Process for The Parameterization of a Soil Erosion Model Based on a Small Rainfall Simulator

Zuzana Nemetova¹, Michaela Danacova¹

¹ Slovak University of Technology, Department of Land and Water Resources Management, Radlinského 11, 810 05, Bratislava, Slovakia

zuzana.nemetova@stuba.sk

Abstract. Soil erosion due to water is an extensive problem in many countries, especially accelerated erosion, where the natural rate has significantly increased in the most recent period. Its extent impacts on land management practices and is the main factor causing soil degradation. Rainfall simulators are very popular as a standard instrument to conduct research on topics such as soil erosion, infiltration or surface runoff. They are used in laboratory or field experiments in erosion studies to assess the impacts of changes in the tillage management with regard to the erodibility of soil. Results of the experiments can be used in the modelling of surface runoff and sediment transport by hydrological models. This study presents the results of experimental measurements of surface runoff made by an artificial rainfall on an experimental plot. The artificial rainfall was generated using a small rainfall simulator, which allows changes in rainfall intensity and duration. The object of this study was analysed after the surface runoff occurred and the weight of the soil particles was transported from the experimental plot. These results have been used to determine the soil input parameters for the physically-based EROSION-2D model and for the verification of the model parameters. The EROSION-2D model represents a physically and event-based approach for the prediction of soil loss and runoff. The model only requires eight soil input parameters. Some of those parameters can be easily obtained by classic and widely-used methods (soil analyses, terrain measurements, soil map evaluations), and other parameters can be determined from rainfall experiments which represent the main aim of the study. The rainfall intensity has been set at 5 mm/min with 20 minutes of simulated rain, and it corresponded to an intensity with a return period of 100 years. During the experiment a continuous course of the surface runoff and soil moisture was recorded. The results from the simulations were applied to simulate the soil erosion processes in the physically-based EROSION-2D model. For the parametrization of the model, artificial rainfall events were used with an intensity of 2.7 mm/min and rain durations of 12 and 13 minutes. The parametrization of such models represents a necessary and significant part of any scientific work. The experimental results show that outputs from the rainfall simulations can be reproduced successfully, and, based on the results, the process of determining the model’s parameters can be successfully performed.
1. Introduction
The world's greatest environmental problem, which threatens not only developed but also developing countries, is soil erosion. Consequences from water and soil erosion are noticeable not only in economic losses but also, and more importantly, in the loss of the fundamental living resource that human beings rely on.

The general problem of erosion modelling can be seen in the validation and verification of the methodologies used. This is especially true in the case of modelling soil water erosion. Erosion rates are rarely measured, due to both the financial demands of such projects and the lack of suitable sites as well. One way to deal with this issue is to use rainfall simulators. Rainfall simulators represent an important tool for evaluating soil losses on different types of soil, different slope conditions, and different types of land cover with varying rainfall intensities [1], [2]. The fundamental and basic purpose of creating rainfall simulators is the simulation of natural rainfall events. Rainfall simulators not only simulate natural rainfall in a precise manner, but also control the intensity and duration of the rainfall. The simulators provide substantial data that are necessary and irreplaceable for the calibration and validation processes of all types of mathematical models, including empirical, conceptual, and physically-based rainfall-runoff models [3].

It is well known that the energy of raindrops has a significant effect on soil water erosion [4]. One of the most important processes connected with soil water erosion is runoff, which is directly influenced by variations in the intensity of rainfall, drop sizes, and drop energy, and the temporal and spatial resolution of a rainfall event [5]. A rainfall simulator is a device capable of duplicating the physical characteristics of natural rainfall as closely as possible, i.e., its similarity to natural rain in the case of kinetic energy, its repeatability when applying the same simulated rainfall events, and its improved mechanical or technical reliability for simple and easy transportation within the plots investigated [6].

The main objective of the study is to determine the amount of surface runoff and the amount of sediments by using a small rainfall simulator in laboratory conditions; the results were then used to quantify the soil input parameters for the physically-based EROSION-2D model and for the verification of the model parameters. The laboratory experiment was used as a possible set up of the parameters of a physically-based model of the impact of a slope gradient on the time after which surface runoff occurred.

