Conversion of the universal soil loss equation to SI metric units 361

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ABSTRACT: The Universal Soil Loss Equation (USLE) is widely used to estimate erosion in the United States and foreign countries. With foreign application of the USLE and adoption of the International System of Units (SI) in the United States, conversion of the USLE to SI units is necessary. Conversion factors were derived by considering the dimensions of each variable of the USLE factors. These conversion factors may be used to convert USLE factor values given in U.S. customary units to SI units. However, when basic data for the USLE factors are already in SI units, values for the USLE factors can be computed directy in SI units without conversion from U.S. customary units.

INTERNATIONAL application of the universal soil loss equation (*6*) and gradual adoption of the *Systeme International d' Unites* (International System of Units) in the United States (*1, 3*) necessitates conversion of USLE units and dimensions to the SI metric system. But many users of the USLE are unaware of considerations necessary to develop metric conversion factors.

Several sets of metric conversion factors for the USLE have been proposed. Wischmeier and Smith's factors (*6*) are for an older metric system. They are not the same factors needed for conversion to the SI system. More recent conversion factors (*5*) give USLE factor values similar to those in U.S. customary units. Common practice has been to publish maps, figures, and tables for USLE factors without noting the units of the factor values (*6*). The potential for confusion is obviously great if new maps, figures, and tables in SI units have factor values similar to those in U.S customary units.

To avoid the need to change the numerous maps, figures, and tables already in field handbooks, Mitchell and Bubenzer (*4*) proposed that USLE factor values not be changed from their values in U.S. customary units. Because the USLE is a regression equation having nonhomogenous dimensions, Mitchell and Bubenzer suggested treating factor values as unitless coefficients. A single conversion factor would appear in the USLE to convert computed soil loss to its equivalent SI value. A disadvantage of this proposal is that computation of USLE factor values in nations using the SI system would require conversion to U.S. customary units for values originally measured in SI units. Such a system would be confusing and would encourage continued use of a dual system of units.

Our proposal is to use SI conversion factors that give USLE factor values greatly different and easily distinguishable from those in U.S. customary units. New maps, figures, and tables required by the change would show the units for the factor values that can be determined directly from metric charts and measurements under the SI system. Conversion and use of the USLE by our proposal is convenient and easy.

Dimensions of USLE factors

The USLE is

$$A = R\,K\,L\,S\,C\,P \qquad [1]$$

where A is the rate of soil loss, R is a factor for annual rainfall erosivity, K is a factor for soil erodibility, L is a factor for slope length, S is a factor for slope steepness, C is a factor for cover-management, and P is a factor for supporting practices. Factors A, R, and K have dimensions. L, S, C, and P are dimensionless.

Table 1 presents the dimensions and U.S. customary units of the USLE factors. The factors can be written in other units if correct dimensions are maintained. However, because A, R, and K have dimensions, their units usually should be written. For example, R = 125 would be written as R = 12,500 ft-tonf•in/acre•hr•yr or in some other manner so the meaning is clear.

Conversion of USLE factors to SI units

Table 2 gives the conversion factors for soil loss and other USLE factors. The basis for each factor in table 2 is described below. Although conversion factors with four significant digits are shown in table 2, the final factor value, after conversion, should use significant digits consistent with those for the corresponding value in U.S customary units.

Soil loss (A). The factor A represents soil loss per unit area per unit time. Because L, S, C, and P are dimensionless, units for A result from the multiplication of R and K in the solution of the USLE. Units may be chosen for R and K to give units for A of kilograms per square meter (proper SI units) or metric tons per hectare (accepted SI units) because of common usage (*1*). The time unit of A depends upon the time period of R, which is usually average annual for a calendar year. This one-year unit is usually not shown, because the customary application of the USLE is to estimate average annual soil loss for a practice or rotation, even though the rotation may extend over several years. In modeling applications, soil loss in grams per square meter is sometimes convenient (*2*). To convert metric tons per hectare to grams per square meter, multiply by 100. This simple change of units within the SI system is one of its advantages.

