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The generation of surface runoff in laboratory conditions using two portable rainfall simulators – an experimental study

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The use of laboratory methods in soil water erosion studies and rainfall simulation experiments has recently been considered more important because of the many advantages in controlling rainfall-runoff processes and sediment transport. In a laboratory study, rainfall simulation experiments (one alone and two identical rainfall simulators connected in a series) were focused on an analysis of the impact of the size of the irrigated area on the temporal distribution and volume of the surface runoff and the amount of eroded soil material. The experiments were conducted on a disturbed soil sample exposed to quasi-continuous 60-minute simulated rainfall events with an intensity of 2.7 mm min^{-1}. The two experiments were carried out on slopes of different lengths of 0.25 m (irrigated area: 0.0625 m^2) and 0.5 m (irrigated area: 0.125 m^2). The results showed the effects of the size of the irrigated area on surface runoff generation and changes in the soil structure, sediment concentration, and amount of soil loss. Knowledge of the rate of changes in the volume of the surface runoff and soil loss with respect to the size of the irrigated area in the laboratory conditions and subsequent generalization of the results provides essential information, which is irreplaceable for the preparation of field measurements and obtaining essential calibration and validation data for erosion and rainfall-runoff modelling.

KEY WORDS: laboratory experiment, rainfall simulator, surface runoff, eroded sediments

Introduction

In recent decades, rainfall simulators have become a popular tool for conducting research on topics such as infiltration, the generation of surface runoff, and soil erosion. Most of these studies mainly focus on sediment, nutrient, and pollutant transport as well as on evaluating the impacts of tillage management on compaction in agricultural soil (Aksoy et al., 2012). A portable rainfall simulator is easy to use, transport, and assemble in the field, making it possible to perform numerous repetitions of an experiment to draw reliable conclusions. The advantage of using a rainfall simulator is the elimination of the erratic and unpredictable variability of real rainfall and the enabling of the specific and reproducible assessment of several parameters that can be rapidly collected, while maintaining relatively uniform rainfall conditions (Iserloh et al., 2013). Simulators can provide substantial datasets that are necessary and essential for the calibration and validation of various processes in mathematical models (e.g., erosion, sediment transport, rainfall-runoff) of all types of complexity, including the empirical, conceptual, and physically-based (Aksoy and Kavvas, 2005). Small portable rainfall simulators are primarily used with a connection to agricultural land, where the quantification of erosion processes is of high importance (see Abudi et al., 2012; Iserloh et al., 2013; Hänsel et al., 2016). Nevertheless, numerous studies have shown that rainfall simulators can also be successfully used on different sites such as sloping olive groves (Palese et al., 2015), forest roads (Zemke, 2016), forested areas (Danáčová et al., 2017; Chouksey et al., 2017), headwater catchments (Holko et al., 2018), and alpine grasslands (see Schmidt et al., 2019).

In the previous field experiment campaign of Hlavčová et al. (2019), eight independent rainfall simulation experiments were carried out on south-facing slopes in the Myjava Hills (Myjava – Turá Lúka region of western Slovakia). All the experiments were carried out using different parameters such as the initial soil moisture (low, medium, high), the slope of the experimental plot (9% – 22%), and the vegetation cover (bare soil, winter crops, maize, rapeseed) to investigate the volume of the surface runoff and the weight of the eroded sediments. The rainfall simulations were conducted in the study using an Eijkelkamp-type rainfall simulator for erosion tests with a possible range of rainfall intensities of 180–420 mm hour^{-1}. This rainfall intensity is comparable with the real rainfall energy of a flash flood for the Myjava region (Myjava – Turá Lúka rain gauge, ID 15040). The results of the study showed that the field measurements were burdened by relatively uncertainties due to the small size of the experimental plots.

The objective was to test, in a simple laboratory experiment, the effect of the size of the irrigated area on bare soil with a low intensity of artificial precipitation and with a longer duration (more than 3 minutes), where the time to runoff, surface runoff volume, and sediment transport were monitored. This would allow for expanding knowledge about the possibility of using small portable rainfall simulators in parameterizing erosion-transport or rainfall-runoff models and shedding a light on the uncertainties of using parameters from either laboratory or field measurements in real-life studies (see Szabó et al., 2020; Dunkerley, 2021).

