

SENSITIVITY ANALYSIS OF SOIL PARAMETERS AND THEIR IMPACT ON RUNOFF-EROSION PROCESSES

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Abstract: The modeling of soil erosion processes is affected by several factors that reflect the physical-geographic conditions of the study site together with the land use linkage. The soil parameters are significant in the modeling of erosion and also runoff processes. The correct determination of a soil's parameters becomes a crucial part of the model's calibration. This paper deals with a sensitivity analysis of seven soil input parameters to the physically-based Erosion 3D model. The results show the variable influence of each soil parameter. The Erosion 3D model is very sensitive to initial soil moisture, bulk density, and erodibility.

Keywords: Sensitivity analysis, Soil parameters, Erosion 3D, Runoff and erosion processes

1. Introduction

Models are always simplifications of actual systems. However, if the input data reflect, or are at least representative of, conditions believed to be true, the parameter values and assumptions of any model are subject to change and potential error [1]. These errors and their impacts on conclusions can be investigated by a sensitivity analysis [2]. The model's parameterization is very important in an erosion modeling based on physical models, because there is a wide spread of soil parameters input with a variable influence on the results modeled [3]. In this paper, seven soil parameters input of the Erosion 3D model were analyzed to reveal the interconnections between the in-

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and out- puts, together with the sensitivity of the model's results on the changes in the inputs.

The main point of a sensitivity analysis is to determine how much the value of the model's outputs are affected by changes in the model's input values. A fundamental principle of sensitivity analysis states: 'Change the model and observe the behavior'. A principal aspect of sensitivity analysis describes how certain variables impact a dependent variable and how much the changes in those variables will influence the results.

According to Saltelli et al. [4] and Loucks and Beek [5], a sensitivity analysis is a study of how uncertainty in the output of a model can be allocated to uncertainty in the model's input values (*Fig. 1*). A sensitivity analysis is directly connected with an 'uncertainty analysis', which concentrates instead on quantifying uncertainty in a model's output values. An important question should be: 'Why is it needed to use the sensitivity analysis?' In general, what makes a model so difficult to rely on is uncertainty [5]. Parameters in all models are more or less uncertain, and if the parameters are uncertain, a sensitivity analysis can give extremely valuable information in making a decision or recommendation [1]. Because model outputs are based on a model structure and hydrological and other inputs and because these inputs describe the system being simulated, it is necessary and crucial to investigate the individual parameters input, especially in a physically-based model when each process is expressed by a set of different variables. That is why it is hard to forecast the future with precision; at least it is obvious that a model's outputs of possible conditions are uncertain [1].

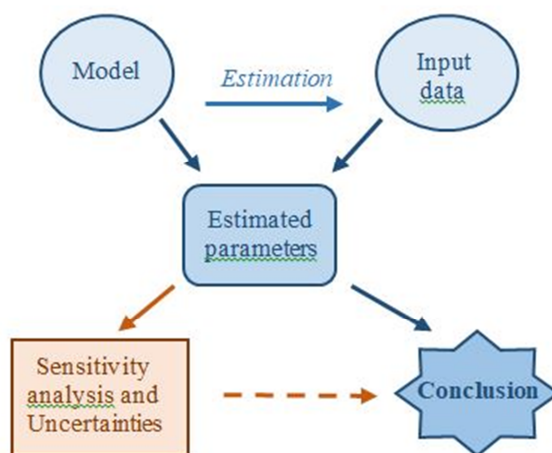


Fig. 1. The principles of sensitivity and uncertainty analysis according to Loucks and Beek, [5]

An uncertainty analysis is not the same as a sensitivity analysis, although it is possible to carry out a sensitivity analysis of a model and then use it as a part of the uncertainty analysis. The input of data errors and modeling uncertainties can interact in different ways that are not independent of each other [6]. While uncertainty analysis

assesses the uncertainty in model outputs that derives from uncertainty in inputs, a sensitivity analysis indicates how different values of the independent variable can impact a dependent variable under certain specific conditions.

Using of sensitivity analysis:

- a key application of sensitivity analysis is to indicate the sensitivity of a simulation to uncertainties in the input values of the model;
- results of the analysis help in decision making;
- the sensitivity analysis is a method for predicting the outcome of a decision if a situation turns out to be different when compared to the key predictions;
- it helps in assessing the riskiness of a strategy;
- it helps in identifying how dependent the output is on a particular input value;
- it analyses if the dependency in turn helps in assessing the associated risk;
- it helps in making informed and appropriate decisions;
- it aids in searching for errors in the model.

