Estimating effectiveness of crop management for reduction of soil erosion and runoff

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Abstract. The paper focuses on erosion processes in the Svacenický Creek catchment which is a small sub-catchment of the Myjava River basin. To simulate soil loss and sediment transport the USLE/SDR and WaTEM/SEDEM models were applied. The models were validated by comparing the simulated results with the actual bathymetry of a polder at the catchment outlet. Methods of crop management based on rotation and strip cropping were applied for the reduction of soil loss and sediment transport. The comparison shows that the greatest intensities of soil loss were achieved by the bare soil without vegetation and from the planting of maize for corn. The lowest values were achieved from the planting of winter wheat. At the end the effectiveness of row crops and strip cropping for decreasing design floods from the catchment was estimated.

1. Introduction

Soil erosion by water is one of the most widespread forms of soil degradation [1] which can lead not only to soil loss but also to other soil threats. It causes the greatest loss of soil in Europe compared to other soil degradation processes and it is listed in the Soil Thematic Strategy of the European Commission in 2006 as one of the eight threats to soil. Recent policy formulated by the European Commission have called for quantitative assessments of soil loss intensity at the European level [2]. The analysis and quantification of soil erosion processes and the assessment of their impact on soil loss on slope, catchment or regional scales are required by water managers and catchment stakeholders. Various erosion models have been developed to predict soil erosion intensities by water. These models differ in terms of their complexity, inputs, and spatial and temporal scales, so that different modelling approaches can lead to significantly different soil erosion rates [3].

Approaches to soil conservation on cultivated lands are based on agronomic measures, soil management or mechanical methods. Agronomic measures for soil conservation use the protective effect of plant covers to reduce soil erosion. The simplest way to combine different crops is to grow them consecutively in rotation or in strips. With strip-cropping, row crops and protection-effective crops are grown in alternating strips aligned on the contour. Erosion is limited to the row-crop strips and soil removed from these is trapped within and behind the next strip downslope [4].

This paper presents an engineering approach for the quantification of soil erosion and sediment transport on a catchment scale. Methods based on crop management are applied for the reduction of soil loss and sediment transport from the catchment and their effectiveness for decreasing soil erosion and runoff is estimated. The paper is structured in the following way: A brief introduction of the problems studied is presented in Chapter 1. In Chapter 2 the methodology used is described. We characterise the USLE, SDR and WaTEM/SEDEM models for estimating the soil erosion and
sediment transport on a catchment scale. Chapter 3 describes the study area of the Svacenický Creek catchment and the Svacenický Creek polder. Chapter 4 contains the results of modelling the soil erosion and sediment transport by the USLE/SDR and WaTEM/SEDEM models under selected crops and crop management. Chapter 5 discusses the results and states our conclusions.

2. Methods

2.1. Erosion models

Two modelling approaches were applied for quantifying the soil erosion by water on a catchment scale. First, the mean annual soil loss and sediment transport from the catchment were estimated by the Universal Soil Loss Equation (USLE) and the Sediment Delivery Ratio (SDR) model. The second approach was presented by the WaTEM/SEDEM spatially-distributed soil erosion and sediment delivery model.

The Universal Soil Loss Equation (USLE) is an empirical model which can be used to estimate soil loss with an emphasis on sheet and rill erosion. In the modified version of USLE the USLE 2D methodology was applied to calculate the LS topographical factor. The LS factor is derived for closed eroded units based on a raster digital elevation model and increasing slope’s length in the direction of the surface runoff is expressed by a unit contributing area, which is defined by several algorithms.

The USLE model does not take into account the sediment transport and deposition. Therefore, the sediment transport was estimated using the Sediment Delivery Ratio (SDR) model by [5]. The SDR calculates the percentage of total soil loss that is delivered to a catchment outlet by the equation (1):

$$ SDR = 1.366 \times 10^{-11} \cdot A^{-0.0998} \cdot S_r^{0.3629} \cdot CN^{5.444} $$

where $A$ is the catchment area [km$^2$], $S_r$ is the relief ratio [m/km$^{-1}$], $CN$ is the average SCS curve number of the catchment.

The second modelling approach is represented by the WaTEM/SEDEM spatially-distributed soil erosion and sediment delivery model developed at the Physical and Regional Geography Research Group of KU Leuven [6]. The model consists of two submodels that calculate water and tillage erosion, including sediment delivery to rivers. The soil loss is estimated by the RUSLE equation [7] using a 2D approach to the topographical factor. The second submodel calculates the amount of sediments that is exported towards surface water. This is done by routing the sediments towards the surface water and taking into account the possible deposition of sediments. This deposition is controlled by the transport capacity ($T_c$), which is calculated for each pixel. The transport capacity is proportional to the volume of the potential gully erosion (see equation (2)):

$$ T_c = ktc \cdot Eprg = ktc \cdot R \cdot K \cdot (LS - 4.12 \cdot Sg \cdot 0.8) $$

Where $k tc$ is the transport capacity coefficient, $Eprg$ is potential gully erosion, $Sg$ is the local slope (meter per meter), and $R$, $K$ and $LS$ are the factors from the RUSLE equation.

