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The Effects of Long-Acting Water Erosion on the Hydro-Pedological Characteristics of Chernozems

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Abstract: In sloped and intensively managed land, the soil characteristics are influenced mainly by water erosion intensity. In the present study, we evaluate the characteristics of Chernozems damaged by long-acting water erosion, particularly their retention and infiltration properties and possible impacts on soil fertility. Using infiltration experiments and a collection of intact samples, we performed analyses of the physical soil properties in individual transects. Our results confirm the lower infiltration capacity of deteriorated soil in the accumulation slope parts, which corresponded with the analyses of soil samples. The reduced bulk density in the accumulation slope parts exceeded 1.5 g·cm^{-3}, indicating unsatisfactory (non-structured) soil conditions. In the transportation and eluvial slope zones, porosity values reached satisfactory numbers only at a depth of 10 cm. The median values of aeration showed a similar trend, but we recorded a higher value fluctuation.

Keywords: hydraulic conductivity; erosion; soil degradation; infiltration capacity

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1. Introduction

Soil has an irreplaceable position in the landscape ecosystem and provides important regulatory services, including water infiltration (replenishing underground water resources and delaying surface runoff), water filtration, water retention and accumulation, storage of nutrients, transportation, transformation, and recovery function [1]. Twenty-first-century perspectives on climate change in the Central European region signaled the risk of more prolonged and intensive drought episodes, particularly in the period from April to September, preparing us to expect significant unfavorable effects on agriculture, forestry, and water management [2,3]. One of the main contributors to temperature rising and the number of dry periods is farming on extensive arable land blocks sowed with monocultures [4]. In addition, the soil condition is threatened by several degradation processes, the most severe being water erosion. The erosion processes lead to the degradation of more stable forms of organic matter in the soil, resulting in reduced infiltration and retention of precipitation water [5].

In Europe, more than 4 million hectares of land are at risk of erosion, exceeding 5 tons per year [6]. In the Czech Republic (CR), water erosion threatens more than 50% of arable land. Deteriorated soil properties reduce both productive and non-productive functions [7]. Essential non-productive functions of agricultural land, particularly regarding the consequences of attenuating droughts and flash floods, include the soaking of precipitation water and its subsequent retention in the soil environment [8,9]. The danger of floods and drought risk can be attenuated by water retention in the catchment by applying adequate measures [10]. Suitable land use and change in the landscape structure can improve the ratio of infiltration/runoff in favor of infiltration [11]. Infiltration is the process by which water penetrates the soil, representing one of the key flows in the hydrological cycle. The two main processes influencing the water balance are water infiltration and subsequent water redistribution in the subsurface environment [12]. The process of water penetration into the soil is highly dependent on hydraulic soil properties, which are spatially variable, both in vertical and horizontal directions. In natural conditions, the net sum of precipitation that enters the soil also depends on the vegetation cover, which captures the precipitation water and protects the soil surface against the impact of falling raindrops [13]. Several important parameters play a role in the infiltration process: precipitation intensity, soil moisture, air content in the soil, amount of aggregates and pseudo-aggregates, porosity, and non-capillary soil conductivity. For instance, [14] reported that natural infiltration usually involves 30–50% of precipitation in mild, humid climates, 10–20% in Mediterranean-type climates, and about 0–2% in dry climatic conditions.

According to [15], the infiltration process is one of the most important components of the hydrological cycle. The infiltration process is quantified by establishing the amount of water infiltrated over time and deriving the cumulative infiltration and infiltration rate [16,17]. One of the dominant hydraulic soil characteristics is the saturated hydraulic conductivity of the upper soil layer [18,19]. Saturated hydraulic conductivity, Ks, indicates the soil's capacity to conduct and transfer the water needed by plants to the root zone and drain it from the root zone [20]. The extent of infiltration, however, depends on the soil conditions [21], the amount of organic matter [22,23], crop management, and agrotechnical operations [24,25]. When the soil is in good structural condition, it can absorb large amounts of water [9]. Water retention capacity decreases with increasing soil skeleton content. This phenomenon is associated with erosive processes that deplete the soil of humus substances and fine particles. Intensively managed sloped areas affected by erosion display marked differences in the color and quality of individual slope parts, as reflected by their deteriorating hydro-physical properties.

