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Surface runoff of horse grazed pasture – a disregarded hydrological response unit in low mountain ranges

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Abstract

Accurate prediction of surface runoff is of vital interest for flood prediction which in turn requires the process knowledge about key factors affecting its temporal and spatial variability. Antecedent soil moisture and grazing intensity have been detected as important factors, but there exists no explicit field study investigating the spatial and temporal variability of surface runoff generation on horse grazed pasture. In our study, for the first time the surface runoff generation on horse grazed pasture was analyzed using a rainfall simulator along with measurements of soil water content and soil physical properties. The results were compared with concurrent investigations on cattle grazed pasture land. The analyses of 8 rainfall simulations on 1 m^2 plots at a rate of 46.6 mm/h revealed mean runoff coefficients ranging from 0.9% to 50.5%. The most important findings of our study are that the antecedent soil moisture distinctly impacts the amount of surface runoff and the runoff coefficient is significantly higher on horse grazed pasture than on cattle grazed pasture. These results underline the importance of further experimental studies to obtain a broader process knowledge about this specific hydrological response unit, especially in regard to the increasing portion of horse grazing in the low mountain ranges.

Zusammenfassung

Die genaue Abschätzung des Oberflächenabflusses ist von großem Interesse für die Hochwasservorhersage. Dies erfordert wiederum ein genaues Prozessverständnis über die wesentlichen Faktoren, die die zeitliche und räumliche Variabilität des Oberflächenabflusses beeinflussen. Die Bodenvorfeuchte und die Beweidungsintensität sind als sehr wichtige Einflussfaktoren erkannt worden. Trotzdem existieren keine Feldstudien, die die zeitliche und räumliche Verteilung von Oberflächenabfluss explizit auf Pferdeweiden untersucht haben. In dieser Studie wird anhand von Beregnungsversuchen, Bodenfeuchtemessungen und bodenphysikalischen Analysen erstmalig die Oberflächenabflussentstehung auf Pferdeweiden untersucht. Die Ergebnisse von acht Beregnungsversuchen bei einer Intensität von 46,6 mm/h auf 1 m^2 Fläche liefern durchschnittliche Abflussbeiwerte von 0,9% bis zu 50,5%. Zum Vergleich stehen simultan durchgeführte Beregnungsversuche auf Rinderweiden zur Verfügung. Dabei zeigt sich, dass die Bodenvorfeuchte den Abflussbeiwert auf Pferdeweiden stärker beeinflusst und verstärkt als auf Rinderweiden. Pferdeweiden sind bisher nicht als eigene spezifische hydrologische Einheit identifiziert worden. Diese ersten Resultate unterstreichen aber, wie wichtig weitere Feldstudien sind, um das Prozessverständnis über die Oberflächenabflussentstehung auf Pferdeweiden zu verbessern, insbesondere im Hinblick auf deren steigenden Flächenanteil in Mittelgebirgen.

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Keywords surface runoff, rainfall simulation, runoff coefficient, low mountain ranges

