Calibration and validation of the Modified Universal Soil Loss Equation for estimating sediment yield on sloping plots: A case study in Khun Satan catchment of northern Thailand

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Pongsai, S., Schmidt Vogt, D., Shrestha, R. P., Clemente, R. S. and Eiumnoh, A. 2010. **Calibration and validation of the Modified Universal Soil Loss Equation for estimating sediment yield on sloping plots: A case study in Khun Satan catchment of Northern Thailand**. Can. J. Soil Sci. **90**: 585–596. In this study, model testing, calibration, and validation of the Modified Universal Soil Loss Equation (MUSLE) model were carried out in Khun Satan catchment, Thailand, for the estimation of sediment yield in plots of different slopes using the *S* factor from the classic Universal Soil Loss Equation (USLE) and the McCool model, as the calibration parameter. In situ experimental plots were established with five different inclinations (9, 16, 25, 30, and 35%), with the other model parameters (e.g., erodibility, conservation practice, etc) being treated as constants. Sediment yields were recorded from 27 rainfall events between July and October 2003. It was found that both the classic USLE and the McCool models over-estimated sediment yields at all slope angles. However, the classic USLE produced a smaller relative error (RE) than the McCool model at plots with slopes of 9 and 16%, while the McCool model performed better at plots with slopes over 16% inclination. The calibration of the model using the *S* factor was then made for two slope range intervals, and the slope algorithm was later modified. The calibrated *S* factors were used in the prototype model for slope ranges of 9 to 16% using classic USLE and for slopes from 16 to 35% using the McCool model. The results revealed that an acceptable accuracy can be obtained through model calibration. The model validation based on paired t-test, on the other hand, showed that there was no difference ($\alpha = 0.05$) between measured and estimated sediment yield using both models. This result indicates that if data on various slope gradients are limited, MUSLE needs to be calibrated before application, especially with respect to topographic factors, in order to obtain an accurate estimate of the sediment yield from individual rainfall events.

Key words: Model calibration, MUSLE, Northern Thailand, sediment yield, soil erosion, steep slope

Pongsai, S., Schmidt Vogt, D., Shrestha, R. P., Clemente, R. S. et Eiumnoh, A. 2010. **Étalonnage et validation du modèle MUSLE pour estimer la production de sédiments sur les parcelles en pente: la zone de captage de Khun Satan, dans le nord de la Thaïlande**. Can. J. Soil Sci. **90**: 585–596. Les auteurs ont étudié, testé, étalonné et validé le modèle MUSLE dans la zone de captage de Khun Satan, en Thaïlande, afin d'estimer la production de sédiments sur des parcelles de pente variable, en utilisant comme paramètre d'étalonnage le coefficient S du modèle classique USLE et du modèle de McCool. Des parcelles expérimentales ont été aménagées sur les lieux selon cinq déclivités (9, 16, 25, 30 et 35%), les autres paramètres (à savoir, érodabilité, méthode de conservation, etc.) étant considérés comme des constantes. La production de sédiments a été enregistrée après 27 précipitations, de juillet à octobre 2003. On a découvert que le modèle classique USLE et le modèle McCool surestiment la production de sédiments pour toutes les pentes. Cependant, le premier donne une erreur relative plus faible que le second pour les pentes de 9 et de 16%, alors que le modèle McCool donne de meilleurs résultats pour les parcelles d'une déclivité supérieure à 16%. Le modèle a été étalonné avec le coefficient S pour deux plages de déclivité, puis on a modifié l'algorithme de la pente. On s'est ensuite servi du coefficient S étalonné selon le modèle USLE classique pour les pentes de 9 à 16% du modèle expérimental et selon le modèle McCool pour les pentes de 16 à 35%. Les résultats indiquent que l'étalonnage confère une précision raisonnable au modèle. En revanche, la validation du modèle avec les tests t appariés révèle qu'il n'existe aucun écart ($\alpha = 0,05$) entre la production réelle de sédiments et celle estimée selon les deux modèles. On en conclut que si les données sur le gradient de déclivité sont restreintes, il faut étalonner le modèle MUSLE avant de l'employer, surtout eu égard aux paramètres topographiques, de manière à obtenir une estimation précise de la quantité de sédiments produite après chaque précipitation.

Mots clés: étalonnage de modèle, MUSLE, nord de la Thaïlande, production de sédiments, érosion du sol, pente abrupte

Abbreviations: **AE**, average error; **MUSLE**, Modified Universal Soil Loss Equation; **RE**, relative error; **SE**, standard error; **USLE**, Universal Soil Loss Equation

Accelerated erosion on the steep slopes of northern Thailand caused by unsustainable land use practices (Hansen 2001; Forsyth 2007) has been a problem for centuries (Land Development Department, Thailand 2002). Erosion on fields, among other consequences, reduces potential crop production (Lal 1998). The most important consequence of erosion is sediment yield from the watershed, which causes siltation of canals, loss of storage volume in reservoirs, nutrient pollution, flooding, etc. (Vanoni 1982; Morgan et al. 1998; Mihara et al. 2005; Sadeghi et al. 2007a). This affects not only the downstream environment, but also the socioeconomic development of the entire region. In order to reduce sediment yield and promote proper soil and water conservation and sustainable land use, information about sediment yield is required, together with suitable modeling tools for obtaining such information.

There are several ways to estimate sediment yield, including modeling approaches such as the conventional Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). The USLE is widely used with a combined sediment delivery ratio (SDR) to calculate sediment yield at the watershed outlet (Ferro 1997; Kothyari and Jain 1997; Cambazoglu and Gogos 2004). Originally, the USLE was developed to estimate the annual soil loss with no direct consideration of runoff, and hence its application to storm-based events leads to large errors (Kinnell 2005; Chang 2006; Sadeghi et al. 2004, 2007a). Its accuracy can be improved if the USLE is coupled with a hydrologic rainfall-excess model (Epifanio et al. 1991; Novotny and Olem 1994; Sadeghi et al. 2004; Hrissanthou 2005; Mishra et al. 2006). Also, due to a lack of sediment data for the determination of delivery ratios, and a lack of consistency in regional regression relationships for estimating delivery ratios in many areas, application of an SDR model involves parameters similar to those of the USLE, resulting in a duplicate step. These drawbacks can make the SDR model an impractical and time-consuming process (Chang 2006; Sadeghi et al. 2007a).

