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Measuring of infiltration rate in different types of soil in the Czech Republic using a rainfall simulator

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Abstract: Knowledge of the issue of water movement in the soil is the basis for agricultural activity, but also for many other sectors. One of the basic indicators that is evaluated in soil science is the rate of water infiltration into the soil. The article specifically states how soil texture and soil moisture affect the rate of water infiltration. The results show that changes in water infiltration can be significant and certain trends can be traced. The rate of water infiltration into the soil is most affected by the sand fraction (soil particles 0.05–2 mm). The higher the percentage of these soil particles in the soil, the lower the changes in infiltration rate depending on the degree of saturation. The article further evaluates soil moisture in relation to texture. The results were obtained at several research locations within the period 2014–2021 in the territory of the Czech Republic. The above findings are primarily applicable to the region of Central Europe or can be used as comparative values for regions in the rest of the world.

Keywords: soil erodibility; soil moisture; soil texture; surface runoff; water infiltration rate

The water infiltration rate into soils is one of the critical factors that influence the soil water regime (Novák & Hlaváčiková 2019). It indicates how much precipitation will be in the form of surface runoff and how much will infiltrate into the soil (Rawls et al. 1992). The higher the infiltration capacity of the topsoil, the more water can infiltrate (Suttisong & Rattanadecho 2011). Knowledge of soil water flow and its variations is needed in many environmental fields, such as runoff modelling (Chandler et al. 2018), soil conservation (Heard et al. 1988), irrigation systems (Bhardwaj et al. 2007), slope stability (Vardon et al. 2016), land drainage (Youngs 1976), earth dam design (Ferdos et al. 2015) or flood management (Simpson & Meixner 2012).

The process of water infiltration is reported to be affected by many factors such as soil properties, underlying surface or rainfall characteristics (Ahuja et al. 2007; Neris et al. 2012). Most soil physical properties are highly variable throughout the year,

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but soil texture is relatively stable. Therefore, this article is primarily focused on verifying the relationship between water infiltration and soil texture. The problematics of water infiltration and surface runoff is also important in relation to climate change. The probability of extreme weather occurrence (torrential rains or droughts) has increased in the last decades (Kornhuber et al. 2019) and this trend is still continuous (Min et al. 2011; Zwiers et al. 2011). Extreme climatic conditions fundamentally affect a number of important soil properties (Seneviratne et al. 2010). One of these properties is soil moisture, which is closely related to infiltration rate. For this reason, this property of the soil is also evaluated in the article. Of course, there are other factors that affect the infiltration rate, such as the amount of organic matter in the soil (Nemes et al. 2005), soil structure (Kodešová et al. 2009), soil compaction (Zhang et al. 2006) etc., but these are not the focus of this paper.

The main goal of the article is to verify how much initial moisture in soils with different textures affects water infiltration. Three hypotheses are verified in this article:

The relationship between water infiltration rate and soil texture could be determined.

There is a relationship between initial soil moisture and water infiltration rate.

Relationship between water infiltration rate and soil loss.

MATERIAL AND METHODS

The research was carried out between 2014 and 2021. A rainfall simulator was used to measure water infiltration in the soil. It is a research device used worldwide to study soil erosion and hydrological processes (Dunkerley 2008; Rodrigo-Comino et al. 2018). The rainfall simulator provides a comprehensive set of information from which infiltration rate can be determined. The principle of measuring using a rainfall simulator is based on the simulation of precipitation in a defined area. The rainfall simulator developed at Research Institute for Soil and Water Conservation (RISWC) was used for the research, where the size of defined area for simulation is 21 m^2 (Kabelka et al. 2019; Hofbauer et al. 2023). The device has four nozzles (fulljet type) at a height of 3.0 m, which are connected by a pipe system. Each nozzle covers an area up to an angle of 104° at a pressure of 34.5 kPa. The size of the water drops is close to the size of natural raindrops (Kovář et al. 2012). The intensity of the simulated rainfall was set around 1 mm/min.

