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THE 'EMIRE' LARGE RAINFALL SIMULATOR: DESIGN AND FIELD TESTING

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ABSTRACT

A rainfall simulator for 5×10 m plots was designed and tested within the EMIRE (Etude et Modélisation de l'Infiltration, du Ruissellement et de l'Erosion) program. The simulator is intended to be used in the field and to reproduce natural tropical rain storms. The simulator is composed of fixed stand pipes. The nozzle (Spraying Systems Co. 1H106SQ) mounted on the top of the pipes sprays square areas. At a water pressure of 41·18 kPa the mean drop diameter is 2·4 mm and the calculated kinetic energy 23·5 J m^{-2} mm^{-1}. The pipes are located at the corners of a $5{\cdot}5 \times 5{\cdot}5$ m square grid. The rainfall intensity is constant (65 mm h^{-1}) and spatially uniform (Christiansen's coefficient of uniformity is 78 to 92 per cent) over the plot. Repeatability of application rate and spatial variability of rainfall intensities were tested by analysing (1) variations in intensity for different experiments on the same plot, and (2) variations in intensity between different plots. The study is based on data collected during nine field rainfall simulation experiments. Three replications of the same rain were applied on three 50 m^2 plots. The results show good performance in all cases. The values of the mean rainfall intensities and coefficient of uniformity obtained from field data agreed with the laboratory values. The performance of this simulator is comparable to others described in the literature. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: rainfall simulator; spatial variability; Christiansen coefficient of uniformity; Senegal

INTRODUCTION

In the sahelian areas with a very short rainy season (three months or less) and irregular distribution of rainstorms, the use of simulated rain is the only way to obtain results in a reasonable time period (Neff, 1979). Monitoring experiments in such areas are expensive and dependent on the meteorological conditions during the period of collecting data. Many years of monitoring are required to obtain enough information. To complete the data obtained from natural events, the use of a large rainfall simulator was planned. The data collected from rainfall simulation experiments also provide fundamental information on the processes involved in both runoff production and soil erosion.

There does not exist at the present time a universal rainfall simulator applicable to all situations. During the last 40 years a great number of rainfall simulators have been designed (Hall, 1970; Bubenzer, 1979). The simulators are usually classified according to the way in which the drops of rain are produced. Two main types exist: (i) drip formers (Farmer, 1973; Römkens *et al.*, 1975; Munn and Huntington, 1976) and (ii) nozzles (Meyer and McCune, 1958; Swanson, 1965; Asseline and Valentin, 1978; Niebling *et al.*, 1981; Luk

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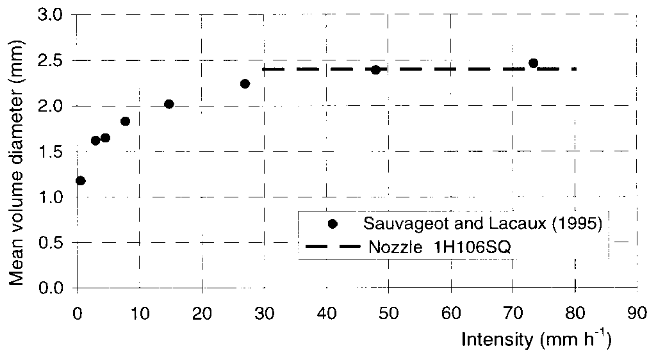

Figure 1. Measured mean drop diameters as a function of rain intensities from the data published by Sauvageot and Lacaux (1995) for West African continental tropical rains

et al., 1986; Miller, 1987; Parsons *et al.*, 1990; Lascano *et al.*, 1997; Riley and Hancock, 1997). The commonly used method for large area field studies (e.g. 10 to 500 m^2) is the pressurized nozzle (Meyer and McCune, 1958; Swanson, 1965; Niebling *et al.*, 1981; Parsons *et al.*, 1990; Riley and Hancock, 1997). Development of a simulator for large areas involves compromises between the capacity to reproduce natural rainfall characteristics and technical constraints. A portable rainfall simulator requires fast and easy assembling and transportation from one plot to another.

