A Review of the Application of the MUSLE Model Worldwide

Article *in* Hydrological Sciences Journal/Journal des Sciences Hydrologiques · February 2014

DOI: 10.1080/02626667.2013.866239

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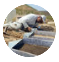

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Hydrological Sciences Journal
Publication details, including instructions for authors and subscription information:
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A review of the application of the MUSLE model worldwide

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Published online: 20 Dec 2013.

To cite this article: S.H.R. Sadeghi, L. Gholami, A. Khaledi Darvishan & P. Saeidi , Hydrological Sciences Journal (2013): A review of the application of the MUSLE model worldwide, Hydrological Sciences Journal, DOI: 10.1080/02626667.2013.866239

To link to this article: http://dx.doi.org/10.1080/02626667.2013.866239

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Hydrological Sciences Journal – Journal des Sciences Hydrologiques, 2013
http://dx.doi.org/10.1080/02626667.2013.866239

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Received 31 December 2012; accepted 16 April 2013; open for discussion until 1 August 2014

Editor Z.W. Kundzewicz

Citation Sadeghi, S.H.R., *et al.*, 2014. A review of the application of the MUSLE model worldwide. *Hydrological Sciences Journal*, 59 (2), 1–11.

Abstract The sediment yield model of the MUSLE (modified universal soil loss equation) is applied extensively throughout the world, but different performances have been reported of its success relative to measured data. A review of all the available literature is presented to assess the application of the model under different conditions and, ultimately, make a comprehensive judgement on the different aspects to allow readers to adjust their further research. A review of 49 papers showed the variable accuracy of the model, which depends on the manner of calculation and determination of the input and output, and the study time and space scales. There were differences in land use, in correspondence of the physiographic characteristics with those of the original conditions of model development, and even in the experience of researchers in applying the model. The results also show the need to consider the original application of the model, as proposed by its developers, to achieve comparable results.

Key words MUSLE model; sediment yield; storm event; soil erosion models; model goodness of fit

Revue de l'application du modèle MUSLE à travers monde

Résumé Le modèle de production de sédiments de l'équation universelle modifiée des pertes de terre (Modified Universal Soil Loss Equation—MUSLE) est largement appliqué dans le monde entier, mais des performances variées ont été signalées quant à son applicabilité pour les objectifs proposés. Nous présentons une revue de toute la littérature disponible pour évaluer l'application du modèle dans des conditions différentes et, à terme, pour porter un jugement complet sur les différents aspects de cette application, de manière à permettre aux lecteurs d'ajuster leurs recherches futures. L'examen de plus de 49 articles a confirmé la précision extrêmement variable du modèle en fonction du mode de calcul et de détermination des entrées et sorties, et des échelles temporelles et spatiales d'étude. Des différences existaient dans l'occupation des sols, la correspondance entre les caractéristiques physiographique d'étude et celles utilisées lors du développement du modèle, et même dans l'expérience des chercheurs dans l'application du modèle. Les résultats montrent aussi la nécessité de prendre en considération les conditions originales d'application du modèle, tel que cela est suggéré par ses développeurs, afin d'obtenir des résultats comparables.

Mots clefs modèle MUSLE; apport en sédiments; orage; modèles d'érosion des sols; qualité d'ajustement du modèle

INTRODUCTION

Accelerated soil erosion has detrimental effects on productivity, income distribution and the environment at national and global scales. Erosion phenomena and sediment transport in channels and rivers are the most complex issues in a watershed. The heavy erosion and continuous transmission of sediment is not only the cause of an imbalance of natural rivers and streams, but also the cause of change in the river channel and sediment accumulation behind dams reducing their storage volumes.

The rate of soil erosion has dramatically increased during recent decades and globally has been reported as 0.5, 0.75, 1 and 2.2 × 10^9 t in 1951, 1961, 1971 and 1993, respectively (Hosseini and Ghorbani 2005). However, not only are these figures unreliable, but they need to be updated frequently. Consequently, regular estimation of soil erosion or its consequences, such as sediment yield, is a must, which basically can be realized by applying appropriate models. Soil erosion process models have generally been developed in particular places in the world and exported to other parts, and some have been extensively applied. Therefore, assessment of their applicability and soundness is important for proper calibration of models, or for drawing necessary conclusions and designating true strategies.