Significant erosion processes mostly occur in areas with steep and/or long slopes, intensively farmed as arable land, and impacted by frequent heavy precipitation [26]. The Czech Republic has the largest production blocks in the EU, and the Land Parcel Identification System records an average of 4.6 times larger production blocks than Austria [27,28]. Consequently, more than 50% of agricultural land in the CR is at risk of water erosion, and over 500 thousand are already damaged. Furthermore, over 14% are at risk of wind erosion, 45% of the land is compacted, the soil lacks organic matter is acidified, and the biological component, namely soil life, is disturbed. Land damaged by erosion gradually loses its productive capacity, negatively affecting crop yields.

We evaluated the properties of Chernozems damaged by long-acting water erosion, focusing on their retention, infiltration capacity, and possible impacts on soil fertility. The purpose of our study was to determine differences between the soil properties of various slope parts—eluvial, transportation, and accumulation zones. We performed the field measurements over five years in different localities of Southeast Moravia in the Czech Republic.

2. Material and Methods

2.1. Study Area

The selected study area is situated in an intensively farmed region characterized by very sloped land parcels and large land blocks. The structure of the cultivated crops conforms to the market demands, and the rotation of crops mainly include crops involving erosion risk (corn, sunflower, rapeseed) and, to a lesser extent, cereals (winter wheat) (Figure 1). We selected localities in southern Moravia with Chernozems for field experiments on sloped land parcels impacted by the long-lasting effects of erosive processes with a cultivated wide-row crop (corn) at the measurement time.

The studied area is located at an altitude of 200–275 m.a.s.l. The geomorphic area is warm and dry, with an annual average temperature of 8.8–9.2 °C. The annual total precipitation is 530–560 mm, depending on the location. The soils here are Chernozems modal, partly degraded, and the parent substrate consists of loess. It is mainly undulating, sometimes sloping to strongly sloped terrain, and is affected by water erosion processes. The texture of these soils is medium-heavy to light, without a skeleton.

