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ANALYSIS OF FACTORS INFLUENCING THE INTENSITY OF SOIL WATER EROSION

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Soil water erosion is one of the most widespread and most damaging processes of degradation in the world. Despite the fact that extensive research on it is carried out by a large number of scientists all around the world, it still occupies a leading position among global threats. Because soil erosion is a complex and quite complicated process, small steps have to be undertaken in order to reach any relevant conclusions. In most cases, in order to simulate soil erosion processes, mathematical models are widely used that are considered useful and helpful tools since the measurement of the erosion of terrain consumes time and space and is impossible in many parts of the world. The aim of the study presented lies in an analysis of elements input into a physically-based erosion model. Those input factors directly influence the model's end results, i.e., the soil erosion processes. The article attempts to define to what extent they affect the model results and soil erosion processes as well. The specific parameters of the soil erosion model, i.e., resistance to erosion and hydraulic roughness, were determined by simulated rainfall experiments. The results identify changes in the parameters input to the final model results together with different initial conditions.

KEY WORDS: surface roughness, erosion resistance, soil water erosion, rainfall intensity, surface runoff

Introduction

Soil erosion is a very popular and well-known research topic; nevertheless, it poses some unanswered and scientifically unexplored questions. The reason is that soil erosion is a natural and complex process ongoing in nature; it is quite variable in space and over time and is strongly dependent on many factors. Some of the most significant elements in soil erosion research are soil roughness and the state of the vegetation cover to protect the surface of soil against external factors. Soil roughness characterizes micro-variations in surface elevations that have especially occurred due to management practices and tillage systems (Vázquez et al., 2005). Soil roughness also indicates irregularities of soil surfaces resulting from the soil's texture and type, the sizes of aggregates and rock fragments, the surface cover, land use, and management practices used (Thomsen et al., 2015). According to (Michael et al., 1996), the roughness of surface soil represents a hydraulic parameter (roughness coefficient) and means a reduction in the flow velocity of the surface runoff, thanks to microrelief irregularities (soil aggregates, plant residues). Increasing the values of this coefficient leads to a reduction in the flow velocity and other related soil processes. Because soil roughness increases water retention and infiltration, it is considered a principal element influencing wind and water erosion (through the reduction of runoff volume and speed). Soil roughness represents one of the factors controlling surface runoff and soil loss, but it is also a main indicator of the degradation of a soil's microstructure. However, few studies have been conducted on this parameter. The roughness of the soil surface is directly connected with land use management practices in several ways. The preparation of the soil can influence the soil roughness, depending on the soil type and mineralogy and the management techniques used (Bramoski et al., 2012). The roughness of the soil surface influences the speed and accumulation capacity of the surface runoff, the infiltration rate, and the related soil erosion processes (Römkens et al., 2002). Two components are used to define soil roughness, i.e., random roughness (RR) (Currence and Lovely, 1970) and the tortuosity index T (Boiffin, 1984). Both components mentioned describe the relationships of the surface water storage in the soil (Govers et al., 2000; Kamphorst et al., 2000).

In order to reduce potential soil loss and decrease the intensity of soil erosion processes or the volume of surface runoff, one of the first measures taken should be to analyse the agricultural practices in the area under consideration. As mentioned above, the roughness of the soil surface directly influences soil erosion processes and is affected by management practices; therefore, a small change in the agricultural practices used can lead to increasing the roughness of the soil surface (Honek at al., 2020).

Another parameter strongly impacted by the loss of soil is represented by soil erosion resistance, which represents the total of various forces. This parameter is influenced by different physical and chemical soil attributes such as aggregate stability, organic matter content, rooting, soil cover, surface structure, and tillage practices, and is variable over time and in space within the same soil texture group.

Because soil erosion is a complicated process influenced by many changeable factors, in most cases the models developed to simulate the soil erosion contain some parameters that are used to modify the unstable condition and the prediction errors. In the model used in this study, this parameter is called the "skin factor"; it not only allows eliminating the errors resulting from the simplified assumptions of the model, but also evaluates the impact of agricultural management practices on the soil (Michael et al., 1996).