Among soil erosion models, the universal soil loss equation (USLE) (Wischmeier and Smith 1965, 1978) is the most widely used, and misused, soil loss estimation equation in the world (Kinnell 2001). The USLE was originally applied to the prediction of soil losses from agriculture in the USA, in order to preserve soil resources, but has been extended for use in numerous countries (Kinnell 2001). This model was obtained for soil loss estimation based on 10 000 plot-years of data using field experiments under natural or simulated rainfalls in the USA (Kinnell 2001). The USLE, with some modifications and revisions, is still a useful tool in watershed management. A large number of existing erosion and sediment transport models are based on the USLE (Sadeghi *et al.* 2007a). Their application is, however, limited to the environmental circumstances from which the USLE was generated (Aksoy and Kavvas 2005). Since the USLE was developed for estimation of the annual soil loss from small plots of an area of some 40 m^2, its application to individual storm events and large areas leads to large errors (Hann *et al*. 1994, Sadeghi 2004, Sadeghi and Mahdavi 2004, Kinnell 2005, Chang 2006, Sadeghi *et al.* 2007a), but its accuracy increases if it is coupled with a hydrologic rainfall-excess model (Novotny and Olem 1994, Sadeghi and Mahdavi 2004). One problem with the USLE model is that there is no direct consideration of runoff, although erosion depends on sediment being discharged with flow, which varies with runoff and sediment concentration (Kinnell 2005). Yet, Banasik (1985) showed that application of the USLE with a sediment delivery ratio (SDR) is possible for computing sediment yield from small watersheds in Poland.

However, using the SDR in conjunction with watershed gross erosion, estimated by the soil erosion model as an estimation method, is tedious and inadequate if one is interested in single storms. Unless one is already available, developing an SDR model may involve parameters similar to those of the USLE and other models that are used to estimate gross erosion, a duplicate step and time-consuming process. Stream sediment is affected by the carrying capacity and deposition processes of overland flow. However, the storm event factor used by the USLE often fails to account for the effective rainfall that generates surface runoff. Also, the SDR varies with storms; the assumption of a constant SDR adds another source of error to the estimates (Williams 1977, Chang 2006, Sadeghi *et al.* 2007a, 2008). An improved erosivity factor was therefore introduced by Williams (1975, 1977) and Foster *et al.* (1977) to also take into account the runoff shear stress effect in terms of the product of runoff volume and peak discharge, on soil detachment for single storms. The approach of Williams and Berndt (1977) in developing a modified version of the USLE was to derive a sediment yield estimation model based on runoff characteristics as the best single indicator for storm-event sediment yield prediction at the watershed outlet (Williams 1975, Beasley *et al.* 1980, Sadeghi and Mahdavi 2004, Hrissanthou 2005, Mishra *et al.* 2006, Sadeghi *et al.* 2007a, 2007b, Mishra and Ravibabu 2009) and some factors affecting soil erosion. Williams (1975) showed that the estimate of stream sediment yield for individual storms could be simplified by using the USLE with its rainfall factor (*R*) replaced by a runoff factor. He developed the following revised form of the USLE using 778 storm-runoff events collected from 18 small watersheds, with areas varying from 15 to 1500 ha, slopes from 0.9 to 5.9% and slope lengths of 78.64 to 173.74 m (Williams and Berndt 1977, Hann *et al.* 1994) and called it the modified universal soil loss equation (MUSLE). The MUSLE was given in the following general form:

$$S_y = a(Q'q_p)^b K\ L\ S\ C\ P \tag{1}$$

where S_y is sediment yield (in t) on a storm basis and for the entire study watershed, Q is volume of runoff (in m^3), q_p is peak flow rate (in m^3 s^{-1}) and K, L, S, C and P are, respectively, the soil erodibility (in t ha h ha^{-1} MJ^{-1} mm^{-1}), slope length, slope steepness, crop management and soil erosion control practice factors similar to the USLE model, and a and b are location coefficients. For the areas where the equation was developed, a and b were 11.8 and 0.56, respectively, for metric system units. The optimization technique suggested by DeCoursey and Snyder (1969) was used for the development of the prediction equation and designating a and b. A disagreement with the principle of dimensional analysis of the MUSLE has been explained by Cardei (2010).