Sensitivity analysis is one of the tools that help with providing more than a solution to a problem. It provides an appropriate insight into the problems associated with the referenced model. In light of the modeling of runoff and erosion-deposition processes, a sensitivity analysis focuses on the soil parameters input to expose the effect of a soil condition on the processes caused by surface runoff. This paper is aimed at a sensitivity analysis of seven soil parameters input of the Erosion 3D model. Only a few studies have dealt with a similar topic [3], [7], [8]. As the Erosion 3D model has begun being applied also in Slovakia [9], [10], so it is necessary to parameterize and understand the model's functionality.

2. Study site

The Svacenícký Creek catchment (6.3 km²) is located in the western part of Slovakia in the middle of the Myjava Hill Land (*Fig. 2*). The Myjava Hill Land is well known for its quick response to runoff and erosion/deposition processes, and soil water erosion is the dominant soil threat there [11], [12]. The climate is continental, warm and moderately humid, with a mild winter and warm summer. The mean annual precipitation in the catchment is between 650 and 700 mm (1981-2015); the mean annual temperature is about 8.8 °C (1981-2013), as measured at the Myjava meteorological station. The elevation ranges from 311.4 m to 545.6 m Above Mean Sea Level (MASL) (*Fig 2*).

The relief is composed of narrow stream valleys with steep slopes in the upper part of the catchment and by moderate slopes in the lower part of the catchment. The study area is part of the flysch massif of the White Carpathians. The dominant soil kind is Luvisols (68.0%), followed by Pararendzina (28.7%), and Cambisols (3.7%). The arable land covers 65.7% of the catchment (*Table I*), and a small reservoir is located in the bottom of the catchment (*Fig. 2*).

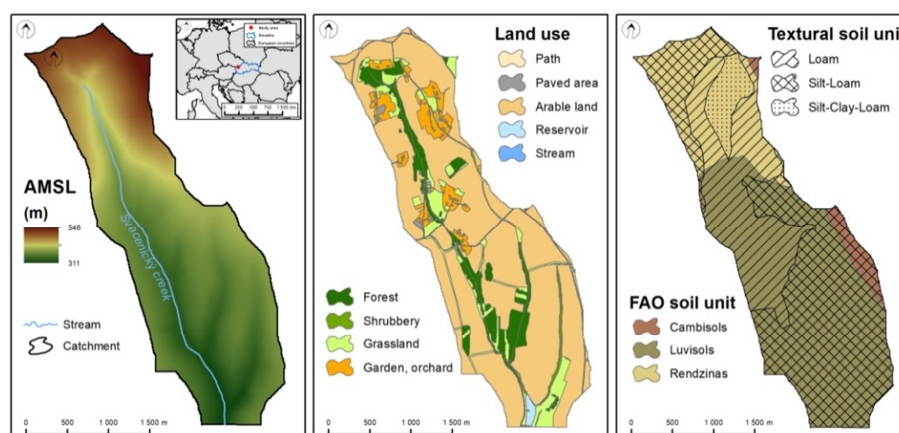


Fig. 2. The location and characteristics of the study site

Table I

The land use categories in the study site

Land use category	Total	Path	Paved area	Arable land	Water body	Forest	Shrubbery	Grassland	Orchard, garden
Area (km ²)	6.26	0.03	0.11	4.11	0.49	0.55	0.06	0.54	0.37
Area (%)	100	0.5	1.8	65.7	7.8	8.8	1.0	8.6	5.9

3. Data and methodology

The sensitivity analysis was conducted for seven soil input parameters to the physically-based Erosion 3D model [13]. The Erosion 3D model simulates the detachment of soil particles, the transport and deposition of detached soil particles by overland flow as well as the delivery of sediment; it is predominantly based on physical principles. The momentum flux approach developed by Schmidt [14]-[16] represents the basis of the model's principles. The fundamental equation of the model is the erosive impact of overland flow and raindrops and is proportional to the momentum fluxes exerted by the kinetic energy of the falling raindrops and flow [7].

The following soil input parameters were used for the sensitivity analysis:

- Bulk density (kg/m³);
- Organic carbon content (%);
- Initial soil moisture content (%);
- vegetation cover (%);
- Manning's roughness coefficient (s/m^{1/3});
- Erodibility (Erosion resistance) (N/m²);
- Skin factor (-).

