

Effects of rain intensity and initial soil moisture on hydrological responses in laboratory conditions

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A b s t r a c t. Although the possibility of measuring and analysing all parts of the rainfall, infiltration, runoff, and erosion process as a natural hydrologic cycle in field conditions is still one of the more unattainable goals in the hydrological sciences, it can be accomplished in laboratory conditions as a way to understand the whole process. The initial moisture content is one of the most effective factors on soil infiltration, runoff, and erosion responses. The present research was conducted on a 2 m² laboratory plot at a slope of 9% on a typical sandy-loam soil. The effects of the initial soil moisture content on the infiltration, runoff, and erosion processes were studied at four levels of initial soil moisture content (12, 25, 33, and 40 volumetric percentage) and two rainfall intensities (60 and 120 mm h⁻¹). The results showed a significant ($p \leq 0.05$) correlation between rainfall intensity and downstream splash, with $r = 0.87$. The results reflected the theory of hydrological responses, showing significant ($p \leq 0.05$) correlations with $r = -0.93, 0.98, -0.83, 0.88,$ and 0.73 between the initial soil moisture content and the time-to-runoff, runoff coefficient, drainage as a part of the infiltrated water, downstream splash, and total outflow sediment, respectively.

K e y w o r d s: initial soil moisture, sandy loams, rainfall simulation, time-to-runoff, hydrological response

INTRODUCTION

Several interacting factors that control runoff generation determine the hydrological responses of the watershed to rainfall events (Castillo *et al.*, 2003). Understanding the spatial and temporal variations of the main effective parameters on runoff and subsequent erosion, including infiltration, time-to-runoff and runoff coefficient, drainage, erosion and sediment yield, and knowing the critical condi-

tions leading to the production of increased runoff and more sediment is essential for better sediment yield prediction, model development, and land management (Banasik *et al.*, 2012; Hejduk *et al.*, 2006; Kovar *et al.*, 2012; Krajewski *et al.*, 2014; Madeyski and Banasik, 1989; Rejman *et al.*, 2008). However, the measurement and analysis of all parts of the rainfall, infiltration, runoff, and erosion processes, as a natural hydrologic cycle in the field conditions, are some of the more unattainable goals in the hydrological sciences (Boomer *et al.*, 2008; Rejman *et al.*, 1999). To address this deficiency, simulated rainfalls and laboratory erosion plots are used to understand more about the whole process (Bashari *et al.*, 2013; Defersha and Melesse, 2012; Fox and Bryan, 1999; Hawke *et al.*, 2006; Khaledi Darvishan *et al.*, 2014; Watung *et al.*, 1996).

The amount and intensity of rainfall, initial soil moisture, infiltration, drainage, runoff, splash, and erosion are some of the main factors affecting various parts of the hydrological processes. These factors can decrease or increase the risk of runoff and soil erosion, not only through individual effects, but also through both antagonistic and synergistic interactions. Splash, for example, may play a synergistic role in soil erosion by developing the surface seal, which in and of itself leads to a decreased surface infiltration rate and an increased runoff coefficient.

On the one hand, the initial soil moisture content is an important factor that controls the runoff during medium and low intensity storms (Castillo *et al.*, 2003) and rainwash, and differs by 4-5 times in the full range of initial soil

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moisture content, from air-dried to near-saturated levels (Luk, 1985; Luk and Hamilton, 1986). On the other hand, rainfall intensity and erosivity are known to be important factors in controlling the runoff and soil erosion processes (Banasik *et al.*, 2001, 2012; Wischmeier and Smith, 1978). Despite their important roles, the interactions between the effective factors, especially on all of the main variables of hydrologic responses, have rarely been studied. The aim of this study was to determine the interaction between the initial soil moisture content and the rainfall intensity under four levels of soil moisture content.

