DEVELOPMENT AND CALIBRATION OF A RAINFALL SIMULATOR

R. Pall, W. T. Dickinson, D. Beals, and R. McGirr

School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1

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A rainfall simulator involving a large-capacity wide-angle spray nozzle and a spray interception device has been developed for the soil erosion research program at Guelph. A rotating disk with multiple variable aperture openings has been used for spray interception. Calibration tests show that the simulated rainfall intensity and the uniformity of application are affected by the aperture angle, nozzle pressure, disk angular velocity and the interaction of nozzle pressure and aperture angle. Aperture angle has the greatest effect on intensity. Nozzle pressure demonstrates the most significant effect on uniformity of simulated rainfall. The uniformity of distribution for a small plot is also affected by the size of the collector units considered in the determination of the uniformity coefficient. For selected combinations of nozzle pressure, aperture angle, and disk angular velocity, the simulated rainfall intensity and the uniformity of distribution can be represented by a linear model involving the plot dimensions of length and width.

INTRODUCTION

One very effective approach to the study of soil erosion processes and the analysis of possible remedial strategies involves the use of rainfall simulation. Although to date it has proven virtually impossible to reproduce artificially all the physical characteristics of natural rainfall, rainfall simulation offers researchers control of precipitation conditions such as intensity, frequency and duration. Simulation, therefore, has become a powerful research tool for the development and evaluation of soil conservation programs.

Although the use of rainfall simulation for soil erosion research is not new, literature regarding the development and particularly the calibration of such simulators appears sparse. Therefore the purpose of this paper is to describe the development of a simulator system, calibration methodology, and some calibration results.

TYPES OF RAINFALL SIMULATORS

The artificial reproduction of rainfall to study different hydrologic processes has led to the development of different types of rainfall simulators (Mutchler and Hermseimer 1965). On the basis of the drop-forming mechanism used, simulators can be grouped into two major categories: (i) dripping rainfall simulators form drops at the tip of a material and initiate the fall of drops with zero velocity, and (ii) nozzle rainfall simulators force water drops from a nozzle at significant velocities.

In dripping simulators the common practice has been to form drops at the tip of a material by some suitable device (i.e. a drop former) until the weight of the drop overcomes the surface tension force of the drop former and the drop falls with an initial velocity of zero. In the early stage of development of such simulators, hanging yarns (Barnes and Costel 1957) and glass capillary tubes (Adams et al. 1957) were used as drop formers. Recent designs include metal tubes (Mutchler and Moldenhauer 1963; and Gabriels and DeBoodt 1975), hypodermic needles (Romkens et al. 1975; Walker et al. 1977), and polyethylene and plastic tubing (Chow and Harbough 1965; Chow and Yen 1974; Kinnell 1974).

To create a wider drop size distribution, many different types of nozzles have been used for rainfall simulation (Meyer and McCune 1958; Bubenzer and Meyer 1965; Morin et al. 1967; Amerman et al. 1970; Cluff and Boyer 1971; Rawitz et al. 1972; Marston 1978; Meyer and Harmon 1979). In nozzle simulators, the spray pattern, median drop size and drop size distribution are governed by the shape characteristics and discharge of the nozzle. Available nozzles can produce drop and energy characteristics comparable to natural rainfall but relatively high capacity limits their use in rainfall simulation. The problems of high flow rates have been resolved by the following methods.

1. Covering a large area by spraying the water upward (Simulators using F type and sprinkler irrigation nozzles belong to this group).
2. Physically moving the nozzle back and forth across the plot (e.g. the simulator developed by Meyer and McCune (1958)).
3. Intercepting a major portion of the spray by introducing a physical obstruction (as done by Morin et al. (1967) by placing a rotating disk with an aperture in the nozzle spray path).

SELECTION OF A SIMULATOR

The first step in the development of a rainfall simulator is the establishment of selection criteria depending upon the rainfall characteristics required and objectives of the research program. For erosion research some of the most important characteristics for rainfall simulation have been outlined by Bubenzer (1979) to be:

1. Drop size distribution similar to natural rainfall.
2. Drop impact velocity approximating terminal velocity of natural raindrops.
3. Rainfall intensity in the range of the requirements of the research program.
4. Uniform rainfall and random drop size distribution.
5. Total energy corresponding to natural rainfall.
6. Accurate reproduction of given storms.