A one-way sensitivity analysis was used in the study. It was performed by changing one parameter at a time and keeping all the others constant. The parameter values were increased and decreased by 10% compared to the original values. The reference values (*Table II*), i.e. the original values used as a baseline, were taken from a parameter catalogue [13] that was established for the Slovak soil system [9]. The calculations were carried out for a silage corn land cover type and for a rainfall event that occurred on 27.08.2017 (6.92 mm/17 min.), which was measured at the Myjava meteorological station.

Table II

The reference values for the sensitivity analysis

Soil type	Bulk density (kg/m ³)	Organic carbon content (%)	Initial soil moisture content (%)	Cover (%)	Manning's roughness (s/m ^{1/3})	Erodibility (N/m ²)	Skin factor (-)
Loam	1399	1.473	10	0	0.015	0.0015	0.1
Silt-Loam	1322	1.420	10	0	0.015	0.0010	0.1
Silt-Clay-Loam	1370	1.557	10	0	0.015	0.0012	0.1

4. Results

Selected seven soil input parameters were entered into the Erosion 3D model's equations (*Table III*). The estimation of the sediment volume is based on all the soil parameters; however, the net-erosion (the difference between the intensity of the erosion and the deposition of the eroded material) was not included with the vegetation cover, and the surface runoff is derived only from four soil input parameters (*Table III*).

Table III

Connection between model's inputs and outputs

Input/output	Runoff	Sediment volume	Net-erosion
Bulk density	✓	✓	✓
Cover	X	✓	X
Erodibility	X	✓	✓
Initial soil moisture content	✓	✓	✓
Manning's roughness coefficient	X	✓	✓
Organic carbon content	✓	✓	✓
Skin factor	✓	✓	✓

There was also a wide variability in the effect of the soil parameters' influence on the results calculated. *Table IV* shows the mean percentage of the changes in the results

according to the increase or reduction of the input parameter values. The greatest changes occurred in the initial soil moisture content, bulk density and erodibility.

Table IV

Results of the sensitivity analysis - the mean percentage of outputs changes

<i>Increase in values input</i>									
Parameter	Runoff (m ³)			Sediment volume (m ³)			Net-erosion (t/ha)		
Soil condition	Loam	Silt-Loam	Silt-Clay-Loam	Loam	Silt-Loam	Silt-Clay-Loam	Loam	Silt-Loam	Silt-Clay-Loam
Bulk density	22.9	115.1	0.7	30.4	191.6	0.2	30.8	191.9	0.0
Cover	-	-	-	-0.01	-0.1	-0.01	-	-	-
Erodibility	-	-	-	-7.4	-19.6	-1.3	-7.4	-19.6	-1.3
Initial soil moisture content	77.1	58.3	1.2	23.1	52.7	5.9	65.3	57.7	28.6
Manning's roughness	-	-	-	-15.6	-15.6	-15.6	-15.8	-15.8	-15.8
Organic carbon content	-2.0	-13.7	-0.1	-4.2	-23.3	-0.1	-4.0	-23.1	0.0
Skin factor	-1.1	-4.8	-0.1	-2.1	-8.6	-0.02	-2.1	-8.7	0.0
<i>Reduction in values input</i>									
Parameter	Runoff (m ³)			Sediment volume (m ³)			Net-erosion (t/ha)		
Soil condition	Loam	Silt-Loam	Silt-Clay-Loam	Loam	Silt-Loam	Silt-Clay-Loam	Loam	Silt-Loam	Silt-Clay-Loam
Bulk density	-32.0	-63.8	-3.6	-50.1	-90.0	-3.5	-50.3	-89.5	-4.0
Cover	-	-	-	0.01	0.1	0.01	-	-	-
Erodibility	-	-	-	59.1	155.1	7.4	59.4	155.6	7.7
Initial soil moisture content	-77.1	-58.3	-1.2	-23.1	-52.7	-5.9	-65.3	-57.7	-28.6
Manning's roughness	-	-	-	61.2	61.2	61.2	61.5	61.5	61.5
Organic carbon content	1.8	11.3	0.1	4.7	22.2	0.0	4.7	22.3	0.0
Skin factor	1.1	4.8	0.1	2.1	8.6	0.02	2.1	8.7	0.0

The Manning's roughness coefficient also has a great influence, but it does not depend on the soil conditions. On the other hand, the vegetation cover had a very small effect, i.e. only on the sediment volume. In light of the model's outputs, the same percent of changes in the sediment volume and net-erosion occurred, which points to a strong interconnection between both calculations. In the case of the surface runoff, the initial soil moisture content had a decisive influence on the estimation. Finally, the initial soil moisture content and bulk density had a positive impact on the results calculated, because the rest of the input parameters caused a reduction in all the processes.

