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Cover: This pristine aspen stand in the Grand Mesa National Forest in Colorado leads one to reflect on the challenges facing multiple use of national forest land. See page 626. Forest Service photo by R. E. Grossman.

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to the virgin, uncultivated site. The lower organic matter levels at the cultivated, eroded sites promoted faster seal development than occurred at the virgin site. Seal development and runoff steadily increased with severity of erosion among the cultivated sites as organic matter gradually decreased and clay content of the surface horizon increased.

The higher organic matter level at the virgin site resulted in greater aggregate stability and lower total soil loss, 30.9 Mg ha^{-1} (13.8 tons/acre) compared to 80.2, 71.4, and 58.6 Mg ha^{-1} (35.8, 31.8, and 26.1 tons/acre) for the slight, moderate, and severely eroded phases, respectively. The decrease in soil loss with increased severity of erosion among the eroded sites was attributed to greater cohesion associated with increased clay in the surface horizon. Sediment sizes were substantially larger at the virgin site due to greater aggregate stability. Conversely, sediment sizes among the cultivated sites did not differ appreciably because aggregate stability was generally similar.

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Apparent geographic and atmospheric influences on raindrop sizes and rainfall kinetic energy

G. F. McIsaac

ABSTRACT: Rainfall kinetic energy was calculated from average drop size distributions measured at six locations. Median raindrop diameters in North Carolina, New Jersey, and the Marshall Islands tended to be less than those observed in Panama, Indonesia, Washington, D.C., and Zimbabwe. Calculated rainfall kinetic energies for Panama and Indonesia were within 10% of that predicted by the universal soil loss equation (USLE) rainfall energy equation. Calculated rainfall energies for New Jersey, the Marshall Islands, and North Carolina ranged from 5% to 28% less than that predicted by the USLE rainfall energy equation. An uncertainty interval of 15% to 30% of the estimated rainfall energy value is suggested to reflect uncertainties in geographic differences in raindrop sizes. Increasing the rainfall energy estimate by 7% for each 1,000 m (3,280 feet) of elevation above sea level is suggested to account for increased raindrop velocity under reduced atmospheric pressure. Additional research is recommended on the geographic effects on raindrop sizes and raindrop detachment of soil, particularly in West Africa, at higher elevations and for periods exceeding 2 years.

IN the United States and many other countries, the standard method of estimating erosion from agricultural fields is the universal soil loss equation (USLE) (*28*). The USLE rainfall and runoff factor, R, is calculated from rainfall kinetic energy. For intensities less than 76 mm/hr, rainfall kinetic energy is estimated by the following equation:

$$E=0.119+0.0873\ \log(I) \quad [1]$$

where E is the kinetic energy per mm of rain in MJ/ha-mm and I is the rainfall intensity in mm/hr. This equation is based on raindrop size distributions measured in Washington, D.C., by Laws and Parsons (*12*).

Hudson (*6*), working in Zimbabwe, and Carter and associates (*3*), working in Mississippi, reported that as intensity exceeded 76 mm/hr, a range in which Laws and Parsons had few observations, median drop size and kinetic energy per mm of rainfall remained constant or decreased. Subsequently, for rainfall intensities greater than 76 mm/hr, Wischmeier and Smith (*28*) recommended a constant energy value of 283 kg/ha-mm of rain.

Atmospheric conditions and/or geographic location appear to influence raindrop sizes (*24*), terminal velocities (*1, 5*), and, therefore, kinetic energy (*8*). Lal (*11*) and Kowall and Kassam (*10*) reported rainfall energies of 640 and 395 kg/ha-mm, respectively, in Nigeria.

Raindrops form on hydrophilic particles (nucleation sites) in air that is supersaturated with water vapor. A high concentration of nucleation sites may lead to a large number of small drops, as may be the case in a maritime environment where airborne salt particles are abundant. After formation, raindrops may coalesce, break up, or evaporate. Because raindrops of different sizes have different drag characteristics and terminal velocities, raindrops are sorted by size in falling. In arid conditions, small drops may evaporate before reaching the ground. The distribution of raindrop sizes observed at the ground is the result of these processes, which vary in time and space.

Raindrop size distributions have been described as normal (*12*), log normal (*17*), shifted log normal (*24*), exponential (*13*), and as unique mathematical functions (*16*). These different descriptions may reflect influences of local atmospheric conditions, measurement techniques, and/or data interpretation.

Stout and Mueller (*26*) reported raindrop size distributions of nine locations measured by a direct photographic technique (*7*). Kinnell (*8, 9*) analyzed some of these data to compute and compare rainfall energies for Miami, New Jersey, and the Marshall Islands. He concluded that there were

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statistically significant geographic and storm type effects on the relationship between rainfall intensity and kinetic energy. Rainfall energies in New Jersey and the Marshall Islands were about 20% less than those calculated for Miami, and there was little difference between intensity-energy relationships developed from data collected in Miami and Rhodesia and equation 1. Rogers and associates (*25*), using the photographic technique to measure raindrop-size distributions in Illinois, concluded that the average difference between calculated rainfall energy and equation 1 was 2%, although differences as great as 30% were observed for a single storm.

