



Rainfall erosivity: An historical review

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ABSTRACT

Rainfall erosivity is the capability of rainfall to cause soil loss from hillslopes by water. Modern definitions of rainfall erosivity began with the development of the Universal Soil Loss Equation (USLE), where rainfall characteristics were statistically related to soil loss from thousands of plot-years of natural rainfall and runoff data. USLE erosivity combines the energy of the rainfall and the maximum continuous 30-min intensity in the event. Energy of rainfall is estimated as a function of the storm intensity through the rainfall event. The USLE erosivity has been used effectively for conservation planning purposes for more than 5 decades. When the USLE was replaced by the Revised Universal Soil Loss Equation (RUSLE), a new energy-intensity equation was adopted. The new equation was not extensively tested prior to adoption, leads to significant under-predictions of erosivity, and was later replaced in RUSLE2. The RUSLE energy-intensity equation is no longer recommended by the RUSLE and RUSLE2 development teams. RUSLE2 also introduced the concept of erosivity density, which resulted in significant improvements in the calculations and mapping of rainfall erosivity. Calculations of erosivity as a whole are entirely based on rainfall intensities, and erosivity is an empirically-based index. The science indicates that the direct role of kinetic energy of rainfall as the driver of hillslope erosion in all cases is not warranted by the overall evidence, because many times the kinetic energy of raindrops is not the driving force behind rill erosion. The USLE erosivity empirically explains much of the variance in the soil loss from natural rainfall erosion plots.

1. Introduction

Cook (1937) identified three categories of physical entities involved with the process of soil erosion by water: soil, water, and plants, and from that defined three independent variables that control the erosion process, those being “soil erodibility,” “potential erosivity,” and “cover protectivity.” Cook’s discussion of potential erosivity does not coincide with the current definitions and usage of the term “erosivity,” but it does foretell the thinking process that went into the development of the concept in later times. Cook defined “potential erosivity” as the capacity of a natural rainfall and runoff occurrence to cause erosion from a “standard” area. In short, Cook’s potential erosivity was a measure of the capacity of any natural rainfall-runoff combination to produce erosion from a unit strip of land running up and down the slope. This idea of a “standard” area was analogous to or formed a basis for the later concept of Wischmeier and Smith’s (1965) “unit plot,” which will be discussed below. Cook also identified seven factors that largely control potential erosivity for a unit strip (of land): “1) total rainfall, 2) rates of rainfall, 3) velocities of raindrops, 4) infiltration characteristic of

the soil, 5) storage capacities of the surface (includes interception), 6) slopes, and 7) length of slope.” As we will see, in the later quantitative definitions of erosivity (e.g., Wischmeier and Smith, 1965), erosivity was dependent explicitly on the total and rates of rainfall, and implicitly on raindrop velocity, while infiltration and storage capacities were implicitly included in erodibility and cover factors, and slope gradient and length became their own, separate factors in computations.

Zingg (1940) developed one of the earliest quantitatively-based soil erosion prediction equations. In that equation soil erosion was related to slope length and gradient based on data from five experimental sites in the United States. That equation did not include a rainfall erosivity factor. Musgrave (1947) introduced a set of equations for estimating erosion that included slope length, slope steepness, soil erodibility, a vegetal factor, and the maximum precipitation amount falling a 30-min period during a storm. This 30-min rainfall factor was based on an unpublished report of the USDA Soil Conservation Service by O.E. Hayes based on data from La Crosse, WI. The maximum 30-min intensity, later referred to as I_{30} , continues to be widely used as part of the

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rainfall erosivity factors of today.

In the late 1920s an educational campaign, led by Hugh Hammond Bennett, was undertaken by the US Department of Agriculture to bring to attention the problem of soil erosion in the United States. This attention was brought about by the increasing recognition of the major problems of soil erosion that inevitably occur with the development and cultivation of large areas of new lands as they are brought into agricultural production, as happened in the United States during the 1800s and early 1900s. As a result of this effort the U.S. Congress appropriated money in the 1930 budget to begin the process of establishing experimental erosion stations across many parts of the country (Bennett, 1939). That number grew from an initial 10 erosion stations to a total of 35 stations in the mid-1950s, and later finally to 49 stations from which data were collected. Today very few of these stations are active. All of these erosion stations recorded and sometimes published and analyzed their own data. The Hayes report from La Crosse, WI is one such example of many unpublished records.

