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RAINFALL ENERGY CHARACTERISTICS FOR SOUTHEASTERN ARIZONA

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ABSTRACT: Drop-size distributions were determined for thunderstorms in southeastern Arizona using a transducer whose output is a function of impact energy. Continuous observations were taken for 24 thunderstorms during 1981 and 1982.

Median drop diameter and kinetic energy distributions were characterized at one-minute intervals for each event. The kinetic energy was exponentially related to rainfall intensity by:

$$KE = 7960 \exp .135(I)^{.175} - 8030$$

where: KE = kinetic energy in foot-tons(f)/acre-in
I = intensity in inches/hour

The southeastern Arizona relationship yielded higher values than published kinetic energy relationships for Mississippi, Louisiana and Washington, D.C. Annual erosivity values (R) for 12 years of record at two sites on the Walnut Gulch Experimental Watershed yielded values about 15 percent higher than values calculated using the Universal Soil Loss Equation (USLE) kinetic energy algorithm.

INTRODUCTION

Raindrop size and velocity are primary factors in calculating storm energies and subsequent soil losses. Several raindrop size and energy equations have been developed for specific areas of the United States. A generalized, more widely applicable, version has become the basis of the energy term (R) of the Universal Soil Loss Equation (USLE) developed by the United States Department of Agriculture (17).

Suggestions have been made that the relationship among the USLE factors may be different for various climatic regions. In reference to kinetic energy-soil loss relationships, Kinnell (9) writes ". . . it is apparent that for a given rain type the detachment power of rainfall may also vary between locations." Simanton et al. (16) comment, "if the USLE is to be applied to the rangeland conditions of the semiarid southwest, considerable research is needed into the hydrology-erosion-biotic relationship of this climatic region."

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The accurate measurement of drop size characteristics is, even with current technical advances, a complex problem. Common techniques, as outlined by Rowland (15), include optical methods, replicating techniques and impact sensors. Robinette and McCool (14) summarize techniques for measuring drop size characteristics.

SAMPLING SITES

Rainfall data for this study were collected in southeastern Arizona at Tombstone in 1981 and at Tucson in 1982. Tombstone is an upland area at the 4850 foot level, while Tucson is situated in the lower Santa Cruz River basin at 2400 feet. The climatic pattern for both sites is similar.

In southeastern Arizona, annual precipitation ranges from about 10 inches on the valley floors to over 25 inches in mountainous areas. Rainfall is bimodally distributed, with 40 to 70 percent occurring during the summer thunderstorm period, July to September (5). Unstable air masses advancing from the south produce moderate to intense afternoon thunderstorms during this period. Generated over the strongly heated terrain, these generally high-intensity, short-duration thunderstorms are often of limited areal extent (13). Gentle, widespread, intermittent rain showers produced by winter cyclonic storms advancing inland from the Pacific, account for the remainder of the yearly precipitation.

METHODS AND PROCEDURES

Individual storm data were collected on a per-drop basis utilizing a Joss-Waldvogel disdrometer provided by the Illinois State Water Survey. The disdrometer (drop distribution meter) consists of two units, the impact transducer and a signal processor. The transducer, as described by Joss and Waldvogel (7), transforms the mechanical momentum of an impacting raindrop into an electric pulse, whose amplitude is a function of the drop diameter. Pulse output voltages range from 0.3 to 10.0 volts for the processed output signal, while pulse length is approximately 0.5 milliseconds. Figure 1 provides an exploded view of the transducer.

The impact of a drop produces a downward movement of the sensing body and attached coils. Movement of the sensing coil induces a voltage which is amplified and applied to the driving coil. This produces a force which counteracts the initial movement, returning the sensing mechanism to its original position. The amplitude of the pulse at the amplifier output is a measure of the drop size that caused it.

The signal processor provides the power supply to the transducer and houses the test and signal circuitry. Signal processing circuitry consists of 1) a noise rejection filter, 2) a dynamic range compressor and 3) a signal recognition circuit. Output from the signal processor is passed to an encoder, where it is modified for recording on a magnetic recorder. The raindrop encoder houses a peak detector and an analog-to-digital (A to D) converter. Data recordings were made of each rainfall event using a standard reel-to-reel magnetic tape recorder. Recorded data were later decoded and loaded into a computer through a tape interface.

