Comparison of Sediment Loss Modelling by Using the Physically-Based Erosion-3d Model and The USPED Empirical Model: A Case Study of the Svacenicky Creek Catchment (Slovakia)

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Abstract. The study presents a validation of the physically-based EROSION-3D model and the USPED empirical model and compares them with actual measured data. During the last decade there has been an intention to develop a new generation of erosion models in order to replace the Universal Soil Loss Equation used worldwide with more effective methods. One of those methods is represented by physically-based models, which provide a tool that relies upon descriptions of the processes that occur in actual natural conditions. The essential element of physically-based models is that they are process-based and reflect the most recent advances in erosion and hydrological research. In the modelling of soil erosion, the validation and verification of the methodologies used are considered as general problems. The importance of a model’s validation can be seen in the building of confidence in the ability of the model to generate satisfactory simulation results in order to discover the strengths and weaknesses of the model used. The physically-based EROSION-3D model is suitable not only for research purposes, but also for engineering practices, e.g., for assessing the effect of changing agricultural management practices and their impact on soil losses. The validation of the models has been performed on a continuous rainfall series for the selected period 2015 - 2016. The modelled results were compared with the actual measured sediment deposition data acquired by a bathymetry survey of the Svacenicky Creek polder using the EcoMapper Autonomous Underwater Vehicle device in the same period. The Svacenicky Creek polder is a part of the flood protection measures in the investigated territory of the Myjava region in Slovakia. The final results present a comparison between the outputs from the models used together with a confrontation of the modelled and observed results obtained by the bathymetry measurements.

1. Introduction
The intensity and extent of soil degradation processes has increased significantly in many parts of the world in recent years [1], [2]. Soil degradation represents a growing and critical global problem, with implications for different types of policy areas; i.e., climate change, food production, flood risk management, drought tolerance, drinking water quality, biodiversity, and future genetic resources [3]. Among the different degradation processes, soil water erosion occupies the most serious position, which in many cases leads to the complete damage and destruction of soil. Until now the long-term and large-scale impact of soil water erosion has been caused by the depletion of large land areas in many countries.
According to [3], the major cause of soil degradation is land use changes and inappropriate land management practices. The current state of our investigated area represents the results of the ~600-year anthropogenic transformation of a naturally forested landscape, which was predominantly formed by oak and beech forests. Land use changes from native forests to arable land and agriculture land can not only cause soil degradation and the decomposition of vegetation, but also a reduction in the organic carbon of soil. Soil organic carbon improves the physical properties of soil and is a major component of soil organic matter [3]. Soil organic matter indicates the soil quality and plays an important and vital role in agricultural production. Small changes in soil organic carbon can cause a large amount of atmospheric carbon concentrations [6], because there are more than three times as much organic carbon in the soil as there is carbon in the atmosphere [7].

This is the reason why it is important to pay attention not only to the solution of the problem but also to research and implement practical measures and innovative methods to decrease its intensity. While many studies have recently been conducted using empirically-based models, more research is needed to evaluate soil processes for different land uses, management practices, and different sites that use more sophisticated and comprehensive methods. One of those methods is covered by physically-based models, which can be considered as an effective approach to quantify and assess soil erosion [8].

In recent years, a number of water erosion studies have been made, and many methods have been developed to assess soil erosion intensity, but the validation and verification of the methodologies developed remain general problems [9]. The terrain measurement of erosion is limited not only by the financial demands of the projects, but also by the lack of suitable sites. One of the ways to determine the erosion rate is to measure sediments in reservoirs. There are a number of approaches describing the methods of measuring the amount of sediments in reservoirs [9], [10], [11], and a number of works have been conducted to resolve this issue [12].

The main aim of the study is the validation of the physically-based Erosion-3D model and the USPED empirical model, which are based on continuous rainfall events and a confrontation of the results modelled with the actual measured sediment load data in the Svacenicky Creek catchment in Slovakia.

