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Effects of Roughness Coefficients and Complex Hillslope Morphology on Runoff Variables under Laboratory Conditions

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Abstract: The geometry of hillslopes (plan and profile) affects soil erosion under rainfall-runoff processes. This issue comprises of several factors, which must be identified and assessed if efficient control measures are to be designed. The main aim of the current research was to investigate the impact of surface Roughness Coefficients (RCs) and Complex Hillslopes (CHs) on runoff variables viz. time of generation, time of concentration, and peak discharge value. A total of 81 experiments were conducted with a rainfall intensity of 7 L min^{-1} on three types of soils with different RCs (i.e., low = 0.015, medium = 0.016, and high = 0.018) and CHs (i.e., profile curvature and plan shape). An inclination of 20% was used for three replications. The results indicate a significant difference (p-value ≤ 0.001) in the above-mentioned runoff variables under different RCs and CHs. Our investigation of the combined effects of RCs and CHs on the runoff variables shows that the plan and profile impacts are consistent with a variation in RC. This can implicate that at low RC, the effect of the plan shape (i.e., convergent) on runoff variables increases but at high RC, the impact of the profile curvature overcomes the plan shapes and the profile curvature's changes become the criteria for changing the behavior of the runoff variables. The lowest mean values of runoff generation and time of concentration were obtained in the convex-convergent and the convex-divergent at 1.15 min and 2.68 min, respectively, for the soil with an RC of 0.015. The highest mean of peak discharge was obtained in the concave-divergent CH in the soil with an RC of 0.018. We conclude that these results can be useful in order to design planned soil erosion control measures where the soil roughness and slope morphology play a key role in activating runoff generation.

Keywords: rainfall-runoff processes; soil erosion; hillslope morphology; surface flow; roughness

1. Introduction

Soil erosion processes lead to soil depletion, reduced fertility, and consequently affect crop quality and crop yields [1–5]. At the pedon scale, soil erosion can be attributed to the separation of soil particles by raindrops and runoff during interrill erosion processes, so preventing this process is an important goal in the management of water and soil resources [6–8]. The amount of runoff is a function of navigation time, therefore the accurate estimation of the time of concentration and runoff threshold results in a more accurate hydrograph of flooding [9]. Designing methods and structures for soil water conservation requires accurate estimation of the amount and time of flood peak discharge and time of concentration. To achieve these goals, it is necessary to study the factors affecting the amount of runoff produced, the time to runoff generation, the time to the concentration of runoff and, consequently, the nature of the hydrograph [10,11].

It is well known that the runoff process consists of three parts: surface runoff, subsurface runoff, and baseflow. In arid and semi-arid areas, the soils show some inherent properties that produce an elevated irregularity of these hydrological mechanisms, generating mixed models of surface and subsurface flows [12]. A representative example of this kind of mixed and complex dynamic is the degraded soils of Iran. Since most soils in Iran have low permeability, precipitation exceeds infiltration, hence, surface runoff becomes dominant [9,13].

Research in recent years on the behavior and performance of surface runoff indicates the impact of various climatic and physiographic factors such as rainfall intensity, slope steepness, and surface Roughness Coefficient (RC) on surface runoff variables in different temporal and spatial scales (e.g., [14–23]). In this regard, Vermang et al. [24] studied the effect of RC on runoff and soil loss rate using a rainfall intensity of 50.2 mm h^{-1} on a silt loam soil. Soil particle sizes were divided into four size groups of 3–12, 12–20, 20–45 and 45–100 mm under a slope steepness of 5%. The results showed a significant decrease ($p \leq 0.05$) in the rate of runoff changes along with an increase in RC. However, in RC with particle sizes larger due to the impact of raindrops and breaking of aggregates and the formation of a seal layer on surfaces, the permeability decreased, and the runoff rate reached a steady state. Ding et al. [25] also measured runoff and sediment at different times using rainfall simulation under laboratory conditions on two types of soils with different RCs. The results showed that high RC delayed runoff generation and concentration of runoff, but no significant changes in the amount of runoff were observed. Another example can be found in Vaezi and Ebadi [26]. They recently investigated the effect of nine rainfall intensities from 10 to 90 mm h^{-1} under five slope steepness' from 0% to 40% as the most important factors in producing surface runoff under laboratory conditions. Their results show that the runoff threshold in interrill erosion occurred using rainfall intensities close to 20 mm h^{-1}. They also reported that the highest surface runoff occurred under a slope steepness of 20%, with no significant difference for runoff as the slope increased.

In recent years, Complex Hillslope (CH) (i.e., profile curvature and plan shape) has also been considered as an effective factor in surface and subsurface runoff dynamics. Once a mutual relation is proven between the shape of the hillslope and the hydrological processes, it can be both useful and efficient in managing natural and urban watersheds [27,28]. Hillslope shape is an effective measure in studying the complex impact of topography on the different runoff variables. Troch et al. [14,29] introduced nine different CHs through the combination of three plan shapes (convergent, divergent, and parallel) and three profile curvatures (convex, straight, and concave). Agnese et al. [30] showed that for constant plan shapes, the convex profile generates more surface runoff than the other profiles. For the constant profile curvatures, the converged plan obtained higher amounts of surface runoff than the parallel and divergent plans. In addition, Talebi et al. [31] also demonstrated that convex and divergent hillslopes could be generally more stable than other types of hillslopes and that concave and convergent hillslopes could be less stable. According to the results obtained by Geranian et al. [32] on the effect of CH plan and profile on surface runoff changes, the impact of plan on runoff generation and time of concentration of runoff could be much greater than profile curvature, and convergent hillslopes with surface runoff concentration had an earlier runoff activation time than divergent and parallel hillslopes. Moreover, the runoff thresholds on convex hillslopes could be lower than on concave hillslopes. In addition, they observed that the peak discharge in divergent and parallel hillslopes was much higher than for convergent hillslopes due to the greater width at the outlet of the hillslope. Thus, the effect of profile on the rate of discharge changes needs further investigation.

