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Role of Rainfall Simulators in the Study of Soil and Water Dynamics - A Review

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A B S T R A C T

Rainfall simulation technique is used worldwide to identify and assess the nature and pattern of rainfall occurring in any particular area and its impact on the soil taking into consideration the various climatic and topographical factors. Whenever rainfall occurs heavily, it generates some unwanted physiographical processes such as high run-off, flood, soil erosion of different forms, landslides, etc. thereby redistributing the soil far from its original placement and sometimes rearranging the land topography to a large extent. Due to occurrence of flood, crops in agricultural fields get damaged and also quality of soil deteriorates resulting in incapability to produce crop in the future, to its full potential. Hence for evaluating the influence of rainfall on soil and water dynamics under varied conditions of land slope, rainfall intensities, soil types, soil infiltration rates, rainfall simulators of different types depending upon the need, are being considered as the best solution in the present day scenario. Rainfall simulators are generally laboratory based models which duplicate natural rainfalls and are designed considering various parameters as and when required. In the present paper, a number of important literatures on the role of rainfall simulators in identification and mitigation of rainfall created problems in various sectors concerning humans, such as soil erosion in agricultural fields, floods causing landslides, etc. have been collected and studied in depth for better understanding of those simulators of different types, based on the need and area of study by taking into account the various parameters concerning their studies.

Introduction

Assam receives ample amount of rainfall throughout the year. It starts from early monsoon season, increasing heavily during the monsoon season and gradually reducing post monsoon. The average annual rainfall of Assam ranges between 2000 to 3000 mm as reported by IMD from time to time, since the last 30 years. The rainfall attains its peak during the monsoon season i.e June to mid-September. During this season, there is emergence of floods in most parts of the State, causing huge devastations in human and animal life. The impact of flood not being limited to destruction of man-made structures, but also it creates huge problems in agricultural sectors, industrial and domestic sectors. Whenever rainfall occurs for prolonged time, be it of medium or high intensity, it generates run-off of large volume and results in sediment transfer thereby destroying the crops in agricultural fields.

This also alters the soil fertility conditions affecting the health of soil, hence arising questions for the scope of crop seeds to be implanted in future. Hence, the nature of rainfall and its pattern has to be precisely studied under numerous climatic, land slope and soil conditions for redressal of problems such as soil erosion, flood, etc. generated due to heavy rainfall.

Soil erosion occurs as a result of combination of three processes viz. detachment, transportation and deposition of soil. Detachment and transportation of soil mass are done by erosive agents such as flowing water (run-off and flood). When there is insufficient energy left of the flowing water to carry the soil particles further, then deposition occurs. Major factors for initiation of soil erosion are rainfall and wind, the latter being a matter of serious concern in Assam. Hence, in order to study the rainfall characteristics under laboratory conditions, different types of rainfall simulators have been developed by many researchers from time to time, which have the capacity to properly duplicate natural rainfalls, thereby creating models of the same and enabling the researchers to study rainfall characteristics and its impact on soil and water dynamics. Rainfall simulators have been designed to satisfy the requirements of extensive quantification for reducing soil erosion and run-off (Meyer, 1994). The simulators integrated with tilting flume are also being developed for detailed study of soil loss from an area under different slope conditions and rainfall intensities.

Different Types of Rainfall Simulators

Rainfall simulators has proven to be an extensive tool for studying hydrologic processes which involves impact of rainwater on soils, resulting in soil erosion, runoff generation, and infiltration (Caracciolo *et al.*, 2012; Aksoy *et al.*, 2012; Fister *et al.*, 2012; Schindewolf and Schmidt, 2012; Schindler *et al.*, 2012; Iserloh *et al.*, 2013). Good correlations can be found out between the values of measured soil loss measured in any erosion plot under subjected simulated rainfall and which occurs in a watershed, though there exists minor differences between simulated and natural rainfall, (Hamed *et al.*, 2002). No standard design of rainfall simulators have been declared yet and there are variations in respect of various parameters such as rainfall intensity, spatial and temporal rainfall distribution, area of target, drop size, droplet velocity and kinetic energy (Iserloh *et al.*, 2013). However, it is to be noted that the primary objective of these rainfall simulators is to replicate the natural rainfall and then study the characteristics and impact of it on various sectors. In order to build a sound decision support system for mitigating the problems of soil erosion, a generated database has to be constituted for the assessment of runoff and soil erosion.