With regard to the differences between the three soil types of the study area (*Table IV*), the study showed the silt-loam soil to be very sensitive to changes in the soil parameters. In contrast, the silt-clay-loam soil showed much resistant to changes in the parameters. These changes could be explained by the variable amount of clay content in the soil.

4.1. Initial soil moisture content

The initial soil moisture content is one of the main input parameters for the Erosion 3D model, and this soil parameter can be relatively easily determined by measurement of the terrain. Its effect is mainly seen in the calculation of the surface runoff and net erosion. The loam soil is especially sensitive to changes in the moisture content. Nevertheless, the highest output values were acquired for the silt-loam soil (*Fig. 3*).

There is an obvious inconsistency between the beginnings of the processes among the soil types, when the silt-loam soil primarily needs a much higher content of soil moisture than the silt-clay-loam soil. This disharmony could be affected by the clay content in a particular soil type.

4.2. Bulk density

The rising value of a soil's bulk density can cause a rapid increase in the results calculated for silt-loam soil (*Fig. 4*). Otherwise, small or no response is seen and the calculations are stable. A remarkable influence can be observed in the case of the silt-loam soil type (the mean percent increment exceeds 100% per 10% of increased input value). Again, the processes on the silt-clay-loam soil are almost constant. This soil parameter is the second key input parameter for the Erosion 3D model, and it can also be easily defined by measurement of the terrain.

4.3. Erodibility (erosion resistance)

Erodibility is one of the main input parameters for a soil's resistance to erosion processes when the growth of the value results in a rapid decrease of the soil erosion processes and sediment production as well. In the percent range, the variability among the soils is obvious in the study site, and again the silt-loam soil shows the greatest disproportions (*Fig. 5*). This parameter does not enter into the estimation of the surface runoff.