Most researchers using rainfall simulators (Borst and Woodburn 1940; Meyer and McCune 1958; Bertrand and Parr 1961; Chow and Harbough 1965; Nassif and Wilson 1975; Munn and Huntington 1976; Shriner et al. 1977) agree with the aforementioned criteria, and Meyer (1965, 1979) added the following characteristics:

7. Rainfall intensity nearly continuous throughout the study area.
8. Angle of impact nearly vertical for most drops.
9. Sufficient area of coverage.
10. Satisfactory characteristics under varying climates.
11. Complete portability from site to site.

We believe that, in addition to the above criteria, a reliable rainfall simulator must have efficient and simple controls. The developers of the various rainfall simulators have claimed excellent per-
formance for their units, but certain strengths and limitations can be identified to be characteristic of the two main types. The dripping simulators are simple in design and operation. They produce drops of nearly uniform size (2.2–5.5 mm) depending upon the type and dimensions of the drop former. The application rates over the covered area are fairly uniform. The main advantage of this type of simulator is that it can produce large-size drops at a low rate of application. The drop size distribution is generally narrow but can be improved at the cost of uniformity of distribution. The randomness of drop size distribution is always a big problem, although in some units the drop former and/or plot are oscillated to achieve this. Forced air has also been used to resolve this problem. As drops start from zero velocity, the drop former must be at a sufficient height from the impact surface to attain reasonable rainfall energy levels. Intensity in these simulators is controlled by changing the pressure head and the size of the drop former. In the light of these characteristics, the dripping simulators are best suitable for infiltration and runoff studies. They are also useful in splash erosion research where uniform drop size is an advantage.

Nozzle simulators produce storms of wider drop size distribution. The type F nozzle (Parsons 1943) was specially developed to produce a high-energy spray at low application rates. The drop size produced was large but the impact velocity of upward sprayed drops was small and resulted in a reduced-energy spray. The velocity was controlled by the height at which the vertical component of the velocity became zero. From a drop velocity point of view, the nozzle simulators facing upwards are similar to the dripping rainfall simulators. The rainulator developed by Meyer and McCane (1958) uses the Spraying Engineering Company’s 7LA nozzles were used by Amerman et al. (1970), and Rawitz et al. (1972) in a modified version of sprinkler infiltrimeters. No attempt was made to measure drop size. Spraying Systems Fulljet nozzles (1.5H30 and 1HH12) used by Morin et al. (1967), Cluff and Boyer (1971), and Marston (1978) were preferred for erosion research. The spray characteristics of the 1.5H30 Fulljet nozzle at a pressure of 60.8 kPa were similar to natural rainfall. The median drop size of 2.6 mm compared well with 2.5 mm for 50 mm/h natural rainfall intensity. The kinetic energy of the simulated rainfall was better than simulators using Veejet nozzles. These simulators were portable and stable up to a wind speed of 25 km/h.

From available literature regarding tested rainfall simulators, only the rotating disk simulators using Fulljet nozzles come very close to satisfying all the aforementioned criteria. Rainulator and dripping simulators fall second and third, respectively, in the rating. Particularly on the basis of better performance, drop characteristics and energy levels, a rotating disk rainfall simulator was selected for development for the erosion research program at Guelph.

**DESCRIPTION OF GULEPH SIMULATOR**

The development and construction of the rainfall simulator has addressed the essential characteristics mentioned earlier. Special attention has been given to the cost, portability and operational features of the unit. A schematic diagram of the unit is presented in Fig. 1. The interception concept of Morin et al. (1967) used in a rotating disk simulator was adopted. The major deviation from the original design is that the Guelph unit has only one disk with variable apertures. The shape of the aperture is similar to a sector of a frustrum of a cone. Two equally spaced apertures have been used, so that the simulator can be operated at lower disk angular velocities than the original design of Morin et al. (1967).

The nozzles used to date include Fulljet 1.5H30 and 1HH12, manufactured by Spraying Systems Co., Bellwood, Ill. The digits following H indicate the discharge of the nozzles in US gallons per minute at a pressure of 48 kPa. Both nozzles have a wide spray pattern with a nominal spray angle of about 90°.

