APPLICATION OF PHYSICALLY-BASED EROSION MODEL IN THE SMALL CATCHMENT OF MYJAVA RIVER BASIN

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Anotácia

Príspevok sa zaoberá aplikáciou erózneho modelu Erosion-3D v podmienkach malého povodia. Erosion-3D model je fyzikálne založený model pre predikciu vodnej erózie na poľnohospodársky využívanej pôde a predstavuje dobrý nástroj pre simuláciu a kvantifikáciu pôdnej erózie, ale doposiaľ nebol aplikovaný v našich podmienkach. Hlavným cieľom príspevku je testovanie vytvorenej metodiky v mierke malého povodia modelovaním rozličných scenárov najcitlivejšieho vstupného parametra modelu, ktorým je počiatočná vlhkosť pôdy.

Kľúčové slová: fyzikálne založený model, zrnitostný trojuholník, vodná erózia, modelovanie povrchového odtoku, návrhové zrážky

ANNOTATION

The scope of this study is the application of new approach for estimation of potential soil erosion in the small catchment. Erosion 3D model is a physically-based computer model for predicting soil erosion by water on agricultural land and it represent good tool for simulate and quantify soil erosion, but has not been established in Slovakian basins yet. The main purpose of this study is application of created methodology in the small catchment using different scenarios of the most sensitive soil input parameter of the model – initial soil moisture.

Key words: physically based model, textural system, initial moisture, water erosion, surface runoff modelling, design rainfall

1. Introduction

Soil erosion is a process of natural character, but is strongly accelerated by human activity (Stankoviansky, 2003). The fact that it is a natural process means that soil erosion cannot be completely eliminated by any measures or interventions. The only thing that is possible and necessary to do is to reduce its intensity and impact (Antal et al., 2013).
Erosion is a diffuse process which occurs at relatively low and widely varying rates from year to year and from location to location (Kenderessy, 2012).
Many factors like soil physical characteristics, slope features, land surface cover, will influence soil loss amount. It is necessary to distinct their effects on soil loss mathematically and to evaluate them. (Baoyuan, et al., 2002).

Effective modelling of water erosion can provide crucial information about erosion patterns and trends and moreover allow scenario analysis in relation to current or potential land uses (Millington, 1986). Estimating the spatial distribution of soil erosion is the most important priority for making successful policies to reduce soil loss, taking into account the geographic conditions of the study area (Panagopoulos, Ferreira, 2010). Many models have been developed to predict areas that are susceptible to water erosion, to predict soil loss, and to evaluate soil erosion-control practices. There have been many studies on soil erosion models and related experiments since 1940's, but the models were limited in local levels and difficult to expand to broad regions due to data collected without universal standard (Baoyuan, et al., 2002).

First of all: Why do we need hydrological model? The answer on this question is many, but the rationale for model building was perhaps best expressed by Rosenblueth and Wiener (1945):

> "No substantial part of the universe is so simple that it can be grasped and controlled without abstraction. Abstraction consists in replacing the parts of the universe under consideration by a model of similar but simpler structure. Models, formal or intellectual on the one hand, or material on the other, are thus a central necessity of scientific procedure".

In general there is no 'best' model for all applications. The most appropriate model will depend on the intended use and the characteristics of the catchment being considered.

The most important reason is that practical measurement of soil erosion is quite difficult. In fact, there are many problems associated with monitoring and surveying erosion processes. Modelling of erosion and erosion-accumulation processes allows to identify sites susceptible to erosion-accumulation forms and to estimate the intensity of processes at different scales (Vysloužilová, Kliment, 2012). According to Merrit (2003) models fall into three main categories, depending on the physical processes simulated by the model, the model algorithms describing these processes and the data dependence of the model:

- Empirical or statistical/metric,
- Physically based or theoretical,
- Conceptual.

At first, *empirical models* was widely used. They are generally the simplest of all three model types. They are based primarily on the analysis of observations data (Wheater, et al., 1993). These models are also called observation oriented models, data driven models or black box model. The models take only the information from the existing data without considering the features and processes of hydrological system (Devia, et al.2015).

