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Application of Artificial Rain Technology to Insure Quality Performance in Rain Distribution for Soil and Water Experiment in Duhok-Iraq Kurdistan

Jiyar Hussein Ali [1] **Abdulsattar Haji Sulaiman** [1]
[1]*Department of Soil and Water Sciences, College of Agriculture, Duhok University, Duhok, IRAQ.*
*Corresponding Author: jiyar.hussein@uod.ac.

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ABSTRACT

The artificial rainfall technique (or rainfall simulation) uses a rainfall simulator device that sprays water over the soil surface in a controlled and systematic way to imitate real rainfall conditions in terms of drop size, intensity, terminal velocity and duration, the study was conducted on Duhok University Campus 7 km southwest of Duhok City-Iraqi Kurdistan region. RCBD was used to evaluate the artificial rainfall on 12 experimental plots, each measured 2×10 meters in dimension, the sprinkler tool with 2 mm diameter openings hole was applied to generated raindrop with an intensity of 65.7 mm/hr. Rainfall distribution was observed by 24 catch cans positioned uniformly inside the 12 plots. Christiansen coefficient and Wilcox–Swailes was used to statistically evaluate the performance of the artificial rainfall distributed. The result has shown that drop size properties of artificial rain based on the available values of 2 mm diameter of sprinkler holes and 65.7 mm/h rainfall intensity. The product of terminal velocity was ranged between 6.03-13.46 m/s, and according to the rainfall intensity kinetic energy was ranged between 27.75-28.10 J/m²·mm. The Christiansen Uniformity Coefficient (CU) and Wilcox–Swailes Uniformity Coefficient (U) showed excellent uniformity in artificial rain across the study area, with a high value of 99.04–99.22% respectively. The primary objective of this study is to systematically compare the outcomes obtained through specific performance indicators to evaluate the homogeneity and uniformity distribution of artificial rainfall. This assessment aims to establish artificial rainfall as a feasible and reliable alternative to natural rainfall, particularly in regions where natural precipitation is inconsistent or insufficient. By employing a rigorous experimental design and quantitative analysis, the study seeks to provide empirical evidence supporting the use of artificial rainfall simulations in environmental research and land management practices.

***Keywords*:** Artificial rainfall, kinetic energy, soil erosion, terminal velocity, uniformity coefficient.

INTRODUCTION

Artificial rainfall serves as a vital for many applications in hydrology, agriculture, and environmental sciences. It enables the performance of controlled studies that provide understanding on the processes that involve erosion, runoff, and infiltration, and soil erosion researchers are able to modify rainfall variables including intensity and duration. When assessing soil degradation processes, this adaptability is especially valuable since it enables accurate experiments under established conditions [1,2,3].

Nevertheless, the methods used greatly affect the accuracy of artificial rainfall studies, and the evaluation of artificial performance is often not rigorously validated [4]. Since they provide an initial basis for assessing the accuracy of water distribution and uniformity of artificial rainfall studies, the parameters developed by Christiansen, Wilcox, and Swailes are essential in this context.

previous studies [5] have shown that reliable modelling and prediction of hydrological and erosion processes depend on precise artificial rainfall. However, typical spray systems often exhibit irregular water distribution, which is influenced by external factors including operating pressure, nozzle design, wind direction and speed [6]. Interpretation of experimental data may be affected by these variables, which add inequality in the spatial distribution of rainfall.

Christiansen's Coefficient of Uniformity (CU), which measures how uniformly water is delivered across an experimental area, is frequently applied by researchers to evaluate distribution uniformity in artificial rainfall. In erosion research, CU is a useful indicator for assessing artificial performance since higher values indicate greater uniform distribution. The Wilcox and Swailes Coefficient (U), which focuses on the application areas, is another crucial measure that offers a more sensitive assessment than CU. This coefficient indicates how crucial it is to make sure that the most under-applied zones receive enough water, since this is necessary to sustain steady crop growth and hydrological equilibrium. Based on field-specific variables such sprinkler spacing, nozzle type, wind effect, and overall system performance, (U) values typically fall between 67% and 95% [7,8]

Artificial rainfall technique is an essential and required tool in field studies relevant to soil management and conservation, especially when high intensity rainfall is needed but not available or natural rainfall is insufficient. A couple of studies have combined these indicators to evaluate the effectiveness of artificial rainfall made especially for erosion assessments, even though both CU and U have been used independently in irrigation studies. This is a significant research gap because integrating the two indices enables a more thorough assessment of rainfall distribution that takes into account both under-application zones and general uniformity. Improving the accuracy and usefulness of artificial rainfall in erosion and hydrological studies requires this combination assessment.