The MUSLE has been applied to many different watersheds around the world and for different purposes (Asokan 1981, Das 1982, Nicks *et al.* 1994, Banasik and Walling 1996, Kinnell and Riss 1998, Erskine *et al.* 2002, Khajehie *et al.* 2002, Rezaiifard *et al.* 2002, Kandrika and Dwivedi 2003, Cambazoglu and Gogos 2004, Fontes *et al.* 2004, Sadeghi 2004, Sarkhosh *et al.* 2004, Kandrika and Venkataratnam 2005, Varvani *et al.* 2006, Sadeghi *et al.* 2007a, 2007b, 2008, Khaledi Darvishan *et al.* 2009, Zhang *et al.* 2009, Lpez-Tarazn *et al.* 2012), and this model was modified in some cases. Because the MUSLE model was produced for specific conditions, its application without calibration has resulted in huge errors. Therefore, the present review was made to evaluate the application conditions and methods used to determine the MUSLE model variables in previous research.

MATERIALS AND METHODS

To review the application and the performance of the MUSLE model across the world, the available research records were first collected from related conference articles, journal papers and other scientific documents. Based on the available information in the documents, the details were evaluated as to the methodology used in determining the different input variables that appear in equation (1), namely runoff volume and peak, soil erodibility, topographic factors of slope steepness and length and crop management and control practice factors were extracted. The results of the model application, as well as its performance evaluation, were examined according to the available data or methodology explained in the documents, and also by reviewing the observed and estimated results. Finally, the possible alternatives for model calibration and any type of modification were evaluated to reduce the systematic or random errors.

RESULTS

The results of the review of use of the MUSLE model in many parts of the world, other details regarding the application and quality of the model calibration and the overall assessment of the research methodology described in the previous section, are summarized in Table 1.

DISCUSSION

As seen in Table 1, the MUSLE model has been used in a variety of conditions and from different perspectives. The input variables have been determined or estimated through various approaches with different levels of accuracy. It is interesting to note from Table 1 that, in some cases, no calibration or modification has been made in the MUSLE, despite the weak performances resulting from application of the MUSLE. Most of the studies were conducted in Asia, North America and Europe, with several studies also in Iran, especially during the last 10 years. The minimum, median and maximum values of the watershed areas to which the models have been applied are 0.04, 1713 and 386 000 ha, respectively. Few studies have been done in experimental plots (e.g. Golson *et al.* 2000, Sadeghi *et al.* 2008), or at the field scale (e.g. McConkey *et al.* 1997), so the proportions of studies at the watershed, plot and field scales are 90, 7 and 3%, respectively. The results of the review also showed that the model could not provide appropriate estimates in experimental plots, except at the Thomas research station (Golson *et al.* 2000). This can be attributed to the dissimilarity of conditions and governing processes between areas where the model was originally developed and the plots applied in different studies.

The results on erodibility factor showed that the values were obtained by using available information, with the help of the Wischmeier and Smith diagram in 60.87% of studies, and by using individual sampling (Cordova 1981, Smith *et al.* 1984, Jackson *et al.* 1987, Banasik *et al.* 1988, Erskine *et al.* 2002, Mahmoudzadeh *et al.* 2002, Cambazoglu and Gogos 2004, Appel *et al.* 2006, Ma 2006) and seasonal sampling (McConkey *et al.* 1997) in 13.04% and 2.17% of the studies, respectively. But the method of estimation of the erodibility factor was not given in 23.91% of studies. The results also showed that the erodibility estimation methods did not affect the accuracy of the model estimates.

The topography factor was estimated by the direct use of a topographic map at a scale of 1:50 000 in 43.48% of studies, with the help of a geographic information system (GIS) in 26.09% (Blaszczynski 2003, Chen and Mackay 2004, Basson 2005, Appel *et al.* 2006, Ma 2006, Mishra *et al.* 2006, Arekhi 2007, Jaramillo 2007, Pandey *et al.* 2009, Zhang *et al.* 2009) and by direct field measurement in 13.04% of the studies (Table 1); 14.39% of studies did not provide the methodology. The results showed that the use of GIS could improve performance of the model estimates.

The crop management and control practice factors were estimated by using existing data (34.78% of

Table 1 Details of application of the MUSLE in different parts of the world (WMd: Wischmeier and Smith diagram; N.A.: Not provided or unavailable data or information).