Little quantitative information is available on drop size distributions and falling velocities of drops in natural rainstorms in west Africa. Barat (1957) presented the results of a study of drop size distribution in natural rains, of different intensities, at Madagascar and in west African countries using the coloured absorbing paper method. Rain drops of natural rainfall have diameters between 0·7 and 5 mm. In a recent paper Sauvageot and Lacaux (1995) studied the shape of averaged drop size distribution from a sample of data collected in Ivory Coast, Niger and Congo using a disdrometer (Joss and Waldvogel, 1967). They gathered the instantaneous drop size distributions in height classes of rain rate. The distribution of measured mean drop diameters, as a function of rain intensities, is given in Figure 1. The mean drop diameters range from 1·18 mm for rain rates below 2 mm h^{-1} up to 2·46 mm for rain rate greater than 60 mm h^{-1}.

The present paper describes the design characteristics and testing of a large portable simulator able to cover plots 5 × 10 m or larger. Results from the application of this simulator to a cultivated plot are presented in a companion paper (Planchon *et al.*, 2000).

MATERIAL AND METHODS

Rainfall simulator

The basic unit of the simulator is a 6·58 m high, 25·4 mm galvanized vertical standpipe and a nozzle mounted at the end of the standpipe which sprays a square area of 7 × 7 m. Figure 2 presents the different parts of the simulator. Six units mounted along two lines allows the spray to cover a 50 m^2 plot. Several trial and error designs were tested until a suitable water pressure and spray pattern produced the desired rain rate, drop-size distribution and spatially uniform rainfall rate. The best nozzle arrangement is a square pattern with jets pointing upwards. The distance between pipes is 5·5 m and water pressure of 47·8 kPa at the nozzle level. With enough pipes it is possible to cover a plot of any size. Guy ropes attached to standpipes are used to stabilize the system. A 1H106SQ Spraying Systems nozzle is mounted on the top of the pipe at a height of 6·53 m. The water is jetted to a height of approximately 7·5 to 8 m. This altitude is higher than the necessary falling distance to achieve terminal velocities. A cut-off valve and an oil-immersed pressure gauge allow a fine control of the pressure at the bottom of each pipe.

The system is supplied with water pumped from a storage tank located near the plot. The water supply to each standpipe is through a 51·2 mm plastic reinforced flexible hose. Two lines are supplied from the