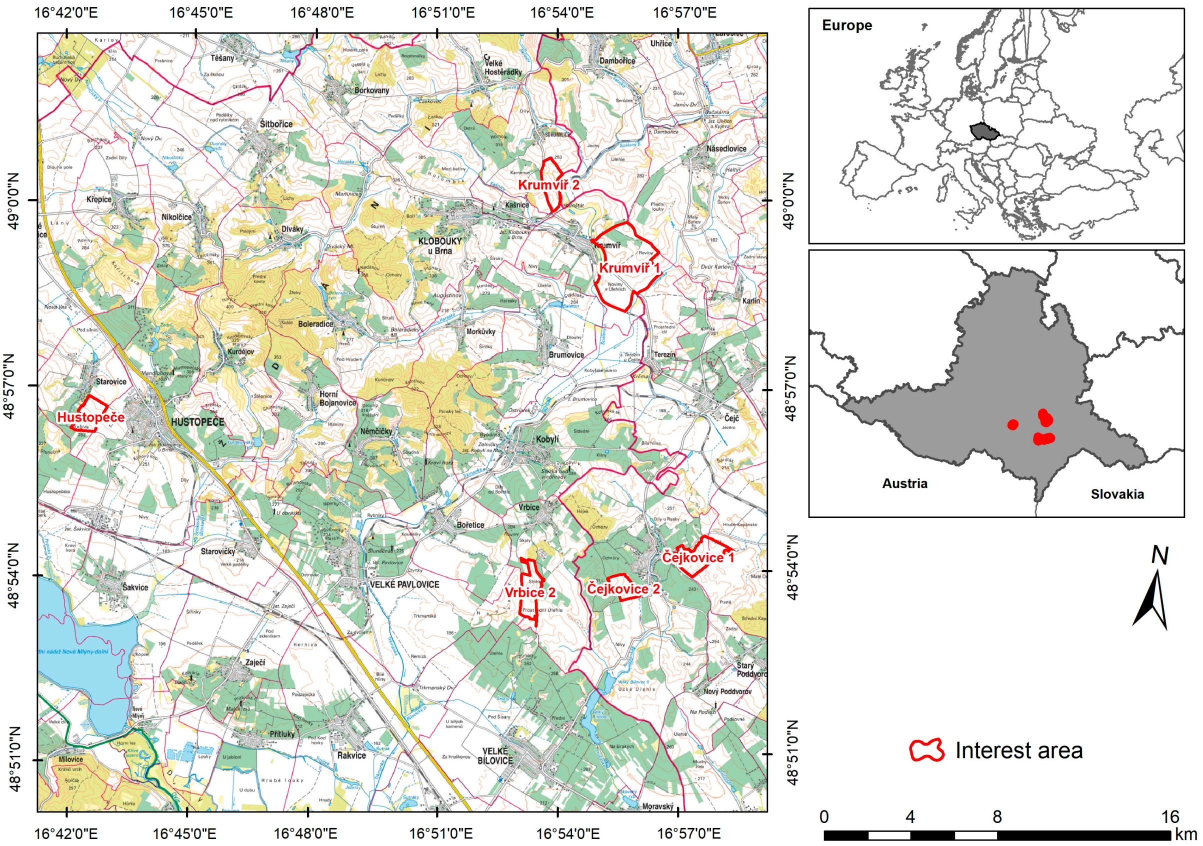

Figure 1. Localities under treatment in the Czech Republic.

2.2. Methods

To measure the soil infiltration capacity, we performed infiltration experiments in all cases after crop harvest, followed by field collection of undisturbed soil samples. The infiltration experiments were conducted in previously defined transects with indicated and geo-referenced soil sampling and infiltration testing sites. The sampling sites were established to cover the accumulation area of eroded material (ACU), the middle slope part (transportation area—TRANS), and the upper slope part—eluvial (ELU). We measured each site of the individual slope area for two hours using three pressure infiltrometers. We performed 20 measurements in 10 localities, including infiltration experiments in three transect sites (ELU, TRANS, and ACU) in triplicate. In total, we completed 180 experimental measurements.

The locality of Hustopeče, with the marked points ELU, TRANS, and ACU is presented in Figure 2 below.

During the infiltration experiments, we always collected the soil samples from 10 and 30 cm depths in triplicate measurements using Kopecký's cylinders of unified 100 cm^3 volume. The sampling was performed nearby during the infiltration measurement. In total, we analyzed 360 soil samples. The analyzed values were bulk density (ρd), porosity (P), and aeration (A). The tests were conducted in an accredited laboratory at the Research Institute for Soil and Water Conservation using standardized methods. (https://www.vumop.cz/akreditovane-laboratore (accessed on 12 April 2018)).