2. Materials and methods

2.1. Physically-based EROSION-3D model

The physically-based EROSION-3D model has been used for quantification of the amount of sediments in the Svacenicky creek catchment. The model has been developed since 1995 by Michael von Werner at the Department of Geography, Georg August University Goettingeng in Berlin [13]; it is able to simulate and predict the amounts of soil erosion, surface runoff, sediments, deposition, and the volume and concentration of eroded sediments [14], [15].

The processes describing the model system in a complex way are shown in Figure 1. The scheme contains theoretical explanations of the processes within the model and explains how they affect each other. As mentioned above, the Erosion-3D model consists of two submodels (the erosion and infiltration models), but because of the restricted number of pages here in, only the scheme of the erosion model is presented below.
2.1.1. Long-term simulation in the EROSION-3D model

The Erosion-3D model has been predominantly developed as an event-based model, but some of the sub-models have a continuous character and can perform long-term simulations. The long-term simulation model is able to run more calculations one after another, and, after each event, the digital elevation model is adapted according to the amount of erosion and deposition [16].

There are several ways to conduct a long-term simulation [17]:

a) The iterations represent one or more events that have recurred, and the iteration value defines how often the single events (or a sequence of events) are repeated.

b) The sequences sum up the event results using a combination of individual single events and offer an overall result like a continuous model.

c) A long-term simulation is based on a continuous rainfall series.

In the study, the amount of sediments has been calculated for a small catchment. The long-term simulation is based on a continuous rainfall series. The rainfall series consist of effective erosive events which occurred within the period from September 2015 to October 2016. Each rainfall event requires its own soil data set, whose parameters account for the current soil conditions and stages of crop growth of that date.
2.2. **USPED empirical model**

Unit Stream Power Based Erosion (USPED) is an empirical model built on the concept of the Universal Soil Loss Equation (USLE) of the 1990s [18], [19]. The model can be used for the modelling of potential soil erosion and deposition on agricultural land. The input parameters are a digital elevation model (DEM) and the values of factor R (rainfall erosivity), K (soil erodibility factor), C (cover management values), and P (building erosion control).

2.3. **Bathymetry measurement of the Svacenicky Jarok polder**

The Svacenický Creek polder is a part of the flood protection measures of the area analysed and was built to reduce the flood waves of the Myjava River. A hydrographical survey of the Svacenicky Creek polder was conducted from 2015-2017 using the EcoMapper Autonomous Underwater Vehicle (AUV) device, which generates high-resolution maps of water quality, water currents, bathymetry, and sonar imagery. The hydrographic measurement of the Svacenicky Creek polder was performed in cooperation with the Slovak Academy of Science in Bratislava, Slovakia.

2.4. **Description of the study area**

Svacenický Creek catchment is located in the western part of Slovak Republic, in the cadastral area of the town of Myjava, Tura Luka and the district of Myjava (Figure 2). The area is endangered by quick runoff respond and related muddy floods and the dominant soil threat represents water erosion. The entire catchments is drained by several small streams with total length 7.86 km². The change of the Myjava landscape from forest to farmlands with the rapid settlement of the region has caused intensive runoff-erosion processes. At present agricultural land covers more than 50 % of catchment area. The other segments of the land use categories are shown in the Table 1. The morphometric features of the catchment are summarized in the Table 1.

![LAND USE](image)

**Figure 2.** Location of the Svacenicky Creek catchment and the land-uses of the study area

| Land use category | Total Area (km²) | Path area | Paved area | Arable land | Water bodies | Forests | Shrubbery | Grassland | Garden orchard |
|-------------------|-----------------|-----------|------------|-------------|--------------|---------|-----------|------------|---------------|
|                   | 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           |
Table 2. Morphometric characteristics of the Svacenicky Creek catchment