The straight hillslope reaches a peak discharge earlier than the convex hillslope, which reaches a peak discharge earlier than the concave hillslope. Sabzevari et al. [9] found that the geometry of the hillslopes could change the peak discharge of hydrograph several times since the divergent hillslopes had a higher peak discharge than the parallel and convergent hillslopes. In addition, their results indicated that the highest peak discharge could be found in concave-divergent hillslopes. In their investigation of the effect of hillslope geometry on surface and subsurface runoff, they also showed that the rate of change in the hydrograph of the divergent hillslopes was decreasing, and the concave curve was downward. In another study, Sabzevari et al. [33] further examined the effect of hillslope geometry on the temporal variables of runoff, such as lag time and time to equilibrium. The results showed a 33% increase in time to equilibrium in the divergent hillslopes as compared to the convergent hillslopes. Talebi et al. [18] examined the effect of CH plan and profiles on separation and deposition of sediment particles caused by sheet erosion. They stated that the rate of particle separation because of runoff on convex profiles is about 15 times higher than that in straight profiles. Regarding this, Fariborzi et al. [34] employed the subsurface time area model for the prediction of subsurface flow in CHs. To validate these results, a rainfall simulator on a sandy loam soil was tested, which was used under three rainfall intensities and three inclinations. Then, subsurface time area model results were compared with those of a laboratory of subsurface flow. The results showed an accurate estimation with a determination coefficient of 0.85 for the method of subsurface time area in CHs.

Although there is a great number of research on the individual effect of RC and CH on the performance and dynamics of surface runoff and subsurface flow, the combined effects of RC and CH morphology on runoff variables during rainfall-runoff processes in laboratory conditions is still unknown. The main aim of this study is to perform a comparative analysis of the individual and combined effects of RC and CH on runoff production and parameters related to runoff, such as start time, time of concentration, and runoff peak, by using hydrographs. To achieve this goal, a total of 81 rainfall simulations under laboratory conditions were conducted with a rainfall intensity of 7 L min^{-1} on three soils with different RCs (i.e., low = 0.015, medium = 0.016, and high = 0.018) and CHs (i.e., profile curvature and plan shape). An inclination of almost 20% was used in three replications per treatment.

2. Materials and Methods

2.1. Preparing Rainfall Simulator Conditions

In the current research, a laboratory model was used to investigate the rainfall-runoff processes in CHs under three different types of RCs. The longitudinal profiles and slope plans were designed based on the Evans model [35]. According to Troch et al. [14], nine different CHs were designed with the simultaneous change of plan and profile of the hillslopes (Table 1). To investigate the plan shapes (convergent, divergent, and parallel) and three profile curvatures (convex, straight, and concave), a three-dimensional geometric model of the hillslopes were considered [34,36]. To introduce a suitable function that can represent the geometry of the CHs, the model proposed by Troch et al. [14] was used.

In this study, a rainfall simulator was used with a uniform rainfall intensity of 71 min^{-1} (210 mm/h). The simulator has a plot with a length of 2 m, a width of 1 m, and a depth of 0.8 m. The height of the surface of the plot to the precipitation nozzles is 20 cm. The simulator has a water tank with a capacity of 200 L beneath the unit where the water is pumped into the nozzles and rained down on the surface of the plot. There are two jacks below and on the left side of the plot for longitudinal slope adjustment. A slope steepness of almost 20% was used, as this value was considered a representative inclination of the most eroded areas in Iran [26] Surface runoff was also measured using the outlet pipes of P2 and P4 in outlet plot (Figure 1).

Table 1. Geometric characteristics of complex hillslopes (CHs).

No.	Longitudinal Profile	Plan Shape	CHs	H (m)	n (No Dimension)	L (m)	ω (m^{-1})	A (m^2)
1		Convergent					+0.0997	1.8
2	Concave	Parallel		0.36	1.5	1.90	0.0000	2.4
3		Divergent					−0.0997	1.8
4		Convergent					+0.0997	1.5
5	Straight	Parallel		0.36	1	1.90	0.0000	2
6		Divergent					−0.0997	1.5
7		Convergent					+0.0997	1.8
8	Convex	Parallel		0.36	0.5	1.90	0.0000	2.4
9		Divergent					−0.0997	1.8

H: maximum heights relative to the baseline; L: total length of the hillslope; n: profile curvature parameter; ω: plan curvature parameter calculated [14].