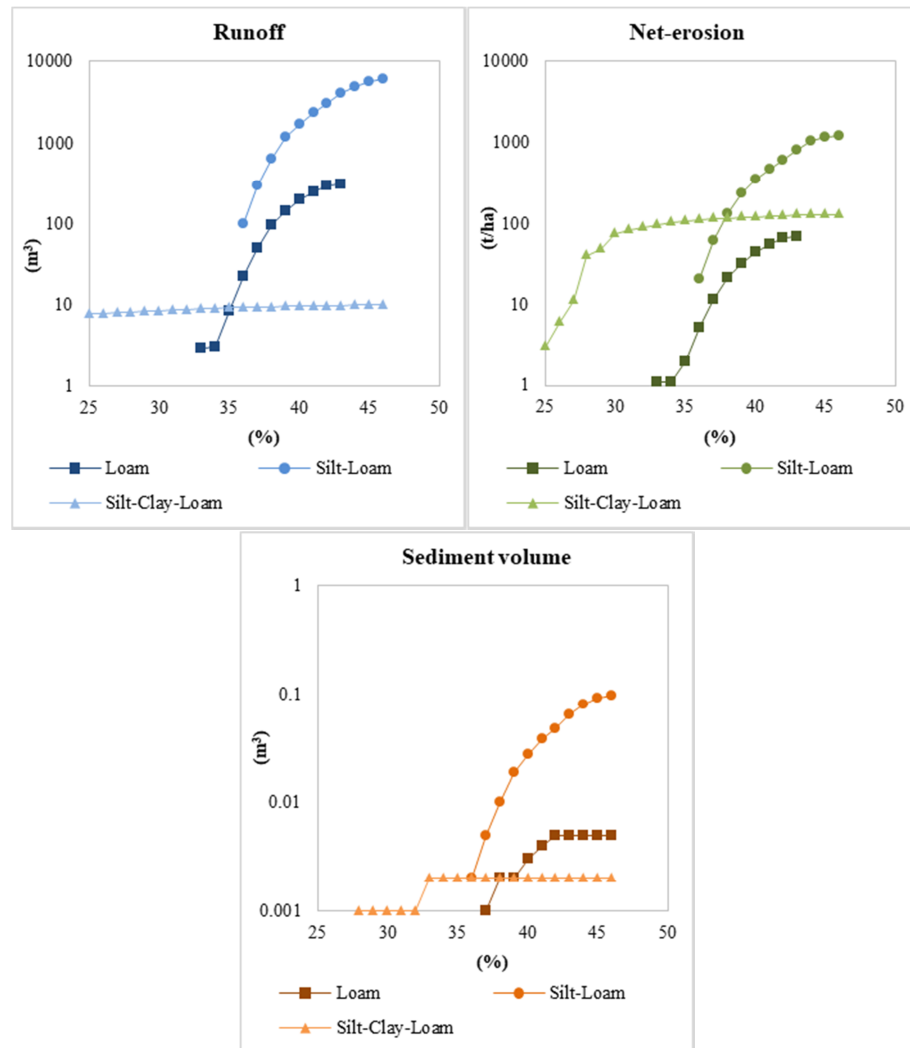


Fig. 3. The sensitivity of model's results on initial soil moisture (base line was set at 25 % of initial soil moisture content based on field survey and the value was increased gradually by 1 % until the model simulation stopped)

5. Discussion

The parameterization of physically-based models is a major challenge in any area, and the process demands depend on the number of parameters input. The Erosion 3D model is based on eight soil parameters; five soil parameters can be achieved with standard methods (soil analysis or estimation from soil maps), i.e. soil texture, initial soil moisture content, bulk density, vegetation cover and organic carbon content [3].

The other three, i.e. erodibility, Manning's roughness coefficient, and the skin factor, can be estimated by methodologies based on an extensive database or determined from rainfall experiments [3], [7], [8].