At the moment, the empirical models are gradually replaced by physically based models (Hofierka, Šúri, 1999). *Physically based erosion models* require specific parameters describing the decisive processes involved the infiltration of rainwater into the soil or the detachment of soil particles by raindrop splash and surface runoff in order to estimate soil loss by water (Schindewolf, Schmidt, 2012). These are also called mechanistic or theoretical models that include the principles of physical processes. Erosion processes are described through mathematical expressions based on large number of assumptions (Pandey, et. al, 2016). It uses state variables which are measurable and are functions of both time and space. The hydrological processes of water movement are represented by difference equations. Physical model can overcome many defects of the other two models because of the use of parameters having physical interpretation (Abbot, et al., 1986).

Application of physically based models represents the recent trend in soil erosion research, together with development of GIS and remote sensing techniques. A large amount of physically based erosion models have been developed worldwide for prediction of soil erosion and sediment yield and the amount is still increasing. Since it was first 'blueprinted' (Freeze, Harlan, 1969) distributed physically based modelling has become very widespread (Muligan, Wainwright, 2004). The catchment hydrologic models have been developed for many different reasons and therefore have many different forms (Chong-Yu Xu, 2002).

The middle between empirical and physically-based model represent conceptual model. This model describes all of the component hydrological processes. The model parameters are assessed not only from field data but also through calibration. Semi empirical equations are used in this method. Large number of meteorological and hydrological records is required for calibration (Devia, 2015).

In this article, Erosion-3D is used model, which represents an ideal compromise in combining the demands for less input parameters and desired quality of simulation of hydrological and erosion processes.

2. MATERIAL AND METHODS

This section contain description of used model, study area and also the process of methodology creation.

2.1 Erosion-3D model

EROSION-3D is a physically-based erosion model which predicts soil erosion resulting from natural rainfall (Werner, 2006). EROSION-3D model has been developed since 1995 by Michael von Werner at the Department of Geography at the Free University of Berlin. The basic idea of the model is the assumption that the erosive impact of overland flow and droplets is proportional to the momentum fluxes carried out by the flow and the falling droplets respectively (Schmidt, 1991).

The model calculates the amount and the direction of overland flow by taking into account the slope and the exposition of the considered land surface, and the infiltration rate which is estimated by an infiltration sub-routine based on the approach of Green and Ampt (Kenderessy, 2012). It simulates surface runoff, erosion, deposition and the textural composition of the eroded sediment for single erosion events as a function of time and space (Weigert, et al., 2003).

Erosion-3D model requires these input parameters:

1. *Relief parameters:*
   - the only input parameter for the relief parameters is a Digital Elevation Model (DEM) in form of a square grid.
2. *Soil parameters:*
   - bulk density [kg/m^3]
   - initial soil moisture content [%]
   - organic carbon content [%]
   - erodibility [N/m^2]
   - Manning's n [s/m$^{1/3}$]
   - cover [%]
   - grain size distribution [%]
   - skin factor [-]
3. *Precipitation parameters:*
   - duration of precipitation [min]
   - intensity of precipitation [mm.min^{-1}]

The model produces raster-based output parameters, quantitative estimates of soil loss, soil deposition and the sediment delivery into the surface water system.
Model´s output are divided to:

a) Parameters related to area:
   - erosion and deposition for a chosen grid cell [t/ha], [kg/m^2]
   - erosion and deposition and net erosion for the watershed draining into a chosen grid cell [t/ha], [kg/m^2]

b) Parameter related to cross-section of flow:
   - runoff [m3/m]
   - sediment delivery [kg/m]
   - sediment concentration [kg/m^3]
   - particle size distribution of the transported sediment (percentages of clay, silt and sand by mass)

2.2 Creation of methodology for soil input data

The soil system of Erosion 3D is based on the fourth edition of the Bodenkundliche Kartieranleitung („KA 4“, AG Boden, 1994). In Slovakia it is used USDA classification system. Because of different soil types it was required to create an overplot KA 4 textural triangle with USDA textural triangle used in Slovakia. In the software R we created overplot KA 4 textural triangle (Fig. 1) with USDA triangle (Fig. 2). After creating overplotted triangle (Fig. 3), it was quantify every soil type of KA4 classification within the USDA classification of soil types. In the study was modelling seven scenarios of initial moisture in the range of 10-40 percent. The range was determined based on real measured terrain data. 100-years rainfall with intensity 31 mm/h were applied in the modelling.