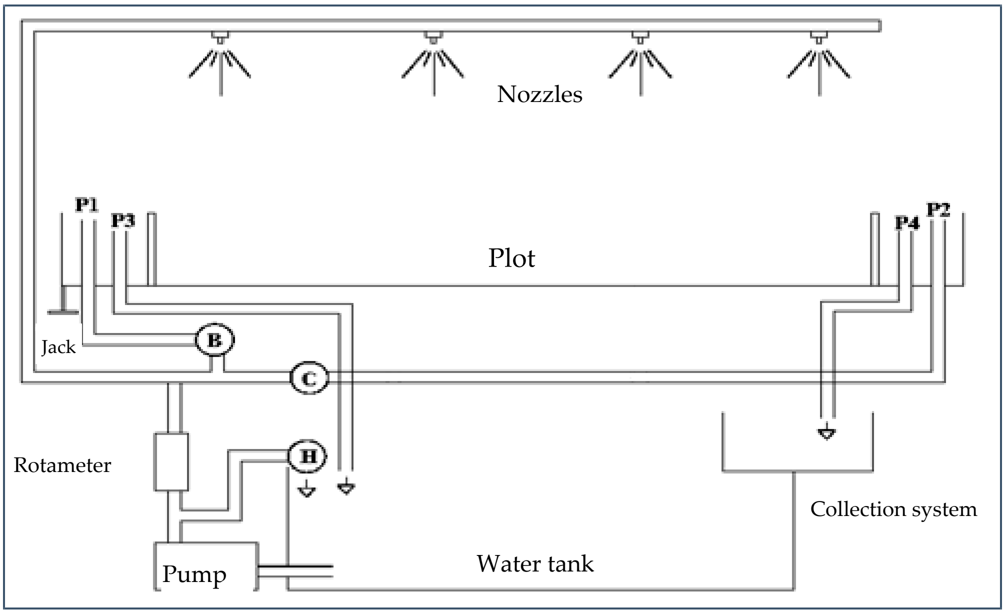

Figure 1. Schematic diagram of the water cycle within the rainfall simulator [32].

A rectangular weir was used to measure the time of concentration and amount of runoff generated in CHs. After preparing the rainfall simulator and adjusting the slope and rainfall intensity, a digital chronometer was turned on. Then, the start time of the runoff was recorded by observing runoff on the within plot and runoff travel from the plot most distant point to the outlet plot as the time of runoff generated and time of runoff concentration, respectively. In the following, runoff peak (L min^{-1} m^{-2}) was measured using a hydrograph, so that the maximum amount of runoff in each hydrograph was considered as the runoff peak. Then, the amount of runoff was measured in intervals of 1 min with a total duration of 15 min after runoff generation under different CH and RC conditions. Finally, using the rectangular weir information at different times, the peak discharge rate was also determined [26].

2.2. Determining the RC

Soil RC has a great impact on the surface storage, velocity, and direction of runoff [37]. In this research, in order to investigate the effect of RCs on the rainfall-runoff processes in CHs, soil particle diameter in the plot was considered as a factor influencing hydrological processes on RCs, and three different granulation types were used to investigate different RCs. Various relations have been proposed to determine the hydraulic RC through granulation. Therefore, in order to select the appropriate RC, the granulation curve of three soil types was determined by granulometry tests. The soil uniformity was then calculated using Equation (1) [38]:

$$C_u = \frac{d_{60}}{d_{10}} \tag{1}$$

where C_u is the soil uniformity and d_{60} and d_{10} represent the diameters at which 60% and 10% of each soil type are comprised of particles with a diameter less than those values, respectively. For C_u smaller than 5, the soil is uniform. For $5 < C_u < 15$, it is non-uniform, and for larger than 15, it is very non-uniform [38]. Finally, Soils 1, 2, and 3 (Figure 2) were uniform with a $C_u < 5$ (C_u: 1.5, 2.63, and 1.74, respectively). Thus, the Strickler equation (Equation (2)) was used to determine the RCs of Soils 1, 2, and 3. Their RCs, according to the granulation curve, were obtained to be 0.015, 0.016, and 0.018, respectively. In this equation, d_{50} (mm) is the median diameter of particles [39].