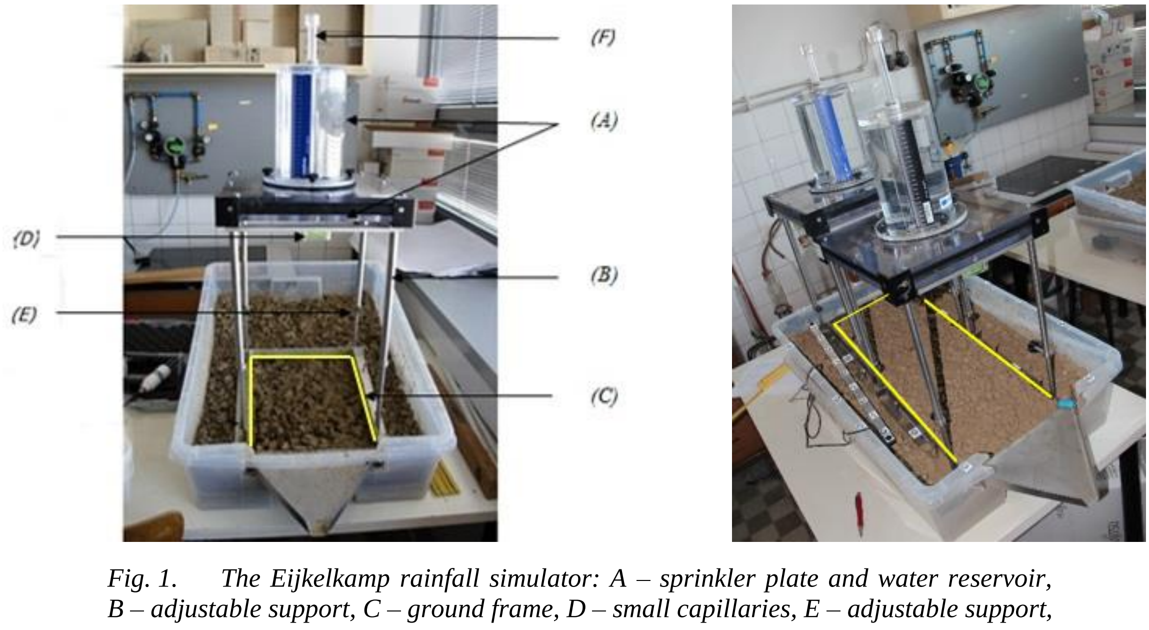
The main objective of the study was to carry out a series of laboratory experiments with rainfall simulators (one alone and two identical ones connected in a series) to analyse the impact of the irrigated area on the generation of surface runoff (amount and time distribution) and the amount of eroded soil material. The results of the study should answer the following questions: What effect will the size of the irrigated area (including the slope length) have on the generation of surface runoff? What will be the volume of water and eroded soil loss relative to the irrigated area? Can the results of laboratory experiments be used to calibrate parameters of erosion-transport or rainfall-runoff models?

Methodology and data

Rainfall simulators are key tools for investigating the dynamic processes of surface runoff, infiltration, and soil erosion characteristics (Iserloh et al., 2013). They are often used in laboratory or field experiments. The advantage of laboratory experiments is the elimination of uncertain natural conditions such as wind, solar radiation, soil moisture, and the antecedent soil conditions (Grismer, 2012).

In this experiment, the disturbed soil sample designated for the rainfall simulations in the laboratory conditions was taken from an agricultural field in the Myjava region, part of Turá Lúka. The soil sample used in the experiment was a type of loamy soil (according to Novak's soil classification system, see Novák and Hlaváčiková, 2016). The depth of the soil sample was 20 cm, and the sample was kept in a solid plastic container. The soil moisture was measured continuously using a soil moisture sensor. The sensor was placed at a depth of 5 cm in the lower part of the irrigated area. In order to simulate the vertical movement of water, the bottom side of the container was perforated and put into a container of the same type (see Fig. 1) that was used to store the infiltrated water. The Eijkelkamp Small Rainfall Simulator (Fig. 1) was used to generate artificial rainfall of a constant intensity. In the first experiment (A), a single rainfall simulator was used to irrigate the area of 0.0625 m^2 (length of slope: 0.25 m). The second experiment (B) used two identical rainfall simulators, which were put one after the other to extend the rainfall irrigated area to 0.125 m^2 (length of slope: 0.50 m).

