EVALUATING SAMPLING STRATEGIES
FOR
RAINFALL SIMULATION STUDIES

A DISSERTATION

Submitted in partial fulfillment of the
Requirements for the award of the degree
Of
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In
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By

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CANDIDATE DECLARATION

I hereby certify that the work which is being presented in this Dissertation entitled **"EVALUATING SAMPLING STRATEGIES FOR RAINFALL SIMULATION STUDIES"** in the partial fulfillment for the award of the Degree of Master of Technology in Hydrology, submitted in the Department of Hydrology of the Indian Institute of Technology, Roorkee, is an authentic record of my work done under the guidance of **Dr. Sumit Sen, Assistant Professor and Dr. M.K. Jain, Associate Professor**, Department of Hydrology, IIT Roorkee.

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CERTIFICATE

This is to certify the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Rainfall simulation experiments were carried out on an outdoor experimental plot in the Department of Hydrology at IIT Roorkee, India using a rainfall simulator fabricated with four fixed stand pipes on which a header with 11 nozzles attached to it. The height of the header of the rain simulator can be adjusted up to 3.35m. Six types of full cone nozzle with different orifice diameter were used. Studies were carried out on 3m x 1.5m plot for different pressure and different heights. In order to determine the rainfall intensity and uniformity coefficient, several tests were carried using six sets of nozzles (B1/8GG-SS4.3W, B1/4GG-SS10W, B1/4GG-SS14W, B3/8GG-SS17W, B1/2G-SS30W and B1/2GG-SS40W) with four different header heights (2m, 2.5m, 3m & 3.35m) and three different operating pressure heads (0.4kg/cm^2, 0.8kg/cm^2 and 1.6kg/cm^2). Three replications of same nozzle at same height and same pressure head were carried out. Taguchi method was used with objective to identify the key factor that contributed most to the rainfall intensity. It was found that percentage contribution of key factor nozzle size was 62.41% which means nozzle size is a sensitive key factor that influence more on the rainfall intensity optimum condition is observed at pressure of 1.6 kg/cm ^{2}, a height of 2m and nozzle orifice dia. of 3.6 mm. A multiple linear equation ($R^2 = 0.941$) was developed to calculate rainfall intensity as a function of operating pressure head, height of nozzle header and orifice diameter of nozzle. Developed equation can be used to know rainfall intensity based on operating parameters of the rainfall simulator. The measured rainfall intensity ranged from 55mm/hr to 780mm/hr and uniformity coefficient ranged from 84.49% to 92%.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Rainfall simulation experiments provides valuable simulation environment to understand varies processes operating in many disciplines such as hydrology, agriculture, science, geomorphology and many other areas. Initial rainfall simulation experiments were developed by the Soil Conservation Service in the 1930s as a way to measure erodibility and infiltration capacity of soil. From these early experiments, the Universal Soil Loss Equation (USLE) was developed (Wollmer, 1994). Since then, rainfall simulation has evolved from a simple procedure, in some cases involving nothing more than a common sprinkling, to a complex process involving electronic and hydraulic machines (Meyer, 1988). General idea behind using a rainfall simulator is to allow controlled releases of water to fall onto a confined plot area. The commonly used method for large area field studies (e.g. 10 to 500 m^2) is the pressurized nozzle (Meyer and McCune, 1958; Swanson, 1965; Niebling et al., 1981; Parsons et al., 1990; Riley and Hancock, 1997). Agriculture research uses rainfall simulator for erosion and rainfall-runoff studies. It is a convenient, cheap and quick method as it independent of natural rainfall (Herngren et al., 2005). The use of rainfall simulators in urban hydrology studies is relatively recent. Araujo et al. (2000) and Silva (2006), for instance, used pressurized nozzle simulators in experiments with permeable pavements, while Egodawatta (2007), Egodawatta et al. (2007, 2009) and Miguntanna (2009) used a rainfall simulator, developed by Herngren (2005), for pollutant build-up and wash-off process researches, and for urban water quality research. The application of rainfall simulator is to collect the data of runoff, infiltration and erosion both in field and laboratory. Results obtained from these experiments help in understanding the surface characteristics such as slope soil properties, fire, vegetation and micro-topography which can affect infiltration mechanism, water routing, sediment generation and transport ranging from point to hillslope.

Presently there is no universal rainfall simulator which can be applicable to all situations. During last 40 years many rainfall simulators have been designed by Hall in 1970 and by Bubenzer in 1979. Rainfall simulator is classified according to the way rain drops are produced. The two types are (a) drip formers (Farmer. 1973; Romkens et. al, 1975) and (b) nozzles (Meyer and Mccune, 1958; Swanson, 1965). Pressurized nozzle (Meyer and McCune1958; Swanson ,1965) is used commonly for large area field studies (10 to 500 m^2). For the development of the simulator for the large areas involves compromise between the capacity to produce natural rainfall characteristics and technical constraints. In the past decades portable rainfall simulator corresponding to plot sizes of 1 or 2 square yard were deployed. These simulators are well suited to wide range of field studies particularly where field-access is difficult or multiple-replication is needed across large area. However, these simulators fail to accurately replicate natural rainfall characteristics due to their portability, cost design or management limitation. Since 1930 United States has explored the pioneer work on soil erosion using rainfall simulator by creating artificially the condition for performing the hydrological processes. In such studies uniform surface slope on small plots were subjected to artificial rainfall generated by the nozzles. Experiments conducted in the field to study rainfall - runoff relationships is totally dependent upon the weather. The occurrence of both high and low flow are largely random as rainfall sometimes may be high or sometimes may be low. In such study rainfall simulator is use to generate artificial rainfall on small plots of uniform slopes The plot was used to study the behavior of different combination of soil types and vegetal cover under condition favoring occurrence of erosion. An approach to investigate the general hydrological problems like the production of floods by heavy rainfall, applied during 1950s and1960s. The scale models (which enable to demonstrate some behavior or property of the original object without examine the original object itself) were used in solving hydraulic problem to study relationship between rainfall and runoff. The use of scale models in solving hydraulic problems with complex boundary condition were made to apply the same principle to study the relationship between rainfall and runoff. The topographical features of natural catchments referred as prototype used on appropriate scale by considering a laboratory model by which we can predict the prototype behavior obtained by similarity criteria.

Rainfall simulator is used to produce accurate physical features of natural rainfall; however, some tolerance has to be allowed in the interests of simplicity and cost. Thus producing controllable, reliable and predictable simulation of rainfall events. Majority of times, a rainfall simulator cannot produce the variable rainfall intensity as of natural rainfall. Even though rainfall simulator cannot perfectly replicate the natural rainfall, they are still the best means to study the overland flow generation. Artificial rainfall can be generate by using two type of simulator; pressurized spraying nozzles and non-pressurized drip former. The drip former use gravity or pumping to attain required head at the nozzle. More recent studies going on to focus on the effects land cover or land use change on hydrologic cycle, these studies provide the information how runoff and erosion is going to change at the plot and hillslope after vegetation and agriculture disturbances. One is the laboratory scale simulator which can produce rainfall intensity ranging from 7.74 to 28.57mm h^{-1} and uniformity coefficient from 5.04 to 11.55% (Foster et al. 2000). The diameter of hole and pressure in the tank can control the drop size and rainfall intensity. Another type of rainfall simulator that can be used on small plot, rainfall simulator with small disk nozzles that directs water to the plot. It has uniformity coefficient of 75% at full range of intensities. In general, rainfall simulators with smaller plot are easy to carry. However, due to their limited size (approx. $1m^2$) makes them not well suited to capture plot-scale heterogeneity in surface properties. For field plots up to $10m^2$, we can use sweeping sprinklers and nozzle type rainfall simulator. One of the early simulator of this type was developed by Moore (1913) which was using oscillating nozzle to produce intensities 3.5 to 185 mm h^{-1} with uniformity coefficient 80.2 to 83.7% over a 4.6m x 6.1 m plot. Similarly, the ‘EMIRE” rainfall simulator of Est eves et al. (2000) cover plot area of 5mx5m with mean intensities from 60 to 76 mm h^{-1} and mean uniformity of 80.2%. Fister et al. (2012) developed a rainfall simulator for plot area $2.2m^2$ which can achieve intensity of 85-96 mm h^{-1} with mean uniformity coefficient of 60%, one of the advantage of the two devices is that they can achieve high drop velocity as compare to drip tank due to water pressure in the nozzle. Sweeping and oscillating sprinkler rainfall simulator include intricate parts which need to be run by computer, adding to the system expense and complexity. Row and array of spray tend to have lower uniformity coefficient due to stationary nozzle pattern. Rainfall simulator has a wide application in soil crusting and soil erosion studies for more than last 30 years. Hignettt et al. (1995) presented some properties that rainfall simulator required (a) precise production of natural drop size; (b) continuous and uniform rainfall on the plot area; (c) should be capable to produce desire rainfall intensity; (d) should be cheap and portable.

Many types of rainfall simulator have been developed to study the performance of sediment transport and chemical movement of soil due to rainfall (Deng et al.,2008) Varying the height of the droplets or by changing the droplet sizes we can examine the influence of water droplet kinetic energy. Terminal velocity depend upon the droplet size, smaller the droplet, the terminal velocity is low and also the height required is less to reach that velocity (Laws and Parson, 1943). Rainfall simulator should be designed such that it releases water in controlled manner in both time and space.

In nozzle-type simulator, average intensity increases with working pressure but decrease the mean drop -size and range within the rainfall, just opposite to natural rainfall. (Tossel et al,1990) Alternatively, by using tubing-tube rainfall simulator of fixed tube diameter, the result is production of uniform drop sizes (Hall,1970). Generally, the main difficulty in designing the rainfall simulator are (i) maintaining the constant pressure at different heights; (ii) uniformity of application; (iii) measuring droplet size distribution; (iv) application rate consistency control and (v) terminal velocity attainment for the droplet distribution.

1.2 OBJECTIVES

The objectives of the present work were:

1. To conduct experiments for the estimation of rainfall simulator parameters such as uniformity coefficient and rainfall intensity at different operating pressure heads, different height of nozzle head and nozzles of different orifice diameters (6 nozzles of different sizes).
2. To develop suitable model for calculating the rainfall intensity using operating pressure head, height of nozzle head and nozzle orifice diameter.
3. To identify the key parameters that exerts greatest influence on simulated rainfall intensity.