Most studies of raindrop-size distribution and raindrop velocities have been conducted near sea level. According to equations developed by Beard (*1, 2*) and verifications by Hinkle and associates (*5*), terminal velocities are inversely proportional to the air density raised to the 0.45 power. Because kinetic energy is proportional to velocity squared, for a given raindrop size, kinetic energy is inversely proportional to the air density to the 0.9 power. Because air density decreases by about 7% for every 1,000 m (3,280 feet) of elevation, kinetic energy of a falling raindrop will be about 7% greater at 1,000 m elevation than at sea level. This may explain why Tracy and associates (*27*) observed rainfall energies at 900 and 1,800 m (2,950 and 5,900 feet) elevation in Arizona that were about 15% greater than predicted by the USLE rainfall energy equation.

The USLE may shortly be replaced by the water erosion prediction project (WEPP). Based upon interrill erosion measured under a rainfall simulator designed to apply a rainfall with a drop size distribution similar to that observed by Laws and Parsons (*12*) and with energy similar to that predicted by the USLE rainfall energy equation, WEPP predicts raindrop detachment as a square of the rainfall intensity (*4, 14*).

In our study, we compared relationships between rainfall intensity and rainfall energy calculated from the average drop size distributions measured at various locations.

Study methods

Mueller and Sims (*18, 19, 20, 21, 22, 23*) used a 70-mm camera to photograph a 0.14-m^3 volume during rainstorms at the locations and time periods listed in table 1. The camera was automated so that a series of seven frames were taken during a 10-second interval; this sequence was repeated every minute until the entire roll of film was exposed.

Photographs were developed and the major and minor drop axes were measured using an electronic hand caliper. The smallest measurable drop diameter was 0.5 mm. The volume of the drop was calculated and converted to a spherical diameter of equal volume. The total number of drops in each 0.1-mm size category in the seven frames was recorded as number of drops per cubic meter.

Rainfall intensity was calculated by the following equation:

$$I = K_1 \sum_{d_j=0.5\ \text{mm}}^{d_j=7.9\ \text{mm}} n_j V_j T_j \qquad [2]$$

where I is the rainfall intensity (mm/hr), d_j is the drop diameter category (mm), n is the number of drops of diameter d_j (drops/m³), V_j is the volume of drops of diameter d_j (mm³/drop), T_j is the terminal velocity of drops of diameter d_j (m/sec), and K_1 is the conversion factor 0.0036 m³ mm s/mm³ m hr. Terminal velocity was calculated by the equation of Beard (*1*), assuming standard atmospheric conditions (20°C and 760 mm of Hg) for all locations. For the North Carolina data, calculations were repeated assuming 0.9 atmospheres (690 mm Hg) pressure, due to greater elevation (1,360 m).

Observations were grouped into arbitrary classes of rainfall intensity. Average drop-size distributions were calculated by averaging the number of drops of each size class. These average drop-size distributions and median drop diameters were reported by Mueller and Sims (*18, 19, 20, 21, 22, 23*) and used for the kinetic energy calculations.

The kinetic energy KE_j (J/drop) of each drop size was calculated by the following equation:

$$KE_j = K_2\, 0.5\, m_j\, T_j^2 \qquad [3]$$

where m_j is the mass (mg) of raindrop size j, and K_2 is the conversion factor 10^{-6} g cm²/erg mg m².

Using the average drop size distributions, the kinetic energy flux per millimeter of the rain passing an arbitrary horizontal plane was calculated by the equation:

$$E = (K_3/I) \sum_{j=1}^{j=74} n_j KE_j T_j \qquad [4]$$

where E is energy flux per mm of rainfall (KJ/ha-mm) and K_3 is the conversion factor 36,000 KJ sec m²/J hr ha.

