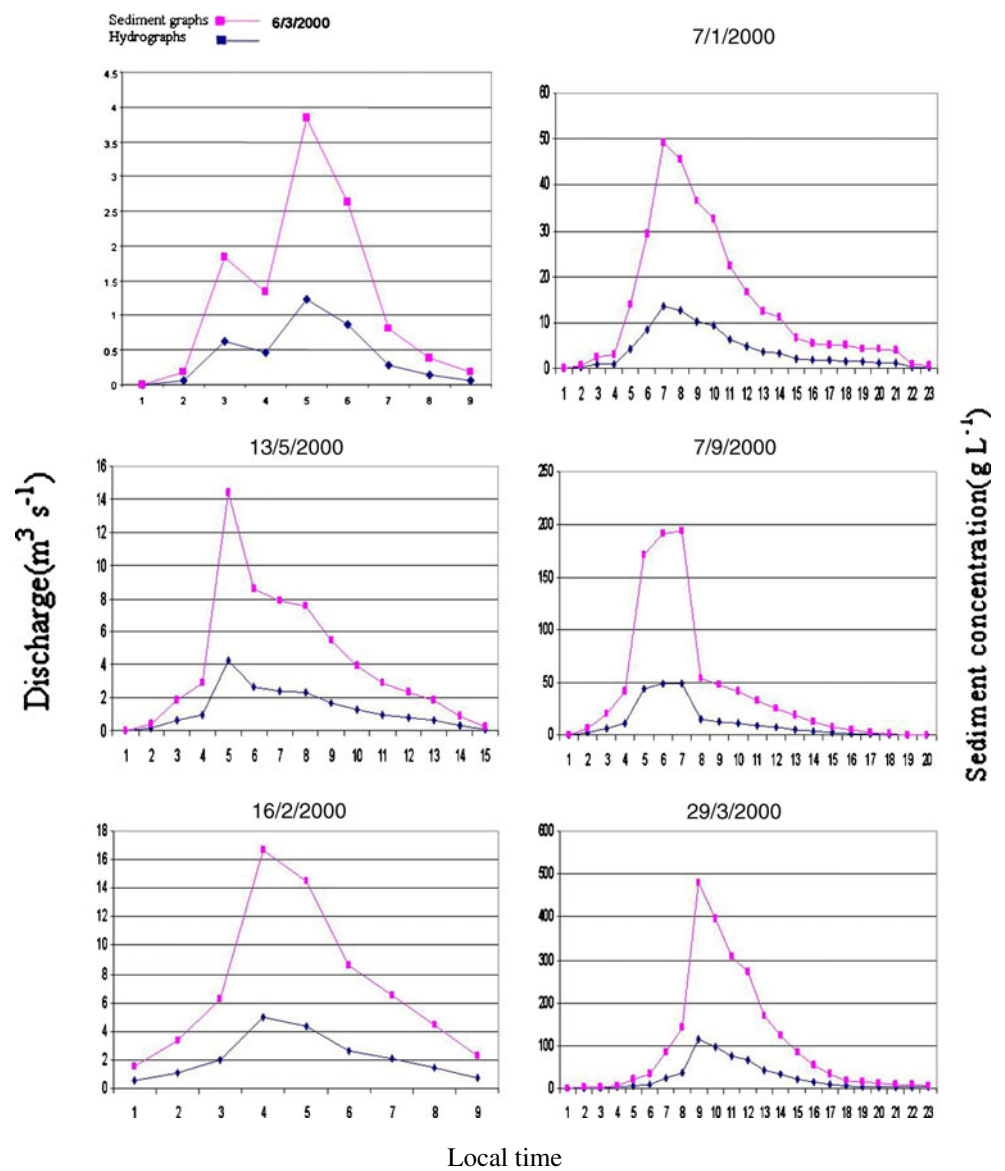
Soil erodibility factor

The K values are usually estimated using the soil erodibility nomograph Method, which uses percent silt plus very fine sand (0.002–0.1 mm), percent sand (0.1–2 mm), percent organic matter, and soil structure and permeability classes to calculate K (Wischmeier and Smith 1978). However, structure and permeability class data in the soil survey data sources are lacking. Therefore, the