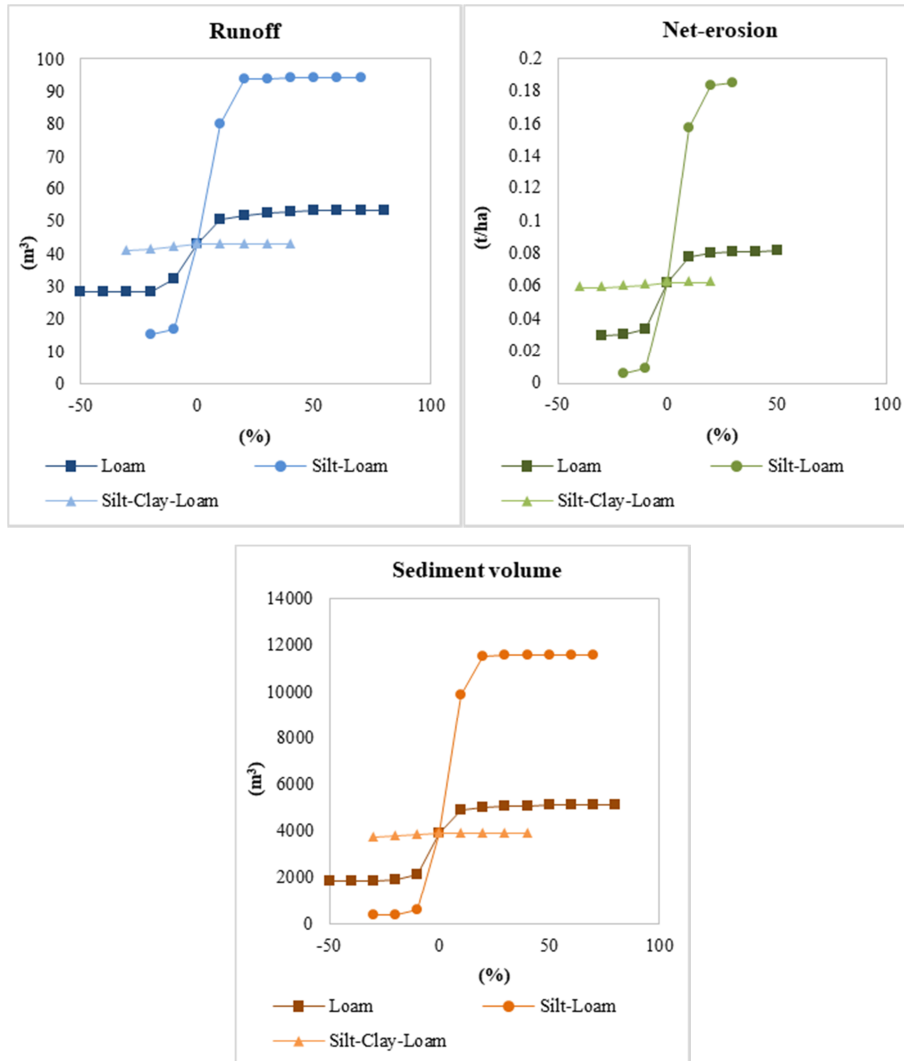


Fig. 4. The influence of bulk density on model's results

The measured input data are more suitable than catalogue-based data derived from other local conditions [16]. In contrast, the limitation of the measured terrain values was objectionable, because these data represent a concrete location (e.g. the values can be different across the slope) and the time of gathering the sample (the value develops

during over the year) [17]. Also, the limited application of the determined value of the moisture content has been pointed out [17], since it is strongly affected by the time of day, the slope's position, the quality and fitness of the vegetation, etc.

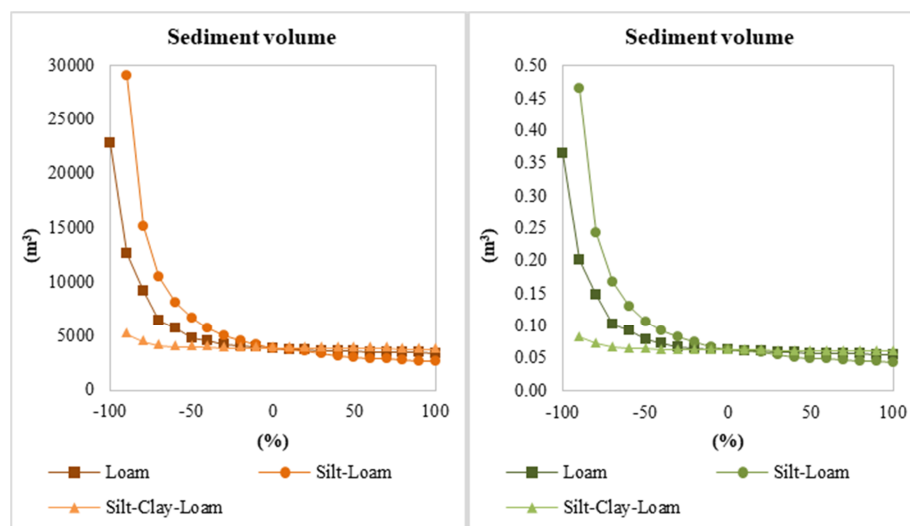


Fig. 5. The erodibility's influence on model's results

A sensitivity analysis is a helpful tool for revealing and understanding the effect of the parameters input on a model's outputs [1], [2]. In the case of the Erosion 3D model, partial analyses have been conducted, as seen in the literature [3], [7], [8]. This paper presents the results of one-way sensitivity analysis to uncover the interconnections between the seven selected soil parameters and the Erosion 3D model's results. The effect of the soil parameters is different, and on the base of the analysis the key parameters are the initial soil moisture content, the bulk density and the erodibility, followed by Manning's roughness coefficient and the skin factor. The effect of the initial soil moisture content was highlighted as the crucial input in the estimation of the surface runoff and the difficulty of obtaining terrain measurements, due to the temporal and spatial variability of the parameters in the study areas was mentioned [16]–[18]. Results show that all the processes modeled are strongly affected by the bulk density, which has been confirmed in the literature [17]; moreover, the lower values for the parameters' skin factor, Manning's roughness coefficient, and erodibility increase sediment erosion [19], which was also confirmed by the recent investigations.

6. Conclusion

A sensitivity analysis is a necessary part of any scientific work, and it can be very helpful to reveal and understand the basic system functionalities and interconnections. In this paper, the analysis pointed to the great number of variabilities among the soil

parameters input and their effect on runoff and erosion/deposition processes. That is why the setting of input soil parameters is a crucial part of any work dealing with soil erosion modeling. This is especially true in the case of a physically-based erosion model like the Erosion 3D, which is based on 8 soil characteristics. The analysis also revealed that the initial soil moisture, bulk density and erodibility are the most important soil parameters that have a great effect on runoff and erosion processes. Nevertheless, it is necessary to take into account all natural conditions (and their interconnections) of a study area to produce correct results and understand them. This analysis is necessary for future applications of the Erosion 3D model in the Slovak conditions.

