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I am submitting herewith a thesis written by Shyam Prasad Rajbhandari entitled "Development of an Air-Entrained Rainfall Simulator for Field Plots." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering.

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DEVELOPMENT OF AN AIR-ENTRAINED RAINFALL
SIMULATOR FOR FIELD PLOTS

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ABSTRACT

Rainfall simulators have been widely used for many years to accelerate and extend studies of soil erosion, infiltration and run-off. Simulators make possible the production of rainfall of selected intensities and durations at any desired time and place. To obtain desirable drop characteristics, most existing simulators produce high application rates. These rates are reduced to desirable intensities by means of intermittent movement of the drop formers. The purpose of this study was to develop a rainfall simulator which would produce non-intermittent rainfall of desirable intensities and durations. The objectives of this research were (1) to design and construct a non-intermittent rainfall simulator, (2) to evaluate the uniformity of distribution obtained with the rainfall simulator and (3) to determine the fall velocity and size distribution of raindrops at selected intensities of simulated rainfall.

An air-entrained rainfall simulator capable of producing non-intermittent rainfall of selected intensities was developed with locally available and easily fabricated materials. It is easy to assemble, disassemble and transport, covers an effective area of 6.1 m x 6.1 m (20 ft x 20 ft) and has a provision for connecting additional units to cover large field plots. To vary the rainfall intensity, compressed air was injected into the water conduit through slits located 180 degrees apart and transverse to the direction of water flow. Photographs of the raindrops were taken using a high-speed camera in order to determine fall velocity and size distribution

of the raindrops. Depending upon combination of water-air pressure, one type of nozzle produced intensities ranging from 65 to 107 mm/h (2.6 to 4.2 in/hr). Distribution uniformity was satisfactory and median drop diameter (mass basis) was in the 2.0 to 2.5 mm range. Using a larger nozzle and various combinations of water-air pressure, intensities ranging from 85 to 154 mm/h (3.3 to 6.1 in/hr) were obtained. In one test, however, excessive air pressure resulted in a median drop size too small for this magnitude of intensity. Fall velocities of the simulated raindrops produced by one nozzle were approximately 15 percent more than the terminal velocities of natural raindrops of equal size. The high velocities were attributed to insufficient fall distance due to laboratory constraints and to inability to precisely determine drop size. While results were generally satisfactory, several minor modifications are suggested to improve performance and testing.

TABLE OF CONTENTS

CHAPTER		PAGE
I.	INTRODUCTION	1
	Brief History of Rainfall Simulation	1
	Need for a New Approach to Simulator Design	2
	Research Objectives	3
II.	REVIEW OF LITERATURE	4
	Rainfall Characteristics	4
	Rainfall Intensity	4
	Drop Size Gradation and Spatial Distribution	7
	Raindrop Fall Velocity	11
	Derived Parameters	13
	Types of Drop Formers	16
	Hanging Yarn	16
	Tubing Tip	17
	Spray Nozzle	18
	Types of Rainfall Simulators	19
	Reciprocating	19
	Rotating Boom	21
	Rotating Disk	21
	Desirable Features in Rainfall Simulators	22
III.	PROCEDURE	25
	Concept	25
	Design and Construction	25
	Desirable Features	25

CHAPTER	PAGE
Plot Size	26
Selection of Nozzle	26
Water-Air System	29
Conduit	34
Water pump	38
Air compressor	40
Frame	42
Testing	45
Facilities	45
Test site	45
Raingages	45
Uniformity of Distribution	46
Rainfall Intensity	48
High Speed Photography of Raindrops	51
IV. RESULTS AND DISCUSSION	55
Simulator Design	55
Uniformity of Distribution	55
Rainfall Intensity	59
Drop Size Distribution	61
Drop Fall Velocity	64
V. SUMMARY AND CONCLUSIONS	67
Summary	67
Conclusions	68
Recommendations for Further Study	69

REFERENCES	70
APPENDICES	75
APPENDIX A	76
APPENDIX B	80
APPENDIX C	100
VITA	105

LIST OF TABLES

TABLE	PAGE
1. Rainfall Characteristics Produced by Different Types of Nozzles	27
2. System Heads (m) for Selected Discharges	39
3. Pump Characteristics	40
4. Uniformity Coefficients and Rainfall Intensities for Various Spacings of Fulljet 50 WSQ Nozzles	56
5. Uniformity Coefficients and Rainfall Intensities for Various Spacings of Fulljet 30 WSQ Nozzles	57
6. Drop Size Distribution Obtained with Two Nozzles at Various Water and Water-Air Pressures	62
7. Comparison of Average Fall Velocities (V_f) of Raindrops Produced by Fulljet 50 WSQ Nozzles at Selected Water-Air Pressures to Terminal Velocities of Natural Raindrops	65
8. List of Materials and Costs	77
9. Simulated Rainfall Depth and Intensity at Different Water-Air Pressure	81
10. Fall Velocities of Raindrops Produced by Fulljet 50 WSQ Nozzles	101

LIST OF FIGURES

FIGURE	PAGE
1. Kinetic energy vs. height of fall for various diameters of water drops (from Palmer, 1962)	6
2. Raindrop size distribution at various rainfall intensities (from Laws and Parsons, 1943)	8
3. Water drop fall velocity vs. fall distance (from Laws, 1941)	12
4. Schematic of air-entrained rainfall simulator	30
5. Photograph of air-entrained rainfall simulator	31
6. Details of air injector and manifold	32
7. Photograph of air injector and manifold	33
8. Comparison of system head-discharge relationships to pump characteristic curve.	41
9. Details of frame connector	43
10. Photograph of frame connector	44
11. Location of raingages beneath simulator	47
12. Effect of nozzle spacing and pressure on uniformity coefficient for Fulljet 50 WSQ nozzles	49
13. Effect of water-air pressure on rainfall intensity for Fulljet 30 WSQ and 50 WSQ nozzles	50
14. Schematic of photographic setup	52
15. Relationship between drop diameter and percentage of indicated drop size (mass basis) at various rainfall intensities.	63

CHAPTER I

INTRODUCTION

A. BRIEF HISTORY OF RAINFALL SIMULATION

Rainfall simulation is a technique of applying water in a manner similar to that of natural rainfall. It makes possible the application of rainfall of desired intensities and durations at strategic times and field sites. Information may be obtained more rapidly and reliably than by depending upon natural rainfall. Rainfall characteristics have a strong influence on soil infiltration, runoff and soil erosion; and simulations have been used for many years in studies related to these phenomena. Soil erosion and associated environmental problems continue to be a plague, however, and a mobile, multiple-intensity simulator is needed to evaluate erosion control practices on large plots.

Soil erosion by water is initiated by the impact of water drops either directly onto the soil or on a thin water layer on the soil surface. Palmer (1965) reported that raindrop impact forces on the soil surface increase when a thin water layer covers the surface. Raindrops which fall on bare soil detach soil particles and reduce their size, thereby reducing the infiltration capacity of the soil and increasing surface runoff. Hadley and Lusby (1967) estimated a soil loss of 40.3 t/ha (18 t/ac) from a 4.9 ha (12 ac) watershed in western Colorado as result of a rainfall having an intensity of 50 mm/h (2 in/hr). Wischmeier (1962) found soil loss from a cotton

field of 8 percent slope at Guthrie, Oklahoma, to be 497 t/ha (222 t/ac) during a rainfall which had a maximum intensity of 152 mm/h (6 in/hr).

B. NEED FOR A NEW APPROACH TO SIMULATOR DESIGN

The soil erosion process consists of soil detachment, transportation and deposition. Soil detachability increases with increase in soil particle size, whereas soil transportability increases as the particle size decreases. Rainfall characteristics such as drop size, distribution, terminal velocity and intensity greatly influence this process. Likewise, the effects of rainfall and runoff on soil erosion are influenced by such factors as crop canopy, plant residue and tillage practices. Natural rainfall having desired intensities and durations cannot be relied upon when studying these effects at selected times and sites. Rainfall simulators are excellent research tools with which to study the complex interactions of rainfall, soil, topography and tillage under more controlled conditions than can be attained with natural rainfall.

Types of rainfall simulators which have been developed include reciprocating (Meyer and McCune, 1958), rotating boom (Swanson, 1965) and rotating disk (Morin et al., 1967). To attain desirable drop characteristics, most of these simulators produce high application rates. These rates are reduced to desirable intensities by means of intermittent movement of the applicator, with a rotating slotted disk under the drop former or by reducing the number of drop formers. In reciprocating and rotating-disk simulators, excess water is caught in

collectors and returned to a sump. Consequently, more water is pumped than is necessary to produce required rainfall intensities.

A somewhat complex mechanism is required for the reciprocating-type simulator, and components are not readily available or fabricated. However, this simulator has a provision for connecting multiple units for use on large plots (25.3 m^2). The rotating boom simulator produces a circular spray pattern which is inconvenient to use on rectangular plots. The rotating disk simulator covers a small area and is suitable for laboratory research only. The purpose of this study was to develop a rainfall simulator which would produce non-intermittent rainfall of desirable intensities and durations. The simulator should employ simple mechanisms fabricated from readily available components and should be applicable to large ($\geq 20 \text{ m}^2$) plots at various locations.

C. RESEARCH OBJECTIVES

Objectives of this research were:

1. To design and construct a non-intermittent rainfall simulator.
2. To evaluate the uniformity of distribution obtained with the rainfall simulator.
3. To determine the fall velocity and size distribution of raindrops at selected intensities of simulated rainfall.

CHAPTER II

REVIEW OF LITERATURE

A. RAINFALL CHARACTERISTICS

Rainfall intensity, drop size distribution and drop fall velocity are interrelated characteristics of rainfall and they have great influence on erosivity of the rainfall. Simulated rainfall, therefore, should closely represent these characteristics in order to produce reliable results.

1. Rainfall Intensity

Rainfall intensity is affected by storm type, location, atmospheric temperature, humidity and other variables. Rainfall intensity affects the amount of kinetic energy expended by raindrops striking the soil surface. Wischmeier and Smith (1978) state, "The energy of a storm is a function of the amount of rain and of all the storm's component intensities. Median drop size increases with rain intensity and terminal velocities of free-falling water drops increase with increased drop size. Since the energy of a given mass in motion is proportional to the velocity squared, rainfall energy is directly related to rain intensity." They derived the following equation to relate intensity to unit kinetic energy:

$$KE = 12.1 + 8.9 \log_{10} i \quad (1)$$

where,

KE = kinetic energy per unit area per unit rainfall,

m-Mg/ha-mm

i = intensity of rainfall, mm/h.

Wischmeier and Smith (1978) found soil erosion to be highly correlated with the product of a storm's kinetic energy (E) and maximum 30-minute intensity (I). They suggested that upper limits of i and I to be 76 mm (3 in) and 64 mm (2.5 in), respectively.

Palmer (1962) has shown a relationship between kinetic energy produced and height of fall for various sizes of water drops (Figure 1). If height of fall is a limiting factor, as when conducting a simulator, these curves may be used to determine the size of drops required to simulate a selected storm. For example, if rainfall of a specific intensity is to be simulated, kinetic energy produced by that intensity is calculated by using the above equation. Drop size required to produce the same amount of kinetic energy from a known height can then be determined from Figure 1.

Gray (1973) reported that the kinetic energy imparted by raindrops can also be calculated by the formula

$$KE = \frac{MV^2}{2} \quad (2)$$

where,

KE = kinetic energy, N-m

M = mass of raindrop, kg, and

V = fall velocity of raindrop, m/s.

He obtained approximately the same values for kinetic energy as those calculated by Wischmeier and Smith (1958). In studies involving

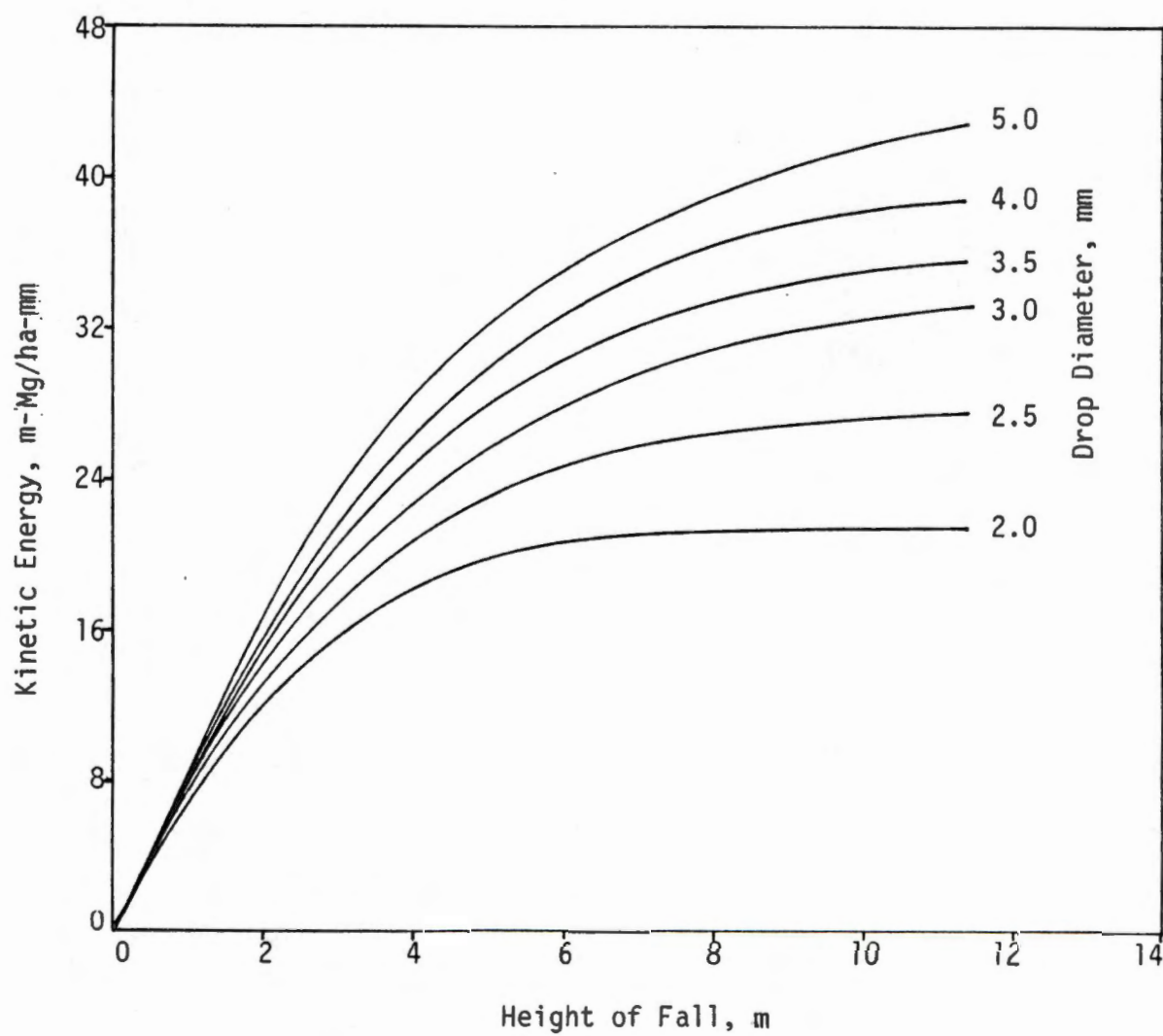


Figure 1. Kinetic energy vs. height of fall for various diameters of water drops (from Palmer, 1962).

sprinkler nozzles, Schleusener and Kidder (1960) found that energy imparted by water drops striking a target near the ground increased exponentially with increased distance from the nozzle.

Meyer (1979) reported that intensities of about 10 to 100 mm/h (0.4 to 4 in/hr) occur quite commonly and thus are of great importance in relationship to soil erosion. Severe erosion often occurs during high (75 to 150 mm/h) intensity storms, and most simulators have been designed to apply water at such intensities. Records of rainfall intensities and durations may be obtained from the National Weather Service, which has a network of meteorological stations throughout the United States.

2. Drop Size Gradation and Spatial Distribution

Natural rainfall contains a wide range of drop sizes. Laws and Parsons (1943) reported that drop sizes may vary from less than 1 mm to 7 mm. Control of drop size distribution is important in rainfall simulation. Because kinetic energy increases with drop size, detachment of soil particles and sealing of the soil surface would also increase with drop size if other factors remain unchanged. This would reduce infiltration and increase surface runoff. Small droplets are subject to wind-drift, whereas excessively large drops result in high concentration in small areas.

Rainfall intensity has a major effect on drop size distribution. Laws and Parsons (1943) presented relationships of drop size to total volume at selected rainfall intensities (Figure 2). They

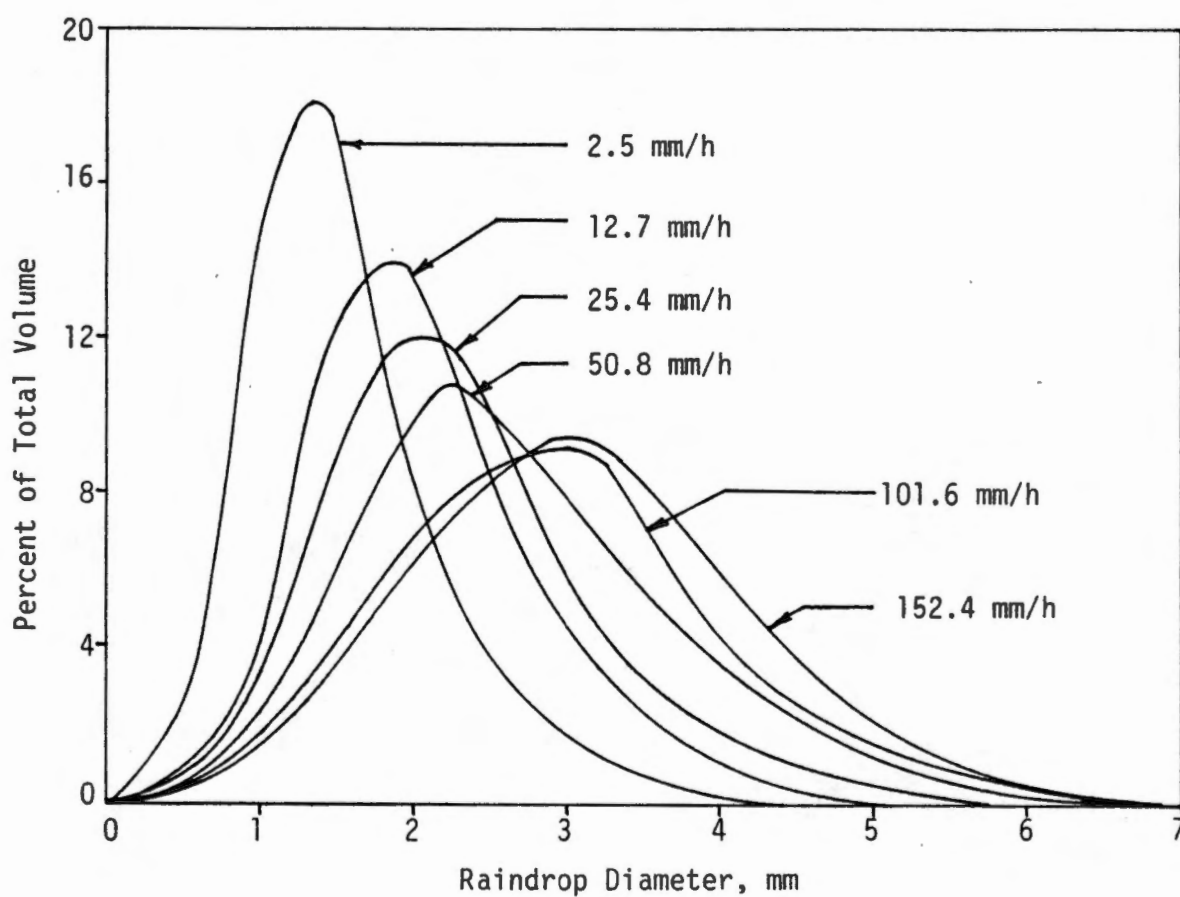


Figure 2. Raindrop size distribution at various rainfall intensities (from Laws and Parsons, 1943)

expressed the relationship between median drop size and rainfall intensity as

$$D_m = 1.24 I^{0.182} \quad (3)$$

where,

D_m = median drop size, mm

I = intensity of rainfall, mm/h

Other studies show the existence of a complex and variable relationship between drop size and rainfall intensity. Rogers et al. (1967) stated that drop size is exponentially related to intensity of rainfall up to an intensity of 50 mm/h (2 in/hr). At higher intensities, the median drop size remains relatively constant. Carter et al. (1974) calculated a cubic equation to describe this relationship for intensities up to 250 mm/h (10 in/hr) in south central United States. McGregor and Mutchler (1976) computed a three-term exponential relationship to relate the median drop size to intensity for Holly Springs, Mississippi, data. The different relationships between raindrop size and intensity found by the various researchers may be due to wide variation within and among storms, lack of data at high intensities and inability to accurately measure drop sizes. However, all the researchers show that mean drop diameter increases rapidly with increase of intensity up to about 50 mm/h (2 in/hr) and then tends to remain nearly constant.

