Evaluation of Surface Runoff Generation Processes Using a Rainfall Simulator: A Small Scale Laboratory Experiment

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Abstract. Nowadays, rainfall simulators are being used by many researchers in field or laboratory experiments. The main objective of most of these experiments is to better understand the underlying runoff generation processes, and to use the results in the process of calibration and validation of hydrological models. Many research groups have assembled their own rainfall simulators, which comply with their understanding of rainfall processes, and the requirements of their experiments. Most often, the existing rainfall simulators differ mainly in the size of the irrigated area, and the way they generate rain drops. They can be characterized by the accuracy, with which they produce a rainfall of a given intensity, the size of the irrigated area, and the rain drop generating mechanism. Rainfall simulation experiments can provide valuable information about the genesis of surface runoff, infiltration of water into soil and rainfall erodibility. Apart from the impact of physical properties of soil, its moisture and compaction on the generation of surface runoff and the amount of eroded particles, some studies also investigate the impact of vegetation cover of the whole area of interest. In this study, the rainfall simulator was used to simulate the impact of the slope gradient of the irrigated area on the amount of generated runoff and sediment yield. In order to eliminate the impact of external factors and to improve the reproducibility of the initial conditions, the experiments were conducted in laboratory conditions. The laboratory experiments were carried out using a commercial rainfall simulator, which was connected to an external peristaltic pump. The pump maintained a constant and adjustable inflow of water, which enabled to overcome the maximum volume of simulated precipitation of 2.3 l, given by the construction of the rainfall simulator, while maintaining constant characteristics of the simulated precipitation. In this study a 12-minute rainfall with a constant intensity of 5 mm/min was used to irrigate a corrupted soil sample. The experiment was undertaken for several different slopes, under the condition of no vegetation cover. The results of the rainfall simulation experiment complied with the expectations of a strong relationship between the slope gradient, and the amount of surface runoff generated. The experiments with higher slope gradients were characterised by larger volumes of surface runoff generated, and by shorter times after which it occurred. The experiments with rainfall simulators in both laboratory and field conditions play an important role in better understanding of runoff generation processes. The results of such small scale experiments could be used to estimate some of the parameters of complex hydrological models, which are used to model rainfall-runoff and erosion processes at catchment scale.

1. Introduction

Nowadays, the rainfall simulators are still being used as a tool to study interactions between rain and soil. From a hydrological point of view, it is applied mainly in areas dealing with soil erosion, the generation of surface runoff and infiltration of water into the soil horizons (see e.g., [1-3]). They have even been used in the studies dealing with the landslides and the impact of land management practices on a hydrological response. Rainfall simulators found their application not only in field measurements, but in many cases even in laboratory experiments, where the impact of weather conditions is undesirable [4].

In this study a 12-minute continuous rainfall of an intensity of 5 mm/min was used to assess the impact of various extreme slope gradients on the amount of surface runoff. The experiments were carried out in laboratory conditions on a corrupted soil sample. It has to be noted here that by removing the soil from its natural location, the connections between groundwater, flora and fauna is lost. Despite some of the disadvantages of the laboratory experiments they still play an important role in the research of the generation of surface runoff or erosion processes. One of the biggest advantages of this type of experiments is their reproducibility under constant external conditions and the ability to monitor multiple variables linked with the generation of surface runoff. In this study multiple experiments were undertaken under the condition of constant initial soil moisture. A major innovation in this study was the adjustment of the rainfall simulator, when the water used to generate rain drops was pumped into the simulator reservoir using a peristaltic pump. This solution removed the limitation of a maximum volume of used water, given by the volume of the cylindrical reservoir. This experiment supplemented the experiments undertaken on the same soil sample in 2016, as well as field measurements carried out within the FP7 RECARE project. The fact that the experiments were undertaken in laboratory conditions enabled to eliminate the impact of multiple factors such as: wind, solar radiation, soil moisture, and the state of the soil surface [5].