The Modified Universal Soil Loss Equation (MUSLE) (Williams 1975) was developed as a watershed-based model to estimate the sediment yield produced by each individual storm event. In the MUSLE, the rainfall (R) factor is replaced with a term that combines storm runoff volume (Q_v in m^3) and peak runoff rate (q_p in $m^3\ s^{-1}$), and interprets the other USLE factors (soil erodibility: *K* factor, slope steepness and length: *LS* factor, crop management: *C* factor, and conservation practices: *P* factor) on a watershed-wide and individual storm event basis. The runoff factors represent the energy used in transporting as well as in detaching sediment, which acts as the best indicator for predicting the sediment yield of each individual storm event (Foster et al. 1977; Hrissanthou 2005; Sadeghi et al. 2007b). The accuracy in estimating sediment yield, especially for micro-watersheds, is increased by eliminating the sediment delivery ratio (Williams and Berndt 1977; Smith et al. 1984).

The MUSLE approach has been used to estimate sediment yield at various sites. Some errors, however, have been associated with both USLE and runoff model estimates, resulting in under- and over-prediction of sediment yield from various rainfall event characteristics and site-specific criteria, and have led to various proposals to increase accuracy after regression analysis is applied (Johnson et al. 1986; Epifanio et al. 1991; Clemente 1991; Clemente et al. 1993; Kinnell and Riss 1998; Erskine et al. 2002; Fontes et al. 2004; Sadeghi 2004; Kandrika and Venkataratnam 2005; Sadeghi et al. 2007a,b; Sadeghi and Mizuyama 2007). The complexity of watershed systems has forced modelers and users to develop modified, calibrated or revised versions of the MUSLE (Sadeghi 2004; Sadeghi et al. 2007a,b). All parameters (Q_v, q_p, *K*, *L*, *S*, *C*, *P*) in the model can potentially be used for calibration and validation, especially when used in conditions different from those in which they have previously been applied and tested.

Due to errors associated with the classic USLE, especially those relating to topographic factors in terms of limited availability of data on steep slope gradients, it is still unclear how the USLE can be applied to complex slopes beyond the range of the extended model. Application of the MUSLE has not been documented. The structure of the MUSLE model has inherited some limitations from classic USLE, especially those related to slope steepness (*S* factor). In the model, *S* parameters can be used both as the classic USLE and as the McCool model (McCool et al. 1987). The *S* factor is, however, very different in the two equations. The *S* factor of the classic USLE was derived based on data from plots with slopes ranging from 3% to 18% steepness (Wischmeier and Smith 1978; Chang and Ting 1986; Risse et al. 1993; Kitahara et al. 2000), while McCool's *S* factor improved the *LS* factor from classic USLE for use in terrain with steeper slopes, with a breakpoint at around 9% slope. The *S* factor of the classic USLE increases with increasing slope steepness and exceeds the slope range of the extended model when applied to watersheds with more steeply inclined slopes. Conversely, McCool's *S* factor increases at a decreasing rate as slope steepness increases. However, McCool's *S* factor separates *S* values into two ranges ($<9\%$ and $>9\%$), and the range should be specified with a smaller interval when applied in a highland watershed. The application of the MUSLE on steep slopes in small watersheds, which are beyond the condition under which the MUSLE was originally developed, should be investigated (Sadeghi et al. 2007a). The model needs to be calibrated before application to obtain an accurate estimate of sediment yield over the entire watershed.

However, the MUSLE model was originally developed from micro-watersheds (Williams and Berndit 1977; Smith et al. 1984). Under micro-watershed conditions, slope gradients are non-uniform and complex, making it difficult to identify and compare the *S* factor and to subject its applicability to critical analysis. Previous studies have recommended that a follow-up study focus on how the variation of *S* factor influences sediment yield by establishing experimental plots at smaller slope intervals in order to evaluate the effect of slope in the model when applied to the sloping terrain of Thailand (Tangtham 2002). Hence, the objective of this study is to test the accuracy of the original MUSLE using the *S* factor from the classic USLE and McCool et al. (1987) at five slope inclinations (9, 16, 25, 30, and 35%), which are representative of the range of slope gradients in small watersheds in Thailand, by setting up other parameters as constants. A null hypothesis of the model considers that it effectively estimates storm-wise sediment yield; if not, calibrating and validating help increase estimation accuracy.

MODEL DESCRIPTION

Model structure

The MUSLE (Williams 1975) is calculated as:

$$X_t = 11.8(Q_v q_p)^{0.56} KLSCP \tag{1}$$

where X_t is the sediment yield from a rainfall event in metric tons, Q_v is the runoff volume (m^3), q_p is the peak runoff rate ($m^3\ s^{-1}$), K is the soil erodibility in Mg $MJ^{-1}\ mm^{-1}$, LS is the slope length and slope steepness factor (dimensionless), C is the crop management factor (dimensionless), and P is the conservation practice factor (dimensionless).

Analysis of *LS* factors in the original MUSLE model

According to the original MUSLE model structure (Eq. 1), the *LS* parameters can be used both as classic USLE (Eq. 2) and as McCool et al. (1987) (Eq. 3). The details can be summarized as follows:

Slope steepness (*S*) and slope length (*L*) or *LS* factor is the topographic factor. The *LS* factor of classic USLE is calculated using the following equation (Wischmeier and Smith 1978):

$$\mathrm{LS} = \left(\frac{I}{22.13}\right)^m (0.43 + 0.30\mathrm{s} + 0.043\mathrm{s}^2)/6.574 \tag{2}$$

where *LS* is the slope length and steepness factor, *s* is the field slope in percent, *I* is the slope length (in meters), and *m* is the dimensionless exponential (varies from 0.2 for slope $<1\%$ to 0.6 for slope $>10\%$ (Renard et al. 1997; Sadeghi et al. 2007a).

However, McCool et al. (1987) improved the *LS* factor from classic USLE for use in terrain with steeper slopes. This can be calculated by the following equation:

$$LS = (I/22.13)^m (16.8\sin\theta - 0.5) \tag{3}$$

where *I* is the slope length in meters, and *m* is the dimensionless exponential calculated from the equation below:

$$m = \frac{\sin\theta}{\sin\theta + 0.269(\sin\theta)^{.8} + .05}$$

where θ is field slope in degrees $= \tan^{-1}(s/100)$, s is the field slope in percent, $S = 3.0\ (\sin\ \theta)^{0.8} + 0.56$ (for slope length shorter than 4 m), $S = 10.8\ \sin\ \theta + 0.03$ (for slope length longer than 4 m and $s < 9\%$), $S = 16.8\ \sin\ \theta - 0.50$ (for slope length longer than 4 m and $s > 9\%$). According to the micro-watershed area, *LS* can be computed as:

$$\mathrm{LS} = \frac{1}{\mathrm{AD}} \sum_{1=1}^{\mathrm{n}} \mathrm{LSiADi} \tag{4}$$

where *AD* is the total watershed area, AD_i is the micro-watershed area relating to LS_i, and *n* is the number of different *LS* factors in the micro-watershed.