Various methods have been used to determine drop size. Drop size can be calculated by weighing a known number of drops of a particular size. This technique was used by Laws (1941). He placed a bottle under a capillary tube and collected 10 to 30 drops. The

drops were then weighed on an analytical balance and the average weight per drop was computed. The diameter of the drop was calculated from the following equation:

$$D = \sqrt[3]{\frac{6W}{\pi\gamma N}} \quad (4)$$

where,

D = diameter of the raindrop, cm

W = weight of the raindrop, gm

γ = specific weight of water, gm/ml

N = number of raindrops.

Laws and Parsons (1943) used flour to determine droplet size. Raindrops were allowed to fall into a 2.54 cm (1 in) deep layer of fine uncompacted flour with a smooth surface. The flour surface was exposed to rain for about four seconds. Each drop produced a dough pellet which correlated very closely in size to the raindrop.

Green (1952) used photography to determine drop sizes. He restricted the depth of field to about 5 cm (2 in) to limit the error that would otherwise occur if the drops pictured were distributed over a wide range of distances from the camera. He placed two sheets of plywood 2.5 to 5 cm (1 to 2 in) apart in a vertical position. Sheet metal was used to prevent splash from entering the photographic field. Chalkboard black paint was used on the background surface. Sodium chloride and silver nitrate crystals were added to the water at a concentration of 10 parts per million for distinct identification of drops.

3. Raindrop Fall Velocity

Fall velocity of a raindrop is defined as distance fallen per unit of time. When raindrops fall through air, they obtain terminal velocities which vary with drop size. Laws (1941) and Gunn and Kinzer (1949) studied extensively the relationship of fall velocity to drop size and fall distance. Laws reported velocities of 3 to 10 m/s (10 to 33 ft/sec) for drops with diameters from 1.15 to 6.14 mm. Gunn and Kinzer studied velocities of raindrops ranging from 0.08 to 5.8 mm. Meyer (1979) reported that fall velocities vary from near zero for mist-sized drops to more than 10 m/s (33 ft/sec) for the largest drop sizes tested. He stated that a common size drop of 2 mm obtains a terminal velocity of 6 to 7 m/s (20 to 23 ft/sec).

Laws (1941) determined fall velocity as a function of drop size and height of fall (Figure 3). From Figure 3 it can be seen that a 2.0 mm diameter drop reaches terminal velocity after traveling a distance of 6 m (20 ft), whereas a 4 mm diameter drop approaches terminal velocity after falling a distance of 9 m (30 ft).

Terminal velocity of water drops may be determined by using a high-speed camera (Laws, 1941, and Green, 1952). They attached a scale vertically to a background board, and time required for a drop to span a given distance was determined by the camera shutter speed.

The terminal velocity of a raindrop can also be calculated by equating the hydrodynamic force with the gravitational force while neglecting other forces. Graf (1971) expressed a general equation to relate the hydrodynamic force with the gravitational force of a

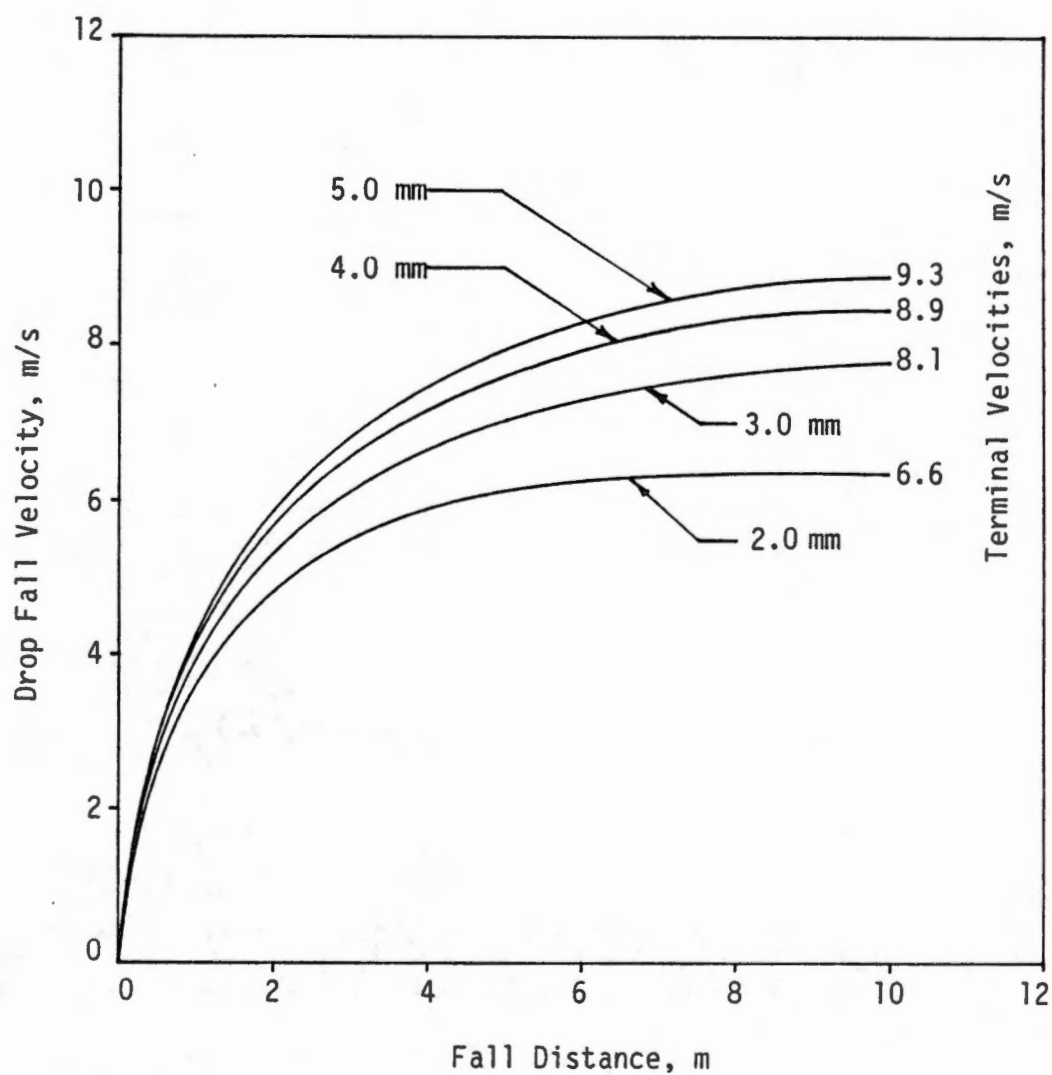


Figure 3. Water drop fall velocity vs. fall distance (from Laws, 1941).

spherical particle falling through a liquid medium. For a spherical raindrop, the equation can be written as follows:

$$C_D r^2 \pi \rho_a \frac{(V_W - V_a)^2}{2} = \frac{4}{3} \pi r^3 (\rho_W - \rho_a) g \quad (5)$$

where,

V_W = terminal velocity of raindrop, m/s

V_a = wind velocity, m/s

r = radius of the raindrop, m

ρ_W = density of water, kg/m³

ρ_a = density of air, kg/m³

g = acceleration due to gravity, m/s²

C_D = drag coefficient.

If the drops are falling through still air, the equation becomes:

$$C_D r^2 \pi \rho_a \frac{V_W^2}{2} = \frac{4}{3} \pi r^3 (\rho_W - \rho_a) g, \text{ and} \quad (6)$$

$$V_W = \left[\frac{8}{3} \frac{rg}{C_D} \left(\frac{\rho_W - \rho_a}{\rho_a} \right) \right]^{\frac{1}{2}} \quad (7)$$

(If C_D is inversely proportional to V^2).

4. Derived Parameters

Various parameters which influence the erosivity of natural rainfall have been studied and suggested for simulation. The most important parameters used for comparing natural rainfall to simulated rainfall are kinetic energy per unit rainfall, momentum per unit rainfall, kinetic energy per unit drop-impact area and momentum per unit drop-impact area. Meyer (1965) related these parameters to drop diameter and impact velocity and expressed erosivity as follows:

$$E \propto d^a V^b \quad (8)$$

where,

E = rainfall erosivity, cm^2/s

d = drop diameter, cm

V = drop fall velocity cm/s

a = 0 or 1

b = 1 or 2.

The values of a and b depend upon the parameter chosen by researchers for simulating rainfall. For example, kinetic energy, when expressed per unit rainfall, is proportional to the drop fall velocity squared (V^2), and momentum per unit of rainfall is proportional to velocity (V). Therefore, when erosivity is considered to be proportional to kinetic energy per unit of rainfall and momentum per unit of rainfall, erosivity will also be proportional to (V^2) and (V), respectively. In such an assumption, the value of (a) will be zero and that of (b) will be 2 and 1, respectively.

Rose (1960) found soil erosion to be more closely related to momentum than kinetic energy for subtropical rainfall conditions. Bubenzer and Jones (1971) applied multiple regression techniques to relate splash erosion to rainfall intensity and kinetic energy. They reported that splash produced by a large drop possessing a certain amount of kinetic energy was significantly greater than the splash produced by a number of small drops having the same amount of total kinetic energy. Bisal (1960) related sand splash to drop characteristics as follows:

$$\text{sand splash} = d V^{1.4} \quad (9)$$

where,

d = diameter of raindrop, cm

V = fall velocity of raindrop, cm/s.

The value of the exponent of velocity, 1.4, can be interpreted to mean that sand splash depends upon both momentum and energy, but not solely on one or the other.

Ekern (1950) stated that the amount of fine sand transported by drop impact was directly proportional to the total mass of water supplied and to a factor representing the energy per unit area supplied by an individual drop. To compare erosivity of storms, he calculated a factor of sand transport by using the following equation:

$$G = IT (-0.203 + 0.039 \frac{E}{A}) \quad (10)$$

where,

G = grams of fine sand transported from a 7.5 cm x 15 cm target

I = intensity of rainfall, cm/h

T = time, min

$\frac{E}{A}$ = average energy per unit area supplied by drops at the desired intensity, ergs/cm².

From the review of research, it appears that no single parameter best describes rainfall erosivity over a wide range of conditions. Therefore, a statement made by Meyer (1965) is still appropriate. He stated, "Until some parameter is proved to be adequate for comparison, this analysis suggests (a) that both the drop size

distribution and drop fall velocity of natural rainfall should be simulated as closely as possible and (b) that an appreciable sacrifice of either for the other is unwise. One of the parameters may be chosen as a guide, but influence should be secondary to a comparison with actual raindrop characteristics."

B. TYPES OF DROP FORMERS

The techniques and equipment most commonly used to produce simulated raindrops are classified into three categories: (1) hanging yarn, (2) tubing tip and (3) spray nozzle.

1. Hanging Yarn

Hanging yarn drop formers are limited to use in laboratory simulators and are best suited to intensive studies of the effect of particular rainfall characteristics. Parsons (1943) and Ellison and Pomerene (1944) used this technique. A muslin cloth was spread on a chicken wire screen. Depressions in the cloth were made at equal spacings and pieces of yarn were hung from the depressions. When applied in the form of spray, water drained into the depressions and filtered through to the hanging yarn to form drops. Application intensity was changed by varying the supply of water through the sprayer nozzle. The applicator operated in a reciprocating motion to prevent water drops from repeatedly falling onto the same spot. Bisal (1960) reported that drop size is dependent on yarn size and is limited to drops with diameters larger than about 4 mm.

2. Tubing Tip

This method of drop formation produces precise drop sizes and is suitable for intensive studies of specific rainfall characteristics such as intensity, drop size and terminal velocity. In this technique, a drop is formed at the tip of a tube and falls when the weight of the drop overcomes its surface tension. Ekern and Muckenhirn (1947) used 22-gage hypodermic needles in a 9.46 L (10 qt) aluminum container. They enclosed the needles in various sizes of glass tubing to vary drop sizes from 2.8 to 5.8 mm.

Mutchler and Moldenhauer (1963) designed and operated a laboratory rainfall simulator using telescoping pieces of tubes of 9, 12, 14 and 19 gage each 2.54 cm (1 in) long and overlapping the next smaller by 1.9 cm (0.75 in). The small tube controlled the flow of water and the large tube formed the required size of drops at the bottom end. Intensity of rainfall was varied by the water head over the drop formers and by the areal density of the drop formers. By using the above sizes of telescoping tubes, Mutchler and Moldenhauer were able to increase the drop sizes from 5.02 to 5.45 mm with increase of head from 7 to 17 cm (2.76 to 6.69 in) and flow rate from 6.34 to 14.23 ml/min. The applicator was rotated at one rpm so that water drops would not fall onto the same spot.

Consideration of fall velocity is important in the design of simulators using hanging yarn, hypodermic needles and telescoping tubes. Since drops formed by these devices do not have initial velocities, large fall distances are required for the drops to attain terminal velocities. As clogging of tubings and needles is one of the

main problems, distilled water is required in simulators which use these drop formers.

3. Spray Nozzle

Nozzles produce a wide range of drop sizes. Meyer (1979) reported that Grinnell 1.5 and Smiling Cat nozzles generally produced drop sizes more similar to those of natural rainfall than did other available nozzles. The nozzles were mounted to spray either upward or horizontally to reduce the application intensity at the ground surface. Since drops started falling from a limited height, velocity at impact was lower than the terminal velocity of raindrops.

Meyer and McCune (1958) used Veejet model 80100 commercial nozzles spraying downward in a simulator they called "Rainulator," and reported the nozzle to be more suitable for rainfall simulation than any other they tried. Morin et al. (1967) used the Spraying System 1.5 H 30 Fulljet nozzle to simulate low-intensity rainfall. Likewise, Fulljet 14 WSQ and 35 WSQ were tested by Lyles et al. (1969) to study effects of rainfall characteristics on cloud disintegration.

Rainfall simulators that use nozzles pointing downward produce raindrops with initial velocities. These velocities increase with pressure; however, drop sizes decrease as pressure increases. If the exit velocities are less than terminal velocities, drops accelerate during their fall. If the nozzles produce drops with velocities greater than their terminal velocities, fall velocities are reduced while traveling downward. According to Meyer (1979), when velocities

of water drops at nozzles are less than terminal velocities for large drops but greater than terminal velocities for small drops, both sizes tend to obtain their terminal velocities while falling.

C. TYPES OF RAINFALL SIMULATORS

The three types of rainfall simulators most commonly used are (1) reciprocating, (2) rotating boom and (3) rotating disk.

1. Reciprocating

This type of rainfall simulator uses the principle of intermittency to vary application rate. Meyer and McCune (1958) developed a rainfall simulator consisting of a series of frames supporting carriages on which Veejet model 80100 nozzles were mounted. A gasoline engine supplied the energy that operated the carriages in a reciprocating motion through a belt, gear and chain drive. Intensities of 64 and 127 mm/h (2.5 to 5 in/hr) were obtained. Meyer and McCune reported that the median drop diameter produced by their rainulator at a nozzle pressure of 41 kPa (6 psi) was 2.13 mm, compared to 2.5 mm diameter for natural raindrops at an intensity of 50 mm/h (2 in/hr). The simulator consisted of multiple units, each of which covered an effective area of 5.5 m (18 ft) across the slope by 4.6 m (15 ft) along the slope. Twelve units covered three plots, each 22.9 m (75 ft) long including borders. Although the Veejet nozzles produced the most desirable drop characteristics, operation had to be intermittent to reduce intensity.

Bubenzer and Meyer (1965) designed a laboratory rainfall simulator having three Veejet 80100 nozzles spraying downward from a height of 2.44 m (8 ft) onto a plot approximately 0.61 m by 3.1 m (2 ft x 10 ft). The nozzles were operated at 41 kPa (6 psi) pressure and oscillated at 180 rpm, each nozzle traversing the plot every 0.5 seconds. The intensity of application was varied by changing either the nozzle pressure or the distance between the shafts of the two drive sprockets.

Meyer and Harmon (1979) developed a rainfall simulator, called the Multiple Intensity Rainfall Simulator, to evaluate row side slope erosion, runoff and sediment size distribution for various types of field conditions on 0.7 m x 0.9 m (2 ft x 3 ft) plots. They used two nozzles side by side on the simulator. Veejet nozzles 80150, 80100 and 8070 were tested, and models 80150 and 80100 were selected because the drop size distribution and impact energy produced by these nozzles were more similar to those of natural rainfall than those produced by model 8070.

Shelton et al. (1981) installed rainfall simulators on ten plots, each 32.9 m (108 ft) wide and 30.5 m (100 ft) long. Each plot therefore covered 0.10 ha (0.25 ac). Riser assemblies were designed to give a drop fall distance of approximately 7.6 m (25 ft). Rain-Bird 65 PJ ADJ TNT sprinklers with 7.9 mm nozzles were used in the simulators. Application rates of 53 mm/h (2.1 in/hr) with one sprinkler and 106 mm/h (4.2 in/hr) with two sprinklers per riser were reported. The authors stated that, by varying the pressure, these intensities could be changed somewhat without appreciably changing

drop size and uniformity of distribution. In order to obtain uniformity of intensity by reducing intermittency and providing overlap pattern, each sprinkler was set to operate through a 90-degree arc. The Christiansen uniformity of application during five tests ranged from 0.75 to 0.94, with a mean of 0.83.