MATERIALS AND METHODS

The present study was conducted in the Water Centre Laboratory of the Warsaw University of Life Sciences - SGGW in Warsaw, Poland. A S12 MKII Advanced Hydrology Study System with a 2 m² laboratory plot (Armfield, 1998) was used to achieve the study purposes. The rainfall subsystem of S12 MKII was changed to three BEX B3/8S24W nozzles at a height of 2 m above the plot in order to obtain the raindrop size distribution that is as similar as possible to natural raindrop distribution. Two study rainfall intensities of 60 and 120 mm h⁻¹ were simulated using one and two spray nozzles, respectively. Tap water was used to simulate the rainfall. The average diameter of the simulated raindrops was about 1.70 mm, and the kinetic energy of the simulated rainfall was 21.13 J m⁻² mm⁻¹. The spatial distribution of the rainfall intensity was tested by taking measurements of the rain amount at 15 points using small plastic cups over the 2 m² plot area. The collected rain amount data were then used in the Christiansen uniformity formula (Abudi *et al.*, 2012; Battany and Grismer,

2000). The spatial distribution of the rainfall intensity over the study area is shown in Fig. 1. Due to the appropriate uniformity of the rainfall intensity and the relative homogeneity of the prepared soil as well as the time limitations in short sabbatical research, a methodology, including an experimental group without repetition, was considered.

The experiments were conducted on sandy-loam soil (12.6% clay, 30.8% silt, and 56.6% sand) that had a granular structure. The studied soil was taken from the top 0-50 cm layer (Kukal and Sarkar, 2010) of a deforested land, 15 km west of Warsaw, Poland. The particle size distribution of the soil studied by laser diffraction using the Mastersizer 2000 Ver. 5.60 instrument is shown in Fig. 2.

Bulk density, pH, EC, and organic content of the soil 'in situ' were measured as 1.67 g cm⁻³, 6.73, 124 μmohs cm⁻¹, and 2.76%, respectively. The soil was then prepared for laboratory simulation following Kukal and Sarkar method (2011). A 4 mm sieve was used to separate small pebbles after air-drying the soil (Agassi and Bradford, 1999; Defersha *et al.*, 2011). A 5 cm layer of artificial pumice and course sand was used as a subsoil drainage layer with a filter structure (Darboux *et al.*, 2001; Defersha *et al.*, 2011). Finally, the main 7-cm soil layer was placed over the drainage layer in the 2 m² plot. A small hand ruler was then used to increase the bulk density of the soil so the soil was as similar as possible to that in the original field condition.

Two rainfall intensities of 60 and 120 mm h⁻¹ had an optimised duration of 14 min after time-to-runoff. In addition, the treatments involved four initial soil moisture contents of 12 (≈ air dried), 25 (≈ field capacity), 33, and 40 (≈ near saturation) volumetric percentages, with a 9%