1. Introduction

Accurate prediction of surface runoff is of vital interest for flood prediction in catchments since it represents the major portion of the peak runoff and clearly influences the magnitude of floods (e.g., *Beven* 2012; *Chifflard* 2006; *White* and *Howe* 2002). Even at the plot scale the factors controlling the surface runoff generation like antecedent soil moisture (*Ali* et al. 2015; *Chifflard* et al. 2017; *Chifflard* et al. 2004; *Penna* et al. 2015; *Tromp-Van Meerveld* and *McDonnell* 2006a; *Tromp-Van Meerveld* and *McDonnell* 2006b; *Zehe* and *Blöschl* 2004), infiltration capacity (*Vidon* et al. 2012), land use (*Leitinger* et al. 2010; *Markart* et al. 2008; *Scherrer* et al. 2007), vegetation cover or grazing intensity (*Mayerhofer* et al. 2017) are not constant parameters, as they show a high temporal and spatial variability (*Blöschl* et al. 2006; *Zemke* 2016). Although it is obvious that these variabilities have to be taken into account to obtain an improved model accuracy, capturing these variabilities is still challenging (*Casper* et al. 2015). This is due to the fact that there is still a lack in reliable process knowledge explaining how surface runoff is generated depending on catchment properties (*Zhang* et al. 2014). So far, rainfall-runoff models often use surface runoff coefficients (RC) for distinct hydrological response units (e.g., *Leitinger* et al. 2010; *Merz* et al. 2006) detected by GIS-approaches (e.g., *Hellebrand* et al. 2011) or by experimental studies using rainfall simulations (e.g., *Kienzler* and *Naef* 2007; *Kienzler* and *Naef* 2008; *Mayerhofer* et al. 2017; *Schmocker-Fackel* et al. 2007; *Weiler* and *Naef* 2003). However, the used RC are often static neglecting the facts that surface runoff generation is temporally a highly nonlinear process and that the pasture land is grazed by different livestock (e.g., cattle, horses, sheep) with differing usage intensities (*Cournane* et al. 2011; *Mayerhofer* et al. 2017; *Unger* 1991; *Wilcox* and *Wood* 1988). The latter can be critical especially for rural catchments as the grazing intensity has been identified as an important factor controlling surface runoff generation (*Mayerhofer* et al. 2017).

Generally, it might be expected that in rural catchments, especially in mountainous regions with a high portion of forest and pasture land, the amount of surface runoff is low due to the permeable surface and the good infiltration conditions. On a pre-alpine hillslope with grassland this assumption is confirmed by experimental studies including artificial rainfall and tracer experiments (*Weiler* et al. 1998). They identified that runoff generation on grassland is mainly controlled by a highly permeable organic soil horizon which leads to subsurface runoff as the main runoff process. In contrast to *Weiler* et al. (1998), recent research has detected the importance of grazing effects (short grass, damages due to mechanical impact by livestock) on surface runoff generation (e.g., *Markart* et al. 2008; *Mayerhofer* et al. 2017; *Scherrer* et al. 2007). Grazing effects, which can be observed in the high mountain ranges between spring and autumn, have impacts on the soil bulk density and hence lead to reduced infiltration rates of the underlying soils (*Cournane* et al. 2011; *da Silva* at al. 2003; *Greenwood* and *McKenzi* 2001; *Markart* et al. 2008; *Sharrow* 2007; *Unger* 1991) and to increased runoff coefficients (*Scherrer* et al. 2007). *Mayerhofer* et al. (2017) even measured runoff coefficients up to 0.78 and *Leitinger* et al. (2010) revealed coefficients up to 0.25 due to soil compaction caused by cattle trampling. These results obtained from sprinkling experiments were predominantly carried out in alpine or pre-alpine grasslands grazed by cattle (*Leitinger* et al. 2010; *Markart* et al. 2008; *Mayerhofer* et al. 2017) where the winter non-grazing season leads to a recovering process of the soil (e.g., decreasing of bulk density) (*Cournane* et al. 2011; *Mayerhofer* et al. 2017).

In the low mountain ranges, where winter pasture is a common land management practice, only a few experiments were carried out on grassland with cattle grazing (*Scherrer* et al. 2007). Cattle grazing is common for low mountain ranges like Hesse, characterized by 13.4% pasture land and 451,933 cattle (*Hessian State Bureau of Statistics* 2014), but cattle livestock has been decreasing by 17% since 1999. In the same period, the livestock of horses has increased by 10%. As this trend is expected to continue, it is of high importance to study pasture land used for horse grazing, because in comparison to cattle grazing the impact of horse grazing is more intense on the grassland (e.g., *Davies* et al. 2014). Horses break up the pasture sward and expose bare ground by overgrazing and exercise. Galloping horses damage the soil with their hooves, cause soil compaction or reduce the soil aggregate stability, which supports surface runoff generation. Different studies investigate the impact of horse grazing e.g. on surface and soil water quality (*Airaksinen* et al. 2007; *Parvage* et al. 2011) or on soil characteristics (*Belsky* and *Blumenthal* 1997; *Davies* et al. 2014), but except for *Rich* and *Reynolds* (1963), no specific study exists so far focusing on surface runoff of pasture land with horse grazing in low mountain ranges.