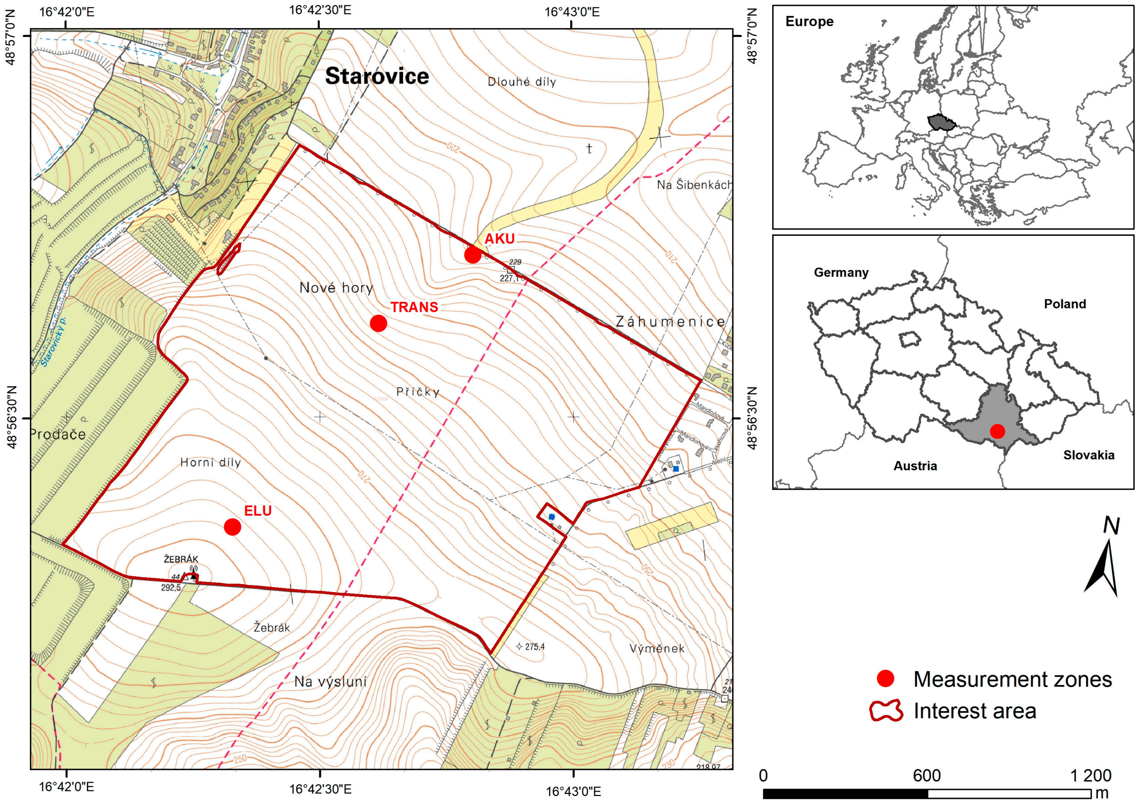

Figure 2. Measured points in Hustopeče.

2.3. Material

We performed the infiltration experiments using the ponding infiltrometer Flowgroup (Flowgroup, Inc., Brno, Czech Republic-according to patent No. 300463), the Mariott bottle principle, an adjustable water ponding depth, and an automatic data record [29]. The authors of [30] operate by measuring the loss of water with a precise surface sensor, and the data from the decreasing water level are automatically saved by a recording unit (data logger), which connects to a computer (Figure 3). The instrument continuously measures the rate of liquid infiltration into the porous soil environment. Then, the maximum immediate value of the infiltration rate is determined. Water from a reservoir soaks at a constant hydraulic decline through an intact soil sample in a cylindrical form delimited by an inserted ring. The loss of water from the reservoir is measured.

The measurement was running until it achieved a stable infiltration rate. We stopped the experiment after about two hours. The user manual recommended this approach, which was discussed with the authors [30]. At this time, the infiltration rate curve stabilized.

For each measurement, we established the values of saturated hydraulic conductivity (Ks) and compared them to the analysis results of the soil samples.

The saturated hydraulic conductivity, Ks, was estimated according to [18,31], by using Philip's equation by solving only the first three parameters, as shown in (1)–(2):

$$I = C_1 t^{1/2} + C_2 t + C_3 t^{3/2} \tag{1}$$

$$v = \frac{1}{2} C_1 t^{-1/2} + C_2 + \frac{3}{2} C_3 t^{1/2} \tag{2}$$

where

C_1—estimate of sorption [cm·min$^{-1/2}$]

C_2, C_3—parameters, C_2 [cm·min^{-1}], C_2 [cm·min$^{-3/2}$]

The estimate of saturated hydraulic conductivity, Ks, is calculated from (3).

$$K = (C_1 C_3)^{1/2} + C_2 \quad (3)$$

Figure 3. Ponding infiltrometer Flowgroup.

3. Results

3.1. Monitoring Infiltration Characteristics

Water infiltration into the soil profile and surface runoff in agricultural land strongly depends on the properties of the soil and the management of the upper soil layer. To analyze data from all the measurements, we established the values of saturated hydraulic conductivity (Ks) in the eluvial, transportation, and accumulation zones. Our results are presented in Figure 4 and Table 1.

Table 1. Value of saturated hydraulic conductivity (cm·hr^{-1}).