To illustrate use of the conversion factors in table 2 for soil loss, assume that A = 6.5 tons per acre per year. Multiply by the conversion factor of 2.242 from table 2 to obtain 14.6 metric tons per hectare per year. Similarly, soil loss tolerance values in U.S. customary units can be converted to values in SI units (t/ha•y) by multiplying by 2.242. For example, 5 tons per acre per year in U.S. customary units is 11 tons per hectare per year in SI units.

Erosivity (R). The R factor is the sum of individual storm erosivity values, EI, for qualifying storms over a time period, usually average annual or perhaps an average crop stage (*6*). Storms of less than 0.5 inch (13 mm) and separated from other rain periods by more than 6 hours are not included in the computations unless as much as 0.25 inch (6 mm) of rain falls in 15 minutes. The factor E is the total energy for a storm and I is the storm's maximum 30-minute intensity. Mathematically, R is

$$R = \sum_{j=1}^{n} (EI)_j \qquad [2]$$

where n is the number of storms in the series. Implicitly, a time dimension is asso-

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ciated with R, although the dimension is seldom shown. The variable EI is the product of the total energy for a storm and the storm's maximum 30-minute intensity.

The equation for computing storm energy when rainfall is given by a continuous function is

$$E = \int_0^D e\, i\, dt \qquad [3]$$

where e is the rainfall energy per unit of rainfall, i is the rainfall intensity for the time differential dt, t is time, and D is duration of rainfall for the storm. In most applications, equation 3 is written in discrete form as

$$E = \sum_{k=1}^{p} e_k \Delta V_k \qquad [4]$$

where e_k is the rainfall energy per unit rainfall and ΔV_k is the depth of rainfall for the kth increment of the storm hyetograph divided into p parts. The hyetograph is divided so that a constant rainfall intensity over an increment can be assumed. This intensity i_k is

$$i_k = \frac{\Delta V_k}{\Delta t_k} \qquad [5]$$

where Δt_k is the duration of the increment over which the intensity is considered to be constant. Unit energy, e_k, is a function of intensity. It is computed in U.S. customary units with

$$e = 916 + 331 \log_{10} i \qquad i \leq 3 \text{ in/hr} \qquad [6]$$

$$e = 1074 \qquad i > 3 \text{ in/hr} \qquad [7]$$

where unit energy e has units of ft-tonsf/acre-inch of rain and intensity, i, has units of inch/hour (6).

An equation is needed to compute unit energy directly in SI units from rainfall intensity in mm/h. Otherwise, rainfall intensity would require conversion to inches per hour for use in equation 6, and the result from equation 6 would require multiplication by the conversion factor 2.638×10^{-4} for e (Table 2). Following is a step-by-step conversion of equation 6 to SI units. This shows how the conversion for e was made and how conversion factors for the other USLE variables were determined.

The first step in converting equation 6 to use intensity in millimeters per hour is to divide intensity by 25.4:

$$e = 916 + 331 \log_{10} (i_m/25.4) \qquad [8]$$

where i_m is intensity in millimeters per hour. Because $\log_{10} (i_m/25.4)$ is the same as $331 \log_{10} (i_m) - 331 \log_{10} (25.4)$, equation 8 reduces to

$$e = 451 + 331 \log_{10} (i_m) \qquad [9]$$

Equation 9 gives a value for e in U.S. customary units, the same as equation 6.

The next step is to convert e from equation 9 to SI units by multiplying equation 9 by the 2.638×10^{-4} conversion factor for e given in table 2:

$$e_m = 0.119 + 0.0873 \log_{10}(i_m) \qquad i_m \leq 76 \text{ mm/h} \qquad [10]$$

$$e_m = 0.283 \qquad i_m > 76 \text{ mm/h} \qquad [11]$$

where e_m has units of megajoule per hectare per millimeter of rainfall (MJ/ha•mm).

The derivation of the conversion factor for e (equation 12, next page) illustrates an orderly procedure for converting units of a variable having multiple units.

The SI unit for force is Newton (N) instead of metric ton, a mass unit used by Wischmeier and Smith (6) in their conversion factors. Joule is the standard SI unit for energy. One Joule is the product of one Newton and one meter (N•m). The conversion of Joule (J) to megajoule (MJ) reduces the magnitude of the numbers.

Equation 13 (next page) shows the derivation of the conversion factor for EI, one unit of average rainfall in U.S. customary units, to SI units.

