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Rainfall Simulation for Environmental Application

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MASTER

Environmental Sciences Division
Publication No. 1067

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RAINFALL SIMULATION FOR ENVIRONMENTAL APPLICATION

D. S. Shriner, C. H. Abner,¹ L. K. Mann

ENVIRONMENTAL SCIENCES DIVISION
Publication No. 1067

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ABSTRACT

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Rain simulation systems have been designed for field and greenhouse studies which have the capability of reproducing the physical and chemical characteristics of natural rainfall. Important parameters of natural precipitation which are duplicated include:

- (1) Rainfall rate (intensity controllable between 0.5 and 2.7 cm/hr)
- (2) Droplet size range (0.1 - 3.2 mm)
- (3) Chemical composition (metering pumps supply carefully controlled concentrations of ions to deionized water stream).

The systems permit the simulation of variations in rainfall and droplet size similar to that of natural precipitation. The systems are completely automatic and programmable, allowing unattended operation for periods of up to one week, and have been used to expose not only vegetation but also soils and engineering materials, making them versatile tools for studies involving simulated precipitation.

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INTRODUCTION

Precipitation events play a significant role in the transport, scavenging, and cycling of contaminants from the atmosphere to plant, soil, and water systems (Summers and Hitchon 1973). Recently recognized negative trends in precipitation quality over large areas of the industrial world have fostered increasing interest in the potential environmental effects of long-term changes in precipitation chemistry. Study of such potential environmental effects requires the ability to simulate natural precipitation events, as well as the ability to manipulate both the physical and chemical properties of the simulant under controlled experimental conditions. The lack of commercially available systems capable of accurate rainfall simulation led to the present developmental effort.

Chow and Harbaugh (1965), Bertrand and Parr (1961), and Mueller and Sims (1971) have reviewed available techniques and the problems involved in simulation of natural rainfall. Unrealistically rapid rates of application and/or small droplet sizes make many commercially available mist nozzles unsuitable. A system employing capillary tubes to form individual droplets, as described by Chow and Harbaugh (1965), while technically efficient, does not permit variation of droplet size during operation, and is of limited portability.

DESIGN CRITERIA

Major emphasis was placed on replication of droplet size. Evidence exists (Purnell and Preece 1971; Blakeman and Szejnberg 1973) which strongly suggests that the mechanical force of water droplets striking a leaf surface can modify that surface. Investigations of the effects of water chemistry should be independent of such physical variables.

Design criteria include:

- (1) Realistic droplet size range (0.5 - 3.0 mm).
- (2) Controllable rates of application.
- (3) Stable, controllable water chemistry.

- (4) Realistic rainfall intensity - lower rates of application than available with other types of spraying equipment (1.0 - 2.5 cm/hr).
- (5) Uniformity of droplet distribution over a target area $\geq 1 \text{ m}^2$ ($\leq 10\%$ coefficient of variation).
- (6) Reproducible rates of application.
- (7) Resistance to corrosive solutions.
- (8) Portability - Field units capable of being moved and set up by one person, and of being operated with a portable power generator in field plots.
- (9) Low cost for field units.

MATERIALS AND METHODS

Portable Field Apparatus

Figure 1 is a schematic diagram of a complete apparatus used for field simulation of rainfall. The rain nozzle used is model SRN 303 (Bete Fog Nozzles, Inc., Greenfield, Massachusetts). The nozzle consists of a two-piece base of type 303 stainless steel, and a polyvinyl chloride or ceramic orifice plate (Fig. 2). The orifice plates have either 14 or 28 holes of 0.25 mm diameter, depending on the desired flow rate. The holes are arranged in three concentric circles, and are drilled at 22° (outer circle), 11° (middle circle), and 5° (inner circle) from the vertical toward the periphery to spread the spray pattern. The nozzles are directed upward, with each stream of water breaking into droplets at approximately 1 m above the nozzle and falling to the target surface.

Lightweight frames suspend the nozzles over the target area (Fig. 1). Each frame is 2.4 m square on legs 1 m high. Each of four nozzles is supported over the center of one-quarter of the enclosed 6.0-m^2 area on the end of a movable arm 0.8 m long. Movement of this arm allows partial compensation for drift at wind velocities below 3 km/hr. The frame can be moved relative to the target area, to

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Figure 1. Schematic diagram of complete portable field apparatus for rainfall simulation.

Figure 2. Rain simulation nozzle SRN 303, with type 303 stainless steel base, polyvinyl chloride orifice plate, and standard 3/8 in. (0.95-cm) pipe threads. (Bete Fog Nozzles, Inc., Greenfield, Massachusetts).

compensate for drift due to wind velocity, a major benefit of portability. With the aid of a removable yoke spanning the width of the frame, one person can lift and move a frame from plot to plot and position to position (approximate weight, 15 kg).