Fig. 2 Hyetographs of studied storms
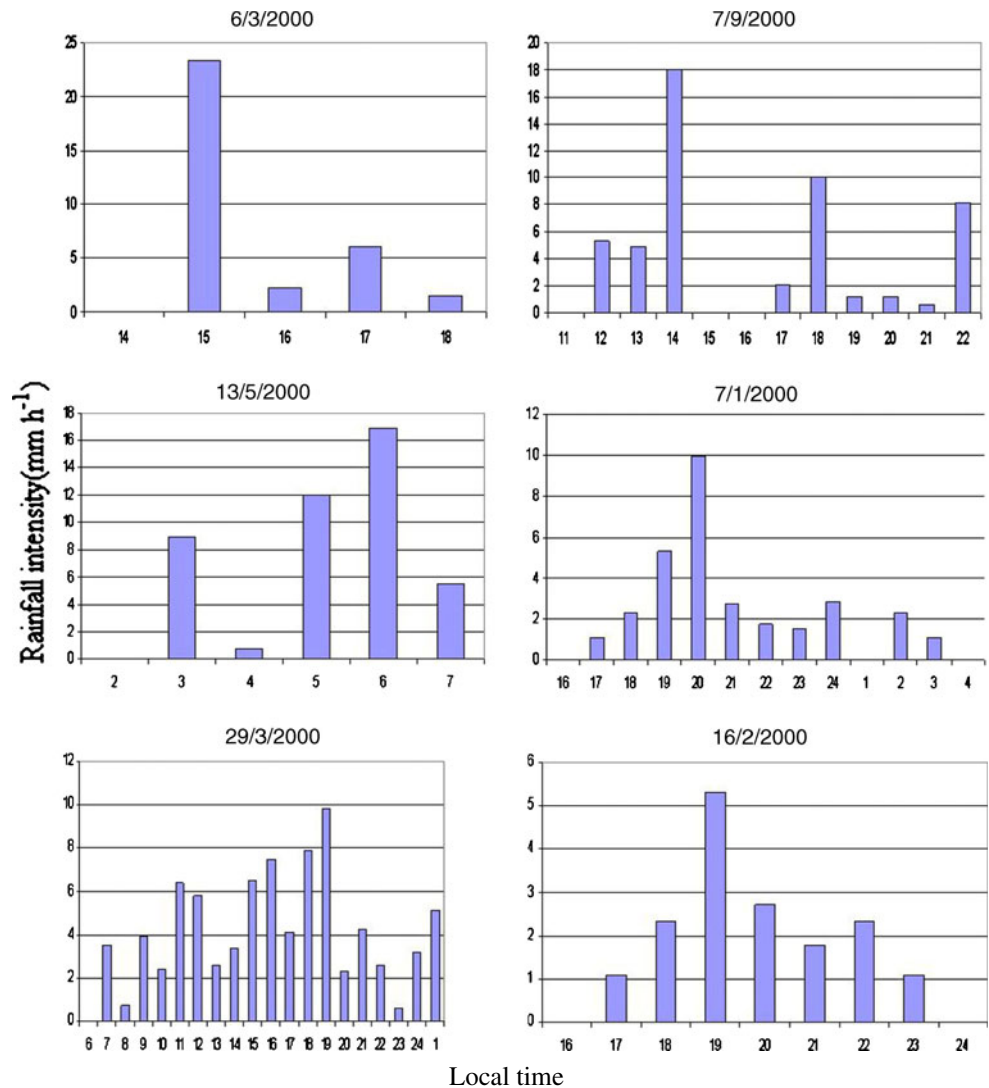
Fig. 3 Hydrographs and sediment graphs of studied storms

following equation is adopted for calculations as recommended by MUSLE in the case of observation data lack (Renard et al. 1997)

$$K = 7.594 * \left\{ \left(0.0034 + 0.0405 \exp\left(-\frac{1}{2}\left(\log(D_g) + 1.659/0.7101 \right)^2 \right) \right) \right\}$$

$$D_g = \exp 0.01 \mathrm{sum}(fi - \ln mi)$$

where:

K, soil erodibility factor (t ha h ha^{-1} Mj^{-1} mm^{-1});
Dg, mean geometric particle diameter (mm);
Di, primary particle size fraction (%);
Mi, arithmetic mean of the particle size limits of that size (mm):

Length (L) and slope steepness (S) factors

The LS factor reflects the effect of topography on soil erosion, where separately L and S represent the effect of

Table 1 Characteristic of selected storms in Kengir watershed, Iran

NO	Storm date	Duration, h	Peak flow, m^3/s	Runoff volume, m^3	Observed sediment yield, t
1	7/1/2000	13	13.61	325283	373.56
2	6/3/2000	5	1.24	13536	13.42
3	13/5/2000	6	4.33	68976	73.21
4	7/9/2000	12	49.19	835956	1046.21
5	29/3/2000	20	96.30	2079576	2730.79
6	16/2/2000	7	4.93	70848	76.85

slope length on erosion and the influence of slope gradient on soil erosion, respectively (Williams 1975a; Williams and Berndt 1977; Lu et al. 2004). McCool et al. (1987) presented the following expression to compute the slope length or L factor as,

$$L = 1.4\left(\frac{\lambda}{22.1}\right)^{m}$$

where λ is the field slope length in meters and m is the dimensionless exponent that depends on slope steepness as being 0.5 for slopes exceeding 5%; 0.4 for 4% slopes, and finally 0.3 for slopes less than 3%. For slope length longer than 4 m, the slope steepness factor is derived into two groups as follows (McCool et al. 1987):

$$S = 10.8\sin\theta + 0.03 \qquad s < 9\%$$

$$S = 16.8\sin\theta - 0.05 \qquad s \geq 9\%$$

where θ is the slope angle in degrees. In this study, the LS factor is derived with the help of Arc View GIS software from digital elevation model (DEM) of the study area.

Cover management factor (C)

The C factor is related to the land use and is a reduction factor to soil erosion vulnerability. This is an important factor in MUSLE, since it represents the conditions that can be changed to reduce erosion. The existing land cover types in the area are dry farm lands, rangelands, and forests. One important surface cover existing in the study area is forest. Forests are the most important protection cover types against erosion. They can be classified into two groups as good undisturbed and poor disturbed forests. The last land use type in the study area is the rangeland grazed by sheep and cattle, and it can be divided into two categories as good and degraded rangelands, which are composed of brush canopy cover, herbaceous cover, and bare soil in different percentages. The C factor for rangeland also depends on the percentage of ground cover. In the study area, the cropping management factor, C, for a watershed, is determined by weighting the C values of each crop and management level according to the size of area where the crop is grown, with the same management level.

$$C = \frac{\sum\limits_{k=1}^{n} C_k DA_k}{DA_{\mathrm{T}}}$$

where C is the cropping management factor for the watershed, C_K is the cropping management factor for an individual crop, k, DA_k is the drainage area covered by an individual crop, k, with a particular management level, DA_{T}

is the total drainage area of the watershed and n is the number of different crops and management levels in the watershed. Finally, crop management factor is assigned into different land use classes as shown in Table 2.