That is, to convert one unit of R that has units of hundreds of ft-tonf•in/acre•hr•yr to MJ•mm/ha•h•y, multiply by 17.02. This conversion factor gives values for EI and R in SI units that are about 17 times those of U.S customary units. Largest values for R in the United States, after conversion to SI units, will be about 10,000 MJ•mm/ha•h•y. This conversion gives numerical values in SI units that are quite different from those in U.S. customary

Table 1. Dimensions of universal soil loss equation (USLE) factors.

Factor	Symbol	Dimensions		Typical U.S. Customary Units
Rainfall intensity	i or I	$\frac{\text{length}}{\text{time}}$	$\frac{L^*}{T}$	$\frac{\text{inch}}{\text{hour}}$
Rainfall energy per unit of rainfall	e	$\frac{\text{length·force}}{\text{area·length}}$	$\frac{LF}{L^2L}$	$\frac{\text{foot·tonf}\dagger}{\text{acre·inch}}$
Storm erosivity	EI	$\frac{\text{length·force·length}}{\text{area·time}}$	$\frac{LFL}{L^2T}$	$\frac{\text{hundreds of foot·tonf·inch}\ddagger}{\text{acre·hour}}$
Soil loss	A	$\frac{\text{mass}}{\text{area·time}}$	$\frac{M}{L^2T}$	$\frac{\text{ton}}{\text{acre·year}}$
Annual erosivity	R	$\frac{\text{length·force·length}}{\text{area·time·time}}$	$\frac{LFL}{L^2TT}$	$\frac{\text{hundreds of foot·tonf·inch}}{\text{acre·hour·year}}$
Soil erodibility	K	$\frac{\text{mass·area·time}}{\text{area·length·force·length}}$	$\frac{ML^2T}{L^2LFL}$	$\frac{\text{ton·acre·hour}}{\text{hundreds of acre foot·tonf·inch}}$
Slope length	L	$\left(\frac{\text{length}}{\text{length}}\right)^m$	$\left(\frac{L}{L}\right)^m$	
Slope steepness	S	dimensionless		
Cover-management	C	dimensionless		
Supporting practices	P	dimensionless		

*F = force, L = length, M = mass, T = time, m = exponent that varies from 0.2 to 0.5.
†Tonf indicates ton force. Ton without a subscript indicates ton mass.
‡This notation, "hundreds of," means that the numerical value for the factor is 0.01 times its true value. That is, if R = 125, its true value is 12,500 ft-tonf•in/acre•hr•yr. The converse is true for "hundreds of" in the denominator of a fraction.

units and do not contain the confusing "hundreds of" as in U.S. customary units (Tables 1 and 2). Whether a factor value is in SI or U.S. customary units is immediately known, even if units are not written.

The conversion shown in equation 13 contains all of the dimensions of the EI factor. However, as shown in table 1, some dimensions cancel, leaving simply F/T as dimensions for EI. Megajoule in equation 13 can be written as megameter Newton (Mm•N). Then, the product megameter millimeter (Mm•mm) in the numerator is the same as 1,000 square meters (m^2), which cancels with hectares (ha) in the denominator. This gives units of Newton per hour (N/h) for EI and a conversion factor of 1.702. This conversion factor gives USLE factor values similar to those in U.S. customary units and eliminates the confusion of the "hundreds of" factor in the U.S. customary units. Also, the SI unit of N/h is easier to write than MJ•mm/ha•h. One disadvantage is that dimensions are cancelled so that EI cannot be recognized as the product of energy and intensity. Also, factor values might be confused with those in U.S customary units because of similar magnitudes.