No.	Researcher(s)	Region(s)	Area (ha)	Land use (and scale)	Goal	Reference data	Methods of estimation and calculation of factors and model variables						Results	Changes in model	
							Peak flow—Volume of runoff	Soil erodibility	Slope length	Slope steepness	Crop management	Control practice		Coefficient	Power
1	Williams (1977)	Elm Creek (USA)	19 400	Forest and grassland (sub-watershed)	Storm-wise sediment	N.A.	SCS method	Existing studies and WMd	Measured in sub watershed				Acceptable results ($R^2 = 80\%$)	Unchanged	
2	Cordova (1981)	Richland County (USA)	304	Pasture and forest (watershed)	Storm-wise sediment	Sampling of six storm events	Measuring storm-wise	Field measurements and WMd	Topographic Map		Field measurements		Overestimate ($R^2 = 80\%$)	Unchanged	
3	Jackson *et al.* (1987)	23 watersheds in three regions (USA)	N.A.	Pasture (watershed)	Annual sediment	Existing data	Average annual runoff	Field measurements and WMd	Topographic Map		Field measurements		Overestimate and calibration model	0.09	1.11
4	Banasik *et al.* (1988)	Trazebunka (Poland)	300	Forest (watershed)	Storm-wise sediment	1 storm event	Measuring storm-wise	Field measurements and WMd	Field measurements				Acceptable results and increased sediment after deforestation extent 126%	Unchanged	
5	Madeyski and Banasik (1989)	Six small watersheds (Poland)	3200 to 7700	Forest (watershed)	Storm-wise sediment	78 events (3-year period)	Measuring storm-wise	Estimated from soils maps	Estimated from topography map		Estimated from cropping history		Acceptable results ($r = 0.87$)	0.00278	0.8
6	Santos and Canino (1997)	Southern Puerto Rico	400	Forest, agricultural and urban (watershed)	Storm-wise sediment	6 events with 24-h periods	Measuring storm-wise	Existing studies and WMd	Topographic Map		Available statistics and weighted average		Acceptable results	Unchanged	
7	Epifanio *et al.* (1991)	Foothill Range Field Station (California)	26	Oak forest (watershed)	Storm-wise sediment	Statistic 20 events available	Measuring storm-wise	Existing studies and WMd	Topographic Map		Available statistics and weighted average		Overestimate and Significant difference even after calibration	0.21	0.76
8	Epifanio *et al.* (1991)	Foothill Range Field Station (California)	106	Oak forest (watershed)	Storm-wise sediment	Statistic 20 events available	Measuring storm-wise	Existing studies and WMd	Topographic Map		Available statistics and weighted average		Overestimate and Significant difference even after calibration	1.7	0.7
9	McConkey *et al.* (1997)	Western Canada	14.58	Rectangular fields (cropland)	Annual sediment	Storm data (31-year period)	Average annual	Seasonality sample	Measuring field				Appropriate estimates after calibration	0.852	0.09
10	Golson *et al.* (2000)	Thomas—Agricultural Research Station (USA)	N.A.	Agricultural Plots (0.02 and 0.45 ha)	Storm-wise sediment	Sampling of 6 storm events	Measuring storm-wise	Existing studies and WMd	Measurement				Appropriate estimates	Unchanged	
11	Mahmoudzadeh *et al.* (2002)	12 watersheds, Sydney, (Australia)	N.A.	Forest, agricultural and pasture (watersheds)	Annual sediment	6–28 year period	Average annual	Sampling	Topographic Map		Measurement		Insignificant relationship between estimations with observation values	Unchanged	
12	Rezaiifard *et al.* (2002)	AfchhvLatyan (Iran)	2876	Pasture (watershed)	Annual and Storm-wise sediment	Statistic 19 events available	Available statistics	Existing studies and WMd	Topographic Map		Available statistics and weighted average		Overestimate (16–24) and calibration with 4 events ($R^2 = 93\%$)	Calibrated, but was not provided	
13	Khajehie *et al.* (2002)	Shahrchii (Iran)	41 330	Pasture (watershed)	Annual and Storm-wise sediment	Statistic 30 events available	Available statistics	Existing studies and WMd	Topographic Map		Available statistics and weighted average		Overestimate and calibration model ($R^2 = 99\%$)	0.001	1.082
14	Erskine *et al.* (2002)	Shale Sydney, (Australia)	N.A.	N.A.	Annual sediment	6–28-year period	Average annual	Sampling	Topographic Map		Measurement		Appropriate estimates	Unchanged	

(*Continued*)

Table 1 (Continued).