Based on this research gap and to assess horse pasture land as a separate hydrological response unit, this study aims at examining the surface runoff generation of horse and cattle grazed pasture land. We assumed that 1) horse grazing leads to an increased amount of surface runoff compared to cattle grazing and 2) the amount of surface runoff increases due to a higher antecedent soil moisture on both horse and cattle pasture land. To test these assumptions rainfall simulations were applied at the plot scale. Rainfall simulations are recognized as a state-of-the-art method that allow the identification of key factors controlling the surface runoff (*Leitinger* et al. 2010; *Mayerhofer* et al. 2017; *Scherrer* et al. 2007; *Schmocker-Fackel* et al. 2007; *Zemke* 2016), if experiments are carried out during different wetness conditions and on plots with different land use. In this way the surface runoff formation can be linked with both the antecedent soil moisture and the surface properties of horse and cattle grazed pasture land. This method was applied at the selected horse and cattle pastures with different grazing intensities. All sites were irrigated twice, representing dry and wet soil moisture conditions.

2. Materials and methods

2.1 Study site

This case study includes eight rainfall simulations on different rural sites with cattle and horse grazing (*Table 1, Photo 1* and *Photos 2-5*). The experiments were performed from Mai 2015 to September 2015 on small plots (1×1 m) located in the central low mountain ranges of Hesse (Germany). This region is characterized by a mean annual temperature of 8.2°C and a mean annual rainfall of 777 mm. The geological underground in this area consists of clay shale and greywacke of the upper Devonian. Loamy cambisol derived from peri-glacial slope deposits is the dominant soils type. The investigated rural sites are located near the village Niederhörlen (Central Hesse) and used as horse and cattle pastures with different livestock (*Table 1* and *Photos 2-5*). Sites A, B, C and D are grazed by horses (4 horses per 0.7 ha) and cattle (4 cattle and 4 calves per 0.7 ha), but A and C have not been used for grazing for one year and therefore the trampling intensity is reduced compared to the sites B and D. Generally, at the investigated sites the horses are pasturing from March till October around the clock and from November till February during the day. The cattle are pasturing from March till October around the clock, but not during the wintertime. At all rural sites the dry bulk density of the upper soil horizon (5 cm depth) was measured (*Table 1*). All rural sites have a similar slope inclination of about 8-9°.

2.2 Experimental design

For the rainfall simulation experiments a self-constructed nozzle rainfall simulator according to *Zemke* (2016), *Iserloh* et al. (2012), *Iserloh* et al. (2013a) and *Iserloh* et al. (2013b) was used (*Photo 1*). The simulator consists of a separable and lightweight aluminium-frame allowing comparatively flexible fieldwork. Four adjustable telescoping legs are attached to a 1 m² frame on which the nozzle (Co. Lechler no. 406.608) and a manometer are built-on. A windshield is attached to the corpus of the simulator to ensure that