2. Materials and methods
2.1. Erosion-2D model
The Erosion-2D model was developed by Jürgen Schmidt at the Department of Geography at the Free University of Berlin [7]. The main purpose of the model is to calculate soil erosion resulting from natural rainfall. The physically and event-based Erosion-2D model can be applied to slopes of any length [8].

The main parts of the application include predicting the amount of soil loss on agricultural land, estimating the sediment input to rivers, predicting the surface runoff resulting from extreme rainfall events, and assessing the effects of different agricultural management practices on the generation of surface runoff and the amount of soil loss. The model requires three input parameters, i.e., a relief characterized by coordinates (m), the soil parameters (Table 1), and precipitation (mm/min).

| Soil parameters          | Units      |
|--------------------------|------------|
| Bulk density             | kg/m³      |
| Initial soil water content| %         |
| Organic carbon content   | %          |
| Erosion resistance       | N/m²       |
| Hydraulic roughness      | m¹/³       |
| Correcting factor        | -          |
| Particle size distribution| % mass    |
The fundamental components of the Erosion-2D model include the following processes [9]:
- Detachment of soil particles from the soil surface
- Transport of the detached particles by runoff

### 2.1.1. Detachment of soil particles
Erosion processes occur when individual soil particles are detached from the soil surface, which is only possible when the fluid forces generated by the overland flow and raindrops overcome the particles' cohesion and gravity [9]. The erosional effects exerted by overland flow and raindrops are summarized by an expression defined as the momentum flux approach and is described by the following equation:

\[
\varphi_q = q \ast \rho_q \ast \Delta y \ast v_q
\]

where:
- \( \varphi_q \) - momentum flux by an overland flow,
- \( q \) - flow [m³/(m*s)],
- \( \rho_q \) - fluid density [kg/m³],
- \( \Delta y \) - the length of a slope [m],
- \( v_q \) - velocity of runoff [m/s].

### 2.1.2. Transport of detached soil particles
The velocity of the sediment particles suspended in a fluid that sink to the bottom (due to gravity) depends on the particle size. The Stokes equation (3) is used to describe the settling velocity of a particle in a fluid:

\[
v_p = \frac{1}{18} \cdot \frac{D^2 \ast (\rho_p - \rho_q) \ast g}{\eta}
\]

where:
- \( v_p \) - settling velocity [m/s],
- \( D \) - particle size [m],
- \( \rho_p \) - particle density [kg/m³],
- \( \rho_q \) - fluid density [kg/m³],
- \( g \) - acceleration of gravity [m/s²],
- \( \eta \) - fluid viscosity [kg/(m*s²)].

When the settling velocity (\( v_p \)) is multiplied by the mass rate of the settling particles (\( w_p \)), the critical momentum flux of the suspended particles (\( \varphi_{scrit} \)) is created:

\[
\varphi_{scrit} = c \ast \rho_q \ast \Delta y \ast v_p^2
\]

where:
- \( c \) - the concentration of suspended particles [m³/(m³)]
- \( \rho_p \) - particle density [kg/m³]
- \( \Delta y \) - the length of a slope [m]
- \( v_q \) - settling velocity of the particles expressed by the Stokes equation [m/s].
2.2. Design of rainfall simulator

The rainfall simulator has become a very popular tool for conducting research on topics such as infiltration, generation surface runoff, and soil erosion. The first use of a rainfall simulator can be dated to about 1895, when it was used by Ewald Wollny for erosion studies in Germany [10].

In erosion studies, simulators are often used in laboratory or field experiments to assess the impacts of changes in vegetation cover, tillage management, and soil erodibility [10]. The advantage of laboratory experiments is the elimination of natural factors such as wind, solar radiation, soil moisture, and the antecedent soil conditions [12].

In this study in order to generate an artificial rainfall of a constant intensity, an Eijkelkamp small rainfall simulator was used (Fig 1). The surface area of the plot investigated is 0.0625 m² (25 x 25 cm).

![Diagram of Eijkelkamp rainfall simulator](image)

Figure 1. Scheme of the Eijkelkamp rainfall simulator: A – sprinkler plate and water reservoir, B – adjustable support, C – ground frame, D - small capillaries, E - adjustable support, F – aeration pipe

The sprinkler has a pressure regulator to calibrate the rain’s intensity. The sprinkler plate includes 49 capillaries to generate an artificial rainfall event. The length of the capillaries is 10 mm (± 1 mm), and the diameter of the capillaries is 0.6 mm (± 0.08 mm).