$$n = 0.0474\ (d_{50})^{1/6}. \tag{2}$$

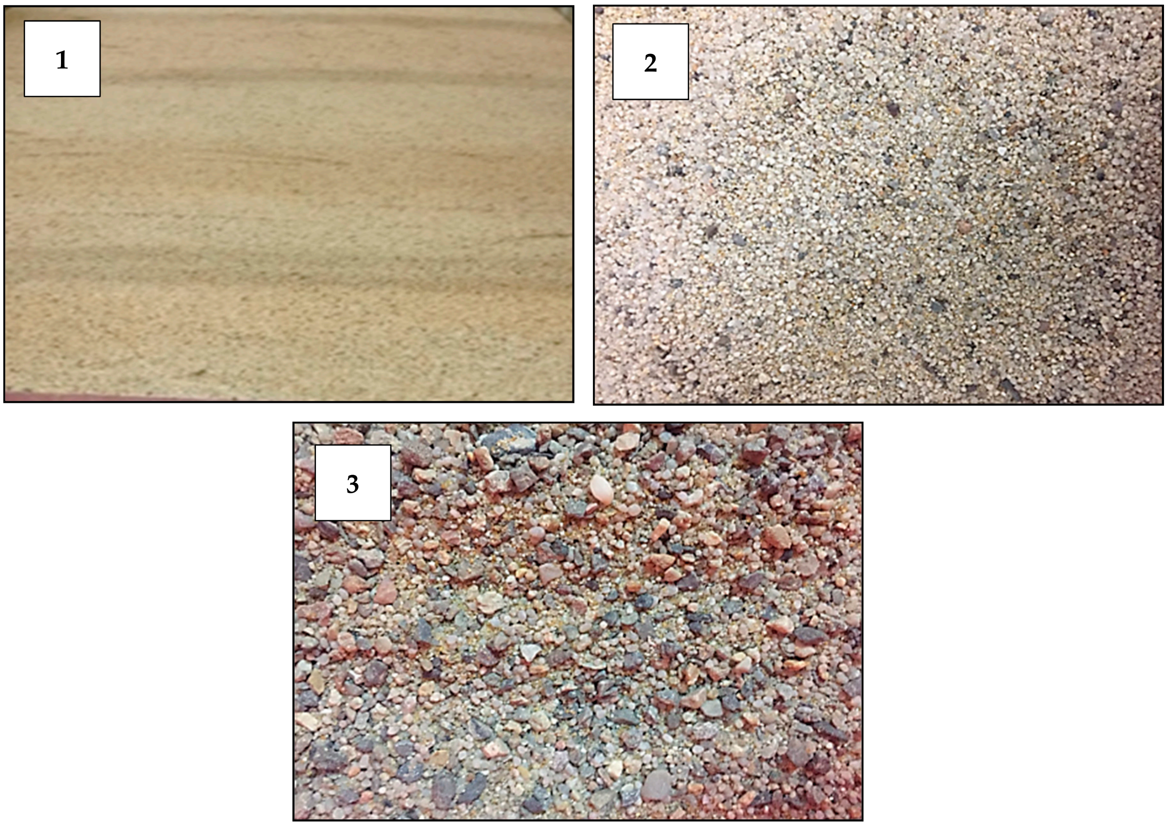

Figure 2. The three soil types with different roughness coefficients (RCs) used during the rainfall simulation experiments, (**1**): Cu: 1.5; (**2**): Cu: 2.63; (**3**) Cu: 1.74.

2.3. Statistical Analysis

After measuring the surface runoff, under different CHs and RCs, the data obtained from the experiments were categorized in Excel 2013 (Microsoft, USA). Before performing any statistical analysis, the normality of the data was tested through the Kolmogorov–Smirnov test. Regarding this, the non-normal data were changed to normal data using a transforming data method and this was then analyzed. In the following, the means of different groups were compared using Tukey's test. Two-way ANOVA tests were used to measure the individual and combined effects of CHs and RCs on runoff variations as was done by Kiani-Harchegani et al. [40].

3. Results and Discussion

3.1. Descriptive Statistics of Runoff Variables in RCs in CHs

Table 2 presents the descriptive statistics, including the mean, standard deviation (SD) and coefficient of variation (CV) of different runoff variables, including start time, time of concentration, and runoff peak in three soil types with different RCs under different CHs.

The results indicate that the slowest start time for Soils 1 and 2 was in the concave-parallel hillslopes (Hillslope No. 2). The slowest start time was observed in Soil 3 in the straight-parallel hillslopes (Hillslope No. 5), showing the longest start time of runoff amongst all CHs. The lowest start time of runoff for all soils was obtained in the convex-convergent hillslopes (Hillslope No. 7) and the earliest start time was Soil 1. The results, as shown in Table 2, also indicate that the highest time of concentration was in Soil 2 with convex-convergent hillslopes (Hillslope No. 7) and the lowest time of concentration in Soil 1 with straight-divergent hillslopes (Hillslope No. 9). Finally, the highest runoff peak was observed in Soil 3 in the concave-divergent hillslopes (Hillslope No. 3) and the lowest runoff peak in Soil 1 with the convex-convergent hillslopes (Hillslope No. 7).

3.2. Start Time of Runoff

According to the results of the two-way ANOVA presented in Table 3, there was a significant difference ($p \leq 0.001$) in the effect of different CHs and different RCs on the start time of runoff. The interaction between RCs and CHs also shows a significant difference ($p \leq 0.001$), indicating different effects of different RCs under CHs on the start time of runoff.

The results of the Tukey's test (Figure 3) also showed that runoff reaches the plot outlet in Soil 1 (n = 0.015) earlier under convex-convergent hillslopes (Hillslope No. 7) due to surface flow concentration, high water height at the plot outlet, and reduced permeability. The earliest start time of runoff in Soils 2 and 3 at the hillslope of No. 7 can be also accounted for the more effective simultaneous permeability effect and profile curvature. Therefore, because of an increased RC of the soil due to coarser soil particles increasing and a higher surface in convex profile, as well as the increased runoff height at the plot outlet, runoff occurs quickly.

By considering the soil profile and type constant, the effect of the plan shape on the runoff start time can be determined, such that the convergence reduces the start time of runoff and the divergence delays the start time of runoff. In addition, by considering the plan and type of soil constant, we can confirm the impact of profile on the start time of runoff, such that concave delays the start time of runoff and convex hillslopes have an earlier start time of runoff. These results are in line with the results obtained by Sabzevari et al. [9] and Geranian et al. [32].

Table 2. Summary of characteristics of runoff variables using different RCs and CHs (three replications).

