SCIENTIFIC NOTES

A RAINFALL SIMULATOR FOR THE *IN SITU* STUDY OF SUPERFICIAL RUNOFF AND SOIL EROSION

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ABSTRACT

A rainfall simulator is an important tool for the study of runoff generation and soil loss because it can be used either under laboratory conditions, or in disturbed or natural soil. The objective of this study was to describe the design and operation of a rainfall simulator to evaluate soil loss *in situ*. The rainfall simulator has four full-cone spray nozzles with a Unijet system mounted in a straight line pipe configuration, and easily transported and assembled. Simulated rainfall uniformity was evaluated in the laboratory, whereas the applicability of the simulator in natural soil erosion plot conditions in an experimental field with different slopes was tested by quantifying runoff and evaluating soil erosion. Twenty simulations were carried out in the laboratory and sixteen in the field with slopes of 11, 21, and 39%. Four water-sprinklers in a straight line generated rainfall with uniformity close to 90%. The constructed simulator was easy to use and low cost, facilitating the necessary experimental replicates to achieve a suitable spatial representation of superficial runoff and soil loss on hillsides.

Key words: soil erosion, superficial runoff, erosion plot, uniformity of rain.

INTRODUCTION

A rainfall simulator allows generating rainfall with a known intensity and duration on an erosion plot in a controlled manner, making it possible to quantify superficial runoff and soil loss, while at the same time allowing very detailed erosion predictions (Martínez-Mena *et al.*, 2001). In this way, simulators have widely contributed to the understanding of soil erosive processes, and though there are differences between natural and simulated rainfall, it is possible to find good correlations between the values of soil loss measured in an erosion plot under simulated rainfall and what occurs in a watershed (Hamed *et al.*, 2002). On the other hand, data generated in the measurements allow calibrating, validating, and verifying erosion predictive models such as Universal Soil Loss Equation-USLE (Wischmeier and Smith, 1978).

Various studies can be found in specialized literature where a rainfall simulator has been used to analyze the different processes involved in erosion. Martínez-Mena *et al.* (2001) studied changes in the physical properties of the soil in 2 x 2 m plots by means of eight 20-min simulations. The simulator consisted of a square frame, 2.5 m side, supported by four 3.6 m pillars. Two types of nozzles were used: the first worked at 100 000 Pa pressure with 33 mm h^{-1} rainfall intensity, and the second used 90 000 Pa and 60 mm h^{-1} intensity. The rainfall uniformity coefficient was 89 and 91, respectively. The simulator's low consumption of water is emphasized, approximately 200 and 350 L for the low and high intensities, respectively, for a 20-min simulation.

Cornelis *et al*. (2004) constructed a wind tunnel and a rainfall simulator to study the effect of wind and rainfall characteristics on soil erosion. The simulator consisted of three pipes covering a 12 x 1.2 m section with sprinklers working with pressurized water. Arnaez *et al*. (2007) used a rainfall simulator to compare runoff and sediment production under distinct rainfall intensities in a vineyard plantation in Spain. The simulator consisted of a sprinkler located at a height of 2.5 m with pressurized water for 30-min simulations on a 0.45 m diameter plot. Three different types of sprinklers were used for three rainfall intensities: < 40, between 45 and 70, and > 70 mm h^{-1}. The authors mention in their conclusions that both the reduced plot size and the difficulty to reproduce natural rainfall limit the information obtained.

