Erosion and Sediment Transport Measurement (Proceedings of the Florence Symposium, June 1981). IAHS Publ. no. 133.

Laboratory and field testing of a programmable plot-sized rainfall simulator*

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ABSTRACT A programmable rainfall simulator for 4 x 11 m and longer field plots (Foster *et al.*, 1979) was tested and compared with a current rainulator. The new simulator uses an oscillating nozzle and is programmable for variable intensities in time and space. The nozzles of the programmable simulator are the same as those of the rainulator, but cycle times of a nozzle have been reduced from about 20 to 0.5 s for a rainfall intensity of 64 mm h^{-1}. Repeatable intensities are easier to obtain with the programmable simulator than with the rainulator, but intensity is slightly more uniform with the rainulator. Runoff and especially soil loss may be less with the programmable simulator than with the rainulator. However, the ease of assembly, short cycle times for minimal effects from intermittent rainfall bursts, and programmable intensities give the programmable simulator definite advantages for research on infiltration, overland flow and erosion.

Travaux de laboratoire et essai sur les lieux d'un simulateur pluvial programmable

RESUME Un simulateur de pluie programmable pour des parcelles de 4 x 11 m ou plus long (Foster *et al.*, 1979) a été essayé et comparé à un "rainulator" (simulateur artificiel de pluie) courant. Le nouveau simulateur est fondé sur le concept d'un gicleur oscillant et il est programmable pour des intensités variables dans le temps et l'espace. Les gicleurs du nouveau simulateur sont les mêmes que ceux du "rainulator", mais le temps des cycles a été réduit d'environ 20 à 0.5 s pour une intensité de 64 mm h^{-1}. Il est plus facile de reproduire des intensités identiques avec le nouveau simulateur, mais l'intensité est légèrement plus uniforme avec le "rainulator". Il y a peut être moins d'écoulement de surface et surtout moins de perte de sol avec le simulateur programmable qu'avec le "rainulator". Toutefois, si l'on tient compte de la facilité de montage, du temps plus court des cycles pour des effets minimaux à cause des

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* Contribution from the US Department of Agriculture-Science and Education Administration-Agricultural Research in cooperation with the Purdue Agricultural Experiment Station, West Lafayette, Indiana, USA. Purdue Journal no. 8342.

chutes intermittentes de pluie, et des intensités programmables, le simulateur programmable a des avantages certains pour la recherche sur l'infiltration, l'écoulement sur le sol et l'érosion.

INTRODUCTION

Rainfall simulators have been used in the USA since the 1930's to study erosion, runoff, and infiltration characteristics of soils under various crop, soil and residue management conditions (Mutchler & Hermsmeier, 1965; Moldenhauer, 1979). Rainfall simulation allows rapid comparisons between several treatments, using a standard storm sequence. Bubenzer's (1979) inventory of current rainfall simulators may be divided into three general classes: (a) laboratory or stationary simulators, (b) portable simulators for field use with "small" target areas, typically 4 m^2 or less, and (c) large portable simulators capable of covering individual plots 4 x 11 m or larger. The Meyer-McCune (1958) rainulator has been extensively used in US Department of Agriculture-Science and Education Administration-Agricultural Research (USDA-SEA-AR) erosion studies on large plots at West Lafayette, Indiana. To overcome some limitations in the rainulator, we developed a programmable rainfall simulator for field plots (Foster *et al.*, 1979). This paper describes the testing of this simulator.

DEVELOPMENT OF A PROGRAMMABLE RAINFALL SIMULATOR

Development of a portable rainfall simulator for large areas inevitably involves tradeoffs between the capacity to reproduce characteristics of natural rainfall and methods of rainfall simulation compatible with fast and easy setup and movement from one test location to another. In 1977, USDA-SEA-AR scientists at Lafayette, Indiana, decided to update their rainulator extensively. Based on the types of erosion and hydrology studies we hope to pursue at West Lafayette, Foster *et al.* (1979) identified performance improvements that should be incorporated into any new or updated simulator.

(a) Current rainulator cycle time (the time lapse between rainfall application at points on a plot that receive water least frequently) of 20 s is too long for the best studies of infiltration and overland flow hydrology (Sloneker & Moldenhauer, 1974; Sloneker *et al.*, 1976). Cycle time should be reduced to 0.5 s or less for application rates greater than 64 mm h^{-1}.

(b) The new simulator should have the capability of easily varying intensities in time and space.

(c) The new simulator should work satisfactorily on slopes as steep as 3:1.

(d) The new simulator should have fewer water and electrical connections and the simulator itself should be composed of fewer, but interchangeable, components.