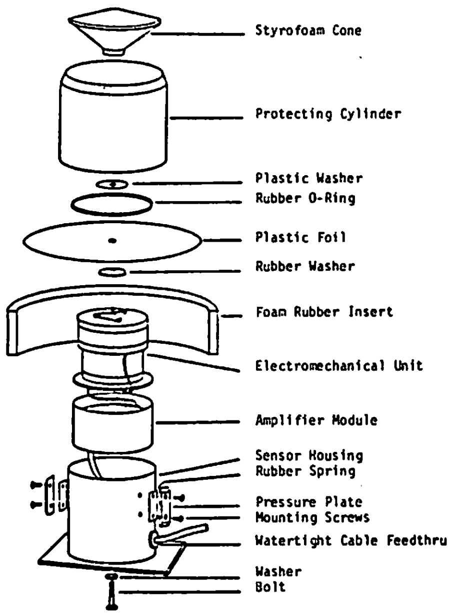


FIGURE 1. Exploded view of the transducer (after Joss and Waldvogel, 1970)

A static drop technique was utilized to calibrate the transducer output voltage (Figure 2). A series of individual drops was produced under constant head, for eight drop sizes. Equivalent diameters for the drops ranged from 1.9 to 6.3 millimeters. Fall height was 42 feet, with all drops calculated to be at terminal velocity using the values published by Gunn and Kinzer (6).

Data sets were collected for 24 storms during the study period. Continuous raindrop impact data were statistically analyzed at one-minute intervals. Drop frequency was tabulated for each interval, and total rainfall depth and average rainfall intensity were computed. Distributional characteristics were calculated for both drop diameter and kinetic energy. These included the mean, standard deviation, skew and the 90th, 60th, 50th, 40th and 10th percentile values for each distribution.

Total kinetic energy was also calculated for each event. Two methodologies were employed; 1) the mass equation, and 2) the USLE energy relation. The Kinetic energy equation (for individual drops) is:

$$KE = 1/2(mv^2) \qquad (1)$$

where: KE = kinetic energy: foot-pounds
m = rainfall mass of individual drops: slugs
v = individual drop velocity: feet per second

Total energy then for a storm requires summing over all drops within an increment and over all increments defined within the storm. The USLE equation is (16 and 17):

$$KE = 916 + 331 \log_{10} I \qquad (2)$$

where: KE = kinetic energy: foot-tons(f)/acre-in
I = intensity: inches/hour

Terminal velocities for Equation 1 were calculated from regressions derived by Dingle and Lee (2) from the terminal velocities of water droplets data of Gunn and Kinzer (6).

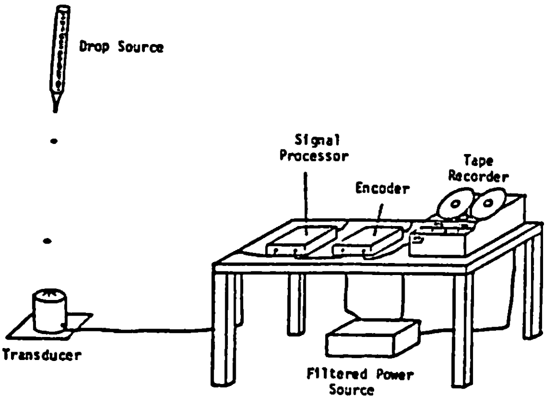


FIGURE 2. Static drop calibration configuration.

Several simplifying assumptions were made to facilitate data analyses. First, it was assumed that drops are falling at their respective terminal velocities. This assumption is well justified for drops in the 0.5 to 5.0 millimeter range (3). Variations in terminal velocity resulting from localized wind turbulance are ignored. Rowland (15) concludes that contamination of the drop size distribution is not serious unless significant updrafts are measured over the analysis period. Second, the horizontal wind velocity component was assumed to be minimal. The horizontal wind component produces no effect if momentum transfer is sensed only in the vertical direction (3). Moreover, instrumentation limitations result in sensing only vertical momentum. Thus, subsequently discussed underestimates of KE are probably further in error because the total energy component (vertical and horizontal) are important from an erosion standpoint.

