Original Research

Relation of Saturated Hydraulic Conductivity to Soil Losses

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Received: June 30, 2004
Accepted: December 20, 2004

Abstract

The relationship between saturated hydraulic conductivity and the soil erosion process are evident. However, the problem has not been so far sufficiently addressed in research, especially for typical Polish soils. Our paper presents the results of a modeling study on soil erosion losses and saturated hydraulic conductivity that was carried out in natural rainfall events on the 10 most typical farming soil types in Poland. The results show the relationship between saturated hydraulic conductivity and soil losses and saturated hydraulic conductivity jointly with sand texture group and soil losses. The conclusion is that the studies dealing with measuring saturated hydraulic conductivity may be applied to assess soil erosion losses.

Keywords: soil texture classes, precipitation, erosion, model experiment, pedotransfer functions

Introduction

The water erosion process is affected both by natural conditions and human activity. The basic relationship between soil losses and erosion factors has been described by [1, 2] (MUSLE) and [3] (RUSLE). Soil losses are caused by six major erosion factors such as: rainfall (R), soil erodibility (K), slope length (L) and steepness (S) as well as cover and management (C) and practice (P) mentioned in the USLE equation [4]. It seems very difficult to acquire the accurate assessment and comparison of the actual runoff and real soil losses on different soil types on the field scale because rainfall energy is spatially differentiated. Thus, some simplifications were accepted to create uniform conditions to compare erosion effects on different soils.

Runoff is generally a function of rainfall intensity and soil infiltration rate and can be stimulated on agricultural land by tillage and residue management practices [5]. In a simplified experiment in Puławy dealing with different soil types, the differences in runoff and soil losses were determined only by infiltration and indirectly by hydraulic conductivity [6].

Data obtained during a six-year experiment carried out under natural rain conditions has been used for analyzing soil losses for individual events.

Saturated hydraulic conductivity K_s is an essential parameter for understanding soil movement and soil hydrology. It is a fundamental input for modeling runoff, drainage, and movement of solutes in soils [7]. Saturated hydraulic conductivity K_s can be used to describe water movement under saturated conditions in the soils. Soils with small values of hydraulic conductivity have low infiltration rates and during intense rains, water run-off will lead to consequent soil losses and surface transport of colloids, nutrients and microbes, which can then cause problems of eutrophication and pollution of downstream areas [8]. Since knowledge of K_s is essential for using water flow models, it is useful to evaluate the influence of measured K_s on modelled runoff.

However, the effect of hydraulic conductivity on soil looses is not well documented. Our paper presents the impact of some physical properties including saturated hydraulic conductivity, particle size distribution, organic matter content and bulk density on soil losses.

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Methods and Materials

Field Experiment Description (site design)

The experiment was designed on the experimental field of the Institute of Soil Science and Plant Cultivation in Puławy, Poland. The microplots (1m x 2 m; 0.3 m deep) were installed on the field with a slope equal to 10% (Fig. 1). Microplots in two replicates were filled with humus horizon of the soil and maintained in clean-tilled fallow (Fig. 2). The experiment was carried out on the 10 most typical soil types in Poland, differentiated both in soil texture and soil organic matter content (Table 1). The textural groups of tested soils diversified from sandy and loamy to silty. The aim of the field microplot study was to determine soil losses and runoff affected by natural rainfall events. The quality and quantity of erosion losses on different soils under field conditions were compared. It was possible when different types of soils were collected in one place where some erosion factors (L, S, C, P) and rain factor (R) were uniform.

Fig. 1. The microplot experiment in Pulawy — one replication.

Fig. 2. The microplot with sandy soil.

Particle Size Distribution, Organic Matter Content and Bulk Density

Standard methods were applied to investigate particle size distribution and organic matter content. Soil texture was classified according to the FAO/USDA classification system [2,9].

Bulk density was determined from the mass of dry soil contained in 100 cm^3 stainless steel sampling cylinders in three replications from all plots. The samples were oven-dried at 105°C for 48 hours. The results were calculated as Mg m^{-3}.

Monitoring of Runoff and Soil Losses

The experiment was located in the immediate vicinity of a meteorological station where rainfall, temperature, humidity and other meteorological data were collected. A pluviograph was used for continuous measurements of rainfall. Runoff and soil losses were sampled for individual erosion storm events. Quality and quantity of runoff and soil losses were analyzed. Runoff from each plot was collected in boxes. Volume of water and soil weight were measured in each sample. The annual average of soil loss was calculated.