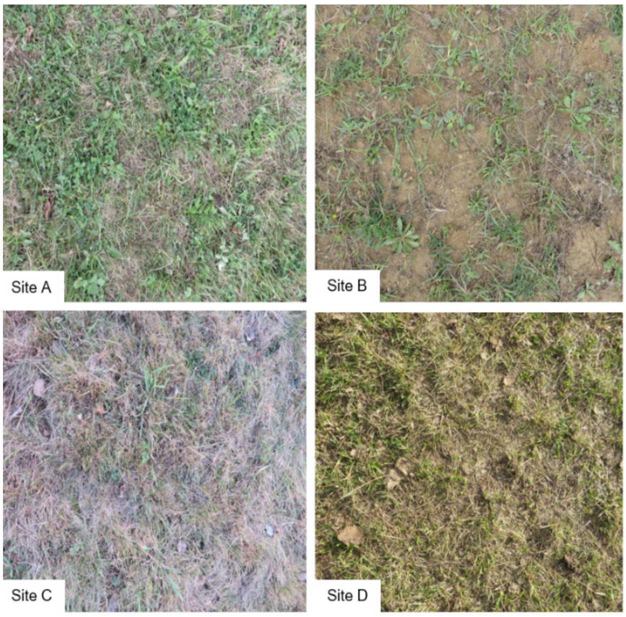
Table 1 Description of the studied irrigation sites. Source: Own elaboration

Site	Plot_ID	Description	ASM (%)	R (l/m²)	SI	Coordinates	BD (g/cm3)
A	A-1 A-2	Horse pasture (non-grazing)	18.8 36.0	46.6	8.8°	N 50° 50.549″ E 8° 26.448″	1.05
B	B-1 B-2	Horse pasture (grazing)	28.6 61.7	46.6	8.5°	N 50° 50.715″ E8° 26.180″	1.60
C	C-1 C-2	Cattle pasture (non-grazing)	28.9 41.0	46.6	8.5°	N 50° 50.419″ E 8° 27.162″	1.14
D	D-1 D-2	Cattle pasture (grazing)	28.7 44.1	46.6	8.5°	N 50° 50.387″ E 8° 27.028″	1. 59

Abbreviations: **ASM** – antecedent soil moisture; **SI** – slope inclination; **R** – rainfall; **BD** – dry bulk density.

there is no wind-induced falsification of the simulated rainfall. A small battery powered bilge pump is used to generate the water flow while the flow rate is controlled by a gate valve. The water output is cross checked by direct output measurements before and after each experiment and by reading the manometer throughout the experiments. An extensive calibration of the dependency between working pressure, drop-size distribution and intensity was conducted (*Zemke* 2016), allowing to verify a valid rainfall intensity by checking the working pressure at drop height. In this study, all sites were irrigated for a duration of 60 min with a rainfall intensity of 46.6 mm/h. This intensity is relevant for the investigated region as it corresponds to at least a 100-year event in this region according to the KOSTRA dataset (*Malit* and *Ertel* 2015). All sites were irrigated two times to capture the impact of different antecedent soil moisture on the surface runoff. The second irrigation was conducted 30 min after the end of the first experiment. Time domain reflectometry (TDR) (*Rajkai* and *Rydén* 1992) was used to measure surface soil moisture content (0-16 cm) at the sites prior to the irrigation.

Photo 1 Applied self-constructed nozzle rainfall simulator. Photo credit: Julian Zemke (2016)



Photos 2-5 Investigated pasture land: Site A: horse non-grazing; Site B: horse grazing; Site C: cattle none-grazing; Site D: cattle grazing. Photo credit: Peter Chifflard (2016)

3. Results

Runoff coefficients, defined as ratio of surface runoff of the plot and artificial rainfall, show a high variability between the different horse and cattle grazing sites and range between 0.9% and 50.5%. Generally, subsurface features of the rural sites are very similar due to the homogenous geological underground and soil types. Thus, the variation of runoff coefficients can be attributed to the different surface characteristics and the antecedent soil moisture (*Table 2*). At all sites the higher antecedent soil moisture of each second irrigation experiment causes a higher mean runoff coefficient which partly increased to the 14^{th}-fold of the first experiment. However, the differences between the runoff coefficients measured at low and high antecedent soil moisture conditions are higher at the horse grazing sites than at the cattle sites. It also has to be mentioned that the highest mean runoff coefficient appears at the horse grazing site (site B-2), whereas the lowest value occurs at the site with cattle grazing (D-1).