Aoki and Sereno (2006) used a micro rainfall simulator to study water infiltration in the soil in a 0.25 x 0.25 m plot consisting of an acrylic drop box in with 49 plastic in its base tubes to form drops with water

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pressure being provided by the height of the water reservoir. Drops with an average diameter of 4.7 mm were produced. Kinetic energy was 12.7 kJ m^{-2} m^{-1} for a 1.5 m drop height. Sheridan *et al.* (2008) used a simulator to obtain a modified erodibility index which could be used to predict annual erosion rates for forest roads. They used a rainfall simulator on 1.5 x 2.0 m plots, and carried out simulations for 30 min with an intensity of 100 mm h^{-1} and an estimated kinetic energy of 0.295 MJ ha^{-1} mm^{-1}, which is similar to the kinetic energy of high intensity rainfall. In Chile, Lagos (2006) and Verbist *et al.* (2009) used a rainfall simulator documented in CAZALAC (2004) to study hydric erosion and compare distinct methods of measuring soil loss. The simulator consists of a straight line of seven sprinklers with a 1 m space between sprinklers that work with pressurized water and cover an area of 5 x 2 m. Verbist *et al.* (2009) obtained soil loss values in 10 plots with bare soil in the Coquimbo Region. Each experimental simulation lasted 20 min, system pressure was 100 000 Pa, and rainfall reached a mean intensity of 130 mm h^{-1}.

The most important characteristics of a rainfall simulator are cost, transport and assembling, capacity to generate homogeneous rainfall, and water consumption. The objective of this study was to describe the design and functioning of a rainfall simulator constructed to measure soil loss *in situ*. For this purpose, the practical experience of assembling and using this device in the laboratory and field are made known.

MATERIALS AND METHODS

Rainfall simulator design

The constructed simulator was a continuous sprinkler system with pressurized water (Figure 1). Supply and discharge consisted of an elbow to connect a water supply hose to the sprinkler system, two fast closing cutoff valves: one opening or closing the interflow of water to the sprinklers and another allowing the discharge of water from the system when the sprinkler interflow was closed (connected to an evacuation hose); furthermore, it had a pressure regulation valve for the functioning of the sprinklers. With the discharge valve, cutoff time of water in the sprinklers was minimized, time which would be greater if the pump were directly cut off. A dual pump with a 30.5 cm^3 cylinder and 1 kW power was used in the system. Pipes were polyvinyl chloride (PVC) with a diameter of 32 mm and the sprinkler system was made up of four full-cone Unijet sprinkler spray nozzles (model TG-SS14W, Spraying Systems Co., Wheaton, Illinois, USA) located on a straight line with a 1 m space between sprinklers, interconnected by PVC pipes, terminals, and two manometers located one in the front and the other at the end of the system controlling working pressure. Pipe fittings facilitated the vertical position of the sprinklers.

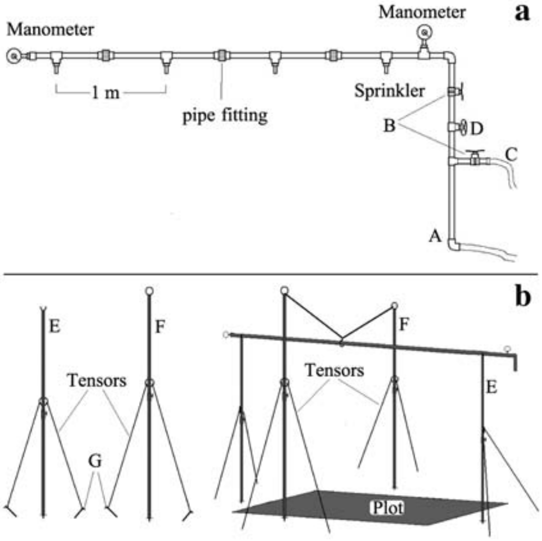

Figure 1. (a) Diagram of rainfall simulator, and (b) supporting structure; (A) water supply, (B) fast closing cutoff valves; (C) evacuation hose, (D) pressure regulating valve, (E) pipe support, (F) lateral pipe support, (G) stakes for tensile ropes.

The support of the structure was on a base of four iron pillars (2 x 1 cm profile) buried 5 cm in the soil and reinforced by wires and stakes. A polyethylene mesh was used as a windbreak screen with 65% shade reinforced by stakes and tensed with a system of ropes to generate rainfall under no-wind conditions, which influences the erosive characteristics of simulated rainfall (Erpul *et al.*, 2002). Figure 1 shows a diagram of the rainfall simulator.