2. Rotating Boom

Swanson (1965) designed and tested a trailer-mounted rotating boom simulator to reduce labor requirements for assembly, operation and transportation. Ten booms were used to support 30 Veejet 80100 nozzles spraying downward. The nozzles were placed on radii of 1.52, 3.04, 4.56, 6.08 and 7.6 m (5, 10, 15, 20 and 25 ft) with 2, 4, 6, 8 and 10 nozzles on each radius. Intensities of 64 and 128 mm/h (2.5 and 5 in/hr) were obtained by operating 15 and 30 nozzles, respectively, at a height of 2.74 m (9 ft). The booms were operated at 3.5 to 4.0 rpm, and the simulator covered an area of 130 m² (1300 ft²).

3. Rotating Disk

Morin et al. (1967) developed a rotating-disk rainfall simulator which utilized large capacity Fulljet 1.5 H 30 full cone nozzles spraying downward. A metal rotating disk with a section aperture was provided under the nozzle. Drops reached the study area only when the aperture was immediately below the nozzle. In other positions, the water was thrown to the circumference of the rotating disk, from which it was drained to a storage tank for reuse. This simulator produced rainfall intensities of 15 to 143 mm (0.6 to 5.6

in/hr) at disk angular velocities of 0.5 to 200 rpm and nozzle pressure of 60 kPa (9 psi). The simulator covered a plot area of 1.04 m^2 (11 ft^2).

D. DESIRABLE FEATURES IN RAINFALL SIMULATORS

Meyer and McCune (1958), Bertrand and Parr (1961), and other researchers have reported the following desirable characteristics for a rainfall simulator:

1. Drop size distribution and fall velocity should be similar to that of natural rainfall.
2. Rainfall intensities should be in the range of storms producing medium to high rates of runoff and erosion.
3. The simulator should be capable of reproducing rainstorms at selected intensities and durations.

Meyer (1979) also suggested four additional design characteristics as follows:

1. Rainfall should be nearly continuous throughout the study area.
2. Angle of impact should be nearly vertical for most drops.
3. Size of the research area should be sufficient to satisfactorily represent the treatments and conditions to be evaluated.
4. The simulator should be easily transported from one site to another.

Most rainfall simulators produce high application rates if the nozzles are not operated in reciprocating or rotating motion. These

rates are reduced as required by moving the nozzles back and forth across the experimental plot (Meyer and McCune, 1958), by reducing number of nozzles on a rotating boom (Swanson, 1965) or by providing a rotating disk with a section aperture under a nozzle (Morin et al., 1967). These actions produce an intermittency of rainfall application which should be avoided for better simulation of natural rainfall. Sloneker and Moldenhauer (1974) studied the effect of varying the off-on time of rainfall simulator nozzles on surface sealing and intake rate, and reported problems when a wide range of intensities were simulated due to recovery of soil suction during the off-time. In reciprocating and rotating-disk simulators, excess water is drained to collectors and returned to a storage tank for reuse. Therefore, structural and power requirements must be greater than would be needed if the pumping rate were equivalent to the application rate.

Construction of reciprocating rainfall simulators requires somewhat complex mechanisms with parts which are difficult to obtain or fabricate. However, the reciprocating rainfall simulator has been designed such that additional units can be attached to cover a large area. The rotating boom simulator accommodates a circular area; therefore, it is inconvenient to use on a rectangular plot. Because it is trailer mounted, it requires minimum labor for assembly, operation and transportation. The rotating-disk simulator covers such a small circular area that it is suitable for laboratory research only.

An efficient, economical simulator which can produce continuous rainfall of desired intensities and durations, needs to be developed. It should be capable of applying all of the pumped water without exceeding realistic intensities. It should be fabricated from readily available materials and should not involve complex mechanisms. Ease of transport and assembly should be a major design criteria. The simulator should be designed such that it has a provision for connecting additional units in order to accommodate large areas when desirable.

CHAPTER III

PROCEDURE

A. CONCEPT

Simulator nozzle pressure must be sufficient to transform a jet pattern into a spray pattern having drop characteristics comparable to those of natural rainfall. Unfortunately, a large nozzle operated at low pressure so as to produce a low intensity produces large drops, but a small nozzle operated at high pressure produces drops which are too small. An idea was conceived, therefore, to inject compressed air into the water conduit so that nozzle pressure could be controlled without varying the discharge. The two-phase flow thus generated, with proper selection of nozzle type, size and operating pressure, would permit non-intermittent flow, utilize all of the pumped water, and provide required drop sizes and intensities.

B. DESIGN AND CONSTRUCTION

1. Desirable Features

The desirable features listed in Chapter II were incorporated into the design. Additional features were:

- a. simple and economical to construct and operate, and
- b. provision for connecting additional units to simulate rainfall on large field plots.

2. Plot Size

To produce most reliable results, field research related to such phenomena as soil erosion, infiltration and runoff should be conducted on plots sufficiently large to be representative of soil, topographic and land-use conditions. Upon consideration of these factors, as well as materials of construction, a plot size of 6.1 m x 6.1 m (20 ft x 20 ft) was selected.

3. Selection of Nozzle

Prior to the design of the prototype simulator, an air-entrained single-nozzle rainfall simulator was constructed to test different types and sizes of nozzles with respect to drop size and intensity. A description of the air-entrainment technique will be given in Section 4. Veejet* 80100 and 80150, Teejet 80100, as well as $\frac{1}{2}$ WSS nozzles produced undesirable drop sizes and/or intensities. Seven sizes of Fulljet Square spray nozzles were then tested at various water and air pressures, and results are given in Table 1. Pressures were not measured at the nozzle but at the pump and at the air supply line. Rainfall was collected in a standard non-recording raingage for 15 minutes during each test, and intensity was calculated. Even by keeping water pressure constant, intensity of rainfall could be easily varied by changing the air pressure (Table 1).

*Mention of trade products or companies in this thesis does not imply that they are endorsed by the Department of Agricultural Engineering. Trade names are used here for convenience in reference only.

Table 1. Rainfall Characteristics Produced by Different Types of Nozzles

Nozzle Type	Water Pressure (kPa)	Air Pressure (kPa)	Intensity (mm/h)		Drop Size	Remarks
			Nozzle Height (m) 2.44	3.00		
Fulljet	48	0	-	91	Small	drops too small
HH 18 SQ	48	34	-	89	Small	
	55	0	142	94	Small	
Fulljet	55	41	132	89	Small	excessive intensity
	48	0	-	171	Medium	
	48	34	-	158	Medium	
	55	0	257	216	Medium	
Fulljet	55	41	236	159	Medium	excessive intensity
	48	0	-	146	Large	
	48	34	-	131	Large	
	55	0	203	162	Large	
Fulljet	55	41	170	128	Large	low intensity, small drops
	48	0	-	28	Small	
	48	34	-	36	Small	
	55	0	33	33	Small	
Fulljet	55	48	43	38	Small	satisfactory
	48	0	-	74	Medium	
	48	34	-	81	Medium	
	55	0	89	79	Medium	
Fulljet	55	48	91	79	Medium	similar to 50 WSQ
	48	0	-	79	Large	
	48	34	-	79	Large	
	55	0	97	79	Large	
Fulljet	55	41	150	84	Large	satisfactory
	48	0	-	79	Large	
	48	34	-	91	Large	
	55	0	99	81	Large	
Fulljet	55	48	135	99	Large	

At this stage of the experiment, drop sizes were qualitatively described as small, medium or large.

Review of literature indicated that the nozzles located at heights of 2.44 m to 3.00 m (8 to 10 ft) produced desirable drop sizes having terminal velocities when they hit the ground. Therefore, the nozzles were tested at these heights. The HH 30 WSQ nozzle produced medium intensity and drop size from heights of both 2.44 m (8 ft) and 3.00 m (10 ft). Results obtained with nozzles HH 45 WSQ and HH 50 WSQ were similar, and intensities and drop sizes were within the required range. Since nozzle HH 30 WSQ produced medium intensity (74 mm/h) and nozzles HH 45 WSQ and HH 50 WSQ produced high intensities (140 mm/h) from heights of 2.44 m (8 ft) and 3.00 m (10 ft), it was decided to use HH 30 WSQ and HH 50 WSQ nozzles for tests in the prototype simulator. When using the Fulljet HH 30 WSQ and HH 50 WSQ nozzles, intensities of rainfall ranged from 74 to 140 mm/h (3 to 5.5 in/hr) and drop sizes ranging from medium to large were produced.

Experiments were conducted to determine if the air-water interface should be internal or external relative to the nozzle. When applying the air jet at low pressure outside the nozzle, there was very little effect on the spray pattern. However, at high pressure, atomized droplets were produced. It was concluded, therefore, that external mixing would not produce desirable drop characteristics. Air was then injected into the water conduit through two 0.64 cm (0.25 in) diameter tubes located 180 degrees apart and transverse to the flow of water. This arrangement created turbulence in the air-

water mixture and produced the desirable combination of intensity and drop size.

4. Water-Air System

A schematic of the prototype rainfall simulator water-air system and support frame is shown in Figure 4 and a photograph is shown in Figure 5. Water for the simulator was pumped from a storage tank and supplied to a manifold with a 4.57 m (15 ft)-long rubber hose. This length was selected to allow for variation of the simulator height. A gate valve was used to control the flow of water. Compressed air was supplied from an air compressor to a 4.57 (15 ft)-long vinyl tube 1.9 cm (0.75 in) in diameter. The air line was divided into two tubes of equal diameter immediately ahead of the mixer. The two tubes were then attached to openings located 180° apart in the water conduit. These openings (0.32 cm x 2.22 cm) were milled into a galvanized nipple (3.81 cm x 5.08 cm). A piece of 1.27 cm x 2.54 cm (0.5 in x 1.0 in) nipple was then welded onto the larger nipple over each opening.

The water and compressed air were mixed in a funnel-shaped chamber of a manifold fabricated from PVC pipe fittings (Figure 6). A photograph of the air injector and manifold is shown in Figure 7. The chamber was supported on the side connector of the simulator structure with its large end facing upward. The large end of the chamber was divided into 40° radial sections. Nine outlets of 1.27 cm (0.5 in) diameter were made on each section at a radius of 5.71 cm (2.25 in) so that distribution of the air-entrained water would be



Figure 5. Photograph of air-entrained rainfall simulator.

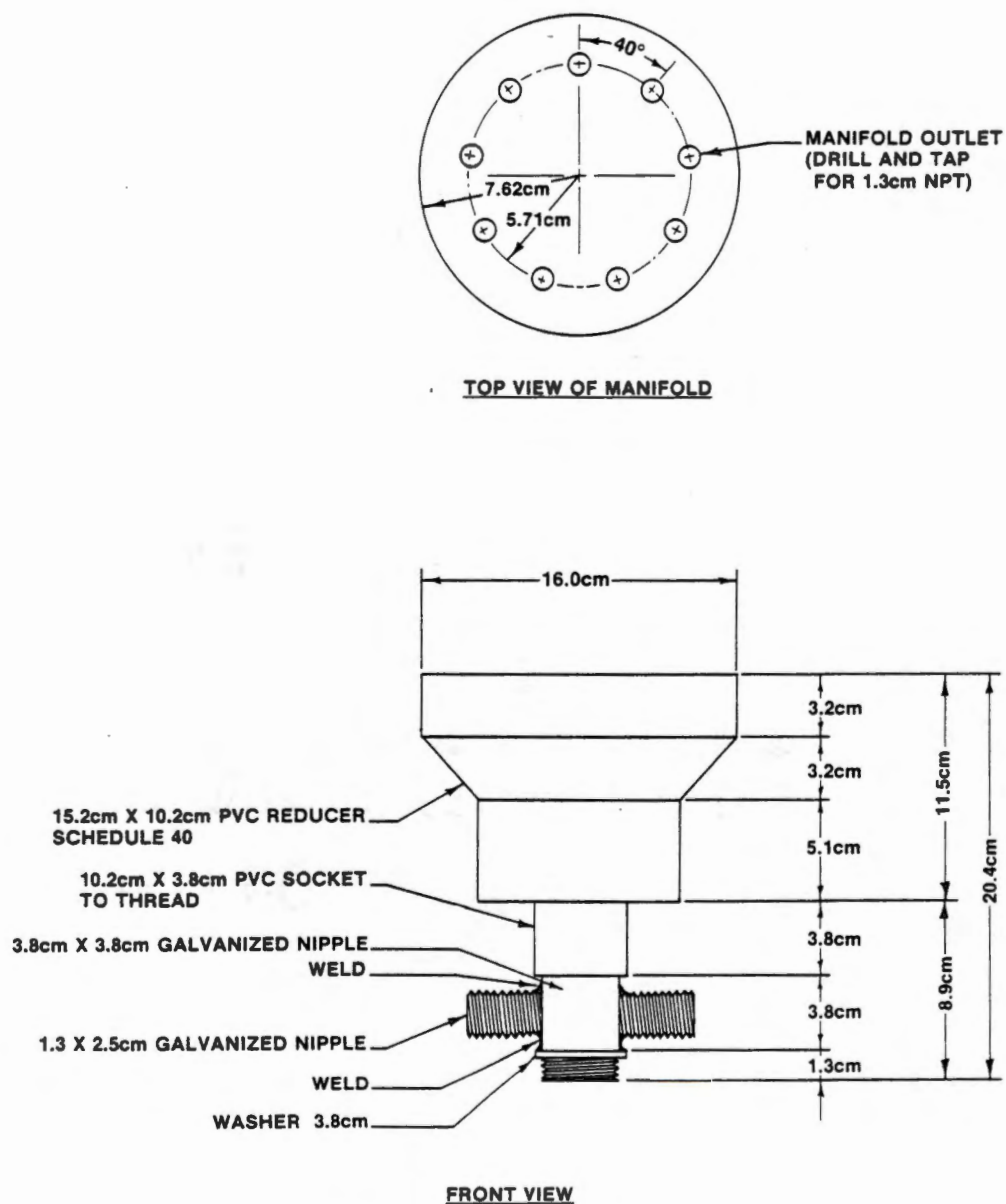


Figure 6. Details of air injector and manifold.

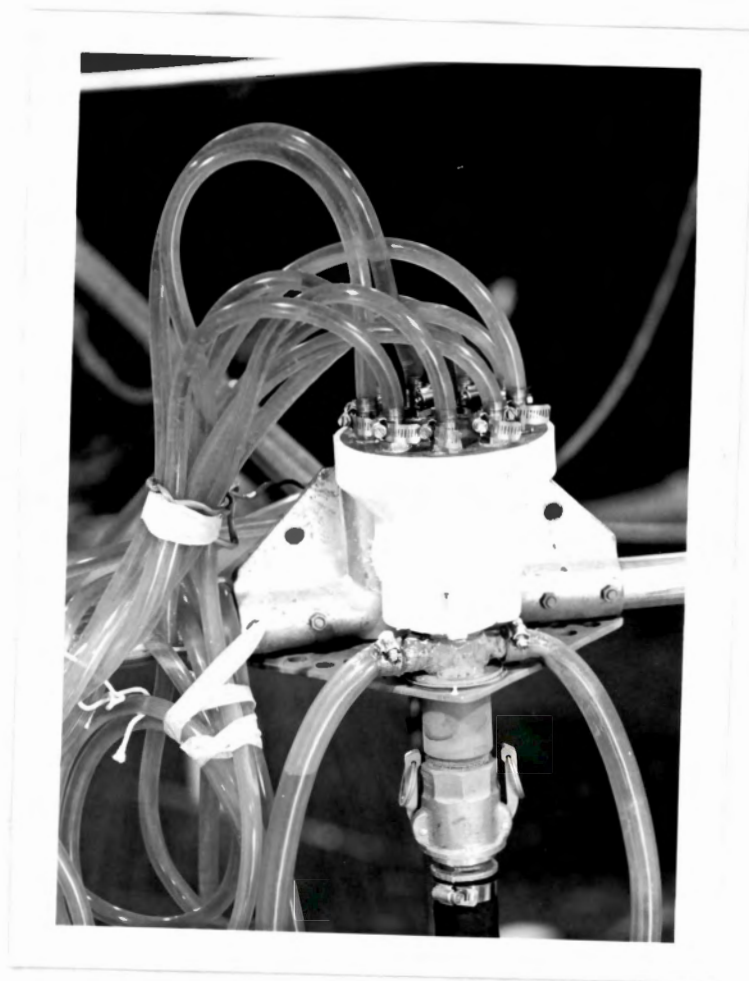


Figure 7. Photograph of air injector and manifold.

uniform in all outlets. A 1.27 cm (0.5 in) vinyl tube extended from the chamber to each of nine nozzles. The nozzles were inserted into brass tees to which brace bands were welded for mounting onto the frame. Nozzle spacings were easily changed by moving braces and/or the pipe on which the nozzles were mounted.

a. Conduit. Computation of frictional loss in a pipe system is a primary consideration of hydraulic design. The frictional loss in the mainline was calculated by using the Hazen-Williams equation:

$$H_f = \frac{10.7 \times \left(\frac{Q}{C}\right)^{1.852} \times L}{D^{4.87}} \quad (11)$$

where,

Q = discharge, m^3/s

C = roughness coefficient

D = diameter of conduit, m

H_f = frictional loss, m

L = length of conduit, m.

If water is removed at intervals along a conduit, the frictional loss for a given diameter and length of conduit would be less than if the flow were constant for the entire length. To accurately determine the frictional loss in the lateral, the calculation should start with the outlet nearest to the supply line and continue past each outlet. Christiansen (1942) simplified this lengthy process by developing an adjustment factor 'F' to correct the frictional loss calculated from the general formula which assumes all of the water is carried to the end of the line.

Christiansen calculated friction loss by using the equation:

$$H_f (L) = F K \frac{L}{100} \left(\frac{Q}{C}\right)^m \quad (12)$$

In the Hazen-Williams equation, $m = 1.852$, and $n = 1.167$. Therefore,

$$H_f = \frac{F \times 10.7 \times \left(\frac{Q}{C}\right)^{1.852} \times L}{D^{4.87}} \quad (13)$$

Values of 'F' can be approximated from the expression:

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2} \quad (14)$$

where,

N = number of nozzles.

Pressure at each nozzle must be equal to produce rainfall of uniform intensity throughout the study area. Therefore, water was supplied from the manifold to each nozzle through individual laterals of equal length so that pressure loss would be approximately equal in all the laterals. Although there were some differences in head loss due to bending and curling of the vinyl tubing, these differences were considered to be negligible. Maximum distance between the manifold and nozzle was about 6.1 m (20 ft), and tube lengths of 6.71 m (22 ft) were used to provide a margin for adjustment of nozzle spacing. For one nozzle per lateral, the value of adjustment factor 'F' is equal to unity, and Christiansen's friction loss equation would be the same as the Hazen-Williams equation for calculating head loss.

The Fulljet model HH 50 WSQ wide angle square spray nozzle produced a maximum intensity of 150 mm/h (6 in/hr) when discharging 0.23 L/s (3.7 gpm) per nozzle at a pressure of 34 kPa (5 psi). Consequently, nine nozzles were needed for uniform application on the 6.1 m x 6.1 m (20 ft x 20 ft) plot area. Frictional losses were computed as follows:

(1) Mainline

(a) Assume internal diameter of rubber hose, $D = 3.81$ cm
(1.50 in) = 0.0381 m;

(b) roughness coefficient for rubber hose, $C = 140$
(from Water and Waste Treatment Handbook, 1961).

