Quantifying the time-specific kinetic energy of simulated rainfall using a dynamic rain gauge system

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Abstract

Raindrop impact derives from the kinetic energy of falling raindrops. Determining the kinetic energy of rainfall requires the size distribution and terminal velocity of raindrops, which necessitates complex instrumentation. To avoid this, empirical relations have been developed that relate rainfall intensity and the rate of kinetic energy, i.e., time-specific kinetic energy (KE_{time}). In this study, a dynamic rain gauge system (DRGS) was used to quantify the KE_{time} generated by a rainfall simulator without need of measuring raindrop size distributions or impact velocities. In a series of 10 rainfall tests, the KE_{time} and rainfall intensity were 860.9 (±88.6) J m⁻² h⁻¹ and 72.1 (±1.9) mm h⁻¹, respectively. Estimated KE_{time} was found to agree well with the power-law relation presented by Petrů and Kalibová for high-intensity simulated rainfall, which are the conditions when higher deviations occur. The DRGS may be a useful tool in quantifying the KE_{time} of rainfall simulators in hopes to better understand raindrop impact mechanisms.

1 | INTRODUCTION

Raindrop impact is a dominant mechanism in aggregate breakdown, which can mobilize and redistribute soil particles across the landscape or into surface waters (Gabet and Dunne, 2003). Developing relationships between raindrop impact and erosion is especially critical as changing climate trends suggest higher frequency of extreme rainfall events (Dunkerley, 2008). During a rainfall event, the kinetic energy (KE) of falling raindrops is transferred to the soil surface at varying magnitudes based on the mass of the drop and its corresponding terminal velocity (Angulo-Martinez and Barros, 2015; Carollo et al., 2016). The total KE delivered during a rainfall event has been estimated using the drop size distribution (DSD) of rainfall (Wischmeir and Smith, 1958) along with assumptions relating terminal velocity to the drop diameter (Sharma et al., 1993). However, measuring the DSD necessitates complex instrumentation, is time and labor intensive, and can only provide a discrete snapshot in time and space (Jayawardena and Rezaur, 2000; Fox, 2004). Although raindrop KE is a pivotal indicator for potential soil disturbance, the lack of DSD data allows these relations to be used at limited spatial extents (Van Dijk et al., 2002).

Abbreviations: DRGS, dynamic rain gauge system; DSD, drop size distribution; KE, kinetic energy; KE_{time}, time-specific kinetic energy.

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To overcome this limitation, studies have used more readily accessible meteorological parameters such as rainfall intensity to derive KE (Ramón et al., 2017; Serio et al., 2019). Salles et al. (2002) concluded that time-specific KE, or rain kinetic energy expended per unit time and per unit area, was best expressed as a power-law expression with rainfall intensity, as it accounted best for the distribution of natural raindrop sizes:

\[ KE_{\text{time}} = aR^b \]  

where \( KE_{\text{time}} \) is time-specific kinetic energy (J m\(^{-2}\) h\(^{-1}\)), \( R \) is rainfall intensity (mm h\(^{-1}\)), and \( a \) and \( b \) are fitting coefficients that are site specific and vary by storm type, geographic location, and measurement technique (Steiner and Smith, 2000; Shin et al., 2016).

Despite identifying functional relationships with rainfall intensity and \( KE_{\text{time}} \), the spatiotemporal characteristics of natural rainfall were found to vary greatly at higher intensities (Mineo et al., 2019), and as a result, estimates of \( KE_{\text{time}} \) under these power-law assumptions were found to have extremely wide ranges (Van Dijk et al., 2002; Nearing et al., 2017).

To overcome the inherent variation in raindrop characteristics found in natural rainfall, studies have used rainfall simulators to provide controllable and repeatable testing conditions to isolate raindrop impact (Bowyer-Bower and Burt, 1989; Dunkerley, 2008; Wacha et al., 2018). However, the \( KE_{\text{time}} \) reported in many of these studies ranges widely due to formulation and assumptions in DSD and drop relations (Legout et al., 2005; Sajjadi and Mahmoodabadi, 2015). Recently, Petří and Kalibová (2018) incorporated disdrometer measurements to capture the DSD and velocity over an extensive range of simulated rainfall intensities to better predict \( KE_{\text{time}} \). They observed significantly lower \( KE_{\text{time}} \) estimates in high-intensity rainfall when compared to power-law expressions, due possibly to the occurrence of smaller drop sizes using pressurized nozzles (Cerdà et al., 1997; Iserloh et al., 2012). This example demonstrates well the need for new robust techniques to estimate KE to inform further research into raindrop impact mechanisms.

In this study, we present an alternative method to estimate \( KE_{\text{time}} \) that does not require complex instrumentation to measure raindrop diameter or size distribution of rainfall. We used a series of rain gauges mounted on a revolving propeller-style bar of a dynamic rain gauge system (DRGS), which is used to quantify both rainfall intensity and a corresponding \( KE_{\text{time}} \) (Lima et al., 2016). The overall objective of this study was to determine the \( KE_{\text{time}} \) and rainfall intensity supplied by a rainfall simulator using the DRGS and see how characteristics compared to reported values in natural and simulated rainfall. We focused on high rainfall intensity to better address deviations with common power-law relations supplied by simulated rainfall.