2. Material and methods

Rainfall simulators can be divided into two categories drop-type and nozzle-type, based on the way they generate rain drops. The biggest advantage of the drop-type rainfall simulators is that they enable to generate homogenous rain drops in the terms of their size and kinetic energy at the time they touch ground [2]. On the other side the biggest disadvantage of this type of rainfall simulators is that the distribution of the rain drop sizes does not correspond with the distribution of real rain drops. In addition, the kinetic energy of the generated rain drops is far from that of real ones, unless they fall from a height of tens of meters. On the other hand, the nozzle-type rainfall simulators generate rain drops of sizes between 0 – 7 mm, which corresponds to distribution of rain drop sizes in real conditions. A big disadvantage of this type of rainfall simulators is that they enable to generate rainfall with intensities much higher than those observed in real conditions. In order to account for this issue, their nozzles are in many cases non-stationary and can be moved from one side of the irrigated area to another [4].

The rainfall simulators could also be classified based on their size. The small and portable rainfall simulators are very popular in a small scale experiments, which goal is to obtain information about some of the basic soil properties. The bigger and more complex rainfall simulators are almost exclusively nozzle-type simulators, which enable to investigate the amount of surface runoff and eroded soil particles in a larger scale [4].

2.1. Rainfall simulator

In this study a small portable rainfall simulator is used (of a Dutch company Eijkelkamp). This rainfall simulator comprises of the following parts:

- cylindrical reservoir and membrane with capillaries,
- adjustable stand,
- aluminium frame.

The membrane with the capillaries is formed of calibrated cylindrical reservoir of a capacity of approximately 2300 ml, which is in contact with the membrane. The 49 capillaries generate rain drops which then fall to the test plot. The intensity of the simulated rain could be adjusted by moving the aeration tube upwards (higher intensity) or downwards (lower intensity). The adjustable aluminum frame should be set to the mean height of 0.4 m. The surface are of the test plot is 0.0625 m^2. Prior to the experiment it is necessary to check, whether the stainless steel ground frame is properly fixed on the soil using four large nails, and whether it prevents any lateral movement of water from the test plot to the surrounding soil.

Apart from a given area of the test plot a small capacity of the cylindrical reservoir is another limiting factor. In order to increase the time of the experiment the rainfall simulator was connected to the external source of water. The water was pumped into the reservoir using a peristaltic pump, which enabled to maintain a constant pressure on the capillaries (see Figure 1). By adjusting the flow rate of water into the reservoir it was possible to change the pressure on the capillaries, and thus the rainfall intensity.

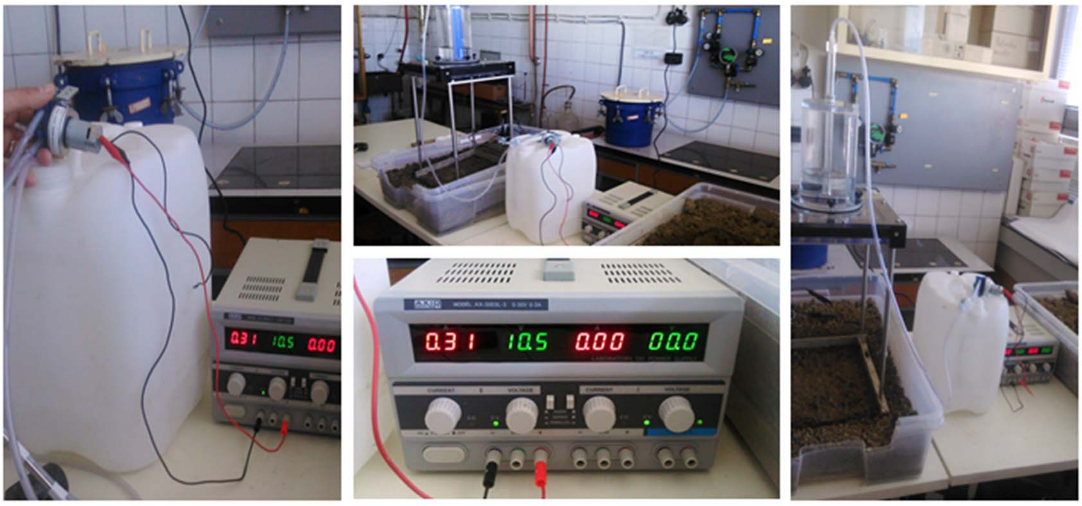


Figure 1. The laboratory equipment used in the experiment. The rainfall simulator was connected to the external source of water, pumped into the reservoir using a peristaltic pump