The aim of the study lies in an analysis of the soil input parameters used in the physically-based Erosion-2D model, which are considered the most important parameters not only in the model analysed (Erosion-2D model) but also in many other soil erosion and erosion prediction models as well. The rainfall simulator is an indispensable device used for parametrization of the soil input parameters and on which basis the laboratory measurements were performed. The rainfall simulator is a tool with which it is possible to simulate the characteristics of natural rainfall events as closely as possible (Clarke and Walsh, 2007). These types of devices are widely used in laboratory and field experiments in order to imitate and analyse the effects of alterations in vegetation cover, management practices or changes in soil.

Laboratory conditions eliminate the external factors such as wind, soil moisture, or the antecedent soil conditions that are considered the main advantages of laboratory experiments (Aksoy et al., 2012). Therefore, this study can also be used for informational purposes of a general character without considering a specific model.

Material and methods

The water erosion of soil is commonly studied in laboratories, and experiments are based on artificially generated precipitation using rainfall simulators. Typically, the influence of various factors, such as the intensity or total amount of rainfall, soil characteristics, or the influence of the slope and length of the eroded area on soil erosion, is evaluated. The results of these experiments are used for a better understanding of erosion processes, estimations of sediment transported on the ground, or the calibration of mathematical simulation models. In this paper, we will focus on the possibility of the parameterization of the Erosion-2D model. The model parameters will be calibrated according to the measurement results and compared with the values in the literature.

EROSION-2D MODEL

The Erosion-2D model is a physically-based and single event erosion model with a focus on simulating soil water erosion on a slope profile. The model can be used for slopes of different lengths with a spatial resolution of 1 m. Because all the calculations are performed for single rainfall events, the erosive impact of a rainfall event is expressed by two major elements (Werner, 2006):

- The intensity and duration of the rainfall,
- The management practices (the type and development stage of the cultivated crop, the type of tillage, etc.).

The Erosion-2D model describes the erosion processes in a complex way and is therefore constructed based on the following components (Werner, 2006):

1. *The digital elevation model,* which includes interpolation of a 1 m grid from the input data, calculation of the topographic parameters from the slope profile, calculation of the individual catchment area and length of the flow path for each cell (runoff concentration),
2. *The Infiltration model which includes* rainfall infiltration (Green-Ampt approach) (Green and Ampt, 2011),
3. *The runoff and erosion sub model* performs the simulation calculations.

The surface roughness in the model is calculated based on the equation given by Manning:

$$v_q = \frac{1}{n} \cdot \delta^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \tag{1}$$

where

v_q flow velocity of surface runoff [m/s],
n roughness coefficient according to Manning-Strickler [s/m$^{1/3}$],
S slope [m/m],
δ flow depth of surface runoff [m].

$$\delta = \left[\frac{q * n}{S^{\frac{1}{2}}}\right]^{\frac{3}{5}} \tag{2}$$

where

q runoff rate [m^3/(s m)],
S slope gradient [-],
n Manning's hydraulic roughness [s/m$^{1/3}$].

$$\mathrm{n} = v_q - \frac{5}{3} \cdot q^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \tag{3}$$

where

n roughness coefficient according to Manning-Strickler [s/m$^{1/3}$],
S slope gradient [-],
q runoff rate [m^3/(s m)].

Rainfall simulator and experimental site

In order to generate an artificial rainfall with a constant rate of intensity, an Eijkelkamp small rainfall simulator was used in the study (Fig. 1). The experiment was performed in a laboratory at the Faculty of Civil Engi-

neering, Slovak University of Technology in Bratislava. The simulated rainfall system is not restricted by nature, i.e., the rainfall and its duration can be adjusted. Several researchers have conducted various runoff and erosion experiments using this system.
The rainfall simulators can be used to study:

- characteristics of soil infiltration,
- erosion and surface runoff,
- relative protection for different stages of vegetation growth,
- relative erodibility.