	ACU	TRANS	ELU
Minimum	0.00	0.00	0.00
25th Percentile	0.95	2.02	7.38
Median	4.11	8.31	15.35
75th Percentile	8.80	14.01	36.00
Maximum	41.99	96.55	284.36

Concerning the median, maximum values, and range of values for saturated hydraulic conductivity, the highest infiltration capacity of soils was found in the eluvial part (ELU median = 15.35 cm·hr^{-1}), followed by the transportation part (TRANS median = 8.31 cm·hr^{-1}). The lowest infiltration was detected in the accumulation part (ACU median = 4.11 cm·hr^{-1}). However, the largest value fluctuation and the highest maximum values were found in the ELU part of the slope. The values of individual parameters are shown in the box graph in Table 1.

Our analysis results suggest that the long-lasting exposure of sloping soils to the effects of water erosion results in the soil's decreasing infiltration capacity and the accumulation of fine granular particles in the toe [32]. High infiltration capacity was found in the eluvial slope parts, but at the potential cost of lower water retention, faster soil surface desiccation, and lower water availability for plants.

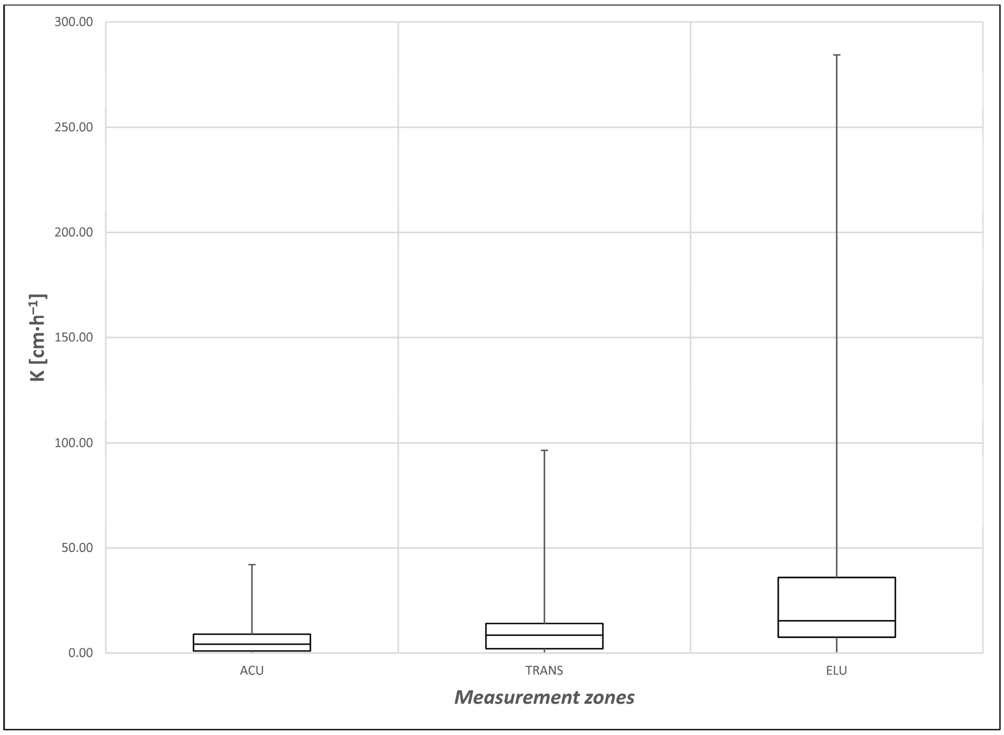

Figure 4. Values of saturated hydraulic conductivity in measurement zones.

3.2. Evaluation of Physical Properties

Figures 5–7 summarize the evaluation analyses of the bulk density, total porosity, and aeration of samples collected from 10 and 30 cm of the soil profile.