During each term of measuring, two rainfall simulations were performed on the same area. The main aim was to verify soil with initial moisture and subsequently the soil with higher moisture obtained from the first rainfall simulation. Before each simulation, soil samples were taken from the experimental plot to determine soil moisture by the gravimetric method as soil water content by mass in % according to the formula:

$$\%\ \text{Soil water} = \frac{\text{Weight of wet soil}(\text{g}) - \text{Weight of dry soil}(\text{g})}{\text{Weight of dry soil}(\text{g})} \times 100$$

Disturbed soil samples for moisture determination were always taken in the upper part of the simulated area in the space below the fourth nozzle. The upper layer of soil with a size of 50 cm^3 was taken. The total time of the first rainfall simulation was 30 min. Then there was a technological 15-min break. During the technological break, another disturbed sample was taken at the moment when all the water had already infiltrated and the surface runoff from the first simulation had ended. A 15-min break was followed by a second rainfall simulation with duration of 15 min. During rainfall simulations, the amount of infiltrated water and surface runoff were measured. The surface runoff was collected in a water-collecting flume in the lower part of the experimental area. Its amount was determined using a tipping bucket. From these measured data, the average infiltration rate of the soil in mm/min was calculated as a difference between surface runoff and the water that infiltrated the soil.

Infiltration rate was always monitored on the bare soil. Bare soil means an experimental plot completely without plant cover prepared according to the methodology Wischmeier and Smith (1965) and Guideline "Erosion Control in the Czech Republic – Handbook" by Janeček et al. (2012). This methodology was the same on all experimental plots. The research was carried out at eight locations in the Czech Republic (Figure 1). During the research, 8 to 20 measurements were made at individual locations, always on the same plot (Table 2). The altitude of the sites varied between 300 and 545 m and the slope 5–10°. A more detailed description, including coordinates, is given below:

(1) Třebsín (49.8542853N, 14.4639703E) – the study area si located in Central Bohemia. The summer climate is slightly warm and humid. The mean

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annual rainfall is 550–650 mm and has a temperature of 7–8 °C.

(2) Solopysky (50.2590500N; 13.7421208E) – the study area is located in Ústí Region. The typical summer climate is slightly warm and dry. The mean annual rainfall is 450–550 mm and the average temperature 7–8.5 °C.

(3) Jevíčko (49.6561078N; 16.7089289E) – the study area is located in Moravia. The summer climate is warm, dry to slightly dry with an average annual temperature of 8.4 °C. Annual precipitation ranges from 650 to 750 mm.

(4) Věž (49.5645353N; 15.4508692E) – the study area is located in Vysočina (area of the Bohemian-Moravian Highlands). The summer climate is mild to slightly cold with an average annual temperature of 7.2 °C and annual precipitation of 600–750 mm.

(5) Petrovice (49.5523536N, 14.3295014E) – the study area is located in Central Bohemia, the summer climate is slightly dry and humid. The mean annual precipitation is 550–650 mm and the temperature is 7–8 °C.

(6) Skoupý (49.5763589N, 14.3567811E) – the study area is located in Central Bohemia, the summer climate is slightly dry and humid. The mean annual rainfall is 550–650 mm and the temperature is 7–8 °C.

(7) Valečov (49.6388550N, 15.4891042E) – the study area is located in Vysočina, especially in the area of the Bohemian-Moravian Highlands. The summer climate is slightly dry and humid. The mean annual rainfall is 650–750 mm and the temperature is 6–7 °C.

(8) Puclice (49.5864069N, 13.0128503E) – the study area is located in Plzeň Region in the area of the Pilsen Uplands. The summer climate is slightly warm and dry. The mean annual rainfall is 450–550 mm and the temperature is 7–8.5 °C.

All data from the experimental plots and measurements were subjected to basic statistics. The statistic was performed for data containing infiltration rate in the first rainfall simulation and in the second simulation. The main objective in this case was to verify whether the change in soil water infiltration rate between simulations is statistically significant. For each location, the average infiltration rate in mm/min and the standard deviation were determined. Subsequently, the normality of the data was verified by the Shapiro-Wilk test (significance level α 0.05). Not all locations met the normality of the data (even after performing a logarithmic transformation of the data), therefore the Mann Whitney U test (significance level α 0.05) was used, which is appropriate in these cases. The same evaluation method was performed for soil moisture information.

RESULTS AND DISCUSSION

Locations with different soil texture were included among the experimental areas (Table 1). Soil texture fractions were analyzed and possible dependencies with infiltration rate and soil moisture were searched for.

Infiltration rate and its changes in relation to soil texture. The results show that the soil texture has a significant influence on infiltration rate. This is in agreement with the authors (Bloemen 1980; Wesseling et al. 2009; Yao et al. 2013) who did similar research.