The simulators of rainfall events started to be used in the 1940s (Wilm, 1942; Meyer and McCune, 1958, in Zachar, 1982). Their development reflected progress in technology and hydrological processes, including an understanding of the infiltration processes.
The advantages of the Eijkelkamp rainfall simulator are the possibility of repeating artificial rain with a set intensity, length of precipitation, adjustable slope of the area investigated, portability and constant rainfall, and easily portable and mobile water sources. The disadvantages can be seen in the limited length of the precipitation (volume of reservoir) and in limiting the size of the area that can be used to perform the experimental simulation. With regard to the study presented, four laboratory experiments with 12 minutes of intermittent rainfall were simulated. The main differences between the rainfalls used lie in the initial soil moisture.
The area from which the soil samples were taken and analysed is located in the urban district of Turá Lúka, which is a part of the town of Myjava and is located in the northern part of the Myjava Hills. A small experimental catchment is located approximately in the middle of the cadastral area of Tura Lúka. This small catchment is endangered by water erosion, especially an eroded gully, due to the size of the catchment. Based on Novák's classification (Novák and Hlaváčiková, 2017), the geology of the area is characterised by a flysch massif, and the dominant soil types are cambisols and rendzina. The climate is characterized as mildly humid and warm with mild winters and an average annual precipitation of 650 to 700 mm. The total area of the catchment is 29 hectares, and the total size (length) of the eroded gully is approximately 300 meters (Hlavčová et. al, 2019). The predominant purpose of the catchment is based on agricultural production with a system of crop rotation. This catchment is a part of a research area managed by the Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology, since 2015 within the 7RP RECARE European project.

Description of laboratory measurements

The soil sample was adjusted by loosening the soil before each rainfall simulation, which consisted of 12 minutes of intermittent rain. The basic characteristics of the selected artificial rainfall events are shown in Table 1.
Because of the limitations of the rainfall simulator (the storage of the reservoirs is only 2.3 litres of water), the rainfall simulations had to be interrupted. After the interruptions, the surface runoff´s volume, sediment weight, and soil moisture were measured.

Fig. 1. Rainfall simulator and laboratory experiment.

Table 1. The laboratory rainfall simulation experiment (plot area =0.0625 m^2)

Experiment No. (12-minutes artificial rainfall with the interruptions)	Slope [º]	Initial soil moisture [%]	Rainfall intensity [mm/min]	Surface runoff volume [l]	Sediment volume [g]
1	10.8	23.7	5.3	3.4	62.6
2	10.8	6	5.3	2.45	73.7
3	9.7	29	5.3	5.4	158.7
4	8	13.2	4.9	3.6	39.5

**Total time artificial rainfall is 42 minutes with the interruptions*

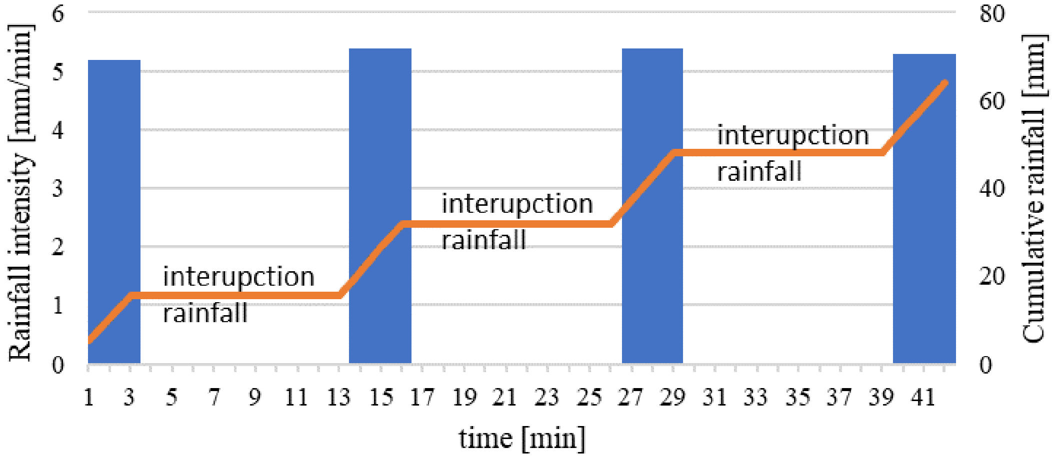

Fig. 2. Scheme of laboratory experiment – 42 minutes of artificial rainfall events (4 x 3 minutes, with 10-minute interruptions).