In both experiments, the rainfall simulation was interrupted every 12 minutes at an intensity of 2.7 mm min^{-1} (quasi-continuous 60-minute rainfall simulation). The reason for these interruptions was the limitations of the rainfall simulator, whose reservoir enables the storage of only 2.3 litres of water. During the interruption, the surface runoff volume, the weight of the sediment, and the soil moisture were measured. Both experiments were preceded by the same initial conditions such as the initial soil moisture, the soil condition (disturbed sample) and management (cultivated bare soil), and the slope of the irrigated area. Table 1 shows an overview of the basic parameters and the initial conditions for both experiments.



Single rainfall simulator – EXPERIMENT **A** (irrigated area: 0.0625 m^2)

Two rainfall simulators – EXPERIMENT **B** (irrigated area: 0.125 m^2)

Fig. 1. The Eijkelkamp rainfall simulator: A – sprinkler plate and water reservoir, B – adjustable support, C – ground frame, D – small capillaries, E – adjustable support, F – aeration pipe.

During both experiments, the soil moisture and surface runoff were continuously measured using a soil moisture sensor and a camera that was recording the measuring cylinder collecting the surface runoff and eroded sediment (see Fig. 2A). These parameters were evaluated at 15-second intervals. Apart from the above steps, the weight of the eroded sediments was evaluated after each interruption by weighting the dried soil sample. The surface runoff along with the transported soil was captured in a measuring cylinder. The methodological procedure for processing the measured data during the quasi-continuous 60-minute rainfall simulation is shown in Fig. 2.

Table 1. Overview of the basic parameters and initial conditions for both experiments

Exp.	**Length of slope** [m]	**Irrigated area** [m^2]	**Slope** [%]	**Initial soil moisture** [%]	**Rainfall intensity** [$mm\ min^{-1}$]	**Number of simulations** [-]	**Total duration** [min]	**Volume of simulated rainfall** [l]
A	0.25	0.0625	20	4.8	2.7	5	60	10.25
B	0.50	0.1250	20	4.2	2.7	5	60	20.5