Measurements of Saturated Hydraulic Conductivity

Saturated hydraulic conductivity was measured by the falling-head method as described by [10]. For this, the samples were measured in the cylinders in which they were collected from top soil with 10 replicates of each plot. The samples were first wetted by capillarity for 24 hours. This was done from the bottom so that air could escape from the upper surface.

The results were analyzed with STATGRAPHICS Plus 2.1 statistical software. Pedotransfer functions for K_s and soil losses were obtained by regression analysis with each predictor variable investigated both separately and in combination (using backwards stepwise multiple regression). Only functions with significant and uncorrelated variables ($p<0.05$) were accepted.

Results and Discussion

Basic Physical Properties of Investigated Soils

The majority of investigated soils were sandy. The mean contents of sand, silt and clay were 61.6 [g $(100g)^{-1}$], 30.7 [g (100g)$^{-1}$], and 7.8 [g (100g)$^{-1}$], respectively. Mean organic matter content reached 1.49 [g (100g)$^{-1}$]. These values look similar to those obtained by [11] for 210 representative soil samples collected all over Poland. The results of particle size distribution and organic matter are presented in Table 1. The highest content of organic matter occurred in sandy loam 2.29 [g (100g)$^{-1}$] and medium in heavy sand soil 1.89 [g (100g)$^{-1}$]. Sandy soil and loamy sand contained the lowest amounts of organic matter: 0.39 [g (100g)$^{-1}$] and 1.13 [g (100g)$^{-1}$], respectively.

The values of dry bulk density ranged between 1.25 and 1.62 [Mg m^{-3}]. Mean dry bulk density amounted to 1.48 [Mg m^{-3}]. The results for dry bulk density are presented in Table 1.

Saturated Hydraulic Conductivity and Soil Losses

The log K_s values presented in Table 1 ranged from -6.185 to -3.282. The results of regression analysis showed that the lower content of both silt and organic matter and lower values of bulk density had increased K_s, according to the pedotransfer function (1).

$$\mathbf{log\ K_s} = 10.7787 - 0.0444797\cdot_{Silt} - 8.66336\cdot_{BD} - 1.13323\cdot_{OM} \quad (1)$$
$$R^2 = 87.1\ \%;\ p = 0.004$$

where:

$_{Silt}$ — silt content [g (100g)$^{-1}$]

$_{OM}$ — organic matter content [g (100g)$^{-1}$]

$_{BD}$ — dry bulk density [Mg m^{-3}]

The effects of some physical properties on saturated hydraulic conductivity were observed by [13-16].

Over the years 1997-2002 there were 54 rainstorms with runoff, meaning that more than 9 events appeared per year. The most intensive rains occurred in July and August. Some gentle rains led to runoff only on the most sensitive soils like silt loam and sandy loam. The heaviest rains occurred during the first two years of the experiment and in that time annual losses of sandy loam and silty loam soil were 25.4 and 24.4 [t/ha/year], respectively [6]. Soil losses in the microplot experiment differed greatly and depended on soil textural class as well as on the intensity and duration of rain (Table 2).

The total annual average soil losses ranged from 0.8 to 16.5 [t/ha/yr]. Minimum losses were recorded on sandy soil [0.8 t/ha/yr] and loamy sand soil [8.4 t/ha/yr], while the most serious losses on loess soil [16.5 t/ha/yr] and sandy loam [alluvial] soil [16.2 t/ha/yr].

The impact of saturated hydraulic conductivity on soil losses calculated using linear regression is presented in Fig. 3 and described by equation (2).

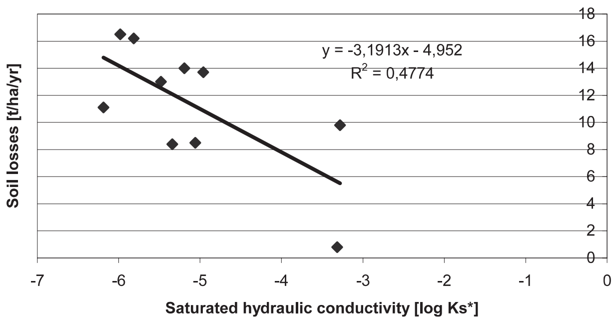

Fig. 3. Relationship between saturated hydraulic conductivity and soil losses computed for this study.

Table 1. Physical properties, texture classes and saturated hydraulic properties of experimental soils.