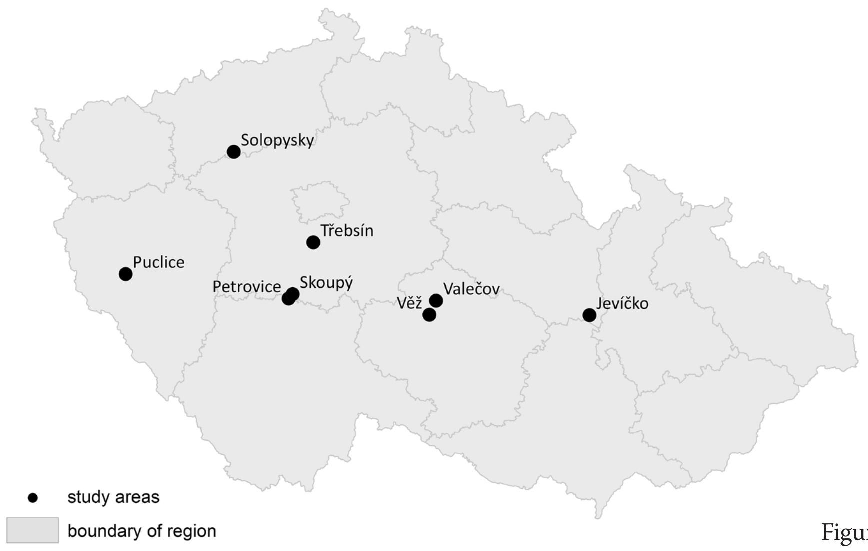

Figure 1. Map of the experimental areas

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Table 1. Basic soil characteristics of the experimental areas

Location	Soil classification (USDA – soil texture triagle)	Soil texture (%)			Content of C_{ox} (%)
		clay (< 0.002 mm)	silt (0.002–0.05 mm)	sand (0.05–2 mm)	
Třebsín	silt loam	9.16	53.98	36.86	1.21
Solopysky	clay loam	24.79	41.77	33.44	1.02
Jevíčko	silty clay loam	28.39	60.8	10.81	1.19
Věž	sandy loam	11.47	35.7	52.84	1.16
Petrovice	sandy loam	7.33	24.07	68.6	1.01
Skoupý	sandy loam	7.05	37.6	55.35	1.32
Valečov	loamy sand	9.33	8.2	82.48	0.98
Puclice	loam	11.03	44.0	44.97	1.49

USDA – The United States Department of Agriculture, C_{ox} – carbon oxides

According to our data, the amount of sand particles (0.05–2 mm) has the greatest effect on water infiltration rate due to changing soil moisture. This fact is clearly visible in Figure 2. The R^2 number for the trend line reaches the value of 0.8535, so it is a relatively strong dependence. For the other two soil texture fractions, the R^2 number reached lower values.

With the exception of one locality (Puclice), the results of the other localities are very close to the established trend. One of the main reasons why Puclice deviates the most from the established trend may be the carbon oxides (C_{ox}) content in the soil, which was the highest there (Table 1). Soils with higher organic matter content are able to infiltrate and retain more water than soils with less organic matter (Hudson 1994; Adamu & Aliyu 2012; Yao et al. 2013).

The rate of infiltration between rainfall simulations changed the most in the Jevíčko location, which has 10.81% sand particles. This is followed by the locations of Solopysky and Třebsín, where the content of sand is around 35%. On the other hand, the rate of infiltration changed the least at localities with the highest sand content, namely at the Valečov and Petrovice locations. This is most apparent in the case of Valečov, where there is loamy sand soil.

It is therefore evident from the results that due to smaller changes in the rate of water infiltration in sandy soils, a more constant surface runoff due to changing soil moisture can be expected in these soils. This is the case of the Valečov location, where the infiltration rate changed between rainfall simulations by only 15.64%. On the contrary, in soils with a low percentage of sandy fraction, there was a more