2.2. The SCS-CN methodology

The SCS-CN method is a rainfall-runoff model developed for United States by the U.S. Soil Protection now NRCS-Natural Resources Conservation Service in 1956. In this method a relationship between watershed characteristics and antecedent rainfall meets in the Curve number parameter. With this simple parameter rainfall depth is transformed to runoff depth. Tables and figures for estimating the CN parameter for soil cover complexes of USA are given e.g. in the publication of USDA [8]. The method of SCS-CN is based on the formula (equation (3)):

$$ Q = \frac{(P-I_a)^2}{S+(P-I_a)} $$
where \( I_a \) is initial abstraction [mm], \( S \) is potential maximum retention [mm], \( Q \) is direct runoff depth [mm], \( P \) is rainfall depth [mm], \( CN \) is curve number [-]. The relation between \( S \) [mm] and \( CN \) [-] has the form (see equation (4)):

\[
S = 25.4 \left( \frac{1000}{CN} - 10 \right)
\]  

(4)

While \( I_a \) can be expressed as \( \lambda S \) (in the original form \( \lambda = 0.2 \), by estimation of design 100-year discharge in our study, the parameter \( \lambda = 0 \) the original formula can be in the form (see equation (5)):

\[
Q = \frac{(P-\lambda S)^2}{S+(P-\lambda S)}
\]  

(5)

3. Pilot area
The catchment of the Svacenický Creek with its area of 8.61 km\(^2\) is located in the Myjava River basin in Western Slovakia (figure 1). The creek has a length of 5.4 km and is a right-hand tributary of the Myjava River. The Svacenický Creek polder is a part of the flood protection measures in Turá Lúka and is located near the outlet of the Svacenický Creek. The Svacenicky Creek polder, which was built in 2012, can reduce a 100-year maximum design flood of 16.00 m\(^3\)s\(^{-1}\) to 0.21 m\(^3\)s\(^{-1}\). The projected volume of the polder’s storage capacity is 215,808 m\(^3\), and it is able to capture a flood wave of 207,330 m\(^3\).

Figure 1. Location of the Svacenický Creek basin.

For modelling the erosion and sediment transport, the catchment’s outlet at the Svacenický Creek polder was considered. The area of the catchment to the polder is 626.32 ha, with 10.76 ha of bare soil (1.72 % of the area), 513.32 ha of arable land (81.96 %), 46.45 ha of forest (7.42 %), 46.78 ha of urban areas (7.47 %) and 9.01 ha of roads (1.44 %).

4. Results
First, the modelling was provided for two different crops (winter wheat and maize for corn) grown on arable lands; and bare soil. The results of modelling the erosion and sediment transport from the Svacenický Creek catchment are presented in the form of mean annual soil loss in (t ha\(^{-1}\) year\(^{-1}\)) and the total mean annual sediment transport to the catchment outlet (polder) in (t year\(^{-1}\)).

Table 1 presents the results of the mean annual soil loss for the selected crops and the bare soil. The comparison shows that the greatest intensities of soil loss were achieved by the bare soil without
vegetation and from the planting of maize for corn. The lowest values were achieved from the planting of winter wheat. Table 2 presents the total mean annual sediment transport to the catchment outlet.

In all tables “WS” is the LS algorithm developed by Wischmeier-Smith; “Nearing-WS” is the LS algorithm developed by Nearing and Wischmeier Smith; and “Nearing-Mc” is the LS algorithm developed by Nearing and Mc Cool.

**Table 1.** Comparison of the mean annual soil loss (t ha⁻¹ year⁻¹) according to the USLE and WaTEM/SEDEM models and various LS algorithms.

| Model        | LS algorithm   | Soil loss (t ha⁻¹ year⁻¹) | Winter wheat | Maize for corn | Bare soil |
|--------------|----------------|---------------------------|--------------|----------------|-----------|
| USLE/SDR     | WS             | 8.93                      | 45.41        | 74.45          |
| USLE/SDR     | Mc Cool        | 9.74                      | 49.49        | 81.13          |
| USLE/SDR     | Nearing-WS     | 7.86                      | 39.97        | 65.52          |
| USLE/SDR     | Nearing-Mc     | 9.43                      | 47.95        | 78.61          |
| WaTEM/SEDEM  | WS             | 11.15                     | 54.77        | 84.95          |
| WaTEM/SEDEM  | Mc Cool        | 12.44                     | 61.35        | 95.66          |
| WaTEM/SEDEM  | Nearing-WS     | 9.78                      | 48.03        | 74.05          |
| WaTEM/SEDEM  | Nearing-Mc     | 12.06                     | 59.44        | 92.64          |