The *S* factor when we fix *I* (slope length in meters) at 22.13 m (the *L* factor will be equal to 1 for both as shown in table 1) is, however, very different in the two equations. The *S* factor of the classic USLE Eq. (2) increases at an increasing rate as slope steepness increases, while in Eq. (3) (McCool et al. 1987) *S* factor increases at a decreasing rate as slope steepness increases. Therefore, the *S* factor equation of the classic USLE and McCool et al. (1987) will be tested for accuracy and calibrated for MUSLE estimation in slope land.

MATERIALS AND METHODS

Study Area

Research was carried out in Khun Satan Research Station, Department of National Parks, Wildlife and Plant Conservation, Thailand, located in Khun Satan catchment, Na Noi district of Nan province, in northern Thailand (Fig. 1). The topography of Khun Satan catchment ranges from flat terrain to mountains, with an elevation of 350 to 580 m above mean sea level, and a slope range of 5 to 35%. Over 60% of the catchment area lies within the high slope terrain. The climate is monsoonal, with three distinct seasons: the rainy season (mid May–October), the cold-dry season (November–January), and the hot, dry season (February–early

Table 1. Comparison of *LS* factor calculations between the classic USLE and McCool et al. (1987)

Slope steepness (%)	Classic USLE			McCool et al. (1987)		
	L	S	LS	L	S	LS
9	1.00	1.01	1.00	1.00	1.46	1.46
16	1.00	2.47	2.47	1.00	2.60	2.60
25	1.00	5.29	5.29	1.00	4.02	4.02
30	1.00	7.32	7.32	1.00	4.78	4.78
35	1.00	9.68	9.68	1.00	5.50	5.50

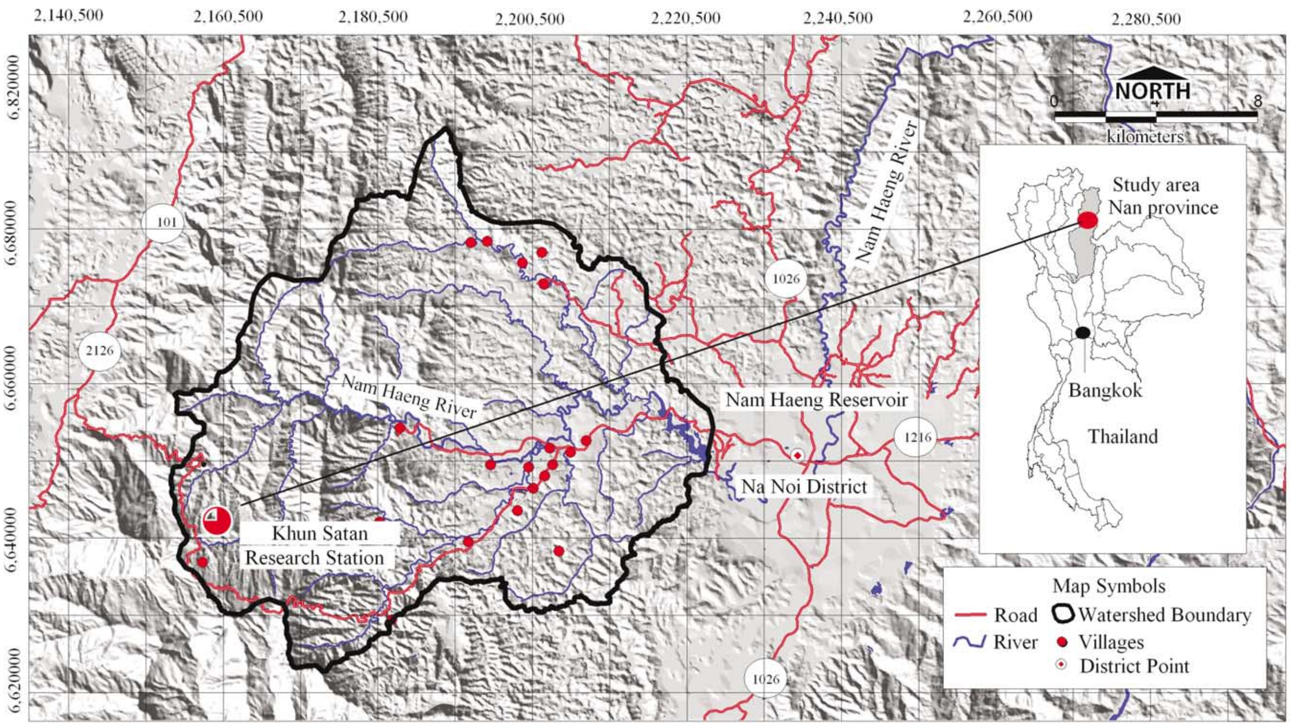

Fig. 1. Location of study area.

May). The land use of the area consists mainly of degraded forest and upland agriculture, with upland rice, maize, and vegetables grown in both shifting cultivation and permanent cultivation patterns (Land Development Department, Thailand 2006).

Data Collection and Plot Design

According to the original MUSLE model Eq. 1, accuracy testing, calibrating and validating, the set of experimental plot measurements can be separated into two groups: a set of testing plots, and a set of validating plots. A set of testing plots is proposed for original MUSLE model accuracy testing [using *S* factor from the classic USLE and McCool et al. (1987)] and the *S* factor calibration process, while a set of validating plots is proposed for accuracy evaluation of the newly fitted *S* factor (new calibrated model). Both experimental plot sets are laid out along different uniform slope gradients (9, 16, 25, 30, and 35%). All of the experimental plots have a length of 22.13 m (standard slope length of classic USLE) and a width of 4 m (Tangtham 2002), with three replications for each plot. Other parameters: soil, rainfall, crop management (without cover crop), and conservation practices (up and down tillage) are the same. The schematic of the experimental plots is shown in Fig. 2.