Methodology and input parameters

The experiment consisted of laboratory measurements of the surface runoff and sediment volume on small experimental plots using a rainfall simulator. In the first step, it was necessary to upscale the small area of the simulator to the scale of the Erosion-2D model (a limited scale) by the regression between the various slope lengths and relevant simulations of the surface runoff´s volume on the slope lengths of 1, 4 and 8 meters. In the second step, the upscaling was used to compare the results of the surface runoff of the model and the surface runoff of the experimental measurements. The flow chart of the experiment is shown in Fig. 3.
Table 2 comprises the ranges of the input parameters that are available in the parameter catalogue for the Erosion 2D and 3D model users. The choice of those parameters depends on the type of soil, cultivation method, and vegetation phase.
At the beginning, the tabular values that are recommended by the catalogue of parameters for the Erosion-2D model (Table 3), were used. In the next step, the changes in the parameters that have a significant impact on the results modelled (erosion resistance, hydraulic roughness, and the skin factor) were performed. In the process of parameterization, the parameters were manually changed (gradually to the entire recommended range), and the sensitivity of the model was monitored together with the process of parametrization.
These input data were specified based on the results of the erosion measurements from the laboratory experiments. The process of the parameterization was done for each intermittent rainfall event separately.
The parameter calibrations were performed:

- for the surface runoff,
- for the surface runoff and sediment,
- for the volume of the sediments.

In this study, the output parameters were primarily searched for the weight of the sediment, which determines the rate of erosion. The calibration of the parameters selected, i.e., erosion resistance, hydraulic roughness, and the skin factor, were chosen because of their influence on the erosion process. The intensity of

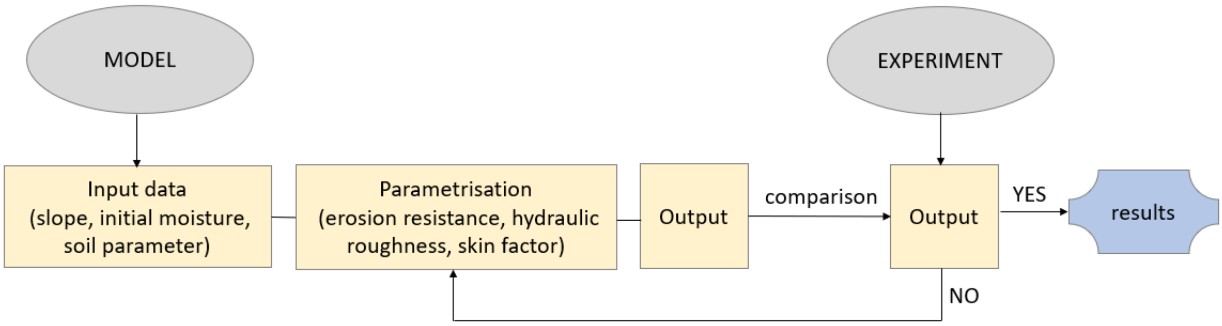

Fig. 3. Scheme of the experiment, consisting of laboratory measurements and hydrological modelling.

Table 2. Range input data of the Erosion-2D model for all the types of soil and types of cultivation method

Bulk density [kg/m^3]	Organic matter [%]	Erosion resistance [kg.m.s^{-2}]	Manning roughness [s.m$^{-1/3}$]	Skin factor [-]	Initial soil moisture [%]	Cover [%]
920–1960	0.8–1.9	0.00005–0.01	0.006–0.900	0.02–60	6–60	0–100

Table 3. Input data of the model Erosion-2D

Bulk density [kg/m^3]	Organic matter [%]	Erosion resistance [kg.m.s^{-2}]	Manning roughness [s.m$^{-1/3}$]	Canopy cover [%]	Skin factor [-]	Clay [%]	Silt [%]	Sand [%]
1800	1.15	0.0008	0.015	0	1	10	36	48

the erosion is the most prominent feature and is not directly measurable. During the process of parametrization it was found that the skin factor has the greatest impact on the formation and volume of surface runoff. The skin factor is also considered as a correcting factor since it is a parameter used to adjust and optimize the infiltration process and minimize the model errors as well.