No.	Researcher(s)	Region(s)	Area (ha)	Land use (and scale)	Goal	Reference data	Methods of estimation and calculation of factors and model variables						Results	Changes in model	
							Peak flow—Volume of runoff	Soil erodibility	Slope length	Slope steepness	Crop management	Control practice		Coefficient	Power
15	Blaszczynski (2003)	N.A.			Annual and Storm-wise sediment	N.A.	SCS method	N.A.	Existing data and GIS				Appropriate estimates	Unchanged	
16	Sadeghi *et al.* (2004)	Amameh (Iran)	3712	Pasture (watershed)	Storm-wise sediment	Statistics 15 storm events	Measuring storm-wise	Existing studies and WMd	Topographic Map		For each storm event	Available statistics and weighted average	Overestimate and calibration (R^2 = 98%) and Application necessary for large storm events	Unchanged	0.081
17	Sadeghi and Mahdavi (2004)	Amameh (Iran)	3712	Pasture (watershed)	Storm-wise sediment	Statistics 15 storm events	Reverse routing (Sadeghi and Singh 2010)	Existing studies and WMd	Topographic Map		Available statistics and weighted average		Underestimate and Significant difference	Unchanged	
18	Sarkhosh *et al.* (2004)	Darakeh (Iran)	2460	Pasture (watershed)	Annual sediment	Statistic 14 events available	Measuring storm-wise	Sampling and WMd	Topographic Map		Laflan's Classification		Comparison MUSLE and MPSIAC and Priority Results MUSLE	0.234	0.53
19	Cambazoglu and Gogos (2004)	Western Black Sea Region (Turkey)	N.A.	Land use not mentioned (42 watersheds)	Annual and Storm-wise sediment with return period 2, 5, 10, 25, 50 and 100	8 storm events	Measuring storm-wise	161 Samples	Topographic Map		Available statistics and weighted average		Underestimate and Significant difference	Unchanged	
20	Chen and Mackay (2004)	Pheasant Branch (USA)	2871	Pasture and agricultural (watershed)	Storm-wise sediment	Sampling in 4 years	Measuring storm-wise	N.A.	Existing data and GIS				Overestimate and Significant difference	Unchanged	1.12
21	Appel *et al.* (2006)	Isábena (Spain)	N.A.	Four badlands	Storm-wise sediment	Sampling for 1 storm event	Measuring storm-wise	Sampling	Existing data and GIS				Underestimate and Significant difference	Unchanged	
22	Basson (2005)	40 sub-watersheds in Mbuluzi (Switzerland)	N.A.	Pasture and agricultural (watershed)	Annual sediment	Sampling for storm event	Measuring storm-wise	N.A.	Existing data and GIS				Appropriate estimates	Unchanged	
23	Porabdullah (2005)	Latyan (Iran)	37.2	Pasture (watershed)	Storm-wise sediment	Statistic 19 events	(calibration) and 4 events (validation)	Available statistics	Existing studies and WMd		Topographic Map	Available statistics and weighted average	Accurate estimates of model compared with SWAT and calculation K intermediate 0.16–0.32	Unchanged	
24	Ma (2006)	Nyando (Kenya) Nzoia (Kenya)	356 200	Forest, agricultural and pasture (watershed)	Storm-wise sediment	Existing data for 55 years	Measuring storm-wise	Sampling	Measured in each sub watershed and GIS				Overestimate and Good estimates after calibration	N.A.	
26	Varvani *et al.* (2006)	Gharachay (Iran)	175 092	Pasture (watershed)	Storm-wise sediment	Sampling of 5 storm events	Measuring storm-wise	Existing studies and WMd	Topographic Map		Available statistics and weighted average		Overestimate and calibration (Estimated average difference of about 133 176 ton)	Unchanged	0.324
27	Arekhi (2007)	Dolikhan (India)	40	Agricultural (watershed)	Annual sediment	7 events (3-year period)	Through KW-GIUH model help GIS	Existing studies and WMd	Through GIS		Available statistics and weighted average		Good estimates based validation with 11 events with average relative error of 7%	Unchanged	
28		Salarotola (India)	47	Forest (watershed)	Annual sediment	Existing data	Through KW-GIUH model help GIS	Existing studies and WMd	Through GIS		Available statistics and weighted average		Appropriate estimates based validation with 4 events with average relative error 49%	Unchanged	
29		Nola (India)	42	Forest (watershed)	Annual sediment	Existing data	Through KW-GIUH model help GIS	Existing studies and WMd	Through GIS		Available statistics and weighted average		Appropriate estimates based validation with 4 events with average relative error 49%	Unchanged	

(*Continued*)

Table 1 (Continued).