2.2. Test procedure in laboratory conditions

In 2016 and 2017 several rainfall simulation experiments were undertaken in laboratory conditions to supplement the results of the filed rainfall simulations in Turá Lúka (see [7]). It was a simulation of a 12-minute rain at about 5 mm/min, interrupted after every 3 minutes. During the experiment the following variables were measured: soil moisture, surface runoff volume, and the weight of the eroded soil particles. The reason for interrupting the experiment was that after approximately 5 min it was necessary to refill the 2.3 l cylindrical reservoir. After connecting the rainfall simulator to the external source of water, the maximum time of simulation is given by the ability to provide a sufficient amount of water.

In this study the results of the laboratory experiment, which was undertaken on the same soil sample as in the previous study are presented. As opposed to the forthcoming study a 12-minute continuous rain with and intensity of 5 mm/min is used here. In this study the impact of interrupting the rainfall simulations on the generation of surface runoff was also evaluated. Figure 2 shows a comparison of the volume of generated surface runoff for the rainfall experiment with intermittent and continuous rainfall.

The results show that the biggest difference in the volume of surface runoff between intermittent and continuous rainfall could be observed at the end of the second 3-minute interval. This is caused by the fact that after the first 3-minute interval the cylindrical reservoir had to be refilled in the case of the simulation with intermittent rainfall. During this process the water could infiltrate from the surface layers into the deeper soil horizons. After the experiment started again some of the water was needed to create conditions for surface runoff. Figure 2 also shows that at the end of the third 3-minute interval (after 2 refills) the observed surface runoff was identical in both experiments. This clearly demonstrates that after 9 minutes, from the beginning of the experiment, the soil saturation was sufficient to immediately create surface runoff.