Therefore, the purpose of this study is to compare results obtained using certain performance indicators and assess the homogeneity of artificial rainfall as an alternative for natural rainfall. Along with other physical parameters like droplet size, rainfall intensity, and terminal velocity, a fundamental prerequisite is the homogeneity of artificial rainfall entire area.

Materials and methods

2.1 Study Site and Experimental Setup:

The study was conducted on the Duhok University campus, 7 kilometres southwest of Duhok City in the Iraqi Kurdistan region. The position is 512 meters above sea level and has the coordinates 36.857181°N, 42.929715°E. The area features clayey soils with stony, formed limestone moderately sloped, semi-arid environment. Grass and weedy plants including Avena spp., Brassica spp., Lagonychium faratum, Anchusa spp., and others make up the majority of natural vegetation. Because they offer natural field settings, the region's physical and meteorological characteristics make it perfect for evaluating the spatial uniformity and variability of artificial rainfall. The region receives 510 mm of precipitation annually on average, primarily throughout the winter and early spring.

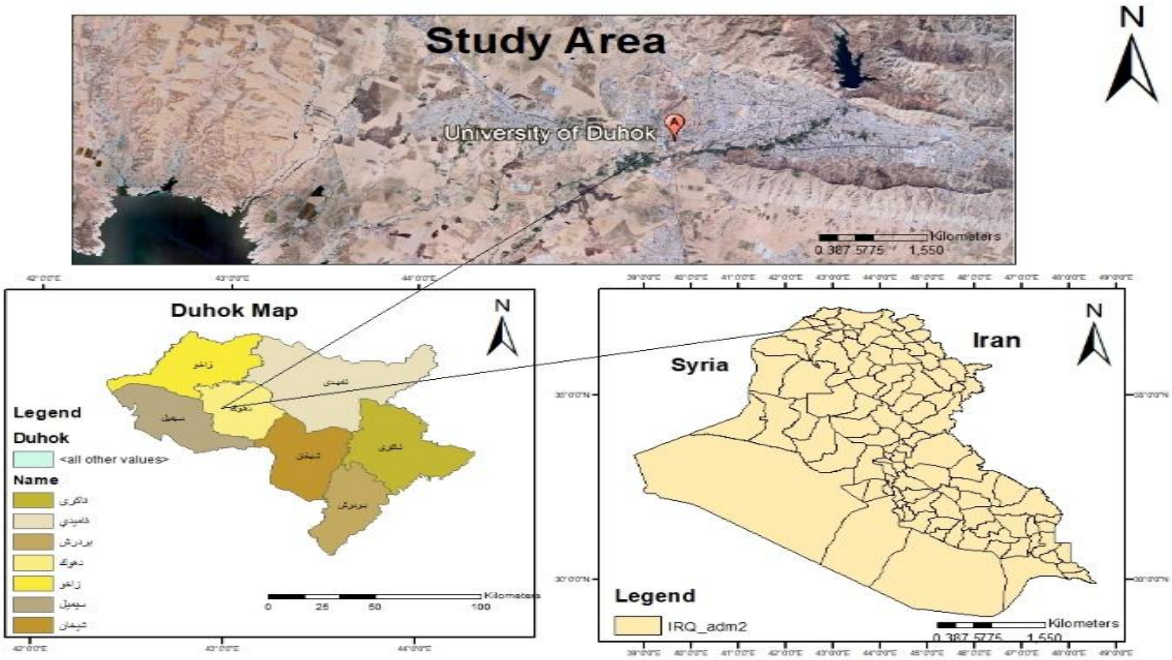

Figure 1. Geographical location of the study site Duhok Governorate, Iraq, including national and district administrative boundaries.

