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Re-interpretation of USLE Datasets for Physically Based Erosion Models with Examples From Southern China and Northern Thailand

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ABSTRACT

The Universal Soil Loss Equation (USLE) has a profound influence on the way in which soil conservation research is conducted around the world. Typically, standard or nearly standard USLE runoff plots are set up on different slopes, and rainfall, runoff and soil loss are measured for individual storm events for various treatments to represent different management practices. What is often missing from this type of experiment is data on the runoff rate. Runoff rate is one of the most important determinants of the rate of soil erosion, especially on sloping lands. Data on runoff rate are explicitly required to drive process-oriented soil erosion models such as WEPP and GUEST. In WEPP, for instance, the rate of soil erosion is related to the peak runoff rate. In GUEST, the sediment concentration at the transport limit is related to a weighted average runoff rate, known also as the effective runoff rate. Analysis of data on 1-min rainfall and runoff rates from several sites in Australia and Southeast Asia has shown that a one-parameter infiltration model is adequate to generate storm hydrographs given rainfall intensity and runoff total. One of the distinct advantages of using this simple infiltration model is that there is no need to select model parameter values for individual storm events. In this paper, we use this methodology to generate hydrographs for two sites in southern China and northern Thailand, respectively, and show how to apply the physically based model GUEST to these sites. In addition, we compare USLE and GUEST erodibility parameters using the same rainfall, runoff and soil loss data for the two sites.

INTRODUCTION

The USLE (Wischmeier and Smith, 1978) and RUSLE (Renard et al., 1997) have a profound influence on the way in which soil conservation research is conducted around the world. Plots have been established at agricultural research stations and other sites in most countries to measure the runoff amount and total soil loss in order to evaluate the effectiveness of various conservation technologies and management practices. In such experiments, eroded sediment and runoff were typically collected in a set of storage tanks mounted near the downslope end of the plots. Usually, meteorological data such as rainfall rates are also available at or near these sites. To a great extent, data collection programs have been and still are oriented towards determining various USLE and RUSLE factors.

As distinct from the variables required for analysis by USLE and RUSLE, variables describing hydrologic processes such as runoff rate and total runoff depth are explicitly required to drive physically based erosion models for soil loss predictions. In WEPP (Laflen et al., 1991a), for example, both detachment and transport capacities are related to the peak runoff rate via hydraulic shear stress (Foster et al., 1995), and the runoff depth is needed to compute an effective runoff duration. In GUEST, sediment concentration is related to the stream power, which in turn depends on the runoff rate (Misra and Rose, 1996). For a storm event, the flow-weighted average sediment concentration is related to an effective runoff rate (Rose, 1994; Ciesiolka et al., 1995). Both the peak and effective runoff rates in these physically based models can be regarded as an equivalent steady-state runoff rate for soil erosion prediction purposes.

In WEPP, a soil erodibility parameter was introduced as a coefficient in the expression for the detachment capacity (Foster et al., 1995), while in GUEST, a different erodibility parameter was used as an exponent relating the sediment concentration at the transport limit to the actual sediment concentration (Rose, 1993). In both cases, data on runoff rate and sediment concentration are needed to evaluate soil erodibility parameters. Extensive experiments using rainfall simulators were undertaken for rangeland and cropland soils in the continental United States to determine soil erodibility for WEPP applications (Laflen et al., 1991b). To evaluate erodibility for tropical and sub-tropical soils in relation to GUEST development, rainfall and runoff rates during natural storm events were measured (Ciesiolka et al., 1995). Apart from a few experimental sites, data on runoff rates are not routinely available in comparison with event-based total runoff and soil loss amounts. This lack of runoff rate data has so far hindered the evaluation of soil erodibility parameters and the application of all process-based soil erosion models, not only the two mentioned above.

Yu et al. (1998) showed that runoff rates can be reliably estimated using data on rainfall rates and total runoff amount. Once runoff rate is known, erodibility parameters can then be evaluated for soils in a wide range of climatic and physiographical environments. The ability to estimate

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runoff rates given rainfall rates and total runoff amount would facilitate widespread application of process-based soil erosion models.