Soil samples were randomly collected both from experimental plots and from nearby surrounding points at depths of 0–30 cm. Soil organic matter was analyzed using the method recommended by Black (1965), while soil texture analysis was made using the pipette method (Gee and Bauder 1986). Soil permeability under disturbed conditions (soil core) was measured using saturated hydraulic conductivity (K-sat) measurement in a laboratory (Klute and Dirksen 1986). Infiltration was measured in the field (undisturbed) using double ring infiltration (Klute and Dirksen 1986).

Twenty-seven rainfall events were recorded by automatic rain gauge from July to October 2003, and were used to measure sediment yield. The total of all 27 rainfall events was 450 mm. In each plot, two tanks (diameter 1 m, height 50 cm) with 10 dividers were erected to collect the runoff water. The amount of runoff was measured by the depth of water in the tank. The runoff volume measurement was taken after the rainfall event so that the collected data represented an event base value. The measured values included runoff and sediment from one storm. Sediment samples were collected from the tanks; samples (1 L) of water were collected from the stirred water using plastic bottles. Filter paper was used to filter the soil particles from the water samples. The filtered sediments were oven-dried for 24 h and then weighed (Tangtham 2002).

Application of the MUSLE

In the present study, sediment yield per storm event was estimated using the MUSLE as given in Eq. 1 for the complete set of storm events occurring during the study period. Values for runoff volume (Q_v) were extracted from data collected during the study period. The SCS triangular hydrograph analysis procedure is a widely

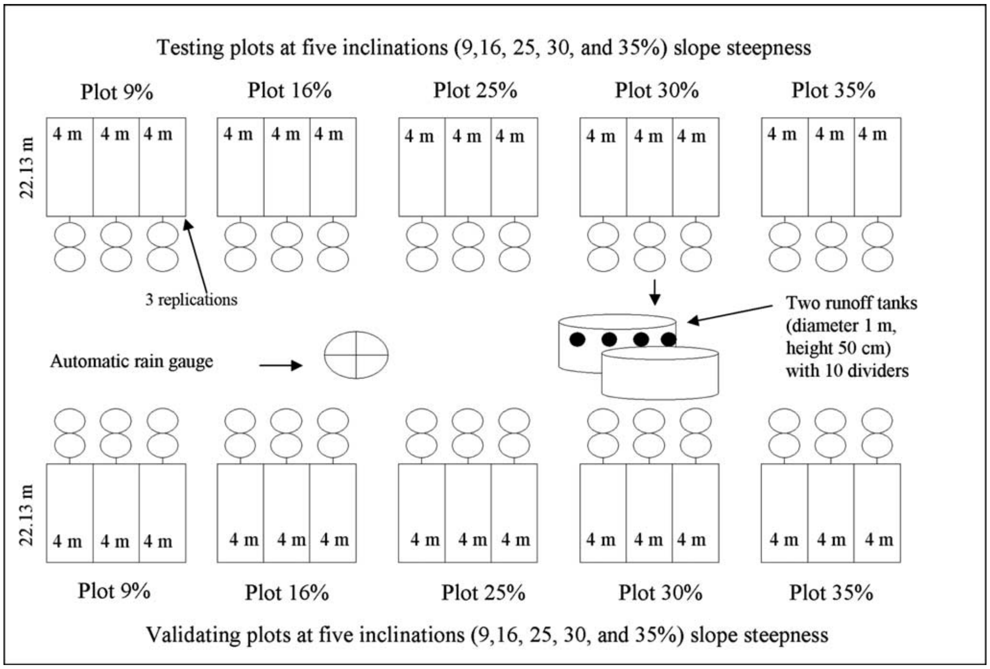

Fig. 2. The schematic of the experimental plots.

used practice among hydrology practitioners due to its predictability, and stability (Hann et al. 1982, 1996). The parameter runoff peak (q_p) for the experimental plot was determined by the following formula based upon the SCS triangular hydrograph analysis procedure:

$$q_p = 0.278Ad/Tp \quad (5)$$

where q_p is peak runoff rate ($m^3 s^{-1}$), A is area (km^2), d is runoff depth (mm), and Tp is the rise time of the hydrograph (h) (time from the beginning of runoff to the time of peak runoff). The rise time, Tp, was calculated as a function of the time of concentration of the plot, which was also calculated through determining the surface runoff velocity by the classical Manning's formula (Hann et al. 1982, 1996; Sadeghi et al. 2007b).

The K value was computed from the nomograph of the USLE (Wischmeier et al. 1971; Morgan 1995) using four parameters: percent of organic matter, soil texture, soil structure, and soil permeability from laboratory soil analysis of experimental plots. The topographic or slope steepness and length (LS) were calculated using Eq. 2 for the classic USLE (Wischmeier and Smith 1978) and Eq. 3 for McCool et al. (1987). The crop management (C factor) for no cover crop and for the up and down slope conservation practice (P) were assigned a value of 1 (Wischmeier and Smith 1978; Tangtham 2002; Laflen and Moldenhauer 2003).

Model Testing, Calibrating and Validating Analysis

The plots used for testing/calibrating and validating process were separately established as mentioned above; therefore, there are a total of 10 plots in the study (9, 16, 25, 30, and 35% per each set). Sediment data from 27 rainfall events were collected from testing and validating plots. The paired t-test (two-tail) method to determine the strength of the null hypothesis (Epifanio et al. 1991; Rasmussen 1992; Sadeghi et al. 2007b; Sadeghi and Mizuyama 2007) was used to compare the mean difference of a single storm between estimated [the classic USLE and McCool et al.'s (1987) S factors] and measured sediment yield data at significance level of 5% (95% confidential interval) and descriptive statistics (average error: AE, relative error: RE, and standard error: SE), were also analyzed, using Microsoft Excel software.

The calibrations were made in accordance with the result of paired t-test and descriptive statistics. A regression method using ordinary least square-OLS to estimate parameters for generating the new S factors (using the single storm estimated and measured sediment yield data sets) was employed. There were 135 samples that were used in testing/calibrating process (27 rainfall × 5 slopes of testing plots sets). In each slope plot, the S factor [from the classic USLE or McCool et al. (1987)] that gave the least error was selected for calibration. Calibration of the S factor for the classic USLE used multiple regression (the independent variables are s and s^2, where s is percent slope), while the S factor for McCool's used simple regression (the independent variable is sin θ). Later on, the new calibrated S models were tested in validating plots. The model validation process was included in the comparison of the new calibrated model and the measured sediment yield from validating plots using 135 samples (27 rainfall × 5 slopes of validating plots sets) with paired t-test and descriptive statistics, which are similar to those used in the testing process.