Evaluation of rainfall simulator

The rainfall simulator was evaluated for: 1) cost, 2) transport and assembling, 3) homogeneousness of rainfall, and 4) water consumption.

Rainfall provided by the sprinklers, as well as its uniformity, was tested in the facilities of the Hydric Resources Laboratory of the Facultad de Ingeniería Agrícola, Universidad de Concepción, Chillán, Chile. Homogeneousness of simulated rainfall was characterized by the Christiansen's uniformity coefficient (CU) according to the following equation:

$$CU = 100\text{x} \left(1 - \frac{\sum|x - \bar{x}|}{\sum x}\right) \qquad [1]$$

where x is the height of the water registered for each container on a uniformly spaced grid and $\bar{x}$ is the mean height registered in the containers.

Sprinklers were evaluated in the laboratory under two working pressures: 75 000 and 100 000 Pa. Tests were carried out for each sprinkler, first separately and then for the four sprinklers located in a straight line to characterize rainfall through tipping buckets located in a 25 x 25 cm grid on the soil, covering an area of 2 x 2 m for each sprinkler, and 1.25 x 3.25 m for the four sprinklers in a straight line.

The functioning of the simulator in field conditions was tested in three sites with average slopes of 11, 21, and 39%. Three 2.5 x 1 m plots were established in each site. Sites were located in the commune of Ninhue, in the dryland zone of the Bío Bío Region, 45 km West of the city of Chillán. Water supply for the land came from a well.

RESULTS AND DISCUSSION

Cost

The construction cost of the simulator was $200 000 Chilean pesos (US$400) including water hoses. The operational cost (only fuel for the pump motor was considered) did not exceed $500 (US$1) for 20 min of operations (approximate performance of the pump was 3 L h^{-1}).

Simulator transport and assembling

The designed simulator was easily transportable given its small volume (Figure 2). A pick-up truck can be used to transport it since the hoses and the windbreak mesh take up the most space. Assembling the simulator in the field can be done by two people. Assembling time varied according to field conditions, especially the slope, but did not exceed 30 min. The simulator must be installed following the slope line of the field, and verifying a structure height of 1.8 m at both ends.

Homogeneity of simulated rainfall

An individual sprinkler wets a circumference with an approximate 1.8 m radius (Figure 3). A 2 x 2 m square was controlled in the trial, obtaining a mean rainfall uniformity of 86%, a minimum of 84.9% and a maximum of 87.4%. Furthermore, the 1 x 1 m central zone was controlled and showed a mean uniformity of 91.4% (minimum 90.5% and maximum 92.0%). Similarly, in the tests of the four sprinklers in a straight line, a CU greater than 90% was obtained for a 1 x 2.5 m effective area with pressures of 75 and 100 kPa, and rainfall means of 124 and 119 mm h^{-1}. The CU value obtained was considered acceptable (Martínez-Mena *et al.*, 2001). For the above-mentioned, it is recommendable that the effective work area be greater than 2.5 m^2. Another important aspect is turning on and cutting off water in the sprinklers in a minimum amount of time using fast closing cutoff valves to produce a greater homogeneousness of rain at the start and end of each simulation.

Figure 2. The top picture shows the rainfall simulator installed on a soil erosion plot with a 40% slope. The center picture shows the dismantled simulator. The bottom picture shows detail of the soil erosion plot, and runoff and sediment sampling.