(c) discharge for nine nozzles @ 0.23 L/s (0.00023 m³/s)
per nozzle, $Q = 0.00023 \times 9 = 0.0021$ m³/s;

(d) total effective length

length of hose = 4.57 m

equivalent lengths of fittings:

gate valve = 0.30 m

tee = 0.70 m

total effective length, $L = (4.57 + 0.30 + 0.70)$ m
= 5.57 m

By applying the Hazen-Williams equation,

$$H_f = \frac{10.7 \times \left(\frac{Q}{C}\right)^{1.852} \times L}{D^{4.87}}$$

$$= \frac{10.7 \times \left(\frac{0.0021}{140}\right)^{1.852} \times 5.57}{(0.0381)^{4.87}}$$

$$= 0.56 \text{ m}$$

$$= 5.49 \text{ kPa (0.8 psi).}$$

For $D = 4.45 \text{ cm (1.75 in)}$

$$H_f = 0.26 \text{ m}$$

$$= \underline{2.59 \text{ kPa (0.37 psi).}}$$

Head loss due to friction in the 3.81 cm diameter hose was more than twice that in the 4.45 cm (1.75 in) hose. The head loss is not critical in this situation, however, and the smaller hose was selected to reduce weight and cost.

(2) Laterals

Friction loss from the manifold to each nozzle was computed as follows:

- (a) Assume a diameter of vinyl tube, $D = 1.27 \text{ cm}$
(0.50 in) = 0.0127 m
- (b) roughness coefficient for vinyl tube, $C = 160$
- (c) discharge per nozzle, $Q = 0.00023 \text{ m}^3/\text{s}$
- (d) length of lateral tube, $L = 6.71 \text{ m}$.

By using the Hazen-Williams equation,

$$H_f = \frac{10.7 \times \left(\frac{Q}{C}\right)^{1.852} \times L}{D^{4.87}}$$

$$= \frac{10.7 \times \left(\frac{0.00023}{160}\right)^{1.852} \times 6.71}{(0.0127)^{4.87}}$$

$$= 1.86 \text{ m}$$

$$= \underline{18.26 \text{ kPa (2.65 psi)}}.$$

For $D = 0.95 \text{ cm (0.37 in)}$

$$H_f = 7.66 \text{ m}$$

$$= \underline{75.06 \text{ kPa (10.89 psi)}}.$$

For $D = 1.90 \text{ cm (0.75 in)}$

$$H_f = 0.26 \text{ m}$$

$$= 2.57 \text{ kPa (0.37 psi)}.$$

Upon consideration of the above head-loss values, and cost and weight of materials, the 1.27 cm vinyl tube was selected for laterals.

b. Water pump. A pump was selected by comparing the system head-discharge curve to the pump characteristic curves supplied by manufacturers. To draw the system curve, discharges produced by different heads were determined as follows:

$$Q_1 = KA \sqrt{P_1} \quad (15)$$

$$Q_1^2 = (KA)^2 P_1 \quad (16)$$

and

$$Q_2 = KA \sqrt{P_2} \quad (17)$$

$$(Q_2)^2 = (KA)^2 P_2 \quad (18)$$

Therefore,

$$\left(\frac{Q_2}{Q_1}\right)^2 = \frac{P_2}{P_1} \quad (19)$$

$$\therefore P_2 = P_1 \left(\frac{Q_2}{Q_1}\right)^2 \quad (20)$$

where,

P_1 = pressure at nozzle, kPa

P_2 = pressure to be determined, kPa

Q_1 = total discharge from all the nozzles at pressure P_1 ,
L/s

Q_2 = discharge at pressure P_2 , L/s.

Assuming that each of the nine nozzles is located at the manifold, and operates at a pressure of 34 kPa (5 psi) and a discharge of 0.23 L/s (3.7 gpm), heads due to lift, friction and discharge pressure for selected discharge rates were computed (Table 2).

Table 2. System Heads (m) for Selected Discharges

Head Source	Discharge, L/s						
	1.51	1.76	2.02	2.10	2.27	2.52	2.77
Lift	5.50	5.50	5.50	5.50	5.50	5.50	5.50
Friction	0.31	0.41	0.52	0.56	0.65	0.79	0.95
Discharge	1.83	2.49	3.25	3.52	4.11	5.08	6.15
Total	7.64	8.40	9.27	9.58	10.26	11.37	12.60

A 373W (0.5.hp) Teel centrifugal pump having a constant operating speed of 3450 rpm was considered. Performance characteristics of the pump are shown in Table 3. To determine operating head and discharge, the system head-discharge relationships were compared to the pump characteristic curve (Figure 8).

Table 3. Pump Characteristics*

Discharge, L/s At Total Head, m			
6	9	12	15
3.23	2.78	2.31	1.73

*Teel Model 3P 551 A

The figure shows that the pump discharges 2.48 L/s (39 gpm) at the operating head of 11.1 m (36.4 ft). The design discharge and head were 2.1 L/s (33 gpm) and 9.58 m (31.4 ft), respectively. The operating discharge and head were close to the design discharge and head, and the selected pump (Teel Model 3P 551 A) was acceptable.

c. Air compressor. A Dayton 246W (0.33 hp) diaphragm compressor (model 4Z024) having a capacity of 1.40 L/s (0.04 cfs) at 414 kPa (60 psi) pressure was selected. The compressor is rated for continuous operation and, with the pump, will develop the maximum air-water pressure of 62 kPa (9 psi) needed at the nozzle to produce desirable intensities and drop sizes.

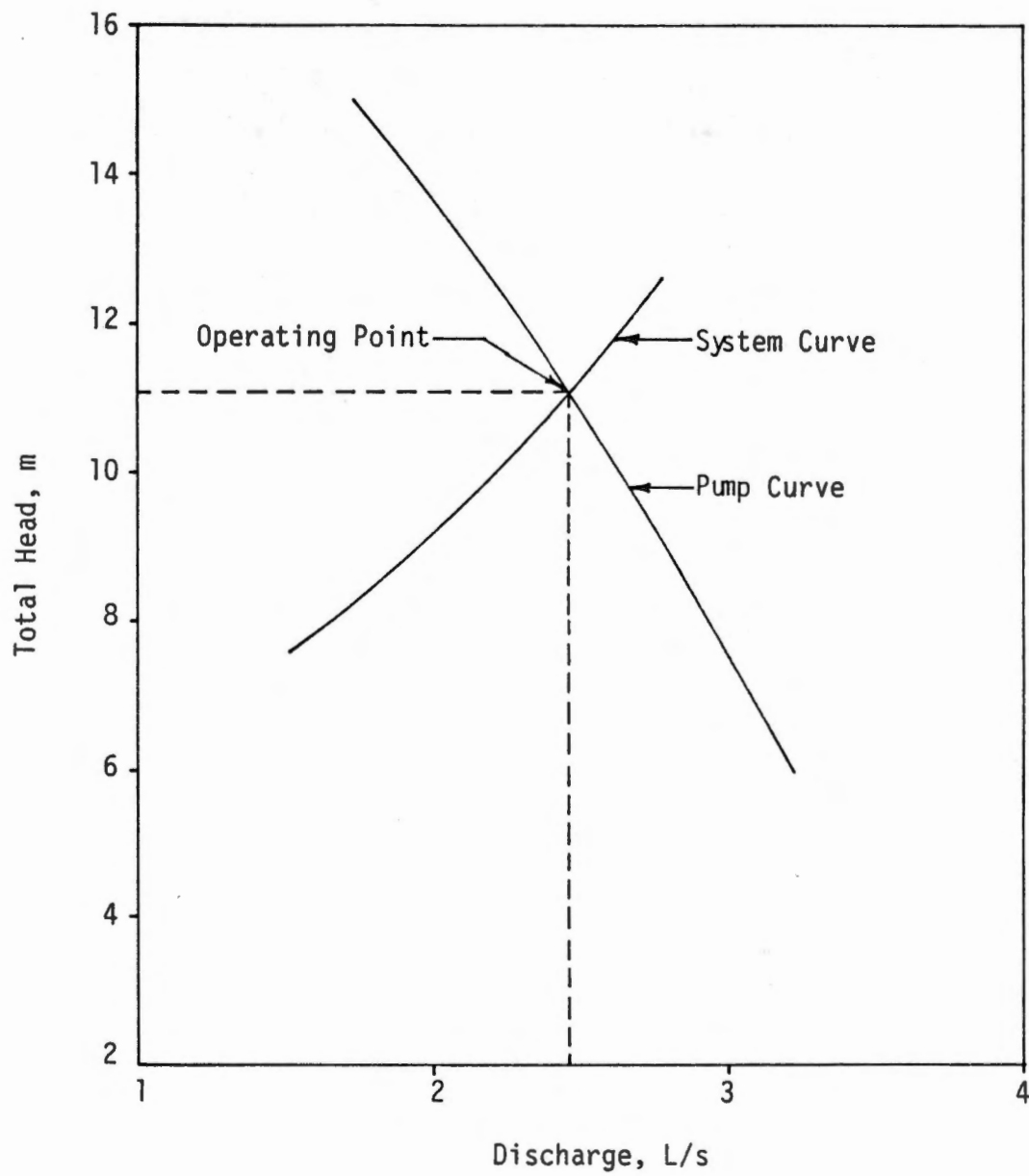


Figure 8. Comparison of system head-discharge relationships to pump characteristic curve.

5. Frame

Most of the simulator frame was fabricated from materials used in construction of chain link fences. Pipe fence rail 4.12 cm (1.62 in) in diameter was cut into eight 3.25 m (10.66 ft) lengths to construct a 6.78 m x 6.78 m (22.2 ft x 22.2 ft) frame (Figure 4, page 30). Gate ells having an inside diameter slightly larger than the outside diameter of the pipe were fastened to the end of each pipe with 0.31 cm x 5.71 cm (0.12 in x 2.25 in) bolts. Pipe ends were joined at the center and corners of the peripheral frame by placing and bolting the gate ells onto a shop-made connector (Figure 9). A photograph of the frame connector is shown in Figure 10. An extra post was welded onto the end and corner connectors to attach additional units if desired.

A pipe 6.71 m (22 ft) long and 4.12 cm (1.62 in) in diameter with gate ells at its ends was used to connect the center of two opposite ends of the frame. Two pieces of pipe, each 3.30 m (10.82 ft) long, were used to connect the center of the sides to the center of the long pipe using gate ells on the side and a line rail clamp at the center. Thus, the entire frame was divided into four square compartments.

Four pieces of pipe 3.34 m (10.96 ft) long were connected to the center and side pieces of the main frame with end and line rail clamps to support the nozzles. The nozzles can be moved relative to the length and width of the plot by loosening the rail clamp on the pipe and on the nozzles. The frame was supported at a nozzle height of 2.38 m (7.81 ft) on four legs positioned at the corners. The

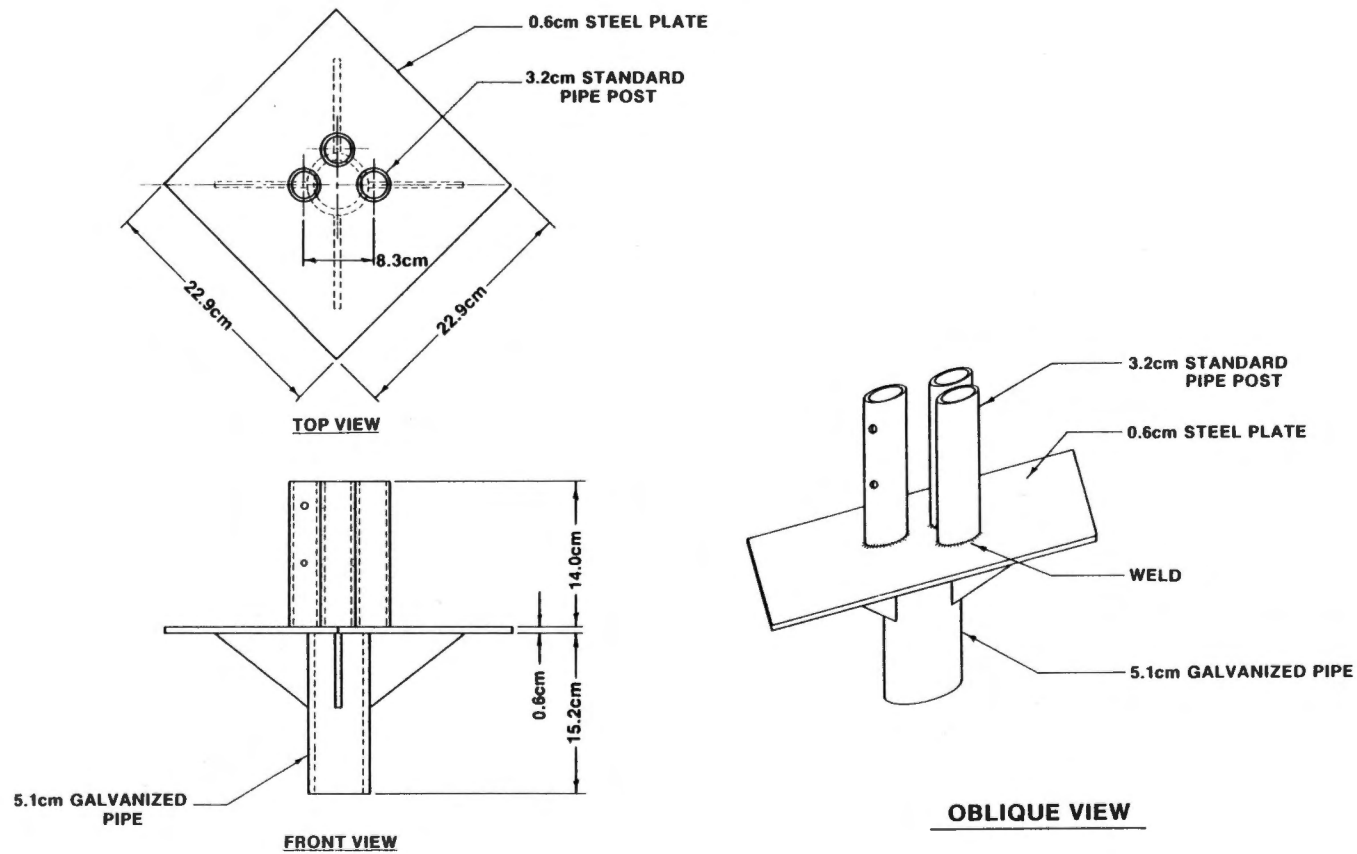


Figure 9. Details of frame connector.



Figure 10. Photograph of frame connector.

nozzle height was limited to 2.38 m (7.81 ft) because a heater located on the laboratory wall prevented a minimum height of 2.44 m (8 ft) as discussed in Section B.3. Telescoping legs permit easy adjustment for nozzle height and field slope. Top rail pipe cut into lengths of 1.52 m (5 ft) was used to brace the frame at the legs. An additional leg was provided at each side of the frame to support the weight of the hose and water supply. Galvanized steel aircraft cable 0.32 cm (1/8 in) in diameter was attached as indicated in Figure 4, page 30, to provide additional support against bending. A list of materials and costs is given in Appendix A (Table 8).

C. TESTING

1. Facilities

a. Test site. The experiment was conducted in the Soil and Water Laboratory of the Department of Agricultural Engineering at the University of Tennessee, Knoxville. A tank located underneath the laboratory floor was used to store water. A vinyl plastic sheet was laid over the floor under the simulator to guide the water to a channel and thence back to the sump for recirculation.

b. Raingages. Sixteen containers made from 15.24 cm (6 in) diameter PVC pipe were irregularly spaced on the floor beneath the simulator to determine rainfall intensity and uniformity of distribution. The pipe was cut to lengths of 20.32 cm (8 in) and circular plates with diameters equal to that of the pipe were cemented at the

bottom of each piece. The top edge of each gage was beveled to a 45 degree angle to prevent splash effect.

2. Uniformity of Distribution

Simulated rainfall should be uniformly distributed over a test area. A numerical expression is required to serve as an index of uniformity of distribution. In a study of distribution patterns of irrigation sprinklers, Christiansen (1942) used a numerical expression called the uniformity coefficient as an index of uniformity. The uniformity coefficient, expressed as a percentage, is defined by the equation:

$$C_u = 100 \left(1.0 - \frac{\sum (x_i - \bar{x})}{N \bar{x}} \right) \quad (21)$$

where,

x_i = individual observation

$\bar{x}$ = mean value

N = number of observations

C_u = coefficient of uniformity (100 percent represents perfect uniformity).

To determine the uniformity of distribution, the sixteen PVC containers were placed within the 6.1 m x 6.1 m (20 ft x 20 ft) area immediately below the simulator, as shown in Figure 11. Tops of the containers were 2.23 m (7.31 ft) below the nozzles. Nine Fulljet nozzles were mounted on the simulator at a selected spacing. The pump was started and the pressure at the nozzles was set by regulating the gate valves located at the pump and compressor. Each test

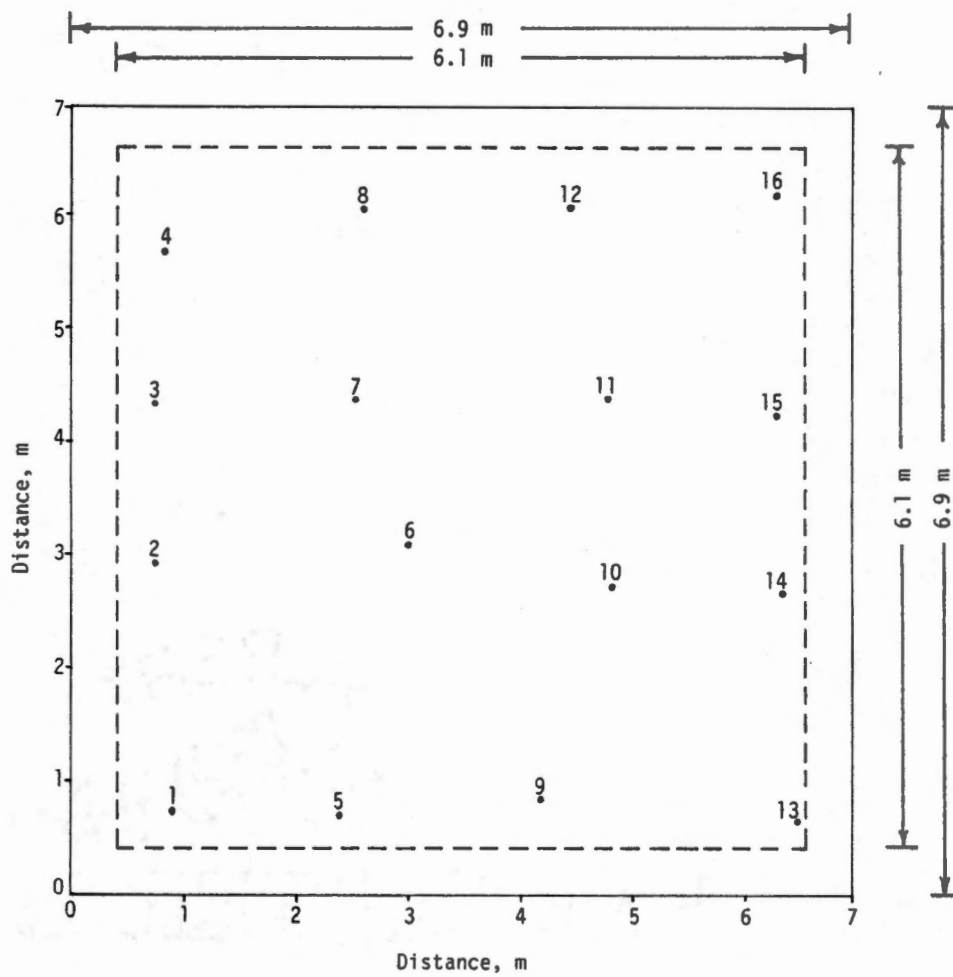


Figure 11. Location of raingages beneath simulator.

was run for 30 minutes, after which depths of water in the containers were measured. For the first test, 50 WSQ nozzles were inserted at a spacing of 2.29 m (7.50 ft). The water pressure at the nozzle was set at 14 kPa (2 psi) and no compressed air was used. Subsequent tests were conducted by maintaining constant water pressure but injecting compressed air into the mixing chamber at selected pressures. The air-water pressure at the nozzle and the catch in each gage were recorded for each test. A second set of tests was run using 21 kPa (3 psi) pressure of water and various air pressures. Similarly, experiments were performed with different nozzle spacings and water pressure (Appendix B, Table 9). Tests were also conducted with Fulljet 30 WSQ nozzles at different air-water pressures and nozzle spacings.