No.	Researcher(s)	Region(s)	Area (ha)	Land use (and scale)	Goal	Reference data	Methods of estimation and calculation of factors and model variables						Results	Changes in model	
							Peak flow—Volume of runoff	Soil erodibility	Slope length	Slope steepness	Crop management	Control practice		Coefficient	Power
30	Chakrabarty *et al.* (2007)	Kistobazar (India)	N.A.	Forest and agricultural (watershed)	Storm-wise sediment	One storm event	SCS method	N.A.					Appropriate estimates	Unchanged	
31	Jaramillo (2007)	Jozeph (Spain)	4100	Forest, agricultural and urban (watershed)	Storm-wise sediment	Sampling of 12 storm events	Measuring storm-wise	Existing studies and WMd			Existing data and GIS		Overestimate and provide good estimates for storms more than 10 mm	Unchanged	
32	Sadeghi *et al.* (2007a)	Matash (Iran)	0.004	Pasture plot with free grazing and hand picked	Storm-wise sediment	Sampling of 24 storm events	Measuring storm-wise	Existing studies and WMd	Measurement				Overestimate (R^2 = 86%)	Unchanged	
33	Sadeghi *et al.* (2007b)	Mie (Japan)	4.8	Forest (watershed)	Storm-wise sediment	Sampling of 8 storm events	Measuring storm-wise	Existing studies and WMd	Topographic Map		Classification Laflan (2003)		Overestimate and calibration (R^2 = 88%)	0.781	60.63
34	Abdulla and Eshtawi (2007)	Kufranja (Jordan)	N.A.	Rural and agricultural watershed	Storm-wise sediment	Existing data	Measuring storm-wise	N.A.					Appropriate estimates	Unchanged	
35	Sadeghi *et al.* (2008)	Khosbijan (Iran)	0.004	Experimental plots, rain-fed	Storm-wise sediment	Statistic 12 events available	Measuring storm-wise	Existing studies and WMd	Topographic Map		Available statistics and weighted average		Insignificant relationship between estimations with observation values	Unchanged	
36	Rostamian *et al.* (2008)	Beheshtabad (Iran)	386 000	Pasture and agricultural (watershed)	Storm-wise sediment	Existing data	Measuring storm-wise	N.A.					Accurate estimates of model in SWAT model sediment (R^2 = 85%)	Unchanged	
37	Pandey *et al.* (2009)	Karso (India)	2800	Forest and agricultural (watershed)	Storm-wise sediment	345 storm events	Measuring storm-wise	Existing studies and WMd	Using GIS		Land studies and RS		Appropriate estimates	Unchanged	
38	Esmali and Abedini (2009)	Pole-Almasi (Iran)	103 200	N.A.	Erosion	N.A.							Acceptable results in the pixel level and inappropriate in watershed level	N.A.	
39	Khaledi Darvishan *et al.* (2009)	Chehelgazi (Iran)	27 233	Pasture and agricultural (watershed)	Storm-wise sediment	Sampling of 11 storm events	Measuring storm-wise	Existing studies and WMd	Topographic Map		Available statistics and weighted average		Overestimate (26–66) and calibration with 3 events and relative estimation and verification errors of 29.05 and 38.40%, respectively	0.003	0.73
40	Zhang *et al.* (2009)	Black Hawk (USA)	2420	Agricultural (watershed)	Storm-wise sediment	Data registered 2 years storm	SCS method	Existing studies and WMd	Using GIS				Appropriate estimates	Unchanged	
41	Mishra and Ravibabu (2009)	Bhalukanala (India)	1006	Agricultural (watershed)	Storm-wise sediment	15 storm events registered	SCS method	Existing studies and WMd	Using GIS		Land studies and RS		Appropriate estimates	Unchanged	
42	Wambua *et al.* (2009)	Njoro (Kenya)	N.A.	Land use not mentioned (watershed)	Storm-wise sediment	N.A.	Measuring storm-wise	N.A.					Appropriate estimates	Unchanged	
43	Shen *et al.* (2009)	Zhangjiachong (China)	162	Forest and agricultural (watershed)	Monthly sediment	N.A.							Overestimate (R^2 = 67%)	Unchanged	

(*Continued*)

Table 1 (Continued).