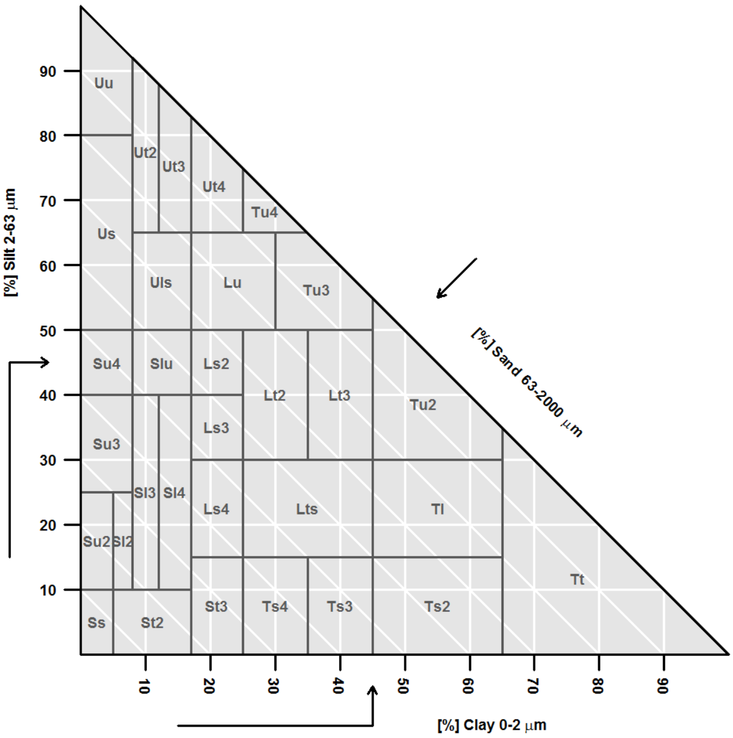

Figure 1: Textural triangle KA4 Bodenkundliche Kartieranleitung

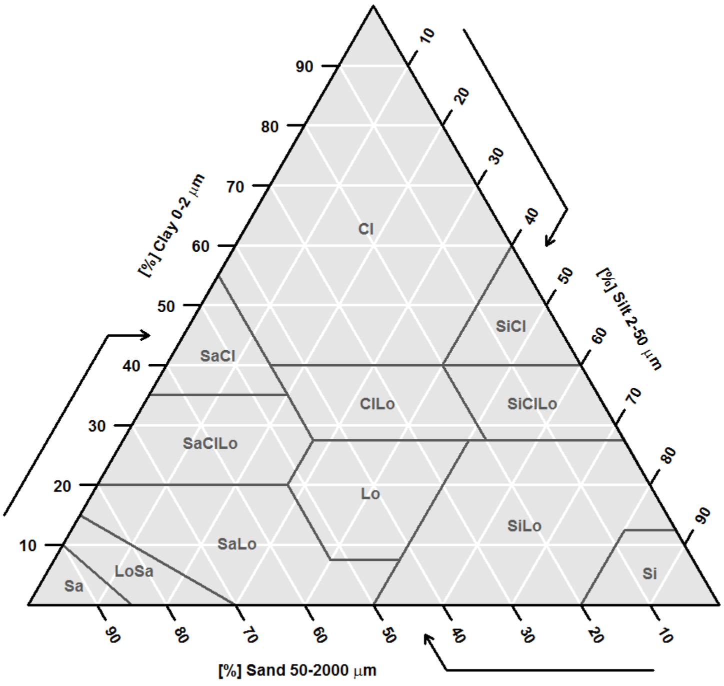

Figure 2: Textural triagle USDA

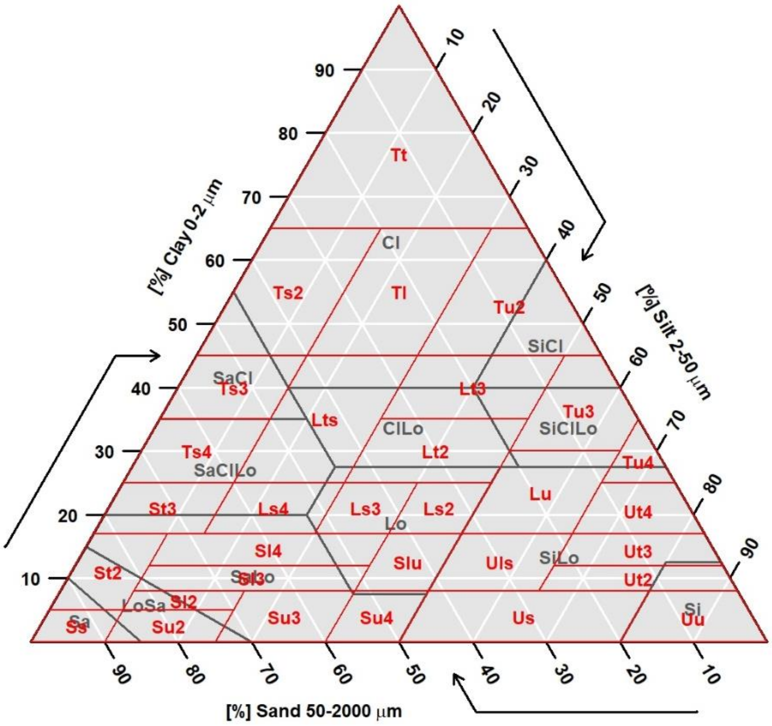

Figure 3: USDA and KA4 overpotted triangle

2.3 Study area

The study area is situated in western Slovakia in the middle of the Myjava Hill land, near to the city of Myjava (Turá Lúka district) (Fig. 4). The elevation ranges from 298 m to 391 m above the mean sea level. For further description of the study area see Table 1. The study area is composed by small watersheds, draining approximately 1 km^2 of the agricultural land. The permanent gully (length about 300 m) is located in the middle of the study area (the minimum altitude is 300.5 meters above sea level; the maximum altitude is 328.8 meters above sea level). The climate of the area is continental, warm and moderately humid, with mild winter and warm summer. The mean annual precipitation is between 650 and 700 mm (1981-2015), with the mean monthly maximum from May to September, and minimum from January to April. The mean annual maximum and minimum temperature in the area are +19 °C (July and August) and -0.5 °C (January) respectively, and the mean annual temperature is about 8.8 °C (1981-2013).