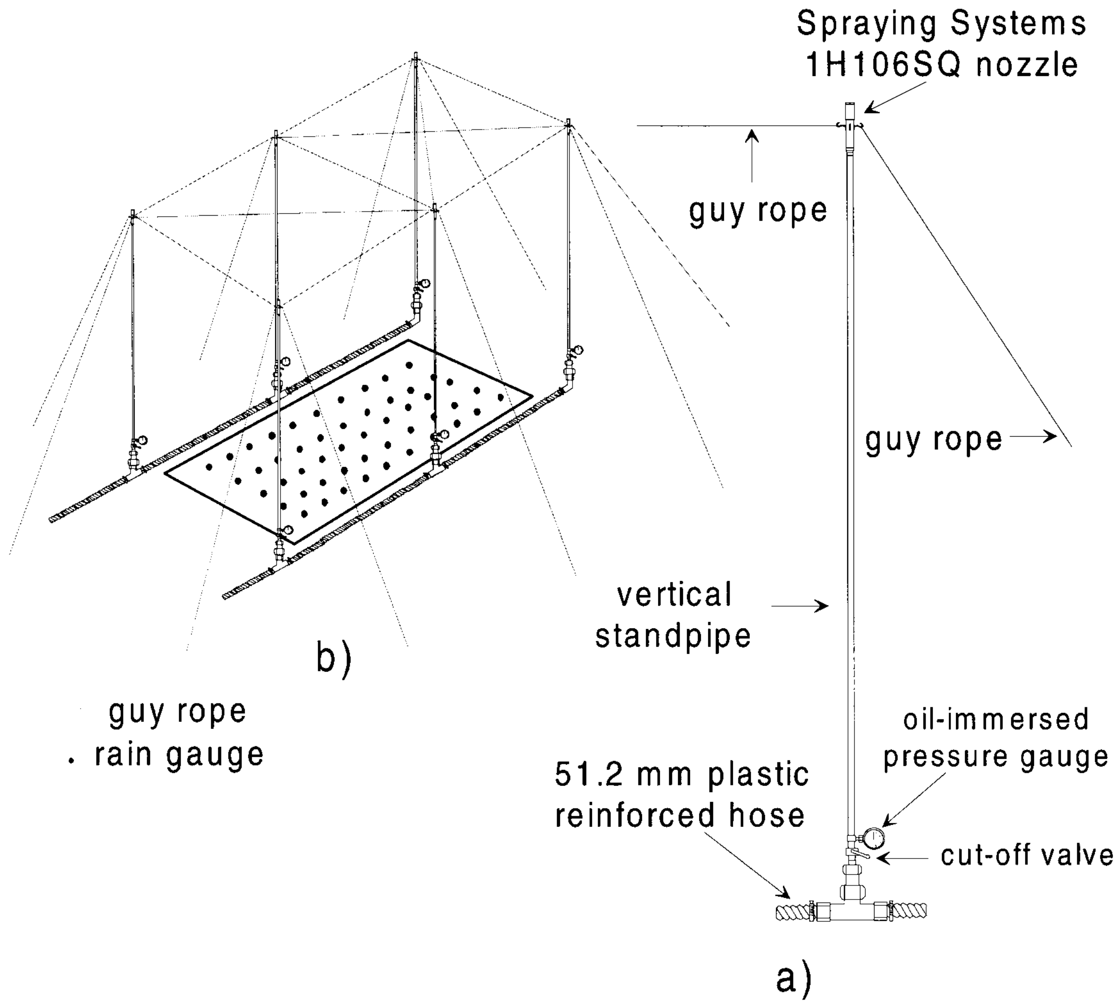

Figure 2. Sketchs of EMIRE rainfall simulator. (a) Sketch of basic unit. (b) View of six basic units assembled for field operation

reservoir by two petrol-driven pumps. The rainfall intensity can be changed by adjusting the water pressure. During all the experiments the water pressure was maintained constant at 47·8 kPa. At this water pressure the basic unit produces a rainfall intensity of 75 mm h^{-1}.

Nozzle

After evaluating a number of different nozzles the 1H106SQ Spraying Systems nozzle was selected. Lascano *et al.* (1997) evaluated the raindrop characteristics of this nozzle when developing their programmable simulator. At a water pressure of 41·4 kPa the mean drop diameter is 2·4 mm and the calculated kinetic energy 23·5 J m^{-2} mm^{-1}. The drop-size distribution was not measured for a 47·8 kPa water pressure. As pressure is inversely related to drop size, an increase in pressure will reduce the drop size. However, considering the small increase of pressure (<7 kPa), we have assumed that the actual raindrop characteristics are similar to those measured by Lascano *et al.* (1997).

Performance evaluation

To assess the ability of a network of nozzles to simulate rainfall, one must pay special attention to the properties of the spray pattern. The performance of the rainfall simulator was evaluated by examining (1) the repeatability and uniformity of the spatial distribution of rainfall for one basic unit in the laboratory; (2) the

Table I. Coefficients of uniformity (CU) and variation (CV) for rainfall rates from the basic unit over a target area of $3{\cdot}2 \times 3{\cdot}2$ m

	P1	P2	P3	Mean
Mean intensity	72·56	74·74	78·37	75·22
Standard deviation	16·21	20·22	18·76	18·4
CV (%)	22·3	27·0	23·9	24·4
CU (%)	82·3	79·2	79·0	80·2

repeatability of application rate over a 50 m^2 area; and (3) assessing the spatial variability of rain during field experiments.