The rainulator (Meyer & McCune, 1958), rotating boom simulator (Swanson, 1965), and US Geological Survey (USGS) simulator

(Lusby, 1977) are currently available designs developed for use on plots as large as 4 x 11 m. All three designs were examined to determine if any could be modified to meet our requirements.

Erosion research using simulated rainfall requires rainfall with drop size distribution and kinetic energy as close as possible to that of natural rainfall of the same intensity (Meyer, 1965). Meyer & McCune (1958) evaluated the raindrop characteristics of many nozzles when developing the rainulator. The Spraying Systems Veejet 80100 nozzle* was selected for use on the rainulator. Exit velocity from the 80100 nozzle is 8.8 m s^{-1} with drops smaller than 4 mm still exceeding or slowing to terminal velocity after a 3.0 m fall (Meyer & Harmon, 1979). Kinetic energy of the raindrops is approximately 75% that of natural rainfall and drop size distribution is slightly smaller than that of natural rainfall (Meyer & McCune, 1958). Barnett & Dooley (1972) and Young & Burwell (1972) compared data collected from plots exposed to natural rainfall with data from the same plots exposed to simulated rainfall and concluded that the rainulator produces acceptable results from erosion studies.

We therefore decided to use the same nozzle on the new programmable simulator. Of the existing large simulators, only the rainulator and rotating boom simulator use this nozzle. Neither of these could meet the criteria for cycle time, operation on steeper slopes or easily and continuously variable intensities in time and space so the decision was made to develop a new simulator using this nozzle.

Since the rainfall intensity from a continuously spraying 80100 nozzle is approximately 6250 mm h^{-1} per m of oscillation (Barnett & Dooley, 1972) some type of intermittent application technique is required. Morin *et al.* (1967) used a rotating disc with a section aperture to intercept a percentage of the flow from a square pattern nozzle. This method did not appear compatible with Veejet pattern nozzles and did not have the range of intensity adjustment within a run that we desired. The oscillating nozzle principle used by Bubenzer & Meyer (1965), and Meyer & Harmon (1979) reduces the rainfall intensity from an 80100 nozzle to a desired level by controlling the frequency with which each nozzle sweeps across an opening to the test surface. When the nozzle is spraying on either side of this opening, the water is diverted and re-used. Since this principle was proven on Bubenzer & Meyer's three nozzle laboratory simulator and on Meyer & Harmon's single nozzle field simulator, we chose to use it for the new simulator.

Working from these requirements, Booker and Associates, Inc., a consulting engineering firm from St Louis, Missouri, in cooperation with USDA scientists, developed concepts and drawings for the new simulator in 1979. A general description of the new simulator follows; the design concepts and the final design are described in detail by Foster *et al.* (1979).

Simulator description

The basic unit of the programmable simulator is an aluminium

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* *Mention of a product name does not imply endorsement.*

"trough" 5.32 m long, 320 mm wide and 250 mm deep. A series of these troughs are mounted across-slope to cover each field plot. The spacing between troughs up and down slope is 1.52 m. With enough troughs, the simulator can cover plots of any length. Five nozzles are mounted 1.10 m apart in each trough at a height of 2.44 m (the same height used on the rainulator) and they oscillate laterally across slope, covering an effective area of 1.5 x 5.5 m. A 90 x 213 mm opening directly below each nozzle is formed by aluminium deflectors projecting upward at about a 45° angle from the trough bottom. Intensity is set by regulating the frequency with which the nozzles oscillate back and forth across the opening. This frequency is controlled electronically with a programmable controller, which allows use of any intensity from 0 to 130 mm h^{-1}. Since each trough is operated independently, intensity can be varied for each 1.5 m increment down the plot in any desired time pattern.

The nozzles spray continuously. Water not applied to the test surface is intercepted within the trough by the deflectors, returned to a sump pump mounted at one end of the trough, and is repumped through the nozzles. Water is added to each trough as needed from a central supply. Pressure at the nozzles in each trough is independent both of pressure from the central supply and of location on the plot (thus, pressure is independent of change in elevation from top to bottom of steep plots).