| SYMBOLS | MORPHOMETRIC CHARACTERISTICS | FORMULA | SVACENICKÝ CREEK |
|---------|-----------------------------|---------|-------------------|
| A       | Basin area (km²)            | GIS     | 6.26              |
| L       | Basin length (km)           | GIS     | 5.27              |
| P       | Basin perimeter (km)        | GIS     | 16.39             |
| PR      | Relative perimeter          | Pr = A/P| 0.38              |
| CIRC    | Circularity Ratio           | Circ = 4πA/P2 | 0.29          |
| ELONG   | Elongation Ratio            | Elong = 2√(A/π)/L = (2/L)^*(A/π)^0.5 | 0.54          |
| COMP    | Compactness Factor          | Comp = P/2√πA | 1.85          |
| SF      | Shape Factor Ratio          | Sf = L^2/A | 4.43          |
| RF      | Form Factor Ratio           | Rf = A/L^2 | 0.23          |
| ARS     | Right side area             | GIS     | 1.87              |
| ALS     | Left side area              | GIS     | 4.40              |
| AC      | Asymmetry coefficient       | Ac = (Ars-Als)/A | 0.40          |
| NU      | Stream Number               | GIS     | 2                 |
| LU      | Stream Length (km)          | GIS     | 7.86              |
| LUR     | Stream Length Ratio         | Lur = Lu/(Lu-1) | 1.15          |
| RB      | Bifurcation Ratio           | Rb = Nu/(Nu+1) | 0.67          |
| D       | Drainage Density            | D = Lu/A | 1.25          |
| LO      | Length of Overland Flow     | Lo = 1/D*2 | 2.51          |
| TC      | Concentration time          | GIS     | 0.67              |
| VR      | Runoff velocity             | GIS     | 2.34              |
| 4       |                             |         |                   |
| Z       | Maximum Basin Height        | GIS     | 545.60             |
| Z        | Minimum Basin Height        | GIS     | 311.40             |
| R       | Relief (m)                  | R = Z -z | 234.20             |
| ZMEAN   | Mean Basin Height (m)       | GIS     | 394.00             |
| ZCENTR  | Basin Centroid Height (m)   | GIS     | 373.40             |
| SL      | Basin Slope                 | GIS     | 6.50               |

2.5. Input data

The input parameters for both models are rainfall (duration and intensity), a digital elevation model (spatial resolution of 10 x 10 m), and soil input data. The rainfall events (a one-minute step) were observed at the Myjava meteorological station during the period selected (IX.2015-X.2016). The model’s runs were performed for 27 rainfall events, which are considered to be the most extreme rainfall events that occurred during the period selected. The frequency of the characteristic rainfall events is shown on Figure 3. A summary of the soil input parameters for the physically-based EROSION-3D model is introduced in Table 3. The variability of the soil input parameters is mainly due to the dates of the rainfall events. A summary of the input parameters to the USPED empirical model is presented in Table 4.
### Figure 3. Graphic interpretation of rainfall events during the period selected

#### Table 3. Summary of soil input parameters for the physically-based Erosion-3D model

| Soil parameters          | Fallow land cover type | Winter wheat |
|--------------------------|------------------------|--------------|
|                          | Loam soil              | Silt-loam soil | Silt-clay-loam soil | Loam soil | Silt-loam soil | Silt-clay-loam soil |
| Bulk density [kg/m³]     | 1200-1350              | 1110-1280     | 1050-1260            | 1341-1491 | 1329-1479     | 1328-1458           |
| Soil initial moisture [%]| 30-45                  | 30-45         | 30-45                | 30-45     | 30-45         | 30-45               |
| Organic carbon content [%]| 1.236-1.356            | 1.156-1.251   | 1.129-1.233          | 1.350-1.650 | 1.750-1.557 | 1.465-1.465         |
| Erodibility [N/m²]      | 0.0015-0.0036           | 0.0002-0.0011 | 0.0001-0.0003        | 0.0008-0.001 | 0.0007-0.0002 | 0.0007-0.0003       |
| Roughness [s/m¹/³]      | 0.0009-0.0023           | 0.0011-0.0012 | 0.0010-0.0012        | 0.015-0.015 | 0.015-0.015 | 0.015-0.015         |
| Surface cover [%]       | 0.023                   | 0.019         | 0.012                | 0.075     | 0.075         | 0.075               |
| Correcting factor of soil [-] | 0.08-15                | 0.08-15       | 0.08-15              | 0.08-1    | 0.08-1        | 0.08-1              |