Assessing the temporal development of the surface runoff on the different sites during the rainfall simulation experiments, the impact of the antecedent soil moisture on the surface runoff is obvious (*Table 2*). At all sites the surface runoff starts earlier in high soil moisture than in low soil moisture conditions. Nevertheless, the time delay between each site is different (*Photos 2-5*) and ranges from 1 min (site C-2) (*Fig. 3*) up to 12 min (site A-1) (*Fig. 1*). In comparison, during low antecedent soil moisture conditions the cattle grazing sites show a faster surface runoff reaction than the horse grazing sites, whereas during high soil moisture conditions the reactions are quite similar except of site C-2. Considering the temporal development of the surface runoff during the experiments at low and high antecedent soil moisture, it has been noticed that except for site A the different sites generate very similar mean amounts of surface runoff after a time step of approximately 10 min. The highest generated runoff coefficients during the single time steps of the rainfall simulation experiments range from 2.7% up to 64.3% which occur not only due to a high ASM (*Table 2*) as they are very similar between the first and the second irrigation at each site. At the site B (horse grazing) (*Fig. 2*) the maximum portion of surface runoff is generated at low antecedent soil moisture conditions after 36 minutes. But is has to be noticed that this high runoff coefficient only appears during a single interval, which therefore could be treated as an outlier.

Assessing the spatial variability of the runoff coefficients it becomes obvious that different land management practices effect the surface runoff generation. At the sites A and B (horse pasture) (*Figs. 1* and *2*) higher runoff coefficients are reached at the grazed site during both antecedent soil moisture conditions. On the other hand, negligible differences between grazed and non-grazed sites occur at the sites C and D (cattle pasture) (*Table 2*).

Table 2 Summary of the results of the rainfall simulation experiments (RC = runoff coeffiecient). Source: Own elaboration

Plot_ID	ASM (%)	Total rainfall (l/m^2)	Total runoff (l/m^2)	Maximum runoff ($l/m^2/min$)	Mean RC (%)	Maximum RC (%/min)	Ratio: mean RC (low ASM) / RC (high ASM)
A-1 A-2	18.8 36.0	46.6	0.8 11.7	0.07 0.24	1.7 25.1	9.2 30.9	14.8
B-1 B-2	28.6 61.7	46.6	18.3 23.6	0.5 0.5	39.2 50.5	64.3 61.3	1.3
C-1 C-2	28.9 41.0	46.6	0.6 1.1	0.02 0.03	1.3 2.4	2.7 3.6	1.9
D-1 D-2	28.7 44.1	46.6	0.4 0.7	0.03 0.03	0.9 1.5	3.3 3.9	1.9