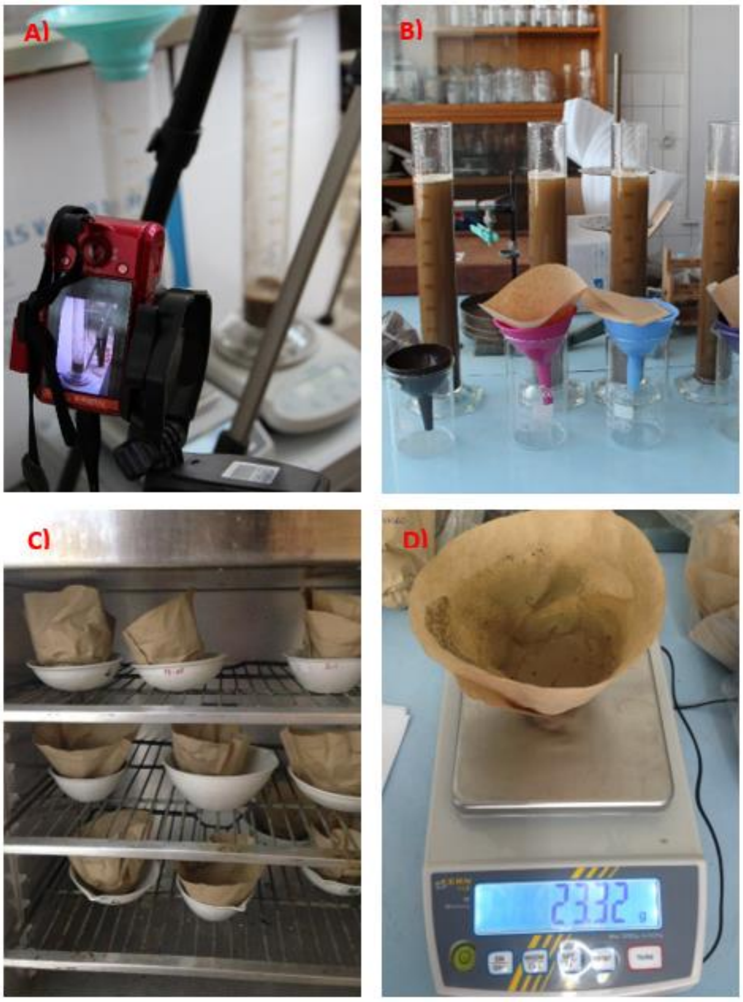


Fig. 2. The procedure of processing the measured surface runoff and eroded soil particles during the quasi-continuous 60-minute rainfall simulation: A) video recording of runoff generation and transport of soil particles; B) filtration of soil particles (sediments) from the measuring cylinders; C) drying of sediments; and D) weighting of sediments.

Results and discussion

For both the A and B experiments, the "time to runoff" (the time before the occurrence of any surface runoff) and its course over the whole experiment (15-second intervals) is shown in Fig. 3. The results showed that in the case of the experiment A with only one rainfall simulator used, the surface runoff appeared 251 s after the beginning of the experiment, while in case of experiment B, with two rainfall simulators arranged in a series, the time to runoff was reduced to 160 s. After the forced interruption of the rainfall simulation (after each 12-min simulation) due to the limitation of the amount of water in the simulator reservoir and its replenishment in both experiments, the surface runoff generation was resumed within 30 s (runs 2–5 of the 12–min simulation). The slope length of the irrigated area had an effect on the course and volume of the surface runoff. For experiment A (slope length 0.25 m), it can be seen that after each interruption at a time when the soil was already saturated, the surface runoff volume oscillated at an interval of 30–40 ml per every 15 s. For a slope length of 0.5 m (experiment B), it occurred in an interval of 60–80 ml per every 15 s, except for the first simulation. Thus, in general, it can be argued that once the soil becomes saturated and small erosion furrows are formed, the surface runoff volume becomes stable (the surface runoff becomes uniform) and varies within a certain range (the interval is also dependent on the amount of eroded soil, as this increases the volume of water in the measuring cylinder). The volume of the surface runoff mainly depends on the size of the irrigated area and on the intensity of the rainfall event (here constant in the all experiments).

A set of experimental parameters was collected within each 12-minute simulation to evaluate the dynamics of the surface runoff generation process, infiltration, and soil loss. Moreover, continuous monitoring of the soil moisture was also conducted. Table 2 gives an overview of the data obtained, which describes the erosion-transport processes within both experiments. The total surface runoff volume during the quasi-continuous rainfall simulation (intermittent 12-minute simulations) stabilized after the formation of small erosion furrows in the irrigated area and after the soil became saturated (during the second run of the simulation); it was stable during the remaining simulations. In both experiments, an increased volume of surface runoff was recorded in the second simulation run compared to the first simulation run. The probable reason is that the surface runoff volume was measured together with the transported sediment. The surface runoff stabilized for experiment A (simulation run 2–5) at 1.5–1.7 l per 12 min and at 2.8–3.3 l per 12 min for experiment B. The ratio of infiltration versus surface runoff was as expected. In the start for experiment A the infiltration was 51% from artificial the precipitation and decreased to 17% in the fifth simulation run (the start time to the surface runoff was 251 s). In the case of the double simulators in the series, the infiltration was 65% in the first simulation run and was decreased in the last simulation run to 19% (the start time to the surface runoff was 160 s). The highest soil loss values were measured for both experiments during the second simulation run (59 g for experiment A and 123 g for experiment B), which only confirms that from this simulation run onwards, the surface runoff increased significantly; moreover, small erosion furrows started to form, increasing the transport capacity of the irrigated area. Table 2 also shows that the concentration of the soil sediment as a component of the surface runoff decreased over time.