Because the data were being collected, and much of them went unpublished, and because there were different quantitative relationships being developed from the many erosion stations with datasets that were necessarily of only regional application, the USDA in 1954 established the National Runoff and Soil Loss Data Center located at Purdue University in West Lafayette, IN (Lafren and Moldenhauer, 2003). The purpose of that center was to act as a collection point and repository for data from all the existing erosion stations, but also to develop from the data a set of mathematical relationships that were based on all of the data, in other words, a “Universal” equation. Walt Wischmeier, trained as a statistician, was named as leader of this group.

Rainfall erosivity is an index that describes the power of rainfall to cause soil erosion. This study presents an historical review of the development of rainfall erosivity since the mid-1950s. Erosivity is used around the world for assessing and predicting rates of soil erosion on agricultural lands. The formulae for computing erosivity have changed over the years based on new scientific results. There is currently significant confusion regarding the appropriate equations to use for calculating rainfall erosivity. In particular, the use of the RUSLE erosivity calculations, as compared to USLE or RUSLE2, does not represent the best current scientific understanding of erosion, and will result in significant bias (under-predictions) of soil erosion. The intent of this paper is to clarify the historical progression of the concept, and guide the user in choosing the appropriate sets of equations to use for greatest accuracy. The result of the paper will be better implementation of erosion science around the world.

1.1. The universal soil loss equation

Soil loss refers to the amount of sediment that reaches the end of a specified area on a hillslope that is experiencing net loss of soil by water erosion. It is expressed as a mass of soil lost per unit area and time. There are several aspects of erosion that are implied in this definition. First of all soil loss refers to net loss, and it does not in any way include areas of the slope that experience net deposition over the long term. As such, soil loss does not equate to the sediment yield from a hillslope that exhibits toe-slope deposition, which are most cases. It is, rather, the sediment delivered to the bottom of the slope area that feeds onto the toe slope. Slope lengths of soil loss areas end where deposition begins. Much soil that is eroded on a hillslope may not leave the watershed within which the slope is located, or even the field edge. This does not mean that no deposition of particles on the slope occurs. In fact, as the sediment particles are transported down a slope many of them will be temporarily deposited on the part of the slope experiencing net loss, either to remain there or to be later picked up and moved again. The area of net loss is where the rate of detachment of soil exceeds the rate of deposition. A second important concept to understand is that, though the area of the hillslope under consideration experiences net loss, and that net loss is expressed as a single value, there will be great variation

of the loss along the slope. Because of these factors, soil loss is a term that is most relevant to on-site soil erosion and the problem of soil degradation, rather than the problem of water quality. Certainly soil erosion from hillslopes is a major source, or in most cases the major source, of sediment that makes its way into streams and other waterways, it is not a direct measure of sediment yield to streams.

Many of the factors in the Universal Soil Loss Equation (USLE), including erosivity, were developed utilizing the concept of the “unit plot”. The unit plot was defined as a plot of 22.13 m long at 9% slope, and kept continuously in a fallow condition by “cultural operations identical to those on the corn plots” (Wischmeier and Smith, 1958). The reason for the exact length of 22.13 m was that most of these plots in the field at the erosion experiment stations were 1.83 m (6 ft) in width, which meant that the unit plots were exactly 1/100 of an acre in size. Before the days of electronic calculators this made for easy conversion of the total mass of sediment collected from the plots to loss per unit area (acres) by simply moving the decimal place on the number representing the mass of soil collected at the end of the plot.

Wischmeier and Smith (1958) developed the first iteration of the modern rainfall erosivity index used today. They defined erosivity as a multiple of two factors, the rainfall energy and the maximum continuous 30-min intensity during the individual storm. The delineation of the “individual storm” was a break in rainfall of six hours (Wischmeier, 1959). Later this definition was refined to state that a break was considered to be one with less than 1.27 mm (0.05 in) falling in six hours (Wischmeier and Smith, 1978). Note the typo in the paper of Brown and Foster (1987) regarding this delineation. The quantitative expression of energy per unit of the rainfall that Wischmeier and Smith (1958) developed was based on the work of Laws and Parsons (1943). The relationships between raindrop fall velocity and size were taken from Gunn and Kinzer (1949), corroborated by Laws (1941), on the relationships between drop sizes and rain intensities. That equation was (in metric units):