In the western United States, where data were insufficient to evaluate average an-

Equation [12]

$$1\ \frac{\text{ft-tonf}}{\text{acre-in}} =$$

$$1\left[\frac{\text{ft-tonf}}{\text{acre-in}}\right]\left[\frac{0.3048\ \text{m}}{\text{ft}}\right]\left[\frac{2{,}000\ \text{lbf}\ 4.448\ \text{N}}{\text{tonf}\cdot\text{lbf}}\right]\left[\frac{\text{acre}}{0.4047\ \text{ha}}\right]\left[\frac{\text{in}}{25.4\ \text{mm}}\right]\left[\frac{\text{J}}{\text{N}\cdot\text{m}}\right]\left[\frac{\text{MJ}}{1.0\times10^{6}\ \text{J}}\right] =$$

$$2.638\times10^{-4}\left[\frac{\text{MJ}}{\text{ha}\cdot\text{mm}}\right]$$

Equation [13]

$$1\ \frac{\text{hundreds of foot-tonf}\cdot\text{in}}{\text{acre}\cdot\text{hr}\cdot\text{yr}} =$$

$$1\left[\frac{100\ \text{ft-tonf in}}{\text{acre}\cdot\text{hr}\cdot\text{y}}\right]\left[\frac{0.3048\ \text{m}}{\text{ft}}\right]\left[\frac{2{,}000\ \text{lbf}\ 4.448\ \text{N}}{\text{tonf}\cdot\text{lbf}}\right]\left[\frac{\text{acre}}{0.4047\ \text{ha}}\right]\left[\frac{\text{in}}{\text{in}}\right]\left[\frac{\text{J}}{\text{N}\cdot\text{m}}\right]\left[\frac{\text{MJ}}{1.0\times10^{6}\ \text{J}}\right] =$$

$$17.02\left[\frac{\text{MJ}\cdot\text{mm}}{\text{ha}\cdot\text{h}\cdot\text{y}}\right]$$

nual R by usual procedures, R has been estimated (6) as

$$R = 27.38\,(P_{2-6})^{2.17} \qquad [14]$$

where R is the erosivity in units of hundreds of ft-tonf•in/acre•hr•yr, and $P_{2\text{-}6}$ is the 2-year-frequency, 6-hour-duration precipitation in inches. The conversion of equation 14 to SI units is

$$R = 0.417\,[(P_{2-6})m]^{2.17} \qquad [15]$$

where R is erosivity in MJ•mm/ha•h•yr and $(P_{2\text{-}6})_m$ is the 2-year-frequency, 6-hour-duration precipitation in millimeters.

We redrew the R map (6) for the USLE (Figure 1) using the conversion factor in table 2 and equation 14. This map features values in SI units that are much larger than values in U.S. customary units and provides additional detail for the western United States.

Soil erodibility (K). The soil erodibility factor, K, is the rate of soil loss per unit of R or EI for a specified soil as measured on a unit plot, which is a 72.6-foot (22.1-meter) length of uniform 9 percent slope continuously in clean-tilled fallow (6). Therefore, K has units of mass per area per erosivity

Table 2. Conversion factors for universal soil loss equation (USLE) factors.

To Convert From:	U.S. Customary Units	Multiply By:	To Obtain:	SI Units
Rainfall intensity, i or I	inch / hour	25.4	millimeter / hour	mm* / h
Rainfall energy per unit of rainfall, e	foot-tonf / acre-inch	2.638×10^{-4}	megajoule / hectare•millimeter	MJ† / ha•mm
Storm energy, E	foot-tonf / acre	0.006701	megajoule / hectare	MJ‡ / ha
Storm erosivity, EI	foot-tonf•inch / acre•hour	0.1702	megajoule•millimeter / hectare•hour	MJ•mm / ha•h
Storm erosivity, EI	hundreds of foot-tonf•inch§ / acre•hour	17.02	megajoule•millimeter / hectare•hour	MJ•mm / ha•h
Annual erosivity, R‖	hundreds of foot-tonf•inch / acre•hour•year	17.02	megajoule•millimeter / hectare•hour•year	MJ•mm / ha•h•y
Soil erodibility, K#	ton•acre•hour / hundreds of acre•foot-tonf•inch	0.1317	metric ton•hectare•hour / hectare•megajoule•millimeter	t•ha•h / ha•MJ•mm
Soil loss, A	ton / acre	2.242	metric ton / hectare	t / ha
Soil loss, A	ton / acre	0.2242	kilogram / meter²	kg / m²