Results and discussion

In the study, four extreme rainfall events with interruptions were analysed. The simulation was performed in the laboratory as a priority to ensure the same conditions. The following elements were significant:

- surface condition (without vegetation, the same tillage management),
- artificial rain (concept, rainfall intensity, duration of rain),
- slope ratios.

There was a significant and fundamental change in the initial soil moisture, which ranged from 6 to 29% (Table 1). Based on the results, it is obvious that the Erosion-2D model does not respond to very low initial soil moisture at the set intensity and duration of the rain. In the second experiment, where the initial soil moisture was 6%, no outputs from the model were obtained. For this reason, only 3 laboratory measurements were further analyzed.

In the following table (Table 4), the results of the erosion parameters obtained during the individual simulations of the parameters calibrated are displayed. The results presented the following schemes: A) original parameter settings, B) calibration of Manning's roughness and changing the skin factor parameter, C) skin factor 1, without any correction and calibration of Manning's roughness and erosion resistance.

The results show that the parameters were chosen in a suitable setting. The aim was to find and analyse the influence of the parameters and their sensitivity with respect to the initial soil moisture and the slope of the relief as well. All the parameters selected (Manning's roughness, the erosion resistance, and the skin factor) affect the erosion process, and their variability is extensive. In the next step, the results achieved were analysed by creating an arithmetical average of the parameters from the results for variants B and C.

Set up parameters:

- setup group 1 (Erosion resistance 0.0008 [kg.m.s^{-2}], Roughness 0.0151 [s.m$^{-1/3}$], skin factor 19),
- setup group 2 (Erosion resistance 0.000916 [kg m s^{-2}], Roughness 0.0248 [s.m$^{-1/3}$], skin factor 1).

A graphic representation of the model results for the groups of parameters is shown in Figure 4.

The results point to further possible improvement of the erosion parameters, where the size of the slope, the initial soil moisture, and the intensity of the rain should be taken into account. The largest volume of sediments from the measurements was confirmed in the third experiment, where the initial humidity was high. In comparison with the first experiment, where the intensity of the rain was the same, but the slope was lower by 1 degree, the volume of sediments was 50% less. For a better analysis, statistical evaluation, and subsequent parameterization of the model, a larger number of experiments is required.

Table 4. Summary from the rainfall simulation – Erosion-2D (plot area = 1 m^2), 12-minute artificial rainfall with interruptions (4 individual rainfalls)

Experiment No.	Scheme	Initial soil moisture [%]	Erosion resistance [kg m s^{-2}]	Manning roughness [s m$^{-1/3}$]	Skin factor [-]	Sediment Volume [kg/m]	Laboratory - sediment Volume [kg/m]
1	A)	23.7	0.0008	0.015	1	2.00	1.01
	B)	23.7	0.0008	0.016	16	1.01	
	C)	23.7	0.0015	0.0165	1	1.01	
3	A)	29.3	0.0008	0.015	1	2.28	2.54
	B)	29.3	0.0008	0.0055	40	2.57	
	C)	29.3	0.0004	0.04	1	2.55	
4	A)	13.2	0.0008	0.015	1	0.76	0.63
	B)	13.2	0.0008	0.024	0.8	0.64	
	C)	13.2	0.00085	0.018	1	0.64	

* Bulk density 1800 [kg/m^3]. organic matter 1.15 [%]. cover [%]

Table 5. Summary from the rainfall simulation – Erosion-2D (plot area = 1 m^2), 12-minute artificial rainfall with interruptions (variants of 4 individual rainfalls)

Exp. No.	Variant (single rainfall)	Total time [min]	Initial soil moisture [%]	Setup group 1 Sediment Volume [kg/m]	Setup group 2 Sediment Volume [kg/m]	Laboratory Sediment Volume [kg/m]
1	1 – 4	12	23.7	1.02	1.32	1.01
	1 – 3	9	23.7	0.76	0.95	0.51
	1 – 2	6	23.7	0.28	0.58	0.13
3	1 – 4	12	29.3	1.74	1.47	2.54
	1 – 3	9	29.3	1.68	1.09	1.83
	1 – 2	6	29.3	0.76	0.71	1.16
4	1 – 4	12	13.2	0.00	0.48	0.63
	1 – 3	9	13.2	0.00	0.28	0.46
	1 – 2	6	13.2	0.00	0.11	0.19