The duration, intensity and kinetic energy of the rainfall also has parameters to ensure the high sensitivity of the measurement results to any changes in the soil properties observed. The advantage of the laboratory experiments is the elimination of natural factors such as wind, solar radiation, soil moisture and the antecedent soil conditions [13], [14].

2.2.1. Experimental design and treatments

For a possible set up of the parameters of physically-based models a laboratory experiment can be used where it is possible to monitor the impact of a slope gradient at the time after which surface runoff with transported sediments has occurred.

The soil sample designated for the rainfall simulations in the laboratory conditions was taken from an agricultural field in Turá Lúka (Myjava basin). The Myjava Hill Land is predisposed to water, rill, and gully erosion [15], [16]. The soil sample used in the experiment was a loamy soil (Novak’s soil classification system) and without any vegetation cover. The soil sample was kept in a plastic container;
the depth of the soil profile was 20 cm. The bottom of the upper container was perforated to simulate the vertical movement of water and to prevent its accumulation in the upper container. The infiltrated water was stored in the bottom container (Fig. 1).

In this study two laboratory experiments were selected. The rainfall simulation experiments were carried out for the slope using 20% of the irrigated soil sample. Before the experiment, the moisture of the soil samples was kept at 5%. In the first experiment the artificial rainfall had an intensity of 5.0 mm/min and the duration of the rainfall was 20 minutes (Fig. 2A, simple rainfall event). In the second experiment, the artificial rainfall had an intensity of 2.7 mm/min, and the 63-minute artificial rainfall was interrupted after every 12 (13) minutes (the duration of the total experiment was 143 minutes). The cause of these interruptions was the limitations of the rainfall simulator, whose reservoir enables storage of only 2.3 litres of water. After the interruption, the surface runoff’s volume, sediment weight, and soil moisture were measured.

![Figure 2. Laboratory experiments: A: 20-minute simple rainfall event, B: 63-minute artificial rainfall event (5 x 12 or 13-minute simple rainfall)](image)

This simple artificial rainfall was used on the parameterization for the Erosion 2D model. The second laboratory experiment was selected for the validation of the model.

2.3. Scheme of the laboratory measurements and hydrological modelling
The experiment consisted of laboratory measurements of the surface runoff 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, 2 and 3 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 presented in Fig 3.

3. Results
The results obtained during the laboratory experiment were used to better understand the processes involved in the generation of surface runoff and the transport of sediments. In the study, a simple artificial rainfall was used for the parameterization of the Erosion-2D model. The artificial rainfall had an intensity of 5.0 mm/min, and the rainfall of the duration was 20 minutes (Fig. 2A). The volume of the surface rainfall (5.03 L), the initial soil moisture before the experiment (5%), and the sediments (255 g) from the irrigated area were recorded. These results were used to calibrate some of the parameters of the physically-based hydrological model for the simulation of the runoff generation processes on a slope. The parameters of the surface runoff were parameterized according to the modelled and measured values of the time of the occurrence of the runoff.
Figure 3. The scheme of the experiment consisted of laboratory measurements and hydrological modelling

Table 2. Results of the model: Simulation of the simple artificial rainfall

| Distance [m] | Surface Runoff [m³/m] | Sediment volume [kg/m³] | Sediment concentration [%] | Clay* [%] | Silt* [%] | Erosion [t/ha] | Deposition [t/ha] | Net erosion [t/ha] |
|--------------|------------------------|-------------------------|---------------------------|----------|-----------|----------------|------------------|-------------------|
| 1            | 0.0379                 | 2.1                     | 38                        | 30       | 70        | 0.5            | 0                | 0.5               |

*Particle size distribution estimated by the Erosion-2D model

These results were used to validate some of the parameters of the Erosion 2D-model for simulation of the runoff generation processes on the slope.

3.1. Validation of the Erosion-2D model

For the validation parameters a 63-minute artificial rainfall with interruptions (5 single rainfall events) was selected. The following table (Table 3) summarizes some of the basic parameters obtained during the individual rainfall simulations under laboratory conditions.