CHAPTER-2

LITERATURE REVIEW

2.1 GENERAL

In this chapter literature review has been done for various aspects of the present work including, some of the previously developed rainfall simulator Rainfall simulator at University of Maine, Rainfall simulator for laboratory catchment studies at University of London, rotating disc simulator at ICRISAT, Spray-nozzle for superficial runoff and erosion studies, European small portable simulator, evaluation of overland flow models using laboratory catchment data etc.

2.2 PREVIOUSLY DEVELOPED RAINFALL SIMULATOR

2.2.1 RAINFALL SIMULATOR BY M.J. HALL AT IMPERIAL COLLEGE OF SCIENCE & TECHNOLOGY, LONDON

Hall (1969) developed a rainfall simulator for the study of overland flow by using 425 swirl-type nozzle in a square array on the horizontal plane. The nozzle was designed in such manner that it can maintain spacing for producing uniform rainfall on the 1.83 m height below the system for wide range of rainfall intensities maximum up to 320 mmh^{-1}. Uniformity of rain was calculated by Christensen formula for evaluating the performance of spraying system. It was found that uniformity coefficient was more than 80% for the network of nozzles installed. Network of nozzles was placed on 25 distributed pipe of 50 mm diameter which was placed parallels and each pipe was carrying 17 nozzles. The first and last distributed pipe was placed above the ends of the tank for minimizing the edge effects. Nozzle orifice plane was placed approximately 1.83 m above the tray. To prevent the choking of nozzle orifice diameter in any line a tolerance was given of less than 1 mm.

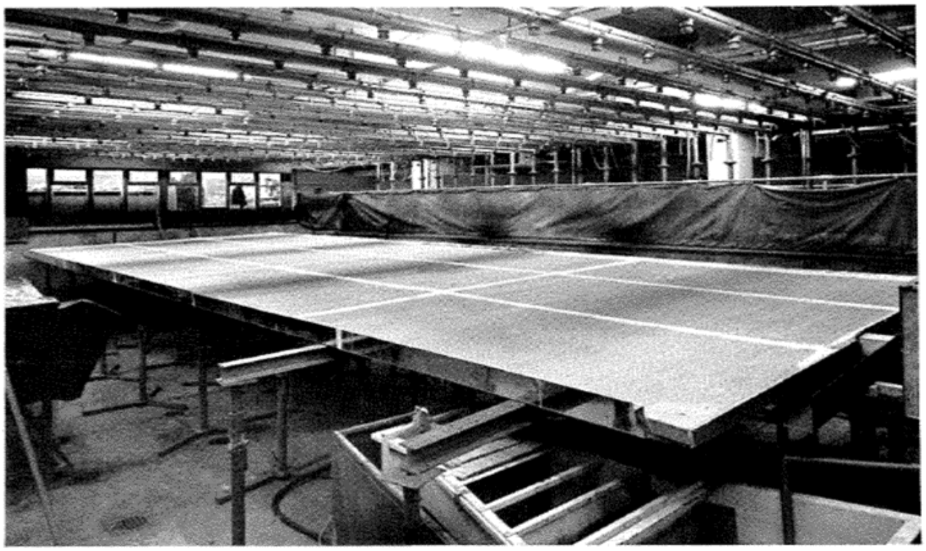

Figure 2.1 General view of M.J Hall artificial catchment area at Imperial College of science and technology, London. Source; Hydrological sciences, journal-des sciences Hydrologiques,34,6/1989.

2.2.2 Norton Simulator

Norton simulator used oscillating-type nozzle and spray water on a plot area at a different speed to produce variable intensity storm. Scott Mcfee and Darrel Norton designed the Norton simulator at Purdue University for experiments at the USDA National Soil Research Lab. Spraying of nozzle was control by boxes which were around each nozzle for proper nozzle overlapping. This control box give signal to start and stop the boom which drives by a small gear motor drives. Four nozzle was supplied in set of two. Each set of nozzle has its own hose and pressure gauge and adjusted at different height. Rainfall simulator used Veejet 80100 spraying nozzle manufacture by the Spraying system. It yields flow rate ranging from 13.2 to 132 liters per minute at a pressure range of 34 to 34000 kPa. At a pressure range of 41 kPa, it produces drop size and rainfall intensity near to the natural rainfall. Maximum nozzle generated an irregular spray when used beyond its capacity limit. Thus, we cannot the same nozzle for small intensity by reducing the pressure because with the reduction its uniformity also decreases. Hence, a new nozzle is require with small capacity range which can produce low intensity having same drop size and rainfall intensity.

2.2.3 GUELPH RAINFALL SIMULATOR (GRS) II

In light of merits and shortcomings of the various simulator types, a new continuous-spray simulator design has been selected and developed for both field and laboratory soil erosion studies at the University of Guelph. Special attention has been given to the portability of the system, simple operational features and cost. The GRS II has a downward–oriented single nozzle, continuous–spray design, employing a selection of nozzles providing different flow rate. Six nozzles with a full–cone spray angle of 1200 (at 70 kPa), nozzles from spraying system, have been selected to provide a range of rainfall intensities. Tossell et. al. (1957) performed experiment on the developed rainfall simulator and found that rainfall intensity and uniformity coefficient were dependent on nozzle size, operating water pressure and nozzle height above the plot surface. Each nozzle was tested using operating pressure 48.3 kPa, 69 kPa and 96.5 kpa while the distance from the nozzle to the plot was varied from 0.8 m to 1.7 m in increment of 0.1 m or 0.2 m. Study showed that rainfall intensity increased with increasing nozzle size. The smaller nozzle showed smallest range in intensity as a function of nozzle height. The larger nozzle provides larger range of intensity with changes in height. The combination of nozzle height, water pressure and nozzle size provide broad range of rainfall intensity. Finally, concluded that current GRS II design provided a flexibility and suitability for a wide variety of research applications.

Figure 2.2. Photograph of Guelph rainfall simulator in the field. source; Canadian Agriculture Engineering Vol.29 No.2 summer 1987.

2.2.4 ICRISAT SIMULATOR

Rainfall simulator with a rotating-disc and nozzle was developed at International Crop Research Institute for the Semi-Arid Tropics (ICRISAT). It was provided by four-wheeled mild steel trolley making it portable covering a plot area of 2.4 mx2.4 m. One end of the trolley had pump and water tank while the other end carried generator and control panel. Trough crab gave forward and backward movement and height was adjusted by corner screw. This simulator was able to produce rainfall intensity of 15-150 mmh^{-1} by using appropriate nozzle and rotating-disc slot aperture.

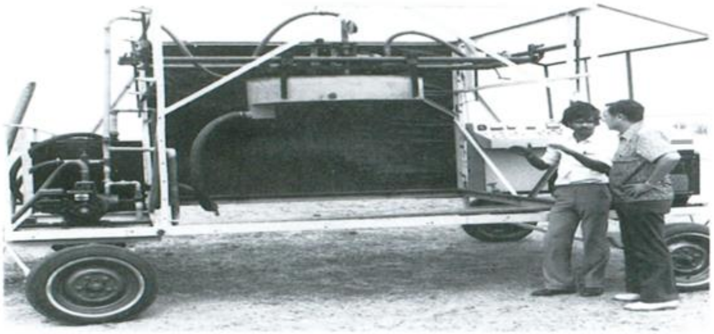

Figure 2.3. Rainfall simulator developed at International crop research institute for the semi-arid Tropics (ICRISAT) source: J. agric. Engng Res. (1989)

The uniformity coefficient of the simulator ranges from 91.2 to 94.3%. It was noticed that above 30 mm/h rainfall intensity, the kinetic energy of simulated rainfall was very close to natural rainfall. A linear relationship was observed between intensity and angle of opening (aperture) for angle 15° to 60° ($Y= 2.6876X-11.38$, $r^2 = 0.9981$). Oil method was used to calculate the kinetic energy and it was found to be 32 Jm^{-2} mm^{-1}. Rainfall simulator was able to produce various rainfall intensities and also help in quick assessing of soil erosion infiltration and runoff data.

2.3 Laboratory rainfall simulator at University of Maine

Epstein and Grant (1961) developed a laboratory rainfall simulator at the University of Maine for the study of soil erodibility and the determination of soil erodibility factor (K) used in universal soil loss equation. To produce a 5.01 mm drop, two drop former were used. Natural raindrops range up to 6 mm in size for all intensities. The volume of rain 5.0mm or larger drops in high intensity natural rainfall was about 3.0 mm. To produce drops of 3.2 mm diameter a 2 m gauge stainless steel tubing was used. Result shows that drop diameter and kinetic energy was dependent on head. Rainfall simulator can also be used for basic studies in soil erosion, infiltration and water movement, and movement of chemicals and pesticides through the soil.

2.4 Portable rainfall simulator for field and laboratory studies

Tossell et al (1987) developed a rainfall simulator which was portable and can be used for both field and laboratory soil erosion research at the University of Guelph. They used continuous-spray design nozzles serving low-to medium flow rate. This simulator was capable to produce storm intensities ranging from 17.5 mmh^{-1} to 200 mmh^{-1}. Rainfall intensity varies with nozzle size, nozzle water pressure and the nozzle height above the plot surface. The simulator named as Guelph simulator, provides a flexibility that renders it suitable for wide variety of research application. Experiment carried by six nozzles choosing different height from 0.8 to 1.10 m in increment of 10 m and water pressure at nozzle ranging from 48.3 kPa to 69 kPa.

2.5 Rainfall simulator for laboratory catchment studies at University of London.

Rainfall simulator apparatus was set up by Hall et al. (1989) for the laboratory studies. They study overland flow model using the data obtained by rainfall simulator in the laboratory. Study on set apparatus was carried out at Department of Civil Engineering at University of London. The objective of setting the laboratory apparatus was to provide reliable data for hydrological analysis and co-releate it results with field or natural catchment by investigating on explicit component of hydrological cycle and to produce drop size distribution and terminal velocity of drop at different intensity of natural rainfall. Laboratory catchment was consisted of reinforced concrete tank with depth of 1.52 m, length of 11 m and 7 m width. Rainfall simulator was consisted of 425 swirl type nozzle. which can generate maximum intensity of 320 mmh^{-1}, network of 425 nozzles was placed on 25 distributed pipe of 50 mm diameter which was placed parallel and each pipe was carrying 17 nozzles. Concluded that rainfall simulator was sufficiently flexible to permit the wide variety of storm patterns including stationary, uniform and variable intensity of rainfall. According to test requirement laboratory catchment orientation can be set with respect to rainfall simulator. Hence, it was capable to produce different variations in rainfall intensity and movement of storm in one direction without any limitation in experiment.

