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A rainfall simulator for laboratory-scale assessment of rainfall-runoff-sediment transport processes over a two-dimensional flume

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ABSTRACT

A rainfall simulator is an ideal tool for infiltration, soil erosion, and other related research areas for replicating the process and characteristics of natural rainfall. In this study, a laboratory-scale rainfall simulator is developed. Rainfall characteristics including the rainfall intensity and its spatial uniformity, raindrop size, raindrop velocity, and kinetic energy confirm that natural rainfall conditions are simulated with sufficient accuracy. Pressure nozzles are used to spray water corresponding to rainfall intensities ranging from 45 to 105 mm h^{-1}. The simulator produces rainfall with uniformity coefficient changing between 82 and 89%. The raindrops falling with an initial velocity from a height of 2.43 m have median diameters of 2.2–3.1 mm. The impact velocities of the median size raindrops deviate from their terminal velocities with a relative error between 6 and 15%. The accompanying erosion flume can be given slope up to 20% in lateral and longitudinal directions. During the experiments, flow measurement is taken from two outlets at the end of the flume to distinguish the contribution of interrill areas into rills. Experiments result in typical rainfall-induced hydrographs and sedigraphs observed under natural conditions. This shows the ability of the rainfall simulator for use in sediment transport processes over hillslopes.

1. Introduction

Rainfall simulators have been used as research tools extensively for field and laboratory characterization of hydrogeomorphological studies including runoff, infiltration and erosion characteristics as well as studies of sediment, nutrient, and pollutant transport within watersheds. They are also used for measuring impacts of revegetation, consolidation, and armoring on soil physical properties and erodibility. Rainfall simulators are important tools also in studies of impacts of tillage management on compaction and infiltration in agriculture as well. All at once, rainfall simulators can produce unique data that are vital for calibration and validation purposes of empirical, conceptual or process-based rainfall-runoff-sediment transport mathematical models (Aksoy and Kavvas, 2005).

The primary purpose of a rainfall simulator is to simulate natural rainfall accurately and precisely. At the same time, rainfall simulators control the intensity and duration of the rainfall which is random otherwise. Rainfall simulators are advantageous because rainfall can be produced quickly on demand, wherever necessary without having to wait for natural rain at the intensity and duration required, thereby eliminating the erratic and unpredictable variability of natural rain.

Soil loss from a catchment due to rainfall can be estimated by up-scaling soil loss measured with a variable rainfall intensity simulator (Hamed et al., 2002). Rainfall erosivity is kept constant by controlling the rainfall intensity. This allows one to isolate features related to soil detachability and determine an index of erodibility for different soils. Rainfall simulators at laboratory have less disruptive effects of wind, temperature and humidity (Clarke and Walsh, 2007). On the other hand, rainfall simulators might be disadvantageous due to the fact that usually cheap, simple, and small simulators which rains onto a test plot of small areas are preferred, as simulators covering an area of 100 m^2 or more are expensive to set up. In addition, although large simulators exist, they are generally impractical, non-portable and therefore difficult to use in field researches in remote areas. A portable rainfall simulator can be useful in that sense due to its fast and easy assembling and transportation from one plot to another. Development of a simulator for large areas in the field involves the capacity to reproduce natural rainfall characteristics and technical constraints (Koca and Aksoy, 2010).

Desirable characteristics for rainfall simulators used in erosion and hydrological studies include the rainfall intensity, spatial rainfall uniformity over the entire test plot, the drop size, its distribution and

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terminal velocity. Also important are the accurate control of rainfall intensity; similarity to natural rainfall in terms of kinetic energy; repeatability of applying the same simulated rainstorms; and improved mechanical and technical reliability for simple and easy transportation within research areas (Clarke and Walsh, 2007).

Rainfall simulators are, basically, devices to duplicate the physical characteristics of natural rainfall as closely as possible. Their size changes from a very small portable infiltrometer with 15 cm diameter rainfall area (Bhardwaj and Singh, 1992) to the complex Kentucky rainfall simulator that covers 4.5 m×22 m (Moore et al., 1983). Rainfall simulators can be separated into two main groups according to the way in which the raindrops are produced: (i) non-pressurized nozzle (drop forming) simulators, (ii) pressurized nozzle simulators. In the drop forming simulators, water drops fall under the effect of gravity. Drop-former rainfall simulators emerged due to the uncertainties associated with nozzle-generated drop sizes, distributions and intensities. These simulators become impractical for field use since a huge distance (10 m) is required for drops to reach terminal velocity. Unless the device is raised up very high, the drops strike the ground at a velocity much lower than the terminal velocity and with a lower kinetic energy. Therefore, the pressurized nozzle simulators are commonly preferred for studies at large area fields (e.g. 10 to 500 m^2) (Esteves et al. (2000) and references therein). The pressurized rainfall simulators produce raindrops through single or multiple nozzles. While this type of simulators produces satisfactory droplet velocities and kinetic energy values at lower fall heights than natural rainfall, drop intensities and velocities are usually exaggerated as the water is released under pressure. Also an unnaturally intense storm is created as the result of the continuous spray from the nozzle. A rotating disc, a rotating boom, an oscillating bar or a solenoid-controlled simulator can be used as methods of starting or stopping the spray in order to reduce the exaggerated rainfall intensity among which a rotating or oscillating bar can be the simplest solution (Bubenzer, 1979). Besides these two types of rainfall simulators, more sophisticated vehicle-supported designs are also available (Greene and Sawtell, 1992; Onstad et al., 1981; Tossel et al., 1990a, 1990b).