Therefore, design of a proper rainfall simulator is a crucial aspect and hence precise knowledge of rainfall characteristics is a fundamental need. Moreover, simplicity of model, flexibility, portability and economic aspects also needs to be taken under consideration.

Rainfall simulators generally are more efficient and adaptable tool than natural rainfall for the purpose of studying soil and water dynamics in depth. The rate of influence of water droplet generating kinetic energy can be determined by making variation in fall height of rain droplets, changing droplet sizes, or by covering the soil surface with some residues in order to dissipate the droplet energy (Meyer, 1965).

Rainfall Simulator in Erosion Determination

The use of rainfall simulators in the study of soil erosion control is not new (Young and Burwell, 1972). As many researchers mention the requirement of repetitive testing of erosion and sediment control experiments, hence the use of rainfall simulation technique for generation of runoff has increased (Benik *et al.*, 2003; Bjorneberg *et al.*, 2000; Flanagan *et al.*, 1997; Flanagan *et al.*, 2002; McLaughlin and Brown, 2006; Peterson *et al.*, 2002; Roa-Espinosa *et al.*, 1999; Sepaskhah and Bazrafshan Jahromi 2006; Shoemaker, 2009; Wilson, 2010).

Mutchler and Hermsmeier (1965) mentioned in their study that the use of drip simulators could replicate a combination of relatively large raindrops at a low rate of application. However, unless the dripper is placed at a height of more than 10 m above the soil, impact velocities of those approaching drops could not be obtained. Hence, due to this necessity of height, drip simulators were not found to be practical in regard to simulation operations.

Roth *et al.,* (1985) in his research work developed a rainfall simulator for control soil erosion in Brazil, which was simple and easy to operate. Water was delivered in the form of raindrops from a height of 3 m above the ground where four water reservoirs were mounted. Rain drop size were dependent upon the different tube diameters and also rainfall intensity was varied between 0-185 mm h^{-1} by adjustment of water head in the reservoir.

In the experiment conducted by Cerda *et al.,* (1997) used a structure in which a nozzle of height 2 m (6.6 ft) above soil surface, was installed and necessary connections were given for water supply and pumping of water. A wind protector was provided to avoid any interference of wind during the conduction of experiments. A single pipe was used for providing direct connection between the nozzle and the pump. The pumping system was employed mechanically or manually by hand. The study revealed that the most homogenous rainfall distribution was found at a water pressure of 1.55 kg cm^{-2} and at a rainfall intensity of 54.6 mm h^{-1} at this pressure.

Arnaez *et al.,* (2007) conducted a research work in which a rainfall simulator was used for comparing runoff produced and sediment transfer under varied rainfall intensities. This study was conducted in a vineyard plantation in Spain. The rainfall simulator included a sprinkler placed at a height of 2.5 m which delivered pressurized water for a duration of 30 minutes on a 0.45 m diameter plot. For the purpose of generating three different rainfall intensities (less than 40 mm h^{-1}, between 45 and 70 mm h^{-1} and > 70 mm h^{-1}), three different types of sprinklers were used. In the conclusion, the authors mentioned that there was difficulty in replicating natural rainfall due to reduced plot size and hence the experiment could not reveal proper information about run-off and sediment transfer.

Sheridan *et al.,* (2008) in their experiment of rainfall simulation, used a simulator on plot of size 1.5 m x 2 m (5 ft x 6.6 ft) for predicting the modified erodibility indices which will lead to estimate the average annual erosion rates of forest roads. The rainfall intensity was kept fixed at 100 mm h^{-1} for a 30 minutes duration of simulation and calculated kinetic energy of 0.295 MJ ha^{-1} mm^{-1}, which was like the energy of a high-intensity rainfall as stated by Fosters *et al.,* (1981).