The descriptive statistics testing includes average error (AE), relative error (RE), and standard error (SE), and can be calculated by the following equations (Rasmussen 1992):

$$AE = \sum_{i=1}^{n} (C_{i,m} - C_{i,a})/n \tag{6}$$

$$RE = (AE/C_{mean,a}) \times 100 \tag{7}$$

$$SE = \left[\sum_{i=1}^{n} (C_{i,m} - C_{i,a})^2/(n-1) \right]^{0.5} \tag{8}$$

where $C_{i,m}$ is the sediment yield (g) from model estimation rainfall event i, $C_{i,a}$ is the sediment yield (g) from the actual experimental plot rainfall event i, n is the total amount of rainfall event on the sample, and $C_{mean,a}$ is the mean sediment yield (g) from the experimental plot.

RESULTS AND DISCUSSION

The input parameters for MUSLE in Eq. 1 were derived from data collected from 27 rainfall events. Soil erodibility (K factor) of the area was 0.05 (Table 2). Runoff volume (Q_v) was measured at the experimental plots (Table 3), and the runoff peak (q_p) was calculated using Eq. (5), the results of which are summarized in Table 3. The L factor was set as 1 for both the classic USLE and McCool et al. (1987). The S factors used for the classic USLE and the McCool model on different slopes are shown in Table 1. C and P factors were assumed to be constant at 1 (Wischmeier and Smith 1978; Tangtham 2002; Laflen and Moldenhauer 2003), and Manning's roughness coefficient was estimated at 0.10 as suggested by Haan et al. (1982, 1996) and Tangtham (2002).

Table 2. Soil properties and soil erodibility (K factor) of experimental plot (depth 0–30 cm)

Soil properties	Value	Remark
Sand (%)	64.00	
Silt (%)	19.00	
Clay (%)	17.00	
Texture (USDA)	Sandy loam	
Organic matter (%)	2.00	
Permeability (cm h^{-1})	0.765	
Permeability class	1	Permeability classes[z] code 1 = rapid to moderate code 2 = moderate code 3 = moderate to slow code 4 = slow code 5 = very slow
Soil structure	Fine granular	Structure code[z]
Structure code	2	code 1 = very fine granular code 2 = fine granular code 3 = moderate to coarse granular code 4 = massive clay
Soil erodibility (K value) (Mg MJ^{-1} mm^{-1})	0.05	
Bulk density (g cm^{-3})	1.35	

[z]Data source: Wischmeier et al. (1971).

Accuracy tests of the MUSLE using field-measured data in test plots showed that the S factor from both the classic USLE and the McCool model led to an over-estimation of event-based sediment yield at all slope levels. The mean difference between the measured and the estimated sediment yield of each storm event (the same as average error: AE) was statistically not significant as indicated by the paired t-test depicted in Table 4. However, the descriptive statistical analysis (AE, RE, SE) showed that the accuracy of the MUSLE model using the classic USLE and McCool's parameters varies with slope steepness, indicating the effect of slope on the accuracy of sediment estimation and, therefore, the need to calibrate the model.

With regard to over-estimation by the model, the findings of this study are in agreement with several previous studies; for instance, Johnson et al. (1986), Epifanio et al. (1991), Sadeghi et al. (2004) and Sadeghi et al. (2007a), all concluded that the MUSLE over-estimated in storm-wise sediment yield prediction. However, this research contradicts findings that reported under-estimations (Sadeghi et al. 2007b), and some applications of MUSLE that did not need any modification to the model (Clemente 1991; Clemente et al. 1993; Sadeghi and Mizuyama 2007). The resulting under- and over-estimation, depend on various site-specific conditions, for instance rainfall characteristics, watershed size, land use; and the reliability of observed sediment data (Fontes et al. 2004; Kandrika and Venkataratnam 2005; Sadeghi et al. 2007a; Sadeghi and Mizuyama 2007). In addition, the MUSLE model, which has been designed for application on a watershed scale (Kinnell and Riss 1998; Erskine et al. 2002), has not performed well in terms of sediment yield in plot-sized area (Sadeghi et al. 2007b). The tendency of predictions to over-estimate is probably caused by the topography factor, especially on mountains with steep slopes and in very small catchments (Sadeghi et al. 2007a), conditions fundamentally different from those under which the MUSLE (Williams 1975; Williams and Berndt 1977) was originally developed. Its accuracy, however, can be improved through calibration.

In plots on 9–16% slopes, using the S factor from the classic USLE provides better estimates of sediment yield than the McCool model, as indicated by the smaller average error (AE), relative error (RE), and standard error (SE) shown in Table 4 and Fig. 3. The mean difference values between the measured and estimated sediment yield or average error (AE) values at slopes of 9 and 16% were 92 and 315 g for classic USLE (with RE 125 and 239%), and 166 and 340 g for McCool's (with RE 226 and 257%), respectively. The estimation

Table 3. Rainfall and runoff volume (Q_v) characteristics for 27 storm events on the testing and validation plots

