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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 (Laflen 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):

$$e = 0.119 + 0.0873 log_{10} i \tag{1}$$

where e (MJ ha^{-1} 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

$$\mathrm{E} = \int_0^{\mathrm{D}} e\ i\ dt \tag{2}$$

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

$$E = \sum_{k=1}^{p} e_k \Delta V_k \tag{3}$$

where e_k (MJ ha^{-1} 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