Verbist *et al.,* (2009) used a rainfall simulator documented in CAZALAC (2004) for studying soil erosion and comparing different methods of soil loss measurement. The rainfall simulator contained a line of seven sprinklers with a spacing of 1 m between the sprinklers which delivers pressurized water, covering an area of 5 m x 2 m. Soil loss measurement was done for 10 plots with bare soil in the Coquimbo Region. Each experimental simulation was conducted for a period of 20 minutes, with a system pressure of 100000 Pa and mean rainfall intensity of 130 mm h^{-1}.

Performance of Rainfall Simulator

In the research work of Freebairn and Gupta (1990), they used a drop-former simulator on long plots of size 0.91 m (3 ft) wide and 1.52 m (5 ft). The rainfall simulator was installed at a height of 2.5 m (8.2 ft) above the plots with simulated rainfall intensity of 100 mm h^{-1}. The runoff generated was measured with the help of a tipping bucket mechanism. The study revealed that due to the presence of surface roughness due to the presence of some covers had decreased the run-off rate.

Navas (1993) in his study, employed a nozzle type simulator on plots of size 1.3 m x 1.3 m (4.1 ft x 4.1 ft), in order to evaluate the soil loss influenced by varied slopes, types of soil and soil cover. In the first test run, the soil surface was wetted with the inclusion of cover, and afterwards the cover was removed during the second test run. Runoff generated was collected at a regular interval of 3 minutes. It was found that, runoff got decreased when the soil was covered and increased with the steepness of slope.

Greene *et al.,* (1994) in their research work, used a trailer mounted, nozzle type simulator over plots of 1 m^2 (10.76 ft^2) for studying the effect of plant coverage on runoff and soil erosion in Australia. The work revealed that, run-off generated was of uniform nature between rainfall duration of 30 to 60 minutes. Runoff was collected through a channel by using a steel plot frame, at the down-slope end. They also found that with the increase of soil coverage, the run-off got decreased but no effect on sediment concentration.

Esteves *et al.,* (2000) designed a field tested rainfall simulator for study plots of 5 m x 10 m (16 ft x 32 ft). The designed rainfall simulator was of 6.58 m (22 ft) height and included a 25.4 mm galvanized vertical standpipe. A nozzle was installed at a height of 6.53 m (21 ft), at the upper end of standpipe, through which the water was jetted to an approximate height of 8 m (26 ft). The spray delivered by nozzle covered a square area of 7 m x 7 m (23 ft x 23 ft). There was a pressure gauge immersed with oil and a cut off valve installed at the bottom of the pipe to regulate the pressure. There were six rainfall simulators combined, placed along two lines for spraying over an area of 50 m^2 (538 ft^2) plot. Ropes were attached to standpipes for stabilizing the system. Water was supplied from a storage tank near the plots with the help of a pump. Rainfall intensity was changed by adjusting water pressure. The rainfall simulator produced a rainfall intensity of 75 mm h^{-1} at a constant water pressure of 47.8 kPa (7 psi).

Martinez *et al.,* (2001) developed a rainfall simulator which included a square frame of 2.5 m (8.2 ft) sides and was supported by four pillars of 3.6 m (11.8 ft). The simulator was designed for studying the variation in physical properties of soil plots of 2 m x 2 m (6.6 ft x 6.6 ft) size. Two different nozzles were employed under water pressures of 100 KPa (14.5 psi) and 90 kPa (13.05 psi) in order to generate rainfall intensities of 33 mm $h^{-1}$and 60 mm h^{-1} respectively.

In the experiment conducted by Sanguesa *et al.,* (2010), a rainfall simulator was employed having four full-cone spray nozzles with Unijet sprinkler spray nozzles (model TG-SS14W, Spraying Systems Co., Wheaton, Illinois, USA). They are placed on a straight line pipe arrangement with spacing of 1 m from each other. The rainfall simulator was transportable and could be easily assembled. A total of 20 simulations performed in the laboratory and 16 simulations were conducted in the field at slopes of 11%, 21%, and 39%. The rainfall simulator was used in erosion control plots such as natural hillsides, for in-situ studies of soil loss. Run-off generation and sediment transfer were evaluated with great importance. The results obtained from laboratory and field tests also lead to the determination of co-efficient of rainfall uniformity and applicability domain of the simulator on soil erosion plots at different slopes. The rainfall simulator produced satisfactory homogeneous rainfall to analyse the operation of superficial runoff and erosion with a uniformity of about 90%.