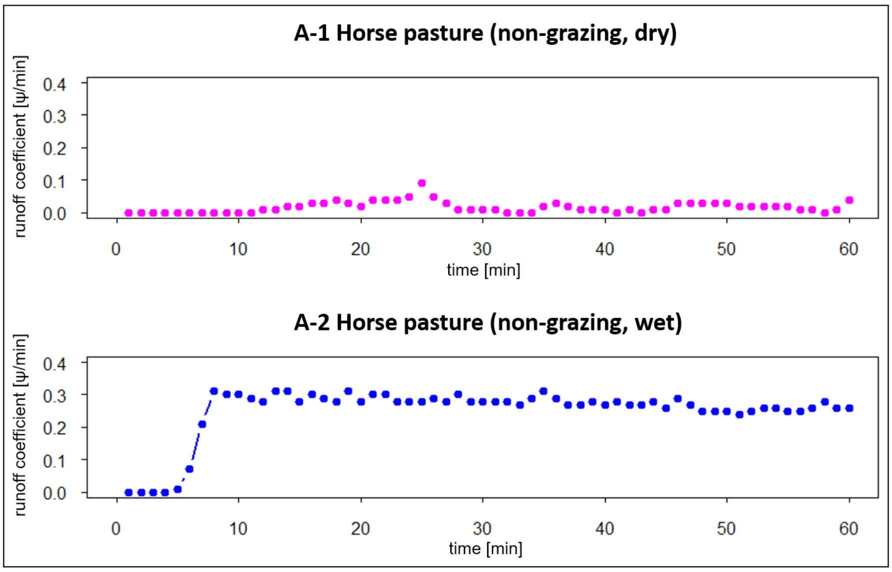


Fig. 1 Temporal variability of surface runoff on site A (horse pasture, non-grazing) with low (A-1) and high antecedent soil moisture (A-2). Source: Own elaboration

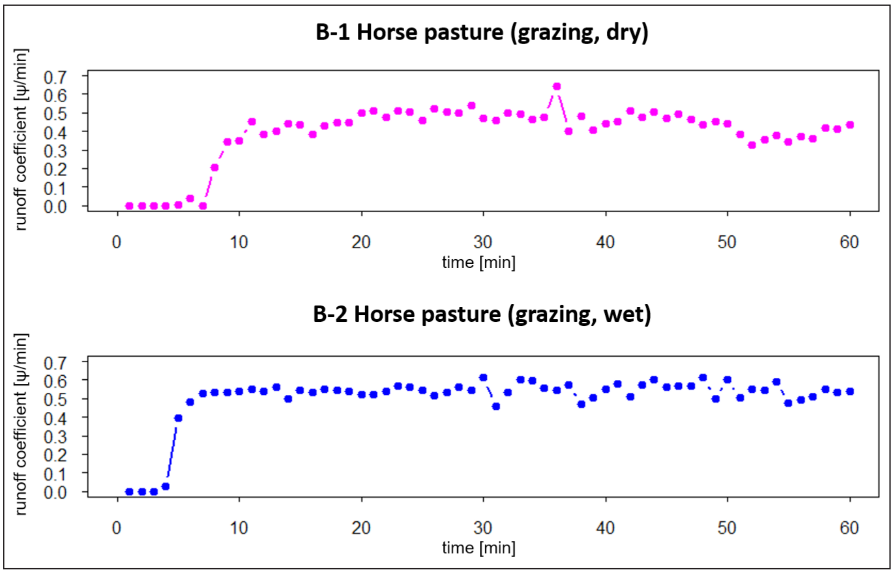


Fig. 2 *Temporal variability of surface runoff on site B (horse pasture, grazing) with low (B-1) and high antecedent soil moisture (B-2). Source: Own elaboration*

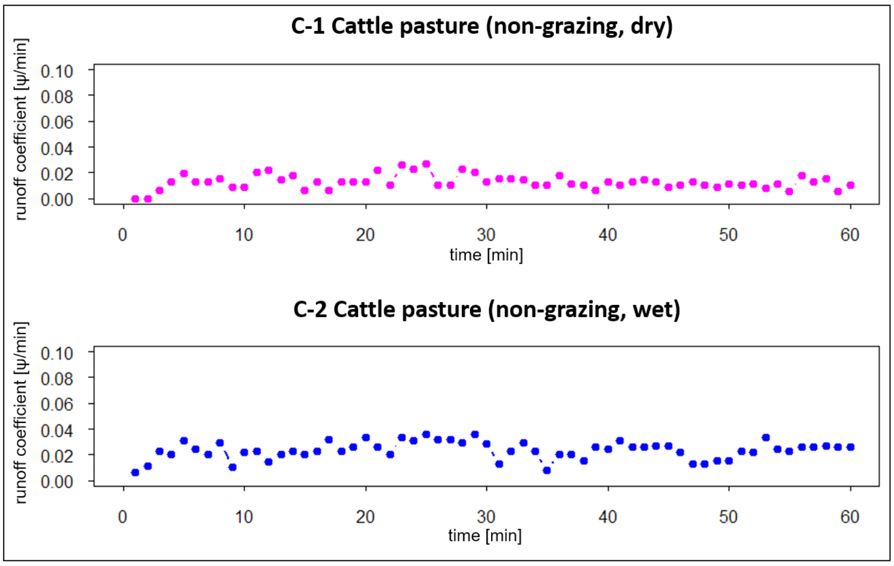


Fig. 3 *Temporal variability of surface runoff on site C (cattle pasture, non-grazing) with low (C-1) and high antecedent soil moisture (C-2). Source: Own elaboration*