Twelve (2*10 m) erosion plots were constructed in an experimental field using a randomized complete block design (RCBD), according to the natural slope (6.4% gradient). In September 2024, experimental plots and a springer irrigation system were installed. To prevent cross-treatment interference, a 2-meter buffer was placed between adjacent sites.

2.2 Artificial Rainfall Characteristics

2.2.1 Drip Size Distribution:

A manual artificial rainfall was created and used to study the properties of drop size distribution (DSD) associated with soil erosion and surface hydrology. The artificial is a sphere-like metal sprinkler head that is about 10 cm broad and connected to a light plastic delivery pipe that is about 1.5 meters long. The sprinkler head has 99 uniformly distributed holes, each about 2 mm in diameter, that are designed to produce individual water droplets. The system was linked to a regulated water supply via a pressure-regulating coupling. The water flow rate that this connection delivered was around 5387.76 L/hr.

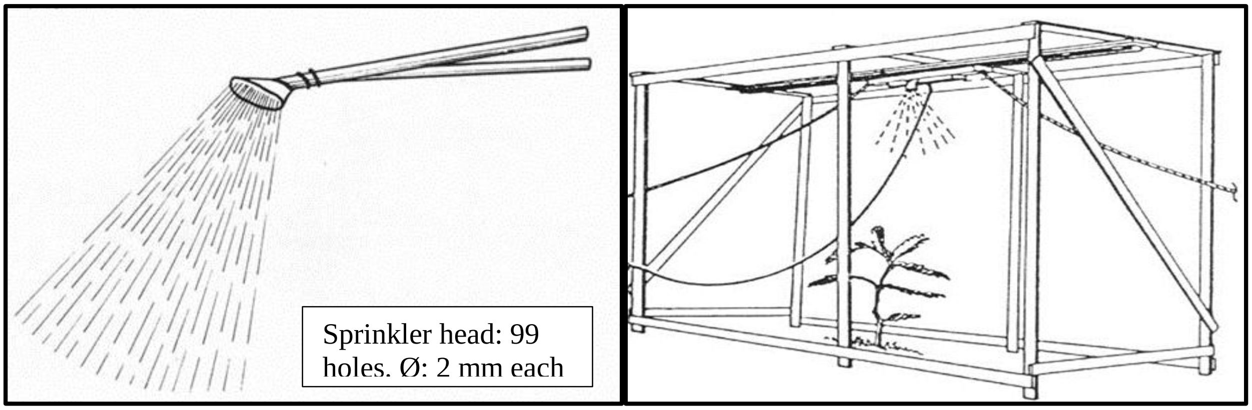

Figure 2. Sprinkler Irrigation System Equipment's.

2.2.2 Rain Intensity:

The artificial rainfall was controlled manually, and the intensity of the rainfall was set at 65.70 mm/h. In order to calibrate the pressure valve controlling water flow and maintain a constant discharge rate, catch containers met water at specified times. When we ensured a consistent distribution over the test plot as the water volume increased per unit area per hour, the intensity calculation was completed. This level of intensity mimics moderate rainfall events that are important for study of soil erosion.

$$\text{Rainfall Intensity (I)} = \frac{\text{Flow rate (L/hr)}}{\text{Total area of one block } m^2} \qquad \textbf{(1)}$$

Where:

The rainfall intensity (I), measured in millimetres per hour (mm/hr), indicates the depth of rainfall for each time unit. The volume of rainfall that was collected: the amount of water that was collected in the area where it falls and converted to equivalent rainfall in (mm/hr) according to the equation 1.

2.2.3 Terminal Velocity:

When air resistance balances gravitational force, a raindrop reaches its terminal velocity (Vt), which is a constant speed. Three separate empirical equations were used in this study to estimate the terminal velocity as a function of raindrop diameter (D). These equations were created to meet a variety of raindrop sizes and enhance accuracy in both real world and simulated rainfall conditions.