Table 3. Summary from the laboratory rainfall simulation experiment (plot area= 0.0625m²)

| Variant (single rainfall) | Total time [min] | Rainfall duration [min] | Slope [%] | Soil moisture before [%] | Soil moisture after [%] | Rainfall intensity [mm/min] | Surface runoff volume [ml] |
|---------------------------|------------------|-------------------------|-----------|-------------------------|------------------------|---------------------------|--------------------------|
| 1                         | 13               | 13                      | 20        | 5                       | 15                     | 2.7                       | 1000                     |
| 2                         | 25               | 12                      | 20        | 15                      | 35                     | 2.7                       | 1640                     |
| 3                         | 38               | 13                      | 20        | 35                      | 40                     | 2.7                       | 1525                     |
| 4                         | 51               | 13                      | 20        | 40                      | 42                     | 2.7                       | 1800                     |
| 5                         | 63               | 12                      | 20        | 42                      | 42                     | 2.7                       | 1730                     |

Total of 63-minute artificial rainfall with the interruptions: 7695

The Erosion-2D model requires morphological characteristics (slope, distance), soil parameters (bulk density, initial soil water content, organic carbon content, erosion resistance, particle size distribution), and design rainfall. The hydraulic roughness and correcting factor were used from the first experiment (Table 2).
Table 4 summarizes some of the basic parameters obtained during the individual and combined rainfall simulations of the Erosion 2D-model. For a comparison of the simulated surface runoff, the scale of the experimental plot using a regression function was determined. Table 5 contains a comparison between the modelled and measured values of the volume of the runoff.

**Table 4.** Results: Summary from the rainfall simulation – Erosion 2D (plot area = 1m²), 63-minute artificial rainfall with interruptions (5 individual rainfalls and their combinations)

| Variant (single rainfall) | Total time [min] | Surface Runoff [m³/m] | Sediment volume [kg/m] | Erosion [t/ha] |
|---------------------------|------------------|------------------------|------------------------|---------------|
| 1 - 5                     | 63               | 0.049                  | 0.55                   | 1.2           |
| 2 - 5                     | 50               | 0.046                  | 0.44                   | 1.1           |
| 3 - 5                     | 38               | 0.037                  | 0.35                   | 0.9           |
| 4 - 5                     | 25               | 0.031                  | 0.33                   | 0.8           |
| 5                         | 12               | 0.025                  | 0.28                   | 0.5           |

**Table 5.** Summary results from the laboratory rainfall simulation experiment (plot area = 1m²)

| Variant (single rainfall) | Laboratory experiment Surface runoff [m³/m] | Erosion 2D-model Surface runoff [m³/m] | Difference between the measured and simulated surface runoff [%] |
|---------------------------|---------------------------------------------|---------------------------------------|-----------------------------------------------------------------|
| 1 - 5                     | 0.052                                       | 0.049                                 | 6.1                                                             |
| 2 - 5                     | 0.048                                       | 0.046                                 | 4.3                                                             |
| 3 - 5                     | 0.0385                                      | 0.037                                 | 4.0                                                             |
| 4 - 5                     | 0.032                                       | 0.031                                 | 3.2                                                             |
| 5                         | 0.027                                       | 0.025                                 | 8                                                               |

**Figure 4.** The volume of the surface runoff (Erosion-2D model and rainfall simulator)
4. Conclusions
The laboratory experiment was based on a possible set up of the parameters of a physically-based model of the impact of a slope gradient on the time after which surface runoff occurred, the soil moisture, and the weight of the sediments transported.

The experiments were conducted in laboratory conditions, which enabled the maintenance of constant conditions (an artificial rain with a given intensity and the slope of the irrigated area) and eliminated uncertainties associated with weather conditions. By comparing the measured results to other measured results, a researcher may set up a scale for the sensitivity to erosion of the researched soil.

From the validation results, it can be concluded that the volume of surface runoff in all the combinations is higher in the simulation of rainfall events using a simulator in laboratory conditions. The percentages are in Table 5, where the range is from 3 - 8%.

In this study, the parameters of the Erosion-2D model, i.e., the correcting factor, erosion resistance, and hydraulic roughness, were adjusted (parameterised) by comparing the modelled volumes of the surface runoff with the measured data on the experimental plots. The parameters of the surface runoff were parameterised according to the modelled and measured values of the time of the occurrence of the runoff.

The parametrization of such models represents a necessary and significant part of any scientific work. The experimental results show that outputs from the rainfall simulations can be reproduced successfully and, based on them, the process of determining a model’s parameters can be successfully performed.

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