This paper illustrates how runoff rates and soil erodibility could be estimated for two experimental sites in southern China and northern Thailand. Physically based erosion model GUEST was applied to these two sites. Soil erodibility parameters in the context of GUEST and USLE/RUSLE were compared.

MATERIALS AND METHODS

Rainfall, runoff and soil loss data

Considered in this paper is the Luodian site in southern China, the Chiang Rai site in northern Thailand. These two sites are part of the *ASIALAND* Sloping Lands network (IBSRAM, 1992). General site descriptions are summarized in Table 1 and given below is additional information on rainfall, runoff, soil properties, and rill geometry if rills existed.

At Luodian, rainfall rate was collected using charts, while at Chiang Rai, data were collected using an automatic weather station. The measurement time interval was standardized at 10 min for both sites. For each storm event, total rainfall, runoff and soil loss were recorded. The storm events were defined in relation to runoff occurrence. Daily data from rain gauges were used to verify rainfall intensity data. Runoff rate was estimated using program GOSH (Yu, 1997) using a spatially variable infiltration model. This model has been compared with and consistently out-performed other commonly used infiltration models (Yu et al., 1998; Yu, 1999).

Soil samples were collected in July 1997 at Luodian, and in November 1997 at Chiang Rai so that particle size distribution and wet density could be determined for the sites.

Severe rilling occurred at Luodian, and a field survey was carried out to determine the average rill geometry in July 1997. At Chiang Rai, the current soil surface in November 1997 was uneven, although no well-defined rills could be identified. Thus plane geometry was assumed for the site. For Chiang Rai, preferred pathways of the overland flow, most in the form of broad depressions, were clearly visible. Both theory and experimental results show that when the width/depth ratio of the rill is large and rill density is small, so that the difference between assuming a plane geometry or a rill geometry is minimal as far as the calculated soil losses are concerned (Fentie et al., 1997). For the bare plots at Luodian and Chiang Rai, weeds were controlled chemically early in the wet season and remained uncultivated throughout the experiments.

For each storm event and for the two sites, the sediment concentration at the transport limit, c_t, was computed using program GUEPS v 2.2 (Yu and Rose, 1997). This version represents a minor improvement over v 2.1 used for Yu et al. (1999) to take into consideration the threshold stream power, although there is little difference in the calculated soil erodibility between the two versions of GUEPS. For given c_t and observed sediment concentration, the soil erodibility parameter for individual storm events can be computed. Because the calculated soil erodibility shows considerable variation for all sites, the erodibility values were correlated with other variables such as time and rainfall intensity so that variation in the predicted soil erodibility can be reduced (Yu et al., 1999). Although only flow-driven processes were considered in determining soil erodibility and evaluating cropping systems for sloping lands (Soil Technology 1995, Rose et al. 1997), in this paper the rainfall component is included so that its importance can be evaluated explicitly.

To quantify model performance, we use the Nash-Sutcliffe coefficient of efficiency (Nash and Sutcliffe, 1970) whenever appropriate. The coefficient of efficiency is identical to R^2 for linear regression models except that variance from the 1:1 line is considered rather than variance from the 'best fit' line, and is by far the most widely used measure of model performance in hydrology and soil sciences (e.g. Loague and Freeze, 1985, Risse et al., 1993).

Standard procedure for RUSLE (Renard et al., 1997) was followed to determine the LS factor and storm erosivity values for the two sites.

A brief description of GUEST theory and its data requirements

The theory behind the physically based erosion model GUEST has evolved over a period of years, and the theory when overland flow is the dominant cause of erosion is given in Hairsine and Rose (1992a and 1992b). There has since been some minor changes, including the introduction of the soil erodibility parameter as a surrogate variable for the original soil erodibility parameter (Rose, 1993), and incorporating the concept of saltation stress (Bagnold, 1977) which can become important when the sediment concentration is high. The theory and parameter sensitivity for both rainfall and runoff driven processes were presented in Misra and Rose (1996), although the latest version of GUEST contains only the module on runoff-driven processes which are dominant on steeplands (Rose et al., 1997; Fentie et al., 1999).