$$e = 0.119 + 0.0873 \log_{10} i \quad (1)$$

where e ($\text{MJ ha}^{-1} \text{mm}^{-1}$) is the energy of the rainfall per unit rainfall depth and i is rainfall intensity in mm hr^{-1} . In the first version of the USLE (Wischmeier and Smith, 1965) there was no mention made of any limits on e , but in the second version (Wischmeier and Smith, 1978) and subsequent revisions the value of e was limited to 0.283, which is equivalent to a rainfall intensity of 76.2 mm hr^{-1} . This is because drop sizes of rain do not continue to significantly increase beyond approximately this intensity.

The data for the relationship developed by Laws and Parsons (1943) between rainfall intensity and size of raindrops was collected in Washington D.C., U.S.A., and was shown to closely follow the data reported earlier by Lenard (1904) and Wiesner (1895), collected in Europe.

The energy for an entire storm, E (MJ ha^{-1}), is estimated as

$$E = \int_0^D e i dt \quad (2)$$

where D is the duration of the event. Usually this quantity is calculated using k event time segments and E is computed as

$$E = \sum_{k=1}^p e_k \Delta V_k \quad (3)$$

where e_k ($\text{MJ ha}^{-1} \text{mm}^{-1}$) is the energy per unit rainfall, p is the number of time segments in the event, V_k (mm) is the rainfall depth for each increment k , and e_k is computed using Eq. (1) (Foster et al., 1981). Breakpoint rainfall data was used to compute the energy of the storm using Eq. (3). “Breakpoint” is a term that implies the manner in which rainfall chart records were visually read by separating sections of the curve where the slope changes, or “breaks,” indicating a visible change in rainfall intensity. In current use the term may refer in general

to finer temporal resolution intensity data. Thus the storm is broken into p number of segments such that the rainfall intensity in each segment does not vary greatly, and the i value used in Eq. (1) for each time segment used to compute e_k is simply the average intensity for each segment, i.e., the depth of rain falling in each segment divided by the time duration of each segment. It is worthwhile to note that today's instrumentation can provide a much more detailed record of rainfall intensity pattern during a storm. It is not exactly clear what effect this might have on the calculation of rainfall erosivity calculations, but it would seem to be prudent to keep this in mind when writing algorithms for computing erosivity from modern rain gage data.

The rainfall erosivity value for a single storm is calculated as the energy of the storm, E , multiplied by the maximum contiguous, 30-min rainfall intensity of the storm, I_{30} (mm hr.⁻¹). The I_{30} hails from the unpublished report of Hayes (discussed above). Wischmeier and Smith (1958) also evaluated using the 15 min maximum intensity on three sites and sets of plots and found the 30-min intensity to be statistically superior. After data were transferred to computer punch cards, analyses were conducted on 8000 plot-years of data from 37 erosion stations. The maximum 30-min intensity, I_{30} , was found to be better correlated to soil loss than the maximum 5-, 15-, or 60-min intensities (Wischmeier et al., 1958). Very few studies have evaluated the best period of maximum intensity time for erosivity, in part because such evaluation requires sufficient data from erosion plots under natural rainfall. A study by Zheng and Chen (2015) found that 10- or 20-min maximum intensities worked as equally well as the 30-min intensity, based on data from five plots in China.

For conversion of metric to U.S. Customary units, which are what the USLE was originally developed in, and which are still used today in the United States, see Foster et al. (1981). Note that there is often confusion in the conversion of erosivity on the issue that erosivity in customary U.S. units is reported and used as hundreds of foot-ton inch per acre hour (Wischmeier, 1959). Conversion of common U.S. to metric units for both storm and annual erosivities uses a factor of 17.02 (Foster et al., 1981).

Annual and other periodic values (e.g., seasonal, monthly, or bi-monthly) of rainfall erosivity are obtained by summing the values of the $E * I_{30}$ (referred to as EI) over the time of interest. Thus the annual R-factor in the USLE has units of MJ mm ha⁻¹ h⁻¹ yr⁻¹:

$$R = \sum_{j=1}^n EI_j \quad (4)$$

where n is the number of storms being added. Wischmeier (1959) and later revisions of USLE only used storms of greater than 12.7 mm (0.5 in) in the calculations, unless at least 6 mm of rain fell within a 15 min period. An example calculation of EI was given by Wischmeier and Smith (1978) in the appendix of that document.