N	Hillslopes No.		1	2	3	4	5	6	7	8	9
Variables	Soil Type	Profile Plan	Concave			Straight			Convex		
			Converge	Parallel	Divergent	Converge	Parallel	Divergent	Converge	Parallel	Divergent
Runoff generation (min)	1	Mean	2.15	4.43	4.12	2.24	3.25	3.39	1.15	2.91	3.45
		SD	0.50	0.76	0.29	0.51	0.45	0.32	0.50	0.10	0.50
		CV	0.23	0.17	0.07	0.23	0.14	0.09	0.43	0.03	0.14
	2	Mean	2.53	6.17	3.70	4.08	5.43	3.67	2.20	4.12	4.47
		SD	0.58	0.58	0.00	0.29	0.58	0.58	0.10	0.29	0.58
		CV	0.23	0.09	0.00	0.07	0.11	0.16	0.05	0.07	0.13
	3	Mean	4.25	6.67	7.42	3.93	7.78	6.25	1.82	3.18	5.43
		SD	0.50	0.58	0.29	0.29	0.76	0.50	0.29	0.10	0.58
		CV	0.12	0.09	0.04	0.07	0.10	0.08	0.16	0.03	0.11
Time of runoff concentration (min)	1	Mean	4.00	4.86	3.15	3.33	3.53	2.77	5.28	3.37	2.68
		SD	0.20	0.11	0.09	0.15	0.15	0.12	0.03	0.06	0.16
		CV	0.05	0.02	0.03	0.05	0.04	0.04	0.01	0.02	0.06
	2	Mean	5.27	5.68	3.78	4.28	5.63	4.27	7.78	4.93	3.87
		SD	0.38	0.03	0.03	0.19	0.15	0.06	0.03	0.03	0.06
		CV	0.07	0.01	0.01	0.04	0.03	0.01	0.00	0.01	0.01
	3	Mean	5.68	6.68	5.47	6.65	6.75	4.47	7.45	3.52	4.73
		SD	0.16	0.16	0.15	0.00	0.05	0.15	0.13	0.10	0.21
		CV	0.03	0.02	0.03	0.00	0.01	0.03	0.02	0.03	0.04
Runoff peak (L min^{-1} m^{-2})	1	Mean	1.95	1.89	2.35	2.42	1.84	3.02	1.27	1.92	2.43
		SD	0.10	0.06	0.06	0.15	0.14	0.06	0.03	0.13	0.06
		CV	0.05	0.03	0.02	0.06	0.08	0.02	0.02	0.07	0.02
	2	Mean	2.02	1.89	2.52	3.02	2.10	2.98	1.48	1.72	2.02
		SD	0.15	0.06	0.06	0.49	0.01	0.15	0.15	0.06	0.15
		CV	0.08	0.03	0.02	0.16	0.01	0.05	0.10	0.03	0.08
	3	Mean	2.30	1.89	2.89	2.86	2.17	2.96	1.74	1.94	2.60
		SD	0.14	0.07	0.10	0.03	0.14	0.21	0.06	0.15	0.20
		CV	0.06	0.04	0.03	0.01	0.07	0.07	0.03	0.08	0.08

SD, standard deviation; CV, coefficient of variation.