2.2.3.1 Third-Order Polynomial Equation

Terminal velocity was determined using a third-order polynomial for raindrop sizes that range from 0.5 and 6 mm. For kinetic energy estimations and rainfall effect studies linked to soil erosion, this equation offers a useful and precise approximation:

$$Vt = -0.19274 + 4.9625D + 0.90441D2 + 0.0563584D3 \qquad (2)$$

Where:

Vt: Terminal velocity (m/s)
D: Raindrop diameter (mm)

Terminal velocities were calculated using this polynomial and observed drop size distribution data. The estimated rainfall erosivity and raindrop kinetic energy were supported by the measured velocities. The equation complies with traditional studies of raindrop fall velocity, as those conducted by [9], who revealed empirical connections between the size between raindrops and their terminal velocity in static air.

2.2.3.2 Power Law Equation

Terminal velocity is often determined using a power law for raindrops dropping within particular size ranges:

$$V_t = aD^b \qquad (\mathbf{3})$$

Where:

V_t = terminal velocity (m/s)
D = drop diameter (mm)
a, b= empirical constants depending on the size range of the drop

The nonlinear connection between drop size and terminal velocity is reflected in this equation, which is commonly employed in soil erosion and hydrological research because of its empirical reliability and simplicity in use. The coefficients used in a widely used version, which was first developed from laboratory data by [9] and then improved by [10] is shown as below:

$$V_t = 3.78D^{0.67}$$

2.2.3.3 Quadratic Empirical Equation:

An empirical quadratic equation derived from data by [9] and improved by [11] was used to apply to drops that were generally between 0.5 mm and 3 mm:

$$V_t = 0.25 + 3.7\mathrm{D} - 0.4\mathrm{D}^2 \qquad (\mathbf{4})$$

Where:

V_t= Terminal velocity of the raindrop (m/s)
D =Diameter of the raindrop (mm)

2.2.4 Kinetic Energy

In order to determine the total kinetic energy (KE) of rainfall per unit of rainfall depth and area, many empirical techniques have been developed. Below are two relationships that are often used in hydrological and soil erosion studies.

1. Logarithmic Equation [12, 13].

Using rainfall intensity (I) and the logarithmic relationship, the kinetic energy per unit rainfall depth is determined:

$$\mathrm{KE} = 11.897 + 8.73\log \mathrm{I} \qquad (\mathbf{5})$$

Where:

KE = Kinetic energy per unit rainfall depth (J/m²·mm).
I = Rainfall intensity (mm/h).

This equation provides an indicator for comparing simulated and real rainfall events by calculating the energy released when one millimetre of rain falls on a square meter.

2. Intensity Dependent Equation [14].

Kinetic energy is estimated using a different empirical model that shows a negative correlation with rainfall intensity equation:

$$\mathrm{KE} = 30 - \frac{125}{I} \qquad (\mathbf{6})$$

Where:

KE = kinetic energy of rainfall (J/m²·mm).
I = rainfall intensity (mm/h).

When rainfall intensities exceed 25 mm/h, this equation is particularly relevant because kinetic energy increases rapidly and stabilizes at around 30 (J/m²·mm).

2.3 Rainfall Depth Measurement Method

The overall distribution of rainfall was assessed by distributing 24 catch cans to 12 experimental plots throughout 3 blocks, making sure that each plot included two catch cans. In order to ensure consistency, consideration was taken to maintain a constant operating pressure and an equivalent spraying height during the artificial rainfall distribution. As indicated in the Table 1, the amount of water collected in each catch can was measured in cubic centimeters (cm³) and then converted to rainfall depth (mm) by using the Figure 3:

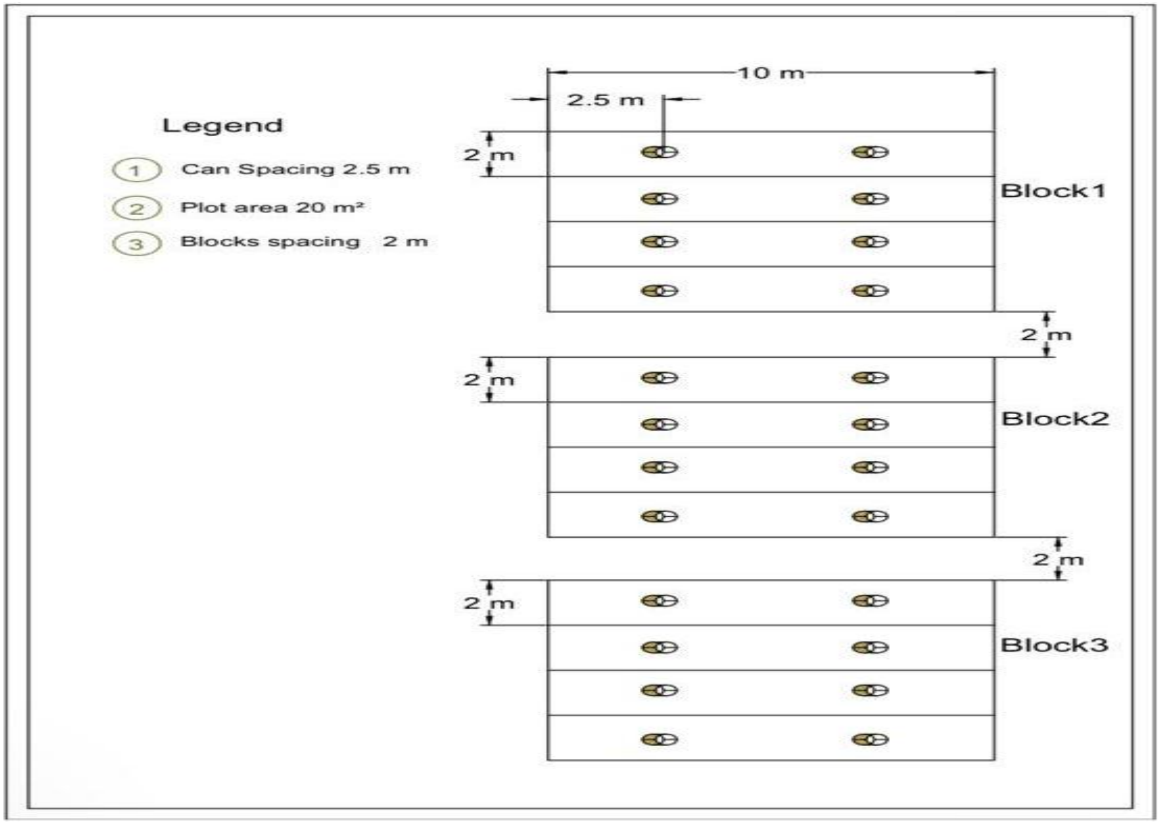

Figure 3. Layout of the field experiment with three replicated blocks and uniformly spaced plots.

Rainfall depth (mm) = $\frac{\boldsymbol{Volume\ cm^3}}{\boldsymbol{Area\ cm^2}} \times \mathbf{10}$ **(7)**

Table 1. Determination of Rainfall Depth from Catch Can Measurements.

Block	Replication	Average volume cm3	Area cm2	Rainfall depth mm
B1	1	346.5	56.77	6.10
	2	347.0	56.77	6.11
	3	347.5	56.77	6.12
	4	347.5	56.77	6.95
B2	5	339.0	56.77	6.97
	6	342.5	56.77	6.03
	7	345.0	56.77	6.08
	8	342.5	56.77	6.03
B3	9	345.5	56.77	6.09
	10	343.5	56.77	6.05
	11	347.5	56.77	6.12
	12	346.5	56.77	6.10

2.4. Statistical Analysis

The statistical variance (S^2) and standard deviation (S) were estimated using the observed rainfall depth at each catch can in order to assess the homogeneity of artificial rainfall distribution. The variance indicates the degree of uniformity of the artificial rainfall by statistically quantifying the deviation of the various rainfall depths from the mean rainfall. The following is the variance formula:

$$S = \frac{1}{n-1} \sum_{i-1}^{n} (Xi - \bar{X})^2 \qquad \textbf{(8)}$$

Where:

S = sample variance (mm²)
n = number of observations
xi = individual rainfall depth (mm)
$\bar{X}$ = mean rainfall depth (mm)
$(Xi - \bar{X})^2$ = squared deviation from the mean

The standard deviation (S) is simply the square root of the variance:

$$S = \sqrt{S} \qquad \textbf{(9)}$$

2.4 Uniformity Coefficients Using Methods of Wilcox & Swailes and Christiansen:

The Christiansen Uniformity Coefficient (CU%) and the Wilcox & Swailes coefficient were both determined using their respective formulas.

$\textbf{2.4.1 Christiansen Coefficient Uniformity (CU\%)} = \mathbf{1} - \frac{\textbf{Average Deviation from Mean}}{\textbf{Mean Depth of Applied Water}} \times \mathbf{100}$

Christiansen's Coefficient of Uniformity (1942), CU

$$\textbf{CU} = \mathbf{100}\left(\mathbf{1} - \frac{\sum|\boldsymbol{Xi} - \bar{\boldsymbol{X}}|}{\boldsymbol{n}\,.\,\bar{\boldsymbol{X}}}\right) \qquad \textbf{(10)}$$

Where:

CU = is the uniformity coefficient percentage of uniformity (%)
xi = individual water application or rainfall measurements (e.g., mm or m³/m²)
$\bar{X}$ = is the mean of all measurements.
n = is the total number of observations.

2.4.2 Wilcox & Swailes Uniformity Coefficient (1947), U

$$\textbf{U} = \mathbf{100}\left\{\mathbf{1} - \frac{\boldsymbol{\sigma}}{\bar{\boldsymbol{X}}}\right\} \qquad \textbf{(11)}$$

Where:

U = Uniformity Coefficient based on Wilcox & Swailes (1947)
σ = standard deviation of the observations
$\bar{X}$= mean of all measurements

Higher uniformity is indicated by values approaching 100% for these coefficients, which range from 0 to 100%. Values above 85% indicate good performance, while those over 90% are considered as excellent, under literature guidelines [6,8].

All data analysis was carried out with Microsoft Excel and individually confirmed. The calculated values were compared to standards set in associated studies on irrigation uniformity and artificial rainfall in order to understand the results [6,7].

Results and Discussions

Artificial rainfall was used in order to replace the limited precipitation and provide consistent water input for the experiments because natural rainfall was scarce during the hydrological year 2024–2025. According to the process, several requirements must be achieved in order for field research to simulate natural rainfall effectively. In this study, uniform raindrops with a diameter of 2 mm were produced using locally made nozzles and continuously dropped from a height of around 9 meters. Equation (1) was used to determine the rainfall intensity, due to high intensity, soil erosion was caused; however, lower intensity might not produce erosion. which was precisely controlled and maintained at 65.7 mm per hour during the experiment. In the semi-arid Kurdistan Region, where such erosive rain events are rare and temporary, simulating a rainfall intensity of 65.7 mm hr^{-1} is especially critical [15,16]. These observations show that the artificial offers accurate predictions of the dynamics of raindrop impact, providing an effective foundation for experimental studies of soil erosion.

The terminal velocity of 2 mm raindrops was estimated using three empirical equations. [9]., third order polynomial, Equation (1), showed a terminal velocity of 13.80 m/s, which is considerably greater than the accepted laboratory value of 6.5 m/s, as observed in Table 4. This suggests that little to medium-sized raindrops cannot be adequately modelled using Equation (1). On the other hand, a velocity of 6.02 m/s was obtained from Equation (2), the power law model by [10], and 6.05 m/s from Equation (3), the quadratic expression developed by [11]. Both demonstrate better adaptability for resembling raindrop dynamics in erosion and hydrological studies, and they are in close agreement with the reference value in Table 1. For artificial rainfall research, Equations (2) and (3) are thus advised, although Equation (1) need to be used gently and ideally limited to greater drop sizes.