2.6 Rotating disc rainfall simulator at ICRISAT

Thomas et.al.(1989) construct and calibrate a rainfall simulator with a rotating disc and nozzle for at International Crop Research Institute for the Semi – Arid Tropics (ICRISAT). for the study of field erosion, infiltration and runoff process. This simulator was capable to produce rainfall intensity of 15 mmh^{-1} to 150 mmh^{-1} by incorporating different size of nozzles. Uniformity coefficient measures ranging from 91.2 to 94.3% and above 30mmh^{-1} it simulates rainfall kinetic energy very close to natural rainfall. At last concluded that Rainfall simulator was able to produce various rainfall intensities and also help in quick assessing of soil erosion infiltration and runoff data.

2.7 Comparing physical characteristics of rainfall with natural rainfall

Assouline et al. (1996) compare the physical characteristics of simulated rainfall with natural rainfall by using the model. Drop size distribution and drop velocity was modelled at three intensities by developed expression for natural rainfall. They developed relationship between kinetic energy per unit of mass and intensity for simulated rainfall and compare it with natural rainfall at same intensities. It was found that kinetic energy per unit mass of simulated rainfall was very close to natural rainfall value at same. intensity. However, different trends were noticed in kinetic energy and rainfall intensity relationship due to different drop size distribution. Since, simulated kinetic energy has no linear relationship with intensity. Therefore, rainfall cannot be treated as independent variable in models applying to process which affect the rainfall kinetic energy.

2.8 Modified rainfall simulator for infiltration, runoff and erosion studies

Singh et al. (1999) evaluated performance of modified rainfall simulator infiltrometer for infiltration, runoff and erosion studies, calibrated for various rainfall intensities. They used computer vision technique to determine the drop size at 60 mmh^{-1} and 100 mmh^{-1} rainfall intensity. Field test show that rotating drop producing chamber provide better result for simulation of natural rainfall for soil erosion, infiltration and runoff studies. Result showed that to produce rainfall intensity of 60 mmh^{-1} and 100 mmh^{-1} with drop forming mechanism head of 20 mm and 39.5mm required. Average velocity found to be 4.957 m/s after a fall of 1.4 m for the rain drops of 5.17 mm size with intensity of 60 mmh^{-1}. Finally concluded that modified rainfall simulator infilometer was simple and efficient to use, though its modification increases it cost and gave good service in developing rainfall – runoff relationship for watershed management studies in the management of water resources for agriculture purposes.

2.9 EMIRE large rainfall simulator

Esteves and Planchon et.al. (2000) designed and tested in field the EMIRE large rainfall simulator. Simulator was intended to use in the field and can produce natural rainstorms. Nozzle from the spraying system cooperation 1H106SQ was used with operating water pressure of 41.18kPa the mean drop diameter is 2.4 mm and the calculated kinetic energy 23.5 Jm^{-2} mm^{-1}. The rainfall intensity was constant 65 mmh^{-1} with uniformity coefficient of 78 to 92 % over the plot. Study was done to collect data during rainfall simulation experiments. Three replication was done with the same rain on the 50 m^2 plot area. Interpreting good performance in all cases. Uniformity of rainfall calculated by Christiansen (1941) formula fell within acceptable limits, but affected by the pressure and wind. Experiments was being designed to characterize the drop size distribution of rain in different area of the plot by using an optical spectro-pulviometer.

2.10 Non- potable laboratory scale rainfall simulator

Regmi and Thompson (2000) designed and constructed a non-portable rainfall simulator for laboratory purpose to produce droplet condition similar to natural rainfall. They use positive displacement principle to produce rainfall intensity ranging from 0.025 cm/h to 16 cm/h in increments of 0.025 cm/h. Suspended drop redistribution screen was used to produce drop size distribution similar to natural rainfall.

2.11 Mathematical model for evaluation effect of wind on rainfall simulator

Lima et.al. (2002) developed a mathematical model for evaluating the effect of wind on downward-spraying rainfall simulator. Model used was three dimensional used for the study of movements of individual drop after their releasing from the nozzle for the estimation of kinetic energy. It was proved to be helpful in selecting nozzle, size of the plot area for simulation to get high uniformity coefficient for the plot area. Laboratory and field experiments were performed to evaluate the adequacy of the proposed methodology. Result concluded that drop size distribution with and without wind differ considerably, smaller drops are more affected by wind than those bigger drops and it also provide a simple way of visualizing spray pattern and different sloping surfaces and for different wind condition.

2.12 Comparison of rainfall simulator erosion with observed data of the catchment at Tunsia.

Hamed et al. (2002) compare observed reservoir sedimentation in an erosion-sensitive semiarid catchment with erosion occur with rainfall simulator They developed a method for estimating catchment scale soil loss by observing rainfall using a rainfall simulator whose intensity can be varied in an erosion -sensitive catchment in semi-arid, Tunisia. A 7-year data (1992-1999) of observed sedimentation reservoir was chosen to test a methodology. Methodology was based on energy adjustment for the used simulator as simulator have different kinetic energy of the simulated rain and the natural rainfall of same intensity and upscaling of simulated erosion in which rill erosion was estimated by adjusting the difference between slope lengths for the plots versus the catchment after onset of runoff. Finally, conclusion showed that there is linear relationship between total soil loss and erositivity factor, accumulated soil loss for the investigated three periods was 96%, 36% and 80%, respectively of the observed sedimentation in the reservoir. Overall concluded that upscaling of variable rainfall simulator observations may provide a good estimate of catchment erosion.

2.13 Portable rainfall simulator

Humphry, Daniel et al. (2002) developed a new rainfall simulator that was easy to operate and portable, also maintaining rainfall characteristics of natural rainfall. The frame of the simulator was constructed from aluminum pipe using single nozzle 50WSQ at height of 3 m working on water pressure of 28 kPa producing 70 mmh^{-1} rainfall intensity over a plot area of 1.5 m x2 m with uniformity coefficient of 93 %. Kinetic energy of rainfall was about 25 Jm^{-2} mm^{-1}, approximately 87% of natural rainfall. Main advantages of simulator was its ease operation and portability from laboratory to fields experiment for runoff studies. Material required to build the simulator were not very costly and also required minimum labor for its construction.

2.14 Norton ladder type rainfall simulator

Blanquies et.al. (2003) designed and constructed a rainfall simulator which can easily be set up and maintained along with capability to create variety of rainfall regimes. Simulator was based upon the principle of Norton ladder type rainfall simulator. They construct it at Cal poly’s farm shop, Pressurized nozzle with a cam-operated oscillating boom was used. The plot area 1m x3.56 m can be covered by the nozzle of this type of simulator which emit uniform rainfall covering 1m x3.56 m plot area. The nozzle was manufactured by spraying system company of size 3/8k SS45 which emit an average drop size of 1.7 mm at 47.6 kPa and a range of drop sizes of less than 1 mm to 7 mm correlating to storm less than 50 mmh^{-1}. Aluminum support was used to support four -nozzle boom. The number of oscillation occurring per minute of the nozzle across the box opening determines the intensity. Finally, the simulator designed that was similar to original rainfall simulator with some critical changes. Nozzle they choose produce drop size and distribution near to natural rainfall, uniformity coefficient of rainfall simulator was greater than 90%, since it was computer operated it produce pattern that can be varied over wide range of intensities.

2.15 Prediction of sediment yield using rainfall simulator

Vahabi and Nikkami (2008) used a single portable rainfall simulator for assessing dominant factors affecting soil erosion, It was used for producing 24.5 and 32 mmh^{-1} rainfall intensities of 30 min duration at 144 locations over soil erosion plots with dimension of 95x125 cm and classes of slope 12-20 and 20-30%, different soil textures, different antecedent soil moistures and medium to poor vegetation cover conditions, for the 24.5 and 32 mm/hr. rainfall intensities sediment yield had high correlation of -0.771and -0.796 with vegetation cover and slight correlation of 0.045and 0.029 with land slope respectively . Regression equation for predicting the sediment yield were also developed for different condition. The portable non-pressurized rainfall simulator was used, which developed at the soil conservation and watershed management research institute Iran. Rainfall simulator was supported by a frame having height of 0.04 m and had a plate of 1.2 m length and 0.84 m width, working on oscillating mechanism with a drive motor which uniformly distributes the drop across the plot. It was found from the result that for determining the sediment yield the most efficient factor were recognized is vegetative cover and land slope and later found that it has slight effect on sediment yield. Coefficient of correlation were positive except for sand content and vegetation cover indicating positive effects of the slope, antecedent soil mixture, clay content and silt content and negative effects of sand content and vegetation cover on the sediment yield.

2.16 Rainfall simulator for erosion studies

Raquel Perez-Rodriguez et al. (2009) tested rainfall simulator nozzles for suitability within soil erosion plots, experiments were carried out on outdoor experimental plots in Aranjuez (Madrid), where annual rainfall is about 427 mm. Three types nozzles were used for plot area of 1 m x1 m gave 108 mmh^{-1} intensity for 115 nozzle, 157 mmh^{-1} for a 90 nozzle and 72 mmh^{-1} for D4 nozzle, 3 other nozzle (3B0qD4) were selected instead so that the cones overlapped. In order to measure rainfall intensity and rain uniformity coefficient, several test were carried out with all the nozzle (minimum three test per nozzle). Six test were performed to estimate drop size, out of all the nozzle 90 nozzle which was working on 1 kg/cm was the only nozzle with CU of 80% and thus cannot be acceptable for the plot. This study confirms the difficulty of the natural rainfall intensity, different nozzles they used have different intensities and uniformity coefficient. Nozzle 90 is not useful for erosion studies due to its uniformity coefficient less than 80%. Nozzle 115 shows the good CU and can be used for two adjacent erosion plots.