The time course of the soil moisture over the two experiments, which was measured by a soil moisture

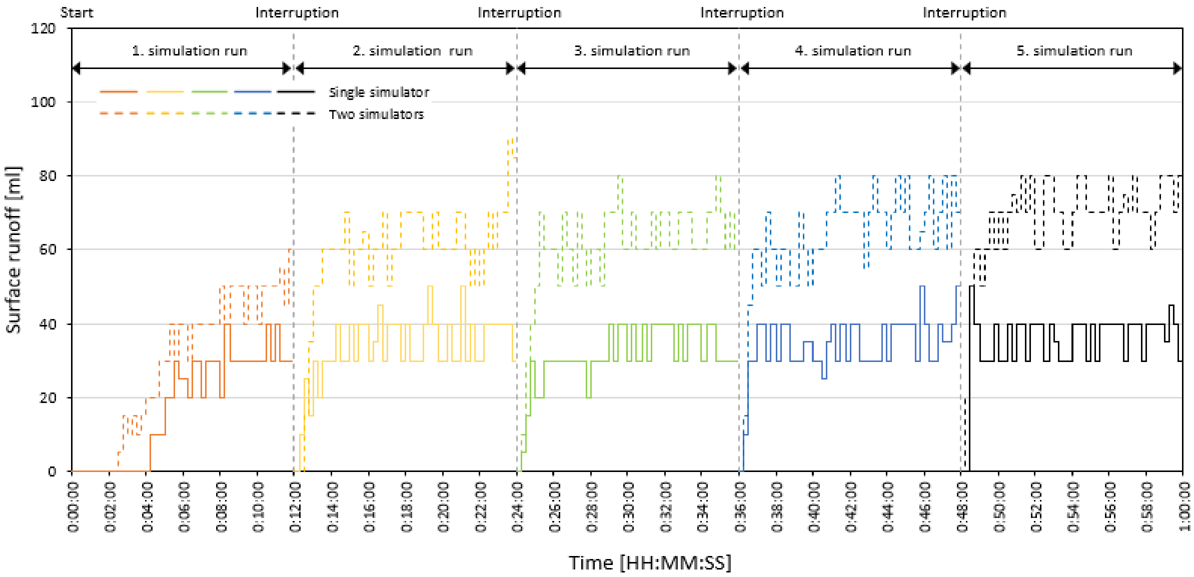


Fig. 3. Time course of the surface runoff under similar initial conditions: Experiment A (Single rainfall simulator), Experiment B (Two rainfall simulators).

sensor placed 5 cm under the surface in the lower part of the irrigated area, is shown in Fig. 4. In both experiments, the soil moisture began to increase at the end of the second simulation run (including a significant increase during the third simulation run), settling at around 45% of the soil moisture (experiment A) and 40% for experiment B by the fifth simulation run.

A comparison of the two experiments in terms of the size of the area on the surface runoff and soil particle transport for the quasi-continuous 60-minute rainfall event with an intensity of 2.7 mm min^{-1} is presented in Figs. 5–6.

Although the area and the length of the slope of the irrigated area in experiment B were two times greater than those in experiment A, the difference in the cumulative volumes of the surface runoff is different for the two experiments. It has been observed that with the increased time of the simulation, the surface of the irrigated area becomes more and more eroded, resulting in the creation of small erosion furrows and thereby causing an increased generation of surface runoff. Over time, the cumulative volume of the surface runoff in experiment B was almost twice as large as that in experiment A, which we believe was caused by the larger dynamic (kinetic energy) of the surface runoff in experiment B. Fig. 6 shows that the slope length significantly affects the transport of soil particles (sediment), as the mass of the dried sediment sample in each simulation run in experiment B significantly exceeds the values obtained in experiment A. The amount of sediment in the experiment with two simulators, and thus a longer slope length, increased by approximately 50–70 g during each 12-minute simulation run compared to the single simulator experiment. A possible explanation is that after reaching

Table 2. **Measured characteristics of the 12-minute simulations for both experiments: Experiment A (Single rainfall simulator), Experiment B (Two rainfall simulators)**

Exp.	Simulation run No. [-]	Volume of simulated rainfall [l]	Volume of surface runoff [l]	Infiltration vs. Surface runoff [%]	Soil moisture [%]	Sediment soil mass [g]	Concentration soil sediment [g l^{-1}]
A	1.	2.05	1.0	51% (49%)	4.8–4.9	36	36
	2.	2.05	1.6	22% (78%)	4.9–5.0	59	37
	3.	2.05	1.5	27% (73%)	5.0–22.7	31	21
	4.	2.05	1.6	22% (78%)	22.7–41.4	35	21
	5.	2.05	1.7	17% (83%)	41.4–45.1	32	19
B	1.	4.1	1.4	66% (34%)	4.2–4.3	103	74
	2.	4.1	2.8	31% (69%)	4.3–9.4	123	44
	3.	4.1	2.9	29% (71%)	9.4–34.1	95	33
	4.	4.1	3.0	25% (75%)	34.1–39.3	101	33
	5.	4.1	3.3	19% (81%)	39.3–40.0	82	25