RESULTS AND DISCUSSION

Joss and Waldvogel (7) describe the accuracy of the impact transducer as ± five percent of the measured drop diameter. Kinnell (10) analyzed the effects of drop size, shape and velocity on the Joss-Waldvogel transducer. He concluded that variations in velocity and shape resulting from air movements might produce unacceptable error in measurement under some rainfall conditions. Joss and Waldvogel (8) reply that the conditions under which the transducer was tested are seldom found in natural rainfall. They state that "the error . . . introduces a small additional scatter but no bias when estimating mean diameter or rainfall intensity", and that "additional scatter is negligible compared to the scatter due to limited sample size."

Rainfall intensity and total precipitation depth calculations for the transducer data were compared to values obtained from corresponding recording raingage records to evaluate reproducibility. Intensity values calculated from the transducer output compared favorably with the chart record, as shown in Figure 3 for Storm 9 (9/03/81). The largest differences may be attributed to the discrete nature of chart evaluation.

Based on preliminary analysis, various nonlinear forms were tested for fit to kinetic energy data as a function of rainfall intensity. An exponential form provided the most acceptable data fit, with the lowest error term and the best visual fit.

Data for raindrop characterization consisted of 1258 one-minute samples. Kinetic energy values were calculated as the average kinetic energy over the one-minute interval. An optimized best-fit nonlinear least squares regression was computed for kinetic energy as a function of rainfall intensity. The relationship is:

$$KE = 7960 \exp .135I^{.175} - 8030 \tag{3}$$

where: KE = Kinetic energy in foot-tons(f)/acre-in
I = Rainfall intensity in inches/hour

or converted to SI metric units:

$$KE = 2.10 \exp .0766I^{.175} - 2.12 \tag{4}$$

where: KE = Kinetic energy in megajoules/hectare-millimeter
I = Intensity in millimeters/hour

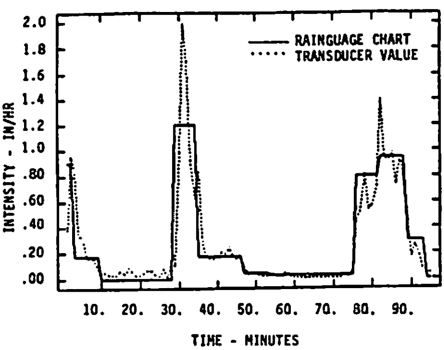


FIGURE 3. Rainfall intensity correlation.

The best-fit curve and the distribution of the residuals ($y-\hat{y}$) about the best-fit value for kinetic energy are shown in Figure 4. The upper portion of the figure is a plot of the best-fit regression (solid line) and the standard error envelopes (dotted lines about the best-fit line). The outer envelope is the two standard error envelope, and the inner envelope is for one standard error. In the lower portion of the plot, the residuals (solid line) are plotted about the best-fit value (dotted line), and the root mean squared error is presented.

The kinetic energy relationship for southeastern Arizona was compared to the relationships observed in the southcentral U.S. (1), Holly Springs, MS (12), and Washington, DC (11). The relationships for the southcentral U.S. and Mississippi were derived from samples collected at intensities up to and exceeding 10 inches/ hour. Data for Washington, D.C. were extrapolated for intensities of 4 to 6 inches/hour by Laws and Parsons (11) and later for intensities of 6 to 10 inches/hour by Wischmeier and Smith (17). Due to the lack of data at higher intensities, extrapolations made for the Arizona data are questionable. A plot of the kinetic energy relationships with the Arizona data, and their respective equations are presented in Figure 5. Kinetic energy values increase with increasing intensity. However, the calculated values for the Arizona samples are higher than those observed for the three eastern sites.

An analysis of 12 years of rainfall data for raingage 83 on the Walnut Gulch Experimental Watershed Showed the occurrence of short-duration maximum intensities well above the 3.5 inch/hour rate measured