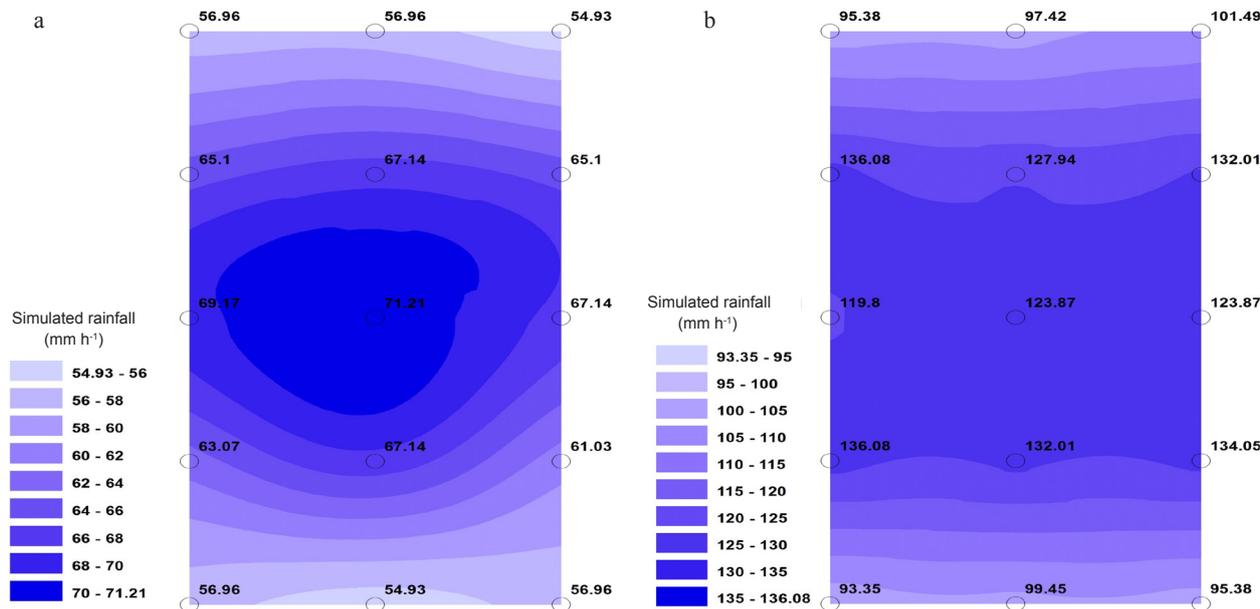


Fig. 1. Spatial distribution of rainfall intensity over the study area: a – 60, b – 120 mm h⁻¹.

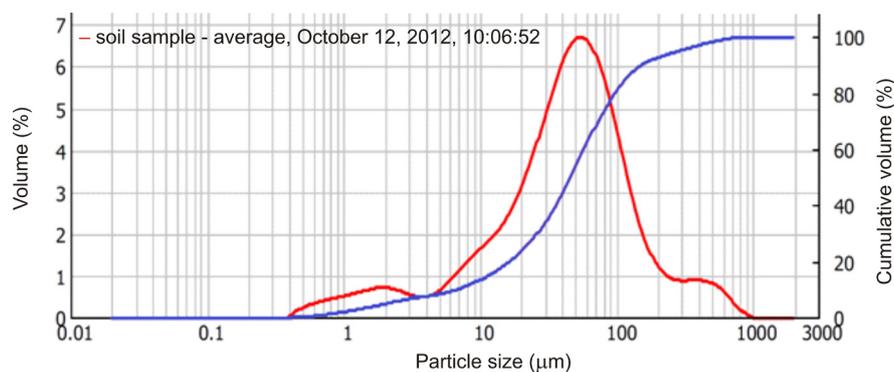


Fig. 2. Particle size distribution of the studied soil.

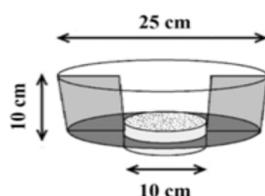


Fig. 3. Designed splash cup.

Table 1. Treatment levels

Treatment code	Rainfall intensity (mm h ⁻¹)	Initial soil moisture (volumetric %)
60-12	60	12
60-25		25
60-33		33
60-40		40
120-12	120	12
120-25		25
120-33		33
120-40		40

slope. The procedure used to determine the four levels of initial soil moisture involved having a relatively complete range of soil moisture, from air dried to near saturation.

In order to measure the amount of splash erosion induced by the raindrops in both the upslope and downslope directions, one splash cup (Khaledi Darvishan *et al.*, 2014; Morgan, 1978) was placed in the centre of the experimental plot. The designed splash cup is shown in Fig. 3.

A total of eight experiments, including two levels of rainfall intensity and four levels of initial soil moisture content (Table 1), were conducted in this study. A 2 cm top layer of the soil was removed and then replaced before each experiment in order to prevent or decrease the effects of the

previous splash and surface seals on the results. The 5 cm layer of remaining soil was given at least one day to reach the balance optimum moisture and remove the unwanted effects of water content for the subsequent experiments. Each level of soil moisture was then obtained through non-erosive small raindrops (spray raindrops), while simultaneously controlling the soil moisture.