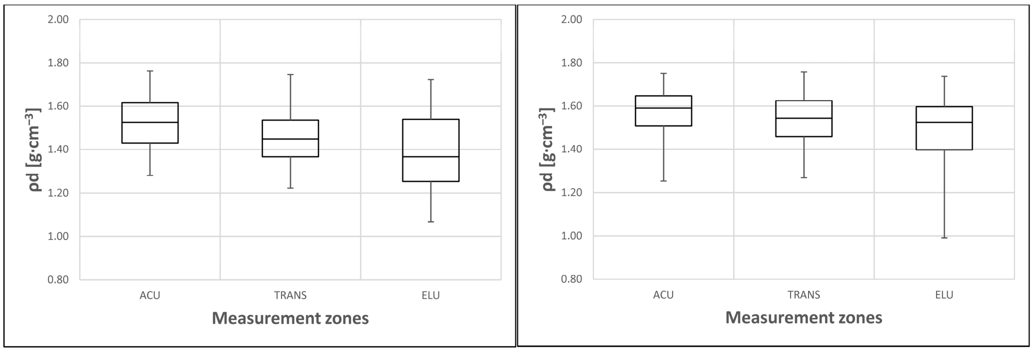

Figure 5. Bulk density at the depths of 10 (**left**) and 30 cm (**right**) in the soil profile.

The obtained values were compared to values from different soil structure qualities, as presented in the literature [30].

Bulk density (ρd) is used as an indicator of soil quality, reflecting its state of loosening or compaction. A bulk density of >1.4 $g{\cdot}cm^{-3}$ indicates unsatisfactory soil conditions and compaction. For loamy soils, the critical bulk density value is 1.45 $g{\cdot}cm^{-3}$.

Porosity (P) is one of the main parameters of the spatial organization of soil mass. Pores are sites of all physical, physical–chemical, and biological processes. The values of soil porosity assess soil density and, indirectly, the soil structure. The porosity of loamy soils ranges within 40–50%. Values of <40% indicate unsatisfactory soil conditions and soil structure disturbance.

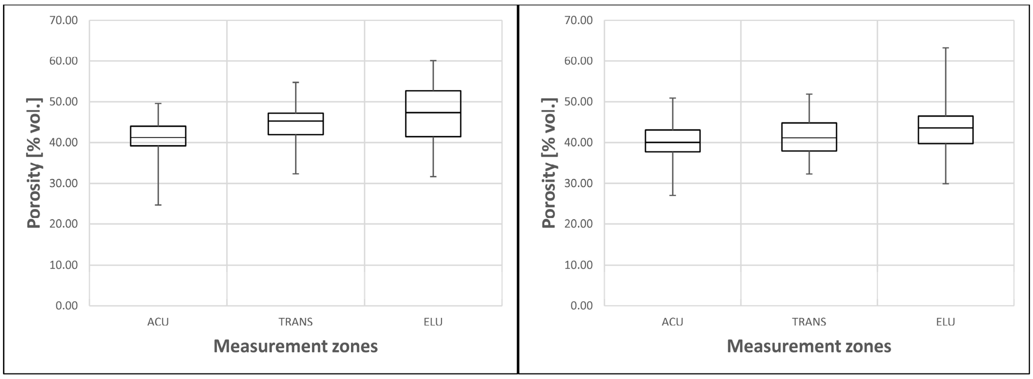

Figure 6. Porosity at the depths of 10 (**left**) and 30 cm (**right**) in the soil profile.

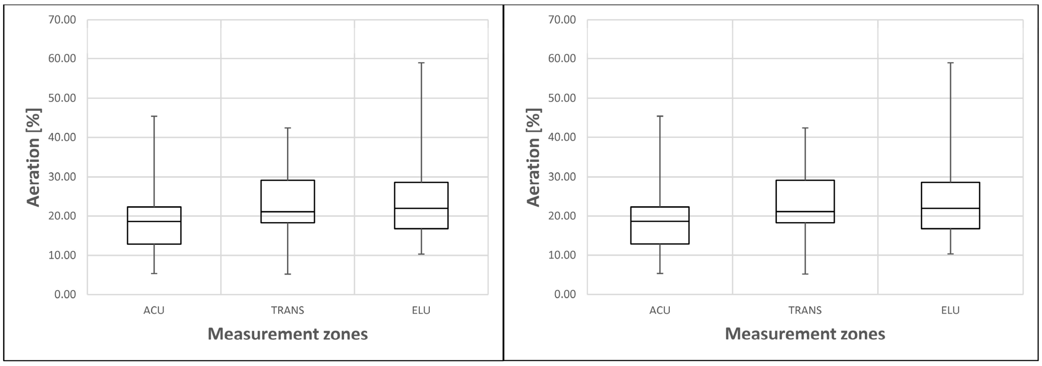

Figure 7. Aeration at the depths of 10 (**left**) and 30 cm (**right**).