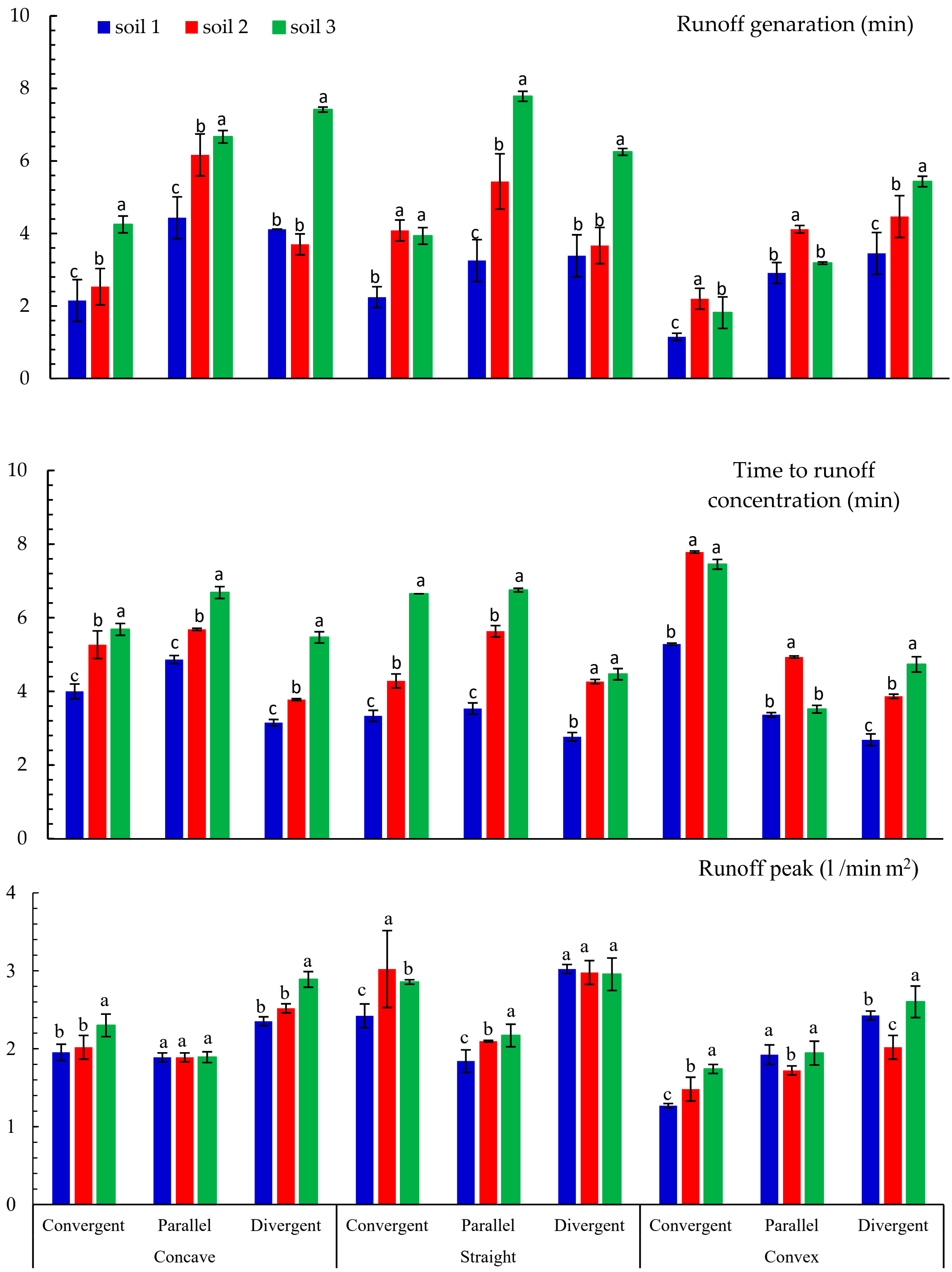

Figure 3. Effect of different RCs and CHs on runoff variables by Tukey's test. (a, b and c are statistically different at $p \leq 0.05$ on three soil types in each hillslope). Means followed by the same letters are not significantly different according to Tukey's HSD at $p \leq 0.05$.

Table 3. Effect of different RCs and CHs and their interaction on runoff variables using two-way ANOVA.

Variables	Factors	df	Mean Squared	F-Value	*p*-Value
Start Time (min)	**CH**	8	55,945.03	2237.80	0.00
	RC	2	114,643.11	4585.72	0.00
	CH × RC	16	8513.61	340.54	0.00
Time of concentration (min)	**CH**	8	32,212.25	1288.49	0.00
	RC	2	84,037.00	3361.48	0.00
	CH × RC	16	5248.25	209.93	0.00
Runoff peak (L min^{-1} m^{-2})	**CH**	8	82.36	82.40	0.00
	RC	2	25.44	25.40	0.00
	CH × RC	16	5.07	5.07	0.00

df: degrees of freedom; F-value: variation between gropes mean/variation within the gropes; *p*-value: *p*-value ≤ 0.01 and *p*-value > 0.05 indicates a significant variation within the group and a low variation within the group, which leads to the rejection and acceptance of the null hypothesis, respectively.

3.3. Time of Concentration

The results of the two-way ANOVA presented in Table 3 indicate a significant difference ($p \leq 0.001$) in the individual effect of different CHs and RCs on time of runoff concentration. The interaction between CHs and RCs also shows a significant difference ($p \leq 0.001$), indicating different effects of different RCs and CHs on the time of concentration.

The results of means of different groups using Tukey's test in Figure 3 also show that the divergent hillslopes decrease the time of concentration and concave hillslopes increase it, which results in an increased time of concentration on the concave-divergent hillslopes (Hillslope No. 3) with increasing RCs (n = 0.016 to n = 0.018). This shows that hillslope profiles have a greater effect than plan shape. Therefore, as soil permeability increases, more time is needed to accumulate runoff at the bottom of the plots, thus increasing the time of concentration [22]. In the convex-parallel hillslopes (Hillslope No. 8), with increasing soil RC, the time of concentration was first increased and then decreased. The reason may be that with the low slope of the convex profile at the bottom of the plot as well as water accumulation, the water is discharged earlier [41,42]. The results also show that the convergent plan, due to the concentration of surface and subsurface runoff, retains more water and takes longer to discharge. As well, the runoff path is curved to reach the exit plot outlet in the convergent plan, but in other plans, it follows a smooth path. This finding is consistent with those obtained by Geranian et al. [32].

In examining the CH profiles with increasing RCs, it was noticed that concave profiles with a lower slope angle at the end of the plot required a considerable runoff, thus an increasing trend was observed with RCs in different plan shapes. In straight profiles, due to the uniformity of the slope, time of concentration is affected by the RC and soil permeability [43].