Christiansen's equation for uniformity coefficient was programmed into a desk calculator. Coefficients of uniformity were calculated by inputting the depths of water collected for each 30-minute test. Uniformity coefficients were plotted against nozzle spacings in order to determine the relationship between spacings and uniformity of distribution for each nozzle (Figure 12).

3. Rainfall Intensity

Using the procedure described in part 2, rainfall intensity was determined for various combinations of air and water pressure with Fulljet 30 WSQ and 50 WSQ nozzles (Appendix B, Table 9). Data were plotted to evaluate the relationship between air-water pressure and rainfall intensity (Figure 13).

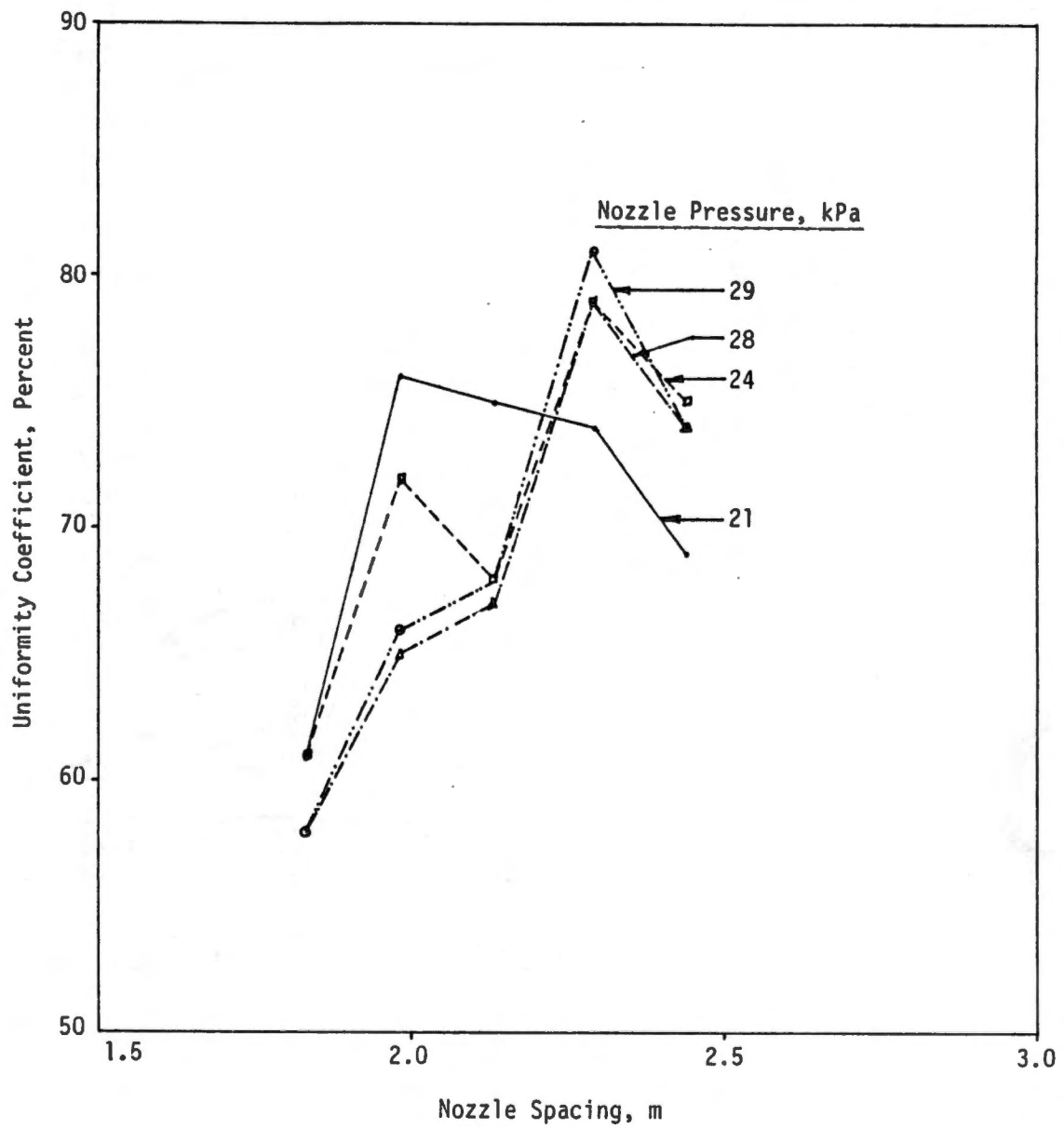


Figure 12. Effect of nozzle spacing and pressure on uniformity coefficient for Fulljet 50 WSQ nozzles.

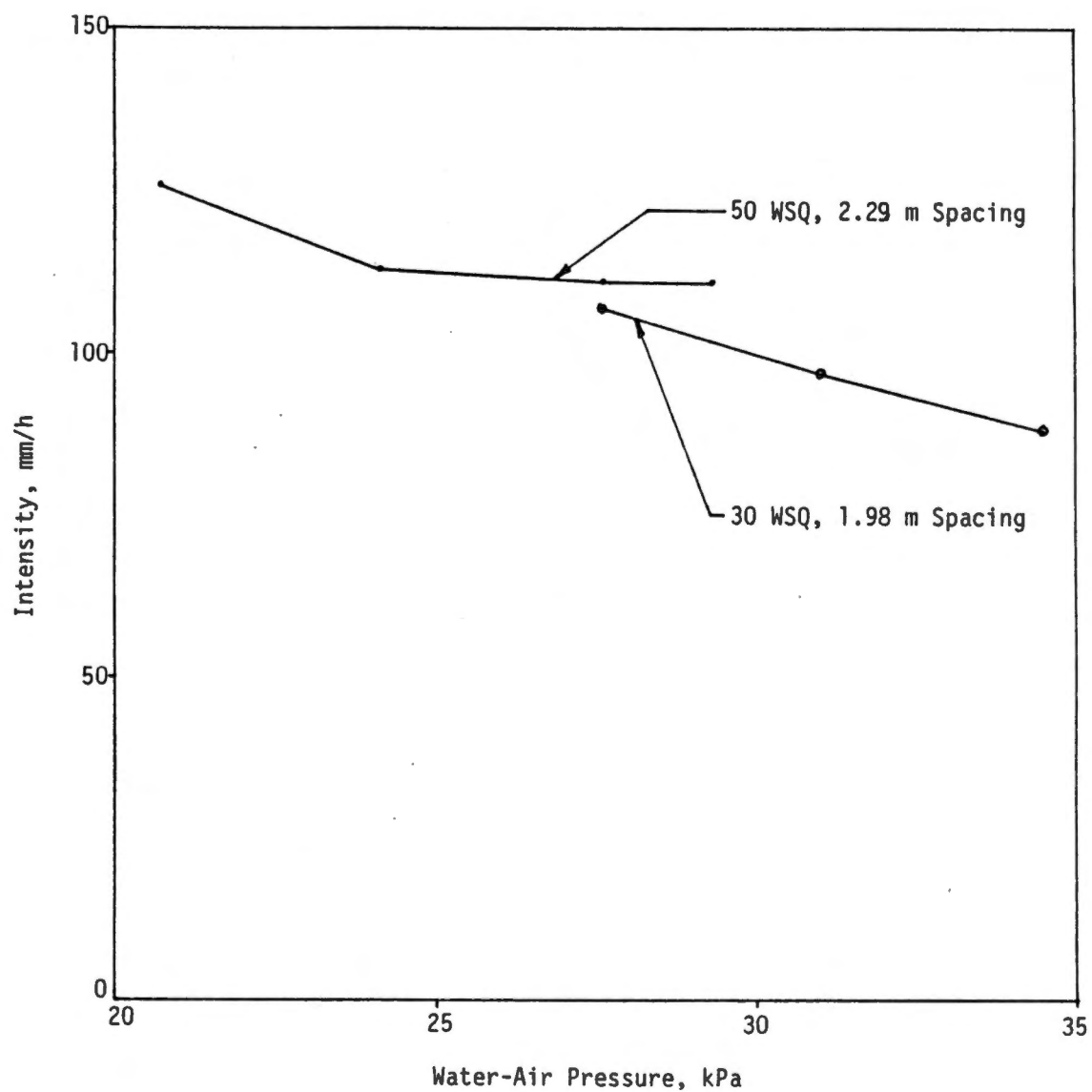


Figure 13. Effect of water-air pressure on rainfall intensity for Fulljet 30 WSQ and 50 WSQ nozzles.

4. High Speed Photography of Raindrops

A device constructed to facilitate the use of high-speed photography to determine size and velocity of the falling drops is shown schematically in Figure 14. The two vertical sections were clamped together so that the spacing between the two pieces of sheet metal was 5.0 cm (2 in). A plastic grid with millimeter divisions was fastened onto the front of the rear section of the device such that the bottom of the grid was 1.83 m (6 ft) below the nozzle orifice. A Hycam model K 2004E camera was used to photograph drops falling between the two sections. Consequently, drops falling through a zone 5 cm (2 in) deep and 24 cm (5.5 in) wide were photographed. A plastic sheet was fastened to the top front of the device and extended beyond the camera to protect the camera, lights and operator from falling water. Food coloring was added to the water to enhance imagery of the drops.

The camera speed was determined by the following equation:

$$F = \frac{0.4 \text{ KVCos } \phi}{WB} \quad (22)$$

where,

F = camera speed, frames/sec

K = camera shutter constant (0.4 for Hycam)

V = subject velocity, in/sec

ϕ = angle between line of motion and film plane, degrees

W = field width, in, as viewed through camera

B = image blur, in (assume 0.002 maximum).

The terminal velocity of medium size (3.0 mm) drops is about 8 m/s (26.0 ft/sec), therefore, this was considered to be the

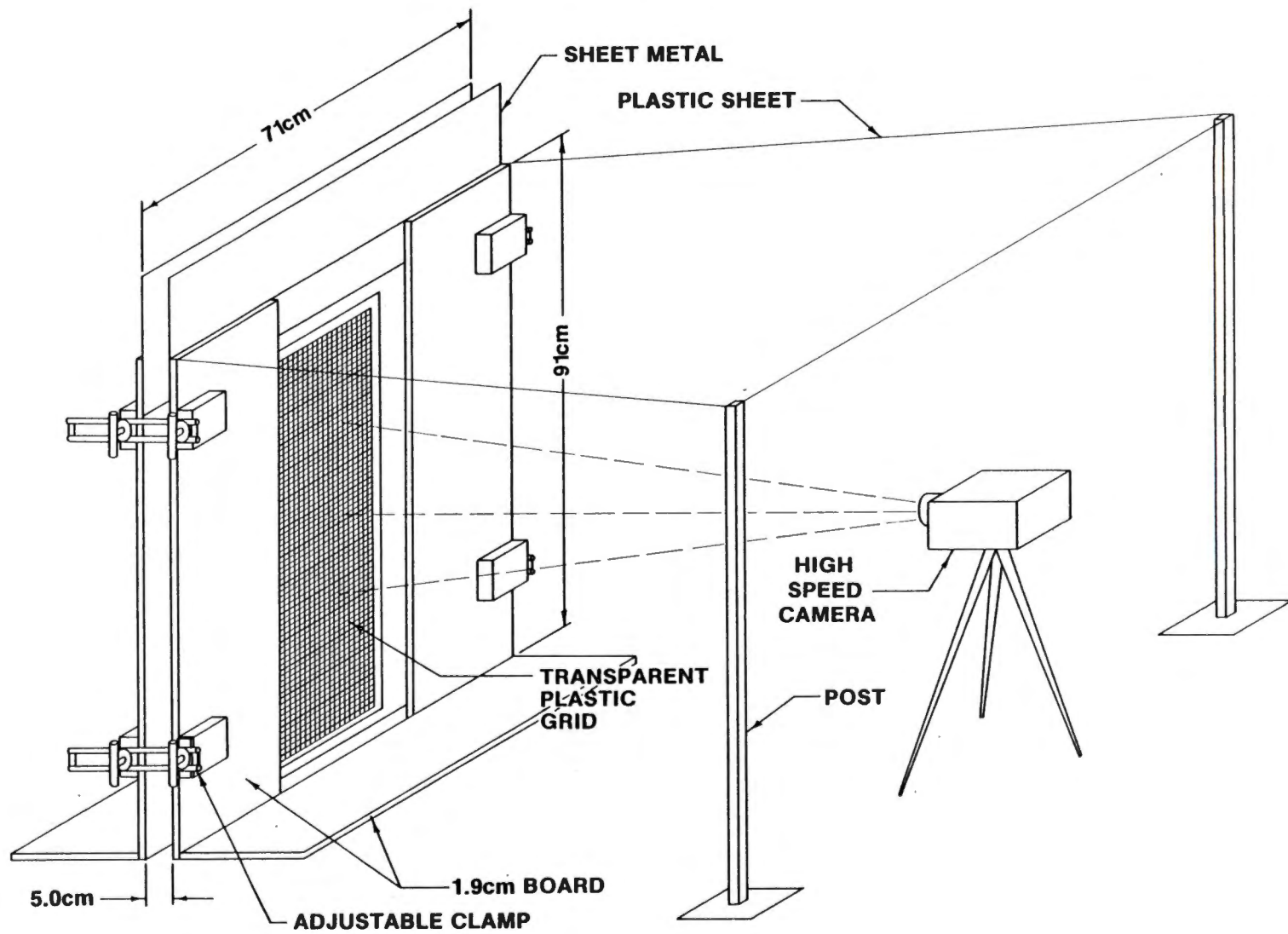


Figure 14. Schematic of photographic setup.

maximum subject velocity for purposes of determining camera speed. The value of ϕ was made equal to zero by adjusting the film frame parallel to the plane of motion. Location of the camera relative to a vertical plane through the center of the zone of falling drops resulted in a field width of 13 cm (5 in). By entering the above values in equation (22), a camera speed of 4992 frames/sec was computed. Four 1000-watt flood lights and two 650-watt lights were positioned beside the camera and directed toward the photographic field. A timing light was used to mark the side of the film so that velocity of the raindrops could be determined.

The pump was started and pressure at the nozzle was set. All lights were then turned on and the camera was started. The first test was conducted with 50 WSQ nozzles at water and air pressure of 21 kPa and 0.0 kPa, respectively. For the next test, water pressure was kept constant and air pressure was set at 9 kPa (1.25 psi). Similarly, raindrops produced by the 30 WSQ nozzle at 21 kPa (3 psi) and 28 kPa (4 psi) water pressure with selected air pressures were photographed.

A film analyzer was used to determine drop size distribution. Each frame of the 30.5-m (100 ft) roll of Kodak 16 mm 4X reversal film was studied by operating the analyzer in the forward, reverse or stop mode as necessary. A distinct image was produced as a drop fell past a piece of black tape located at the bottom edge of the grid. Dividers were used to transfer the drop diameter to the grid for measurement. The size of each drop was recorded to the closest

0.5 mm for the entire length of film, and the drop size distribution was determined.

Due to malfunction of a timing-mark generator in the previous tests, separate photographs were taken to determine fall velocities of raindrops produced by 50 WSQ nozzle at selected water-air pressures. Representative drop sizes were measured on the film to the nearest 0.5 mm increment. The number of frames required for a drop to pass through a distance of 25 mm was counted. Locations of the drop at the start and the end of 25-mm distance were marked on the side of the film. The timing mark precedes the photographic image by five frames in the Hycam camera; therefore, timing-mark distance between the preceding fifth frame and the frame located at the closest timing mark at or after 25-mm distance was measured and the number of timing marks required to cover that distance was counted (Appendix C, Table 10). Because the width (pitch) of 16-mm film was 7.62 mm (0.3 in), the number of timing-mark frames was determined by dividing the timing-mark distance by 7.62 mm (0.3 in). Time per frame, which was determined by dividing time elapsed by timing-mark frames, was used to calculate the time required by the drop to fall 25-mm distance.

CHAPTER IV

RESULTS AND DISCUSSION

A. SIMULATOR DESIGN

The simulator is simple to construct using locally available materials. It is easy to assemble and transport and is simple to operate. It covers an effective area of 6.1 m x 6.1 m (20 ft x 20 ft), and larger areas may be covered by maintaining the 6.1 m (20 ft) width while increasing the length by simply attaching additional units. The air-entrainment concept permits non-intermittent application of rainfall.

B. UNIFORMITY OF DISTRIBUTION

Depths of water collected in the sixteen containers during 30-minute tests were measured and recorded (Appendix B, Table 9). Christiansen's coefficients of uniformity for various combinations of nozzle spacings and water-air pressures are given in Tables 4 and 5. Table 4 shows that the 50 WSQ nozzles spaced at 2.44 m (8 ft) produced a maximum uniformity coefficient of 77% at a water-air pressure of 31 kPa (4.5 psi). At this spacing some portions of the test area received very little rainfall. Uniformity increased substantially after injecting compressed air into the water conduit. For a nozzle spacing of 2.29 m (7.5 ft), the highest uniformity coefficient obtained was 81% at water-air pressures of 29 kPa (4.25 psi). Table 4 also shows that, of the water pressures tested, most

Table 4. Uniformity Coefficients and Rainfall Intensities for Various Spacings of Fulljet 50 WSQ Nozzles

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Uniformity Coefficient, Cu (%) and Average Intensity, I (mm/h) for Various Spacings									
			2.44 m		2.29 m		2.13 m		1.98 m		1.83 m	
			Cu	I	Cu	I	Cu	I	Cu	I	Cu	I
52	0	14	53	97	66	104	58	116	72	129	21	86
52	50	17	69	90	77	103	75	111	75	119	50	109
52	53	21	75	88	72	101	72	99	73	118	54	110
52	59	22	73	88	75	101	76	92	67	114	53	111
64	0	21	69	105	74	126	75	133	76	154	61	143
64	62	24	75	94	79	113	68	120	72	137	61	141
64	66	28	74	85	79	111	67	118	65	126	58	140
64	67	29	74	85	81	111	68	116	66	125	58	134
72	0	24	73	101	73	132	75	142	77	157	66	173
72	67	28	75	100	73	117	67	130	73	147	67	167
72	71	31	77	96	77	114	70	122	69	134	59	142

Table 5. Uniformity Coefficients and Rainfall Intensities for Various Spacings of Fulljet 30 WSQ Nozzles

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Uniformity Coefficient, Cu (%) and Average Intensity, I (mm/h) for Various Spacings					
			2.29 m		2.13 m		1.98 m	
			Cu	I	Cu	I	Cu	I
41	0	14	61	77	47	78	35	72
41	41	17	64	64	57	72	46	72
41	43	21	72	63	63	70	49	69
48	0	21	63	79	73	85	72	93
48	48	24	70	66	63	78	68	85
48	50	28	73	65	61	73	69	79
59	0	28	73	84	73	100	81	107
59	57	31	66	79	68	89	76	97
59	60	35	70	77	68	85	69	88
86	0	47	76	105	73	117	72	122
86	81	52	73	91	71	97	67	98
86	85	55	76	84	66	87	61	87

uniform distribution was obtained at a water pressure of 64 kPa (9.25 psi) at the pump and various air pressures. At nozzle spacings of 2.44 and 2.29 m (8 and 7.5 ft) more uniform distribution of water was obtained with the use of compressed air and water than with water alone. The maximum uniformity coefficient for a nozzle spacing of 2.13 (7.0 ft) was 76% at water-air pressure of 22 kPa (3.25 psi). When the nozzles were spaced at 1.98 m (6.5 ft), the maximum uniformity coefficient was 77% at water pressure of 24 kPa (3.5 psi). For every combination of water and air tested, the uniformity of coefficient was minimum at a spacing of 1.83 m (6.0 ft).