2.17 Spray-nozzle simulator for superficial runoff and erosion studies

Sanguesa, and Arumi eta al. (2009) develop a rainfall simulator for the in-situ study of superficial runoff and soil erosion using four full- cone spray nozzles with uni-jet system mounted on header. Rainfall intensity was tested in the laboratory and soil erosion was evaluated in an experimental field with different slopes (11, 21, and 39%). Total 20 simulations were performed in the field and in the laboratory. Laboratory and field test Result help in calculating the rainfall uniformity and check whether the simulator is applicable for erosion plots or not with different slopes. Simulator produce even and uniform rainfall near 90% to study processes of superficial runoff and erosion. Finally, apparatus was easy to handle, cheap and portable, thus allowing the necessary experimental replicates to be carried out.

2.18 Dripper-type rainfall simulator

Elbasit, Salmi et al. (2010) investigated the effect of rainfall characteristics produced by dripper – type rainfall simulator on soil splash erosion. Piezoelectric transducers using vaisala RAINCAP rain sensor was used to estimate the kinetic energy and drop size distribution. The soil splash was evaluated for the intensity range 10 to 100 mmh^{-1} using splash cup method. It was found that simulated rainfall intensity and kinetic energy relation was different from natural rainfall, it follows the natural trend until rainfall intensity reached 30 mm/h and above it kinetic energy stats decreases. Splash soil erosion was found to be highly correlate with kinetic energy when data produced rainfall intensity ranged from 10-100 mmh^{-1}.

2.19 Rainfall simulator for urban hydrology research

Sousa Junior and Siqueira (2011) designed and calibrated a rainfall simulator for urban hydrology research. Developed simulator was able to simulate raindrops of median diameter of 2.12 mm and kinetic energy of 22.53 J/mm.m^2 representing 90.12% of kinetic energy of natural rainfall events and uniformity coefficient was ranged from 68.3 to 82.2 %. Rainfall simulator was able to produce 40 mmh^{-1} to 182 mmh^{-1} rainfall intensity. Two full jet 1/2SSHH40 nozzles were used placed 1.06 m apart, were fitted to a 12.7 mm diameter PVC pipe with spray nozzle height of 2.80 m with water pressure of 70 kpa produced a solid cone-shaped spray pattern with a round impact area. Solenoid valves were used in PVC pipes for obtaining variable intensities. Rain produced by the simulator was covering 3 m^2 plot area. Concluded that simulator uniformity coefficient ranges from 68.3% to 82.2 % and can produce drop size diameter between 0.65 and 4.75 mm and was able to produce a very close resemblance of natural rainfall. Rainfall characteristics like terminal velocity and kinetic energy reached 86.83 % to 100 and 90.12% respectively of the natural rainfall events and can be used in urban hydrology research to reproduce rainfall intensities of return periods from 1 to 10 years and duration of 10 to 60 minutes.

2.20 Rainfall simulator used in soil crusting and soil erosion laboratories

Carmi et.al (2012) design and construct the rainfall simulator for field runoff studies and used it in soil crusting and soil erosion laboratories. A high accuracy rainfall simulator of portable type was designed to estimate drop distribution, intensity, drop size, drop velocity and kinetic energy. Main purpose for the design and construction of this portable simulator was to simulate rainfall in field that induce crusting and thus lead to generation of runoff and eventually soil erosion. They used blotting paper method to estimate the drop size which can accept low intensity rainfalls characterized by a median drop size in the range 1.5 mm to 2.5 mm.

2.21 Parameterization of EROSION 2D/3D SOIL EROSION MODEL Using small scale rainfall simulator

Schindewolf and Schmidt (2012) studied of runoff feeding device, which was able to multiply the plot length virtually by supplying sediment loaded runoff from upstream and parametrize the EROSION 2D/3D soil erosion model using a small- scale rainfall simulator and upstream of runoff simulation. Experiments were conducted for the study of infiltration and surface runoff and sediment transport. When infiltration rate is constant the runoff started and additional runoff was supplied by sediment loaded from the upstream side. Concluded on comparing with 15-year-old data on large scale plots 1. The presented approach proved to produce reasonable result, as EROSION 2D/3D model for conservation tillage, properties of tillage is taken in account especially for conservation tillage.

2.22 Assessment of rainfall-runoff sediment transport using laboratory scale rainfall simulator

Aksoy et.al.(2012) developed a laboratory scale rainfall simulator for the assessment of rainfall - runoff sediment transport process over a 2- dimensional flume. Pressure nozzle was used to spray water with intensity ranging from 45 to 105 mm/h and uniformity coefficient 82 to 89%. The initial velocity of which rain drop falling from height 2.43 m having median diameter of 2.2-2.4 3 m having median diameter of 2.2-3.1 mm. The median size impact velocity deviates from the terminal velocity with a relative error of 6 and 15%. Adjustable flume was used which can be adjusted to the slope up to 20% in horizontal and vertical direction. Flow was measured from the outlet of the flume to differentiate the interill-area contribution into rills. Typical hydrograph and sediment hydrograph was developed by using the simulator in order to know the ability of rainfall simulator for sediment transport process over hill slopes.

2.23 Studying influence of rainfall characteristics on runoff and water erosion

Moussouni, Mouzai and Bouhadef (2012) studied the influence of rainfall characteristics on runoff and water erosion by doing laboratory experiments keeping in mind the rainfall intensity influence of hydraulic characteristics. Experimental results concluded that there is some major correlation between rainfall intensity and hydraulic characteristics of runoff and sediment concentration. They produced artificial rain by using commercially–available type of nozzle: H1/4VV 8008, H1/4VV 8004, H1/4VV 8002 and TEEJET SS 65 60. Simple absorbent paper method helped to quantify the kinetic energy. They observed that all the characteristics increases with increases the rainfall intensity and develop relationship by using the Reynold number and Froude number.

2.24 Single nozzle rainfall simulator for studying soil erodibility in hycranian forests

Pasakhoo et al. (2012) calibrated a portable rainfall simulator with single nozzle for study of soil erodibility in hyrcanian forests, assessing the following rainfall parameters; rainfall Intensity-Duration – Frequency (IDF), kinetic energy, drop size and coefficient of uniformity. Result obtained shows that IDF curves decreases with increases time interval for a given return period. Velocity of raindrops with an average diameter of 3 mm was 780 cm/h. Kinetic energy found to be 25.06 J^{-2} mm^{-1} for 32.4 mm/h intensity. It uniformity coefficient was estimated by Christiansen formula found to be acceptable limit of 81 to 82 %.

2.25 European small portable rainfall simulator for the comparison of rainfall characteristics

Iserloh, Ries et al. (2013) developed an European small portable rainfall simulator for the comparison of rainfall characteristics. They artificially generate the rain by using rainfall simulator of 13 types based on various European research institutions from Germany, the Netherlands, Spain and Switzerland was characterized by using laser precipitation monitor and rain collectors in all simulations in order to ensure comparability of the results. Conclusions show that rainfall characteristics provide a good data by which we can improve the data of various simulators and have consistent picture of the parameters, detailed understanding about relevant features of simulators as well as calibration and test procedure strategies help us to focus on the parameters which can be controlled for maintaining the intensity.

2.26 Field rainfall simulator

Wilson et al. (2014) designed transportable rainfall simulator with variable intensity and tested in the laboratory as well as in the field. In the laboratory the simulator was tested for three configurations producing 62,43 and 32 mmh^{-1} rainfall intensity with uniformity coefficient of 76, 65 and 67% respectively, for the plot area of 5.12 m^2. In the field testing was done on a grassy field with silt loam soil where they collected rainfall, soil moisture and runoff data.. To find the optimal values Philip infiltration model was used for the saturated hydraulic conductivity of the soil surface and bulk soil, due to low cost. It can be used to recognize the field parameters for hydrological modelling. There was some limitation of the system, Pattern pf rainfall intensity is not uniform as desired by the rainfall simulator addition, some water also fall outside the plot area and system is not water efficient. Its low operating pressure, not make it suitable for steep slope. Finally, water sprayed upwards, system does not work properly in wind condition without wind shields. Purpose of collecting data was to calibrate model parameter for a coupled hydrologic- vegetation dynamic model.

2.27 Study of hydrologic system

Isidoro and Lima (2015) studied the hydrologic system which is attached to the outlet of rainfall simulator to ensure constant pressure and discharge resulting in constant rainfall intensity at ground level, throughout the rain event. They almost simulated fifty rainfall events which were carried out at 5 different pressures. Result showed that with this hydraulic system rainfall can be operated with constant intensity throughout the entire simulator or sequence of events even if there is fluctuation in the water supply.

2.28 Rainfall simulator for landslide triggering experiments

Lora, Camporese et.al. (2016) designed and tested the rainfall simulator equipped with nozzles for the production of high rainfall intensities which they want to applied for the study infiltration dynamics and landslide triggering on the artificial hillslope for the plot area of 2m x 6m. The objective of designing the simulator was that, it can produce rainfall intensity of 50-150mm/h with at least 80% uniformity coefficient. To attain these objectives three type of nozzle tested individually to get the variable which effect the function and performance. According to the desired rainfall range, different range of configuration nozzle configured. The drop size was estimated by oil separation method and used it for the calibration of a numerical model aimed at estimating impact energy of drops falling into the soil. At the specific pressure and nozzle position the impact of kinetic energy was estimated by the MODEL which maximum erosion occur there is low rainfall intensity and large drop size. Maximum value of kinetic energy it can attained was 20 Jm^2/mm which show that simulator had the capability to produce high rainfall intensities ranges from 50-150 mm/h having no risk of erosion which can change the dynamics of infiltration on the artificial hillslope experiment.

Table 2.1. Main features of reviewed rainfall simulator and their different characteristics.