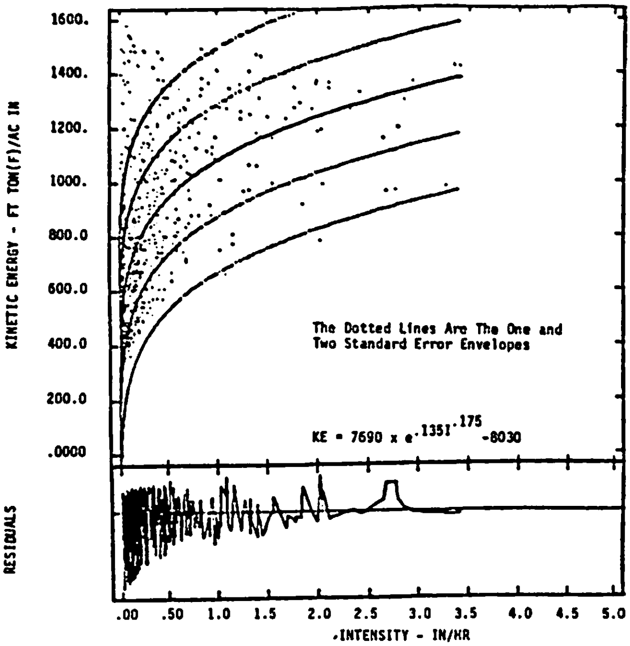


FIGURE 4. Kinetic energy relationship versus intensity relationship with standard error envelopes of the least square fit line.

in this study. Table 1 shows the distributions of 2-, 5-, and 30-min maximum intensities for the 12 year record. Two min maximum intensities ranged to over 9 in/hr with 21 events recording 2 min maximum intensities exceeding 3.5 in/hr.

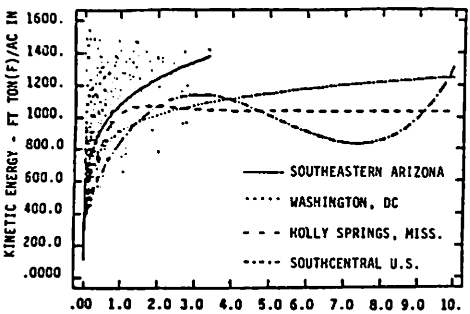
Annual erosivity values (R) were computed for 12 years of record (1970 - 1981) at two locations on Walnut Gulch Experimental Watershed using Eq. 3 with a KE value set to that for I =3 in/hr when I > 3 in/hr. Table 2 compares the R values calculated for the Arizona relationship (Eq. 3) with values computed using the USLE energy term (Eq. 2). Rainfall energies were computed to be about 15 percent higher when using the Arizona equation.

Table 1.--Frequency Distributions for Maximum Storm Intensities at Gage 83, Walnut Gulch Experimental Watershed for 1970-1981*

Maximum criteria	Storm Maximum Intensity (in/hr) 0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
2 minute maximum	590	61	24	13	9	3	2	1	0	1
5 minute maximum	600	61	25	10	7	0	1	0	0	0
30 minute maximum	678	22	3	0	1	0	0	0	0	0

* n=704

Computed values are lower than the expected annual R values of about 70, from the isoerodent map published in Agricultural Handbook



Arizona:	$KE = 7960 \exp .135I^{.175} - 8030$
Mississippi	$KE = 1035 + 822 \exp^{-1.22I} - 1564 \exp^{-1.83I}$
Southcentral U.S.:	$KE = 429.2 + 534I - 122.5I^2 + 7.8I^3$
Washington, DC:	$KE = 916 + 331 \log_{10} I$

where KE = Kinetic energy in foot tons(ft)/acre inch
I = Rainfall intensity in inches/hour

FIGURE 5. Comparison of kinetic energy relationships developed in different climatic/geographic regions.

537 (18). However, below average rainfall (10.0 inches) during the 12-year period may have biased the calculated energy values. The 57-year (1897-1957) average annual rainfall for Tombstone is 14.1 inches.

CONCLUSIONS

The raindrop impact transducer proved to be a relatively simple, efficient and reliable method of collecting information on raindrop energy. The transducer provides a continuous record of each rainfall event, which can be incorporated into an automatic sampling system.

Kinetic energy data for southeastern Arizona showed distributional trends similar to those documented for Louisiana, Mississippi and Washington, D.C. A best-fit relationship for kinetic energy precipitation intensity was found to be higher in Arizona than that developed for southern and eastern sites. Rainfall erosivity values (R) calculated with the southeastern Arizona relationship (Equation 3) yielded values about 15 percent greater than the USLE energy term (Equation 2). However, the lack of data at higher intensities limits the applicability of the Arizona relationship for predictive purposes.