The time-to-runoff in each experiment was recorded precisely when the first drops of runoff were found at the outlet of plot. The amount of runoff was then collected in two-minute intervals for 14 min after the time-to-runoff measurement began. The suspended sediment concentration (SSC) for all of the samples and the amount soil particles splashed in both the up and down directions in the splash cup were determined using settling, decantation, and drying methods (Gholami *et al.*, 2013; Walling *et al.*, 2001). In this procedure, the water layer that was over the settled suspended sediment was decanted after a 24 h period for settling the sediment in a sample with a volume of 200 ml. The settled sediment was then washed by distilled water into pre-weighed aluminium foil dishes, before oven drying at 105°C for 24 h (Gholami *et al.*, 2013; Sadeghi *et al.*, 2008).

The total amount of water that was infiltrated into the soil was calculated by subtracting the total amount of runoff from the total amount of rainfall. Next, the infiltration coefficient was calculated as a ratio between the total infiltrated water and the total amount of rainfall. The time-to-drainage was then recorded as the elapsed time from the first drop that flowed from drainage pipe at the end of the plot. The drainage coefficient was calculated as the ratio of the total amounts of drained and infiltrated water.

Determining the effects of rainfall intensity and initial soil moisture content after equalising the various running times for all of the experiments was necessary because of the various time-to-runoff values in order to remove the unwanted effects of rainfall duration. In other words, due to the undeniable effects of rainfall duration on runoff and soil loss, equalisation of running time was necessary in all experiments. The shortest time-to-runoff was added to a value of 14 min to determine the base rainfall duration.

Following this, all other experiments were equalised with the same base rainfall duration by removing some samples from the end of data sets.

The collected data were analyzed using SPSS software (SPSS Inc. Released, 2009) to determine the correlation coefficients and significant effects. The one-way ANOVA test was also used to study the effects of rainfall intensity and initial soil moisture as independent factors on infiltration, runoff, drainage, erosion, and sediment. The collected data for all eight experiments are shown in Table 2. According to Table 2, the runoff threshold and infiltration coefficient were decreased and the runoff coefficient, downstream splash, and total sediment were increased with increasing rain intensity. The Spearman-Rho correlation coefficient was used to estimate the correlations between the quantitative characteristics of runoff, infiltration, and sediment production (Seeger, 2007), which are shown in Table 3. The Duncan test ($\alpha=0.05$) was used to separate the homogenous subsets of initial soil moisture levels, which are shown in Table 4.

RESULTS AND DISCUSSION

The results showed significant ($p \leq 0.05$) correlation coefficients of 0.87 between rainfall intensity and downstream splash (g m^{-2}), and -0.93, 0.98, -0.83, 0.88 and 0.73 between the initial soil moisture content and the time-to-runoff (s), runoff coefficient (%), drainage as a part of infiltrated water (%), downstream splash (g m^{-2}) and total outflow sediment (g), respectively (Table 3). In the case of interactions between rainfall intensity and initial soil moisture, the results showed an antagonistic effect on the

time-to-runoff and the suspended sediment concentration and a synergistic effect on downstream splash and total outflow sediment.

The relationships between the initial soil moisture content and all of the studied parameters, including downstream splash, infiltration coefficient, time-to-runoff, runoff coefficient, time-to-drainage and drainage coefficient, average suspended sediment concentration, and total outflow sediment in the various rainfall intensities are shown in Fig. 4.