The modification in the original design
is that the variable aperture is achieved by a double disk mechanism. In the disk assembly, one disk with two equally spaced apertures of 40° overlaps a second disk of similar shape and size with three 40° apertures located 90° from center to center. Sketches of the disks are presented in Figs. 2 and 3. The upper disk can be rotated over the lower disk to vary the aperture opening. Two apertures can be achieved by using alternate openings on both disks. An option has also been provided for a single aperture angle. This can be achieved by matching the intermediate opening on the lower disk with any opening on the upper disk. With this arrangement, one or two apertures from 0° to 40° can be obtained.

The disk is powered by a 0.124-kW D.C. electric motor. A high-quality SCR (Boston Gear Ratiopack RP1) motor control and single action 90° gear reducer are used to adjust the disk speed up to 100 rpm.

In the early design, the disk was shaped to a shallow cone from a 0.5-mm stainless steel sheet, but the maintenance of close contact between the disks was a problem. In a subsequent model, the disk has been machined from an aluminum sheet to a shallow cone with an approximate side slope of 7.5%. The tail edges of the disk aperture openings have been knife-shaped. The lower disk has four equally spaced 6-mm-diameter holes on a 65-mm-radium circle (Fig. 2) while the upper disk has four 6-mm-wide, 40° arched slots at a radius of 60 mm located 90° from center to center (Fig. 3). The holes in the lower disk can be lined to any position with the slot in the upper disk. Socket head screws through the slots into the holes are used to adjust the aperture angle. Six holes of 3-mm diameter are drilled along the periphery of the lower disk. A nut, bolt and washer system through these holes maintains close contact between the two disks near the periphery.

The disk unit is placed in a horizontal plane about 20 mm below the nozzle in such a way that the center of the aperture angle and nozzle orifice are in a vertical line. A panlike collector is mounted under the disk to collect intercepted water spun from the outer periphery of the disk. The bottom of the pan is shaped convex upward with a circular opening of 200-mm diameter below the nozzle. A 38-mm hose is used to drain the pan.

**CALIBRATION PROCEDURE AND PERFORMANCE RESULTS**

The developed rainfall simulator has been calibrated for intensity, uniformity of application, and rainfall kinetic energy. The nozzle has been tested for operating pressures of 30.4, 40.5, 60.8, 81.1 and 101.3 kPa, disk aperture angles of 5, 15, 20, and 40°, and disk angular velocities of 15, 40, 70 and 100 rpm.

The intensity of simulated rain has been determined by collecting the volume of water during the known run period (approximately 30 min) in closely placed 106-mm-diameter and 178-mm-high cylindrical cans. From the volume of water collected, the intensity of application with respect to length and width of plot has been computed. The uniformity of application has been determined according to the procedure of Christiansen (1942). Each run was replicated twice. In cases when the two observations did not match, a third replication was performed.

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**Figure 2.** Detailed description of the lower disk.
velocity of the disk. Theoretically, angular velocity should not have any effect on the intensity of application, but the results (Fig. 4) indicate an irregular variation of intensity with disk, angular velocity at all combinations of nozzle pressure and aperture angle. Application of the Duncan multiple range test indicates that only the angular velocity of 15 rpm has a significant effect on the intensity at the 5% level. The change in intensity and nozzle discharge with pressure shows a similar trend. At all pressures, the increase in intensity with aperture size is approximately linear (Fig. 7).

Further analysis has revealed that the nozzle pressure, aperture angle, disk angular velocity, and the combination of nozzle pressure and aperture angle has a significant effect on the uniformity coefficient. However, as exemplified in Fig. 8, the uniformity coefficient is influenced primarily by nozzle pressure. An increase in pressure increases the nominal spray angle, resulting in an improvement in the uniformity of simulated rainfall. Application of the Duncan multiple range test indicates that, except for the conditions involving 15 rpm or 5° or both, the uniformity coefficient is not significantly affected by disk angular velocity or aperture angle.

In all cases, the uniformity coefficients are noted to slightly lower than those reported by Morin et al. (1967). The difference in experimental procedure may be responsible for these discrepancies. Morin et al. (1967) did not mention the size of the container used to determine the uniformity coefficient.

At 15, 40, 70, and 100 rpm, two equally spaced apertures provide precipitation with application intervals of 2, 0.75, 0.43 and 0.3 sec, respectively. These application intervals are considerably smaller than the 10 sec recommended by Sloneker and Moldenhauer (1974), and Young (1979) to avoid delay in surface sealing.