#### Table 4. Summary of the input parameters for the USPED empirical model

| Parameter                           | Fallow land cover type | Winter wheat |
|-------------------------------------|------------------------|--------------|
| Rainfall erosivity [MJ.mm.ha⁻¹.h⁻¹] | 169.3                  | 169.3        |
| Soil erodibility factor [t.ha.ha⁻¹.MJ⁻¹.mm⁻¹] | 0.017                  | 0.017        |
| Cover management values [-]         | 0.65                   | 0.12         |
| Building erosion control [-]        | 1                      | 1            |

3. Results and discussions
The intensive erosion processes in the Svacenicky Creek catchment are connected with areas having a slope higher than 10°. These areas are located close to the water bodies or small gully rills and channels.
on the soil surface, which confirm the ongoing erosion processes in the catchment. In these endangered areas the deposition of eroded material is occurring and is accumulated in the bottom of the slope. In general, the erosion rate has a medium intensity in the catchment (up to 5 tons per hectare/year).

Considering the crop management scenarios, it can be stated that a soil surface without vegetation (fallow land) represents a great danger, which can lead to significant runoff-erosion processes and degradation processes as well. Vegetation cover plays an effective role in preventing erosion to the extent that it absorbs the kinetic energy of raindrops, covers a large proportion of the soil during periods of the year when rainfall events are most extreme, slows down runoff, and keeps the soil surface porous [20]. The results confirm that appropriate management practices can be significantly protective against erosion processes because crop canopies dramatically reduce the kinetic energy exerted by raindrops and therefore preserve the soil surface from the impact of raindrops and related processes [21].

The physically-based Erosion-3D model predicts a more than double erosion rate in the case of a fallow land cover type (Figure 4), and the USPED empirical model estimates the soil erosion rate as more than four times greater (Figure 5). In both of the models used, winter wheat strongly decreases the intensity of the erosion processes. It is clear that crops are one of the significant factors decreasing the negative impact of soil erosion on agricultural land. The results calculated are summarized in Table 5. According to the bathymetric survey, about 301.5 m$^3$ of sediments settled in the reservoir during the period analysed. The results calculated for the winter wheat by the physically-based model are very close to this value. The outputs from the USPED empirical model overestimate the amount of sediments (for a fallow land cover type, up to 2986.8 m$^3$). The USPED empirical model is more suitable to determine the long-term intensity of potential erosion and deposition and the spatial localization of places endangered by water erosion (Figure 5). The accuracy of the calculations of the sediment volume (USPED model) is affected by the inaccuracy of the input parameters, which only parameterize the actual natural conditions [22]. Based on the results, it can be concluded that the fully distributed Erosion-3D model represents a more appropriate approach for quantifying the amount of sediments and other characteristics when considering the variability of the input data.

| Scenarios of crop management | EROSION-3D | USPED | Measured sediments (m$^3$) |
|-----------------------------|------------|-------|---------------------------|
| Winter wheat               | 270.0      | 712.9 | 301.5                     |
| Fallow land cover           | 790.0      | 2986.8|                           |

4. Conclusions

The aim of the study was to quantify the amount of sediments by the physically-based Erosion-3D model and the USPED empirical model and to compare these results with the measured amount of sediments in the Svacenicky Creek polder. The calculations were performed for two crop management scenarios, i.e., winter wheat and fallow land cover types. The winter wheat reflects the current management practices in the catchment. Based on the results modelled, it can be concluded that the USPED empirical model significantly overestimates the amount of sediments in comparison with the physically-based Erosion-3D model. On the other hand, the USPED model can be a useful tool for areas prone to erosion processes. Considering the variable crop management practices, it can be stated that the physically-based Erosion-3D model approaches the measured data to an appreciable extent. The results show that the Erosion-3D model is a satisfactory tool for agricultural management problems such as assessing the impact of changing crop rotations on soil losses based on the long-term soil erosion simulations. The Erosion-3D model demonstrated the higher degree of accuracy of the model’s results for the data from
the bathymetry measurements than the USPED empirical model and simulated the impact of continuous rainfall events on erosion very well.

Figure 4. The amount of sediments for the fallow land cover type and winter wheat (Erosion-3D model)

Figure 5. The amount of sediments for the fallow land cover type and winter wheat (USPED model)
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