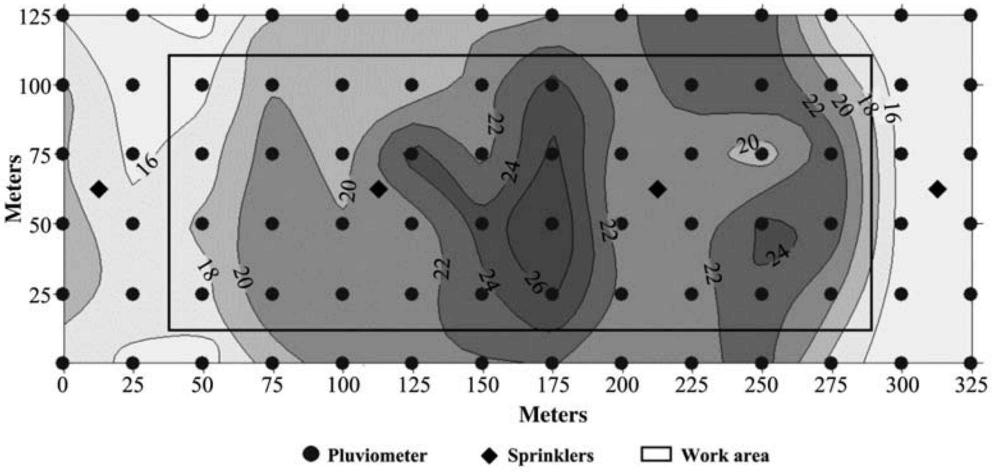

Figure 3. Spatial distribution of rainfall (mm) simulated with four water sprinklers in a 10-min test with pressure of 100 kPa. The interpolation method used is linear interpolation with triangulation.

Water consumption

Water consumption of the rainfall simulator was 1800 L h^{-1}. Real consumption in a simulation is a function of time which depends on the initial soil water content. For low soil water content, between 5 and 6%, simulation times between 50 and 60 min are required to generate minimum runoff. For high soil water content, near 20%, simulation time required varies between 10 and 20 min.

CONCLUSIONS

The rainfall simulator shown can be used for an *in situ* study of soil loss. It was used in erosion control plots on natural hillsides and generation of runoff and sediment transport was verified for each simulation.

Results of laboratory and field tests allowed evaluating uniformity of the rainfall generated and the applicability of the simulator on erosion plots with different slopes. The simulator generated adequate homogeneous rainfall to study processes of superficial runoff and erosion with uniformity near 90%.

Finally, the constructed simulator was an easy to use tool, low-cost, and easy to transport and assemble in the field, thus allowing the necessary experimental replicates to be carried out.

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RESUMEN

Un simulador de lluvia para el estudio *in situ* de la escorrentía superficial y la erosión de suelos. El simulador de lluvia es una herramienta importante que permite estudiar los procesos de pérdida de suelo y escorrentía generados por la acción de la lluvia; éste puede utilizarse en laboratorio, bajo condiciones de suelo removido, o en terreno en condiciones naturales de suelo. El objetivo de este estudio fue describir el diseño y el funcionamiento de un simulador de lluvia construido para medir la pérdida de suelo *in situ*. El simulador de lluvia tenía cuatro boquillas de aspersión de cono lleno con sistema Unijet (Spray nozzles) ubicados en línea, alimentadas mediante un sistema de tuberías de fácil transporte y montaje. En pruebas de laboratorio se evaluó la uniformidad de la lluvia generada; mientras que en terreno se evaluó la aplicabilidad del simulador sobre parcelas de erosión ubicadas en laderas naturales con diferentes pendientes, donde se cuantificó la escorrentía superficial y la erosión del suelo. En total se realizaron 20 simulaciones en laboratorio y 16 en terreno con pendientes de 11; 21 y 39%. Los cuatro aspersores en línea generaron una lluvia con una uniformidad cercana al 90%. El simulador construido fue una herramienta de fácil uso y bajo costo, que facilitó la realización de las repeticiones experimentales necesarias para lograr una adecuada representatividad espacial de la escorrentía superficial y pérdida de suelo en laderas.

Palabras clave: erosión del suelo, escorrentía superficial, parcelas de erosión, uniformidad de la lluvia**.**

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