Water is pumped to nozzles through 0.79-cm-diameter Tygon tubing by an electrically powered, variable-pressure, positive displacement, self-priming pump (Model no. R2S1, Flotec, Inc., Norwalk, California). The entire system can be operated with a portable gasoline-powered electric generator for remote field studies.

Simulated rain water is stored prior to use in 465-liter polypropylene reservoirs (Nalgene Corp., Rochester, New York). A small check valve is necessary on the intake line in the reservoir to maintain the pump prime. A glass wool filter is utilized on the intake line to eliminate coarse debris reaching the nozzle orifices.

Stationary Greenhouse Apparatus

Mixed-bed resin deionizer cartridges (such as Model # C135, Hydro Services and Supply Co., Inc., Durham, North Carolina) are used to supply large amounts of water with very low ion concentrations (resistance 18 megohms/cm³). Concentrations of ions found in natural rain water may be added to provide a realistic simulation of the chemical composition of natural rainwater (Gambell and Fisher 1966; Likens 1972). Totally artificial rain water formulations also could be used.

Amounts and frequency of rain can be adjusted to simulate natural rates. The U.S. Department of Commerce Weather Bureau data provides useful guidelines for determination of realistic amounts and frequencies of application.

Because more reliable environmental control is afforded by greenhouse facilities, finer control of rain simulation is desirable for a greenhouse system than is possible with a field system.

Figure 3 is a schematic diagram of water flow and the associated electrical controls for a greenhouse system. This system utilizes a combination of six mist nozzles and three of the rain nozzles described above to allow reproduction of the episodic nature of natural precipitation events. By utilizing the principle of droplet collision and coalescence, a broader range of droplet sizes is generated by this system than with a system using rain nozzles alone.

To achieve maximum uniformity of distribution over the target area, the greenhouse system is designed to include a 1.2-m-diameter turntable which revolves at the rate of 2 rpm.

Water for the greenhouse system is drawn from building tap water, distilled, deionized, carbon filtered, and piped to the instrument at 55 psi ($3.79 \times 10^5 \text{ N/m}^2$). At the instrument, the make-up water is amended with desired chemical constituents by means of stock solutions metered into the flow stream by dilution pumps. The dilutions are mixed in 6.6-liter mixing cylinders, and samples of the diluent may be drawn at sample draw-off valves for chemical analysis. The stream then flows through 0.15- μm filters and solenoid valves into flow meters to allow flow regulation from operation to operation. The solenoid valves and the turntable motor are operated on a programmable 1-hr time clock, which is in turn operated by a programmable 24-hr time clock, permitting the cycling of as many rain events as desired through a daily regime.

Performance Measurements - Chemical

All solutions are routinely analysed for the following ions as recommended by Reuss (1975). Concentrations in parentheses are representative of levels (mg/l) occurring in natural rainfall (Cogbill and Likens 1974; Shriner 1976): Ca^{++} (0.21), Mg^{++} (0.06), Na^+ (0.12), K^+ (0.09), NH_4^+ (0.22), $\text{SO}_4 =$ (0.53), NO_3^- (0.74), Cl^- (0.43) and HCO_3^- (0.13).

Performance Measurements - Physical

To compare simulated rainfall with natural rainfall, the following physical measurements were made:

NOTE: THE SYSTEM CONSISTS OF THREE IDENTICAL SOLUTION DISTRIBUTORS. FOR CLARITY, ONE IS SHOWN

Figure 3. Schematic diagram of greenhouse system for rain simulation.

- (1) Droplet diameter,
- (2) Droplet velocity,
- (3) Droplet distribution, and
- (4) Intensity.

Droplet diameter was determined by two procedures: (1) the "flour" method described by Laws and Parsons (1943), and (2) the ozalid paper technique described by Engelmann (1962).

Droplet terminal velocity (V_t) was calculated by the formula (Miller 1967)

$$V_t = \frac{2}{9\pi} \cdot \frac{r^2 g d}{n}$$

where: r = radius of drop in cm,
 g = acceleration due to gravity,
 d = density of drop, and
 n = viscosity of air.

Intensity, reproducibility, and variability were measured by placing 49 600-ml beakers on a grid covering the target area. The depth of water collected in each beaker was recorded per unit of time (Fig. 4, Table 1).

PERFORMANCE RESULTS

Field and greenhouse evaluation over a period of three years of nearly continuous daily operation of the systems has proven them to be dependable with only routine maintenance required. In addition, as many as six frames have been operated in the field simultaneously from one pump and reservoir base, significantly reducing the cost of multiple-unit operation.