*Hour and year are written in U.S. customary units as hr and yr and in SI units as h and y. The difference is helpful for distinguishing between U.S. customary and SI units.
†The prefix mega (M) has a multiplication factor of 1×10^{6}.
‡To convert ft-tonf to megajoule, multiply by 2.712×10^{-3}. To convert acre to hectare, multiply by 0.4071.
§This notation, "hundreds of," means numerical values should be multiplied by 100 to obtain true numerical values in given units. For example, R = 125 (hundreds of ft-ton•in/acre•hr) = 12,500 ft-tonf•in/acre•hr. The converse is true for "hundreds of" in the denominator of a fraction.
‖Erosivity, EI or R, can be converted from a value in U.S. customary units to a value in units of Newton/hour (N/h) by multiplying by 1.702.
#Soil erodibility, K, can be converted from a value in U.S. customary units to a value in units of metric ton•hectare/Newton•hour (t•h/ha•N) by multiplying by 1.317.

unit. In the SI system, one set of units (metric ton•hectare•hour/hectare•megajoule•millimeter) can be abbreviated as (t•ha•h/ha•MJ•mm). K values in these SI units will be about 0.13 times those of U.S. customary units. A maximum K will be on the order of 0.10 (t•ha•h/ha•MJ•mm). This conversion eliminates the confusion of the "hundreds of" factor, which is in K as well as R for U.S. customary units. It also gives numerical values in SI units that are quite different from those in U.S. customary units. Although hectares in the numerator cancels hectares in the denominator, both are left to show that K is soil loss per unit area per unit of EI.

If EI is expressed in units of N/h and soil loss in t/ha, then K can be expressed in t•h/ha•N. The value for K in these SI units will be similar in magnitude to the value for K in U.S. customary units, which could be confusing if units of values from these two systems are not shown.

The conversion factors for K (Table 2) were derived like the ones were derived for R in equation 13. The soil erodibility nomograph (6), redrawn in SI units, is shown in figure 2.

If values for K are to be determined from measured data, units for K depend upon those chosen for soil loss and storm erosivity. Soil loss, a_f, measured on the given field plots, is adjusted to estimated soil loss for unit plot conditions by

$$a_\mu = \frac{a_f}{L_f S_f C_f P_f} \quad [16]$$

where a_μ is the soil loss for a storm of a given EI and adjusted to unit plot conditions with L, S, C, and P factor values for the given field plot (6). A value for K is the slope of the regression line from

$$a_\mu = (EI)\,K \quad [17]$$

Therefore, if a_μ has units of t/ha and EI has units of MJ•mm/ha•h, K has units of t•ha•h/ha•MJ•mm from equation 17. Obviously, ha cancels in the numerator and denominator, but they are left again to emphasize that K is soil loss (mass per unit area) per unit of EI.

A value of K may also be estimated from

$$K = \frac{\sum_{j=1}^{n} (a_\mu)}{\sum_{j=1}^{n} (EI)_j} \quad [18]$$

where a_μ and EI are accumulated over a series of n storms that preferably are from several years of natural rainstorms or several simulated rainstorms that can be used to represent several years of data from natural rainstorms.

Slope length and steepness (LS). The factors L and S for effect of slope length and steepness are dimensionless ratios of soil loss from a given slope to that from a unit plot with all other factors equal. The equation for the slope length factor is

$$L = (\lambda/\lambda_\mu)^m \quad [19]$$

where m is an exponent that depends upon slope steepness, λ is the length of the given slope, and λ_μ is the length of the unit plot (6). Because the ratio λ/λ_μ is dimensionless, any units for length can be used so long as they are the same for the two variables. No conversion is necessary for the slope steepness factor.

Cover-management (C) and supporting practices (P). Values for the crop-management and supporting-practices factors are ratios of soil loss with given cover, management, and supporting practices to that from a soil in continuous fallow with periodic tillage to control weeds and break the crust; all other factors are equal (6). These dimensionless ratios require no conversion.