The strip cropping was based on alternating row crops (winter wheat or maize for corn) with protection effective crops (grass) aligned on the contour. Table 2 presents the comparison between the mean annual sediment transport for the row crops (winter wheat or maize for corn) and strip cropping (winter wheat/grass and maize for corn/grass).

**Table 2.** The mean annual sediment transport (t year⁻¹) according to the USLE/SDR and various LS algorithms.

| Model        | LS algorithm   | Sediment yield (t year⁻¹) | Winter wheat (row crops) | Maize for corn (row crops) | Winter wheat/grass (strips) | Maize/grass (strips) |
|--------------|----------------|---------------------------|--------------------------|---------------------------|-----------------------------|----------------------|
| USLE/SDR     | WS             | 2684.36                   | 18374.76                 | 1149.33                   | 6822.75                     |                     |
| USLE/SDR     | Mc Cool        | 2925.02                   | 20022.09                 | 1252.37                   | 7434.43                     |                     |
| USLE/SDR     | Nearing-WS     | 2362.42                   | 16171.00                 | 1011.49                   | 6004.47                     |                     |
| USLE/SDR     | Nearing-Mc     | 2834.38                   | 19401.67                 | 1213.57                   | 7204.06                     |                     |

**Table 3.** Design floods for various types of crop management.

|                | CN  | Hz  | Runoff | V   | Q₁₀₀     |
|----------------|-----|-----|--------|-----|---------|
| Winter wheat   | 72.94 | 32.51 | 8.34  | 52237.78 | 11.81 |
| Maize for corn | 77.04 | 32.51 | 9.17  | 57426.38 | 12.98 |
| Winter wheat / grass | 70.89 | 32.51 | 7.73  | 48394.67 | 10.94 |
| Maize for corn / grass | 72.94 | 32.51 | 8.34  | 52237.78 | 11.81 |
| Bare soil      | 82.78 | 32.51 | 9.77  | 61179.20 | 13.83 |

Evaluation of effectiveness of the strip cropping for the reduction of direct runoff form the catchment was provided by the SCS-CN methodology. The 100-year design rainfall (Hz) of the duration equal to the time of concentration was derived by simple scaling methodology from the daily design rainfall at the Myjava station. The flood wave volume (V) of a triangular shape was estimated and used for estimation of the maximum peak discharge. The values of estimated 100-year design maximum discharges (Q₁₀₀) for various types of the crop management are presented in table 3. We can
observe that the peak discharge has lowered when combining crop with grass strips in comparison to row crops and the highest runoff was achieved for bare soil. In the comparison with bare soil, the row crops (winter wheat) decreased design discharges $Q_{100}$ from the catchment by 14%, maize for corn by 6%, strip cropping (wheat/grass) by 20% and strip cropping (maize for corn/grass) by 14%.

5. Conclusions
The main objective of this study was to quantify both the soil loss from agriculturally arable lands and the transport of sediments to the dry water reservoir (polder) of the Svacenický Creek. For estimating the mean annual soil loss and sediment transport in the Svacenický Creek catchment an empirical (USLE/SDR) and conceptual (WaTEM/SEDEM) approaches were applied. The results of various modelling approaches were consistent and comparable. The AUV EcoMapper was used to gather the data on the Svacenický Creek polder in September 2015. From the filed measurement, we determined that during the last four years the clogging of the reservoir by sediments was over 10,474 m$^3$. The sediment transport was estimated to be 4994.4 t.year$^{-1}$. The modelled sediment transport from the Svacenický Creek catchment to the polder proved that the applied rotation of winter wheat and maize /grass on the field gave comparable result of annual soil erosion to the field measurements. Next the erosion modelling was provided for various crop management on arable lands based on row crops and strip cropping. The comparison shows that the greatest intensities of soil loss were achieved by the bare soil without vegetation and from the planting of maize for corn. The lowest values were achieved from the planting of winter wheat. The strip cropping consisted of alternating row crops with protection effective crops aligned on the contour. The agronomic measures based on strip cropping reduced the sediment transport from the catchment area by 50 – 60% compared to the row crops. We can observe that the peak discharge has lowered when combining crop with grass strips in comparison to row crops and the highest runoff was achieved for bare soil.

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