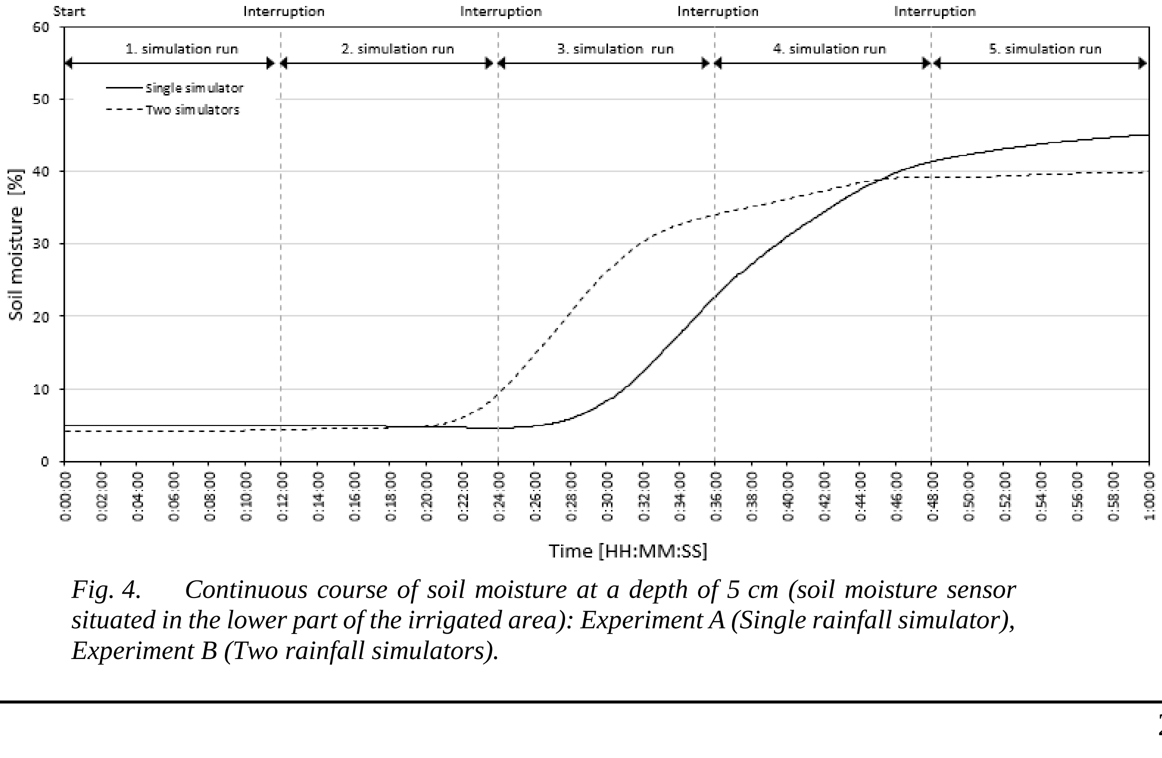


Fig. 4. Continuous course of soil moisture at a depth of 5 cm (soil moisture sensor situated in the lower part of the irrigated area): Experiment A (Single rainfall simulator), Experiment B (Two rainfall simulators).

the point of saturation of the rainfall area, there was approximately the same ratio of eroded sediments between the simulation runs.

A summary of the data obtained and a basic statistical comparison of the measured rainfall-runoff and transport parameters of the two experiments is presented in Table 3. The results presented in the table show the increase in the volume of the surface runoff during the quasi-continuous 60-minute rainfall simulation (intermittent after 12 min) in the two-simulator experiment was 81% (+6 l) higher compared to the one-simulator experiment; the sediment mass after drying was 161% (+311 g) higher; the sediment concentration in the surface runoff was 44% (+11 g l^{-1}) higher; and the infiltration values were 21% higher.