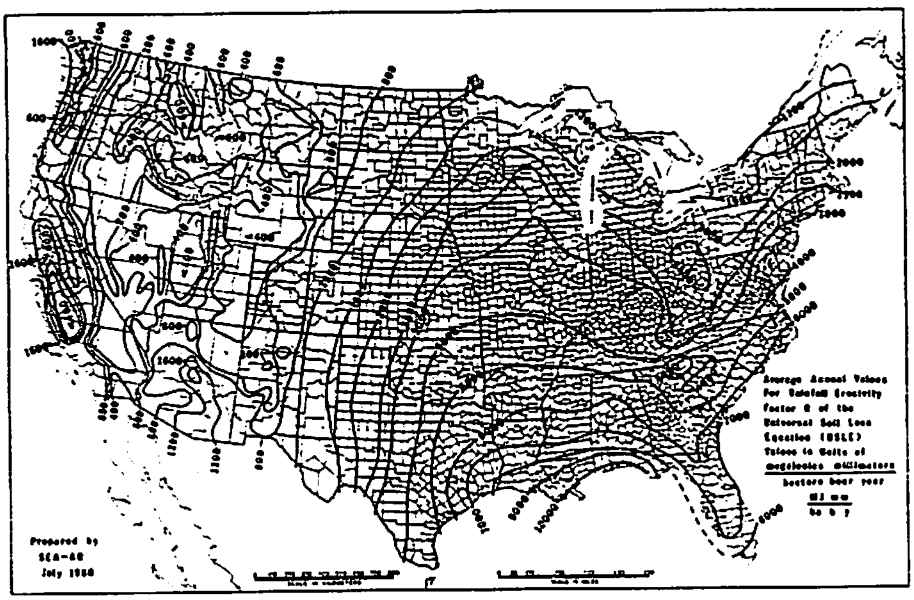

Figure 1. Erosivity (R) map in SI units.

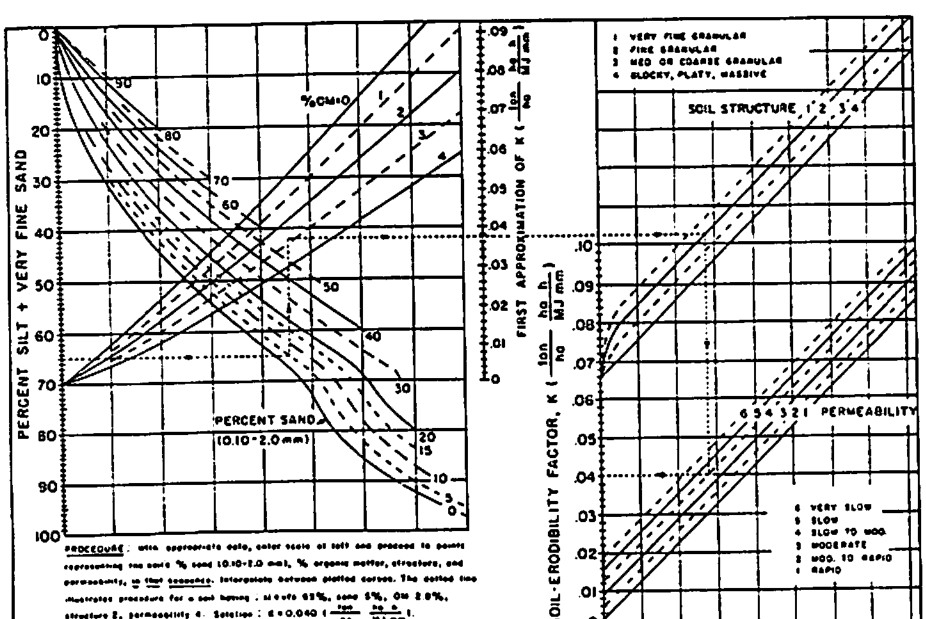

Figure 2. Soil erodibility (K) factor nomograph in SI units.

Direct computation of EI

Obviously, factor values already in U.S. customary units can be converted to SI units with the conversion factors in table 2. However, where values do not exist, direct computation of a USLE factor in SI units is preferred.

Units for EI and R evolve directly from computations with equations 2, 4, 5, and 6 and 7, or 10 and 11. Table 3 illustrates the determination of EI directly in SI units from rainfall data in SI units. This example also appeared in two earlier publications (5, 6). The rainfall hyetograph is divided into increments where intensity is assumed to be uniform (Table 3, column 1). Cumulative rainfall amounts are given in column 2. Duration, amount, and intensity for the increments are shown in columns 3, 4, and 5. Unit energy for each increment is shown in column 6. These values are obtained by substituting intensity for the increment (column 5) into equation 10 or by reading a value from table 4. Rainfall energy for an increment (column 7) is the product of e (column 6) and the volume of rainfall for the increment (column 4). Total energy for the storm is the sum of the energies for each increment (column 7), or 8.64 MJ/ha in this case.