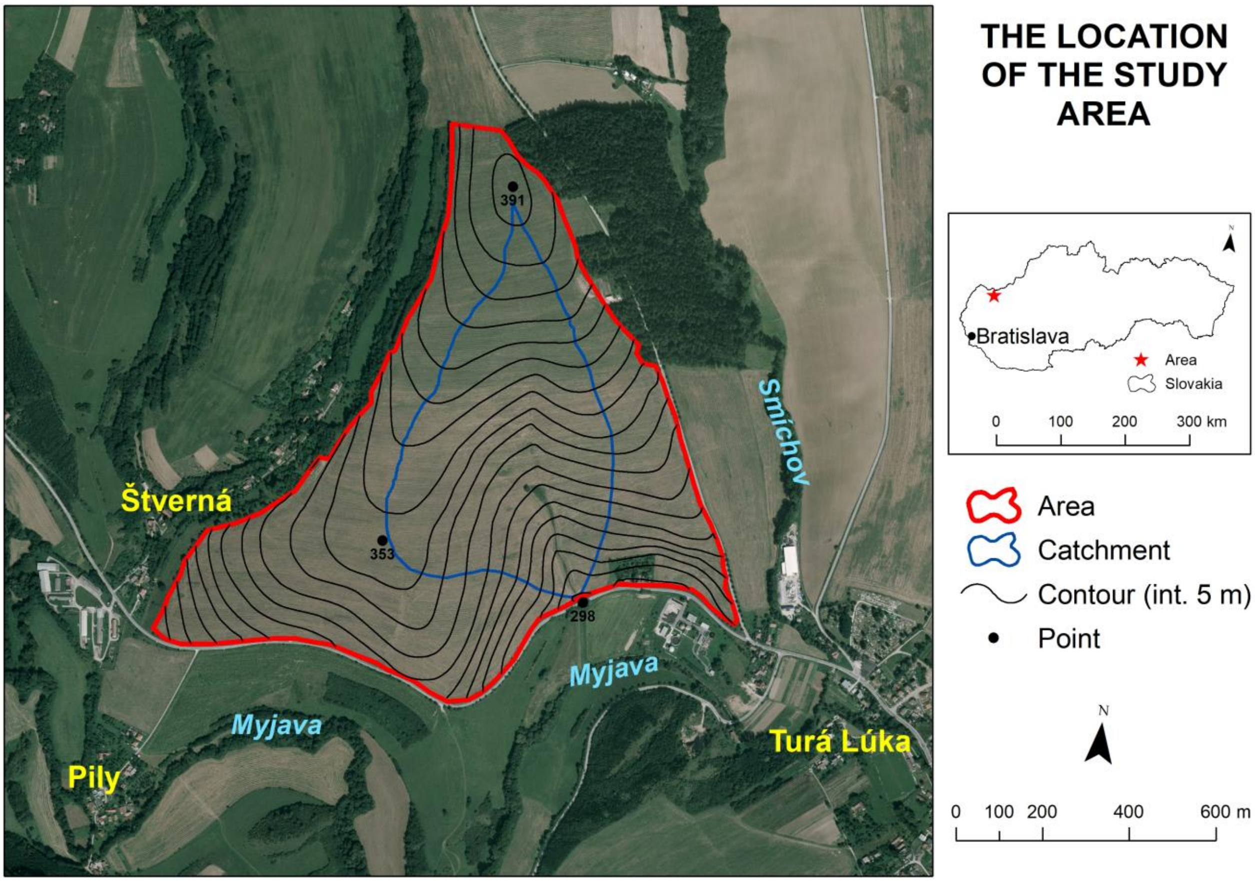

Figure 4: The location of the research area in Turá Lúka

Table 1. The main catchment and climatic characteristic of the study area.

Location	The Myjava Hill Land	**Highest point**	391 m (AMSL)	**Geology**	flysch massif	**Climate**	warm, moderately humid with mild winters
Cadastral territory	The city of Myjava	**Lowest point**	298 m (AMSL)	**Soils**	rendzina, cambisol	**Mean annual precipitation**	650 – 700 mm
District	Turá Lúka	**Slope lenght**	1 100 m	**Crops**	silage and grain corn, winter rape, winter wheat	**Mean annual temperature**	8 °C – 10 °C
Area	1 km^2	**Average gradient**	10.9 %				

3. THE RESULTS

Scenarios of initial moisture give us the view into the sensitivity of the model to this parameter. Because this parameter is very variable in the field, it is very useful modelling the range of values which were determined based on the real measurements. The results provides us with several results in two spatial scales – the channel and the catchment. The first important result is the runoff and for example the Figure 5 presents the runoff in the catchment scale. It is obvious, that the runoff is increasing together with the growing value of the initial soil moisture. However, the scenario 1 is without values of runoff, because entire precipitation was infiltrated (the initial moisture was 10%).

The potential soil erosion has similar increasing trend shown at figure 6. The biggest intensity is in the middle of the catchment, corresponding with the location of the biggest value of runoff. The main stream and also the small gully are located in this part of the catchment. On the other hand, the lowest value of erosion is located here too, because the deposition is very strong here. This opinion is confirmed by the values of the sediment mass (Figure 7).

The table 2 shows the values estimated for the entire catchment in the endpoint of the catchment, describing the temporal development of the values in the 10-minutes time resolution. The results in the table 2 are in the cumulative order and they prove the graduation of the values among the soil moisture scenarios.