Results

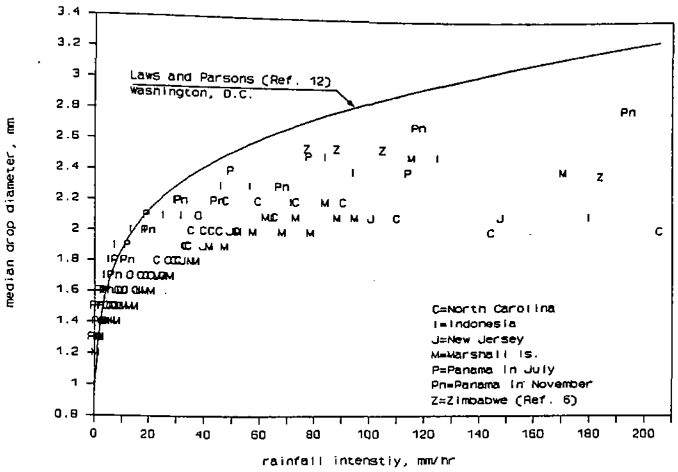
Median drop sizes from various locations. At the Marshall Islands, median drop diameters for intensities less than 100 mm/hr were less than median diameters observed at all other locations (Figure 1). However, for intensities greater than 100 mm/hr in the Marshall Islands, the median drop diameters were similar to those reported by Hudson (*6*) for similar rainfall intensities in Zimbabwe. Median drop diameters in New Jersey and North Carolina were consistently less than those predicted by the Laws and Parsons relationship and less than those drop sizes at similar intensities reported by Hudson. In Panama, in November, median drop sizes for rainfall intensities greater than 100 mm/hr were considerably greater than those reported by Hudson. Median drop sizes for Indonesia and Panama in July were similar to those reported by Hudson.

Kinetic energy per millimeter of rainfall. Kinetic energy per unit area per millimeter of rainfall calculated for Panama and Indonesia generally were within 10% of the USLE rainfall energy equation (Figure 2). In Panama, the energy calculated at 110 mm/hr was 10% greater in November than in July. The rainfall energy in New Jersey was 5% to 15% less than the USLE rainfall energy equation. The rainfall energy in the Marshall Islands was up to 28% less than the USLE, with the greatest difference occurring for intensities between 5 and 40 mm/hr. For intensities greater than 100 mm/hr, rainfall energy calculated for the Marshall Islands was about 6% less than the USLE rainfall energy equation.

Rainfall energies calculated for North Carolina were up to 25% less than the USLE rainfall energy equation, using raindrop terminal velocities corresponding to 1 atmosphere pressure (Figure 3). When the terminal velocities were calculated assuming

Table 1. Locations of raindrop camera measurements.

Location	Latitude	Longitude	Elevation (m)	Period of Measurement	Number of m³ Observations	References
Bogor, Indonesia	6°30′S	106°48′E	260	10/31/59—4/10/61	1,872	*22*
Island Beach, New Jersey	39°52′N	74°5′W	3	10/30/60—5/24/62	3,135	*19*
Franklin, North Carolina	35°2′N	83°28′W	1,360	12/21/60—3/25/62	4,742	*18*
Majuro, Marshall Islands	7°5′N	171°23′E	3	3/11/59—4/39/60	2,660	*20*
Pina Range, Panama	9°22′N	79°58′W	50	6/27/68—7/19/68	1,129	*21*
Fort Sherman, Panama	9°22′N	79°58′W	50	11/6/68—11/21/68	1,394	*23*



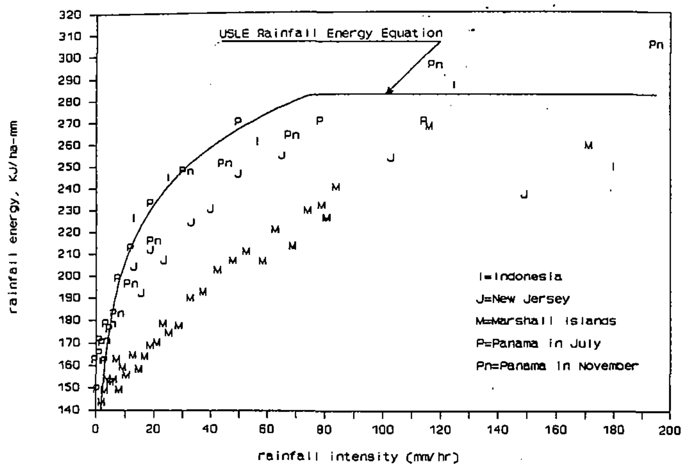


Figure 1 (above). Median drop diameter for various intensities and locations as reported by Laws and Parsons (*12*), Hudson (*6*), and Mueller and Sims (*18, 19, 20, 21, 22, 23*).

Figure 2 (above, right). Kinetic energy per millimeter of rainfall from the USLE rainfall energy equation and calculated from average drop-size distributions from Mueller and Sims (*19, 20, 21, 22, 23*).