Support practice factor (P)

The supporting practice P-factor describes the effects of practices such as contouring, strip cropping, concave slopes, terraces, grass hedges, silt fences, straw bales, and subsurface drainage. Supporting practices typically affect erosion by redirecting runoff around the slope, so that it has less erosivity or by slowing down the runoff to cause deposition, such as on concave slopes or because of barriers such as vegetative strips and terraces. The lower the p value, the more effective the conservation practice is deemed to be at reducing soil erosion. If there are no support practices, the P-factor is 1.0. Contemporary agricultural practices consist of up and down tillage without the presence of contours, strip cropping, or terracing. In this study, no major conservation practices are followed. Hence, the conservation practice of 1 is assigned to this watershed (Morgan 1995).

The MUSLE is then applied for the selected storm events and using corresponding information obtained from the watershed under consideration. The sediment yield estimates per each individual storm are ultimately compared with those obtained through observed sediment graphs.

Results and discussion

All required information and data were either collected or determined for the application of the MUSLE at Kengir watershed in western Iran. The watershed parameters and the runoff data collected for six storm events occurring from April to October 2000 were used to apply the MUSLE model (Eq. 1) to the Kengir watershed. The runoff volumes and peak runoff rates are monitored at the outlet of the recording station of the Kengir watershed. The other

Table 2 Landuse/land cover statistics of the study area

Land use/land cover class	Area, ha	Area, %
Densed forest	22,945	55.47
Densed rangeland	1,732	4.14
Dry farm land	1,410	3.38
Semi-densed forest	8,269	18.94
Semi-densed rangeland	2,760	6.69
Low densed rangeland	2,362	5.71
Barren land	1,885	4.55

variables in Equation (1), viz. soil erodibility, topographic factor (LS), crop management, and soil erosion control practices factors, are determined using the methodology suggested by Renard et al. (1997). The soil erodibility, crop management, and soil erosion control practice factors, which are more sensitive to temporal variations than other watershed parameters, were assumed to be constant as study period is short as advised by Kinnell (2005). The average weighted values of 0.09 t ha h ha^{-1} Mj^{-1} mm^{-1}, 3.36, 0.02, and 1 are thus allotted to the watershed factors of K, LS, C, and P, respectively. Subsequently, all the parameters are substituted in the MUSLE equation in order to derive event-wise sediment yields. Furthermore, the MUSLE model is validated by comparing the estimated sediment yields with the observed sediment yield for six storm events occurring from April to October 2000. The results of application of the MUSLE model for the storms are shown in Table 3. The results of the comparative evaluation between measured and estimated sediment yield data is presented in Fig. 4.
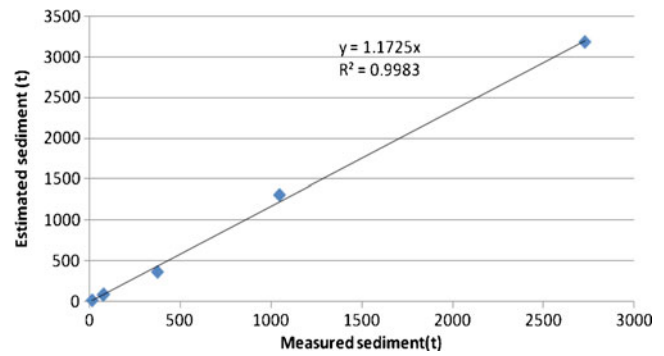
The runoff–sediment yield relationship is also evaluated using sediment rating curve analysis. The equation in Fig. 5 is the best fit among different relationships to approximately 77 pairs of discharge (q) and sediment concentration (s$_d$).

The watershed parameters and runoff on the Kengir watershed (Table 1) are used in the application of Equation (1), and the MUSLE results are presented in Table 3. The comparison of the sediment yield measurements and predictions is shown in Fig. 4, which indicates that the data points are very close and clustered around the 1:1 straight-line. Scrutinizing the results in Table 3 and Fig. 4 shows that the MUSLE performes well in the prediction of storm-wise sediment yield in the Kengir watershed. The value of coefficient of determination (R^2) is about 0.99.