		Rainfall characteristics		Q_V (10^{-3}) Testing plots of slope (%)					Q_v (10^{-3}) Validation plots of slope (%)				
Event no.	Date	(cm)	(h)	9	16	25	30	35	9	16	25	30	35
1	2003 Jul. 08	1.50	2.00	42	41	39	38	35	42	38	41	37	33
2	2003 Jul. 08	2.10	2.75	58	57	55	53	51	59	58	56	53	53
3	2003 Jul. 12	2.00	2.50	42	39	38	37	34	43	40	34	34	33
4	2003 Jul. 12	1.50	2.75	47	42	40	38	35	47	46	41	39	38
5	2003 Jul. 14	1.50	1.75	100	96	93	91	88	100	97	95	93	90
6	2003 Jul. 14	0.40	0.50	38	33	29	26	24	38	36	29	26	24
7	2003 Jul. 29	2.40	3.00	47	44	43	43	41	47	43	40	38	37
8	2003 Jul. 31	0.80	1.75	22	18	17	15	15	22	21	17	12	11
9	2003 Aug. 02	1.60	2.25	40	40	36	32	32	40	37	39	37	36
10	2003 Aug. 12	1.90	3.00	47	46	45	43	40	46	42	41	40	39
11	2003 Aug. 12	1.40	1.75	51	50	47	45	44	51	48	46	44	41
12	2003 Aug. 18	2.80	2.75	58	57	52	51	51	58	57	55	53	50
13	2003 Aug. 18	0.40	0.75	33	32	28	25	22	33	29	30	28	28
14	2003 Aug. 31	1.80	3.00	47	42	40	39	39	46	44	39	38	37
15	2003 Sep. 03	1.22	2.50	40	40	36	33	32	39	39	37	36	33
16	2003 Sep. 03	1.50	2.75	47	44	43	40	39	48	43	43	43	41
17	2003 Sep. 07	1.80	2.25	40	36	35	32	30	40	39	34	34	32
18	2003 Sep. 07	1.35	3.00	33	30	25	24	23	34	32	25	20	19
19	2003 Sep. 09	1.80	3.50	60	56	53	49	46	59	59	53	52	50
20	2003 Sep. 13	1.80	2.50	38	33	30	30	26	38	35	30	26	26
21	2003 Sep. 13	1.40	1.75	51	50	49	49	47	51	49	48	43	40
22	2003 Sep. 20	0.80	1.00	38	34	32	30	27	37	36	33	28	28
23	2003 Sep. 24	2.30	2.75	75	72	68	66	64	74	71	68	66	64
24	2003 Sep. 24	1.90	2.50	29	28	23	21	19	29	24	25	22	20
25	2003 Sep. 30	2.70	3.00	47	43	39	39	36	48	46	43	42	41
26	2003 Sep. 30	1.22	2.50	40	36	33	32	32	40	36	31	29	29
27	2003 Oct. 08	3.20	4.50	60	55	55	53	52	60	55	54	50	50

Each value is a mean from three-replicate plots.

tendency of the classic USLE is very close to the standard topography for which the USLE was originally developed, as also reported by Chang and Ting (1986); effects of L and S on erosion are well-defined by USLE, especially in plots on slopes varying from 3 to 18%.

McCool's model, on the other hand, performed better on 25–35% slopes than the classic USLE (Table 4, Fig. 3). The mean difference values between the measured and estimated sediment yield for sediment yield were 756, 1102 and 1482 g for the classic USLE (with RE of 289, 358 and 410%), and 512, 612 and 686 g for the McCool model (with RE of 196, 199 and 190%) for slopes of 25, 30 and 35%, respectively. The McCool model shows that RE decreases with increasing slope steepness, while the classic USLE shows RE increasing as slope steepness increase (Fig. 3). The slope factor of the McCool model in Eq. 3 increases at a decreasing rate with increase in slope steepness as indicated by decreasing RE with increasing slope steepness. This result has confirmed the validity of the McCool model, which is also strongly supported by experimental data for slope steepness greater than 9%, and up to 84% (Renard et al. 1997). The coefficient of sin θ was within the range covered by Eq. 3; thus, this equation should also be valid for use in slope $>9\%$. However, McCool's S factor separates S values into two categories ($<9\%$ and $>9\%$), and the range should be specified with a smaller interval when applied in a highland watershed of Thailand.

At higher slopes (i.e., $>16\%$), the classic USLE did not perform well, as shown by the over-estimated values of sediment yield for S factors of 25, 30 and 35% (Table 4). These findings are in line with Morgan (1995), who noted that the amount of sediment increases rapidly from a gentle to a moderate slope. The rate of increase reaches its maximum level on a slope with 14–18% inclination, and from then on will decline. A possible reason is the higher initial soil infiltration prior to rainfall events at different slope angles. The lower the initial soil moisture content, the higher the initial soil infiltrability will be (Mao et al. 2008). The higher hydraulic gradient at steeper slopes will increase the infiltration rate at which water will be quickly absorbed into the subsoil layer, and the upper topsoil will then dry out more quickly. Consequently, runoff and sediment yield will decrease as the slope increases [Food and Agriculture Organization (FAO) 1996; Chen and Young 2006] as shown in Table 3. In this sense, runoff and slope gradient are related and inseparable. Under the same rainfall characteristics, runoff is lower on very steep slopes than on not so steep slopes, mainly because at increasing slope levels, soil moisture content tends to decrease faster, which results in higher infiltration. One would normally expect sediment yield to increase with

Table 4. Comparison between measured sediment yield and MUSLE estimates using the testing plot data

Event no.	Measured sediment yield (g) of testing plots slope (%)					Estimated sediment yield (g) of testing plots slope (%) data: Classic USLE *S* factor					McCool et al. (1987) *S* factor				
	9	16	25	30	35	9	16	25	30	35	9	16	25	30	35
1	62	115	218	267	309	146	414	937	1313	1683	212	437	712	857	957
2	120	215	435	512	581	208	588	1380	1938	2528	301	620	1049	1264	1437
3	57	96	199	226	285	146	389	924	1293	1637	212	411	702	844	930
4	92	163	314	399	451	164	418	968	1315	1655	237	440	736	858	941
5	246	444	896	1067	1177	384	1066	2483	3536	4697	555	1124	1887	2308	2670
6	50	85	179	198	237	129	323	675	866	1111	187	340	513	565	632
7	88	162	314	356	438	164	442	1060	1513	2007	237	466	806	987	1141
8	4	7	15	16	20	71	164	379	462	631	103	173	288	302	359
9	63	115	225	251	319	138	394	852	1104	1488	199	415	647	720	846
10	73	128	254	300	372	164	462	1092	1524	1961	237	487	830	995	1115
11	88	161	297	371	426	181	514	1169	1622	2140	262	542	889	1059	1216
12	88	154	313	360	423	208	590	1298	1850	2538	301	622	987	1207	1442
13	38	68	139	156	195	112	307	647	838	1011	163	324	492	547	575
14	66	112	225	269	320	164	418	961	1385	1892	237	441	731	904	1075
15	51	92	179	206	244	139	401	857	1144	1490	202	422	651	747	847
16	58	104	200	244	290	164	439	1037	1389	1882	237	463	788	907	1070
17	46	84	158	196	226	138	353	824	1109	1419	199	372	626	724	806
18	55	95	195	229	261	112	287	568	806	1029	163	302	431	526	585
19	89	164	309	361	437	217	575	1316	1771	2279	314	606	1000	1156	1295
20	35	62	116	146	165	129	324	707	1005	1217	187	341	537	656	692
21	78	134	285	332	387	181	512	1202	1748	2304	262	540	914	1141	1310
22	42	78	154	175	210	129	333	765	1006	1235	187	351	581	656	702
23	126	234	443	544	609	280	773	1745	2468	3264	406	815	1327	1611	1855
24	17	31	60	75	82	96	267	527	672	827	139	281	400	438	470
25	79	141	279	319	400	164	429	936	1358	1720	237	452	711	886	978
26	45	79	157	190	218	139	352	779	1110	1490	202	371	593	724	847
27	134	250	496	558	674	217	569	1380	1939	2629	314	600	1049	1265	1494
Paired t-test						22.248^{z}	16.605^{z}	14.763^{z}	13.369^{z}	12.286^{z}	18.692^{z}	16.357^{z}	15.828^{z}	14.553^{z}	13.129^{z}
AE						92.348	315.834	755.931	1102.365	1481.679	166.633	340.187	511.954	612.260	686.302
RE (%)						125.278	238.593	289.065	357.696	409.993	226.051	256.990	196.016	198.667	189.906
SE						21.568	98.833	266.063	428.461	626.643	46.321	108.066	168.073	218.611	271.628