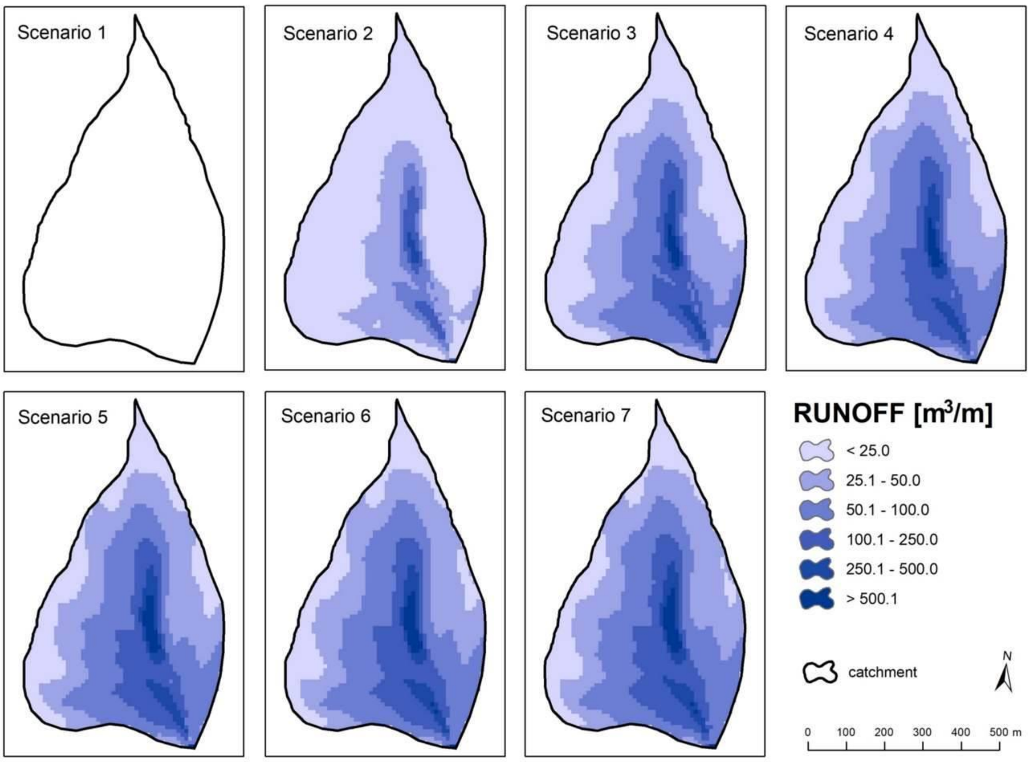

Figure 5: Runoff for selected scenarios of initial moisture (1-7)

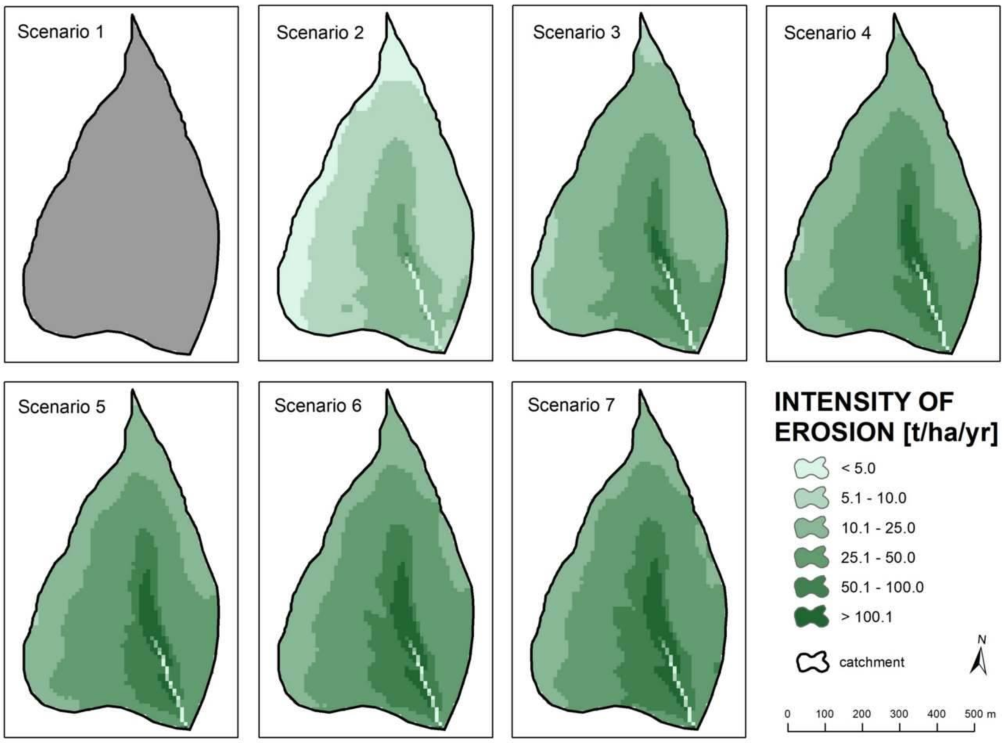

Figure 6: Intensity of erosion for selected scenarios of initial moisture (1-7)