Sousa and Siqueira (2011) developed a cost-efficient rainfall simulator for studies associated with urban hydrology. They developed the rainfall simulator to produce simulated rainfall events with raindrops of median diameter (D_{50}) of 2.12 mm generating kinetic energy (KE) of 22.53 J m^{-2} mm^{-1} and rainfall intensities from 40 mm h^{-1} to 182 mm h^{-1}. The Christiansen’s Uniformity coefficient (CUC) of the simulated rainfall ranged from 68.3% to 82.2%.

Yakupoglo *et al.,* (2015) conducted a research work where a “Eijkelkamp Rainfall Simulator” was used, for a 12 minutes duration initially for producing simulated rainfall of 360 mm h^{-1} intensity, on pans of soil. After a time span of 48 hours from first rain application, simulated rainfalls in sequence were applied on same pans. During the last phase of study, minimum and maximum runoff quantities (RQ) were measured under the influence of first rainfall and was found to be 11.9 mm and 40.6 mm, respectively, whereas these values were measured as 22.6 mm and 49.1 mm under sequential rainfall, the application pans being the same. In the first rainfall simulation event, soil quantities transported by runoff (SQTR) were found to be ranging from 89.1 to 3923.1 gm m^{-2} on the application pans. In the sequential rainfall simulation event, SQTRs ranged between 91.8 and 4739.4 gm m^{-2} on the same pans. Mhaske *et al.,* (2019) introduced a comprehensive rainfall simulator which consisted of four types of full-jet spray nozzles for replicating and producing rainfall intensities of 65, 93, 112, and 148 mm h^{-1}. A hydraulic jack unit was used in the experimental plot to attain a maximum slope angle of 40°. A temperature simulator was also employed create natural conditions in the laboratory. Simulations, both of physical and numerical nature were performed for determination of characteristics of simulated rainfall and comparing them with those of natural rainfall conditions. The Christiansen Coefficient (Cu) of the designed rainfall simulator was varying from 81% to 88%. The rain droplet sizes ranged from 1 to 5 mm and their corresponding terminal velocities were found to be between 4.76 m s^{-1} and 10.64 m s^{-1} with striking velocities between 5.56 m s^{-1} and 9.63 m s^{-1}. The kinetic energies ranged from 0.0081 MJ to 3.0342 MJ. The total raindrop kinetic energy striking the soil surface in the entire area of0.5 m^2 depends on the rainfall intensity and varied between 6 J to 12 J.

Different types of rainfall simulators developed and used by researchers since so many years reveals the fact that these simulators have significant contributions in the field of agricultural engineering, such as for determination of soil erosion values, run-off velocity *etc.* However, parameters such as simulator drop intensities, matching with that of natural rainfall, as per the need of research to be conducted, must be calibrated to the most possible extent.

As there is no standard design for developing a rainfall simulator and it solely depends on requirement of the area of research, hence variety of rainfall simulators with a wide range of specifications can be developed. However, care should be taken that the designed simulator, replicates the natural rainfall characteristics which is the prime objective of any simulator and some values signifying the properties of a natural rainfall, should not go beyond certain limitations. The height from which simulated raindrops are made to fall should be given importance while designing, such that these raindrops attain the terminal velocity alike natural rainfalls. Land slope and type of soil also plays major role in the design criteria of rainfall simulators.

Also, it is noteworthy to mention that nozzles used for simulating natural rainfalls should not have any blockages in their pathway and they should collectively cover the entire area subjected under study of rainfall simulation. This will help in appropriate determination of soil and water dynamics relevant to the study area. Difference in size of liquid droplets when it emerges from the nozzle hole and till the time it falls on the soil have to be evaluated properly by any suitable method. Uniformity co-efficient of simulated rainfall also has been found to be a significant factor, which needs to be determined with utmost accuracy for better understanding of soil-water dynamics.

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