The key to GUEST theory is an assumption that a certain fraction of the stream power is involved in maintaining the sediments in suspension. Without the stream power of overland flow (or rainfall), all sediment would settle out of the water column. Under equilibrium conditions, the capacity to maintain sediments in suspension balances out the downward flux of sediments due to gravity. For overland flow, the water depth can be of the order of the diameter of larger soil particles or soil aggregates. Thus, when runoff rate, and hence water depth, is low, only finer soil particles will be fully immersed in the flow and involved in the erosion processes. The effective settling velocity, or the effective depositability and that fraction of the soils fully immersed in the flow would be low when the water depth is low.

The actual sediment concentration is related to that at the transport limit by a soil erodibility parameter (Rose, 1993). This erodibility parameter in GUEST, β is defined as

$$\beta = \frac{\ln c}{\ln c_t}$$

where c is the actual sediment concentration. β is broadly related to a more fundamental erodibility parameter in terms of the amount of energy required to erode a unit mass of soil (Rose, 1993), and experimental evidence suggested that the soil erodibility parameter depends on soil strength to some extent (Misra and Rose, 1995).

To predict soil loss, information on soil erodibility is needed. To evaluate this soil erodibility, certain minimum data is required for each site. The data requirements in general can be classified into three categories: 1) those in relation to the plot geometry, such as its slope and length; 2) those in relation to the soil characteristics; and 3) hydrological data, i.e. the rainfall and runoff rates.

The length, the width and the slope can characterize plot geometry. If there are rills, information on rill geometry is also needed. The depth, top and bottom width, and the inter-rill spacing can specify rill dimensions.

As far as the GUEST model is concerned, the most important aspects of the soil characteristics are the sand fraction (> 0.02 mm) determined using mechanical analysis, and the particle (including water-stable aggregates) size distribution obtained using the wet sieving method converted to a settling velocity distribution (Lisle et al., 1996). Soil samples should be taken from the surface layer from which erosion is most likely to occur. The sand fraction can be used to estimate the wet density of the eroded soil particles (Loch and Rosewell, 1992).

To use GUEST to determine soil erodibility, data on runoff rates at small time intervals are needed. Rainfall and runoff rates at 1 min intervals are routinely measured at ACIAR sites to evaluate soil erodibility parameters (Coughlan and Rose, 1997). For the *ASIALAND* and other sites where data on runoff rate are not available, program GOSH (Yu, 1997) can be used to estimate runoff rates given runoff amount and rainfall rates before estimating soil erodibility parameters. Fig. 1 shows an example of the predicted hydrograph using GOSH. Therefore the minimum requirements for hydrological data are the rainfall rates at small (30 min or less) intervals in addition to total runoff amount for each storm event. The average sediment concentration for each runoff event is needed to calculate the soil erodibility.

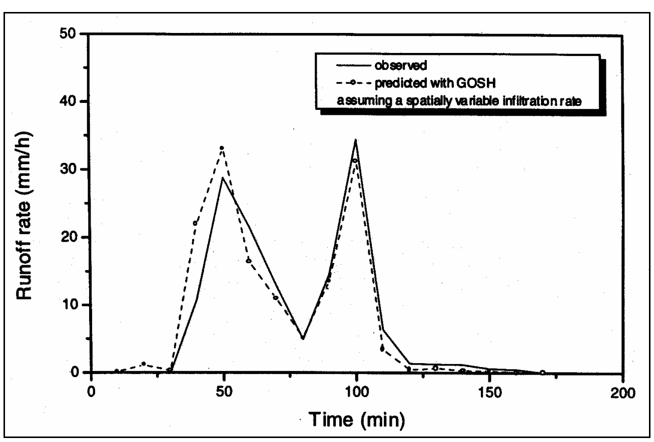

Figure 1. Predicted and observed runoff hydrographs for the May 12, 1994 event at Kemaman, Malaysia.

RESULTS AND DISCUSSION

For the two experimental sites, results are presented separately before the erodibility parameters in relation to GUEST and USLE/RUSLE are compared.