^{z}Significantly different at the 5% level.

increasing slope steepness as a result of increase in velocity and volume of surface runoff. However the effect of slope on runoff is variable (Renard et al. 1997), especially in areas with predominantly steep slopes. This may be a possible reason why velocity and runoff volume energy in slopes >16% was lower than extended by the classic USLE.

With respect to the parameters set for MUSLE, the *K*, *L*, *C* and *P* factors were constant at all slope steepness levels. Runoff was strongly correlated with sediment yield, which confirms that the runoff factor represents energy used in transporting as well as in detaching sediment and can therefore act as the best indicator of storm-event-based sediment yield prediction (Foster et al. 1977; Hrissanthou 2005; Sadeghi et al. 2007b), its coefficient being affected by slope gradient (FAO 1996; Chaplot and Bissonnais 2003; Adediji 2006). Because it varies with slope steepness, we consider the *S* factor as a potential calibrating factor. To facilitate *S* factor application on slopes in watersheds of Thailand, which range from 5 to 35% inclination, the calibration analysis

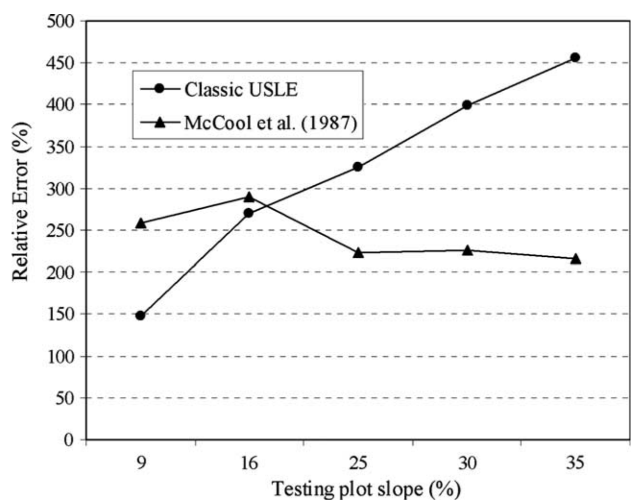

Fig. 3. Relative error between estimated and measured sediment yield (RE) versus testing plot slope for the classic USLE S-factor and the McCool S-factor.

was designed to generate a continuous platform of *S* factor by separating the *S* factor from both the classic USLE and the McCool model, specifically for slopes at which they perform best.

According to the results of the paired t-test, the descriptive statistics, SE, AE, and RE showed that the *S* factor for classic USLE performed better on a 9–16% slope interval, while the *S* factor for the McCool model was better at the 25 to 35% slope interval. Fifty-four samples (27 rainfall event in plots on slopes with 9 and 16% inclination) were used to calibrate the *S* factor for the classic USLE using multiple regression, and 81 samples (27 rainfall events in plots on slopes with 25, 30 and 35% inclination) for calibrating the *S* factor for the McCool model using simple regression, as discussed in the methodology section.

The calibrated *S* factor resulted in a high determination coefficient for the classic USLE on slopes of 9 to 16% inclination, and for McCool's on slopes of 16 to 35%. The calibration resulted in an adjusted *S*, explained in the following equations:

$$S = (1.28 + 0.109s + 0.007s^2)/6.574\ (R^2 = 78.23\%, P \text{ value} = 0.92) \quad (9)$$

$$S = -0.11 + 6.54\sin\theta\ (R^2 = 73.54\%, P \text{ value} = 0.94) \quad (10)$$

Where *s* is the slope steepness in %

The calibrated MUSLE was then validated using data collected from 27 rainfall events in the validation plots of slopes with 9, 16, 25, 30 and 35% inclination (135 samples). The results showed that the calibrated MUSLE performed quite satisfactorily in predicting the sediment yield for single-storm events. There was no difference between estimated and observed sediment yield for both models, as confirmed by a paired t-test ($\alpha = 0.05$) (see Table 5). In addition, both of the new calibrated classic USLE and the McCool model resulted in very high determination coefficients ($R^2 = 92.14$, 89.95%) for validation plot slopes of 9 and 16% for MUSLE using *S* factor Eq. 9, and determination coefficients $R^2 = 90.81$, 89.83% and 90.79% using

Table 5. Comparison between measured sediment yield and MUSLE estimates using the validation plot data and the calibrated *S* factors

	Measured sediment yield of validation plots slope (%)					New calibrated *S* model estimated sediment yield (g) of validation plots slope (%)				
						Equation 9		Equation 10		
Event no.	9	16	25	30	35	9	16	25	30	35
1	63	115	215	263	318	64	117	276	308	335
2	119	205	413	495	630	93	187	394	465	561
3	57	99	202	240	293	66	124	228	279	336
4	91	166	335	399	445	73	146	277	333	387
5	244	417	899	1053	1183	171	336	707	874	1016
6	49	90	182	203	248	57	111	187	210	227
7	88	155	303	361	449	74	136	266	322	383
8	4	7	15	17	20	32	59	104	91	97
9	63	116	220	249	322	60	116	263	311	366
10	71	131	261	307	365	71	131	279	336	396
11	87	149	309	381	443	80	152	313	379	424
12	88	149	310	371	455	92	185	382	470	533
13	38	71	138	156	192	48	87	192	233	272
14	64	116	230	271	323	72	137	261	320	382
15	50	87	181	200	256	60	121	245	305	336
16	57	104	213	246	301	74	136	292	367	422
17	47	84	165	185	227	61	121	225	284	324
18	55	100	197	225	269	51	96	159	157	181
19	89	153	321	385	463	95	192	372	458	532
20	33	60	117	136	172	58	107	192	210	252
21	79	144	280	332	392	81	155	328	368	409
22	43	76	151	171	207	56	109	215	225	271
23	126	219	435	544	638	121	237	490	597	702
24	18	30	58	74	85	42	70	160	177	185
25	79	138	268	320	391	74	144	289	356	418
26	45	78	167	197	221	61	111	204	237	286
27	134	242	474	567	692	96	178	378	441	526
Paired t-test						0.021NS	1.848NS	1.871NS	2.028NS	1.380NS
AE						0.087	11.195	22.963	28.296	20.642
RE (%)						0.118	8.641	8.785	9.148	5.573
SE						21.075	31.472	63.778	72.485	77.734

NS, not significantly different at 5% level.