Wischmeier (1959) recommended that annual values of the R-factor be based on 20 or more years of rainfall data. Shorter records have the potential to be biased by unusual wet or dry periods.

The USLE was designed to predict long term average rates of erosion. The USLE was not designed to predict soil loss events (Wischmeier, 1976). Wischmeier related with the measured plot data that the equation could predict annual values of soil loss reasonably well, but that predictions for individual storms were not accurate. The variability of soil losses from individual storms on individual plots is quite high (Wendt et al., 1986; Nearing et al., 1999) and such variability is not captured accurately by the USLE.

1.2. The Revised Universal Soil Loss Equation

The Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) used the same erosivity calculations for rainfall erosivity as did the USLE, with the exception of the rainfall energy calculations. The rainfall energy equation used in RUSLE was based on the work of Brown

and Foster (1987).

The Brown and Foster (1987) equation took the form

$$e = e_m [1 - a \exp(-b i)] \quad (5)$$

where a and b are empirical coefficients and e_m is the maximum unit energy as intensity becomes large. The form of this equation was introduced by Kinnell (1981). The value of e_m was taken as 0.29 based on the work of Rosewell (1986). This is approximately the same as the limit of energy of 0.283 used by Wischmeier and Smith (1978) for Eq. (1). The value of coefficient a was taken to be 0.72 based on work by McGregor and Mutchler (1976), and the value of coefficient b was taken to be 0.05. The value of 0.05 was derived using Eqs. (1) and (5). Using a ratio of $e/0.283$ equal to 0.95 in Eq. (1) gives a value of i of 52 mm hr.⁻¹. Rounding that value off to 50 mm hr.⁻¹, Brown and Foster (1987) apparently plugged that intensity into Eq. (5) with a ratio of e/e_m of 0.95, using the value of coefficient a of 0.72, and rounded the result to 0.05. They noted that this value was approximately the same as that found from previous work. Thus they recommended the equation

$$e = 0.29[1 - 0.72 \exp(-.05 i)] \quad (6)$$

Brown and Foster (1987) noted that Eq. (6) gave results that were approximately 12% less than those from Eq. (1) for rainfall intensities below 35 mm hr.⁻¹ and approximately 2% greater for intensities greater than 100 mm hr.⁻¹.

The primary purpose of the Brown and Foster (1987) study was to determine if the time segments of the breakpoint data of rainfall intensity in a natural rainstorm could be re-ordered from greatest to lowest, described with an analytical equation, and then used to calculate rainfall erosivity. In doing so they note that the maximum 30-min intensities, I_{30} , are not the same as for natural storms. This is because the I_{30} from the re-ordered storms are often greater those from natural storms, because in natural storms the intensities must be continuous in time during the storm, while in the re-ordered storms the periods of greatest intensities are grouped together. Thus the I_{30} from the re-ordered storms will generally be equal to or greater than those of natural storms.

Brown and Foster (1987) found good agreement, on a limited data set, between their method of calculating erosivity and that of the original USLE. However, in the development of erosivities for RUSLE the storm data were not re-ordered and the I_{30} value was based on natural storms. As such, it is not surprising that the values of RUSLE erosivities are significantly less than those from the original USLE. In fact, the Brown and Foster (1987) equations were mis-applied in RUSLE, because the methodologies between RUSLE and Brown and Foster (1987) were not consistent.

1.3. The Revised Universal Soil Loss Equation version 2 (RUSLE2)

The Revised Universal Soil Loss Equation version 2 (RUSLE2) (USDA-Agricultural Research Service, 2013) is the replacement for RUSLE used commonly today in the United States by government agencies for conservation planning purposes. RUSLE is no longer officially used by government conservation agencies in the U.S. Also, current recommendations are that if the now out-of-date RUSLE is used, then RUSLE2 erosivities should be used (<https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/watershed-physical-processes-research/docs/revise-universal-soil-loss-equation-106-current-version/>).