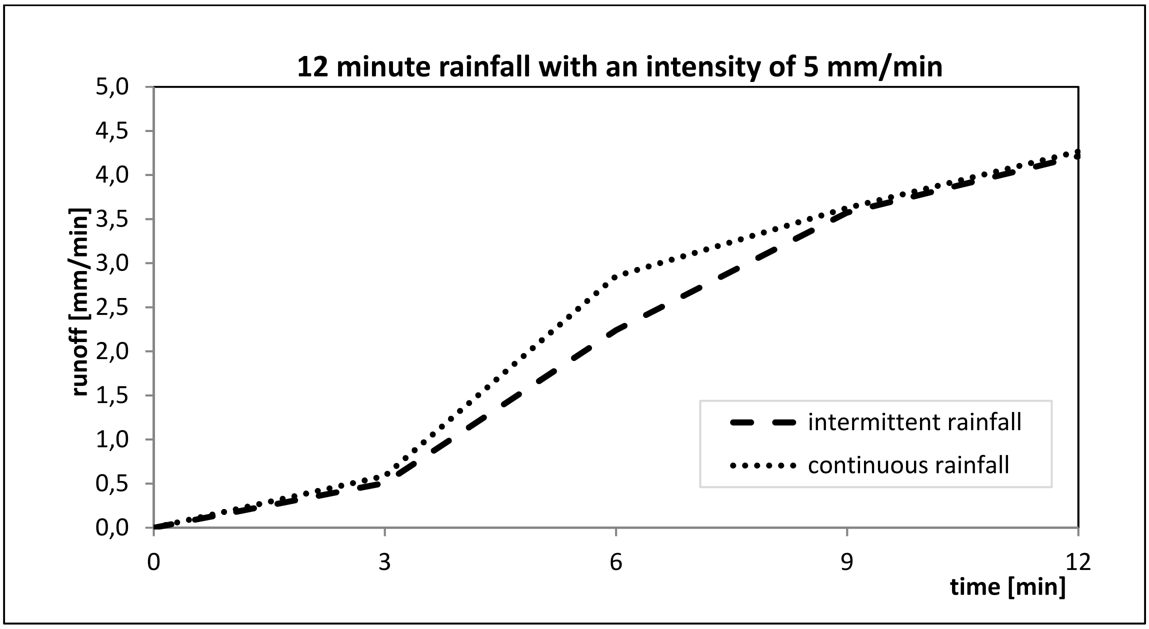


Figure 2. Comparison of a 12-minute intermittent and continuous rainfall evaluated after every 3 minutes

2.3. Laboratory experiments

The comparison between simulations with intermittent and continuous rainfall shown in the previous section led to the changes in the experiment. The experiment was expanded to include the following points:

- simulations of a 12-minute continuous rainfall and the recording of the volume of surface runoff after every 3-minute interval,
- continuous measurements of soil moisture,
- focus on the extreme slope gradients of the test plot.

This experiment enables to monitor the course of soil moisture during the whole time of the experiment under the extreme slope gradients (in the previous experiment slopes between 5-16% were used). In the experiment the surface runoff volume and the corresponding weight of eroded soil particles were recorded after each 3 minutes.

The soil moisture was monitored in the depth of 5 cm at two locations within the test plot. The two sensors were located in the axis of the test plot in the middle of the first and last third of its length. A datalogger *MicroLog V3A* together with two soil moisture sensors *WaterScout SM100* was used to collect soil moisture data in a 3-second time interval (see Figure 3).

Figure 3. Location of the soil moisture sensors in the test plot

Figure 4 shows the course of the soil moisture values during one of the experiments with a 12-minute duration of the simulated rainfall and an intensity of 5 mm/min. The results show that the steepest increase in the soil moisture could be observed during the first 3-4 minutes of the experiment. It is also possible to see that the sensor which was situated in the bottom part of the test plot recorded higher values of soil moisture in the early stages of the experiment.