Luodian, China

With a very steep slope of 40% at this site, the sediment concentration at the transport limit is very high with an average of 1090 kg/m^3 for the 30 events. Calculated soil erodibility (β) shows a significant time trend (r = -0.52, and *p*-value = 0.003) for the period from 1992 to 1997. Following investigation of a number of independent variables, it was found that the soil erodibility is significantly correlated with the peak rainfall intensity (r = 0.35). The soil erodibility for the site is therefore related to peak rainfall intensity, and the temporal trend in erodibility is also considered. Fig. 2 shows a comparison between observed versus estimated event soil loss for the site considering flow-driven processes only, but allowing soil erodibility to vary with time and peak rainfall intensity. The model efficiency is 0.74. It can be seen that event soil loss is highly variable at the site. Of the 30 storm events, 24 have soil loss less than 10 t/ha, and collectively they contribute a total of 107 t/ha or 34% of total soil loss produced during the 30 storm events. The largest of the 30 storm events in terms of soil loss occurred on 14 May 1993. This storm alone contributes 35% of the total soil loss (310 t/ha) produced during the 30 events. This storm was actually not the largest in terms of rainfall (75.4 mm) or runoff (47.7 mm), and ranked only 6th and 7th, respectively, in terms of these quantities. The peak 10-min intensity (105 mm/h) was, however, the highest of all the 30 storms. It appears that the dependence of soil erodibility on peak rainfall intensity occurs partly because of this extreme event.

The LS factor for the site was calculated according to RUSLE manual (Renard et al., 1997) (Table 1). A simple regression through the origin between event soil loss and the product of the LS factor and storm erosivity EI_{30} is shown in Fig. 3. The slope of the graph gives an estimate of the soil erodibility in the context of the USLE/RULSE for the site.

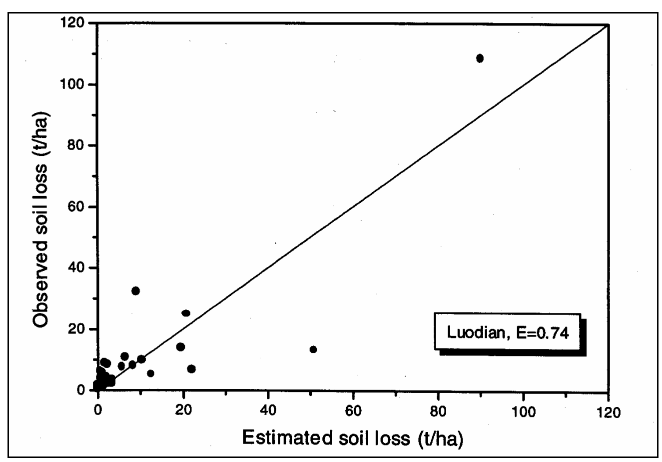

Figure 2. Observed vs. estimated event soil loss for the Luodian site. Soil erodibility was allowed to vary in time and with peak rainfall intensity

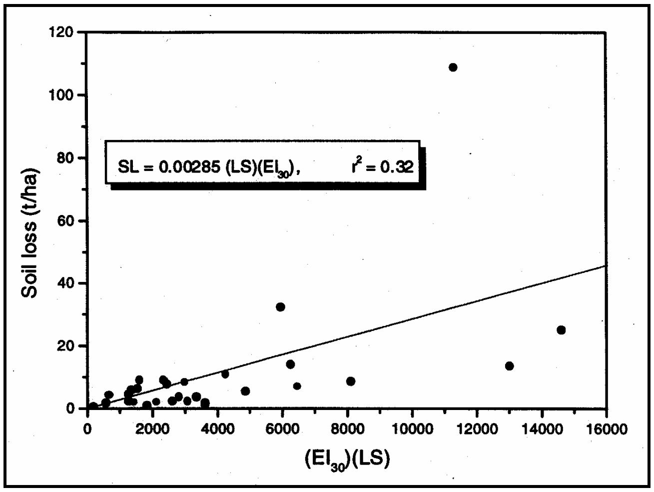

Figure 3. The relationship between event loss as a function of the product of EI_{30} and the LS factor for the Luodian site. The straight line represents the best fit through the origin.