The most widely used measure of spatial uniformity is the coefficient of uniformity (CU) defined by Christiansen (1941). The CU (in per cent) is calculated from the formula:

$$CU = 100\left(1 - \left(\frac{\sum_{i=1}^{i=n}\left|X_i - \overline{X}\right|}{\overline{X}}\right)\right) \quad (1)$$

where $\overline{X}$ is the mean rainfall intensity (mm h^{-1}), n is the number of observations, and X_i ($i = 1,2,\ldots,n$) are the individual observations. The more uniform the pattern of rainfall, the closer CU approaches to 100. It does not give any indication on pattern. It is possible for two very different patterns to result in the same CU value. In spite of this limitation, the CU is still the most used index of spatial uniformity of rainfall. CU values of the order of 80 to 90 per cent are generally considered acceptable (Neff, 1979). For large plot areas, values of 70 per cent have been accepted in some studies (Luk *et al.*, 1993).

Rainfall depths and distribution of rainfall intensities were measured with collecting cans (micro-raingauges) distributed over the plot in a square grid. Each can is 5·5 cm in diameter. For the laboratory experiments the distance between the cans was 0·8 m. During field experiments the spacing of the raingauges was 1 m.

RESULTS AND DISCUSSION

Performance characteristics of a basic unit

The CU values and coefficient of variation (CV) of the rainfall collected in the cans distributed over an area of 10·2 m^2 ($3{\cdot}2 \times 3{\cdot}2$ m) beneath one basic unit are presented in Table I for three replications (P1 to P3). A typical pattern is shown in Figure 3. Application of the Student–Newman–Keuls test (Snedecor and Cochran, 1980) to the results showed that differences in rainfall intensities between the three replications were not significant at the 5 per cent level. The mean values of CU and CV are slightly different to those reported by Lascano *et al.* (1997) for the same nozzle. These differences could be explained by the finer grid used by Lascano *et al.* (1997), who used 64 collecting cans over an area of 2×2 m instead of 25 cans over an area of $3{\cdot}2 \times 3{\cdot}2$ m in the present study.

Repeatability of rainfall intensity in field experiments

Three 30 min rainfall experiments (R1 to R3) were performed on three plots (PA to PC). At the design rainfall intensity these nine rain events correspond to a rainstorm with a return period of one year. The amount of simulated rainfall was measured using ten rows of five collecting cans each aligned across the plot between the lines of nozzles. The results are summarized in Table II. For the nine rainfalls, the average intensity was 68·2 mm h^{-1}. The values ranged from 60·5 to 76·3 mm h^{-1}. Application of the Student–Newman–Keuls test to the results of each plot showed that differences in rainfall intensities were not significant at the 5 per cent level for plot PB and PC except for R3 in plot PC.