No.	Researcher(s)	Region(s)	Area (ha)	Land use (and scale)	Goal	Reference data	Methods of estimation and calculation of factors and model variables						Results	Changes in model	
							Peak flow—Volume of runoff	Soil erodibility	Slope length	Slope steepness	Crop management	Control practice		Coefficient	Power
44	Noor *et al.* (2010)	Kojor (Iran)	13 000	Forest (watershed)	Phosphorus losses	Sampling of 7 storm events	Measuring storm-wise	Existing studies and WMd	Existing data		Vegetation map	Available statistics and weighted average	Overestimate and calibration ($R^2 = 93\%$)	0.087	0.34
45	Smith *et al.* (1984)	Oklahoma (USA)	0.04 to 122	Pastoral and agricultural	(25 watersheds)	Storm-wise sediment	Storm data for 3–5 years	Measuring storm-wise	Sampling		Measurement	Appropriate estimates		Unchanged	
46	Lpez-Tarazn *et al.* (2012)	Isábena (Spain)	44 500	Land use not mentioned (watershed)	Storm-wise sediment	Sampling	N.A.						Appropriate estimates	Unchanged	
47	Qiu *et al.* (2012)	Zhifanggou watershed (China)	827	Woodland, grassland and cropland	Daily and applied for the SWAT model	1998–2008	N.A.						Under estimate of SWAT	Unchanged	
48	Yang *et al.* (2012)	Huaihe River watershed (China)	27 000 000	Paddy, farmland and woodland	Flood events and coupling with the Xinanjiang model	2000–2008	Xinanjiang model	Xixian soil survey	Using DEM and GIS		National land-use map of 2000		Appropriate estimates	Unchanged	

studies), the Laflen and Moldenhauer (2003) classification (4.35%), GIS (26.09%) and field measurement (21.74%); 13.04% of studies did not note the method of estimation. The results also showed that considering the temporal variation of these factors could significantly improve the performance of the model, although it has been rarely taken into account. The crop management and control practice factors were estimated with the help of the available tables and generating a weighted average, and through field measurement (Table 1).

The peak flow and the volume of runoff were obtained through direct measurement of runoff on a storm-event basis (58.70% of studies), using existing data (6.52%) (Khajehie *et al*. 2002, Rezaiifard *et al.* 2002, Porabdullah 2005), applying GIS (6.52%) (Arekhi 2007), lumped runoff values (8.70%) (Jackson *et al*. 1987, McConkey *et al*. 1997, Erskine *et al*. 2002, Mahmoudzadeh *et al*. 2002), the Soil Conservation Service (SCS) method (10.87%) (Williams 1977, Blaszczynski 2003, Mishra *et al*. 2006, Chakrabarty *et al.* 2007, Zhang *et al*. 2009) and reverse routing (2.17%) (Sadeghi and Mahdavi 2004). In 6.52% of studies, no details were given. Our analysis also demonstrated the greater appropriateness of field and direct measurements of runoff on a storm-event basis for better performance of the model output compared to use of indirect methods. Recently, the MUSLE has frequently been used as a module for hydrological models, such as the Soul and Water Assessment Tool (SWAT) (Qiu *et al.* 2012, Yang *et al.* 2012), to estimate sediment yield. In these studies, the MUSLE is used in its original form and no modification is usually considered. In some cases, the weakness of the main model is attributed to its dependence on many empirical and semi-empirical models, such as SCS-curve number and MUSLE, which cause the main model to have less accuracy.

The 49 MUSLE applications evaluated showed that the MUSLE model has been applied for different purposes of sediment yield estimation, i.e. on a storm basis (in 73.91% of studies; see Table 1), on a monthly basis (2.17%) (Shen *et al.* 2009) and an annual basis (17.39%; Table 1), as well as for estimation of soil erosion on a storm-wise scale (Esmali and Abedini 2009), for pollutant estimation (Noor *et al.* 2010) and annual sediment yield with different return periods (in 2.17% of cases each). While the MUSLE model has been basically developed for estimation of sediment yield from large storm events occurring on rangeland watersheds (Williams and Berndt 1977), its application in other conditions was found by other researchers to generate high errors sometimes very different from the observed data. The research reports assessed here show application of the MUSLE model in various land-use scenarios (with percentage of studies): pasture (17.39%), agricultural (6.52%), forest (15.22%), pasture-agricultural (10.87%), forest-pasture (2.17%), forest-agricultural-urban (10.87%), forest-pasture-agricultural (4.35%) and agricultural-urban (2.17%); the type of land use was not reported in 15.22% of studies.