PERFORMANCE CHARACTERISTICS

Repeatability of application rate

Laboratory tests Two troughs, covering a 5.5 x 3 m area were suspended 2.4 m above a 1.4 x 1.5 m test area. Intensity levels of 32, 64 and 127 mm h^{-1} were tested. In a second set of tests, three troughs, covering a 5.5 x 4.6 m area, were suspended 2.4 m above a set of cans that covered a 1 x 3 m test bed. Intensity levels of 25, 50, 75, 100 and 125 mm h^{-1} were tested. Each rate was replicated four times in both sets of tests. Application of the Student-Newman-Keuls test to the results showed that differences in replication (time) means were not significant at the 5% level. A definite downward trend was present in the data at all intensity levels. Most of this decrease in intensity over time was because of observed wear in the linkage that oscillates the nozzles. This wear, which occurred over a 15 h period of simulator run time, caused the nozzles to remain at rest on either side of the opening for a larger portion of each revolution of the drive mechanism, decreasing the ratio of "on" time, time that the plot is receiving rainfall, to "off" time, time that water from the nozzles is intercepted and recirculated within the trough. Even with the decrease in intensity because of wear, the standard deviation of the four observations at each intensity ranged from only 0.57 mm h^{-1} at 25 mm h^{-1} to 2.67 mm h^{-1} at 125 mm h^{-1}. The drive linkage has been modified and recent tests show that this wear problem has been corrected. Figure 1 contains data from both test areas. The coefficient of uniformity of rainfall on the larger area had less scatter but had a lower mean

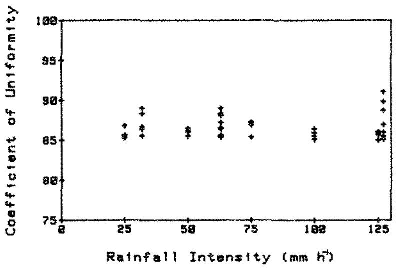

Fig. 1 Coefficient of uniformity for the programmable simulator at eight rainfall intensities for a 1 X 3 m test area (intensities of 25, 50, 75, 100 and 125 mm h^{-1}) and a 1.2 X 1.7 m test area (32, 64 and 127 mm h^{-1} intensities).

value. Areal variability, as measured by the coefficient of uniformity, appeared to be independent of rainfall intensity.

Field tests The rainulator and the programmable rainfall simulator were each set up over a field plot with a grid of cans located at three randomly selected locations on each plot. Three replications were made at each sampling location. Results are shown in Table 1. A two-way analysis of variance showed no significant (5% level) difference in rainfall intensity between simulators, between locations or for any interaction between simulators and locations. The simulators were judged equal in their repeatability from run to run and variability of intensity with location on the plot. The programmable simulator has the practical advantage, however, of requiring much less attention to maintain intensity than does the rainulator, particularly when changing from one intensity to another.

Areal variability

Areal variability was tested three ways. (a) Variation in intensity between nozzles spaced 1.40 m apart in a trough was tested in the laboratory using eight rows of six cans each, set parallel to the length of the trough, between two nozzles. (b) Variation in intensity between nozzles on adjacent troughs

Table 1 Rainfall intensity measured at three different locations within a field plot for both rainulator and programmable rainfall simulator

		Intensity (mm h^{-1}) for replication			
Simulator	Location within plot	1	2	3	Mean*
Rainulator	Top	75.8	76.9	74.7	75.8a
	Middle	62.9	65.7	59.8	62.8b
	Bottom	77.4	79.2	76.9	77.8a
Programmable simulator	Top	†	75.2	75.0	75.1a
	Middle	70.2	69.6	66.3	68.7a
	Bottom	†	71.2	71.3	71.2a

*Means not followed by the same letter are significantly (P = 0.05) different as evaluated by the Student-Newman-Keuls test.

†Changes made to control unit before these runs produced a different intensity storm.

(spaced 1.52 m apart) was tested in the laboratory using 11 rows of cans between the nozzles and three columns of cans on either side of the centreline between the nozzles. (c) The variation over an area bounded by four nozzles was tested in the field, using an 8 x 11 grid of cans for the programmable simulator and a 6 x 11 grid for the rainulator. Nozzles were 2.44 m above the top of the cans for laboratory tests and 2.29 m above the cans for field tests.

Variation between nozzles on a trough Variation in application rate between four pairs of nozzles on eight different troughs was tested. Four replications were conducted for almost all pairs of nozzles. A typical distribution between two nozzles, the average of four replications, is shown in Fig. 2, with intensity varying from 95.8 to 104.6 mm h^{-1}. Since the nozzles oscillate to cover the distance between nozzles on a trough the spray pattern should remain fairly constant during the oscillation and should produce a uniform application rate along the trough. The region of greatest variation should be where spray from adjacent nozzles meets. Figure 2 shows good uniformity along the trough.