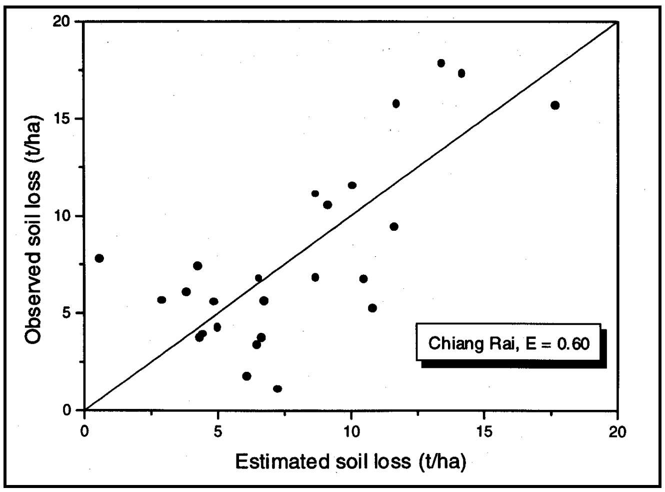

Figure 4. Observed vs. estimated event soil loss for the Chiang Rai site. Soil erodibility was allowed to vary with peak runoff rate.

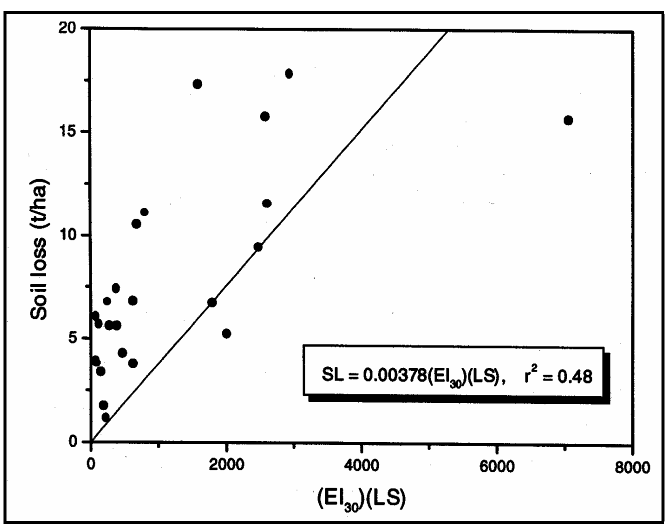

Figure 5. The relationship between event soil loss as a function of the product of EI_{30} and the LS factor for the Chiang Rai site. The straight line represents the best fit through the origin.

Table 1. Summary description of the two experimental sites from southern China and northern Thailand.

	China	Thailand
Site	Luodian, Guizhou	Doi Tung, Chiang Rai
Location	106°46'E, 25°26'N	99°50'E, 20°19'N
Elevation (m)	630 asl	900 asl
Mean annual rainfall (mm)	1200	1800
Soil texture	Silty clay loam	Silty clay or clay loam
Parent material	Shale	Granite
Median particle size[A] (mm)	0.327	1.15
Depositability (m/s)	0.0942	0.0738
Slope (%)	40	30
Plot length (m)	25	36
Plot size (m^2)	400	360
LS factor	6.23	5.70
Main crop	Corn + soy bean	Upland rice
No. of storm events and the period	30, 1992 - 1997	24, 1993
Average event rainfall (mm)	65	31
Average event runoff (mm)	37	7.2
Erodibility K for RUSLE	0.00285±0.00056	0.00378±0.00057
Erodibility β for GUEST	0.413±0.144	0.975±0.178

[A] From wet sieving analysis

If the two largest events were excluding the coefficient squared would be increased to 0.61, and the soil erodibility would be reduced by half to 0.00145.