### Core Ideas
- Kinetic energy estimates typically assume raindrop size distributions and velocities.
- The dynamic rain gauge system can quickly determine raindrop KE without complex instrumentation.
- Rainfall simulators produce different drop size distributions than natural rain under high rainfall intensity.

## MATERIALS AND METHODS

### 2.1 Rainfall simulator

In this study, a single unit rainfall simulator was constructed at the USDA National Erosion Research Laboratory in West Lafayette, IN. Briefly, the simulator consists of a reservoir, spray box, and control box. The reservoir houses the pumping system components and regulates the supply of water to the nozzle assembly (VeeJet 80-100; Spraying Systems Co.) using a submersible marine pump. A programmable microcontroller (Arduino) controls the speed and direction of the motor, which in turn rotates the spindle and nozzle assembly back and forth in a sweeping motion to increase or decrease rainfall intensity. A control valve is used to adjust nozzle pressure to 6 psi (41.4 kPa), a pressure found to promote a uniform distribution of raindrop sizes (Elhakeem and Papanicolaou, 2009; Wacha et al., 2020). The simulator is mounted 2.5 m above the testing area to ensure terminal velocities of raindrops are achieved (Pappas et al., 2008; Abban et al., 2017). The effective or testing area of the rainfall simulator is approximately 1.5 m\(^2\).

### 2.2 Dynamic Rain Gauge System (DRGS)

Following methods proposed by Lima et al. (2016), the DRGS consists of a piece of flat bar of aluminum (110 cm) fabricated to hold a collection of 29 individual rain gauges. The flat bar is fastened to a spindle motor that allows the bar to revolve at rotational speeds of 0–145 revolutions per minute (RP). Rain gauges are positioned along the flat bar with one circular aluminum rain gauge (3.2 cm diam., 10 cm height) placed in the center and 14 rain gauges of the same dimensions on both the left and right sides of the bar (Figure 1a). Rain gauges are constructed from aluminum square tubing and cut at a 45-degree angle cross section (Figure 1b).
During a rainfall test, the DRGS is positioned directly under the nozzle of the rainfall simulator, allowing the rotating flat bar to spin and collect rainfall within the 29 gauges. It is assumed the central gauge collects raindrops with velocity greater than zero whereas the other gauges are filled with raindrops with velocities according to their respective radial position (Lima et al., 2016). Each rain gauge on the radial arm has a unique corresponding horizontal velocity, \( v_h \) (m s\(^{-1}\)), that can be determined by the following equation:

\[
v_h = \frac{2\pi r_i}{60} \text{ (RPM)}
\]  

(2)

where subscript \( i \) denotes the number or position of the rain gauge on the radial arm, \( r_i \) (m) is the distance from the center of rain gauge \( i \) to the center of the flat bar, and RPM is the rotational speed of the flat bar in revolutions per minute. With the cross-section of the rain gauges cut at 45 degrees, Lima et al. (2016) found the vertical velocities of drops that can enter a given rain gauge to be estimated as

\[
v_v = 1.414v_h
\]  

(3)

where \( v_v \) (m s\(^{-1}\)) is vertical velocity at each radial position, \( i \).

To ensure the entire range of raindrop velocities were being collected in the rain gauges, the rotational speed of the DRGS was increased until no rainfall was collected in the outermost gauge. This served as an indicator for a properly calibrated DRGS with respect to a given rainfall intensity.

### 2.3 Quantifying kinetic energy of rainfall

In this study, a sequence of 10 high intensity rainfall simulation tests were performed, with each test run for 10 min. At the end of a test, the mass of rain collected in each rain gauge was recorded. The rainfall mass collected within the central gauge was used to quantify the rainfall intensity by converting mass to depth and test duration. The rain gauges to the left and right of the center gauges were averaged based on radial positions 1–14. To quantify the \( KE_{\text{time}} \) of rainfall during each rainfall simulation test, the following equation was developed:

\[
KE_{\text{time}} = \frac{1}{2} \sum_{i=1}^{n} \left( M_{i-1} - M_i \right) \frac{v_{v_i}^2}{A_g \times t_{fs}}
\]  

(4)

where the subscript \( i \) denotes the number or position of the rain gauge on the radial arm, \( n \) is the number of rain gauges on the left or right side of the flat bar (14), \( M \) is the mass of rainfall collected in the gauge (kg), \( A_g \) is area of rain gauge (m\(^2\)); and \( t_{fs} \) is the duration of rainfall (h).