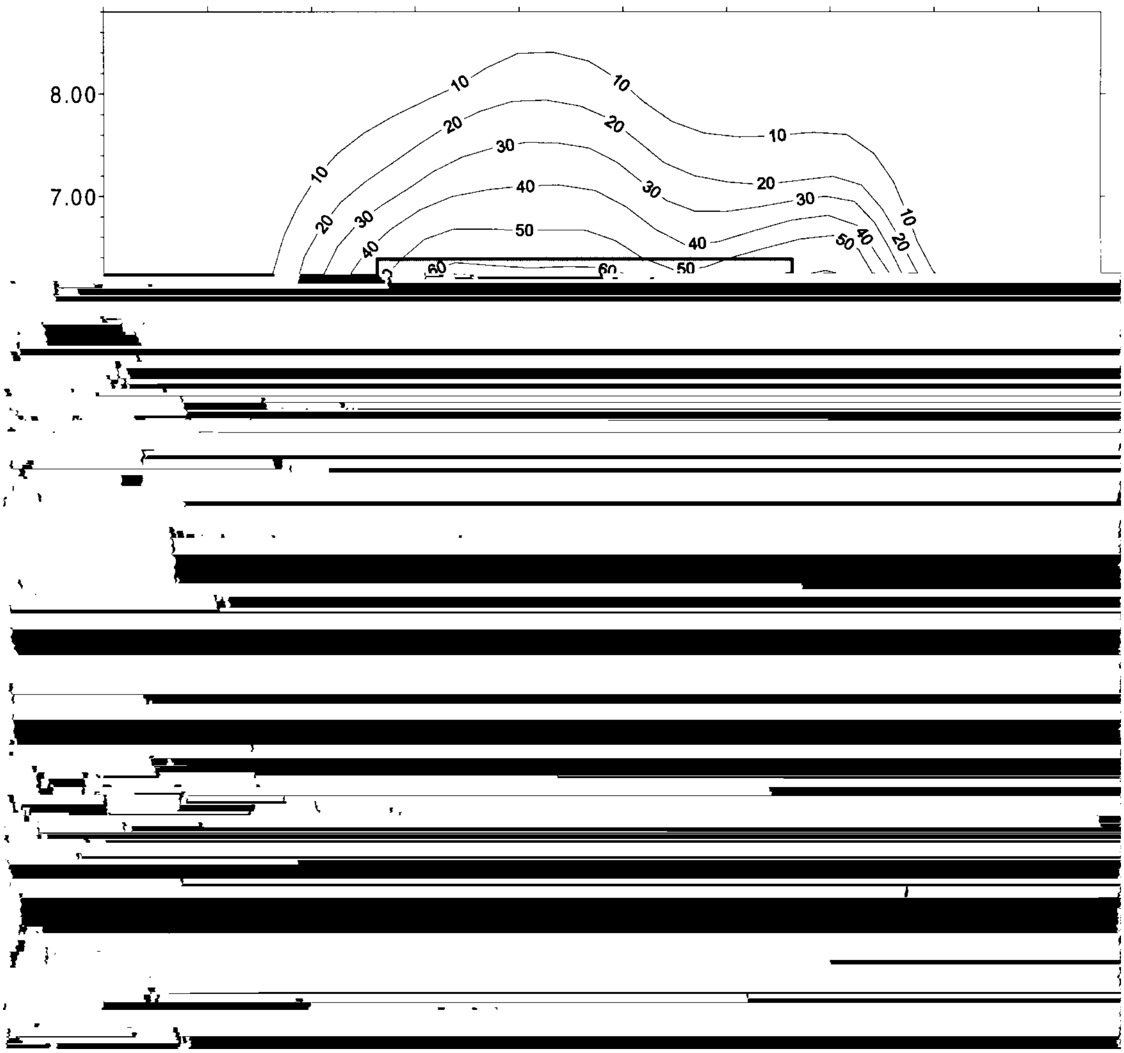

Figure 3. Typical spray pattern obtained from a 1H106SQ Spraying System nozzle under a pressure of 47·8 kPa. Contours are rain intensities expressed in mm h^{-1}

Table II. Mean, minimum and maximum rainfall intensities for three 5 × 10 m plots. The minimum and maximum values are expressed as a percentage of mean intensity

Plots	R1			R2			R3		
	Mean intensity (mm h^{-1})	Minimum (%)	Maximum (%)	Mean intensity (mm h^{-1})	Minimum (%)	Maximum (%)	Mean intensity (mm h^{-1})	Minimum (%)	Maximum (%)
PA	60·4	69·3	129·0	64·8	84·3	118·4	69·0	60·9	135·5
PB	76·4	62·6	130·7	75·3	59·7	143·6	76·3	67·6	135·7
PC	66·7	53·9	143·9	64·7	49·3	145·1	60·5	41·0	130·5