McGregor et al. (1995) analyzed data from 29 recording rain gages in the Goodwin Creek watershed of northern Mississippi, U.S. for erosivity. From those data they compared three equations for erosivity: the USLE equation (Wischmeier and Smith, 1978), the RUSLE equation (Brown and Foster, 1987), and the McGregor-Mutchler equation (McGregor and Mutchler, 1976). The results showed that the McGregor-Mutchler equation gave results that were approximate to those from the

USLE, but approximately 9% greater than those from RUSLE. They noted that changing the b coefficient from 0.05 to 0.082 in the RUSLE equation would result in an equation that was nearly identical to the McGregor-Mutchler equation, which results in:

$$e = 0.29[1 - 0.72 \exp(-.082 i)] \quad (7)$$

Eq. (7) was adopted in the development of RUSLE2. Details of the methods used to calculate erosivities for RUSLE2, and hence those currently used in RUSLE, may be found in Hollinger et al. (2002), Angel et al. (2005), and USDA-Agricultural Research Service (2013). Data from stations with 15-min precipitation were used in developing isorodent maps of erosivity for the United States for RUSLE2. The developers recognized that 15-min data was not adequate for estimating the I_{30} of a storm because the data would not capture the true maximum 30-min period, but noted that the number of stations with finer breakpoint data was limited. In order to account for the difference between the calculated erosivities using 15-min and breakpoint data, they analyzed data series from breakpoint data and compared them. They adjusted the values of I_{30} from the 15-min data by a factor of 1.04. This compares with the analogous value derived by Yin et al. (2007) of 1.041 using data from China.

We, the authors, compared computed erosivity values from 18 stations in China, 36 stations in Italy, and 2 stations in Arizona, U.S.A. The stations in China were located in the humid, eastern part of the country, while the AZ stations are semi-arid. Italy has generally a Mediterranean climate, and erosivities tended to fall between those found in China and AZ. The average of the differences for these 56 stations were that erosivities for RUSLE was 14% less than those for USLE. None of the 56 stations showed a greater USLE value than RUSLE. RUSLE2 values was, on average, only 3.7% less than those for USLE. All but 5 of the 56 had lower RUSLE2 than USLE values.

RUSLE2 introduced the new concept of “erosivity density” for calculating and mapping rainfall erosivity in the United States (Dabney et al., 2012; USDA-Agricultural Research Service, 2013). Erosivity density is calculated as an amount of erosivity per unit of rainfall depth, generally calculated on a monthly basis at a given location. The units of energy density are energy per unit time per unit area ($\text{MJ ha}^{-1} \text{min}^{-1}$). These values are multiplied by average unit depth of precipitation (mm) for the period of interest (e.g., monthly) to give the average erosivity for the time period. The erosivity density concept was used to map erosivity for the United States for the use of RUSLE2, and is considered to have advantages over the previous method of direct calculation and summation of erosivity from the rainfall records.

One of the most important of these advantages is that in using this method it was possible to use data from daily precipitation record gages, which are much more numerous than those with 15-min records. In the US, kriging was used to map monthly erosivity density based on information from 15-min precipitation stations, then applied to stations with daily data to provide a more complete and smoother map of erosivity. Details are described in USDA-Agricultural Research Service, 2013. Another advantage of the method was that missing data have a much lesser impact on the resulting values of erosivity. The developers of RUSLE2 found that rainfall measured by the 15-min gages underestimated the total rainfall compared to data from nearby daily stations. Since the erosivity density approach calculates a ratio of erosivity to rainfall amount, the effect of missing data can be addressed by multiplying the calculated erosivity density by the measured rainfall from daily data. It should be noted, too, that the developers of RUSLE2 were aware of, and corrected for, the difference between erosivity calculated from 15-min gages and breakpoint data, using a factor of 1.04.