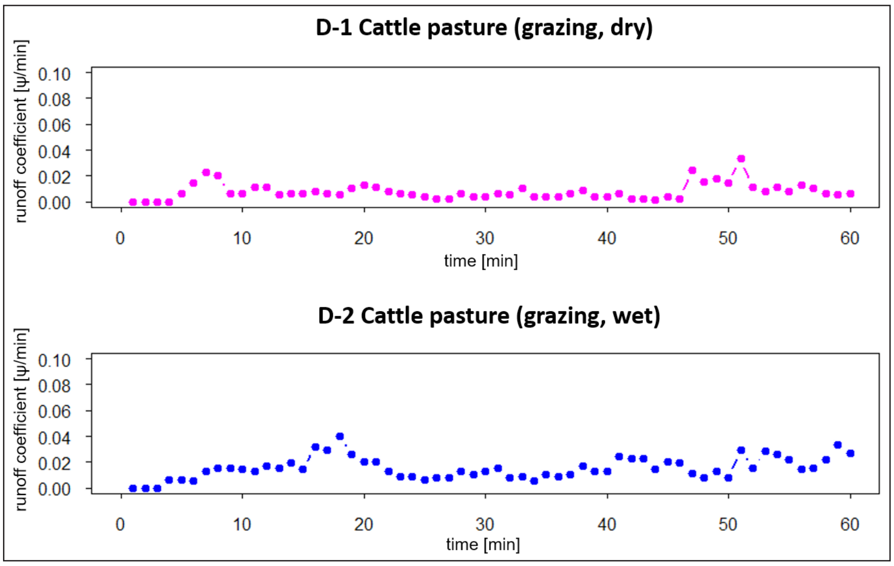


Fig. 4 *Temporal variability of surface runoff on site D (cattle pasture, grazing) with low (D-1) and high antecedent soil moisture (D-2). Source: Own elaboration*

4. Discussion

In this study at all horse and cattle grazing sites the runoff coefficients increased due to a higher antecedent soil moisture. The ratio between the mean surface runoff at low and high antecedent soil moisture conditions range from 1.3 to 14.8 (*Table 2*) and indicate the important impact of soil moisture on runoff generation independent of the grazing animals. Indeed, in mountainous regions the impact of antecedent soil moisture on the surface runoff generation on pasture land is well known (*Blume* et al. 2009; *Chifflard* et al. 2017; *Chifflard* and *Zepp* 2008; *Zehe* et al. 2010; *Penna* et al. 2011) and can be confirmed by the results of this study. But beside the antecedent soil moisture, rainfall or relief characteristics, this study underlines that surface runoff on pasture land especially depends on the degree of vegetation cover which is influenced mainly by grazing (e.g., *Badoux* et al. 2006; *Markart* et al. 2008). On comparable soil types (cambisols), *Scherrer* et al. (2007) conclude that soil compacting effects produced by grazing cattle appeared to be the cause of low infiltration and the increasing runoff coefficients compared to sprinkling experiments on grassland without soil compaction. Furthermore, *Mayerhofer* et al. (2017) and *Leitinger* et al. (2010) detect soil compaction due to cattle trampling which leads to a decreasing infiltration capacity and consequently to higher surface runoff coefficients of up to 0.78 and 0.25, respectively. These results are predominantly carried out in alpine or pre-alpine grasslands grazed by cattle (*Markart* et al. 2008; *Leitinger* et al. 2010). Only a few experiments are carried out in low mountain ranges (e.g., *Scherrer* et al. 2007). In such regions (e.g., Hesse) the increasing amount of horses and their impact on vegetation and soils has to be taken into account. In general, horse pasture grazing mostly has lower stock density than cattle grazing, but due to their different behavior the trampling intensity of horses is much higher than of cattle which leads to a higher soil compaction (e.g., *Davies* et al. 2014). The results of this study confirm this assumption and reveal that the runoff coefficients of the sites with horse grazing (site A and B) (*Figs. 1* and *2*) are distinctly higher than on the sites with cattle grazing (sites C and D) (*Figs. 3* and *4*) under constant boundary conditions (e.g., bulk density, soil depth at all rural sites approximately 1.20 m). Additionally, the comparison of sites A (non-grazing) and B (grazing) show that horse pasture rotation is useful to provide recovering processes of the soil to reduce surface runoff generation. According to *Leitinger* et al. (2010), this study underlines the importance to consider the land management strategies and the duration of grazing to estimate the surface runoff coefficient correctly. They highlight the livestock density as a decisive variable for runoff coefficient estimates. But our results show that not only the livestock density but also the exact specification of the species (cattle or horse) has to be considered as a further important influencing factor. Thus, more detailed process studies which focus on the soil compaction of horse pasture have to be carried out to understand the spatial and temporal variability of surface runoff generation.