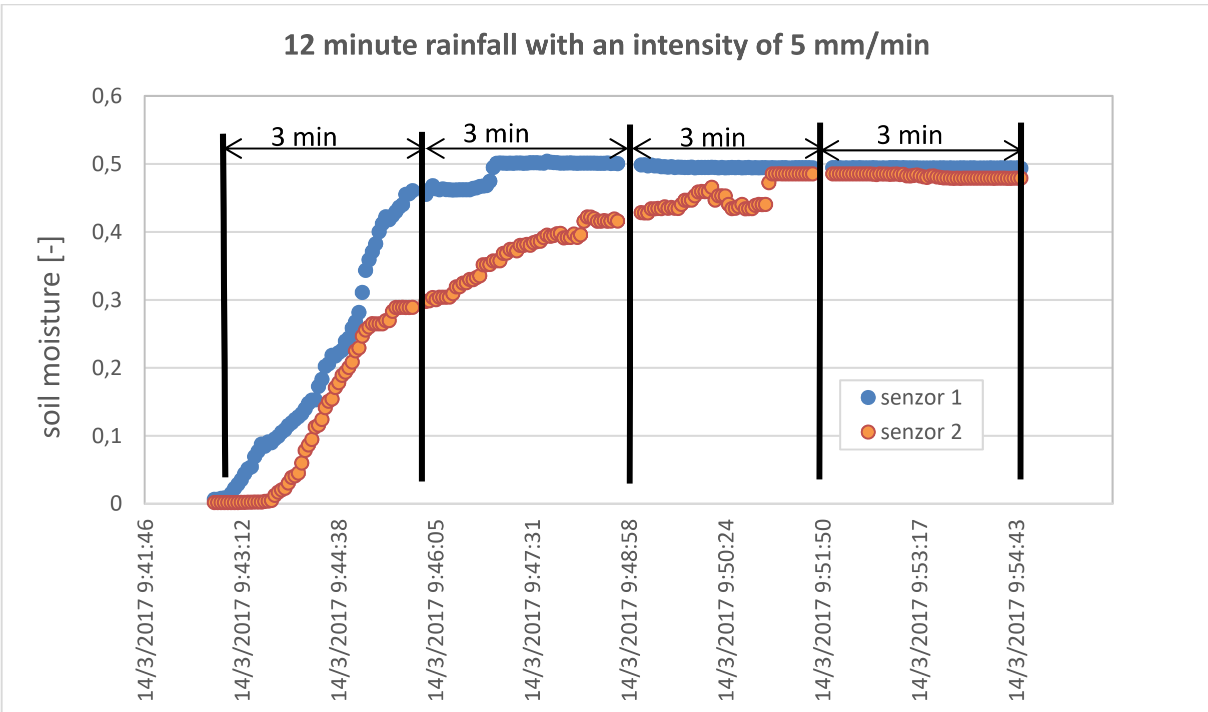


Figure 4. Soil moisture record during the 12-minute rainfall simulation in a depth of 5 mm

3. Results and discussions

Table 1 shows some of the characteristics and results of the individual experiments. In the first step a runoff coefficient was calculated as a ratio between the volume of surface runoff and the total volume of the simulated rainfall. This coefficient was calculated for each 3-minute interval, with a linear course between the individual measurements.

Table 1. Description and results of the individual rainfall experiments.

Date	Slope [%]	Moisture before [%]	Moisture after [%]	Runoff volume [ml]				Sediments [g]
				3 min	6 min	9 min	12 min	
05.05.2017	30	5	46	110.0	590.0	690.0	790.0	162.1
10.05.2017	17	3	42	47.5	340.0	672.5	770.0	108.3
29.05.2017	13	4	46	0.0	115.0	485.0	630.0	106.0