Designer	**Simulator type**	**Drop forming apparatus**	**Rainfall intensity (mm/h)**	**Water distribution by Christiansen**	**Portability**
Morin et al. (1976)	Spraying nozzle	Single nozzle with rotating disc	29-142	0.8-0.9	Not portable
Meyer and Hudson (1978)	Spraying nozzle	Oscillating single nozzle	10-140	0.8-0.9	Portable
Miller (1987)	Spraying nozzle	Triple nozzle with solenoid Valves	43-116	0.83	Portable
Cerda et al. (1997)	Spraying nozzle	Low pressure angle nozzle	10-60	0.93	Portable
Blanquies et al. (2003)	Spraying nozzle	Oscillating single nozzle	10-60	0.93	Portable

(Source: Abudi et al., 2012)

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 RAINFALL SIMULATOR

The rainfall simulator used in this study was designed at the Department of Hydrology, IIT Roorkee. The instrument consists of 3 m x 2 m frame connected with a PVC pipe attached with header (supporting 11 nozzles) and pressure gauge. A photograph of field set-up is given in Figure 3.1, and schematic of rainfall simulator is shown in Figure 3.2. Frame supported by four telescopic legs of 4 m. The rainfall structure is connected to a centrifugal pump capable of control by the water pressure, lifting up the water from a tank near the pump. The main components of the simulator are: (a) Frame; (b) Header for nozzle mountings; (c) Nozzles and (d) Pumping station. The system is supplied with water pumped from a storage tank located near the plot. The water supply to each standpipe is through PVC pipe. Water pressure in the system can be adjusted by a pressure regulator, and by applying back pressure on the outflow end of the simulator system by means of a “shut-off” valve. Another valve has been used to facilitate accurate control of water pressure for the nozzles.

Figure 3.1. Rainfall simulator at Department of Hydrology IIT Roorkee.

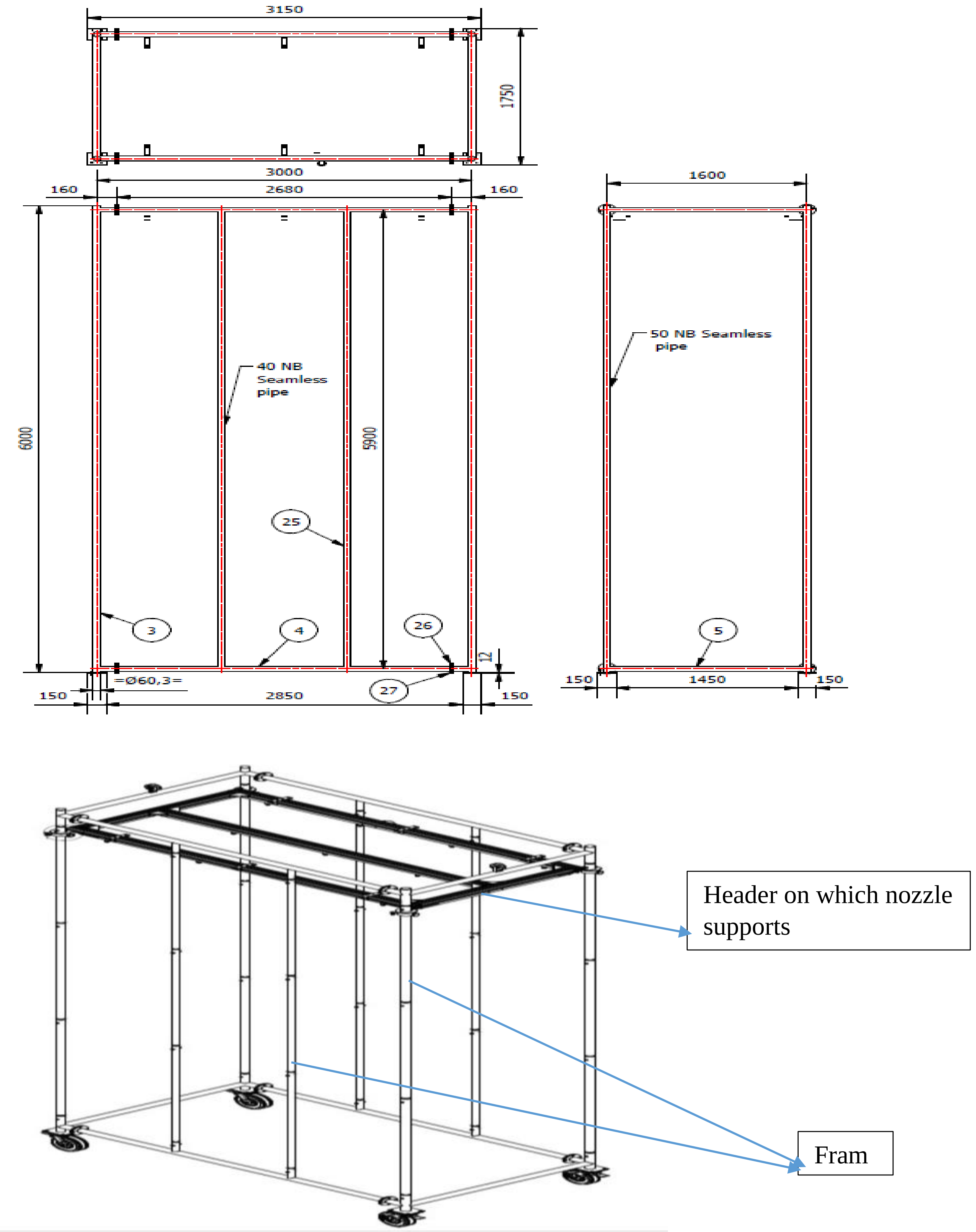

Figure 3.2. Schematic diagram of rainfall simulator. Source: Spraying system co. pvt ltd, Bangalore.

3.2 NOZZLES

Six full-cone nozzles manufactured by Spraying Systems Co. were used: B1/88G-SS4.3W, B1/4GG-SS10W, B1/4GG-SS14W, B3/8GG-SS17W, B1/2G-SS30W and B1/2GG-SS40W arranged from small size to large size employing selection of low to medium flow rate. These nozzle produces a solid cone-shaped spray pattern with a round impact area of medium to large sized drops. Uniform spray coverage and distribution over a wide range of flow rates and pressures is possible. Some models include removable caps and vanes for easy inspection and cleaning, as well as several mounting options.

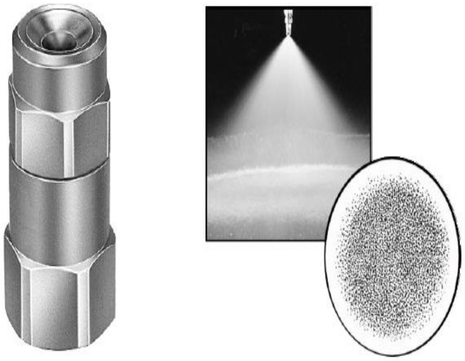

Figure 3.3. Spraying System Co. Full jet G-Style Spray nozzle **Figure 3.4**. Nozzle Spray flume

Table 3.1 Specifications for nozzles employed in rainfall simulator

(Note: Nozzle specifications are supplied by the manufacturer**.)**

Nozzle	**Orifice diameter (mm)**
B1/88G-SS4.3W	2
B1/4GG-SS10W	2.8
B1/4GG-SS14W	3.6
B3/8GG-SS17W	4
B1/2G-SS30W	5.6
B1/2GG-SS40W	6.4

3.3 UNIFORMITY COFFICIENT

Uniformity coefficient tests were performed to determine the uniformity coefficient and rainfall intensity of the simulator. Header can be installed with 11 nozzles of same size at a time. Size of the nozzles is shown in Table 3.1. Test was performed on total six configurations with six different nozzles of six different size, four different heights and three different pressures.

The simulator was run for 10-15 min depending up on the size of the nozzle, water pressure and the height of the header on which nozzles was mounted. The uniformity coefficient was measured using 23 beakers kept in square array, 0.5 m apart, beneath the simulator, covering the plot area of 3 m x2 m. The Christiansen Uniformity Coefficient (CU) was used to evaluate the uniformity of the simulated rain. *The CU is defined as the deviation of individual observation from mean over the mean value and number of observation* (Herngren, 2005) and can be calculated by the equation (1).

$$CU = 100.\left(1 - \frac{\sum|x-\bar{x}|}{n\bar{x}}\right) \qquad (1)$$

Where $\bar{x}$ is the average of all the measurements, $\sum|x-\bar{x}|$ is the sum of the individual deviations from the mean, and n is the number of measurement taken. Figure 3.5 shows the water collecting beakers distributed over the plot area in rectangular grid for uniformity coefficient estimation.

Figure 3.5. Water collecting beakers in array for CU estimation.

Table 3.2. Summary of nozzle configuration and performance.

Configuration	Nozzle	Orifice dia. (mm)	No. of nozzles	Mean intensity (mm h^{-1})
1	B1/88G-SS4.3W	2	11	73
2	B1/4GG-SS10W	2.8	11	175
3	B1/4GG-SS14W	3.6	11	241
4	B3/8GG-SS17W	4	11	341
5	B1/2G-SS30W	5.6	11	447
6	B1/2GG-SS40W	6.4	11	529

The test was replicated for three times to calculate mean intensity and CU for each configuration. Six configurations with different sizes of nozzle had average rainfall intensities of 73, 175, 241, 341, 447 and 529 mmh^{-1} since each configuration has an operating pressure of 0.4 to 1.6 kg/cm^2.

3.4 RAINFALL INTENSITY

Rain-wise tipping bucket rain gauge was used for the estimation of rainfall intensity (Manufactured by Rain-Wise, USA). It consists of funnel that collect water drop into a small seesaw-like container as shown in Figure 3.6. After pre-set amount of rainfall falls, the lever tips and dumps the collected water and send an electrical signal to rain log data logger.

Figure 3.6. Rain wise tipping bucket rain gauge.

Intensity was estimated for 2, 2.5, 3 and 3.35 m heights and 0.4, 0.8 and 1.6 kg/cm^2 pressures by allowing the rainfall for the 15 minutes and collecting the data by rain log data logger.

3.5 DESIGN OF EXPERIMENT (Taguchi Method)

Taguchi methodology is powerful experimental design tool which provide a simple, efficient and systematic approach to determine optimal parameters. This method is based on orthogonal array to study the effect of large number of variables with small number of experiments (Rose 1988). Taguchi method is used with objective to identify the key factor that contributed most to the rainfall intensity.

Table 3.3 Rainfall intensity parameters and their levels

Parameters	**Unit**	**Level 1**	**Level 2**	**Level 3**
Pressure	Kg/cm^2	0.4	0.8	1.6
Height	m	2	2.5	3
Nozzle orifice dia.	mm	2	2.8	3.6

This method is designed such that the procedure for performing experiments using different type of design like, two, three, four or five and mixed level. In our study three level design was chosen for nine experiments as shown in Table 3.3. Parameters that likely affect the rainfall intensity in the rainfall simulation experiments are pressure, height and nozzle orifice dia. which has to be selected to prepare an orthogonal array. A L9 orthogonal array is considered in Table 3.4.