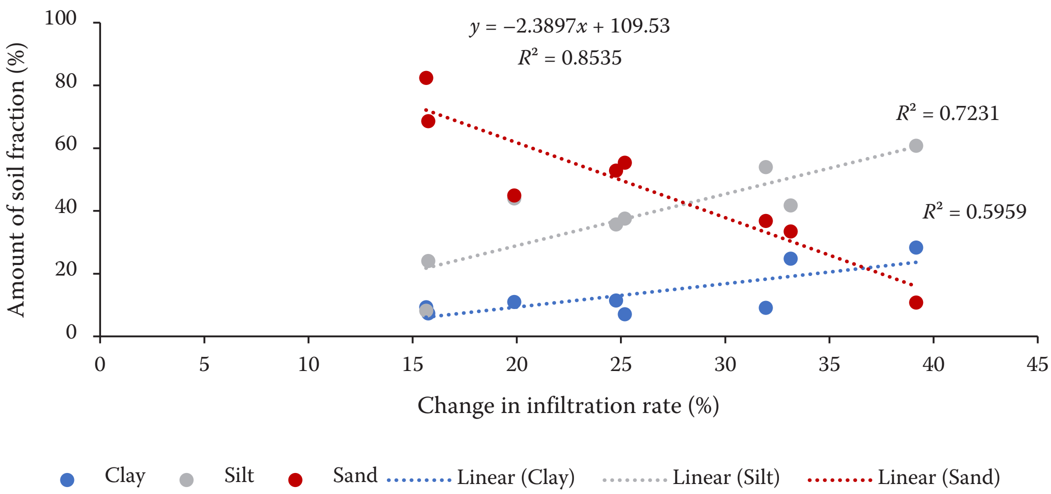

Figure 2. Relationship between infiltration rate and soil texture

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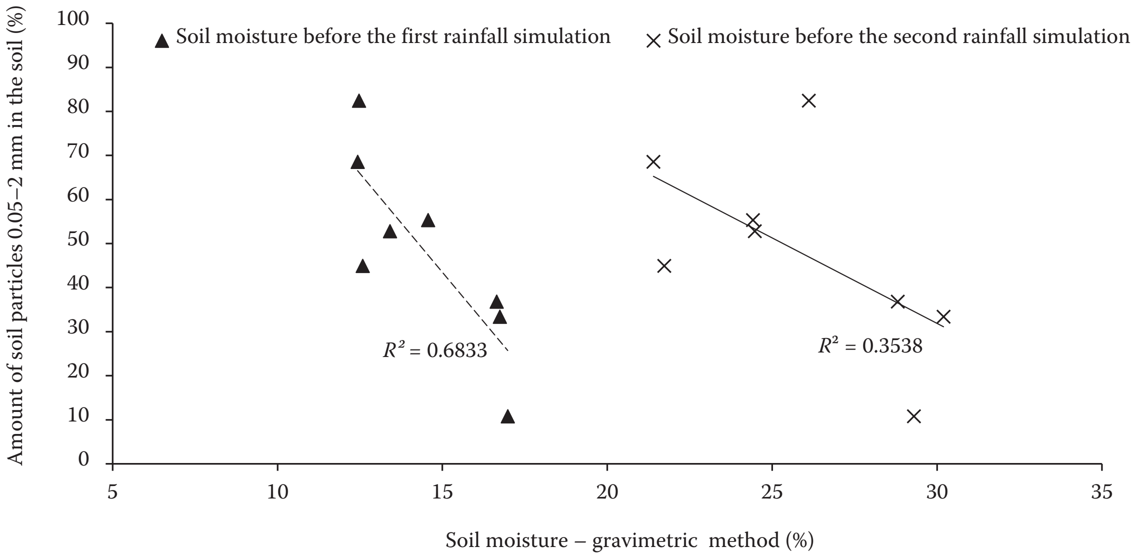

Figure 3. Relationship between soil texture and soil moisture

significant decrease in the rate of water infiltration. In the case of our results, the infiltration rate changed by 39.16% at the Jevíčko location (Table 2), which is a relatively significant change for the subsequent prediction of surface runoff.

As part of the research, various trends in initial soil moisture were also monitored. Figure 3 shows that soil moisture was on average higher in soils with a lower percentage of sand (0.05–2 mm) than in soils with a higher percentage of this fraction. Lighter soils with a higher sand content do not hold water as tightly and dry out faster (Gerard 1965; Oosterveld & Chang 1980; Cosby et al. 1984), which is also in line with our measured results (R^2 = 0.6833). The soil moisture results in Figure 3 may be affected by current weather at the time of simulation, especially the occurrence of the last natural rainfall (Pan et al. 2003) before measuring by the rainfall simulator. However, due to the relatively large number of measurements, this fact should not have a major influence on the established trend. The variation in initial moisture in the individual experimental plots is captured to some extent in the standard deviation of the average soil moisture (Table 2).