These further process studies have to consider methodological issues which were raised by the application of a small rainfall simulator in this study. Generally, in-situ field experiments are always prone to external influences making it difficult to achieve an entirely identical reproduction. In the special case of small scale rainfall simulation, boundary effects caused by hammering in the plot frame are a common source of errors – mostly because of two side effects: 1) water that would have been collected as runoff may leave the plot through a gap between soil surface and plot boundary and 2) hammering in the boundary causes small scale alterations of the soil physical properties. While these methodological problems seem plausible, a description of preventive measures are scarce in the literature. Concerning the problem of water leaving the plot surface, e.g. *Foltz* et al. (2009) describe that they sealed the borders with bentonite in order to prevent water from flowing away. In this study, a similar approach was used as the small gaps were sealed using in-situ material collected in direct vicinity of the plot. Therefore, at least autochthonous material was used to minimize the effect. The second side effect described was minimized by driving the plot frame into the soil with a depth of only 4 cm (*Zemke* 2017). Therefore, only a small top layer was disturbed and soil physical properties remained unchanged as far as possible. Besides boundary effects, there are different disturbances or irregularities that can never be eliminated in the field such as macropores caused by root structures or soil animal activity which lead to altered and primarily higher infiltration rates. Despite all of the inherent methodological issues, small scale rainfall simulation is a reliable and commonly used tool in hydrological field research, delivering a deeper insight in actual on-site processes (e.g. *Iserloh* et al. 2013; *Ries* et al. 2013). Therefore, the results presented within this study aim to provide a first quantitative assessment of underlying processual dependencies.

5. Conclusions

Assessing the spatial variability of surface runoff generation as basis for an accurate flood prediction, the results of our study distinctly show that a differentiation between plots with horse grazing and cattle grazing has to be made and their different various impacts on the surface runoff have to be entirely considered. It is clearly emphasized that horse grazing forces the surface runoff generation which might be caused by the higher impact of horses on soil compaction and on the damage of the pasture sward. To our best knowledge, this study investigated the runoff coefficient of horse pasture in the low mountain ranges for the first time. Thus, in addition to this first-time rainfall simulations, more experimental studies are necessary to obtain a broader process knowledge, particularly in regard to the increasing portion of horse grazing in the low mountain ranges.

Author Contributions

Peter Chifflard wrote the paper and conceived and designed the experiments; Peter Chifflard, Dennis Moulding, Jan-Thorben Petri, Julian J. Zemke and Martin Reiss performed the experiments and analyzed the data.

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