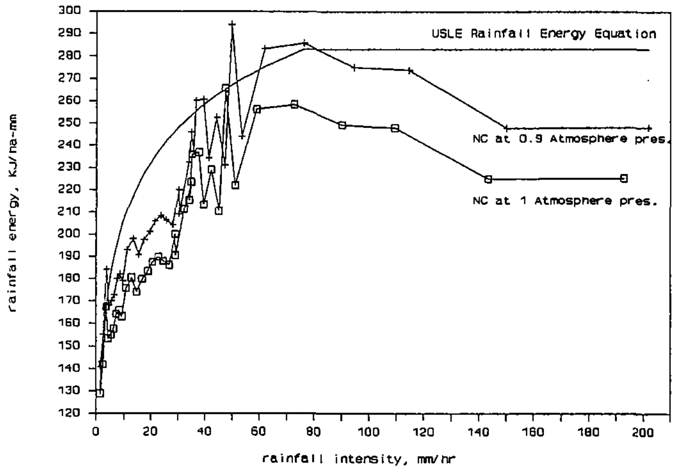


Figure 3 (right). Kinetic energy per millimeter of rainfall as determined by the USLE rainfall energy equation and calculated from average drop-size distributions reported by Mueller and Sims (*18*) for Franklin, North Carolina, and using the terminal velocity equation of Beard (*1*) for two atmospheric pressures: 1 and 0.9 atmospheres.

0.9 atmospheres, kinetic energy increased an average of 9%, and the differences between the USLE and rainfall energy calculated for North Carolina were reduced to 15%.

Discussion

Rainfall kinetic energies calculated from the average drop-size distributions for New Jersey and the Marshall Islands were similar to the results reported by Kinnell (*8, 9*), who used the instantaneous drop-size distributions for these locations.

The apparent deviations between rainfall energies calculated from various drop-size distributions may be due to local, temporal variations in drop-size distributions and/or regional, long-term geographic differences in drop-size distributions, and/or differences in measurement techniques. The average drop-size distributions used in our study were collected over periods ranging from 2 weeks to 20 months and thus may not represent long-term averages at the locations where they were observed. This can only be determined from longer periods of observation. The effects of measurement technique on the calculated rainfall energy are uncertain. Many of the earlier studies used a flour pellet technique (*3, 6, 12*); this method has not been experimentally compared with the photographic technique. However, the magnitude and variations in raindrop size and rainfall energy observed with the photographic technique also have been observed with the flour technique (*6*). Consequently, the effect of two techniques on the observed differences probably is not large.

For most locations, average kinetic energy per millimeter of rainfall was within 15% of the USLE rainfall energy equation. For the Marshall Islands, the USLE rainfall energy equation consistently overestimated rainfall energy by up to 28%. Mihara (*5*) reported that rainfall energy in Japan was 70% of the USLE rainfall energy equation. It is possible that Japan and the Marshall Islands are subject to similar atmospheric conditions, which leads to similar raindrop sizes and rainfall kinetic energy regimes.

There are not sufficient data to categorize raindrop-size distributions for various geographic regions. However, potential geographic variations should be recognized when using the USLE to quantify soil erosion for a particular location or to compare erosion rates from disparate regions. Because rainfall energy is a factor multiplied into the USLE, a consistent 30% overestimation of rainfall energy will lead to a 30% overestimation of soil loss. Perhaps an uncertainty interval of 15% to 30% of the estimated rainfall energy value could be calculated to estimate uncertain geographic influences. Additionally, rainfall energy estimates could be increased by 7% for each 1,000 m of elevation above sea level to account for the effect of decreased air density on raindrop velocity at higher elevations.

While smaller drop sizes at the North Carolina location may reflect a regional effect, it may also reflect an effect of elevation on drop sizes. The greater drop velocities in lower air pressures may enhance raindrop breakup and lead to smaller median drop sizes. Additional research is recommended to determine the effect of elevation and air density on drop-size distribution and rainfall energy.

The WEPP model estimates interrill erosion based on rainfall intensity rather than rainfall energy. Equation parameter estimates have been developed using rainfall simulators with a raindrop-size distribution similar to that observed by Laws and Parsons (*12*). Thus, in locations where raindrop sizes are different than the Laws and Parsons relationship and terminal velocities are different than at sea level, the WEPP model estimates of interrill erosion will contain systematic errors. The magnitude or consequences of these errors on total erosion estimates are unknown and likely will vary with conditions that dictate the relative importance of interrill and rill erosion.

Instantaneous raindrop-size distributions and rainfall energies are much more variable than the averages presented in this study. The instantaneous variations may be important in soil erosion. The relationship between kinetic energy and soil detachment is sometimes nonlinear and subject to threshold values. Consequently, two rainfall events that have different sequences of kinetic energy flux but identical cumulative kinetic energy may lead to considerably different rates of soil detachment (25). Thus, average drop-size distribution functions, which mask temporal variations in kinetic energy, may lead to inaccurate estimates of erosion. Description of instantaneous variations in rainfall energy may be useful in erosion estimation and may be obtained by analyses of instantaneous drop-size distributions. These analyses are recommended for future research. Additionally, raindrop detachment equations need to be verified under natural rainfall conditions. Finally, reports of extremely large rainfall energies in West Africa (*10, 11*) deserve further investigation.

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