After the first rainfall simulation, the differences in soil moisture depending on soil texture (content

Table 2. Calculated results from rainfall simulator data

Location	Time period	Count of measurement	First rainfall simulation				Second rainfall simulation			
			Soil moisture before simulation		Infiltration rate		Soil moisture after the first simulation		Infiltration rate	
			(%)	SD	(mm/min)	SD	(%)	SD	(mm/min)	SD
Třebsín	2015–2021	20	16.64	3.64	0.087	0.028	28.8	3.98	0.064	0.03
Solopysky	2016–2021	20	16.74	3.79	0.069	0.014	30.2	2.53	0.045	0.012
Jevíčko	2015–2021	19	16.98	4.14	0.081	0.017	29.3	3.87	0.051	0.018
Věž	2017–2021	13	13.41	2.82	0.065	0.012	24.47	2.75	0.049	0.012
Petrovice	2015–2018	11	12.43	3.75	0.072	0.016	21.4	2.91	0.06	0.01
Skoupý	2015–2017	8	14.56	2.75	0.083	0.016	24.41	3.45	0.061	0.011
Valečov	2014–2017	9	12.47	3.21	0.063	0.01	26.11	4.28	0.053	0.009
Puclice	2015–2018	12	12.58	2.89	0.054	0.007	21.73	4.72	0.043	0.008

Soil moisture – soil water contents by mass; SD – standard deviation

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Table 3. Basic statistics from the measured date for infiltration rate and soil moisture

Location	Infiltration rate - average change between rainfall simulations						Soil moisture		
	Shapiro-Wilk test (*P*-value)		Mann Whitney U test (*P*-value)	(mm/min)	SD	percentage change (%)	Shapiro-Wilk test (*P*-value)		Mann Whitney U test (*P*-value)
	first RS	second RS					first RS	second RS	
Třebsín	1.10E-02	8.40E-02	1.54E-02	0.023	0.006	31.94	5.42E-01	4.29E-01	4.97E-08
Solopysky	8.80E-02	2.60E-02	2.88E-05	0.023	0.011	33.14	2.21E-01	2.47E-01	1.01E-07
Jevíčko	3.51E-01	1.90E-01	2.66E-05	0.030	0.008	39.16	8.67E-01	8.16E-02	1.36E-09
Věž	2.77E-01	3.15E-01	1.60E-02	0.016	0.006	24.76	4.87E-01	2.52E-01	2.84E-06
Petrovice	1.16E-01	6.81E-02	3.85E-02	0.012	0.007	15.74	8.40E-02	1.38E-01	1.13E-05
Skoupý	4.99E-01	5.81E-01	3.66E-02	0.021	0.007	25.18	6.14E-01	6.90E-04	9.31E-04
Valečov	9.21E-01	2.95E-01	4.16E-02	0.010	0.003	15.64	6.74E-02	3.17E-01	2.17E-05
Puclice	2.85E-01	3.93E-01	3.49E-03	0.011	0.005	19.87	3.05E-01	1.46E-01	8.11E-05

Soil moisture – soil water contents by mass; RS – rainfall simulation; SD – standard deviation; statistics test was performed for comparing data from the first and second rainfall simulation

of 0.05–2 mm soil particles) were less significant (R^2 = 0.3538). A similar trend is confirmed in the study of Vereecken et al. (2007).

The information from this sub-chapter can be used, for example, in environmental modelling. When modelling surface runoff without taking actual soil moisture into account, less accurate results can be expected for heavier soils compared to lighter, sandy soils due to larger fluctuations in water infiltration rate (Table 3). It would therefore be advisable to make some corrections (positive or negative) to the amount of surface runoff based on the current soil moisture for soils with a heavier texture. This recommendation is especially suitable for short-term rainfall-runoff models, where surface runoff from individual rainfall events is modelled.

Infiltration rate during the first and second rainfall simulation. In all experimental locations, it was confirmed that lower initial soil moisture (state before the first rainfall simulation) allows faster water infiltration than if the soil has higher soil moisture (state after the first rainfall simulation) (Figure 4).