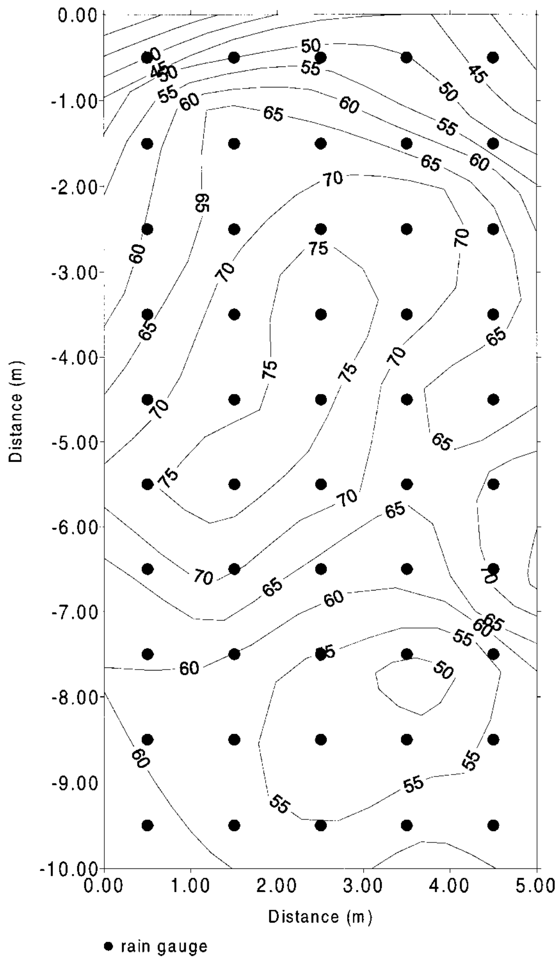

Figure 4. Spray pattern obtained during run R3 on plot PC. Contours are rain intensities expressed in mm h^{-1}

The differences in application rate for plot PA result from nozzle problems that occurred during runs R1 and R2. During run R1 one of the nozzles was partially blocked by a piece of straw. During run R2 the nozzles located on the left side of the plot received less water. A small leak on the circuit caused a small decrease of pressure. As a result, runs have the highest CU values and lowest mean rainfall intensities.

In the case of run R3 on plot PC, unfavourable wind conditions during the experiment explain the difference in intensity of rain. On that day the wind blew parallel to the axis of the plot in an upslope direction causing the spatial pattern of rainfall to shift upslope. Figure 4 clearly shows a water deficit in the lower part of the plot and a reduction in the quantity of total water collected over the plot.

A comparison of the three plots reveals differences between plot PB and the two others. Application of the Student–Newman–Keuls test to the mean rainfall intensities on PA, PB and PC shows that the differences between them are statistically significant at the 5 per cent level. The rain intensities on plot PB are always greater than on the other two. A check of the pressure gauges used on this simulator revealed that the cause of this difference was the malfunctioning of three of them. The values of the pressure indicated by the defective sensors was lower than actual values. Changing the sensors solved the problem. Recent tests showed that this pressure problem has been corrected.

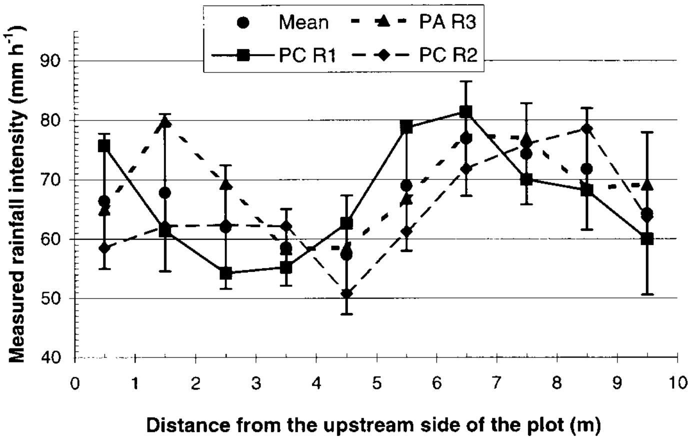

Figure 5. Variation in rainfall intensity across the plot area for three replications. Vertical bars correspond to +/−one standard deviation around mean of measurements