The average rainfall intensity and coefficient of uniformity of distribution on a plot 848 mm × 742 mm at various combinations of nozzle pressure, angular velocity of the disk and aperture size are shown in Figs. 4 and 5, respectively. Analysis of the data has shown that the aperture angle, nozzle pressure, angular velocity and the interaction of pressure and aperture angle have a significant effect on the intensity reproduction at the 1% level. The influence of aperture size on rainfall intensity (Fig. 6) is greater than the effects of nozzle pressure and angular velocity of the disk. Theoretically, angular velocity should not have any effect on the intensity of application, but the results (Fig. 4) indicate an irregular variation of intensity with disk, angular velocity at all combinations of nozzle pressure and aperture angle. Application of the Duncan multiple range test indicates that only the angular velocity of 15 rpm has a significant effect on the intensity at the 5% level. The change in intensity and nozzle discharge with pressure shows a similar trend. At all pressures, the increase in intensity with aperture size is approximately linear (Fig. 7).

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Angular Velocity of Disk

Figure 5. Uniformity of application of simulated rainfall as a function of system variables.

Figure 6. Effect of nozzle pressure, aperture angle and disk angular velocity on the intensity of simulated rainfall.

Figure 7. Simulated rainfall intensity as influenced by aperture angle and nozzle pressure.

Formity coefficient. In the field evaluation of sprinkler nozzles, a change in size of the container has been shown to have a very small effect on the uniformity coefficient, because the area covered by the container is small in comparison with the total area covered (the diameter of the container with respect to the dimensions of the covered area could be represented by a point). The same condition does not exist for laboratory rainfall simulators. The area covered by a single-nozzle rainfall simulator is generally small (1-2 m²). A 50% change in container dimensions can result in a significant variation in the uniformity coefficient. Therefore, this aspect must be taken into consideration when uniformity coefficients are determined and compared.

Comparison of the uniformity of distribution for the nozzle with and without the disk (Fig. 9) has revealed that inclusion of the disk improved the uniformity coefficient for all aperture angles tested. Although, as stated earlier, only a 5° aperture yielded uniformity coefficient significantly greater than the other openings, all disk situations examined resulted in a significantly better uniformity than no disk condition.

The variation of rainfall intensity and uniformity coefficient with plot size is shown in Fig. 10 for a selected combination of nozzle pressure, aperture angle,
and disk angular velocity, i.e. $P = 81.1$ kPa, $A = 40^\circ$, and $S = 100$ rpm. The results of this study indicate a linear model of the form,

$$Z = a + bL + cW$$  \hspace{1cm} (1)$$

where $Z$ is rainfall intensity or uniformity coefficient, $L$ is length of the plot, $W$ is width of the plot, and $a$, $b$ and $c$ are regression coefficients. The coefficients for the situation illustrated in Fig. 10 are 169, $-0.146$, and $-0.161$ for the rainfall intensity model, and 100, $-0.085$, and $-0.045$ for the uniformity coefficient model. The respective determination coefficients were computed to be 0.989 and 0.977.

The experimental results for simulated rainfall using the procedure outlined by Beals et al. (1983) revealed that the velocity of fall for a particular size of drop is comparable to the terminal velocity of similar drops reported by Laws (1941). The average deviation for the velocity of fall from the Laws data was 9%. This could be due to experimental procedure. In the experimental procedure of Laws (1941) the drop size was measured independently from the drop velocity, while in this study the drop size and the fall velocity were measured on the same photograph.

**CONCLUSIONS**

The rainfall simulator developed with large-capacity wide-angle spray nozzle and a rotating disk with multiple variable aperture openings has provided an experimental facility which meets a variety of selection criteria established for a soil erosion research program. The simulator yields a wide range of useful simulated rainfall intensities and exhibits excellent spatial uniformity characteristics. The drop size and velocity of fall of drops of simulated rain are comparable to published data on terminal velocities of sim-

**Figure 8.** Effect of nozzle pressure, aperture angle and disk angular velocity on the uniformity of distribution of simulated rainfall.

**Figure 9.** Comparison of the uniformity of distribution of simulated rainfall with and without disk.

**Figure 10.** Simulated rainfall intensity and its uniformity of distribution as influenced by plot dimensions.
ilar drops. The device is portable, economical to build, and simple to adjust and operate. It provides a versatile and useful facility for the soil erosion laboratory.

REFERENCES