Supporting the theory of hydrological processes, the results of this study demonstrated that in the rainfall intensities of 60 and 120 mm h^{-1} , the initial soil moisture content affected the hydrological responses. However, the results of Castillo *et al.* (2003) differ from our findings, as Castillo *et al.* found that the hydrological response after high intensity storms is independent of the initial soil moisture content. Although some differences might exist because of different soil and laboratory conditions, such as drop size distribution and kinetic energy of simulated rainfalls, in the first minutes of the rainfall events, the effect of initial soil moisture content on hydrological responses was significant, even with high rainfall intensities. In addition to some individual effects of rainfall intensity and initial soil moisture content on infiltration, runoff, drainage, and erosion processes, there are some interaction effects that have the ability to increase or decrease the rates of individual effects. The results of separating homogenous subsets of initial soil moisture levels are shown in Table 4. The statistical results regarding the effects of rainfall intensity and initial soil moisture on infiltration, runoff, drainage, erosion, and sediment are shown in Tables 5 and 6, respectively.

Table 2. Collected data for all eight experiments

Treatment code	Total rainfall (mm)	Time-to-runoff (s)	Runoff coefficient (%)	Infiltration coefficient (%)	Time-to-drainage (s)	Drainage coefficient (%)	Downstream splash (g m^{-2})	Up/down splash ratio	Sediment concentration (g l^{-1})	Total sediment (g)
60-12	14.40	285	11.68	88.32	974	27.32	20.55	0.35	1.22	6.04
60-25	14.40	89	53.39	46.61	685	32.18	23.70	0.43	2.30	37.23
60-33	14.40	33	64.42	35.58	634	25.18	31.52	0.43	4.23	78.25
60-40	14.40	24	68.99	31.01	1090	20.49	35.67	0.42	4.09	81.41
120-12	28.47	184	31.05	68.95	565	30.26	64.81	0.40	3.14	59.26
120-25	28.47	64	56.26	43.74	382	25.58	74.61	0.40	3.76	127.40
120-33	28.47	23	68.19	31.81	697	26.34	89.50	0.43	3.94	155.42
120-40	28.47	14	77.56	22.44	1393	16.60	92.99	0.43	4.35	192.53

Table 3. Spearman-Rho correlation coefficients between the studied factors

Factors	Time-to-runoff (s)	Runoff coefficient (%)	Infiltration coefficient (%)	Time-to-drainage (s)	Drainage coefficient (%)	Downstream splash (g m ⁻²)	Up/down splash ratio	Sediment concentration (g l ⁻¹)	Total sediment (g)
Rainfall intensity (mm h ⁻¹)									
Rainfall duration (s)	-0.327	0.218	-0.218	-0.218	-0.109	.873**	0	0.218	0.655
Total rainfall (mm)									
Initial soil moisture (%)	-0.927**	0.976**	-0.976**	0.586	-0.830*	0.488	0.654	0.878**	0.732*
Time-to-runoff (s)	1	-0.976**	0.976**	-0.476	0.762*	-0.738*	-0.702	-0.881**	-0.905**
Runoff coefficient (%)		1	-1.00**	0.524	-0.833*	0.667	0.639	0.905**	0.857**
Infiltration coefficient (%)			1	-0.524	0.833*	-0.667	-0.639	-0.905**	-0.857**
Time-to-drainage (s)				1	-0.476	0.095	0.243	0.333	0.238
Drainage coefficient (%)					1	-0.5	-0.255	-0.881**	-0.714*
Downstream splash (g m ⁻²)						1	0.319	0.619	0.929**
Up/down splash ratio							1	0.6	0.46
Sediment concentration (g l ⁻¹)								1	0.786*
Total sediment (g)									1

Significant at the level: *0.05, ** 0.01.

The results of separating homogenous subsets in the treatment levels showed that, in the case of runoff and infiltration, there are two groups of homogenous initial soil moisture levels: the lowest level (12%) and the other levels (25, 33 and 44%). This means that there is a more significant difference between the initial soil moisture content of 12% and the other studied levels (25, 33 and 44%). Nevertheless, all levels of initial soil moisture were in one subset group when their effects were considered relative to the erosion and sediment parameters.