### 3 RESULTS AND DISCUSSION

The rotational speed of the DRGS was calibrated at 132 RPM. Rainfall intensity averaged 72.1 (±1.94) mm h\(^{-1}\) for all tests. The mass of rainfall collected in the gauges decreased linearly from the center to the outermost gauge (Figure 2a). The majority of rainfall, i.e., over half, was collected in gauges 1–4. At the rotational speed of 132 RPM, the horizontal velocity increased linearly from 0.54 m s\(^{-1}\) in gauge 1 to 7.05 m s\(^{-1}\) in gauge 14, which corresponds to vertical velocities of 0.76 m s\(^{-1}\) and 9.97 m s\(^{-1}\), respectively (Figure 2b). These vertical velocities were found to be within the range of commonly reported terminal velocities of raindrops in both natural and simulated rainfall, 0.18 m s\(^{-1}\) to 9.17 m s\(^{-1}\) (Iserloh et al., 2012; Johannsen et al., 2020).

The total or cumulative \( KE_{\text{time}} \) for the entire collection of rain gauges was 860.9 (±88.6) J m\(^{-2}\) h\(^{-1}\) (Figure 2c). Although rain gauge positions 1–4 collected over half the rainfall, the \( KE_{\text{time}} \) supplied was 81.0 J m\(^{-2}\) h\(^{-1}\). Conversely, rain gauges 10–13 collected only 15% of the rainfall but supplied over 49% of the total \( KE_{\text{time}} \). Since the velocity term is squared in the \( KE_{\text{time}} \) relation (Equation 4), it becomes heavily weighted toward the outermost radial arm positions of the DRGS. Similar findings were reported by Cerdà et al. (1997), where smaller drops were more abundant in simulated rainfall but generated very little \( KE_{\text{time}} \), possibly because nozzle placements did not allow drop terminal velocities to be achieved.

Using the average rainfall intensity 72.1 mm h\(^{-1}\) recorded by the DRGS runs in commonly used relations by Steiner and Smith (2000), \( KE_{\text{time}} = 11R^{1.25} \), and Wischmeier and Smith (1978), \( KE_{\text{time}} = [11.87 + 8.73 \log(R)] \), produced a \( KE_{\text{time}} \) of 2,311 and 2,027 J m\(^{-2}\) h\(^{-1}\), respectively. These formulae derived under natural rainfall were found to be over 2.5 times higher than values estimated with the DRGS. Using the
FIGURE 2 Summary of rainfall characteristics: (a) frequency of rainfall collected plotted with respect to gauge position; (b) horizontal (black column) and vertical (white column) velocity (white column–primary vertical axis) with respect to gauge position; (c) cumulative (black line) and individual time-specific kinetic energy (black columns) being supplied at each gauge position; (d) comparison of drop size distributions with respect to vertical (terminal) velocity

relation by Petrů and Kalibova (2018) for simulated rainfall, \( KE_{\text{time}} = 50.633R^{0.656} \), produced a value of 838 J m\(^{-2}\) h\(^{-1}\) and agreed well with DRGS runs. These results also highlight that the commonly used VeeJet 80-100 nozzle of the rainfall simulator does not reproduce the drop size and velocity distributions similar to those found in natural rain storms at high rainfall intensities (Iserloh et al., 2012; Petrů and Kalibova, 2018).

The DSD functions by Marshall and Palmer (1948) and Willis and Tattleman (1989) can be expressed as a function of terminal velocity (Atlas et al., 1973). Using the velocity and frequency data from rain gauge positions of the DRGS, a surrogate DSD was made using the rainfall intensity of 72.1 mm h\(^{-1}\). The estimated DSD from the rainfall simulator followed similar trends as the commonly reported functions (Figure 1d). The abundance of small raindrop sizes in natural rainfall were found to be overestimated by Marshall and Palmer (1948). The use of a disdrometer to measure raindrop sizes and velocities in natural rainfall may provide inaccurate readings due to variation in wind speed and direction (Johannsen et al., 2020). These effects may be more important and at higher rainfall intensities. Willis and Tattleman (1989) found for high rainfall intensities a gamma distribution captured the size distribution of raindrop sizes across wide range of geographical locations.

4 | CONCLUSION

This study highlights the capability of the DRGS to quickly assess the KE\(_{\text{time}}\) of simulated rainfall without need of measuring raindrop size distribution and terminal velocities. The KE\(_{\text{time}}\) estimated with the DRGS was found to agree well with power-law formulation by Petrů and Kalibova (2018), derived under high rainfall intensity. However, more runs are needed to see how the DRGS performs under a wider range of simulated rainfall intensities. Rainfall intensity is a far more frequently collected meteorological parameter than raindrop characteristics and DSD. Improving rainfall intensity–KE\(_{\text{time}}\) relations is necessary to better understand raindrop impact mechanisms and improve erosion predictions.

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AUTHOR CONTRIBUTIONS

Kenneth M. Wacha, Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing-original draft, Writing-review & editing; Chi-hua Huang: Conceptualization; Resources; Writing-review & editing; Peter L. O’Brien, Methodology, Visualization, Writing-review & edit-
CONFLICT OF INTEREST
The authors declare no conflict of interest.

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