S factor Eq. 10 for validation plot slopes of 25, 30 and 35%, as shown in Fig. 4.

CONCLUSIONS

The performance of the MUSLE in event-based sediment yield estimation using the *S* factor of the classic USLE was acceptable on slopes with 9 and 16% inclination. However, the MUSLE did not perform well on slopes of 25, 30 and 35% inclination. However, when the *S* factor from the McCool mopdel was used, it performed better than the classic USLE for slopes greater than 16%. That the classic USLE did not yield reasonable results on steep slopes may be due to the higher initial soil water infiltration on steeper slopes, because of the tendency for the upper layer to dry out more quickly, so that absorption is higher prior to rainfall. Consequently, the runoff volume and velocity involved in sediment transport as well as in detaching sediment is less than the extended values from *S* factor algorithm of the classic USLE.

The average error (AE), relative error (RE), and standard error (SE) analyses obtained from both approaches suggest an alternative by which the estimation could be improved through the distinguished calibration of the *S* factor. It was found that the accuracy of the MUSLE can be considerably improved by using a new calibrated *S* factor for the classic USLE on slopes with 9 to 16% inclination, and for the McCool model on slopes with 16 to 35% inclination.

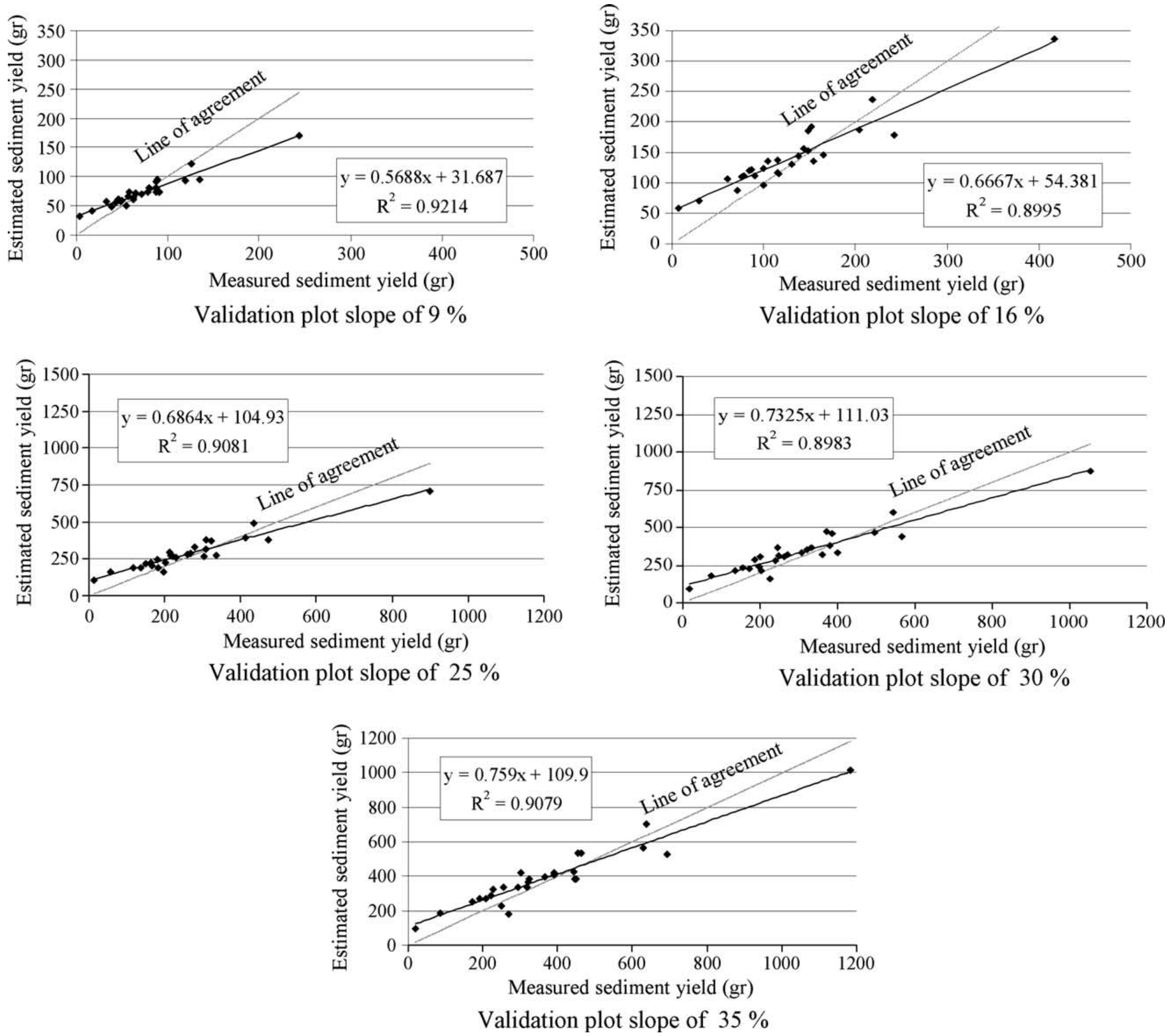

Fig. 4. Comparison between measured sediment yield and MUSLE estimates using the validation plots data and the calibrated *S* factors (Eqs. 9 and 10).

However, because model calibration in this research was conducted only under the uniform conditions of a small experimental plot environment, and because MUSLE was developed for a micro-watershed level, it is recommended that the influence of the *S* factor on event-based sediment yield should be further investigated on a larger scale. If this calibrated model is proved to be useful, it could be applied for evaluation of sediment yield under various alternative land management regimes and for environmental management planning, especially in the high slope watersheds of Thailand.

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