Chiang Rai, Thailand

For the site in Chiang Rai, a total of 24 storm events between June and October 1993 were used to evaluate the soil erodibility parameter and the model's predictive potential. As expected for such a short period, no significant time trend could be detected (p-value = 0.180), neither could a significant correlation between the soil erodibility (β) and peak rainfall intensity be established for the site (p-value = 0.294). It was found instead that the soil erodibility is significantly dependent upon the peak runoff rate (p-value = 0.006). The model performance is improved noticeably when the erodibility parameter is allowed to vary with the peak runoff rate. Unlike the other site, the rainfall term is quite useful or even necessary in explaining the observed variation in event soil loss at the site. The relative importance of the rainfall effect is estimated to be 47% for the site when both rainfall and runoff are considered. The importance of the rainfall is also evident from the fact that assuming a constant rainfall detachability alone could explain 29% of the total variation in event soil loss, while for a constant erodibility the model efficiency is only -0.03. Fig. 4 shows a comparison of the observed and estimated event soil loss for these 24 storm events (E = 0.60) taking into account contribution from both rainfall and runoff at the site.

The LS factor for the Chiang Rai was slightly less than that at Luodain (Table 1). A simple regression through the origin between event soil loss and the product of the LS factor and storm erosivity EI_{30} (Fig.5) yields an estimate of the soil erodibility in the context of the USLE/RULSE for the site. The event with the largest storm erosivity appears to be an outlier in the graph. If this outlier is excluded, the correlation coefficient squared would be increased to 0.54, and the soil erodibility would be increased to 0.00567.

GUEST vs. USLE/RULSE

Erodibility parameters

Strictly speaking, soil erodibility in the context of the RUSLE is only defined with respect to long-term average soil loss and the *R*-factor. Nonetheless, to compare the soil erodibility for GUEST, which is event based, with that for USLE/RUSLE, an equivalent erodibility as the ratio of event soil loss and the product of the LS factor and storm erosivity EI_{30} was contrasted (Fig. 6). It can be seen that the two measures of soil erodibility are broadly related, with both measurement of soil erodibility at the Chiang Rai site systematically greater than that at the Luodian site. Fig. 6 also shows that the relationship between the two erodibility parameters are non-linear, possibly because of the way in which soil erodibility is defined in the two models.

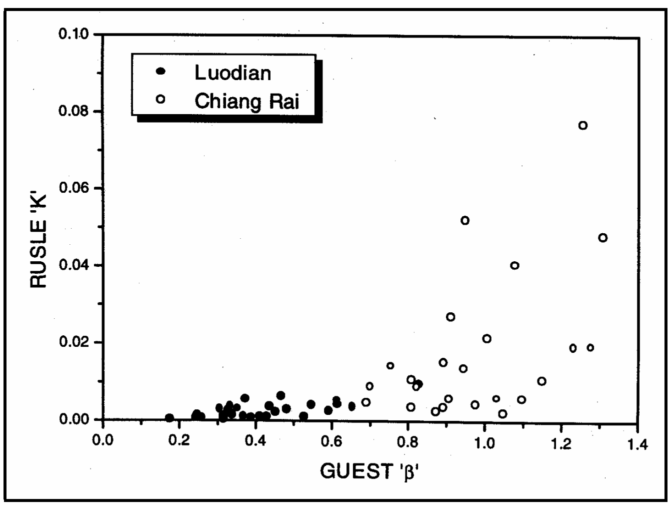

Figure 6. The relationship between RUSLE and Guest erodibility parameters for the two sites.

CONCLUSION

1. Runoff rate, needed for all physically based erosion prediction models, can be readily determined from rainfall rates and runoff amount. Databases from USLE-type experiments can therefore be re-interpreted to determine parameters for physically based models. The only additional information that is required to drive physically based model GUEST are wet-sieved size distribution and rill geometry if rills exist.
2. Application of GUEST is illustrated using data from USLE-type experiments from southern China and northern Thailand to determine the soil erodibility parameter (β), which relate the actual sediment concentration to that at the transport limit. The model efficiency for the two sites was 0.74 and 0.60, respectively.
3. There are broad similarities on a storm event basis in the soil erodibility parameters defined in GUEST and USLE/RUSLE, though the relationship between the two parameters may not be linear.

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