Soil No	Sand g (100g)$^{-1}$	Silt g (100g)$^{-1}$	Clay g (100g)$^{-1}$	Bulk density Mg·m^{-3}	Organic matter g (100g)$^{-1}$	log Ks*	Texture class FAO/USDA system
1	98.5	0.5	1	1.62	0.39	-3.315	Sand
2	84.5	12	3.5	1.54	1.40	-5.060	Loamy sand
3	77	20	3	1.59	1.13	-5.341	Loamy sand
4	68	28	4	1.56	1.89	-6.185	Sandy loam
5	60.5	30.5	9	1.54	1.55	-5.194	Sandy loam
6	64	25.5	10.5	1.41	2.29	-4.960	Sandy loam
7	44.5	52.5	3	1.42	1.72	-5.481	Silt loam
8	19.5	70.5	10	1.40	1.33	-5.980	Silt loam
9	46	28.5	25.5	1.25	1.78	-3.282	Loam
10	53	38.5	8.5	1.46	1.39	-5.815	Sandy loam
Range	19.5-98.5	0.5-70.5	1-25.5	1.25-1.62	0.39-2.29	-6.185-3.282	
Mean	61.6	30.7	7.8	1.48	1.49	-5.061	

Note: * K_s — saturated hydraulic conductivity [m s-1]
Logarithms in this table are to base 10

Table 2. Effect of soil losses on some physical properties

Soil No.	Sand g $(100g)^{-1}$	Silt g $(100g)^{-1}$	Clay g $(100g)^{-1}$	Bulk density $Mg \cdot m^{-3}$	Organic matter g $(100g)^{-1}$	log K_s	Soil losses (t/ha/yr)
1	98.5	0.5	1	1.62	0.39	-3.315	0.8
2	84.5	12	3.5	1.54	1.4	-5.060	8.5
3	77	20	3	1.59	1.13	-5.341	8.4
4	68	28	4	1.56	1.89	-6.185	11.1
5	60.5	30.5	9	1.54	1.55	-5.194	14.0
6	64	25.5	10.5	1.41	2.29	-4.960	13.7
7	44.5	52.5	3	1.42	1.72	-5.481	13.0
8	19.5	70.5	10	1.40	1.33	-5.980	16.5
9	46	28.5	25.5	1.25	1.78	-3.282	9.8
10	53	38.5	8.5	1.46	1.39	-5.815	16.2
Range	19.5-98.5	0.5-70.5	1-25.5	1.25-1.62	0.39-2.29	-6.185±- 3.282	0.8-16.5
Mean	61.6	30.7	7.8	1.48	1.49	-5.061	11.2

$$\textbf{Soil losses} = -3.19513 \cdot_{\log Ks} -4.9624 \qquad (2)$$

$$R^2 = 47.7\ \%;\ p = 0.027$$

where:

log K_s — logarithm of saturated hydraulic conductivity

This relationship accounted for less than 50% of the variability in total soil losses but the impact is significant. A similar effect was found by [17], when they observed that the saturated hydraulic conductivity of Ap horizon decreased with increasing erosion. This was confirmed in our experiment.

Analysis of soil losses using saturated hydraulic conductivity and additional physical parameters of soil are more adequate. Results of multiple regression analysis showed that the lower sand content and lower values of log K_s increase soil losses, according to the obtained pedotransfer function (3).

$$\textbf{soil losses} = 8.86385 - 0.132241 \cdot_{sand} - 2.07151 \cdot \log K_s \qquad (3)$$

$$R^2 = 82.4\ \%;\ p = 0.002$$

where:

sand — sand content [g $(100g)^{-1}$]

log Ks — logarithm of saturated hydraulic conductivity

Saturated hydraulic conductivity together with sand texture group accounts for more than 80% of the variability in total soil losses.

Flangan and Nearing [9] have found that saturated hydraulic conductivity is one of the most sensitive soil input parameters in predicting runoff. However, Humberto Blanco-Canqui et. al., [12] have found relationships between predicted runoff and measured runoff using effective hydraulic conductivity as input computed from saturated hydraulic conductivity (K_s).

Summary and Conclusions

The study showed the relationship between soil losses and saturated hydraulic conductivity (log K_s). The summarized impact of saturated hydraulic conductivity and sand content on soil losses is two times stronger and accounted for more than 80% of the variability. The assessment of a detailed relationship between soil losses and saturated hydraulic conductivity and other physical properties should be further analyzed. Our research suggests that such studies may be a basis for validation of obtained pedotransfer functions for soil losses on independent data sets under field conditions. Large-scale surveys of soil losses may be useful for predicting adverse changes in the soil environment. This would be helpful in protecting rural ecosystems and proper management of the production capacity.

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