The effects of rainfall intensity on the downstream splash and total outflow sediment were significant ($p \leq 0.05$ and $p \leq 0.01$ respectively). Regarding the initial soil moisture content, the effects on the infiltration coefficient,

time-to-runoff, and runoff coefficient were also significant ($p \leq 0.01$, $p \leq 0.05$, and $p \leq 0.01$ respectively). The best linear regression models to estimate the studied processes were found using SPSS and are shown in Table 7. Three factors of rainfall intensity, the total rainfall, and the initial soil moisture were considered as independent variables, but the rainfall intensity was then automatically removed with the Enter method of the regression process. The standardized coefficients (β) in linear regression models were used to prioritise the factors affecting the infiltration, runoff, drainage, erosion, and sediment parameters (Vahabi and Mahdian, 2009). According to this method, a higher beta coefficient indicates a greater effect (Table 8).

Table 4. Homogenous subsets of initial soil moisture levels using the Duncan test ($\alpha=0.05$)

Effective factor = initial soil moisture	Homogenous subsets	
	1	2
Infiltration coefficient (%)	25, 33, 40	12
Time-to-runoff (s)	25, 33, 40	12
Runoff coefficient (%)	12	25, 33, 40
Time-to-drainage (s)	12, 25, 33	12, 33, 40
Drainage coefficient (%)	33, 40	12, 25, 33
Downstream splash (g m ⁻²)	12, 25, 33, 40	–
Up/down splash ratio	12, 25, 33, 40	–
Average suspended sediment concentration (g l ⁻¹)	12, 25, 33, 40	–
Total outflow sediment (g)	12, 25, 33, 40	–