Droplet sizes produced by the nozzles ranged from 0.1 to 3.2 mm (Table 1). The frequency-size distribution was noticeably skewed towards a high frequency of smaller droplets. Simulated rain was

Figure 4. Distribution of simulated rain intensity along a turntable radius, greenhouse system.

Table 1. Comparison of water droplet diameters obtained with greenhouse and field systems

	Droplet size range (mm)	Droplets in size range (%)	Diameter of average droplet (mm)	Total volume (%)
Field system ^a	0.47-0.64	59	0.59	3
	0.65-0.94	35	0.81	8
	0.95-1.11	4	1.03	41
	1.12-1.23	2	1.16	48

Greenhouse system ^b	0.10-0.40	9	0.33	0.43 ^c
	0.41-0.80	48	0.68	1.3
	0.81-1.20	30	1.05	23.6
	1.21-3.20	13	1.60	74.7

^aAs determined by the method of Laws and Parsons (1943).

^bAs determined by the method of Engelmann (1962).

^cTaken from data of Laws and Parsons (1943).

produced at the rate of 0.5 to 2.7 cm/hr, depending on the nozzles used and the duration of their operation with the system operating at approximately 55 psi. Other operating pressures were not evaluated.

In the field, distribution of rain intensity over a 1.1-m^2 target area was the least satisfactory of the parameters evaluated. There was a low variability from "rain to rain", but a 31% variation between extreme points on the sample grid for individual "rains." This variation was confined primarily to the corners and edges of the distribution pattern. This problem was eliminated in the greenhouse system by the turntable, as evidenced by a 4% coefficient of variability.

Adjustable nozzle arms and the portable nature of the field frame allow it to be positioned to compensate for wind drift. Wind speeds above 3 km/hr may become prohibitive, however, necessitating operation of the apparatus either during those periods of the day that are calm enough to allow satisfactory performance, or with a wind shield.

Droplet terminal velocity was calculated to be 7.8 m/sec for 3-mm droplets. Laws (1941) calculated 2.2 m as the height of fall required by a 1-mm droplet to reach terminal velocity. Droplets fall from approximately 3 m in the greenhouse system.

Desired concentrations of ions in solution were satisfactorily maintained.

Variations in cation concentrations of rainfall simulant during operation of greenhouse system, November 1975 to April 1977

	Ca	Mg	Na	K
Mean of 20 random samples (mg/liter)	0.38 ± 0.18	0.26 ± 0.09	0.14 ± 0.06	0.13 ± 0.17

Materials used for construction of the apparatus were stable and suitable for use with corrosive solutions. A list of materials and their costs in 1975 are given in Tables 2 and 3.

DISCUSSION AND CONCLUSIONS

A maximum droplet diameter for "showers" (as opposed to "drizzles" or "heavy showers") has been reported to be between 0.6 and 0.9 mm for natural summer rainfall in Germany (Grunow 1960). Wiesner (1970) categorized rain drop sizes as: (1) steady light rain (0.1-mm av droplet diameter), (2) moderate rain (0.1-1.0 mm), (3) showers (1.0-2.5 mm), and (4) heavy showers (3.05 mm). A high frequency of rainfall droplet diameters in the range of 0.7 to 1.5 mm has been reported for showers studied in Hawaii (Blanchard 1955). The skewness of the droplet frequency-size distribution apparent in Table 1 also has been reported for natural rains (Laws and Parsons 1943).

The most frequent diameter class of droplets falling in a 2.5-cm/hour natural shower was 1.75 to 2.0 mm, according to Laws and Parsons (1943). The simulation systems achieved rates (2.5 cm/hr and mean droplet size (0.9 mm) comparable to those reported by Grunow (1960) for natural summer rainfall, but produced rainfall at a rate greater than that associated with comparable-sized natural droplets measured by Laws and Parsons (1943). In comparison, 0.59-to 1.16-mm droplets produced by the Purdue simulation apparatus had an intensity of 6.1 cm 1 hr (Bertrand and Parr 1961), equivalent to "heavy" natural rains. The apparent differences between the data of various investigators (Blanchard 1955; Grunow 1960; Laws and Parsons 1943) are assumed to represent the variability inherent in natural rainfall in various parts of the world.

The systems described above thus provide satisfactory simulation of rainfall droplet size and intensity comparable to natural rain of moderate intensity (1.27-2.54 cm/hr) (Mason 1962).