Table 2.--Annual Erosivity Values for Tombstone, Arizona (1970-1981)

	RAINGAUGE #82			RAINGAUGE #83		
	Rainfall (in)	Eq.3	Eq.2	Rainfall (in)	Eq.3	Eq.2
Mean	10.0	60.4	50.5	9.1	64.0	53.1
Standard Deviation	3.0	40.8	33.9	2.2	55.3	44.8

Additional rainfall energy data must be collected, especially for storms of higher intensity, if the kinetic energy relationship is to be used as a predictive tool. Due to the spatial and temporal variability of thunderstorm occurrence and intensity in southeastern Arizona, the probability of sampling extreme events is relatively low for short periods of record.

Finally, the apparent difference in the kinetic energy-intensity relationships in different areas indicates that a single algorithm for all conditions in the continental United States is suspect.

APPENDIX I.--References

1. Carter, C. E., Greer, J. D., Braud, H. J., and Floyd, J. M., "Raindrop Characteristics in South Central United States," Transactions, American Society of Agricultural Engineers, 17(6):1033-1037, 1974.
2. Dingle, A. N., and Lee, Y., "Terminal Fallspeeds of Raindrops," Journal of Applied Meteorology, 11:877-879, 1972.
3. Flach, T. E., "An Automated System for the Measurement and Analysis of Raindrop Size Distributions," theses presented to the University of Illinois, at Urbana, Ill., in 1972, in partial fulfillment of the requirements for the degree of Master of Science.
4. Foster, G. R., McCool, D. K., Renard, K. G., and Moldenhauer, W. C., "Conversion of the Universal Soil Loss Equation to SI Metric Units," Journal of Soil and Water Conservation 36(6):355-359, 1981.
5. Green, C. R., and Sellers, W. D., Arizona Climate, The University of Arizona Press, Tucson, Arizona, 1974 503 pp.
6. Gunn, R., and Kinzer, G. D., "Terminal Velocity of Fall for Water Droplets in Stagnant Air," Journal of Meteorology, 6(4):243-248, 1949.
7. Joss, J., and Waldvogel, W., Disdrometer RD-69 Instruction Manual, Distromet Ltd, Box 12, CH-4020, Basel, Switzerland, 1970, pp. 18.
8. Joss, J., and Waldvogel, A., comments on "Some Observations on the Joss-Waldvogel Rainfall Disdrometer," J. App. Metero. 16:112-113, 1977.
9. Kinnell, P. I. A., "The Problem of Assessing the Erosive Power of Rainfall from Meteorological Observations," Proc. SSSA 3:617-621, 1973.
10. Kinnell, P. I. A., "Some Observations on the Joss-Waldvogel Rainfall Disdrometer," Journal of Applied Meteorology 15:499-502, 1976.
11. Laws, O. J., and Parsons, D. A., "The Relation of Raindrop-Size to Intensity," Transactions, American Geophysical Union, 24:452-460, 1943.
12. McGregor, K. C., and Mutchler, C. K., "Status of the R Factor in Northern Mississippi," Special Publication No. 21, Soil Erosion: Prediction and Control, SCSA, Ankeny, Iowa, 1977, pp. 133-142.
13. Renard, K. G., "The Hydrology of Semi-Arid Rangeland Watersheds," USDA-ARS 41-162, 1970, pp. 25.
14. Robinette, M. J., and McCool, D. K., "Techniques for Producing and Measuring Water Drops -- A Literature Review", U.S. Department of Agriculture, Agricultural Research Service, Agricultural Reviews and Manuals, pending, 1984.
15. Rowland, J. R., "Comparison of Two Different Raindrop Disdrometers," Proceedings, 1976 17th Radar Meteorology Conference, Am. Meteo. Soc. held at Seattle, Washington, pp. 398-404.
16. Simanton, J.R., Osborn, H. B., and Renard, K. G., "Application of the USLE to Southwest Rangelands," Hydrology and Water Resources in Arizona and the Southwest, OALS, University of Arizona, 1980, Vol. 10, p. 8.
17. Wischmeier, W. H., and Smith, D. W. "Rainfall Energy and Its Relationship to Soil Loss," Transactions Am. Geo. Union, 39(2):285-291. 1958.
18. Wischmeier, W. H., and Smith, D. W. "Predicting Rainfall Erosion Losses, a Guide to Conservation Planning", Agriculture Handbook #537, USDA-SEA, 1978, pp. 58.