The percent deviation of the storm-wise estimated sediment yield from the observed values varied in the range of 2.30–25.24%(Table 3).The under-prediction or over-prediction limits for the MUSLE model simulation are within 20% for the measured values for all the studied storms and are considered as the acceptable levels of
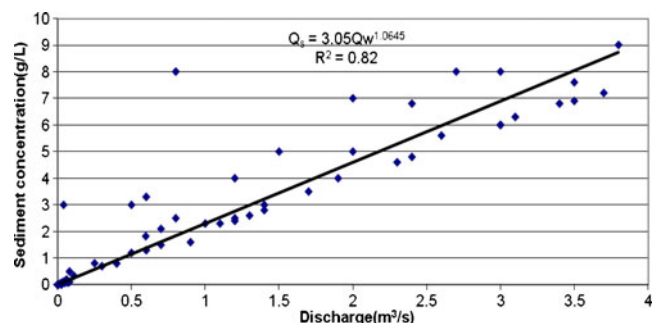

Fig. 4 Comparison of the sediment yield observations and predictions

accuracy for the simulations as reported by Bingner et al. (1989). In other words, the average value of the estimation error for the studied storms as 16.34% is acceptable for the modeling processes in natural phenomena (Das 2000). The slight variation in hydrological response of the watershed in terms of sediment yield during the studied storms might be due to the spatial and temporal distribution of the rainfall, as shown partially in Fig. 2, change in the antecedent hydrological conditions, and the availability of the eroded sediment throughout the watershed, which is not taken into account by MUSLE as for many other lumped models. Though the differences between the predicted and observed sediment yields from the MUSLE model contain some factors of error, MUSLE can be successfully used for estimation of sediment yield in this area. Similar findings are reported by Walling and Webb (1982). From the results obtained through performance evaluation of the MUSLE application in the Kengir watershed, it could be inferred that the MUSLE does not need any modification for reliable application in the Kengir watershed. This clearly contradicts earlier researches (Nicks et al. 1994; Kinnell and Risse 1998; Khajehee et al. 2001; Rezaeifard et al. 2001; Sadeghi et al. 2004, 2007), which emphasized the necessity of the MUSLE calibration for the application in areas other than the place where it is first developed. This result might also be due to the unreliability of the observed sediment data in

Table 3 Results of application of MUSLE to Kengir watershed, Iran

No	Storm date	Observed sediment yield, t	Predicted sediment yield, t	Estimation error, %
1	7/1/2000	373.56	364.97	−2.30
2	6/3/2000	13.42	16.57	23.48
3	13/5/2000	73.21	82.77	13.06
4	7/9/2000	1046.21	1310.29	25.24
5	29/3/2000	2730.79	3179.73	16.43
6	16/2/2000	76.85	90.71	18.02

Fig. 5 Sediment rating curve for the studied storms in Kengir watershed, Iran

the previous studies, which were mostly obtained through discrete and discontinuous sediment sampling, or improper application of the model. Other researches have also found that runoff is a better indicator for sediment prediction than rainfall (ASCE 1970; Williams 1975a, 1975b; Foster et al. 1977; Beasley et al. 1980; Hrissanthous 2005) for the agroclimatic condition of the study area, and this has also reported by Sadeghi et al. (2004) for other parts of Iran.

Conclusion

In the present study, MUSLE model is used for the estimation of storm-wise sediment yield in the Kengir watershed of Iyvan City, Ilam province, Iran. High coefficient of determination (0.99) indicates accurate simulation of sediment yield from the MUSLE model. The percent deviations between the sediment yield measurements and observations vary in the range of 2.30–25.24%. However, the present results could be of use in erosion-based watershed prioritization in the study area. To regionalize the results of the study, greater numbers of storms events as well as case studies need to be considered by researchers. In addition, other simple soil erosion and sediment yield models must be considered with reasonably accurate estimation of system response at the watershed scales, where scarce information exists.

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