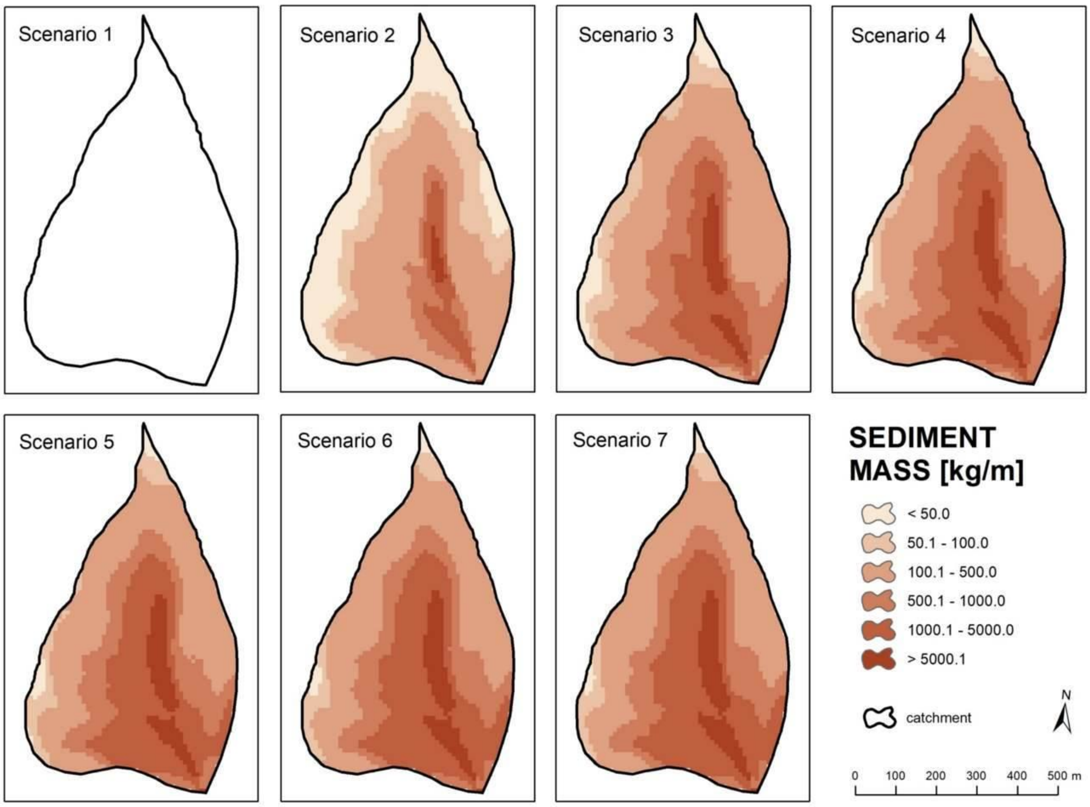

Figure 7: Sediment mass for selected scenarios of initial moisture (1-7)

Tab. 2 Cumulative values of the model´s outputs at the outlets

Time [minutes]	Initial moisture [%]	Sediment mass [kg/m]	Runoff [m3/m]	Sediment volume [kg/m]	Sediment concentration [kg/m3]	Clay [%]	Silt [%]	Total erosion [t/ha]	Total deposition [kg/m2]	Net erosion [t/ha]
60	10	0	0	0	0	0	0	0	0	0
60	15	-134,711	246,07	7390,208	30,033	19	59	2,749	0,251	2,498
60	20	-353,218	538,08	20461,6	38,027	17	54	8,356	1,439	6,917
60	25	-460,232	652,6	27165,859	41,627	16	53	11,868	2,685	9,183
60	30	-531,764	724,03	31709,514	43,796	16	53	14,57	3,851	10,719
60	35	-583,019	773,26	34987,23	45,246	16	52	16,686	4,858	11,827
60	40	-612,447	800,89	36886,117	46,056	16	52	17,955	5,485	12,469
60	45	-612,447	800,89	36886,117	46,056	16	52	17,955	5,485	12,469

4. SUMMARY AND CONCLUSION

The aim of the study was testing of the EROSION 3D model under the conditions of Slovakia and modelling the one of the most sensitive input parameter – initial moisture.

