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Setup and calibration of the rainfall simulator of the Masse experimental station for soil erosion studies

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A B S T R A C T

This note describes the technical characteristics and the preliminary setup and calibration of a nozzle-type rainfall simulator installed at the University of Perugia's Masse experimental station. This simulator includes some innovative features, usually not present in similar low-cost instruments employed in field experiments: 1) both single and multi-nozzle operation are feasible, thus enabling the possibility to simulate variable-intensity rainfall events; 2) events are simultaneously reproduced in two identical plots (width 1 m, length 0.92 m, and slope 16%), thus obtaining two replications for each experiment; 3) the runoff volume coming from the micro-plots and the water volume falling outside the plots are both collected and conveyed to separate outlets, thus allowing an easy calculation of the infiltrated volumes and of the system efficiency.

The first step of the calibration regarded the spatial distribution of rainfall, the stability of the rainfall intensity over time (within the experiment), and the reproducibility of the rainfall intensities both in space (between the two plots) and over time (among successive experiments). Next, the drop size distribution (DSD) and the related rainfall characteristics (median volumetric drop diameter D50 and mean kinetic energy per unit area and unit depth) were evaluated by the oil method for the single and some multi-nozzle applications. An effective automatic drop recognition procedure by the Fiji open-source software is proposed and illustrated.

Results indicate a high uniformity of rainfall (Christiansen uniformity coefficient $> 92\%$) in both single and multi-nozzle operation for both plots. The reproducibility of experiments over short time intervals and under similar environmental conditions is satisfactory (coefficient of variation of mean intensity $< 3\%$). Comparing initial and final rainfall intensity values, a slight decrease was observed within each experiment (about 2% on average). Some systematic differences in rainfall intensity were also detected between the plots. The analysis of both the intensity and the DSD in the multi-nozzle operation indicated the presence of some interference among the individual sprays when larger nozzles are simultaneously activated. Moreover, in agreement with the literature, it was confirmed that this type of rainfall simulator always produces kinetic energy values lower than those associated with natural rainfall of similar intensity.

1. Introduction

The Masse experimental station of the Department of Agricultural, Food and Environmental Sciences (University of Perugia) is located in central Italy (12°16′49.3″E, 42°59′21.1″N). The site includes a number of USLE plots of varying length and width, oriented parallel to a 16% slope and kept free of vegetation by frequent ploughing. Since 2008 the station has enabled the collecting of data from several erosive events, which were mainly used to investigate the relationship between rainfall characteristics and soil loss (Bagarello et al., 2013). The high soil loss variability that characterizes erosive storm events with similar overall characteristics (duration and/or depth) could be explained by the different rainfall profiles of erosive storms (Todisco, 2014) and by the different antecedent characteristics of the soil surface, such as the water content (Todisco et al., 2015) and the roughness (Vinci et al., 2017). In order to analyze these aspects more in detail, the Masse experimental station was recently equipped with a rainfall simulator.

One of the main advantages of rainfall simulators resides in the introduction of the reproducibility of experiments, and for this reason they are often used in soil erosion studies both in laboratory and in field experiments (Iserloh et al., 2013). Several types of rainfall simulators have been designed and employed for studies related to soil erosion in the last half century (Cerdà, 1999). Rainfall simulators on small plots ($< 1\ \text{m}^2$) represent an important category because they make it possible to distinguish the different subprocesses related to runoff generation and erosion (Iserloh et al., 2012). In most cases, the rainfall simulators

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employed for field experiments are characterized by simple and low-cost components compared to the simulator used in laboratory studies. This is due to the fact that the experiment sites are sometimes difficult to reach and energy and water supplies are usually limited.

Whatever the type of simulator, a preliminary calibration, aimed at assessing the characteristics of the rainfall produced, is always necessary (Iserloh et al., 2012). The most important aspects that need to be evaluated are the uniformity of distribution, the reproducibility of experiments, the Drop Size Distribution (DSD) and the drop fall velocities (v_f). The DSD and v_f can be estimated from a variety of methods or instruments (Ries et al., 2009). One of the most up-to-date and accurate methods is based on the use of the Laser Precipitation Monitor (Thies Clima, 2007). Although the use of this instrument is encouraged as a standard method (Iserloh et al., 2013), due to its relatively high cost other methods are still being employed. Among this, the oil method (Eigel and Moore, 1983) has the advantage of not requiring a preliminary calibration and has been also applied in recent experimental works (Lora et al., 2016; Meerveld et al., 2014).

The rainfall simulator installed at the Masse experimental station is a low-cost multi-nozzle rainfall simulator that is able to reproduce both constant and variable rainfall intensities. It is designed to operate simultaneously on two adjacent micro-plots 1 m wide and 0.92 m long, having the same topographic and pedological characteristics of the adjacent USLE plots. The variability of rainfall intensity can be obtained by the simultaneous activation of different combinations of nozzles (multi-nozzle operation). This possibility is useful for a more reliable reproduction of the intra-event dynamics typical of natural rainfall events (Todisco, 2014). Seven intensity values are theoretically attainable through combinations of the three nozzles currently tested (but 53 could be obtained using 4 nozzles).