Because satisfactory uniformity coefficients were obtained with a constant pump pressure of 64 kPa (9.25 psi), and all combinations of nozzle spacing and water-air pressure tested, graphs were plotted to describe the effect of pressure and spacing on distribution uniformity (Figure 12, page 49). The graphs show that uniformity coefficient increased when the spacing was changed from 1.83 m (6.0 ft) to 1.98 m (6.5 ft). Then, for most pressures tested, uniformity decreased as the spacing was increased. When the nozzles were spaced at 2.29 m (7.5 ft), the coefficient of uniformity increased substantially, except when water only was used, but decreased thereafter. The relationships shown in Figure 12 on page 49 are similar to those shown by Christiansen (1942) for uniformity coefficient versus percentage overlap.

Uniformity coefficients were also calculated for Fulljet 30 WSQ nozzles operating at various spacings and pressures (Table 5). For a spacing of 2.29 m (7.5 ft), the highest coefficient was 76% at

a water pressure of 47 kPa (6.75 psi) at the nozzle, whereas 73% was the maximum value for a spacing of 2.13 m (7.0 ft) and a water pressure of 21 kPa (3 psi). Highest coefficient of uniformity (81%) was obtained with the 30 WSQ nozzle having a spacing of 1.98 m (6.5 ft) and a water-only pressure of 28 kPa (4.0 psi). Good results were also obtained with other water-air pressures and this spacing.

Table 5 shows that uniformity coefficient decreased as nozzle spacing increased, except at a water-air pressure of 35 kPa (5.0 psi). Distribution uniformity varied considerably at high water pressure--even with the addition of compressed air. This might be because spray angles became wider and covered more area, resulting in more overlap of the spray pattern for narrow spacings and less overlap for wide spacings. It may also be due to variation in coefficient of uniformity due to experimental error, because only three nozzle spacings were tested. Distribution uniformity at various nozzle spacings and pressures could probably be improved by raising the nozzle height from 2.38 to 3.0 m (7.8 to 9.8 ft).

C. RAINFALL INTENSITY

Table 4 shows that, at a spacing of 2.44 m (8 ft), Fulljet 50 WSQ nozzles produced an intensity of 105 mm/h (4.1 in/hr) at a water pressure of 21 kPa (3.0 psi). When compressed air was injected to make the water-air pressure 29 kPa (4.25 psi), rainfall intensity was reduced to 85 mm/h (3.3 in/hr) and uniformity coefficient was increased from 69 to 74 percent. When the nozzle spacing was reduced to 2.29 m (7.5 ft), rainfall intensity was 126 mm/h (5.0 in/hr) at

the same water pressure, but was reduced to 111 mm/h (4.4 in/hr) with a water-air pressure of 29 kPa (4.25 psi). Although the intensity was reduced 12 percent, non-intermittent rainfall was accomplished. Similarly, when the nozzles were spaced at 2.13, 1.98 and 1.83 m (7.0, 6.5 and 6.0 ft), rainfall intensities were 133, 154 and 143 mm/h (5.2, 6.1 and 5.6 in/hr), respectively, at 21 kPa (3.0 psi) water pressure. These intensities were reduced to 116, 125 and 134 mm/h (4.6, 4.9 and 5.3 in/hr), respectively, when air was mixed with the water. The reduction in intensities ranged from 6 to 19 percent depending upon nozzle spacings and water-air pressures. Thus, by adjusting nozzle pressure and spacing, intensities produced with the Fulljet 50 WSQ nozzle ranged from 85 to 154 mm/h (3.3 to 6.1 in/hr).

When the 30 WSQ nozzles were spaced at 2.29, 2.13 and 1.98 m (7.5, 7.0 and 6.5 ft), and water-air pressure was set at 28 kPa (4.0 psi), resulting intensities were 65, 73 and 79 mm/h (2.6, 2.9 and 3.1 in/hr), respectively. Rainfall intensities were increased to 84, 100 and 107 mm/h (3.3, 3.9 and 4.2 in/hr), respectively, when the water pressure alone was set at 28 kPa (4.0 psi). These intensities were reduced by 8, 15 and 18 percent with the addition of compressed air to the water line. Intensities developed with this nozzle, therefore, ranged from 65 to 107 mm/h (2.6 to 4.2 in/hr)

Water collected in the containers varied with nozzle spacings although nozzle discharge remained constant. This might be because the containers were not moved to the same relative position with respect to the nozzles but were placed at the same position for all the spacings tested (Figure 11, page 47.). Also, the containers

caught the water in a plane only 2.23 m (7.3 ft) below the nozzle orifices, and nozzle spacings in both X and Y directions were kept equal throughout the tests.

The effect of change in air-water pressure on intensity is shown in Figure 13 on page 50. These curves clearly illustrate that intensities decrease with increase of air-water pressure, when the water pressure and nozzle spacing are constant. Tables 4 and 5 show that while attaining a minimum uniformity coefficient of 73 percent intensities of rainfall were varied from 65 to 154 mm/h (2.6 to 6.1 in/hr) by selecting nozzle spacings and air-water pressures.

D. DROP SIZE DISTRIBUTION

Drop size distribution and intensities attained with selected nozzles and pressures are shown in Table 6. Relationships between drop diameter and percentage of size distribution (mass basis) at various rainfall intensities are shown in Figure 15. Table 6 shows that for 21 kPa (3.0 psi) water pressure and 7 kPa (1.0 psi) air pressure, 88 percent of the drops formed by the Fulljet 30 WSQ nozzles were between 0.5 and 2.0 mm in diameter, and the intensity was 65 mm/h (2.6 in/hr). When water pressure was increased to 28 kPa (4.0 psi) and no air was injected, the intensity was 107 mm/h (4.2 in/hr). Forty-seven percent of the drops were 1.0 to 1.5 mm in diameter and 33 percent ranged from 1.5 to 2.5 mm. For the 50 WSQ nozzle, 74 percent of the drops were 1.0 to 2.0 mm, and the intensity was 111 mm/h (4.4 in/hr) for water and air pressures of 21 kPa (3.0 psi) and 9 kPa (1.25 psi), respectively. Although the

Table 6. Drop Size Distribution Obtained with Two Nozzles at Various Water and Water-Air Pressures

Drop Size Range (mm)	Distribution Number, Percent of Count and Percent of Mass											
	Fulljet 30 WSQ						Fulljet 50 WSQ					
	21 kPa Water, 6 kPa Air ^a			28 kPa Water Only ^b			21 kPa Water, 9 kPa Air ^c			21 kPa Water Only ^d		
	No.	Percent of Count	Percent of Mass	No.	Percent of Count	Percent of Mass	No.	Percent of Count	Percent of Mass	No.	Percent of Count	Percent Of Mass
0.5-1.0	20	27	3	8	16	1	11	8	1	2	3	1
1.0-1.5	32	44	23	23	47	19	48	33	11	12	19	4
1.5-2.0	12	17	24	9	19	21	60	41	39	20	32	19
2.0-2.5	7	10	30	7	14	35	21	14	29	19	31	38
2.5-3.0	1	1	8	1	2	9	3	2	8	7	12	26
3.0-3.5	1	1	12	1	2	15	3	2	12	2	3	12
Total	73	100	100	49	100	100	144	100	100	62	100	100

^aIntensity = 65 mm/h.

^bIntensity = 107 mm/h.

^cIntensity = 111 mm/h.

^dIntensity = 126 mm/h.

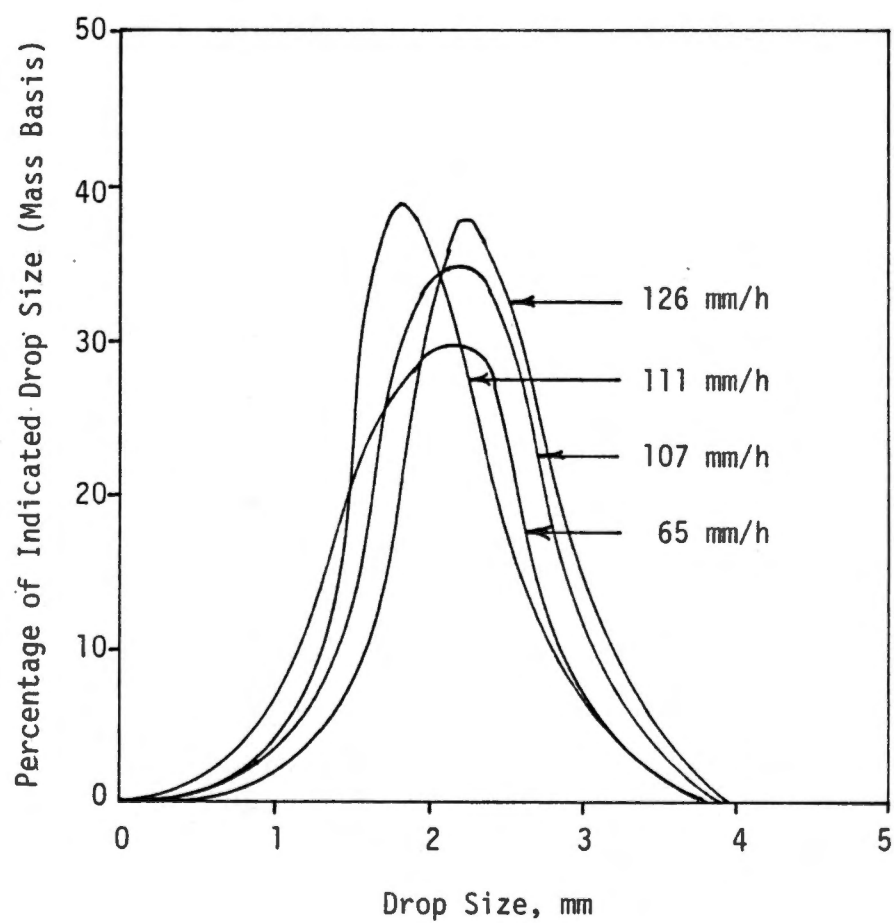


Figure 15. Relationship between drop diameter and percentage of indicated drop size (mass basis) at various rainfall intensities.

coefficient of uniformity was 81 percent (Table 4, page 56), the proportion of small drops was too high for this magnitude of intensity. For water only, the intensity was 126 mm/h (5.0 in/hr) and 43 percent of the drops ranged from 2.0 to 3.0 mm in diameter.

Table 6 shows that the median drop diameter (mass basis) for 65 and 107 mm/h (2.6 and 4.2 in/hr) rainfall intensities was in the 2.0 to 2.5 mm range, whereas for intensities of 111 and 126 mm/h (4.4 and 5.0 in/hr), median drop sizes were in the 1.5 to 2.0 mm and 2.0 to 2.5 mm ranges, respectively. Drop-size distribution curves (Figure 15) are similar to those obtained by Laws and Parsons (1943). However, drop sizes produced by the simulator were slightly smaller than those obtained by Laws and Parsons for natural rainfall. This might be due to the limited measurement time and catchment area, and to excessive air pressure during the test having an intensity of 111 mm/h.

E. DROP FALL VELOCITY

Fall velocities of drops produced by the 50 WSQ nozzles and terminal velocities of natural drops are given in Table 7. The table shows that fall velocities of 0.5-mm drops were 195 percent of the terminal velocity of natural raindrops. This might be due to error in the measurement of drop size, because it was difficult to accurately measure small drops when the film was stopped. With the exception of 0.5-mm drops, the average fall velocities of drops at a water-only pressure of 21 kPa (3.0 psi) were 117 percent of the terminal velocities. When the nozzles were operated at water and air

Table 7. Comparison of Average Fall Velocities (V_f) of Raindrops Produced by Fulljet 50 WSQ Nozzles at Selected Water-Air Pressures to Terminal Velocities of Natural Raindrops

Drop Size (mm)	Terminal Velocity of Raindrops (V_t) (m/s)	Pressure			
		21.0 kPa Water, 0.0 kPa Air		21.0 kPa Water, 9.0 kPa Air	
		V_f (m/s)	$\frac{V_f}{V_t} \times 100$ (%)	V_f (m/s)	$\frac{V_f}{V_t} \times 100$ (%)
0.5	2.1	4.1	195	4.5	214
1.0	4.0	4.5	113	4.6	115
1.5	5.4	6.6	122	5.7	106
2.0	6.5	7.3	112	6.6	102
2.5	7.4	8.9	120	8.0	108
3.0	8.1	9.5	117	9.9	122
3.5	8.5	9.9	116	10.1	119
4.0	8.9	10.3	116	-	-

pressures of 21 kPa (3.0 psi) and 9 kPa (1.25 psi), respectively, average fall velocities exceeded the terminal velocities of natural raindrops by 12 percent. The fall velocities were determined from photographs of drops 1.83 m (6 ft) below the nozzle orifice. The velocities would probably more nearly equal terminal velocities if the drops were photographed at a point 2.44 m (8 ft) to 3.0 m (10 ft) below the nozzle.

The photographs taken for determining drop size distribution show small drop sizes as compared to those from the photographs taken later for determining drop fall velocity. This was probably due to the extremely short real time (about 2.0 seconds) represented on the 30.5-m (100-ft) roll of film. Consequently, additional tests are required to obtain more conclusive results.

CHAPTER V

SUMMARY AND CONCLUSIONS

A. SUMMARY

Rainfall simulators have been used for many years in studies related to soil infiltration, runoff and soil erosion. Simulators make possible the application of rainfall of desired intensities and durations at selected times and places, and provide better control of experiments than is possible using natural rainfall. To attain desirable drop characteristics, most existing simulators produce high intensities. These intensities are reduced to desirable magnitudes by means of intermittent movement of the drop formers. The objectives of this research were (1) to design and construct a non-intermittent rainfall simulator, (2) to evaluate the uniformity of distribution obtained with the simulator and (3) to determine the fall velocity and size distribution of raindrops at selected intensities of simulated rainfall.

A rainfall simulator was designed and constructed with a concept of injecting compressed air into the water conduit so that nozzle pressure could be controlled without varying the discharge. The two-phase flow thus generated, with proper selection of nozzle type, size, spacing and operating pressure, permits non-intermittent flow and utilization of all the pumped water. The simulator covers an effective area of 6.1 m x 6.1 m (20 ft x 20 ft) and has a provision for connecting additional units to cover large field plots. It

is simple and economical to construct using readily available materials, and is convenient to transport and operate.

Two nozzles were selected for detailed evaluation of drop size distribution, drop fall velocity, uniformity of distribution and intensity. Uniformity of distribution was determined at various nozzle spacings and water-air pressures, and a maximum uniformity coefficient of 81 percent was obtained. Intensities obtained with the two nozzles operating at selected spacings and pressures ranged from 65 to 154 mm/h (2.6 to 6.1 in/hr). A high-speed camera was used to photograph the drops in order to determine their full velocity and size distribution. Except for one test in which excessive air pressure resulted in a high percentage of small drops, the median drop diameter produced by the simulator was in the 2.0 to 2.5 mm range. The fall velocities of simulated raindrops produced by Fulljet 50 WSQ nozzles were approximately 15 percent more than the terminal velocities of natural raindrops of equal size.

B. CONCLUSIONS

Results of the study indicate that the concept of entraining air with water to attain desirable rainfall characteristics with a simulator is valid. Specific conclusions are as follows:

1. The air-entrained rainfall simulator was constructed from locally available and easily fabricated materials.
2. Good uniformity of distribution was obtained at desirable intensities of non-intermittent rainfall.
3. Rainfall intensities were in the range of storms which produce medium to high rates of runoff and erosion.

4. Drop size produced by the simulator for a period of about 2.0 seconds were slightly smaller than those reported for natural rainfall of similar intensities. .
5. Fall velocities of the simulated raindrops were approximately equal to terminal velocities of natural raindrops of equal size.

C. RECOMMENDATIONS FOR FURTHER STUDY

While results obtained with the simulator are generally satisfactory, it is believed that substantial improvement in performance and testing can be attained with several minor modifications as follows:

1. Raise the nozzles to a height of 2.44 to 3.00 m (8 to 10 ft) above ground level.
2. Use larger nozzles of the Fulljet WSQ type, and increase the air:water ratio to attain desirable rainfall characteristics.
3. Take additional photographs with the high-speed camera to more reliably sample drop size and velocity.
4. Photograph natural rainfall with the high-speed camera and compare results to those of the simulator.

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APPENDICES

APPENDIX A

List of Materials and Costs. The materials used in the construction of the rainfall simulator and their costs are given in Table 8.