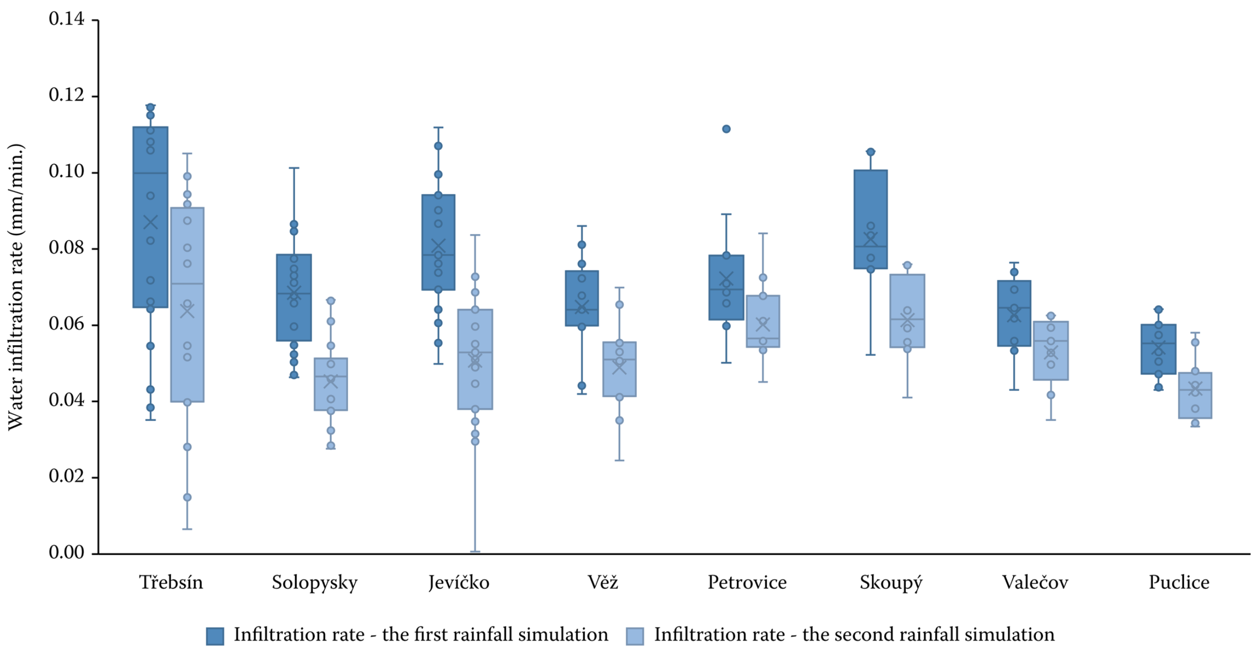

Figure 4. Water infiltration into the soil in the first and second rainfall simulations

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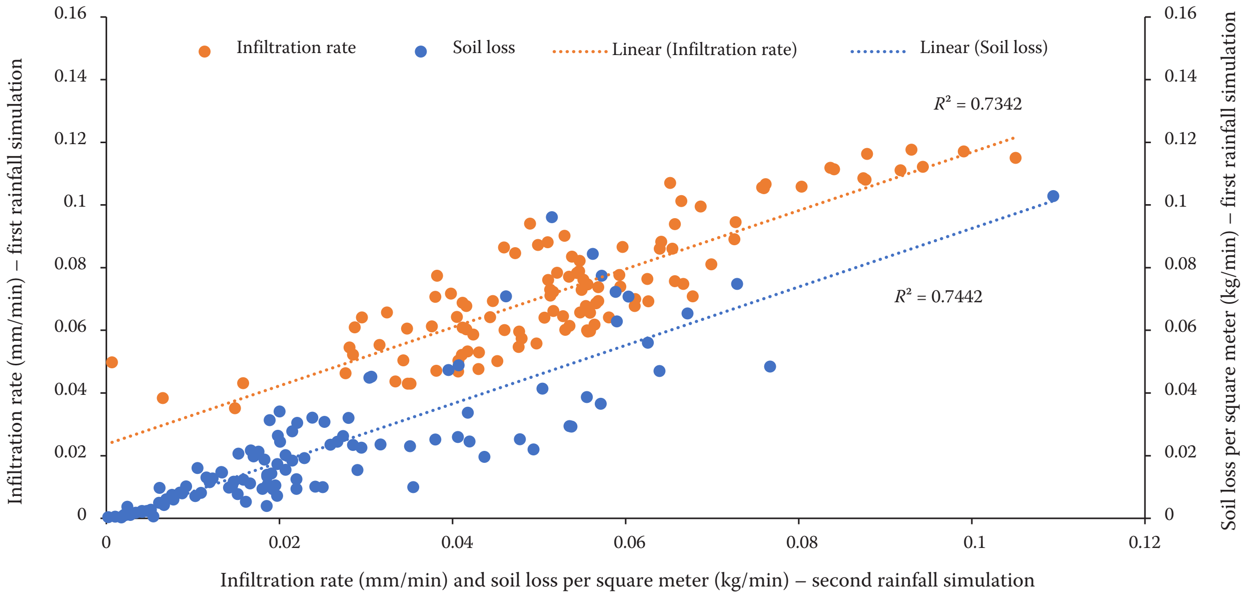