Table 3.4. L9 Orthogonal array.

Run	Pressure (Kg/cm^2)	Height (m)	Nozzle size (mm)
1	0.4	2	2
2	0.4	2.5	2.8
3	0.4	3	3.6
4	0.8	2	2.8
5	0.8	2.5	3.6
6	0.8	3	2
7	1.6	2	3.6
8	1.6	2.5	2
9	1.6	3	2.8

The basic design makes use of three control factors, with three level each. Nine experiments run were used for small nozzle group (for nozzle size 2, 2.8 and 3.6 mm). After selecting the orthogonal array, the statistical analysis of the result was obtained. Experimental data was transformed in statistical measure of performance called Signal to Noise (S/N) ratio as per the Taguchi method (Rose, 1988). After statistical analysis of S/N ratio, an analysis of variance (ANOVA) was undertaken in order to estimate the relative contribution of each rainfall simulator parameter on rainfall intensity.

In the Taguchi method, S/N ratio provide an estimate of the effect of noise factors on output response. The term "signal" means the desirable value (mean) and the term "noise" means the undesirable value (standard variation) The S/N ratio measure the effect of parameters and effect of noise factors on the response so that it can be employed as an indicator for the consistency of the system.

S/N ratio analysis that are generally applicable are the higher-the better, nominal-the-better and lower-the-better. In our study the target is to identify the optimum condition under which maximum rainfall intensity would occur. S/N ratio according to higher-the better analysis use the following equation for the calculation.

$$\frac{S}{N} = -10 \log_{10}\left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y2}\right) \quad (2)$$

Where n is the number of repetitions under the same experimental condition and y is the observed value. Here observed value y is rainfall intensity that was obtained by rainfall simulation test .

The output of Analysis of Variance (ANOVA) table was used to statistically assess the influence of each parameter which affects the rainfall intensity. The percentage contribution of each factor was calculated by the following equation.

$$PC = \frac{(S)P}{(SS)T} \quad (3)$$

Where PC is the percentage contribution, $(S)_P$ is the corrected sum of squares and the $(SS)_T$ is the total sum of square analysis of variance output gives the value of degree of freedom, total sum of squares and corrected sum of squares.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 ANALYSIS OF OPTIMUM CONDITIONS

Signal/Noise (S/N) ratio of the experiments test condition in the Taguchi design was calculated by using Eq. (2) and presented in Table 4.2. The maximum value of the S/N ratio among the nine tests was 51.42 indicated by bold for the rainfall intensity in the 7th test, from all these value of S/N ratio the mean was calculated at each of the ith level for rainfall intensity presented in Figure 4.1. The maximum value of means of the S/N ratio among the three levels of the various factors was then identified as presented in Table 4.1 These values represented the optimum condition that would produce the maximum rainfall intensity in this study. From the response table we can see that pressure is larger for level 3, similarly height is larger for the level 1 and nozzle orifice diameter is larger for level 3. Therefore, the combination of test condition was used in this study, the optimum condition was found to be at pressure of 1.6 Kg/cm^2, height of 2 m and nozzle orifice diameter of 3.6 mm, which produced the maximum rainfall intensity shown in Figure 4.1.

Table 4.1 Response table for signal to noise ratio. Larger is better

Level	Pressure	Height	Nozzle orifice dia.
1	41.58	44.64	38.19
2	43.2	43.32	45.24
3	46.2	43.02	47.55
Delta	4.62	1.63	9.36

Delta represents the overall change in the value. In Taguchi design, delta is the difference between maximum and minimum response across level of the factor. Here for level 1 the delta is 4.62 calculated by taking difference of maximum (46.20) and minimum (41.58). Similarly, the delta is calculated for level 2 a level 3 and found to be 1.53 and 9.36 respectively.

Table 4.2 Rainfall intensity at steady state and the S/N ratio of each of 9 different Taguchi experimental test combinations.

	Factor				
Test number	Pressure (kg.cm^2)	Height (m)	Nozzle orifice dia.(mm)	Rainfall intensity (mm/hr)	S/N
1	0.4	2	2	70.4	36.95145
2	0.4	2.5	2.8	144	43.16725
3	0.4	3	3.6	170	44.60898
4	0.8	2	2.8	189.53	45.55356
5	0.8	2.5	3.6	214	46.60828
6	0.8	3	2	74.42	37.43379
7	1.6	2	3.6	372.4	**51.42019**
8	1.6	2.5	2	102	40.172
9	1.6	3	2.8	224	47.00496

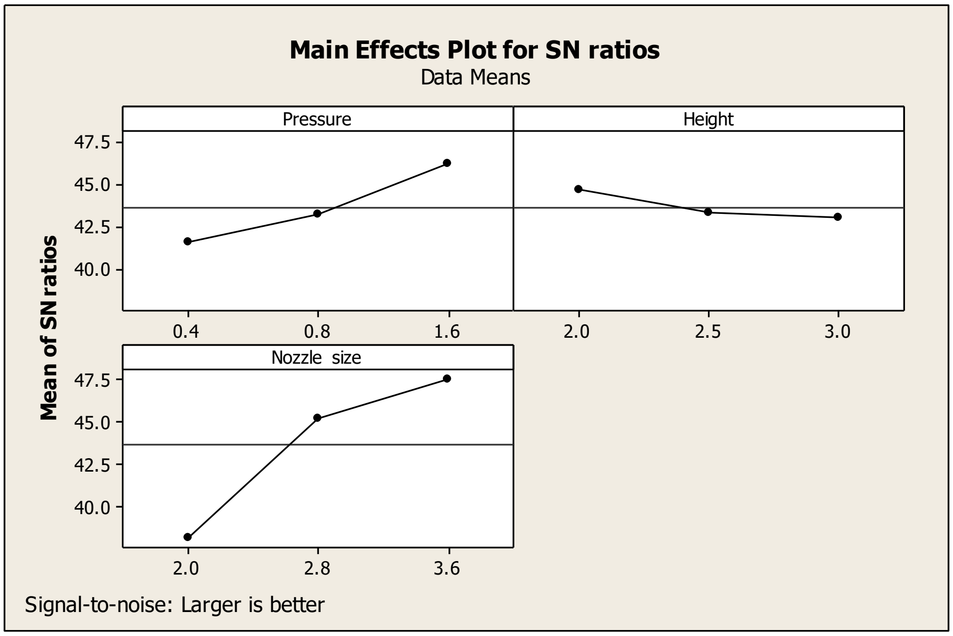

Figure 4.1 Mean Signal to Noise (S/N) ratio for rainfall intensity obtained from Taguchi design as influenced by pressure, height and nozzle orifice diameter.

Table 4.3 Optimum condition for maximizing rainfall intensity in this study

Method	**Variable**		**P**	**H**	**Nd**	**S/N**
Taguchi design	R	Optimum	1.6	2	3.6	47

R, Rainfall intensity (mm/h); P, Pressure Kg/cm^2; H, Height 9m); Nd, Nozzle orifice dia. ; S/N, signal to noise ratio

4.2 PERCENTAGE CONTRIBUTION OF EACH FACTOR FOR OUTPUT RESPONSE

The ANOVA results (Table 4.4) described the contribution of each factor on output response using Eq (3) and was found that pressure and nozzle size are the most influencing parameter. The effect of height was comparatively low. Pressure and nozzle effect more to the rainfall intensity as compared to height as pressure, nozzle size, and height contributed 24.59%, 62.4% and 8.93%, respectively.

Table 4.4. Results of ANOVA for rainfall intensity

Source	Degree of freedom	Seq SS	Adj SS	% Contribution
Pressure	2	17327	17327	24.59
Height	2	6293	6293	8.93
Nozzle size.	2	43974	43974	62.41
Error	2	2856	2856	
Total	8	70450	70450	

4.3 SUMMARY

Taguchi method was applied to first three small nozzles B1/88G-SS4.3W, B1/4GG-SS10W and B1/4GG-SS14W out of six nozzles to analyse at what condition maximum rainfall intensity can be produced by using these nozzles. Control parameters was pressure, height and nozzle orifice diameter on which rainfall intensity was depend. This method evaluates the percentage contribution in order to know that which control factor more affect the rainfall intensity.

4.4 EFFECTS OF OPERATING WATER PRESSURE, NOZZLE HEIGHT AND NOZZLE SIZE ON RAINFALL INTENSITY AND UNIFORMITY COFFICIENT

Rainfall intensity and uniformity coefficient were observed to be dependent upon nozzle size, water pressure at the nozzle and the height of the nozzle above the plot surface. Each nozzle was tested using operating pressures 0.4,0.8 and 1.6 kg/cm^2 while the distance from the nozzle to the plot was varied from 2 m to 4 m in increments of 0.5 m. The rainfall intensity increases with nozzle size. The smaller size nozzle showed smallest range in intensity with increase in height. The larger size nozzle provided large range of intensity with decrease in height. This effect was more evident at the lower height with the rate change of intensity decreases with increasing height. Result were not presented above 3.35 m height because the nozzle cannot be adjusted above this height. An increase in water pressure at the nozzle increased rainfall intensity. The various combination of nozzle size, nozzle height and water pressure provide a broad range of simulated rainfall. Figure 4.2 summarizes this effect with three parameters. The uniformity coefficient increases with pressure and nozzle size. Nozzle height did not showed much effect on the uniformity coefficient. The simulator has the potential to accommodate wide range of research needs. To provide a wide range of rainfall intensity different nozzle was used. Small nozzle 4.3W and 10W produces small range of intensities. Intermediate rainfall intensity can be covered with nozzle 14W and 17W. High rainfall rate, such as thunderstorm, can be produced by 30W and 40W nozzle. Rainfall simulator produces rainfall intensity ranges from 50 to 750 mm/h depending upon the size of the nozzle. All the nozzles represented CU of the order of 84%. R.W. Tossell et. al. (1987) also developed a rainfall simulator at the University of Guelph named Guelph rainfall simulator. They also performed experiment on the simulator using six nozzles at different height and pressure and found that rainfall intensity increases with nozzle size, the water pressure and decreases with increasing height. On individual nozzle basis they found only bigger nozzle exhibited a slight increase in uniformity with nozzle height, remaining nozzle showed no distinct relation between rainfall uniformity and height. Results of current study are showing similar trends to Tossell et al. (1987), though the experiments conducted by Tossell et. al. (1987) were different. For example, height and pressure chosen for the Guelph simulator were 0.8 m to 1.7 m and 48 kPa to 69 kPa, respectively.