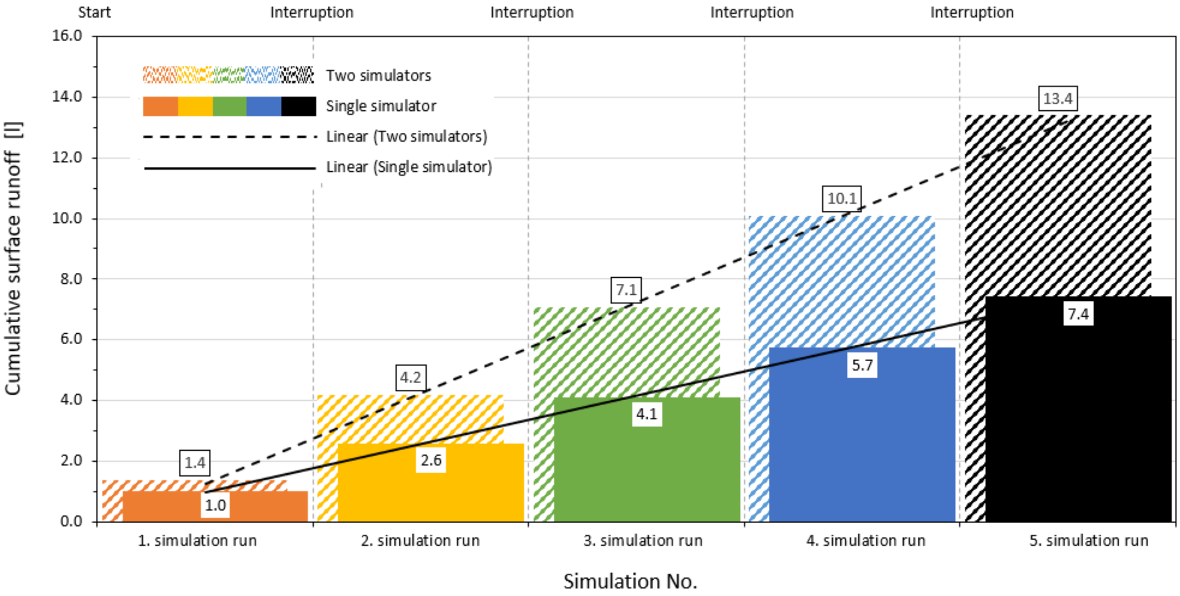


Fig. 5. Comparison of the cumulative surface runoff from a quasi-continuous 60-minute rainfall event (intermittent rainfall every 12 min) with an intensity of 2.7 mm min^{-1}: Experiment A (Single rainfall simulator), Experiment B (Two rainfall simulators).