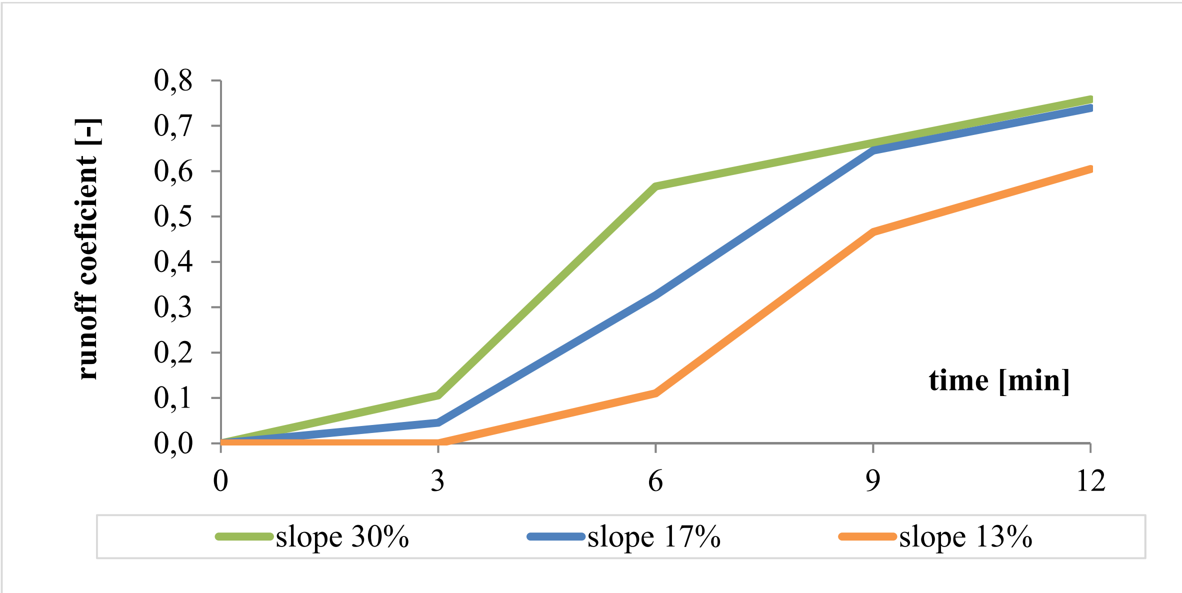
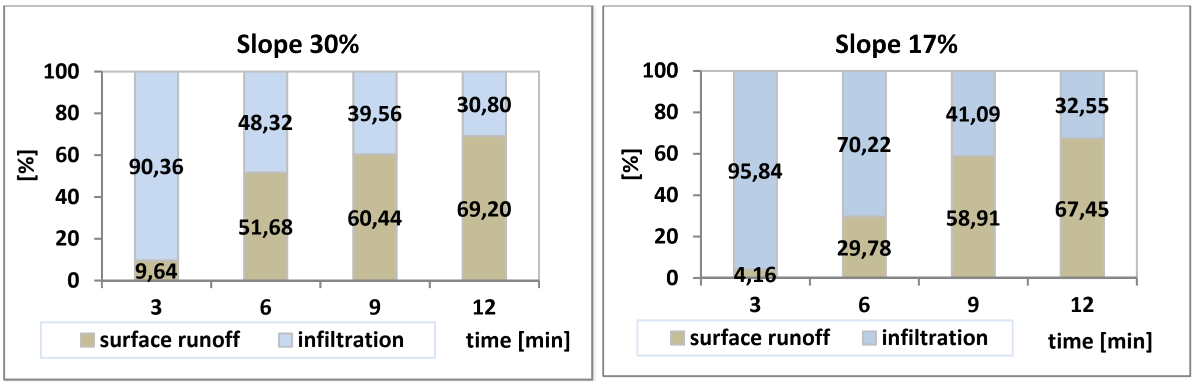
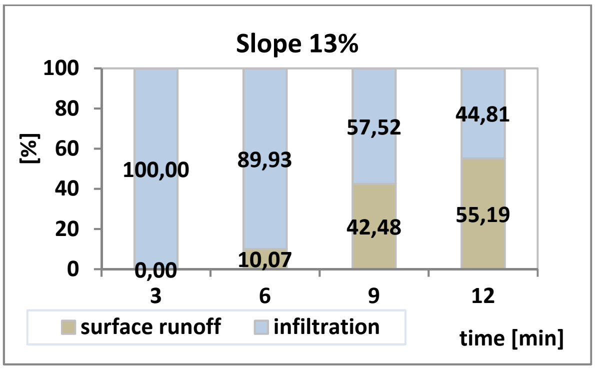


Figure 5. The runoff coefficient with soil moisture (in %)

Based on the known volume of water used in the rainfall experiment and the volume of surface runoff it was also possible to assess the volume of water which infiltrated into the soil. Figure 6 shows the percentage of the volume of surface runoff and infiltrated water from the total volume of water used in the experiment. The results are shown for all three slope gradients and 3-minute time intervals (3, 6, 9 and 12).



a) b)



c)

Figure 6. a-c) The percentage of the surface runoff and infiltration for the simulated rainfall

The results show, that in the case of the experiment with the slope gradient of 13% the surface runoff occurred after the first 3-minute interval. At the end of this experiment the surface runoff constituted for as much as 55% from the total volume. In the case of the experiments with the slope gradients of 17% and 30%, the surface runoff occurred after the first minute. After the first 10 minutes the surface runoff was identical in both experiments. In the case of the experiment with the most extreme slope gradient more than 50% of the rainfall transformed into the form of surface runoff after the first 3-minute interval (see Figure 6).