Another advantage of the method is that shorter time periods of record may be used for calculating erosivity density than direct rainfall erosivity using the 15-min (or less) data. The developers of RUSLE2 determined, based on rainfall records for northern Mississippi, that 15 year records were sufficient. This result had a big impact particularly in the western US where rainfall gages were much more sparsely

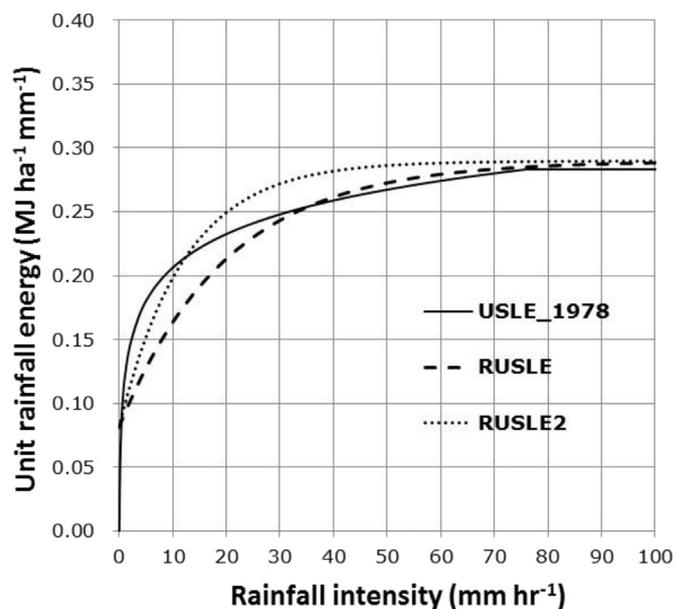


Fig. 1. Unit rainfall energy computed as a function of rainfall intensity using the USLE, RUSLE, and RUSLE2.

located.

In all, the erosivity density approach to rainfall erosivity calculation provides for better estimates of erosivity, smoother mapping across regions, better performance in mountainous areas, the capability to use shorter 15 year rainfall records, and the ability to utilize daily data in conjunction with less common 15-min rainfall data.

2. Discussion

The reason for the lower computed erosivity values for RUSLE compared to USLE are evident in looking at the graph of unit rainfall energy vs. rainfall intensity (Fig. 1). For rainfall intensities less than approximately 35 mm hr^{-1} the USLE energy values are greater than those for RUSLE, and above 35 mm hr^{-1} they are somewhat less, but only slightly so. RUSLE2 values are somewhat less than USLE values for intensities less than approximately 12 mm hr^{-1} , and greater above that level. The result is that RUSLE2 and USLE erosivities are more similar than for RUSLE compared to USLE. The fact that RUSLE2 does give slightly lower erosivity, at least for most stations, implies that rainfall intensities on the lower end of the scale are a very large component on the erosivity calculations.

The original erosivity factor used in the USLE, based on the summation of the energy-intensity index, EI and using Eq. (1) for estimating rainfall energy, was developed by Wischmeier (1959) on thousands of plot-years of measured erosion plot data. It was shown then and used over the decades to reflect long-term erosion rates reasonably well, on average. The energy equation used in RUSLE, Eq. (6), was developed for a very specific application related to re-ordered rainfall intensity data (Brown and Foster, 1987), and in that application was tested only on a limited data set. It was not designed and tested to be used directly in a soil loss equation along with I_{30} values from natural rainfall event intensity data. Adaptation of Eq. (6) into RUSLE was later recognized by the developers of the model to be a poor choice, and the equation was replaced by Eq. (7) in RUSLE2. The developers now recommend that RUSLE2 R-factors should be used when applying the RUSLE model.

While some recent studies involving rainfall erosivity have utilized the RUSLE2 erosivity (e.g., Wang et al., 2017; Yin et al., 2015; Xie et al., 2016), many continue to use the equation used in RUSLE, or Eq. (6) (e.g., Nearing et al., 2015; Borrelli et al., 2016; Panagos et al., 2015). Yet it is clear that the RUSLE erosivity is based on a conceptual mistake.

Our analyses and those from other studies (McGregor et al., 1995; McGregor and Mutchler, 1976; Ramon et al., 2017; Van Dijk et al., 2002) have clearly shown that the RUSLE significantly underestimates erosivity as it was originally developed on large numbers of field plots. Even the developers of the equation (Brown and Foster, 1987) recognized in their original paper that Eq. (6) underestimates energy compared to the original USLE equation (Eq. (1)) over much of the range of the equation application.