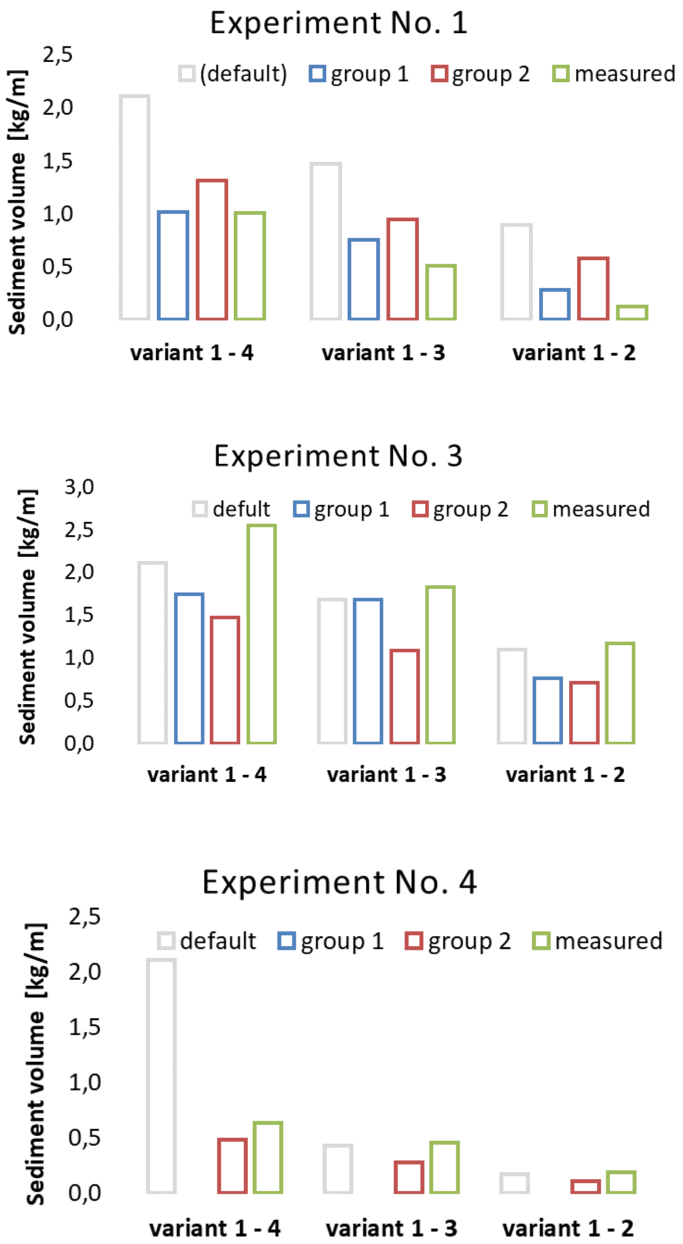

Fig. 4. The sediment volume of the Erosion-2D model and rainfall simulator.

Conclusion

In practice, various physical or empirical erosion models are applied for analysing and determining the intensity of soil erosion processes. In order to estimate the soil loss by water, physically-based erosion models require specific parameters describing the decisive processes involved (the infiltration of rainfall, surface runoff, degradation of the soil). The parametrization of such models represents a necessary and significant part of any scientific work.

In this study, the parameters of the Erosion-2D model, i.e., the skin factor, erosion resistance, and hydraulic roughness, were adjusted (set up) by comparing the modelled volumes of the soil sediment with the measured data on the experimental plots. The results from the laboratory experiments show that outputs from the rainfall simulations can be reproduced successfully and that based on those outputs, the process of determining a model´s parameters can be successfully performed. The disadvantage is seen in the area of the small simulator. The experimental results of the small-scale simulator are susceptible to measurement and model errors. It is necessary to work with a larger number of measurements and analyse the results. In conclusion, it is possible to state that the model overestimates the amount of sediment on higher slopes, which can be modified by a higher degree of roughness.

The skin factor has the greatest influence on the outputs in the Erosion-2D / Erosion-3D model. Further research will be focused on calibration of the skin factor together with the soil roughness for different initial conditions, including the slope elements, intensity of precipitation, and management practices.

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