Aeration (A) of soil expresses the air concentration in the soil. Optimal values of aeration in the topsoil fluctuate within the 18–24% vol range.

Bulk density values reflect the ratio of soil solids and porosity. Our analysis of soil samples shows an increased bulk density value in the accumulation parts at the depths of 10 and 30 cm compared to the transportation and eluvial slope zones. The median values are >1.5 g·cm^{-3} (1.54 and 1.6 g·cm^{-3}, respectively), indicating unsatisfactory, critical values of soil structure conditions. In the transportation and eluvial slope parts, the median values of bulk density at a depth of 10 cm bordered satisfactory conditions (TRANS = 1.44 g·cm^{-3} and ELU = 1.39 g·cm^{-3}). By contrast, at a depth of 30 cm, there were already higher soil compaction indications, probably due to improper agrotechnical management (median of 1.54 g·cm^{-3} in the TRANS part, median of 1.5 g·cm^{-3} in the ELU part). Values of porosity (P) and aeration (A) were higher in the transportation and eluvial parts than in the accumulation part. Regarding the median values of porosity and aeration, the porosity value reached satisfactory numbers in the transportation and eluvial parts only at a depth of 10 cm (TRANS = 45% and ELU = 46.5% vol.). At a depth of 30 cm, the porosity values were even lower (ACU 40%, TRANS 41.2%, and ELU 43.5% vol.). The median values of aeration displayed a similar trend but with higher value fluctuations. Similarly, as for the porosity values, there was a decrease in aeration at a depth of 30 cm. However, aeration values exceeding the optima detected in the transportation and eluvial slope parts at a depth of 10 cm (TRANS 26.3%, ELU 30.1%) indicated the soil profile's potentially low water retention capacity. The soil sample analysis results correlate with the saturated hydraulic conductivity findings, which depend on the soil structure quality and degree of soil compaction characterized by bulk density.

Finally, we performed a correlation analysis of all the studied soils' analyzed hydrophysical properties at the depths of 10 and 30 cm (Tables 2 and 3).

When comparing the correlation coefficients for Ks in all measured zones (10 cm), the correlation coefficients for the ELU and TRANS zones are more significant than the ACU zone. The most significant correlation coefficients are in the ELU zone. A significant negative correlation exists between Ks and ρd 10 (−0.530) in the ELU zone. On the contrary, there is a positive correlation between Ks and P10 (0.511). When comparing the correlation coefficients Ks between the ELU and TRANS zones, there is a decrease in the correlation coefficient values at ρd 10 (−0.386) and P 10 (0.251). On the contrary, the correlation coefficient A 10 increased slightly (0.235). A more significant negative correlation (−0.386) can be observed only for the parameter ρd 10 (TRANS). The low values of the correlation coefficient in the ACU zone do not indicate that the evaluated parameters significantly influence Ks.

Table 2. Correlation analysis of all monitored parameters for hydro-physical properties at 10 cm of the soil profile.

		Ks	**ρd 10**	**P 10**	**A 10**
ELU	Ks	1			
	ρd 10	−0.530	1		
	P 10	0.511	−0.932	1	
	A 10	0.177	−0.360	0.437	1
TRANS	Ks	1			
	ρd 10	−0.386	1		
	P 10	0.251	−0.867	1	
	A 10	−0.235	−0.399	0.297	1
ACU	Ks	1			
	ρd 10	−0.101	1		
	P 10	0.111	−0.667	1	
	A 10	−0.118	−0.112	0.277	1

Table 3. Correlation analysis of all monitored parameters of hydro-physical properties at 30 cm of the soil profile.

		Ks	**ρd 30**	**P 30**	**A 30**
ELU	Ks	1			
	ρd 30	0.073	1		
	P 30	0.080	−0.818	1	
	A 30	−0.258	−0.618	0.573	1
TRANS	Ks	1			
	ρd 30	−0.019	1		
	P 30	−0.025	−0.704	1	
	A 30	−0.347	−0.001	0.193	1
ACU	Ks	1			
	ρd 30	−0.103	1		
	P 30	0.145	−0.698	1	
	A 30	−0.053	−0.022	0.238	1

When comparing the correlation coefficients for Ks across the zones of interest (30 cm), the correlation coefficient values indicate zero correlation between the evaluated parameters. Only the ELU and TRANS zones record a more significant correlation coefficient value for the A 30 parameter (ELU A30 = −0.258 and TRANS A30 = −0.347).