The selection of the water spraying nozzle for the rainfall simulation is an important issue. Meyer (1958) evaluated four nozzles (VeeJet 80100, VeeJet 8070, FullJet 106SQ and FullJet 50SQ) for their drop size, velocity and kinetic energy. At the end of the evaluation the VeeJet 80100 nozzle was selected for rainfall simulation as it closely simulated natural rainfall with an energy level about 75% of that of intense natural rainfall, and a drop size distribution close to that of natural rainfall. The VeeJet 80100 nozzle was used for the rain simulator which has also been used successfully for a field plot rainfall simulator by Swanson (1965).

Due to all these facts it is clear that a universal rainfall simulator applicable to all situations does not exist. Each specific condition requires specific designs for rainfall simulators. For example, motorized simulators cannot be used for plots with high slopes. Motor vehicle entry may not be possible also either due to wet winter soil conditions or grower concern about the cultivation, and unavailability of local water supplies. Therefore, a great number of rainfall simulators have been designed among which small portable simulators fully manageable by one person can be mentioned that come with their disadvantages (Battany and Grismer, 2000).

One option to overcome the disadvantages of the small portable field rainfall simulators is to use laboratory-scale simulators. Therefore, the aim in this study is to develop a laboratory-scale non-portable rainfall simulator to spray rainfall over an erosion flume that can be given both lateral and longitudinal slopes up to 20% each. The study describes first the design characteristics and testing of the laboratory-scale rainfall simulator to be used for assessment of rainfall-runoff-sediment transport processes over the erosion flume. The performance of the rainfall simulator is evaluated based on the rainfall intensity and its uniformity, raindrop size distribution, terminal and impact velocities and kinetic energy of the generated rainfall. Example results are demonstrated after which a discussion is made together with a comparison to some of the existing laboratory-scale pressurized nozzle rainfall simulators by touching upon future possibilities and followed by conclusions.

2. Design of rainfall simulator and erosion flume

Experimental design to perform sediment experiments consists of a rainfall simulator and an erosion flume (Fig. 1). Rainfall simulator is made of a periodically oscillating bar attached with nozzles. The bar is mounted at the ceiling of the laboratory room at a height of 2.60 m from the flume bed to ensure the terminal velocity of rain drops. Oscillation of the bar is given by a motor and its periodicity is adjusted by a frequency converter (Fig. 1). Water is supplied from a water tank connected to the water supply system and pumped up through a main water pipe divided into four or five pipes depending on the number of nozzles used for spraying water over the flume. At the end of each pipe, the nozzles are installed before which a pressure gauge is attached. Laying under the rainfall simulator at a height of 115 cm from the ground is the erosion flume which is 136 cm wide, 650 cm long and 17 cm deep, and can be given slopes up to 20% both laterally and longitudinally.

After evaluating different types of nozzles, the VeeJet type nozzles were selected. Different VeeJet nozzle series were used for each of the rainfall intensities. The simulated rainfall intensities were 45, 65, 85 and 105 mm h^{-1}. Four VeeJet 8030 nozzles were installed on the oscillating bar for 45 mm h^{-1} of rainfall intensity and four VeeJet 8050 nozzles for 65 mm h^{-1}. Five VeeJet 8060 and five VeeJet 8070 nozzles were used for rainfall intensities of 85 and 105 mm h^{-1}, respectively (Fig. 2, Table 1). The number of nozzles was decided to ensure the uniform distribution of rainfall on the flume. The distance between the nozzles was set at 145 cm for rainfall intensities of 45 and 65 mm h^{-1} while it was reduced to 125 cm in rainfall intensities of 85 and 105 mm h^{-1} (Fig. 3). Pressure at each nozzle is fixed at such a level that rainfall sprayed out of each nozzle intersects the rainfall of the neighboring nozzles to secure uniformly distributed rainfall over the flume. Flow meter installed on the rainfall simulator system is used to manually adjust the discharge in the pipe by a valve to the desired rainfall intensity. The pressure at the nozzle affects on the rainfall intensity. Considering both the intensity and uniformity, pressure was fixed at values given in Table 1 depending on the rainfall intensity applied. After several initial experiments, characteristics in Table 1 were found appropriate for the aim of the study ensuring the uniformity of the rainfall at the desired intensity. It is seen that rainfall intensity varies with nozzle equivalent orifice diameter, the pressure at the nozzle, the spacing of the nozzles and the nozzle movement (bar oscillation). With oscillation of the bar during the rainfall application, rainfall is sprayed outside the flume considerably. It was observed that, for rainfall intensities of 65, 85 and 105 mm h^{-1}, more than half of discharge was sprayed outside the flume; even it became as high as two thirds in case of 45 mm h^{-1}.

In the erosion flume, the microtopography of the watershed is simulated. Microtopographical structure of natural slopes within watershed consists of rills and interrill areas. Therefore, the watershed can be divided into hillslope sections, as illustrated in Fig. 4 on which the experimental analysis of this study is based (Kavvas et al., 2006). The plan view of the erosion flume (right hand side in Fig. 4) corresponds to the rectangular area selected from the watershed hillslope in the left hand side. By giving a lateral slope to the erosion flume most of the interrill area flow contributes to the rill. The contributing area changes with the lateral slope given to the flume. A small portion of the interrill area closer to the downstream part of the flume flows directly to the channel. Two outlets were therefore formed on the flume (see right hand side in Fig. 4): Outlet (1) is used for collecting