Table 8. List of Materials and Costs

Item No.	Quantity	Description	Unit Price (\$)	Cost (\$)
<u>Frame</u>				
1	64.83 m	4.12 cm galvanized fence top rail	2.69	174.39
2	9.12 m	5.08 cm galvanized fence top rail	5.38	49.07
3	9.12 m	4.12 cm schedule-40, galvanized pipe	4.53	41.31
4	2.76 m	2.54 cm standard pipe	2.69	7.42
5	3.64 m	3.17 cm standard pipe	2.69	9.79
6	20 ea	4.12 cm galvanized, pressed steel gate ells with galvanized bolts	6.35	127.00
7	8 ea	4.12 cm galvanized, pressed steel brace bands with galvanized bolts	.35	2.80
8	8 ea	5.08 cm galvanized D rail bands with galvanized bolts	0.77	6.16
9	3 ea	4.12 cm x 4.12 cm galvanized line rail clamps with galvanized bolts	1.51	4.53
10	4 ea	4.12 cm galvanized end rail clamps with galvanized bolts	1.51	6.04
11	16 ea	4.12 cm galvanized, pressed steel rail ends with galvanized bolts	1.13	18.08
12	33 m	0.32 cm galvanized aircraft cable	0.18	5.94
13	8 ea	Turnbuckles	0.45	3.60
14	16 ea	S-hooks	0.30	4.80
15	0.57 m ²	0.64 cm steel plate	24.00	13.68

Table 8 (Continued)

Item No.	Quantity	Descriptions	Unit Price (\$)	Cost (\$)
<u>Water-Air System</u>				
16	1 ea	Teel-model 3P551A, 1/2 HP, 3450 rpm, centrifugal pump	198.07	198.07
17	1 ea	Dayton-4Z024, 1/3 HP, 3450 rpm, diaphragm compressor	176.85	176.85
18	4.57 m	3.81 cm heavy duty rubber hose, discharge	2.00	9.14
19	7.0 m	5.08 cm heavy duty rubber hose, suction	2.00	14.00
20	2 ea	3.81 cm aluminum quick coupling	9.79	19.58
21	6.59 m	1.90 cm excelon tube	3.00	19.77
22	60.39 m	1.27 cm vinyl tube	0.92	55.56
23	9 ea	Fulljet HH 50 WSQ brass nozzle	4.02	36.18
24	9 ea	Fulljet HH 30 WSQ brass nozzle	4.02	36.18
25	1 ea	1.90 cm check valve	4.56	4.56
26	1 ea	1.90 cm gate valve	8.00	8.00
27	1 ea	3.81 cm gate valve	12.00	12.00
28	4 ea	Pressure gage, 0-30 psi	28.00	112.00
29	9 ea	1.27 cm brass tees	1.06	9.54
30	1 ea	15.24 cm x 10.16 cm pvc reducer, schedule-40	6.68	6.68
31	1 ea	10.16 cm x 3.81 cm pvc socket-to-thread	2.79	2.79
32	19 ea	1.27 cm brass barbs, 125 HBL-8-8	1.06	20.14

Table 8 (Continued)

Item No.	Quantity	Description	Unit Price (\$)	Cost (\$)
33	9 ea	4.12 cm galvanized brace band with bolts	0.35	3.15
34	24 ea	Stainless steel clamps	0.45	10.80
35		Miscellaneous (welding rods, pipe fittings, etc.)		<u>50.40</u>
Total				1280.00

APPENDIX B

Simulated Rainfall Depth and Intensity Data. The data used to determine coefficients of uniformity are given in Table 9.

Table 9. Simulated Rainfall Depth and Intensity at Different Water-Air Pressure

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xt) (mm)	Intensity (It) (mm/h)	Remarks
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For Fulljet 50 WSO Nozzles Spaced 2.44 m x 2.44 m

52	0	14	46, 13, 53, 53, 74, 20, 84, 71, 86, 03, 69, 58, 38, 71, 03, 36	92, 26, 106, 106, 142, 148, 40, 168, 06, 06, 172, 76, 116, 142, 72	$\bar{x} = 49$ $\bar{I} = 98$
52	50	17	48, 36, 51, 48, 74, 38, 61, 48, 51, 03, 74, 43, 51, 03, 36	96, 72, 102, 96, 148, 76, 122, 96, 102, 06, 06, 148, 72, 86, 102, 106, 72	$\bar{x} = 45$ $\bar{I} = 90$
52	53	21	61, 38, 48, 51, 60, 48, 51, 43, 41, 03, 48, 47, 43, 48, 08, 69, 48	122, 76, 96, 102, 120, 96, 102, 86, 06, 16, 138, 94, 86, 96	$\bar{x} = 44$ $\bar{I} = 88$
52	59	22	61, 48, 46, 53, 51, 51, 51, 36, 36, 05, 51, 64, 56, 43, 43, 05, 51	122, 96, 92, 106, 102, 102, 102, 72, 102, 10, 128, 112, 86, 86, 102	$\bar{x} = 44$ $\bar{I} = 88$
64	0	21	43, 51, 51, 61, 66, 69, 58, 61, 69, 03, 74, 61, 74, 28	86, 102, 102, 122, 138, 116, 122, 138, 06, 20, 148, 122, 122, 148, 56	$\bar{x} = 53$ $\bar{I} = 106$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
64	62	24	53, 71, 51, 53, 56, 66, 48, 48, 46, 03, 06, 66, 48, 48, 51, 41	106, 142, 102, 106, 112, 132, 96, 96, 92, 06, 12, 132, 96, 96, 102, 82	$\bar{x} = 47$ $\bar{I} = 94$
64	66	28	51, 66, 48, 61, 43, 58, 43, 43, 33, 03, 03, 51, 48, 43, 43, 43	102, 132, 96, 122, 86, 116, 86, 86, 66, 06, 06, 102, 96, 86, 86, 86	$\bar{x} = 43$ $\bar{I} = 86$
64	67	29	51, 61, 51, 51, 51, 56, 46, 41, 36, 03, 03, 51, 51, 41, 43, 43	102, 122, 102, 102, 102, 112, 92, 82, 72, 06, 06, 102, 102, 82, 86, 86	$\bar{x} = 42$ $\bar{I} = 84$
72	0	24	46, 81, 51, 61, 58, 66, 51, 53, 56, 05, 15, 66, 51, 56, 66, 28	92, 162, 102, 122, 116, 132, 102, 106, 112, 10, 30, 132, 102, 112, 132, 56	$\bar{x} = 51$ $\bar{I} = 102$
72	67	28	46, 86, 51, 56, 56, 66, 51, 51, 51, 05, 20, 66, 53, 51, 61, 30	92, 172, 102, 112, 112, 132, 102, 102, 102, 10, 40, 132, 106, 102, 60	$\bar{x} = 50$ $\bar{I} = 100$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
72	71	31	66, 71, 51, 61, 51, 56, 46, 46, 36, 10, 15, 56, 56, 46, 53, 46	132, 142, 102, 122, 102, 112, 92, 92, 72, 20, 30, 112, 112, 92, 106, 92	$\bar{x} = 48$ $\bar{I} = 96$
For Fulljet 50 WSQ Nozzles Spaced 2.29 m x 2.29 m					
52	0	14	51, 51, 66, 56, 66, 05, 66, 61, 71, 20, 66, 30, 71, 15, 76, 61	102, 102, 132, 112, 132, 10, 132, 122, 142, 40, 132, 60, 142, 30, 152, 122	$\bar{x} = 52$ $\bar{I} = 104$
52	50	17	51, 61, 61, 51, 71, 05, 71, 46, 51, 46, 51, 33, 76, 36, 61, 56	102, 122, 122, 102, 142, 10, 142, 92, 102, 92, 102, 66, 152, 72, 122, 112	$\bar{x} = 52$ $\bar{I} = 104$
52	53	21	41, 69, 53, 46, 69, 18, 53, 36, 36, 30, 36, 74, 64, 56, 48, 79	82, 138, 106, 92, 138, 36, 106, 72, 72, 60, 72, 148, 128, 112, 96, 158	$\bar{x} = 51$ $\bar{I} = 102$
52	59	22	48, 74, 53, 46, 79, 33, 53, 38, 30, 23, 43, 58, 56, 51, 41, 79	96, 148, 106, 92, 158, 66, 106, 76, 60, 46, 86, 116, 112, 102, 82, 158	$x = 50$ $I = 100$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
64	0	21	41, 91, 71, 56, 64, 20, 46, 71, 61, 25, 86, 91, 61, 76, 81, 66	82, 182, 142, 112, 128, 40, 92, 142, 122, 50, 172, 182, 122, 152, 162, 132	$\bar{x} = 63$ $\bar{I} = 126$
64	62	24	38, 58, 71, 51, 69, 25, 46, 76, 46, 41, 66, 76, 51, 66, 56, 66	76, 116, 142, 102, 138, 50, 92, 152, 92, 82, 132, 152, 102, 132, 112, 132	$\bar{x} = 56$ $\bar{I} = 112$
64	66	28	56, 81, 64, 51, 69, 38, 48, 51, 38, 33, 51, 61, 51, 64, 46, 86	112, 162, 128, 102, 138, 76, 96, 102, 76, 66, 102, 122, 102, 128, 92, 172	$\bar{x} = 56$ $\bar{I} = 112$
64	67	29	56, 76, 64, 56, 71, 46, 46, 46, 38, 29, 56, 56, 51, 64, 46, 86	112, 152, 128, 112, 142, 92, 92, 92, 76, 58, 112, 112, 102, 128, 92, 172	$\bar{x} = 55$ $\bar{I} = 110$
72	0	24	46, 91, 61, 56, 71, 41, 56, 81, 51, 20, 97, 81, 56, 91, 66, 91	92, 182, 122, 112, 142, 82, 112, 162, 102, 40, 194, 162, 112, 182, 132, 182	$\bar{x} = 66$ $\bar{I} = 132$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
72	67	28	51, 81, 43, 51, 76, 58, 51, 46, 41, 25, 86, 61, 46, 81, 48, 91	102, 162, 86, 102, 152, 116, 102, 92, 82, 50, 172, 122, 92, 162, 96, 182	$\bar{x} = 59$ $\bar{I} = 118$
72	71	31	51, 51, 71, 53, 71, 58, 48, 41, 46, 20, 76, 56, 51, 76, 46, 97	102, 102, 142, 106, 142, 116, 96, 82, 92, 40, 152, 112, 102, 152, 92, 194	$\bar{x} = 57$ $\bar{I} = 114$
For Fulljet 50 WSQ Nozzles Spaced 2.13 m x 2.13 m					
52	0	14	76, 84, 81, 56, 15, 08, 64, 69, 71, 33, 20, 20, 109, 61, 69, 91	152, 168, 162, 112, 30, 16, 128, 138, 142, 66, 40, 40, 218, 122, 138, 182	$\bar{x} = 58$ $\bar{I} = 116$
52	50	17	48, 53, 66, 46, 41, 13, 53, 71, 48, 33, 25, 53, 71, 76, 58, 53	96, 106, 132, 92, 82, 26, 106, 142, 96, 66, 50, 106, 142, 152, 116, 106	$\bar{x} = 50$ $\bar{I} = 100$
52	53	21	41, 56, 71, 48, 41, 18, 48, 61, 46, 25, 28, 71, 56, 91, 51, 41	82, 112, 142, 96, 82, 36, 96, 122, 92, 50, 56, 142, 112, 182, 102, 82	$\bar{x} = 50$ $\bar{I} = 100$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
52	59	22	41, 51, 66, 51, 46, 23, 43, 51, 41, 25, 25, 81, 51, 58, 46, 36	82, 102, 132, 102, 92, 46, 86, 102, 82, 50, 50, 162, 102, 116, 92, 72	$\bar{x} = 46$ $\bar{i} = 92$
64	0	21	51, 53, 81, 51, 61, 30, 46, 102, 56, 76, 56, 79, 61, 107, 81, 76	102, 106, 162, 102, 122, 60, 92, 204, 132, 152, 132, 158, 122, 214, 162, 152	$\bar{x} = 67$ $\bar{i} = 134$
64	62	24	46, 56, 97, 51, 76, 51, 43, 71, 46, 20, 46, 101, 46, 107, 53, 48	92, 112, 194, 102, 152, 102, 86, 142, 92, 40, 92, 202, 92, 214, 106, 96	$\bar{x} = 60$ $\bar{i} = 120$
64	66	28	46, 69, 91, 51, 86, 66, 43, 61, 41, 18, 41, 97, 41, 97, 51, 41	92, 138, 182, 102, 172, 132, 86, 122, 82, 36, 82, 194, 82, 194, 102, 82	$\bar{x} = 59$ $\bar{i} = 118$
64	67	29	46, 71, 91, 51, 86, 56, 43, 56, 41, 20, 41, 101, 41, 91, 51, 43	92, 142, 182, 102, 172, 112, 86, 112, 82, 40, 82, 202, 82, 182, 102, 86	$\bar{x} = 58$ $\bar{i} = 116$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (mm) (Xt)	Intensity (It) (mm/h)	Remarks
72	0	24	46, 58, 97, 51, 81, 56, 46, 86, 56, 61, 76, 112, 58, 112, 76, 66	92, 116, 194, 102, 162, 112, 92, 172, 112, 122, 152, 224, 116, 224, 152, 132	$\bar{x} = 71$ $\bar{I} = 142$
72	67	28	46, 56, 97, 43, 97, 76, 46, 76, 46, 41, 53, 112, 43, 107, 61, 43	92, 112, 194, 86, 194, 152, 92, 152, 92, 82, 106, 224, 86, 214, 122, 86	$\bar{x} = 65$ $\bar{I} = 130$
72	71	31	41, 66, 89, 53, 81, 79, 46, 66, 41, 30, 51, 102, 46, 91, 53, 43	82, 132, 178, 106, 162, 158, 92, 132, 82, 60, 102, 204, 92, 182, 106, 86	$\bar{x} = 61$ $\bar{I} = 122$
52	0	14	76, 46, 71, 64, 10, 15, 58, 97, 76, 89, 91, 71, 97, 81, 76, 91	152, 92, 142, 128, 20, 30, 116, 194, 152, 178, 182, 142, 194, 162, 152, 182	$\bar{x} = 69$ $\bar{I} = 138$
52	50	17	51, 76, 64, 51, 36, 36, 48, 81, 46, 51, 56, 91, 61, 102, 56, 48	102, 152, 128, 102, 72, 72, 96, 162, 92, 102, 112, 182, 122, 204, 112, 96	$\bar{x} = 60$ $\bar{I} = 120$