Table 2. Field rain simulator; list of materials and cost in 1973

Quantity/unit	Article	Approximate cost/unit
1	Plot frame, 2.4 m sq x 1 m, (8.0 ft sq x 3.0 ft), 5 cm x 5 cm (2 x 2 in.) pine, legs treated with pentachlorophenol. Braces of 2.5 x 5.0 cm (1 x 2 in.) pine and 1.6 cm (5/8 in.) exterior plywood (see Fig. 1).	\$ 20.00
4	SRN 303-nozzles (see detail) with type 303 stainless steel special polyvinyl chloride disc.	6.60
1 ^a	R2S1 Flotec self-priming positive-displacement pump. Type 316 stainless steel with Viton seals. 0.95-cm (3/8-in. IPS) intake and outlet.	121.00
1 ^a	1/2 hp electric motor	30.00
1 ^a	Time clock, 24-hr, 1 circuit	15.00
1 ^a	465 liter (110 gal) polypropylene reservoir	120.00
1 ^a	Hydro model C135 Ultra Pure water system, 250 liter/hr (60 gph) flowrate. Neutral pH, metal free, 18 megohms/cm ³ resistance @ 25°C, organics free, fluorescence free.	300.00
30.5 m (100 ft)	Tygon tubing, 0.79-cm (5/16-in.) bore, 0.16-cm (1/16-in.) wall	1.20
2	Nalgene tubing connectors	.40
1	Polyethylene "T" connector	.90
3	Polyethylene "Y" connectors	.90
1	Nalgene check valve	.70
2	Hosecocks	1.30
1	Glass wool, Pyrex, 454 g (1 lb)	<u>9.80</u>
Approximate total cost		<u><u>\$686.50</u></u>

^aItem has sufficient capacity to operate at least six units.

Table 3. Greenhouse rain simulator, list of materials and cost in 1975

Quantity/unit	Article	Approximate cost/unit
1	Tubular aluminum frame	\$100.00
3	SRN nozzles, polypropylene holders with ceramic discs, 28 holes 0.006 - in. dia.	60.00
6	PT-5 mist nozzles, 0.005-in. orifice, type 303 stainless steel	90.00
30 ft	Stainless steel tubing 3/8-in. OD	22.20
10 ft	Stainless steel tubing 1/14-in. OD	10.80
	Miscellaneous polypropylene tubing and fittings	118.40
20 ft	PVC pipe 3-in. SCH 40	20.00
6 each	PVC pipe cap	15.66
2	Flow gauges 3 to 290 ml/min water	141.00
1	Flow gauge 30 to 1900 ml/min water	88.25
3	Solenoid valves	51.00
3	15- μ m filters	143.00
1	Programmable time clock, 1-hr, 3 circuits	38.00
1	Programmable time clock, 24-hr, 2 circuits	40.00
3	Metering pumps	351.00
6	Hoke valves	91.35
1	Pressure regulator	6.00
1	Turntable	70.00
1	Controller enclosure 42-in.H x 24-in.W x 8-in.D	77.86
1	Turntable motor	120.00
1	Motor watchman	20.00
	Miscellaneous materials for fabrication and installation	600.00
	Total cost ^a	\$2280.00
	Labor cost in manhours	276.00

^aCost of duplicating the rainfall simulator depends on prevailing material and labor costs and the labor structure of the organization fabricating it.

The major disadvantage of the systems is the ease with which the 0.25-mm-diameter holes in the nozzles become plugged, especially in a field situation. Small caps to cover the nozzles between periods of operation should help correct this problem.

An additional modification which is necessary for systems in continuous operation is the shielding of nutrient-rich simulant stock solutions from sunlight to inhibit growth of algae. This can be achieved successfully at a minimum cost by coating all light-transmissive components of the systems with black paint.

It was determined during test operation of the greenhouse system that it is feasible to operate each third of the delivery system with different chemical constituents, permitting simulation of concentrated pollutant input during the early minutes of an individual rain event, followed by more dilute inputs characteristic of later stages of a rain event.

The systems described met the design criteria as follows:

- (1) Droplet size range from 0.1 to 3.2 mm,
- (2) Rate of application controllable between 0.25 and 5.0 cm/hour,
- (3) Realistic application intensity,
- (4) Droplet distribution maximum acceptable variability over target area = 20% (maximum variability measured was 4% in greenhouse, 31% in field),
- (5) Average rates of rainfall highly reproducible from "rain" to "rain,"
- (6) Complete portability by one person (field system only),
- (7) Resistance to corrosive solutions,
- (8) Cost of \$685/unit - field system, and
- (9) Cost of \$2280/unit - greenhouse system.

The systems have been used to expose not only vegetation, but soils and engineering materials, making them versatile tools in studies involving precipitation simulation.

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