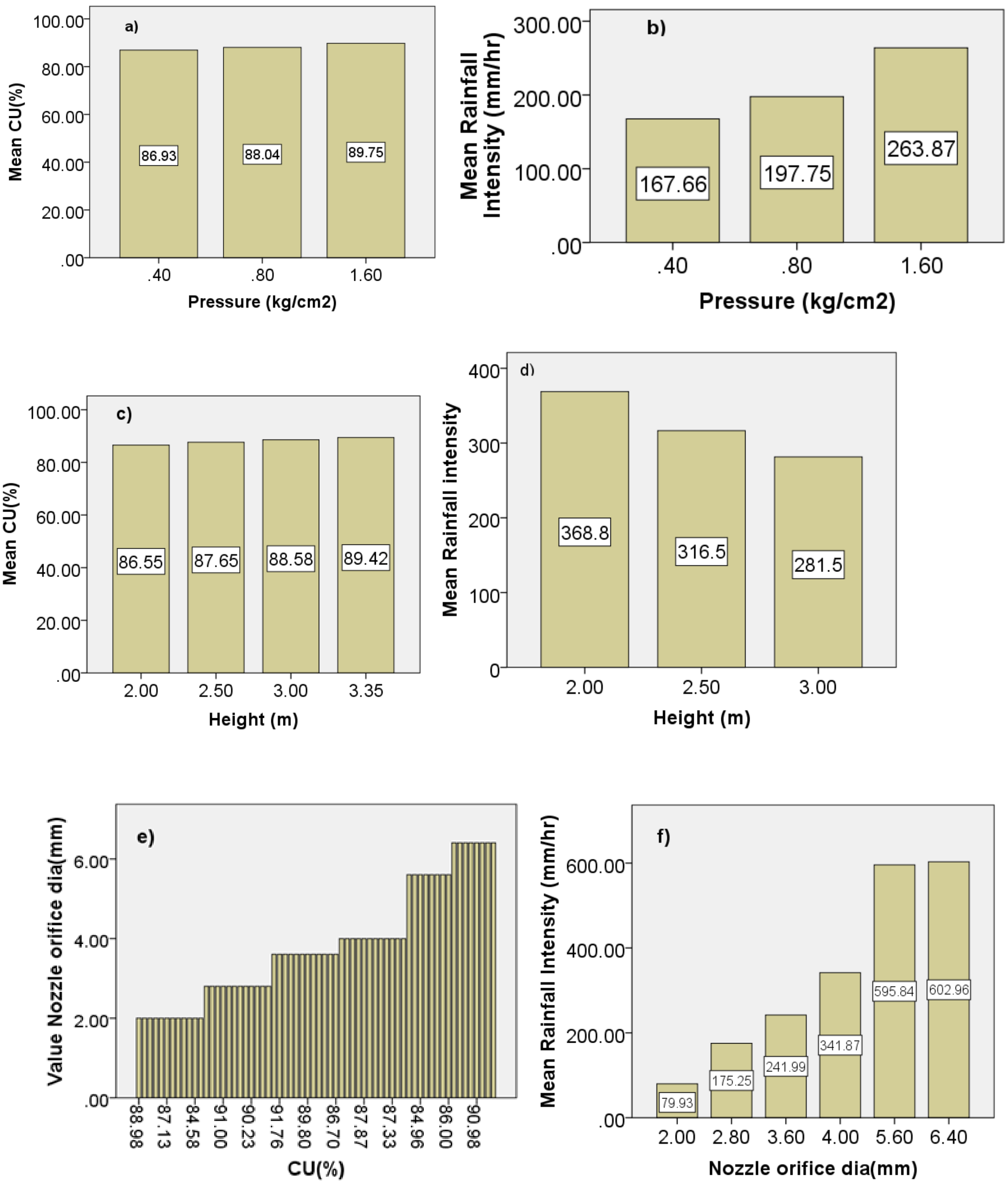

Figure 4.2. Results of experiments at varying operating pressure, nozzle height and nozzle size. Graphs represents; a) and b) variation in mean CU and mean rainfall intensity with pressure; c) and d) variation in mean CU and mean rainfall intensity with height; e) variation in CU with orifice diameter; f) variation in nozzle orifice diameter with mean rainfall intensity

Table 4.5. Rainfall intensity and uniformity coefficient trials for the rainfall simulator at DOH IIT Roorkee.

Nozzle and pressure

	B1/88G-SS4.3W 0.4 Kg/cm^2		B1/88G-SS4.3W 0.8Kg/cm^2		B1/88G-SS4.3W 1.6 Kg/cm^2		B1/4GG-SS10W. 0.4 Kg/cm^2		B1/4GG-SS10W 0.48Kg/cm^2		B1/4GG-SS10W 1.6 Kg/cm^2	
H (m)	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**
2	70	84.56	91	86.19	116	88.22	177.6	88.25	189.53	89.99	241.6	91
2.5	68	84.58	77.33	86.75	102	88.96	144	88.78	162.4	90.6	234.93	91.38
3	60	84.66	74.42	87.13	89.6	88.94	128	90.02	145.4	90.63	224	91.94
3.5	55	84.94	72	87.72	83.2	88.98	114	90.23	146.53	90.91	195	93.22
Avg.	63.25	84.68	78.68	86.95	97.7	88.775	140.9	89.325	160.97	90.53	223.88	91.88

Nozzle and pressure

	B1/88G-SS14W 0.4 Kg/cm^2		B1/88G-SS14W 0.8 Kg/cm^2		B1/88G-SS14W 1.6 Kg/cm^2		B1/4GG-SS17W 0.4Kg/cm^2		B1/4GG-SS17W 0.8 Kg/cm^2		B1/4GG-SS17W 1.6 Kg/cm^2	
H (m)	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**
2	268.4	86.7	293.2	87.18	372.4	87.6	357.6	84.99	386.4	85.43	503.6	86.48
2.5	191.53	89.78	214	89.8	318.8	90.28	273.6	85.64	351.2	87.34	420	87.64
3	170	90.02	196	91.33	274	94.76	228	87.33	304	87.61	400	87.87
3.5	152.4	90.78	92.4	91.66	260.8	93.85	224	87.6	268	87.87	386	87.94
Avg.	195.58	89.33	198.9	89.92	306.5	91.62	270.8	86.39	327.4	87.06	427.4	87.48

	Nozzle and pressure											
	B1/2GG-SS30W 0.4 Kg/cm^2		**B1/2GG-SS30W 0.8 Kg/cm^2**		**B1/2GG-SS30W 1.6 Kg/cm^2**		**B1/2GG-SS40W 0.4 Kg/cm^2**		**B1/2GG-SS40W 0.8 Kg/cm^2**		**B1/2GG-SS40W 1.6 Kg/cm^2**	
H (m)	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**	**RI (mm/h)**	**CU(%)**
2	658.8	84.12	715	84.59	ND	ND	679	84.26	780	86.25	ND	ND
2.5	590	84.23	688.4	84.96	ND	ND	564.8	85.5	663.6	86.25	ND	ND
3	445	84.57	633	85.52	ND	ND	527	88.7	606	89.2	ND	ND
3.5	425	85.15	591.33	87.97	ND	ND	488.4	90.91	535.1	91	ND	ND
Avg.	529.7	84.53	656.93	85.76			564.8	87.342	646.18	88.17		

RI, rainfall intensity;

CU, uniformity coefficient;

ND, not determined

Table 4.5 represents the average rainfall intensity and uniformity coefficient for the replications of experiments conducted on rainfall simulator. The rainfall simulator nozzle height above the plot area adjusted from 2 to 4 m. Nozzle water pressure also kept within the certain limits. Pressure ranging from 0.4 to 1.6 kg/cm^2 was recommended. If water pressure was lower than 0.4 kg/cm^2, smaller nozzle may yield low uniformity coefficient. Conversely, excess water pressure at nozzle greater than 2 kg/cm^2 will produce drop size distribution which is too narrow to be considered as representation of natural rainfall. A selection of smaller to greater nozzle sizes provided a good range of rainfall intensity and uniformity coefficient. Hence, provided a flexibility which makes the current rainfall simulator suitable for a wide variety of hydrology research application. The various combination of nozzle size, water pressure and nozzle height above the plot area will provide other desirable rainfall characteristics.

4.5 MULTIPLE REGRESSION MODEL

The variable parameters which affect the rainfall intensity in our test were operating pressure head, height of nozzle header and nozzle orifice size. The test was run on four different header heights, three different operating pressure head and six different nozzles of different orifice diameters. All these three parameter were responsible for different rainfall intensity. Multiple regression model was applied to determine degree and the type of correlation between variables using SPSS software (IBM SPSS Statistics). For this pressure, height and orifice diameter of nozzle were considered as independent variables and rainfall intensity as dependent variable. The equation that fit the data with three parameters is written below.

$$I = -78.20 + 83.02P - 87.26H + 143.23D \qquad 4$$

Where I is the rainfall intensity in mm h^{-1}, P is pressure in kg/cm^2 and D is the orifice diameter of the nozzle in mm. Rainfall intensity is depending on pressure which ranges from 0.4 to 1.6 kg/cm^2, height ranges from 2 to 3 m and the orifice diameter ranges from 2-6.4 mm as shown in Figure 4.3.