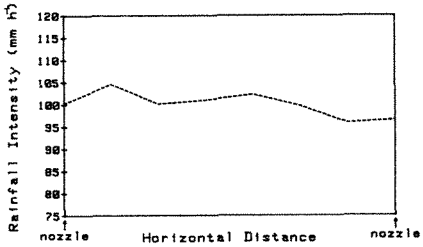

Fig. 2 Variation in rainfall intensity between adjacent nozzles on the same trough.

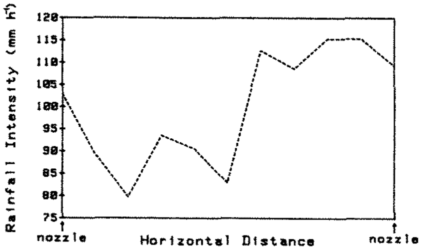

Fig. 3 Variation in rainfall intensity between nozzles on adjacent troughs.

Variation between nozzles on adjacent troughs Variation in application rate between two nozzles on two adjacent troughs was tested at five intensity levels, with four replications per level. A typical distribution is shown in Fig. 3, with intensity varying from 79.7 to 115.4 mm h^{-1}. The plotted data are an average of four replications. Figures 2 and 3 show more variability between troughs (in the direction parallel to the long axis of nozzle spray) than between nozzles on a trough. Testing of individual nozzles by Meyer & McCune (1958), Barnett & Dooley (1972) and Meyer & Harmon (1979) quantified the variation in application rate as a function of the distance from the centre of the nozzle. The shape of this intensity *vs.* distance curve, and the presence of a "hard edge" approximately 1.1 m from the nozzle centreline, produced a pattern of variation in intensity as a function of distance from the nozzle similar to that shown in Fig. 3.

Uniformity within one sub-block of the simulator Both the rainulator and programmable simulator may be visualized as composed of small adjacent blocks of rainfall that cover the entire plot. These blocks, areas bounded on all four corners by a nozzle, are 1.40 x 1.52 m for the programmable simulator and 1.83 x 1.52 m for the rainulator. A grid of cans to measure rainfall intensity was set under three randomly selected blocks

Table 2 Coefficient of uniformity at three different locations within a plot for both rainulator and programmable rainfall simulator

Simulator	Location within plot	Replication 1	Replication 2	Replication 3	Mean*	Standard deviation
Rainulator	Top	91.0	88.3	92.9	90.8ab	2.32
	Middle	92.2	90.8	91.5	91.5b	0.70
	Bottom	90.5	89.7	91.3	90.5ab	0.79
Programmable simulator	Top	89.4	90.0	92.6	90.7ab	1.72
	Middle	89.9	88.3	87.2	88.5ab	1.36
	Bottom	88.2	87.6	84.8	86.9a	1.82

*Means not followed by the same letter are significantly (P = 0.05) different as evaluated by the Student-Newman-Keuls test.

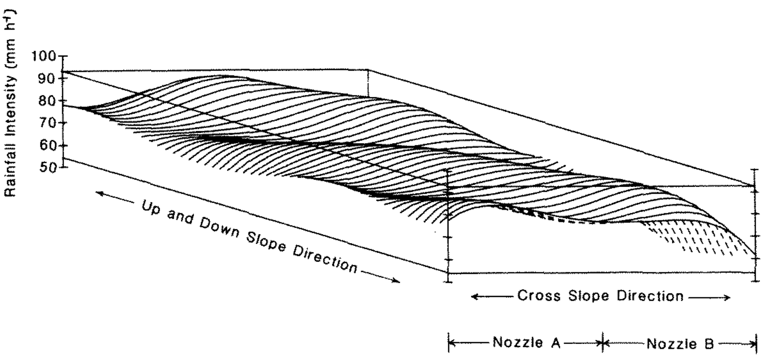

Fig. 4 Areal variability of rainfall on a 1.2 X 1.7 m area under the programmable rainfall simulator. Nozzles are directly above each of the four corners. Results shown are the average of thee replications. Intensity ranged from 43.6 to 81.8 mm h^{-1}.