This paper presents the results of the preliminary calibration experiments, whose main objectives were: 1) the evaluation of the rainfall uniformity, of the stability of the rainfall intensity over time (within the experiments), and of the reproducibility of the experiments both in space (among the two plots) and in time (among successive experiments); 2) the quantification of the DSD and of the related rainfall characteristics (median volumetric drop diameter D50 and mean kinetic energy per unit area and unit depth) by the oil method for the single and some typical multi-nozzle operation. In this regard, a method for the automatic recognition of drops is proposed and detailed in the present work (Appendix I). The method, based on the FIJI open-source software (Schindelin et al., 2012), can be considered as an easily-available alternative to previously proposed procedures (like that by Cruvinel et al., 1999).

2. Materials and methods

2.1. Description of the rainfall simulator

The rainfall simulator is placed over two micro-plots of 1 m × 0.92 m each (called plots 1 and 2 in Fig. 1a), with slope 16%. Each plot is surrounded by an impermeable area.

The runoff volume coming from the micro-plots and the water volume falling outside the plots are conveyed to separate outlets and are both collected. This makes it possible to carry out an a posteriori check of the infiltrated volumes and of the actual intensities. Wind protection tarpaulins, fastened to vertical poles, are unfolded during experiments, in order to prevent the wind-drift effect and also to allow the collection of the water sprayed outside the experimental plots. At present, the water source is tap water, whose pressure head and flow rate are more than enough for the correct functioning of the rainfall simulator.

Each rainfall-simulation experiment is simultaneously carried out in plots 1 and 2. The rainfall simulator can hold up to four different spray nozzles for each micro-plot. Single or multi-nozzle experiments are managed by four computer-controlled solenoid valves (1″, 9 Volt, Hunter Industries) whose outlet pressure is regulated by four low-flow Pressure Regulating Valves (PRV, Bermad). The hydraulic scheme is presented in Fig. 1b. The nozzles are placed at the corners of a small wooden board with a side length of 0.18 m, centered over the plot at a height of 2.8 m above the ground. The results presented here are related to 3 full-cone spray nozzles (https://www.jetsystemsrl.it) which showed good performance in terms of uniformity during the calibration experiments. These nozzles are the EE2.8W, FF14WSQ, FF30WSQ (2.8W, 14WSQ, 30WSQ, hereinafter). The 14WSQ and 30WSQ were often used in rainfall simulation experiments (Covert and Jordan, 2009; Humphry et al., 2002; Lora et al., 2016). The operating pressures for the 2.8W, 14WSQ, 30WSQ nozzles were 110, 70 and 45 kPa, respectively. At present the fourth available position is occupied by a EE2.0 nozzle operating at a very high pressure (about 400 kPa). This nozzle produces a very fine mist and it can be used to increase the initial water content of the plot surface with negligible rainfall kinetic energy.

2.2. Uniformity, temporal stability and reproducibility of rainfall intensity

In the first type of experiment (defined "detailed"), contemporarily carried out in the two plots, the uniformity of the rainfall was evaluated measuring the rainfall intensity at 16 gauges arranged over the 1 m × 0.92 m plot areas according to a regular grid. Each gauge (diameter 0.152 m) occupies a circular area of 0.01815 m^2 and therefore the total area covered by the rain gauges is about 0.29 m^2 (31.5% of the total). The system was stopped after each trial in order to weigh the water collected inside each gauge and to restore the initial arrangement. The corresponding mean intensity in the area of the gauge was calculated for a water density of 1000 kgm^{-3} as

$$I_i = \frac{60x_i}{1000 \cdot t \cdot A_i} \tag{1}$$

where i, single gauge with $i = 1,\ldots, n$ and n, number of gauges; I_i, mean intensity in the area of the gauge (mm·h^{-1}); x, weight of the water collected inside the gauge (g); A, circular area of the gauge (m^2); t, duration of the trial (min).

The duration was adjusted according to the nozzle discharge (3 min for nozzles 30WSQ and 14WSQ, and 10 min for the 2.8W). The mean rainfall intensity for single trial and plot was estimated as

$$\overline{I}_e = \frac{\sum_{i=1}^{16} I_i}{n} \tag{2}$$

The Christiansen uniformity coefficient (UC) was adopted to describe the uniformity of the rainfall events (Christiansen, 1942). It was calculated for each repeated experiment and each plot using the equation below:

$$UC = \left[1 - \frac{\sum_{i=1}^{n} |I_i - \overline{I}_e|}{\overline{I}_e \cdot n}\right] \cdot 100\% \tag{3}$$

Each experiment was replicated 3 times. The coefficients of variation (CV) of I_i, $\overline{I}_e$, UC, were derived to evaluate the reproducibility of the experiments both in space (between the two plots) and over time (among successive experiments). The analyses described above (detailed approach) were applied for both single and some multi-nozzle