The examination of the effect of the plan on time of concentration by considering soil profile and type constant indicates that time of concentration in divergent hillslopes is less than that in parallel and convergent hillslopes [21,44]. The reason may be due to the curved path of runoff in convergent plans. Considering the plan and soil type constant, concave hillslopes are also shown to have a higher time of runoff concentration than convex and straight hillslopes because, on the convex hillslopes, the water flow is faster than other profiles for the high slope and accumulation of runoff [45]. For example, the highest time of concentration for all soils was obtained for the convex-convergent hillslopes. The lowest time of concentration for Soil 1, 2 and 3 was observed in the convex-divergent, concave-divergent, and convex-parallel hillslopes, respectively. In most hillslopes, as the soil RC increases, the time of concentration is delayed, which is consistent with the results obtained by Geranian et al. [32]. However, from the results of simultaneous impact analysis of profiles, plans, and RCs, it is shown that in different RCs, the effect of the profile and plan on runoff variables varies. Moreover, in some hillslopes, by increasing permeability, the effect of profiles is observed more than the plan, and in other hillslopes, the opposite is the case. For example, in the concave-divergent hillslopes (Hillslope No. 3), we can observe the effect of profile (concavity) on the plan (divergence), so by increasing soil RC, the time of concentration and permeability is increased. A similar case can also be observed for Hillslope No. 8 (convex-parallel).

3.4. Runoff Peak

The results of the two-way ANOVA, presented in Table 3, indicate a significant difference ($p \leq 0.001$) for the individual influence of different CHs and RCs on the runoff peak rate. In addition, the interaction between soil RC and CHs shows a significant difference ($p \leq 0.001$), indicating the different effects of different soil RCs and CHs on runoff peak rate.

The results of Tukey's test (Figure 3) also show that in concave-convergent, concave-divergent, straight convergent, and straight-parallel hillslopes (Hillslopes No. 1, 3, 4, and 5, respectively), increasing soil RC relatively increases the runoff peak rate. In the concave-parallel and straight-divergent CHs (Hillslopes No. 2 and 6), the soil RC has no effect on the runoff peak rate. Meanwhile, in the convex-convergent CHs (Hillslope No. 7), increasing soil RCs significantly increases the runoff peak, and in CHs (Hillslopes No. 8 and 9), by increasing the soil RCs, the time of peak rate first decreases and then increases. This is due to the effect of the plan on the runoff peak rate in different RCs and therefore permeability [16,17]. The highest runoff peak rate was also observed in Soil 3 (n = 0.018) with concave-divergent hillslopes (Hillslope No. 3) and the lowest runoff peak in Soil 1 (n = 0.015) with convex-convergent hillslopes (Hillslope No. 7).

A different profile affects the speed of discharge rate with slight changes (Figure 3). But in the CHs plan, due to changes in the width of the down plot, great changes can be observed in the discharge rate. Divergent or parallel plans can pass all runoff but in the convergent plan, there is some runoff accumulation due to a lower width. The individual effect of the hillslope profiles can be attributed to the speed of changes in the discharge rate due to the same amount of input discharge for all hillslopes (assuming hillslope plan and soil type constant). The runoff peak in concave hillslopes has a lower increase than the other hillslopes due to runoff accumulation in the outlet and higher initial discharge [46]. Thus, the runoff peak of the convergent hillslopes is smaller in the outlet than the parallel and divergent plans, which also reflects the higher time to concentration (greater discharge time). This could be consistent with the results obtained by Tucker and Bras [47] and Bonetti et al. [48] if we consider the differences generated at different scales. According to the results of this study, in all soils with constant RC and different CHs, the highest runoff peak is for divergent hillslopes with straight or concave profiles and the lowest amount for convex-convergent hillslopes.

3.5. Hydrographs

Divergent hillslopes have a decreasing rate of change due to parallel and direct movements of runoff toward the outlet and the effect of the lower part of plot on the outlet runoff volume, while parallel hillslopes have a constant rate of head change due to the constant up and down widths of the plot [49]. However, in convergent hillslopes due to a greater area of upward of plot over time, the rate of increase of runoff peak increases [50,51]. The study of the CHs also shows that the start time of runoff and time to concentration increases with increasing soil RCs (Figure 4). But in convex profiles, due to the steep slope of the lower part of the plot, with increasing soil RCs and consequently increasing its permeability, the runoff is discharged earlier and the time of concentration is reduced. So, the hydrographs of Soil 1, 2, and 3 are almost overlapped. Similarly, in convergent hillslopes, the start time of runoff decreases because the convergent hillslope saturation is faster than parallel and divergent hillslopes. The results of this research and previous researches, such as Sabzevari et al. [9] and Geranian et al. [32], show that convergence and convexity of hillslopes accelerate the start time of runoff and divergence and concaveness delay it.