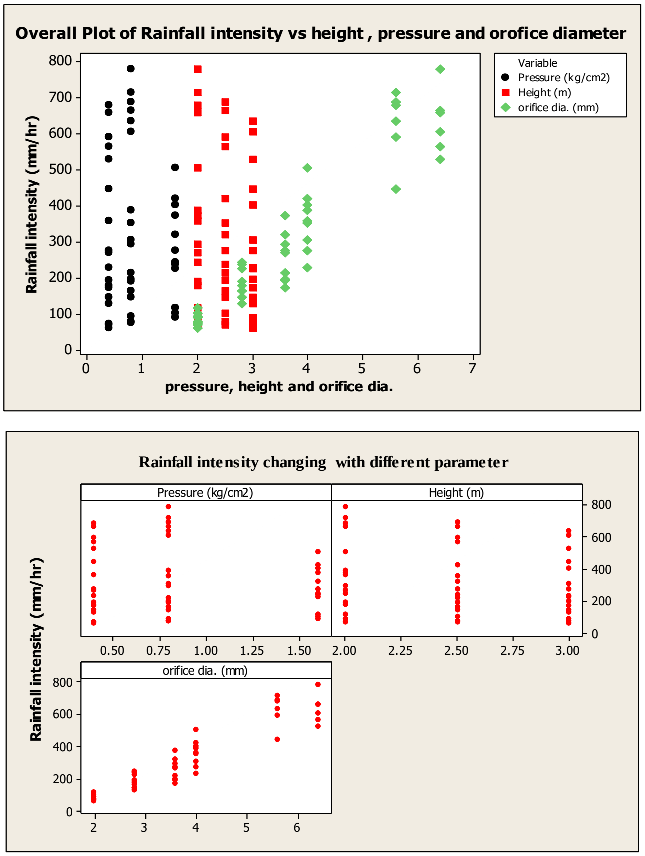

Figure 4.3. Overall plot rainfall intensity versus height, pressure and orifice diameter.

4.6 CALIBRATION OF RAINFALL INTENSITY USING MULTIPLE REGRESSION EQUATION

The variable which affected the rainfall intensity in our test were pressure, height and nozzle size. The test was run on four different heights, three different pressure and six different nozzles. Three replications of same nozzle at same height and same pressure were carried out to estimate rainfall intensity. Nozzle used was B1/8GG-SS4.3W, B1/4GG-SS10W, B1/4GG-SS14W, B3/8GG-SS17W, B1/2G-SS30W and B1/2GG-SS40W for 2 m, 2.5 m, 3 m & 3.35 m heights and 0.4kg/cm^2, 0.8kg/cm^2 and 1.6kg/cm^2 pressure. All these three parameter were responsible for different rainfall intensity. Regression model of rainfall intensity as a function of pressure, height and orifice diameter of nozzle was obtained. Table 4.6 is the coefficient table, provide us the necessary information to predict and determine whether these parameters on which rainfall intensity depend is statically significant to the model or not and also give us the value of regression line which gives the equation (4) by which rainfall intensity predicted and compared with observed rainfall intensity as shown in figure 4.3. Tables 4.7 give the model summary indicating R and R^2 values. The R value represent the simple correlation and is 0.972, which indicates a high degree of correlation. The R^2 value indicates how much of the total variation in dependent variable (rainfall intensity) can be explained by the independent variable (pressure, height and orifice dia. of nozzle). In this case 94.50% can be explained which is very large. Table 4.8 is the ANOVA table, which reports how well the regression equation fit the data. Sig 0.000 indicates the statistical significance of the regression model. Here $p< 0.000$ which is less than 0.05, indicating that model is statically significant. Thus it makes sense to prediction of rainfall intensity based on pressure, height and orifice diameter of nozzle.

Table 4.6. coefficient of rainfall intensity

Coefficients

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-78.205	53.273		-1.468	0.149
	Height (m)	-87.269	17.994	-0.172	-4.850	0.000
	Pressure (kg/cm2)	83.286	16.363	0.187	5.090	0.000
	Nozzle orifice dia (mm)	143.234	5.318	0.990	26.935	0.000

Table 4.7 Model summary Regression Analysis

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.972	0.945	0.941	50.895

Table 4.8. Variance analysis

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1953791.235	3	651263.745	251.427	0.000
	Residual	113972.084	44	2590.275		
	Total	2067763.319	47			

Figure 4.4. Simulated versus observed rainfall intensity.

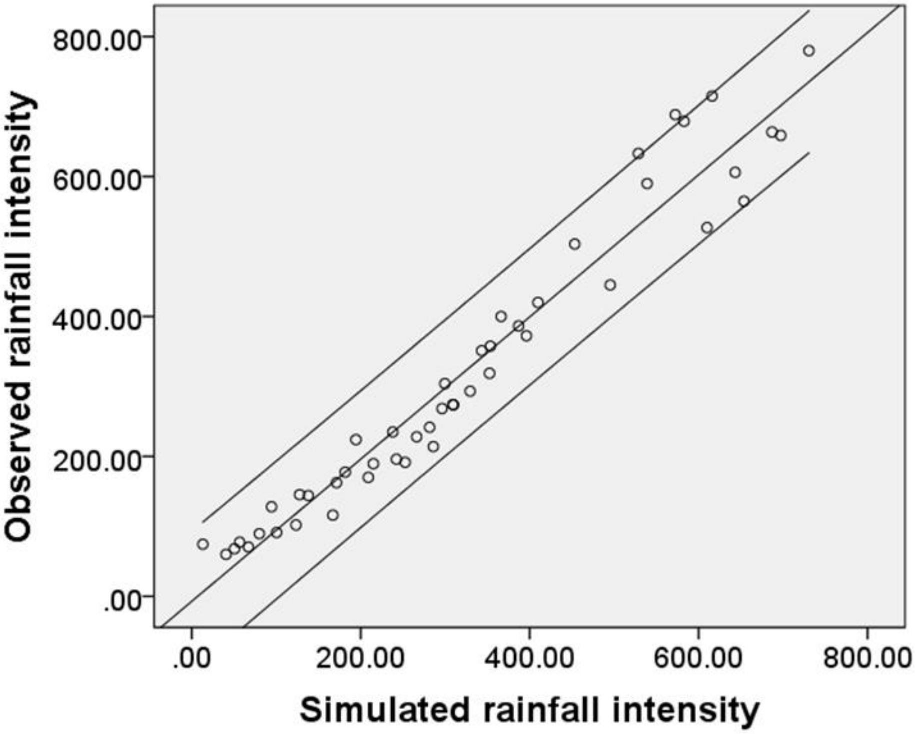

Figure 4.4, shows the graph between of observed rainfall intensity and simulated rainfall intensity. observed rainfall intensity we get from the experiments performed on the rainfall simulator using different pressure, height and nozzle size and simulated rainfall was calculated by the equation (4) we get after applying multiple regression equation model. It was found and can also be seen in the Figure 4.4 that observed rainfall intensity same as simulated rainfall intensity.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 General

Present dissertation work is focused on estimation of rainfall characteristics of simulated rainfall using a rain simulator. Spatial uniformity and intensity of simulated rainfall has been analyses using different nozzle orifice size, height of nozzle hearer with different operating water pressure. This is achieved by firstly, carrying out various experiments on an outdoor experiment plots in Department of Hydrology at IIT, Roorkee. Studies carried out on 3m x 1m plot conducting various experiments (approx. 198 experiments) by choosing different nozzle size, nozzle height and operating water pressure. The height of nozzle head on this simulator rainfall simulator can be adjusted up to 4 m and operating pressure can be varied between 0.2 to 2 kg/cm^2. Secondly, Taguchi method was applied using MINITAB software to get optimum condition for maximum rainfall intensity using control parameters for the three small nozzles and to calculate the percentage contribution of each control factor   Lastly by applying the multiple regression model to determine the degree and type of correlation between variables using SPSS software. For this purpose, nozzle size, nozzle height and operating water pressure were considered as independent variable and rainfall intensity as dependent variable. R value found to be 0.972 from the regression model which indicate high degree of correlation. and R^2 found to be 0.941 which indicate 94.1% of total variation in rainfall intensity is dependent on these three factors. The measured rainfall intensity ranged from 55mm/hr to 780mm/hr and uniformity coefficient ranged from 84.49% to 92%

Following specific conclusion can be drawn from present study:

1. Nozzles having low-to-medium flow-rate provides a good range of rainfall intensities and uniformity coefficient.
2. The developed simulator provides flexibility that renders it suitability for wide variety of research applications.
3. To supplement the great range of nozzle sizes, combinations of nozzle heights above the study surface and nozzle water pressures will provide other desirable rainfall characteristics.

However, the combination of such variables will ultimately depend on the objectives of individual research projects.

4. Study indicate that height of nozzle head, operating pressure head and nozzle orifice size affect rainfall intensity and uniformity coefficient. Generally, rainfall intensity decreases with increase in height of nozzle head and uniformity coefficient slightly increases with increase in height of nozzle head. Small size nozzle gave better uniformity coefficient at low height of nozzle head whether, Bigger size nozzle gave better uniformity coefficient at high height of nozzle head.
5. With increase in pressure head rainfall intensity as well as uniformity coefficient also increases. Rainfall intensity and uniformity coefficient also increases with the increase in nozzle size.
6. The rainfall simulator presented an average uniformity coefficient ranged from 84% to 93% depending upon the pressure and height on which rainfall simulator operated.
7. Taguchi method which was applied to first three small nozzles (B1/8GG-SS4.3W, B1/4GG-SS10W, B1/4GG-SS14W and B3/8GG-SS17W) showed that maximum rainfall intensity was occurring at pressure 1.6 kg/cm^2 , height of 2 m and nozzle size 3.6 mm.
8. The developed multiple regression model has been found suitable to compute rainfall intensity using operating parameters such as operating pressure, height of nozzle head and orifice diameter of nozzle.
9. The rain simulator could be used to simulate rainfall at intensity between 60 mm/h to 780 mm/h with an average uniformity coefficient ranging from 84% to 93% depending upon the pressure and height on which rainfall simulator operated.

5.2 Future scope

Present study is limited to evaluating the parameters for the rainfall simulator which effect the rainfall intensity and uniformity coefficient, having great range of nozzle sizes, combination of nozzle heights and water pressure on the plot area which make it suitable for wide variety of research application. The simulator can be used for Run-off studies and generating hydrograph at different slope and intensity in future. Rainfall characteristics like drop size velocity, drop fall velocity, rainfall kinetic energy and momentum can be estimated by using Laser Precipitation Monitor.

5.3 Constraints of experiment

Experiment performed on the rainfall simulator for pressure (0.4,0.8 and 1.6 Kg/cm^2) and height (2, 2.5, 3 and 3.5 m). Experiment cannot be performed above 2 kg/cm^2 because above it rainfall characteristics is not very close to natural rainfall. There is no data for B1/2G-SS30W and B1/2GG-SS40W nozzle at 1.6 Kg/cm^2 pressure due to capacity of pump. Pump maintenance and choking of nozzles was main constraint while conducting the experiments.

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