The surface runoff enabled to transport some of the soil particles, which were eroded by the falling droplets of water. The weight of these particles was also evaluated, when the intercepted surface runoff was filtered through a paper filter, which was subsequently dried in a laboratory dryer. The weight of the eroded material (without the weight of the filter) was measured by laboratory scales. The results are displayed on Figure 7. As expected, the highest sediment yields came from the experiment with the most extreme slope gradient of 30%. Figure 7 also shows that the weight of the sediment was not proportional to the volume of surface runoff, which transported them.

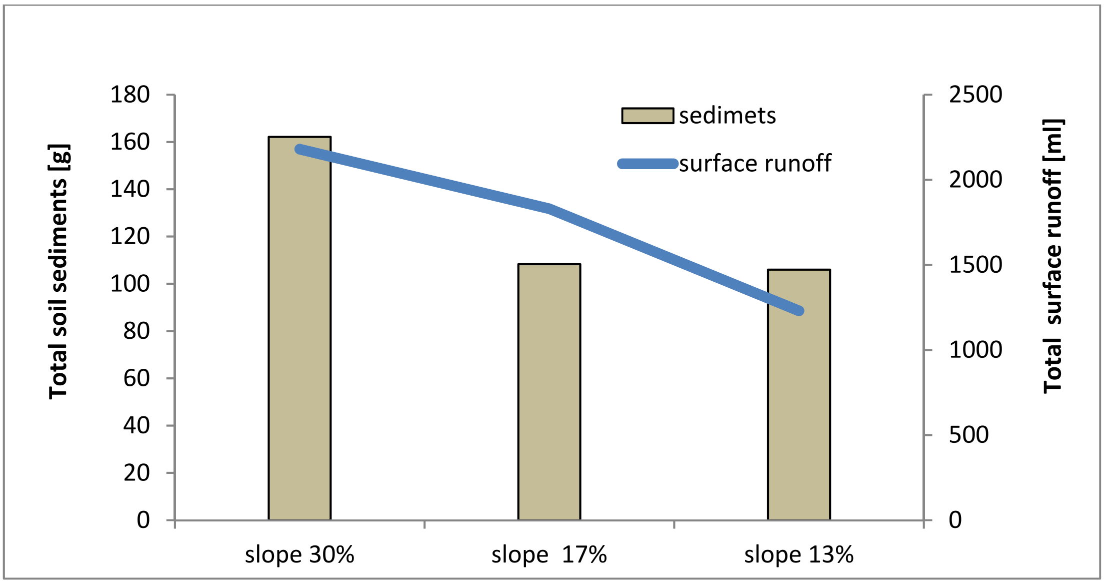


Figure 7. Total soil loss and of surface runoff in the three slopes studied.

4. Conclusions

The rainfall simulators are primarily used to study the genesis of surface runoff, infiltration processes, and an impact of the land management practices on their extent. Nowadays, many research teams, which investigate the problems of water erosion on the hill slopes use portable rainfall generators to estimate some of the parameters of complex erosion models.

In this study a 12-minute continuous rainfall was used to simulate surface runoff from a test soil sample under three different slope gradients (13%, 17% and 30%). The experiment used in this study utilized a new concept, when the rainfall simulator was connected to an external source of water, which was pumped to its cylindrical reservoir using a peristaltic pump. This solution removed the limitation of the original concept of the simulator, when a maximum of 2.3 l of water could be used in the experiment. The experiment was undertaken in laboratory conditions on a bare soil sample with an intensity of the simulated rainfall of 5 mm/min. The surface runoff was collected and later separated from eroded material each 3 minutes. The soil moisture was recorded in a depth of 5 cm at two locations in a 3 s time step. The results of the experiment supplemented the laboratory experiments from 2016 with an intermittent rainfall.

The results confirmed the significant impact of the slope gradient on the generation of surface runoff. The course of the soil moisture throughout the experiment shows, that the highest increase occurs during the first 3-4 minutes. In the experiment with the most extreme slope gradient of 30% as much as 50% of the total rainfall volume represented surface runoff after only the first 3 minutes of the rainfall simulation. The results of this study, together with those from the previous laboratory experiments, will be used to estimate some of the parameters of a complex erosion model.

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