The comparison of modelled scenarios provides insight into the behaviour of the model and it shows us the possibilities and limits of the modelling in the Erosion-3D model. The variability of initial moisture is not only temporal (during the day, before or after the rainfall event) but also spatial (different position on a slope). Possibilities and limits of the modelling in the Erosion-3D model are known after using seven scenarios. The range of the initial moisture (10-45%) is based on the real field measurements. The first scenarios (initial soil moisture = 10%) is without outputs, it means that all flowing water is infiltrated. The last scenarios ((initial soil moisture = 45%) has the same outputs as scenarios with initial moisture 40%. In this case we expect that 40 % is condition when the soil reaches field water capacity. In general intensity of simulation processes is evolving as expected within model scenarios.

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ABSTRAKT

Príspevok sa zaoberá aplikáciou fyzikálne založeného modelu Erosion-3D model v povodí Myjava Turá Lúka. Fyzikálne založené modely predstavujú dobrý nástroj na kvantifikáciu a hodnotenie erózie pôdy. Ich cieľom je vytvoriť matematický popis procesov erózie pôdy. V súčasnosti sú tieto modely považované za vyšší stupeň modelov, pri ktorých je možné s výsledkami pracovať na podstatne vyššej úrovni. Sú však podstatne náročnejšie ako na vstupné dáta, tak aj na výpočtovú techniku. Erosion-3D model je plne distribuovaný epizódny model zrážkovo-odtokových vzťahov, eróznych a transportných procesov. Vstupné aj výstupné veličiny sú tvorené rastrovými vrstvami. Model je možné použiť pre výpočet ako množstva, tak aj charakteru erodovaného materiálu a množstva pretekajúcej vody (Werner, 2006). Výsledky sú uplatniteľné nielen na hodnotenie a určovanie rizikových plôch z hľadiska intenzity erózie, koncentrácie odtoku, ale aj depozície erodovaného materiálu. Jednou z nevýhod tohto modelu je, že nezohľadňuje podpovrchový odtokový proces (dopadajúca zrážková voda je delená na infiltráciu a povrchový odtok), čo môže znižovať celkový odtok z povodia.

Nevyhnutnými vstupnými parametrami sú digitálny model reliéfu, zrážky a pôdne parametre. Je všeobecne známe, že pôdne charakteristiky je najlepšie získať rozborom pôdnych vzoriek odobraných priamo v záujmovom území. Odobraté pôdne vzorky by mali dostatočne husto pokrývať modelované územie, aby bola zabezpečená reprezentatívnosť heterogenity pôdnych podmienok. Vzhľadom k tomu, že takáto príprava dát je časovo a finančne náročná, je nutné vychádzať z katalógu parametrov. Pre jeho aplikáciu v našich podmienkach bolo nutné vytvoriť vhodnú metodiku. Prvým krokom bolo zhotovenie zrnitostného trojuholníka (prekryv KA 4 a USDA). Na základe výsledného prekryvu vychádzajú upravené hodnoty katalógu parametrov pre územie Slovenska, ktoré sú použité ako vstupné pôdne charakteristiky do modelu. Použitý digitálny model reliéfu má veľkosť gridu 10x10 m, storočná návrhová zrážka s intenzitou 31mm/hod je rozdelená v 10 minútovom kroku pre vstup do modelu. Výpočty sú kalkulované pre kukuricu na siláž v mesiaci august pri konzervačnom spôsobe obhospodarovania pôdy a zahŕňajú 4 modelové zrážkové udalosti pre osem vlhkostných scenárov.

Primárne zameranie príspevku je testovanie vytvorenej metodiky pôdnych vstupných parametrov a následné modelovanie počiatočnej vlhkosti pôdy. Premenlivosť tohto parametra je nielen časová (v priebehu dňa, pred alebo po zrážke), ale i priestorová (rôzna poloha v rámci skúmanej plochy, vplyv vegetácie) a zároveň predstavuje i najcitlivejší vstupná pôdny parameter modelu Erosion-3D. Už aj malé zmeny tohto parametru spôsobia veľké odlišnosti vo výsledkoch. Preto optimálnym riešením je vytvorenie rôznych scenárov počiatočnej vlhkosti pôdy, ktorých rozhranie bolo určené na základe reálne nameraných hodnotách v skúmanom povodí. Výsledky modelovania vlhkostných scenárov pre 4 rôzne zrážkové udalosti ukazujú silnú závislosť medzi hodnotami vstupných a výstupných faktorov, čoho dôkazom sú hodnoty korelačných koeficientov približujúce sa k 1.

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