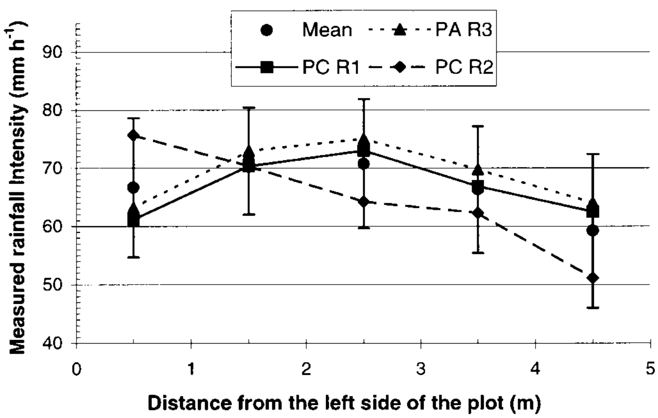

Figure 6. Variation in rainfall intensity along the plot area for three replications. Vertical bars correspond to +/−one standard deviation around mean of measurements

Spatial variability

The spatial variability of the rainfall depths over a 50 m^2 area was investigated by analysing (1) the variation in intensity across the plot, (2) the variation in intensity along the plot and (3) the variation over the plot. To illustrate these analyses we present the data recorded during three replicates: R3 event on plot PA and R1 and R2 events on plot PC.

The pattern of these simulated rain events across the plot are presented in Figure 5. The average rain intensity varied between 59·2 and 71·2 mm h^{-1}. The minimum and maximum values for the three replications never differ from the mean value by more than 45 per cent. The lowest intensities are observed near the border of the plot where the nozzles are located. Since the distance between nozzles is smaller than the diameter of the spraying area, the zone of maximum intensity is located where the sprays of adjacent nozzles overlap.

Figure 6 illustrates variation in simulated rain intensity along the plot. The mean intensity ranged from 59·2 to 78·6 mm h^{-1}. Again, the highest intensities are observed where the sprays overlap. The extreme values along the plot never exceed 45 per cent of the mean values.

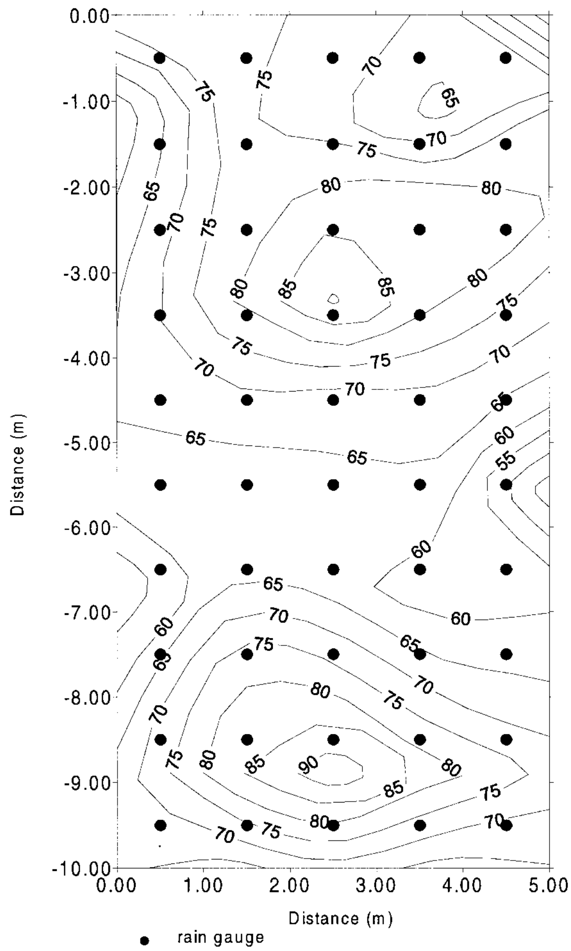

Figure 7. Typical spray pattern obtained during field experiment (R3, plot PA) using six basic units. Contours are rain intensities expressed in mm h^{-1}