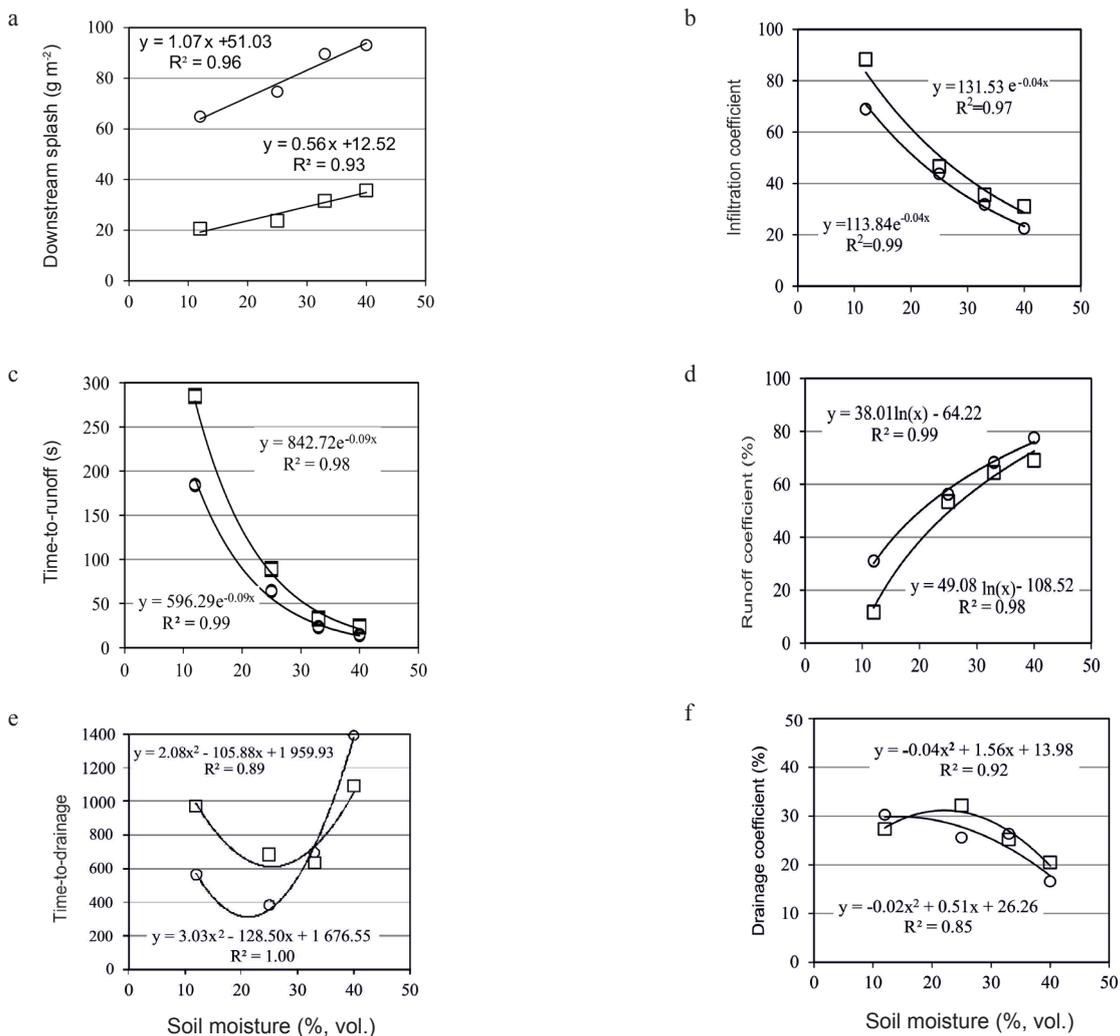


Fig. 4. Relationship between initial soil moisture and: a – downstream splash, b – infiltration coefficient, c – time-to-runoff, d – runoff coefficient, e – time-to-drainage, f – drainage coefficient, g – average sediment concentration, h – total outflow sediment; for rainfall intensity of 60 mm h⁻¹ (squares) and 120 mm h⁻¹ (circles).

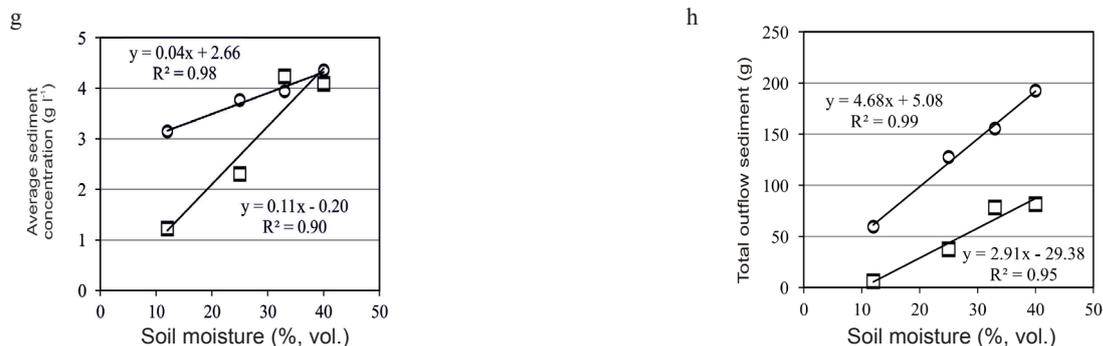


Fig. 4. Continuation.

Table 5. Results of the one-way ANOVA test to determine the effects of rainfall intensity on infiltration, runoff, drainage, erosion, and sediment

Hydrological responses	Sum of squares	Degrees of freedom	F-ratio	Significance of F
Infiltration coefficient (%)	149.47	1	0.275	0.619
Time-to-runoff (s)	2 664.50	1	0.255	0.632
Runoff coefficient (%)	149.47	1	0.275	0.619
Time-to-drainage (s)	14 964.50	1	0.123	0.738
Drainage coefficient (%)	5.10	1	0.179	0.687
Downstream splash (g m^{-2})	5 537.20	1	50.110	0.000
Up/down splash ratio	0.00	1	0.126	0.735
Average suspended sediment concentration (g l^{-1})	1.40	1	1.183	0.318
Total outflow sediment (g)	13 751.45	1	6.161	0.048