Maximum 30-minute intensity, I, for this storm is 2(27) = 54 mm/h. Therefore, EI for this storm is $8.64 \times 54 = 464$ MJ•mm/ha•h.

Example of USLE factor values

Table 5 shows typical values for some USLE factors in both U.S. customary units and the proposed SI units. With our conversion of the USLE, a soil loss of 1 metric ton per hectare per year (t/ha•y) will be recognized as a low soil loss in comparison with soil loss tolerances ranging from 7 to 11 t/ha•y is about 5 to 20 times the soil loss tolerance. An average annual erosivity value of 300 MJ•mm/ha•h•y in the West will be recognizably low in relation to 2,000 MJ•mm/ha•h•y, a moderate erositivity value for the central United States, or 8,000 MJ•mm/ha•h•y, a high value for the southeastern United States. Similarly, a soil erodibility value of 0.01 t•ha•h/ha•MJ•mm will be seen as a low soil erodibility; 0.003 t•ha•h/ha•MJ•mm will be recognized as a moderate soil erodibility; and 0.06 t•ha•h/ha•MJ•mm will be seen as a high soil erodibility.

Once users become accustomed to the USLE in these SI units, they should find magnitudes of factor values convenient, easy to use, and distinguishable from values in U.S. customary units. Likewise, they should find direct computation of factor values from rainfall and soil loss data in SI units more convenient than computation from data in U.S. customary units.

Table 3. Example computation of energy for a rainstorm (SI units).

Chart Readings		Storm Increments			Energy	
Time	Depth	Duration	Amount	Intensity	Per Unit Rainfall	For Storm Increment
	(mm)	(min)	(mm)	(mm/h)	(MJ/ha•mm)	(MJ/ha)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
4:00	0					
:20	1	20	1	3	0.161	0.16
:27	3	7	2	17	0.226	0.45
:36	9	9	6	40	0.259	1.55
:50	27	14	18	77	0.283	5.09
:57	30	7	3	26	0.243	0.73
5:05	32	8	2	15	0.222	0.44
:15	32	10	0	0	0	0
:30	33	15	1	4	0.219	0.22
Totals		90	33			8.64*

*Kinetic energy, E, of the storm = 8.64 MJ/ha.

Table 4. Kinetic energy per unit of rainfall.*

Rainfall Intensity mm/h	Kinetic Energy per Unit of Rainfall (MJ/ha•mm of rain)									
	0	1	2	3	4	5	6	7	8	9
0	0	0.119	0.145	0.161	0.172	0.180	0.187	0.193	0.198	0.202
10	.206	.210	.213	.216	.219	.222	.224	.226	.229	.231
20	.233	.234	.236	.238	.239	.241	.243	.244	.245	.247
30	.248	.249	.250	.252	.253	.254	.255	.256	.257	.258
40	.259	.260	.261	.262	.262	.263	.264	.265	.266	.267
50	.267	.268	.269	.270	.270	.271	.272	.272	.273	.274
60	.274	.275	.275	.276	.277	.277	.278	.278	.279	.280
70	.280	.281	.281	.282	.282	.283	.283†	-	-	-

*Computed as $e = 0.119 + 0.0873 \log_{10}(i_m)$, where e is the kinetic energy in MJ/(ha•mm of rain) and i_m is the rainfall intensity in mm/h (6).
†The 0.283 value also applies for all intensities greater than 76 mm/h (6).

Table 5. Typical A, R, and K values for the universal soil loss equation (USLE) in U.S. customary and SI units.

Factor	U.S. Customary Units	SI Units
A	ton/acre•yr	t/ha•y
	0.5	1.1
	5.0	11.2
	20	45
R	hundreds of ft-tonf•in/acre•hr•yr	MJ•mm/ha•h•y
	20	340
	125	2,130
	475	8,080
K	ton•acre•hr/hundreds of acre•ft-tonf•in	t•ha•h/ha•MJ•mm
	0.05	0.007
	0.25	0.033
	0.45	0.059

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