For Fulljet 50 WSD Nozzles Spaced 1.98 m x 1.98 m

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
52	53	21	43, 79, 61, 46, 66, 51, 51, 71, 36, 41, 51, 112, 56, 94, 48, 36	86, 158, 122, 92, 132, 102, 102, 142, 72, 82, 102, 224, 112, 188, 96, 72	$\bar{x} = 59$ $\bar{I} = 118$
52	59	22	36, 91, 56, 46, 94, 56, 53, 58, 28, 33, 48, 107, 51, 86, 41, 28	72, 182, 112, 92, 184, 112, 106, 116, 56, 66, 96, 214, 102, 172, 82, 56,	$\bar{x} = 57$ $\bar{I} = 114$
64	0	21	69, 107, 56, 53, 46, 48, 51, 104, 71, 89, 84, 112, 81, 102, 81, 79	138, 214, 112, 106, 92, 96, 102, 208, 142, 178, 168, 224, 162, 204, 162, 158	$\bar{x} = 77$ $\bar{I} = 154$
64	62	24	43, 99, 58, 48, 76, 79, 51, 91, 43, 56, 64, 119, 58, 102, 66, 46	86, 198, 116, 96, 152, 158, 102, 182, 86, 112, 128, 238, 116, 204, 132, 92	$\bar{x} = 69$ $\bar{I} = 138$
64	66	28	38, 99, 56, 46, 97, 89, 51, 71, 33, 41, 56, 104, 51, 94, 51, 33	76, 198, 112, 92, 194, 178, 102, 142, 66, 82, 112, 208, 102, 188, 102, 66	$\bar{x} = 63$ $\bar{I} = 126$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
64	67	29	28, 94, 56, 48, 104, 94, 58, 69, 33, 48, 58, 97, 51, 89, 56, 20	56, 188, 112, 96, 208, 188, 116, 138, 66, 96, 116, 194, 102, 178, 112, 40	$\bar{x} = 63$ $\bar{I} = 126$
72	0	24	61, 107, 61, 51, 71, 76, 51, 97, 66, 76, 81, 127, 66, 117, 89, 58	122, 214, 122, 102, 142, 152, 102, 194, 132, 152, 162, 254, 132, 234, 178, 116	$\bar{x} = 78$ $\bar{I} = 156$
72	67	28	48, 102, 61, 51, 86, 97, 61, 86, 46, 76, 76, 117, 58, 107, 76, 30	96, 204, 122, 102, 172, 194, 122, 172, 92, 152, 152, 234, 116, 214, 152, 60	$\bar{x} = 74$ $\bar{I} = 148$
72	71	31	36, 91, 69, 48, 102, 109, 81, 69, 36, 56, 69, 94, 51, 84, 53, 20	72, 182, 138, 96, 204, 218, 162, 138, 72, 112, 138, 188, 102, 168, 106, 40	$\bar{x} = 67$ $\bar{I} = 134$
52	0	14	For Fulljet 50 WSQ Nozzles Spaced 1.83 m x 1.83 m		
			05, 97, 91, 25, 05, 25, 81, 86, 10, 66, 112, 25, 20, 30, 13, 00	10, 194, 182, 50, 10, 50, 162, 172, 20, 132, 224, 50, 40, 60, 26, 00	$\bar{x} = 43$ $\bar{I} = 86$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
52	50	17	05, 97, 89, 48, 08, 58, 61, 66, 23, 71, 97, 76, 76, 71, 25, 00	10, 194, 178, 96, 16, 116, 122, 132, 46, 142, 194, 152, 152, 142, 50, 00	$\bar{x} = 54$ $\bar{I} = 108$
52	53	21	05, 97, 89, 51, 25, 71, 56, 58, 20, 66, 86, 102, 61, 71, 25, 00	10, 194, 178, 102, 50, 142, 112, 116, 40, 132, 172, 204, 122, 142, 50, 00	$\bar{x} = 55$ $\bar{I} = 110$
52	59	22	05, 97, 86, 46, 30, 71, 56, 56, 20, 71, 91, 112, 56, 64, 25, 00	10, 194, 172, 92, 60, 142, 112, 112, 40, 142, 182, 224, 112, 128, 50, 00	$\bar{x} = 55$ $\bar{I} = 110$
64	0	21	15, 112, 102, 109, 20, 91, 71, 86, 48, 58, 132, 81, 71, 81, 48, 20	30, 224, 204, 218, 40, 182, 142, 172, 96, 116, 264, 162, 142, 162, 96, 40	$\bar{x} = 72$ $\bar{I} = 144$
64	62	24	20, 102, 117, 56, 41, 104, 71, 86, 36, 76, 97, 99, 76, 94, 43, 08	40, 204, 234, 112, 82, 108, 142, 172, 72, 152, 194, 198, 152, 188, 86, 16	$\bar{x} = 70$ $\bar{I} = 140$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
64	66	28	15, 97, 112, 53, 66, 132, 66, 76, 25, 76, 102, 122, 61, 81, 33, 05	30, 194, 224, 106, 132, 264, 132, 152, 50, 152, 204, 244, 122, 162, 66, 10	$\bar{x} = 70$ $\bar{I} = 140$
64	67	29	13, 91, 102, 51, 74, 132, 66, 71, 23, 71, 91, 117, 56, 76, 30, 05	26, 182, 204, 102, 148, 264, 132, 142, 46, 142, 182, 234, 112, 152, 60, 10	$\bar{x} = 67$ $\bar{I} = 134$
72	0	24	41, 102, 117, 61, 51, 142, 102, 102, 56, 71, 132, 127, 76, 102, 71, 30	82, 204, 234, 122, 102, 284, 204, 204, 112, 142, 264, 254, 152, 204, 142, 60	$\bar{x} = 86$ $\bar{I} = 172$
72	67	28	41, 97, 117, 56, 66, 142, 97, 97, 51, 91, 112, 117, 71, 107, 66, 10	82, 194, 234, 112, 132, 284, 194, 194, 102, 182, 224, 234, 142, 214, 132, 20	$\bar{x} = 84$ $\bar{I} = 168$
72	71	31	20, 91, 102, 51, 97, 137, 76, 76, 25, 81, 91, 112, 53, 79, 36, 05	40, 182, 204, 102, 194, 274, 152, 152, 50, 162, 182, 224, 106, 158, 76, 10	$\bar{x} = 71$ $\bar{I} = 142$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
For Fulljet 30 WSQ Nozzles Spaced 2.29 m x 2.29 m					
41	0	14	51, 53, 55, 30, 46, 69, 46, 51, 36, 03, 03, 28, 30, 25, 33, 53	102, 103, 110, 60, 92, 138, 92, 102, 72, 06, 06, 56, 60, 50, 66, 106	$\bar{x} = 38$ $\bar{I} = 76$
41	41	17	43, 46, 41, 38, 48, 38, 36, 43, 20, 03, 03, 38, 28, 28, 18, 38	86, 92, 82, 76, 96, 76, 72, 86, 40, 06, 06, 76, 56, 56, 36, 76	$\bar{x} = 32$ $\bar{I} = 64$
41	43	21	38, 46, 41, 36, 38, 41, 38, 38, 28, 05, 03, 33, 23, 36, 28, 30	76, 92, 82, 72, 76, 82, 76, 76, 56, 10, 06, 66, 46, 72, 56, 60	$\bar{x} = 31$ $\bar{I} = 62$
48	0	21	46, 69, 51, 30, 44, 69, 51, 43, 46, 04, 03, 53, 29, 25, 33, 36	92, 138, 102, 60, 88, 138, 102, 86, 92, 08, 06, 106, 58, 50, 66, 72	$\bar{x} = 40$ $\bar{I} = 80$
48	48	24	38, 48, 38, 41, 41, 46, 41, 38, 20, 05, 03, 33, 28, 38, 30, 38	76, 96, 76, 82, 82, 92, 82, 76, 40, 10, 06, 66, 56, 76, 60, 76	$\bar{x} = 33$ $\bar{I} = 66$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
48	50	28	38, 48, 43, 36, 36, 46, 43, 38, 28, 10, 05, 36, 20, 33, 30, 33	76, 96, 86, 72, 72, 92, 86, 76, 56, 20, 10, 72, 40, 66, 60, 66	$\bar{x} = 33$ $\bar{I} = 66$
59	0	28	38, 61, 53, 30, 38, 71, 51, 33, 43, 36, 10, 41, 28, 48, 61, 33	76, 122, 106, 60, 76, 142, 102, 66, 86, 72, 20, 82, 56, 96, 122, 66	$\bar{x} = 42$ $\bar{I} = 84$
59	57	31	36, 61, 56, 30, 38, 71, 51, 36, 30, 18, 08, 38, 25, 58, 51, 30	72, 122, 112, 60, 76, 142, 102, 72, 60, 36, 16, 76, 50, 116, 102, 60	$\bar{x} = 40$ $\bar{I} = 80$
59	60	35	38, 51, 58, 36, 36, 66, 51, 36, 28, 15, 08, 38, 28, 53, 43, 30	76, 102, 116, 72, 72, 132, 102, 72, 56, 30, 16, 76, 56, 106, 86, 60	$\bar{x} = 38$ $\bar{I} = 76$
86	0	47	38, 71, 69, 36, 38, 74, 66, 41, 53, 71, 48, 53, 33, 56, 61, 33	76, 142, 138, 72, 76, 148, 132, 82, 106, 142, 96, 106, 66, 112, 122, 66	$\bar{x} = 53$ $\bar{I} = 106$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
86	81	52	41, 61, 69, 38, 38, 66, 53, 38, 33, 33, 30, 56, 30, 64, 51, 30	82, 122, 138, 76, 76, 132, 106, 76, 66, 66, 60, 112, 60, 128, 102, 60	$\bar{x} = 46$ $\bar{I} = 92$
86	85	55	46, 53, 64, 43, 41, 61, 46, 36, 25, 23, 25, 48, 41, 56, 38, 25	92, 106, 128, 86, 82, 122, 92, 72, 50, 46, 50, 96, 82, 112, 76, 50	$\bar{x} = 42$ $\bar{I} = 84$
For Full Jet 30 WSQ Nozzles Spaced 2.13 m x 2.13 m					
41	0	14	61, 66, 58, 46, 56, 84, 23, 64, 28, 05, 01, 15, 41, 20, 25 30	122, 132, 116, 92, 112, 168, 46, 128, 56, 10, 02, 30, 82, 40, 50, 60	$\bar{x} = 39$ $\bar{I} = 78$
41	41	17	41, 51, 79, 43, 46, 48, 48, 38, 36, 08, 03, 18, 23, 56, 23, 18	82, 102, 158, 86, 92, 96, 96, 76, 72, 16, 06, 36 46, 112, 46, 36	$\bar{x} = 36$ $\bar{I} = 72$
41	43	21	33, 41, 74, 36, 36, 51, 53, 33, 30, 08, 04, 36, 25, 58, 25, 20	66, 82, 148, 72, 72, 102, 106, 66, 60, 16, 08, 72, 50, 116, 50, 40	$\bar{x} = 35$ $\bar{I} = 70$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
48	0	21	38, 58, 86, 43, 46, 48, 53, 46, 46, 23, 05, 25, 30, 48, 41, 43	76, 116, 172, 86, 92, 96, 106, 92, 92, 46, 10, 50, 60, 96, 82, 86	$\bar{x} = 42$ $\bar{I} = 84$
48	48	24	33, 46, 86, 33, 36, 48, 64, 36, 33, 15, 09, 38, 25, 69, 33, 23	66, 92, 172, 66, 72, 96, 128, 72, 66, 30, 18, 76, 50, 138, 66, 46	$\bar{x} = 39$ $\bar{I} = 78$
48	50	28	28, 36, 74, 30, 30, 48, 61, 30, 30, 15, 10, 48, 28, 64, 30, 18	56, 72, 148, 60, 60, 96, 122, 60, 60, 30, 20, 96, 56, 128, 60, 36	$\bar{x} = 36$ $\bar{I} = 72$
59	0	28	30, 58, 91, 41, 38, 46, 74, 43, 58, 56, 25, 41, 33, 66, 56, 43	60, 116, 182, 82, 76, 92, 148, 86, 116, 112, 50, 82, 66, 132, 112, 86	$\bar{x} = 50$ $\bar{I} = 100$
59	57	31	30, 48, 86, 36, 36, 48, 71, 38, 41, 23, 28, 51, 28, 76, 46, 25	60, 96, 172, 72, 72, 96, 142, 76, 82, 46, 56, 102, 56, 152, 92, 50	$\bar{x} = 44$ $\bar{I} = 88$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
59	60	35	30, 43, 81, 33, 33, 43, 69, 33, 38, 23, 28, 56, 30, 74, 43, 25	60, 86, 162, 66, 66, 86, 138, 66, 76, 46, 56, 112, 60, 148, 86, 50	$\bar{x} = 43$ $\bar{I} = 86$
86	0	47	30, 69, 74, 41, 36, 56, 71, 48, 69, 84, 97, 64, 36, 64, 61, 33	60, 138, 148, 82, 72, 112, 142, 96, 138, 168, 194, 128, 72, 128, 122, 66	$\bar{x} = 58$ $\bar{I} = 116$
86	81	52	28, 51, 69, 33, 33, 56, 64, 41, 38, 41, 76, 66, 41, 69, 43, 23	56, 102, 138, 66, 66, 112, 128, 82, 76, 82, 152, 132, 82, 138, 86, 46	$\bar{x} = 48$ $\bar{I} = 96$
86	85	55	28, 46, 64, 30, 30, 56, 61, 33, 33, 33, 64, 66, 41, 64, 36, 08	56, 92, 128, 60, 60, 112, 122, 66, 66, 66, 128, 132, 82, 128, 72, 16	$\bar{x} = 43$ $\bar{I} = 86$
For Fulljet 30 WSQ Nozzles Spaced 1.98 m x 1.98 m					
41	0	14	25, 61, 79, 56, 48, 51, 41, 66, 20, 20, 03, 03, 76, 13, 08, 08	50, 122, 158, 112, 96, 102, 82, 132, 40, 40, 06, 06, 152, 26, 16, 16	$\bar{x} = 36$ $\bar{I} = 72$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
41	41	17	33, 58, 79, 66, 48, 53, 53, 41, 25, 08, 05, 05, 38, 43, 10, 10	66, 116, 158, 132, 96, 106, 106, 82, 50, 16, 10, 10, 76, 86, 20, 20	$\bar{x} = 36$ $\bar{I} = 72$
41	43	21	28, 48, 76, 53, 43, 53, 56, 41, 28, 10, 08, 13, 38, 46, 10, 05	56, 96, 152, 106, 86, 106, 112, 82, 56, 20, 16, 26, 76, 92, 20, 10	$\bar{x} = 35$ $\bar{I} = 70$
48	0	21	41, 53, 97, 51, 43, 56, 64, 58, 53, 46, 18, 25, 38, 46, 28, 28	82, 106, 194, 102, 86, 112, 128, 116, 106, 92, 36, 50, 76, 92, 56, 56	$\bar{x} = 47$ $\bar{I} = 94$
48	48	24	36, 46, 89, 46, 38, 56, 61, 41, 41, 28, 23, 36, 28, 69, 25, 20	72, 92, 178, 92, 76, 112, 122, 82, 82, 56, 46, 72, 56, 138, 50, 40	$\bar{x} = 43$ $\bar{I} = 86$
48	50	28	30, 38, 76, 38, 33, 56, 56, 36, 33, 25, 30, 48, 25, 61, 30, 20	60, 76, 152, 76, 66, 112, 112, 72, 66, 50, 60, 96, 50, 122, 60, 40	$\bar{x} = 40$ $\bar{I} = 80$

Table 9 (Continued).

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
59	0	28	38, 56, 81, 46, 38, 56, 56, 48, 61, 79, 53, 46, 33, 64, 56, 46	76, 112, 162, 92, 76, 112, 112, 96, 122, 158, 106, 92, 66, 128, 112, 92	$\bar{x} = 54$ $\bar{I} = 108$
59	57	31	33, 48, 76, 43, 36, 56, 56, 46, 43, 43, 61, 56, 28, 76, 46, 25	66, 96, 152, 86, 72, 112, 112, 92, 86, 86, 122, 112, 56, 152, 92, 50	$\bar{x} = 48$ $\bar{I} = 96$
59	60	35	30, 41, 71, 36, 33, 56, 56, 36, 38, 33, 64, 56, 25, 69, 38, 20	60, 82, 142, 72, 66, 112, 112, 72, 76, 66, 128, 112, 50, 138, 76, 40	$\bar{x} = 44$ $\bar{I} = 88$
86	0	47	30, 69, 71, 43, 33, 61, 64, 58, 69, 91, 130, 64, 30, 64, 64, 36	60, 138, 142, 86, 66, 122, 128, 116, 138, 182, 260, 128, 60, 128, 128, 72	$\bar{x} = 61$ $\bar{I} = 122$
86	81	52	28, 46, 66, 36, 33, 58, 64, 43, 41, 46, 99, 66, 28, 71, 41, 18	56, 92, 132, 72, 66, 116, 128, 86, 82, 92, 198, 132, 56, 142, 82, 36,	$\bar{x} = 49$ $\bar{I} = 98$

Table 9 (Continued)

Pressure at Pump (kPa)	Pressure at Compressor (kPa)	Pressure at Nozzle (kPa)	Depth for 30 Minutes (Xi) (mm)	Intensity (Ii) (mm/h)	Remarks
86	85	55	25, 41, 64, 33, 28, 58, 61, 33, 30, 36, 79, 71, 28, 64, 30, 18	50, 82, 128, 66, 56, 116, 122, 66 60, 72, 158, 142, 56, 128, 60, 36	$\bar{x} = 44$ $\bar{I} = 88$

APPENDIX C

Fall Velocities of Raindrops. The data used to calculate the fall velocities are given in Table 10.

Table 10. Fall Velocities of Raindrops Produced by Fulljet 50 WSQ Nozzles

Drop Size (mm)	Time Elapsed (millisec)	Timing-Mark Distance (mm)	Timing-Mark Distance (frames)	Time Per Frame (sec x 10 ⁻⁴)	Distance Traveled by Drop (mm)	Distance Traveled by Drop (frames)	Time Required to Travel (sec x 10 ⁻³)	Fall Velocity (m/s)	Average Fall Velocity (m/s)
21.0 kPa Water, 0.0 kPa Air									
0.5	7	83	10.89	6.4	25	10	6.4	3.9	4.1
0.5	7	267	35.04	2.0	25	30	6.0	4.2	
1.0	7	83	10.89	6.4	25	9	5.8	4.3	4.5
1.0	7	83	10.89	6.4	25	9	5.8	4.3	
1.0	9	121	15.88	5.7	25	10	5.7	4.4	
1.0	7	112	14.70	4.8	25	11	5.3	4.7	
1.0	7	112	14.70	4.8	25	11	5.3	4.7	
1.5	7	76	9.97	7.0	25	5	3.5	7.1	6.6
1.5	7	76	9.97	7.0	25	6	4.2	6.0	
1.5	7	83	10.89	6.4	25	6	3.8	6.6	
1.5	9	121	15.88	5.7	25	6	3.4	7.4	
1.5	7	105	13.78	5.1	25	8	4.1	6.1	
2.0	8	79	10.37	7.7	25	5	3.9	6.4	7.3
2.0	7	70	9.19	7.6	25	5	3.8	6.6	
2.0	8	83	10.89	7.3	25	5	3.7	6.8	
2.0	7	89	11.68	6.0	25	5	3.0	8.3	
2.0	7	89	11.68	6.0	25	5	3.0	8.3	

Table 10 (Continued)

Drop Size (mm)	Time Elapsed (millisec)	Timing-Mark Distance (mm)	Timing-Mark Distance (frames)	Time Per Frame (sec x 10 ⁻⁴)	Distance Traveled by Drop (mm)	Distance Traveled by Drop (frames)	Time Required to Travel ¹ (sec x 10 ⁻³)	Fall Velocity (m/s)	Average Fall Velocity (m/s)
2.5	7	67	8.79	8.0	25	4	3.2	7.8	
2.5	7	70	9.19	7.6	25	4	3.0	8.3	
2.5	6	86	11.29	5.3	25	5	2.7	9.3	
2.5	5	102	13.39	3.7	25	7	2.6	9.6	
2.5	5	102	13.39	3.7	25	7	2.6	9.6	8.9
3.0	6	79	10.37	5.8	25	5	2.9	8.6	
3.0	6	105	13.78	4.4	25	6	2.6	9.6	
3.0	5	127	16.67	3.0	25	9	2.7	9.3	
3.0	5	178	23.36	2.1	25	12	2.5	10.0	
3.0	5	178	23.36	2.1	25	12	2.5	10.0	9.5
3.5	7	83	10.89	6.4	25	4	2.7	9.3	
3.5	5	97	12.73	3.9	25	7	2.7	9.3	
3.5	4	146	19.16	2.1	25	12	2.5	10.0	
3.5	4	159	20.87	1.9	25	12	2.3	10.9	9.9
4.0	4	165	21.65	1.8	25	13	2.3	10.9	
4.0	5	193	25.33	2.0	25	13	2.6	9.6	10.3
0.5	8	163	21.39	3.7	25	15	5.6	4.5	4.5

21.0 kPa Water, 9.0 kPa Air

Table 10 (Continued)

Drop Size (mm)	Time Elapsed (militisec)	Timing-Mark Distance (mm)	Timing-Mark Distance (frames)	Time Per Frame (sec $\times 10^{-4}$)	Distance Traveled by Drop (mm)	Distance Traveled by Drop (frames)	Time Required to Travel (sec $\times 10^{-3}$)	Fall Velocity (m/s)	Average Fall Velocity (m/s)
1.0	8	112	14.70	5.4	25	10	5.4	4.6	
1.0	7	107	14.04	5.0	25	11	5.5	4.5	
1.0	8	127	16.67	4.8	25	11	5.3	4.7	
1.0	8	127	16.67	4.8	25	11	5.3	4.7	
1.0	8	127	16.67	4.8	25	11	5.3	4.7	4.6
1.5	8	106	13.91	5.8	25	7	4.1	6.1	
1.5	8	117	15.35	5.2	25	8	4.2	6.0	
1.5	8	112	14.70	5.4	25	9	4.9	5.1	
1.5	8	112	14.70	5.4	25	9	4.9	5.1	
1.5	7	120	15.75	4.4	25	9	4.0	6.3	5.7
2.0	7	84	11.02	6.4	25	5	3.2	7.8	
2.0	7	87	11.42	6.1	25	6	3.7	6.8	
2.0	7	94	12.33	5.7	25	7	4.0	6.3	
2.0	7	100	13.12	5.3	25	8	4.2	6.0	
2.0	7	100	13.12	5.3	25	8	4.2	6.0	
2.0	8	117	15.35	5.2	25	7	3.6	6.9	6.6
2.5	6	83	10.89	5.5	25	6	3.3	7.6	
2.5	6	89	11.68	5.1	25	6	3.1	8.1	
2.5	6	89	11.68	5.1	25	6	3.1	8.1	
2.5	5	77	10.10	5.0	25	6	3.0	8.3	
2.5	5	87	11.42	4.4	25	7	3.1	8.1	8.0

Table 10 (Continued)

Drop Size (mm)	Time Elapsed (millisec)	Timing-Mark Distance (mm)	Timing-Mark Distance (frames)	Time Per Frame (sec x 10^{-4})	Distance Traveled by Drop (mm)	Distance Traveled by Drop (frames)	Time Required to Travel (sec x 10^{-3})	Fall Velocity (m/s)	Average Fall Velocity (m/s)
3.0	7	93	12.20	5.7	25	5	2.9	8.6	
3.0	5	110	14.43	3.5	25	8	2.8	8.9	
3.0	4	107	14.04	2.8	25	9	2.5	10.0	
3.0	4	163	21.39	1.9	25	12	2.3	10.9	
3.0	3	111	14.57	2.1	25	11	2.3	10.9	
3.0	4	146	19.16	2.1	25	12	2.5	10.0	9.9
3.5	5	101	13.25	3.8	25	7	2.7	9.3	
3.5	4	133	17.45	2.3	25	10	2.3	10.9	10.1

VITA

Shyam Prasad Rajbhandari was born on December 3, 1950, in Baglung, Nepal. He was graduated from Vidya Mandir High School in January of 1967. In April of that year, he received a scholarship from His Majesty's Government (HMG) of Nepal to study agricultural engineering in India. He entered the University of Allahabad in July, 1967, and was graduated in 1973 with a B.S. degree in Agricultural Engineering.

He worked for one year as a vocational (agriculture) teacher in high school under the National Development Service Program of the Ministry of Education. In 1974 he was appointed as a Soil Conservation Officer in the Department of Soil and Water Conservation by HMG, Nepal. He participated in the "Seminar on Erosion Control and Reforestation" held at the University of Philippines, Los Banos, in April 1978. He worked in various watershed management projects located in different parts of the country until August 1981. In September 1981 he was provided a scholarship to pursue the M.S. degree in Agricultural Engineering in the United States, and he entered the University of Tennessee in the fall quarter of that year. He was elected to the Gamma Sigma Delta honor society in November 1982.

Shyam was married in 1980 and he and his wife, Rebati, have a son, Susan. He plans to return to his country and continue his job immediately upon receiving the M.S. degree.