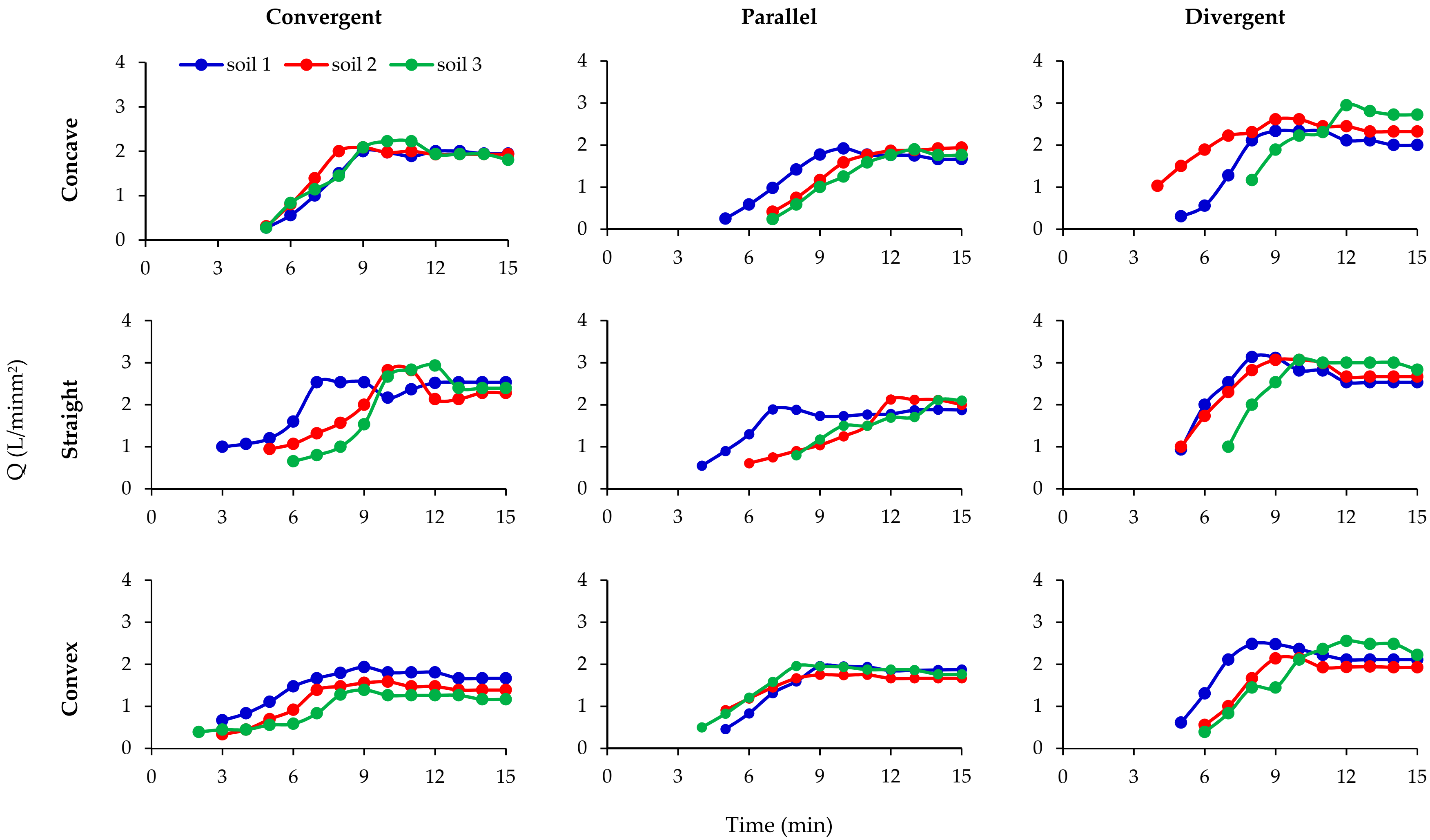

Figure 4. Hydrographs of rainfall-runoff processes at different RCs and CHs.

3.6. Recommendations, Challenges and Future Research Work

We recommend delaying the start time of runoff and its subsequent destructive consequences in one of the following ways in landscapes with high levels of convexity morphology. Firstly, increasing surface RC by changing soil granulation or by changing vegetation, as well as enhancing soil horizon formations, biological processes, and water retention capacity [52,53]. For this purpose, modified natural or synthetic coatings could increase the RC, thereby reducing the start time and time of concentration and runoff peak rate of the runoff. Secondly, it could be possible to introduce an embankment for diverging artificial paths or reducing the convexity of hillslopes with an appropriate stair levelling, which could increase the start time of runoff and relatively reduce the runoff peak rate. This is very common in cultivated fields where terraces are used to retain water, conserve the soil, and reduce hillslope inclination [54,55].

Another point to be discussed at this point as a challenge for the future should be the effect of other external factors to assess the connectivity processes at the pedon scale [56]. It is well known that laboratory experiments are not representative of natural conditions [10,57]; however, they can be very useful to detect the specific factors that condition the activated dynamics and processes. In the future, other related factors that affect the connectivity of the surface and subsurface processes should be considered, such as the number of rock fragments [58], changes in organic carbon contains and litter cover [59,60], or different parent materials [61].

4. Conclusions

The main purpose of this research was to compare the variability of a surface runoff between different soil RCs under different CHs, both individually and together during rainfall-runoff processes. The results showed that the effect of the CH plan due to the change in runoff storage volume at the bottom of the plot was greater than the CH profile. With this, the divergent hillslopes showed a slower start time than the convergent and parallel hillslopes, and with increasing soil RC, the start time of runoff increased. With increasing soil RC, start time on convex profile hillslopes increased because of the higher slope at the end of the plot, and so did the convergent hillslopes due to the concentration of surface runoff at the bottom of the plot. In addition, the examination of the simultaneous effect of profile and plan of CHs and soil RC on time of concentration and runoff peak of surface runoff showed that the percentage of the impact of profile and plan changes with soil RC changes. Finally, the analysis of hydrographs on CHs showed that start time of the runoff and time of concentration increased with increasing soil RC. However, in convex profiles, due to the high slope of the lower end of the plot, by increasing soil RC and consequently increasing its permeability, the runoff is discharged earlier and the time of concentration is reduced. As a result, the hydrographs of all three types of soil are almost overlapped. In order to obtain comprehensive results, it is recommended that experiments be carried out on non-uniform soils using different rainfall intensities and different slope steepness in CHs.

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