Figure 5. Results from rainfall simulator – differences between first and second rainfall simulation (infiltration rate and soil loss)

This is in line with Houser (2003), Steward et al. (2013), Matula et al. (2015) and others. Due to the method of rainfall simulation and preparation of the experimental area (Wischmeier & Smith 1978; Janeček et al. 2012) before the first simulation (loosening the top layer of soil up to 5 cm and then rolling it with a roller weighing 50 kg), the occurrence of a solid upper crust was prevented, which could affect the measurement, especially on heavier soils. The emphasis was also placed on the fact that there were no plant residues on the experimental plots, which could also significantly affect the measurements.

Infiltration rate in relation to soil loss. It is obvious that changes in infiltration rate affect the amount of surface runoff (Blanco-Canqui et al. 2002). This can in turn affect the amount of soil eroded. Due to the large amount of information obtained from the rainfall simulator, it was possible to look for the relationship between water infiltration and soil loss. Individual measurements are shown in Figure 5, specifically shows the average infiltration rate and soil loss from the rainfall simulator in one minute. When evaluating each parameter separately, it is possible to find certain dependencies between rainfall simulations, but when comparing the rate of soil water infiltration and soil loss, our data showed no significant relationships (various combinations were tried). It has not been confirmed that higher water infiltration means lower soil loss, which is consistent with, for example, Szabó et al. (2015).

This confirms the very well-known fact that soil erodibility is a more complex process than water infiltration. Infiltration rate is one of the parameters affecting soil loss, but several other parameters must be taken into account when modelling it, especially the energy of raindrops, which significantly increases the transport capacity of surface runoff (Vaezi et al. 2017). According to many studies (for example Kiani-Harchegan et al. 2019; Zambon et al. 2021;) soil loss increases with rainfall intensity and slope steepness (Sobol et at. 2017). In the case of water infiltration, this fact does not apply. Some studies (Wischmeier 1966; Kinnell 2016) claim that a higher slope means more surface runoff, others do not (Lal 1975; Liu et al. 2015; Jourgholami et al. 2020). The possible causes of this phenomenon are explained by e.g. Roose (1973). The relationship between slope and infiltration rate has different conclusions in a number of studies (see above). In our case, when the slope on the experimental plots was in the little variance of 5–10°, no significant influence on the infiltration rate is expected. This is confirmed by the study of Arjmand Sajjadi and Mahmoodabadi (2015) or Martínez-Murillo et al. (2013), where this issue is well described.

CONCLUSION

Information on the rate of water infiltration and its response to varying soil moisture is important and useful, especially in modelling erosion and hydrological

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processes. The results confirm that the infiltration rate changes due to changing soil moisture. This fact is most influenced by sand particles (0.05–2 mm). It is specifically stated that the more sand in the soil, the smaller the changes in infiltration rate (15.64% – location Valečov). On the contrary, in heavier soils, the rate of water infiltration changes by up to 40% (Jevíčko location). This means that more accurate data can be expected in surface runoff predictions in sandy soils if current soil moisture is not taken into account. The results also show that in all examined cases, the infiltration rate between rainfall simulations decreased. Therefore, it is obvious that different initial soil moisture can change the water regime of the soil. This fact subsequently affects other downstream processes. The results presented in the article are primarily applicable for the territory of the Czech Republic, possibly for the territory of Central Europe, or they may serve as a comparison for other areas.

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