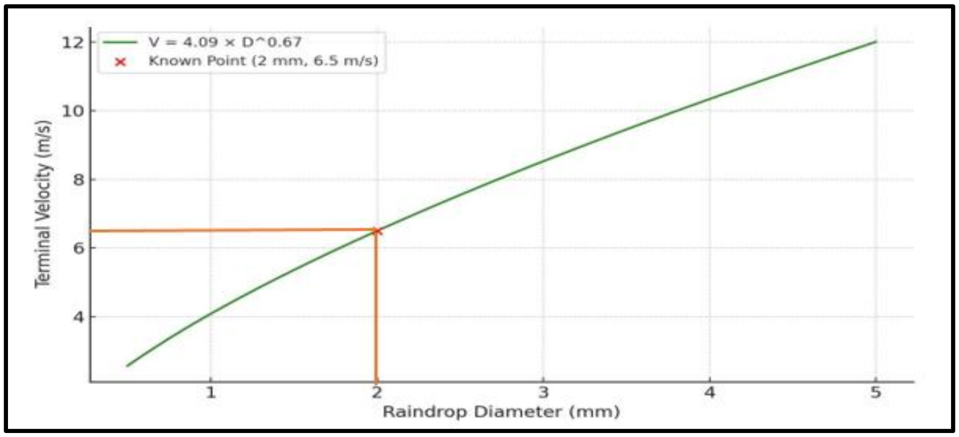

Figure 4. The relationship between raindrop diameter and terminal velocity (Gunn & Kinzer ,1949).

Two models were used to determine the kinetic energy of the Artificial rainfall: The Intensity-Dependent Equation 6, which yielded 28.10 J/m²·mm, and the Logarithmic Equation [12,13], Equation 5, which results in 27.75 J/m²·mm. Strong agreement is demonstrated by the minimal discrepancy between these values (less than 1.25%), suggesting that the simulated rainfall accurately reflects the energy properties of actual rainfall at this intensity and the kinetic energy of rain drop enough to cause erosion.

Twelve observations were used to determine the artificial rainfall distribution. There is relatively little variability in rainfall readings, according to the statistical analysis, which revealed a variance of 0.00341 and a standard deviation of 0.0584. The Christiansen Uniformity Coefficient (CU) and the Wilcox & Swailes Uniformity Coefficient (U) both showed excellent uniformity in the simulated rainfall across the study area, with a high value of 99.22% and 99.04%, respectively, respectively, indicating the uniformity of rainfall distribution Table 2.

Table 2. Statistics and Uniformity Coefficients for Artificial Rainfall Distribution.

Statistic	Value
Number of observations (n)	12
Degrees of freedom (n − 1)	11
Variance (s^2)	0.00341
Standard Deviation (s)	0.0584
Christiansen Uniformity Coefficient (CU)	99.22%
Wilcox & Swailes Uniformity Coefficient (U)	99.04%

Table 3. Statistical analysis of the distribution uniformity and intensity of Artificial rainfall.

Blocks	Replication	Rainfall depth(x_i)	Deviation ($x_i - \bar{x}$)	Squared Deviation $(x_i - \bar{x})^2$
B1	1	6.100	0.037	0.0014
	2	6.110	0.047	0.0022
	3	6.120	0.057	0.0032
	4	5.950	-0.113	0.0128
B2	5	5.970	-0.093	0.0086
	6	6.030	-0.033	0.0011
	8	6.030	-0.033	0.0011
	9	6.090	0.027	0.0007
B3	10	6.050	-0.013	0.0002
	11	6.120	0.057	0.0032
	12	6.100	0.037	0.0014
Mean ($\bar{x}$)	—	6.063	—	$\Sigma = 0.0375$

The mean depth of rainfall $\bar{X}$ was 6.063 mm. A total of 0.0375 was the sum of squared deviations from the mean $\sum(Xi - \bar{X})^2$. The degrees of freedom were 11. This method for artificial rainfall uniformity analysis is compatible with accepted practices in hydrological and irrigation research [6,8].