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References

- [1] Pannell D. J. Sensitivity analysis of normative economic models: Theoretical framework and practical strategies, *Agricultural Economics*, Vol. 16, No. 2, 1997, pp. 139–152.
- [2] Baird B. F. *Managerial decisions under uncertainty: An introduction to the analysis of decision making*, New York, Wiley, 1989.
- [3] Saltelli A., Tarantola S., Campolongo F., Ratto M. *Sensitivity analysis in practice: A guide to assessing scientific models*, Chichester, Wiley, 2004.
- [4] Saltelli A., Ratto M., Andres T., Campolongo F., Cariboni J., Gatelli D., Saisana M., Tarantola S. *Global sensitivity analysis: The primer*, Chichester, Wiley, 2008.
- [5] Loucks D. P., Beek E. *Water resources systems planning and management: An introduction to methods, models and applications*, Paris, UNESCO Publishing, 2005.
- [6] Schindewolf M., Schmidt J. Parameterization of the erosion 2D/3D soil erosion model using a small-scale rainfall simulator and upstream runoff simulation, *Catena*, Vol. 91, 2012, pp. 47–55.
- [7] Stumpf F., Goebes P., Schmidt K., Schindewolf M., Schönbrodt-Stitt S., Wadoux A., Xiang W., Scholten T. Sediment reallocations due to erosive rainfall events in the Three Gorges reservoir area, central China, *Land Degradation and Development*, Vol. 28, 2016, pp. 1212–1227.
- [8] Lenz J., Yousuf A., Schindewolf M., von Werner M., Hartsch K., Singh M.J., Schmidt J. Parameterization for Erosion-3D model under simulated rainfall conditions in lower Shivaliks of India, *Goesciences*, Vol. 8, No. 11, 2018, pp. 396–413.
- [9] Némětová Z., Honek D. Application of a physically-based erosion model in a small catchment of the Myjava river basin, *Proceedings of the 29th conference of Young Hydrologists*, Bratislava, Slovakia, 9–11 November 2017, pp. 1–13.
- [10] Némětová Z., Honek D., Látková T., Šulc Michalková M., Kohnová S. An assessment of soil water erosion in the Myjava hill land: The application of a physically-based erosion model, *Pollack Periodica*, Vol. 13, No. 3, 2018, pp. 197–208.

- [11] Labat, M. M., Korbeřová, L., Kohnová, S., Hlavčová, K. Design of measures for soil erosion control and assessment of their effect on the reduction of peak flows, *Pollack Periodica*, Vol. 13, No. 3, 2018, pp. 209–219.
- [12] Werner M. *Erosion-3D, User manual*, Ver. 3.1.1, Berlin, Geognostics, 2006.
- [13] Schmidt J. A mathematical model to simulate rainfall erosion, in: Bork H. R., De Ploey J., Schick A. P. *Erosion, Transport and deposition processes - theories and models*, Catena Supplement 19, Cremlingen 1991, pp. 101–109.
- [14] Schmidt J. Modeling long term soil loss and landform change, in: Parson A. J., Abrahams A. D. (Eds), *Overland flow - Hydraulics and Erosion Mechacnis*, University College London Press, London, 1992, pp. 389–414.
- [15] Schmidt J. Development and application of a physically based simulation model for the erosion of agricultural land, (in German) Selbstverlag des Instituts für Geographische Wissenschaften, Berlin, 1996.
- [16] Kadlec V., Dostál T., Vrána K., Kavka P., Krása J., Devátý J., Podhrázská J., Pochop M., Kulířová P., Heřmanovská D., Novotný I., Papaj V. Design of technical anti-erosion devices, (in Czech) *Research Institute for Soil and Water Conservation*, Czech Technical University in Prague, 2014.
- [17] Dostál T., Krása J., Kavka P., Vrána K., Devátý J., Kadlec V., Novotný I., Kulířová P., Heřmanovská D., Papaj V., Kapička J., Váňová V. Using GIS data and tools and simulation models to design TAEM, (in Czech) *Research Institute for Soil and Water Conservation*, Czech Technical University in Prague, 2014.
- [18] Janík A., Šoltész A. Flash flood mitigation modeling - case study small Carpathians, *Pollack Periodica*, Vol. 12, No. 2, 2017, pp. 103–116.
- [19] Michael A. Michael A. Application of physically-based erosion models EROSION 2D / 3D- Empirical approaches to determine model parameters, (in German) *PhD Thesis*, Technische Universität Bergakademie Freiberg, 2000.