A typical pattern of simulated rain within the plot is presented in Figure 7. The mean rain intensity is 69 mm h^{-1}. Rainfall intensity increases from the bottom of the pipes to the middle of the plot. There are two maxima in the rainfall intensities located in the downstream and upstream parts of the plot (Figure 7).

The plot area may be approximated as being composed of small blocks of rainfall. We defined three 3 m × 3 m blocks centred at top, middle and bottom of the plot (Figure 7). The mean rainfall intensity for each blocks is summarized in Table III. Application of the Student–Newman–Keuls test to these results showed that differences in rainfall intensities were not significant at the 5 per cent level for any combination of locations and replications.

The results in Table IV show that the values of CU range from 78·6 per cent up to 91·7 per cent over 50 m^2 and average 84 per cent. For comparison, Morin *et al.* (1967) reported a range of CU of 82–86 per cent for a rainfall intensity of 64 mm h^{-1} over a 1·5 m^2 test area. Niebling *et al.* (1981) found a range of 88·5–90·5 per cent for their programmable simulator (2·04 m^2) and 90·5 per cent for the rainulator (Meyer and McCune, 1958) (1·53 m^2), and Miller published a value of 85 per cent for a 3 m^2 plot. Values of CU for large areas have been published by Luk *et al.* (1993) and Riley and Hancock (1997). The former reported values of 70 to 75 per cent for a plot area of 630 m^2, and the latter 75 to 95 per cent over an area of 1000 m^2.

In all the above-mentioned studies, CV is smaller than 20 per cent and ranges from 8·1 per cent to 19·4 per cent. The extreme values seldom depart by more than 50 per cent from the mean intensity for the plot. Spatial

Table III. Mean rainfall intensity for 3 × 3 m blocks at three different locations within the plots

Location	PA R3		PC R1		PC R2	
	Mean intensity (mm h^{-1})	Standard deviation	Mean intensity (mm h^{-1})	Standard deviation	Mean intensity (mm h^{-1})	Standard deviation
Top	75·1	10·4	68·9	15·5	63·1	5·3
Middle	71·5	9·8	77·6	10·2	62·4	10·7
Bottom	75·0	6·8	67·6	8·7	71·3	8·8

Table IV. Coefficients of uniformity (CU) and variation (CV) for three 5 ×10 m plots

Plots	R1		R2		R3	
	CU (%)	CV (%)	CU (%)	CV (%)	CU (%)	CV (%)
PA	90·1	13·1	91·7	8·1	84·5	15·2
PB	77·7	14·7	78·6	17·4	77·6	17·5
PC	83·6	19·4	84·4	18·9	85·6	19·2

variability, as estimated by CU, seems to be dependent on rainfall intensity. High values of CU are associated with low values of mean rainfall intensity.

CONCLUSION

The advantages of the simulator design presented here are low cost and ease of operation. All parts are stock hardware items that can be assembled with little technical assistance. In performance it compares favourably with other large simulators that use nozzles.

Rainfall uniformities estimated by the coefficient of uniformity fell within acceptable limits, but were affected by water pressure variation and wind effects. The water pressure determines the discharge rate of the nozzle, then the rainfall intensity. The wind modifies the rainfall pattern on the ground surface by blowing the rain drop outside the plot. However, under calm wind conditions uniformity is improved. A systematic measurement of the rain depth with collecting cans makes it possible to control the quantities of water application and to highlight any operating problem. Experiments are being designed to characterize the drop size distribution of rain in different areas of the plot by using an optical spectro-pluviometer.

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