Owing to differences between observed and estimated values, attempts have been made to calibrate the MUSLE through adjusting the power or the coefficient of models in some studies (Jackson *et al.* 1987, Epifanio *et al.* 1991, McConkey *et al*. 1997, Khajehie *et al*. 2002, Rezaiifard *et al*. 2002, Sadeghi *et al.* 2004, 2007b, Sarkhosh *et al*. 2004, Khaledi Darvishan *et al*. 2009, Noor *et al*. 2010). In two studies (Chen and Mackay 2004, Varvani *et al.* 2006), only the power of the model was calibrated, which is logically more acceptable. The necessity of model calibration was also emphasized in those studies in which no calibration adjustment had been made. The minimum, median, maximum and standard deviation of the coefficient of the MUSLE in all the studies were found to be 0.001, 0.15, 6.38 and 17.25, respectively. Out of 46 studies, almost 22% had included calibration of the coefficient, whereas another 50% gave appropriate results. In the remaining 28%, the coefficient was not revised, although the necessity of calibration was emphasized. The minimum, median, maximum and standard deviation of the model power were calculated as 0.081, 0.745, 0.70, 1.12 and 0.3, respectively. The model power was calibrated in only 28.26% of the studies; another 43.48% did not undertake any calibration because they produced reasonable results, whereas, for the rest, revision is needed.

Our results also showed overestimation by the MUSLE model in some studies, while in other studies, the model underestimated the measured values (see Table 1). In other cases, conducted in USA watersheds (Williams 1977, Jackson *et al*. 1987, Santos and Canino 1997, Golson *et al*. 2000, Zhang *et al.* 2009), or under similar climatic conditions to that of the original location (Table 1), the model presented good estimates.

According to the results of the present study, it can be concluded that the application of the MUSLE model may produce reasonable estimates when it is applied under appropriate conditions similar to those where the original model was developed (Table 1) or calibrated accordingly. In this context, the MUSLE model values showed a significant difference with measured sediment yield in many watersheds in Iran (Afcheh, Amameh, Shahrchaii, Gharehchi, Chehelgazi and Kojor), the USA (Pheasant Branch and Foothill Range Field Station), western Canada, Kenya (Nyando and Nzoia) and Japan (Mie). The MUSLE model was then calibrated in these study areas (Jackson *et al.* 1987, Epifanio *et al.* 1991, McConkey *et al.* 1997, Khajehie *et al.* 2002, Rezaiifard *et al.* 2002, Chen and Mackay 2004, Sadeghi and Mahdavi 2004, Sadeghi *et al.* 2004, 2007b, Ma 2006, Varvani *et al.* 2006, Khaledi Darvishan *et al.* 2009, Noor *et al.* 2010). The model presented reliable results for sediment yield on a storm basis after calibration and with a low level of estimation error (Sadeghi *et al.* 2007b), as originally developed by Williams (1975). Therefore, the unusual application of the MUSLE model, i.e. for estimation of soil erosion (Sadeghi *et al.* 2004, Esmali and Abedini 2009) or nutrient loss (Noor *et al.* 2010) provides inappropriate predictions at the watershed scale, or even at the plot scale (Sadeghi 2004, Kinnell 2005, 2010, Khaledi Darvishan 2009).

However, an accurate estimation of sediment yield requires a sufficient number of samples or sedimentgraph preparation to give an appropriate basis for comparison and model calibration (Cordova 1981, Smith *et al.* 1984, Jackson *et al.* 1987, Banasik *et al.* 1988, Epifanio *et al.* 1991, McConkey *et al.* 1997, Santos and Canino 1997, Erskine *et al.* 2002, Khajehie *et al.* 2002, Mahmoudzadeh *et al.* 2002, Rezaiifard *et al.* 2002, Cambazoglu and Gogos 2004, Chen and Mackay 2004, Sadeghi and Mahdavi 2004, Sarkhosh *et al.* 2004, Basson 2005, Kinnell 2005, Porabdullah 2005, Appel *et al.* 2006, Ma 2006, Varvani *et al.* 2006, Abdulla and Eshtawi 2007, Arekhi 2007, Jaramillo 2007, Sadeghi *et al.* 2007a, 2007b, 2008, Khaledi Darvishan *et al.* 2009, Kinnell 2010, Noor *et al.* 2010).

Although the MUSLE model has provided good results in some areas, review of the correct values and exact variables used and final conclusions of the application are strictly recommended in order to apply the MUSLE model correctly. Further studies and investigations are needed to draw a comprehensive conclusion.

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