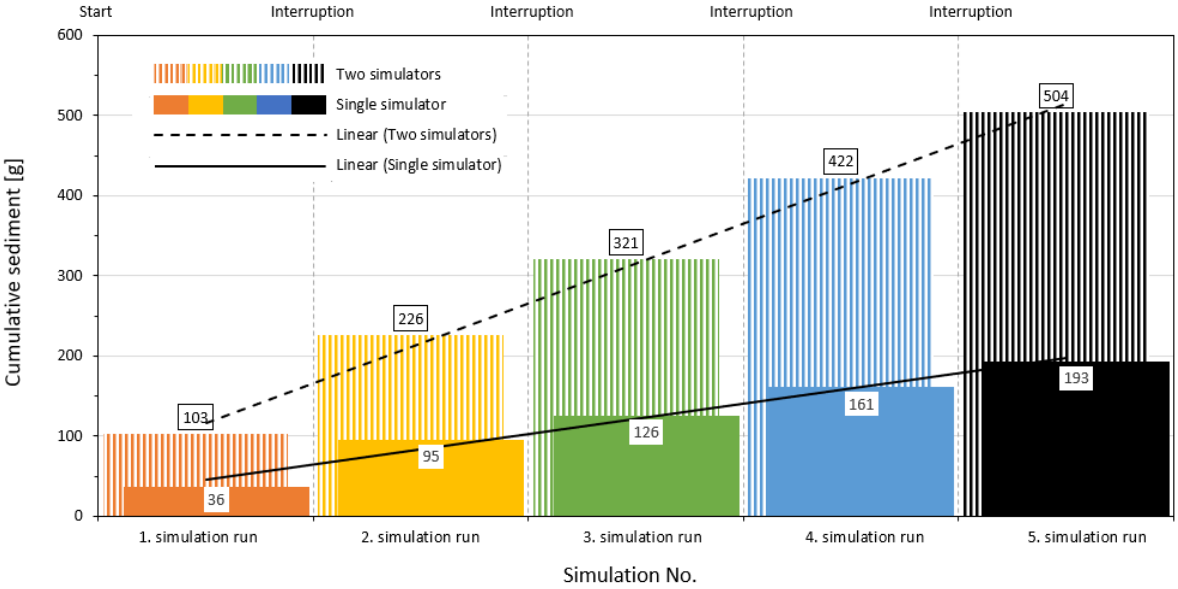


Fig. 6. Comparison of the cumulative soil loss (weight of the sediment sample after drying) from a quasi-continuous 60-minute rainfall event (intermittent rainfall every 12 min) with an intensity of 2.7 mm min^{-1}: Experiment A (Single rainfall simulator), Experiment B (Two rainfall simulators).

Table 3. **Summary of the cumulative rainfall-runoff parameters: Experiment A (Single rainfall simulator), Experiment B (Two rainfall simulators)**

Experiment	Cumulative surface runoff [l]	Cumulative sediments [g]	Concentration soil sediment [g l^{-1}]	Infiltration [%]
A	7.4	193	26.1	28
B	13.4	504	37.6	34
% increase	**+ 81%**	**+ 161%**	**+ 44%**	**+ 21%**

Conclusion

This study presents the results from two laboratory experiments investigating the effect of the slope length and irrigated area on the temporal distribution and volume of generated surface runoff and eroded soil material using compact and transportable rainfall simulators. The experimental measurements of the surface runoff generation were made using a rainfall simulator (irrigated area 0.0625 m^2) and two rainfall simulators connected in a series (irrigated area 0.125 m^2) on a disturbed soil sample subjected to a quasi-continuous 60-minute simulated rainfall event with an intensity of 2.7 mm min^{-1}. In addition to the volume and dynamics of the surface runoff generation, the sediment mass and the fraction of the infiltrated water from the surface runoff were measured under the same initial conditions for both experiments.

The results of the study showed that there is a direct relationship between the irrigated area and the volume of the surface runoff, as well as the slope length and the weight of the soil particles (sediments) transported. The surface runoff started to form about one-third of the time earlier in the experiment with the greater irrigated area compared to the experiment with half of the slope length. After the soil became saturated with water and the first small erosion furrows formed in the irrigated area (after a 12-minute rainfall simulation during both experiments), the volume of the surface runoff stabilized and became roughly uniform. The highest values of the transported soil particles were observed in both experiments between 12–24 min of the rainfall simulation, when the increase in the volume of the surface runoff was most significant.

Moreover, as the duration of the experiment progressed, the extent of the soil erosion increased together with the increased volume of generated surface runoff, especially in the case of the experiment with two rainfall simulators involved. The reason for this was the twofold slope length and irrigated area in experiment B compared to experiment A. Thus, the slope length significantly affects the transport of soil particles (sediment), as the mass of the sediment sample after drying in each simulation run in the two-simulator experiment significantly exceeded the values obtained in the one-simulator experiment. The concentration of the soil sediment as a component of surface runoff decreased with the increasing duration of the simulation in both experiments. In addition, the soil moisture began to increase after 20 minutes into the simulations in both experiments, followed by a significant step increase, with a plateau of around 45 min.

The study confirmed that the area of the experimental plot played an important role in the process of generating the surface runoff and soil erosion and transport (similarly as in studies e.g., Mayerhofer et al., 2017). Based on the results, not only could improvements be made for future experiments, but also unique information could be obtained that could be used in the process of the calibration and validation of mathematical models simulating soil transport and surface runoff. The results from this type of experiment could be used in the process of calibrating models when estimating their parameters and defining the initial conditions (initial soil moisture, time to runoff, surface roughness, runoff coefficient), as well as for validating models such as measuring the volume of the surface runoff and weight of sediments. This study is a good reference point for initiating or continuing future experiments related to rainfall-runoff and erosion-transport processes.

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