4. Discussion

Measuring the temporal-spatial variability of saturated hydraulic conductivity (Ks) is a time-consuming, costly task facing many uncertainties [33]. According to [34], only a weak correlation exists between the saturated hydraulic conductivity, Ks, and soil structure in arable land (<0.3 m depth). By contrast, data show that Ks depends more on bulk density, organic carbon content, and land use. The variability of assessed hydraulic conductivity in different slope parts of several studied localities was also confirmed by [35]. Our results agree with [36], who found that the lowest Ks values were associated with fine-grained, compacted soils. Compacted soils with high soil bulk density and strength have low infiltration rates. These phenomena increase the risk of temporal water logging, runoff, and erosion [37]. In certain conditions, using no-till technologies and heavy mechanization can help exacerbate this phenomenon. Water infiltration into the soil's accumulation parts is mostly reduced, and water stagnates on the soil surface and during wetter year episodes. As [38] mentioned, a surface compacted layer is commonly found in heavy no-tilled soils. However, other soil physical properties were negatively affected after a long period under no-tillage enhanced aggregate stability. A higher bulk density and lower porosity were recorded by [39] in minimum tillage and no-till planting systems. Furthermore, field traffic operations negatively affected aggregate stability, bulk density, and total porosity [40]. A comprehensive evaluation of no-till farming in NW Europe is presented in [41], where no-till farming with crop residues reduces the erosion rate. On the other side, soil structural properties were often poorer under no-till than conventional soils, resulting in decreased water infiltration rates and lower hydraulic conductivity [41]. Soil loss, runoff, and infiltration were measured on conventional and two no-till systems [42]. Removing surface residue significantly decreased infiltration rates and increased soil loss for both conventional till and no-till conditions.

According to [43], soil structure conditions correlate with long-acting water erosion in Chernozems of Southern Moravia. This finding corresponds with the results of our study. Furthermore, [32] reported the effects of soil particle transportation by erosion on the deterioration of soil properties in localities situated under slopes. These findings correspond with several years of experimental results conducted in the ten localities mentioned in this study. The decline in fine particles may result in the loss of larger particles as well [44], with further changes to different soil types in the original Chernozems [43,45,46].

5. Conclusions

Our measurement of infiltration properties and hydro-physical soil analyses in the studied localities from 2012 to 2016 demonstrates the impact of degradation processes caused by water erosion on the quality of Chernozems, particularly in their capacity to capture and retain precipitation water. In the heel slope sections of treated localities, there is an accumulation of eroded material, reduced soil aeration, and subsequent compaction of the soil profile, accompanied by an increase in bulk density.

The eluvial parts show higher infiltration capacity. However, the soil's capacity to retain water in the soil profile can be reduced due to the removal of fine particles and organic matter by erosion. The transport parts of the slope display different signs of erosion activity. Infiltration parameter values are closer to those in the accumulation slope parts. Localities selected for the survey based on similar climatic, soil, morphological, and cultivation properties did not always have identical characteristics (which is impossible in field conditions). Nevertheless, we can conclude that the comparison of soil characteristics in individual slope parts showed better infiltration capacity and favorable physical properties in the eluvial parts of the slope. The accumulation parts mostly displayed higher bulk density, lower infiltration capacity, and lower aeration.

The correlation analyses show only weak correlations among the analyzed factors at a depth of 30 cm. At a depth of 10 cm, the dependencies between the values were tighter in the eluvial and transport zones than in the accumulation zone.

The study of erosion's effect on various soil properties in field conditions tends to be influenced by many variable factors across time and space; therefore, providing exact results tends to be difficult. The issue requires monitoring all events in mutual contexts from which selected soil properties were evaluated for this article, characterizing the soil's ability to absorb and retain rainwater.

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