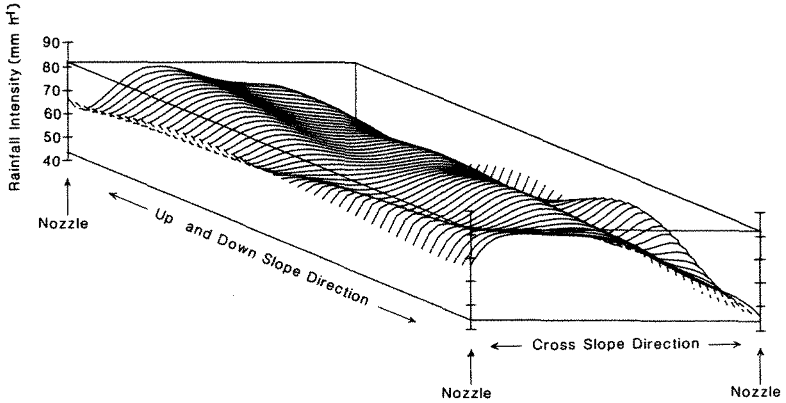

Fig. 5 Areal variability on a 0.9 X 1.7 m section under the rainulator. Nozzle centres are at the top and bottom of the area. One set of nozzles stops spraying at the centre of the section, moving to the left and the next starts spraying at this point and moves on to the left. Results shown are the average of three replications. Intensity ranged from 53.9 to 92.8 mm h^{-1}.

Table 3 Soil loss and runoff from the base of 3.7 X 10.7 m plots for rainulator and programmable rainfall simulator. Each number is the average of two observations

	Soil loss (t ha^{-1})		Runoff volume (mm)	
Run	Rainulator	Programmable simulator	Rainulator	Programmable simulator
Initial	5.49a*	1.23a	26.4b	15.2b
Wet	5.02a	2.89a	22.6b	19.0b
Very wet	6.01a	3.03a	25.9b	23.1b
Wet	5.67a	4.67a	23.1b	26.4b
Very wet	6.12a	4.55a	25.9b	28.4b

*Soil loss and runoff volume values not followed by the same letter are significantly ($P = 0.05$) different as evaluated by analysis of variance and the Student-Newman-Keuls test. Means for each run (row) can be compared between columns for either soil loss or runoff volume. Comparison between rows was not made.

for both simulators. Table 2 shows that statistically the coefficient of uniformity (Christiansen, 1942) is significantly ($P = 0.05$) higher for the rainulator than for the programmable simulator. However, repeated testing of the same sprinkler under identical conditions has shown that in the range of 85-90, the coefficient of uniformity is a repeatable measure to only within ±3 percentage points (Christiansen, 1942). Thus, the two simulators are roughly equal in areal rainfall distribution. Results from one typical block for the programmable simulator (Fig. 4) show the effect of combining variation between troughs and between nozzles on a trough. Figure 5 shows the results for the rainulator. For the plotted runs, the average coefficient of uniformity was 88.48 for the programmable simulator and 90.52 for the rainulator. For comparison, Morin *et al.* (1967) reported a coefficient of uniformity of 82-86 for rainfall intensity of 64 mm h^{-1} from a rotating disc simulator over a 1.5 m^2 test area. The rainulator is more uniform across the plot due to the steady lateral movement of the nozzles than is the programmable simulator with its oscillating nozzles.

Runoff and erosion rates

The rainulator and programmable simulator were compared on four adjacent 3.7 x 10.7 m plots. The plot location was selected to minimize differences in slope and soil type between plots. The two simulators were erected over the first two plots and a 1 h initial run was made on an initially dry soil in seedbed condition. After 24 h a 30 min wet run was made and was followed 30 min later by a 30 min very wet run. Design rainfall intensity for both simulators was 64 mm h^{-1} for all runs and was checked before the initial and wet runs by raining on plastic sheeting that covered the plots. The order of the two simulators was then reversed and the wet and very wet runs were repeated, so that both simulators were tested on both plots. These tests were then repeated on the second set of two plots. Soil loss and runoff volume from both simulators (summarized in Table 3) were averaged from the two sets of plots. Analysis of variance and Student-Newman-Keuls tests showed no significant (P = 0.05) difference between simulators for either soil loss or runoff volume for initial, wet or very wet runs. The order that the simulators were run on a given plot (e.g. rainulator and then programmable rainfall simulator or reversed order) was not significant on the wet and very wet runs for either soil loss or runoff volume.

Even though the statistical tests did not reject the hypothesis that the simulators give equal runoff and soil loss values, the magnitude of the differences between the averages suggested that differences between the simulators may be important and that the programmable simulator may give lower runoff and soil loss values than the rainulator. Differences in runoff were obvious during the initial runs. The rainulator nozzles moved so slowly over the soil surface that local intensity under the nozzles while "on" was much higher than under the programmable simulator. Localized runoff occurred early in the initial run with the rainulator because of this high localized intensity. Also, runoff moved off the rainulator plots in waves, which was obvious from the measured hydrographs, whereas runoff from the programmable simulator was very steady. The flow rate of the wave peaks was greater than the average flow, which could cause more total detachment by runoff and greater transport capacity on the rainulator plots than on the programmable simulator plots.

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