Table 6. Results of the one-way ANOVA test to determine the effects of initial soil moisture on infiltration, runoff, drainage, erosion, and sediment

Hydrological responses	Sum of squares	Degrees of freedom	F-ratio	Significance of F
Infiltration coefficient (%)	3 177.30	3	17.985	0.009
Time-to-runoff (s)	59 893.00	3	14.485	0.013
Runoff coefficient (%)	3 177.30	3	17.985	0.009
Time-to-drainage (s)	569 880.00	3	4.282	0.097
Drainage coefficient (%)	141.37	3	5.489	0.067
Downstream splash (g m^{-2})	601.18	3	0.143	0.929
Up/down splash ratio	0.00	3	2.848	0.169
Average suspended sediment concentration (g l^{-1})	5.53	3	2.470	0.201
Total outflow sediment (g)	12 510.30	3	1.140	0.434

Table 7. The best linear regression models to estimate the studied parameters

Models	R ²	Adj. R ²	Std. error of estimate
Infiltration coefficient = -1.876 IniSoilM - 0.614 TotRain + 110.823	0.937	0.912	6.557
Time-to-runoff = -7.932 IniSoilM - 2.594 TotRain + 363.233	0.874	0.823	40.639
Runoff coefficient = 1.876 IniSoilM + 0.614 TotRain - 10.823	0.937	0.912	6.557
Time-to-drainage = 13.667 IniSoilM - 6.148 TotRain + 558.624	0.236	- 0.069	337.811
Drainage coefficient = -0.335 IniSoilM - 0.114 TotRain + 37.133	0.581	0.414	3.836
Downstream splash = 0.814 IniSoilM + 3.740 TotRain - 48.379	0.986	0.980	4.220
Up/down splash ratio = 0.002 IniSoilM + 0.001 TotRain + 0.347	0.597	0.436	0.021
SSC = 0.087 IniSoilM + 0.060 TotRain - 0.047	0.786	0.701	0.603
Total sediment = 3.794 IniSoilM + 5.893 TotRain - 138.471	0.966	0.952	13.604

IniSoilM – initial soil moisture (%), TotRain – total rainfall (mm).

According to Table 8, the effects of the initial soil moisture on infiltration, runoff, and drainage parameters were more significant than the effects of rainfall in terms of downstream splash and total outflow sediment. In addition, regarding the suspended sediment concentration, the strong effect of the initial soil moisture content on the runoff volume might be the main reason for its significance.

Table 8. Standardized coefficients (β) in linear regression models

Parameter	Standardized coefficients Beta (β)	
	Initial soil moisture (%)	Total rainfall (mm)
Infiltration coefficient (%)	- 0.945	- 0.209
Time-to-runoff (s)	- 0.913	- 0.202
Runoff coefficient (%)	0.945	0.209
Time-to-drainage (s)	0.465	- 0.142
Drainage coefficient (%)	- 0.743	- 0.170
Downstream splash (g m ⁻²)	0.304	0.945
Up/down splash ratio	0.759	0.143
Suspended sediment concentration (g l ⁻¹)	0.788	0.406
Total outflow sediment (g)	0.678	0.712

CONCLUSIONS

1. The effects of rainfall intensity and initial soil moisture on various parts of the infiltration, runoff, and erosion processes are not the same. The rainfall intensity was the dominant factor influencing the splash erosion and outflow sediment, while initial soil moisture content was the dominant factor for infiltration and runoff.

2. Regarding the interactions between rainfall intensity and initial soil moisture, the results demonstrated an antagonistic effect on the time-to-runoff and the suspended sediment concentration as well as a synergistic effect on the downstream splash and total outflow sediment.

3. Although the results were in agreement with the theory of hydrological responses, due to the large differences between the field and laboratory conditions, especially in terms of soil structure, it is highly recommended that the same research framework be used in field plots using portable rainfall simulators and more rainfall intensity levels.

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