It is worthwhile to understand what it exactly means to state that the erosivities are underestimated. The USLE contains six factors, and of those six only two have units, the erosivity and the erodibility. The slope steepness, slope length, cropping management, and control practice components of the equation are all dimensionless factors, or ratios. They represent differences relative to the unit plot, as defined by Wischmeier and Smith (1965). Of the two factors with units, erosivity was defined as the energy multiplied by maximum 30-min intensity term. It does not contain unit of erosion. Thus the erosion units are introduced into the equation by the erodibility factor. Thus, it is the erodibility factor that gives the USLE its units of erosion. Soil erodibility values were determined empirically by setting the values of all the other factors and calibrating the model output to the measured erosion data. In other words, as opposed to the erosivity, there is no physically-based component to the erodibility factor. Thus if one were to determine that one energy vs. intensity relationship were better than another, and significantly different from the USLE in terms of representing actually rainfall energy, then soil erodibility would need to be re-determined or adjusted within the context of the new rainfall erosivity factor values in order to provide estimates of erosion that fit the measured data.

Van Dijk et al. (2002) conducted a thorough analysis of relationships between rainfall kinetic energy and rainfall intensity. They pointed out a number of important characteristics of rainfall energy and evaluated several equations for calculating rainfall kinetic energy from rainfall intensity, including the Wischmeier and Smith (1978) and Brown and Foster (1987) equations. They also developed a new equation based on the best quality data they were able to find from the scientific literature. They reported that energy from individual storms could not be predicted with a high level of accuracy because of natural variability between storm characteristics. They also showed that because of differences in air pressures, the fall velocities of raindrops are related to the elevation of the location, with greater velocities at higher elevations. They found that geography also influences rainfall energy, with greater than expected energies for similar intensities expected in arid vs. humid climates.

It is important to understand when considering the calculations of rainfall erosivity that, even though our intention is to represent rainfall energy in the term, in fact the entire calculation of energy is based on rainfall intensity. The I_{30} is a measure of sustained rainfall intensity and the E value is estimated by various equations as a function only of rainfall intensity. Ultimately erosivity is an empirical function that was derived originally by Wischmeier and Smith (1958) based on thousands of plot-years of measured erosion plot data. Since that time there has been no work done on that scale that relates measured erosion to rainfall characteristics. Studies that have been conducted (e.g., Schwertmann et al., 1990; Auerswald et al., 2009; Sauerborn, 1994) have largely corroborated the viability of the original USLE equation.

It has been shown that splash detachment is statistically related to raindrop kinetic energy (e.g., Rose, 1960; Nearing and Bradford, 1985) but it has also been shown that soil loss from interrill areas (areas dominated by splash and sheet-flow sediment transport) is not correlated to splash detachment (Bradford and Foster, 1996). Within one theoretical framework, soil loss from interrill areas will be limited by either detachment or by transport (Foster, 1982). Which of the two dominates is dependent on the slope of the area, runoff rates, soil erodibility, soil infiltration rates, rainfall intensity, and the size of particles detached from the soil. In cases where soil loss is transport

limited on interrill areas, then the energy of the rainstorm is not the direct driving component of erosivity. Likewise, when rill erosion is active on the slope, then the driving factor of the soil detachment in the rill is the runoff rate, and not the rainfall intensity. Note also that when erosion rates are large it is generally because rills are active (Gilley et al., 1990; Govers, 1990, 1992). In the cases where interrill erosion is limited by transport or where rill erosion is a dominant component of the erosion, then the energy term in the erosivity calculations is acting as a surrogate for the true generative mechanisms of soil loss, which relate to transport in interrill areas and rill erosion. In other words, the 30-min maximum rainfall intensity and 12.7 mm rainfall depth threshold in the erosivity calculations represent, to greater or lesser circumstances depending on the situation, the process of runoff generation, which is needed to deliver sediment and to activate rills. Placing too much emphasis on the direct role of kinetic energy of rainfall itself as the driver of hillslope erosion is not warranted by the overall scientific evidence. What we do know is that the erosivity term developed by Wischmeier and Smith (1978) empirically explains much of the variance in the long term soil loss from natural rainfall erosion plots.

In the future Eq. (6) (used in RUSLE) should not be used for erosivity calculations. Use of the original USLE energy equation (Eq. (1)) or the RUSLE2 equation (Eq. (7)) will provide values of R or EI that most closely represent the bulk of the erosion plot data, and will provide similar results in most applications. Certainly the use of RUSLE erosivity will provide reasonable results in terms of quantifying relative spatial or temporal differences in erosivity, but it must be understood that they represent a significant underestimate of erosivity.

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