Where standard deviation and statistical variance are commonly used to measure the geographic variation in water application. These results show that the artificial is very efficient and appropriate for deeper study in soil science and hydrology. As recommended by [17,18], assessing it in a variety of environmental conditions would further confirm its dependability in many settings.

Conclusion

It is clear that the use of artificial rainfall technology offers a wide range of applications, especially in situations where natural weather conditions are unsuitable or when there is an insufficient amount of precipitation to conduct field experiments. This technique is considered practical and flexible, as the equipment is easy to transport and can be used in various locations, soil types, and slope conditions.

Moreover, the portability of the equipment allows for multiple experiments to be conducted within a single season under different environmental conditions. The minimal effort required to move the system from one site to another further enhances its practicality. Therefore, artificial rainfall technology provides a reliable and efficient alternative to relying solely on natural rainfall, making it a valuable tool for soil and water research, especially in regions with irregular or insufficient precipitation.

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تطبيق تقنية الأمطار الاصطناعية لضمان جودة الأداء في توزيع الهطول المطري لأغراض تجربة التربة والمياه في دهوك – العراق، إقليم كردستان

زيار حسين علي[1] **عبد الستار حاجي سليمان1**
[1]قسم علوم التربة والمياه، كلية الزراعة، جامعة دهوك، دهوك، العراق.

الخلاصة

تستخدم تقنية المطر الاصطناعي (أو محاكاة المطر) جهاز محاكاة المطر الذي يرش الماء على سطح التربة بطريقة منظمة ومنهجية لتقليد ظروف المطر الحقيقي من حيث حجم القطرات، الكثافة، السرعة النهائية، والمدة. أجريت الدراسة في حرم جامعة دهوك على بعد 7 كم جنوب غرب مدينة دهوك في منطقة كردستان العراق . تم استخدام تصميم القطع العشوائية الكامل ***(RCBD)*** لتقييم الأمطار الاصطناعية على 12 قطعة تجريبية، كل منها بقياس 2×10 متر، وتم استخدام أداة الرش بفتحات بقطر 2 مم لتوليد قطرات المطر بكثافة 65.7 مم/ساعة .تمت ملاحظة توزيع الأمطار بواسطة 24 علبة تجميع موزعة بشكل متساوٍ داخل 12 قطعة أرض .تم استخدام معامل كريستيانسن وويلكوكس-سوايلز لتقييم أداء الأمطار الصناعية الموزعة إحصائيًا .أظهرت النتائج أن خصائص حجم القطرات للمطر الاصطناعي تعتمد على القيم المتاحة لقطر فتحات الرش التي تبلغ 2 مم وكثافة الأمطار التي تبلغ 65.7 مم/ساعة .كان ناتج السرعة النهائية يتراوح بين 13.46-6.03 م/ث، وبحسب شدة الأمطار كانت الطاقة الحركية تتراوح بين 28.10-27.75 جول/م^{2}·مم .أظهر معامل تجانس كريستيانسن ***(CU)*** ومعامل تجانس ويلكوكس سويلز ***(U)*** تجانسًا ممتازًا في الأمطار الاصطناعية عبر منطقة الدراسة، بقيمة عالية تتراوح بين 99.22-99.04% على التوالي .الهدف الرئيسي من هذه الدراسة هو المقارنة المنهجية بين النتائج التي تم الحصول عليها من خلال مؤشرات الأداء المحددة لتقييم تجانس وتوزيع انتظام الأمطار الصناعية .يهدف هذا التقييم إلى إثبات أن المطر الاصطناعي هو بديل قابل للتطبيق وموثوق للمطر الطبيعي، لا سيما في المناطق التي يكون فيها الهطول الطبيعي غير منتظم أو غير كافٍ .من خلال استخدام تصميم تجريبي صارم وتحليل كمي، تسعى الدراسة إلى تقديم دليل تجريبي يدعم استخدام محاكاة الأمطار الاصطناعية في الأبحاث البيئية وممارسات إدارة الأراضي.

الكلمات المفتاحية: الأمطار الاصطناعية، الطاقة الحركية، تعرية التربة، السرعة الحدية، معامل الانتظام.