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SOIL LOSS ASSESSMENT IN AN AGRICULTURAL LANDSCAPE AND ITS UTILIZATION IN LANDSCAPE PLANNING

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Abstract

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Enlargement of scale, intensification, specialization and mechanization of agricultural production are factors which often lead to problems such as soil erosion and associated water pollution with soil nutrients. Erosion is a diffuse process which occurs at relatively low and widely varying rates from year to year and from location to location. Estimation of soil loss is a crucial factor in the planning of sustainable land use. For this purpose, many empirical and mathematical soil erosion models have been developed. Application of the modelling approach helps to predict the spatial and temporal variation of soil erosion and deposition at the landscape scale, and it also helps to assess the impact and effectiveness of applied soil erosion measures. This paper summarizes the methodology of the assessment of erosion risk and the impact of passive soil erosion measures such as grassed waterways, buffer strips and parcel size and shape consolidation. The physically based soil erosion model, Erosion 3D, has been used to locate the main areas of soil loss and to simulate the erosion rates before and after the application of soil protection measures. The results showed that applied measures can effectively reduce soil loss rates and they also reinforce that simulation models such as Erosion 3D are able to provide the information necessary for appropriate localization and extent of site-specific measures.

Key words: soil erosion, modelling, validation, erosion mitigation measures

Introduction

Practical measurement of soil erosion is difficult. Soil erosion is a diffuse process that occurs at relatively low rates and widely varying rates from year to year and from location to location. In fact, there are many difficulties associated with monitoring and surveying erosion processes. In most cases, direct measurements of soil loss are limited to small experimental plots on which the relevant hydraulic conditions of erosion cannot be completely reproduced. Similarly, plot measurements cannot be directly transferred to natural slopes and watersheds without taking the differing hydraulic conditions into consideration. Thus, technology to estimate rates of soil erosion has emerged as a major tool to overcome these difficulties. Application of physically based models represents the recent trend in soil erosion research, together with development of GIS and remote sensing techniques. Experimental activities used ANSWERS, and AnnGNPS98 models were applied to modelling of overland flow, erosion processes and river sedimentation (Hlavčová, Macura, 1993). A most remarkable application of physical modelling, model ERDED, was in the work of Hofierka and Šúri (1996), and other works presented by Slovak authors were carried out on territories outside Slovakia. The SMODERP model has been verified on experimental plots in Japan (Janský, 2001) and the USPED model has been successfully applied in modelling erosion hazards in army training sites in the USA (Mitášová et al., 1996). Operational models for regional assessments should be based on simple data requirements, must consider spatial and temporal variability in hydrological and soil erosion processes, and must be applicable to a variety of regions with a minimum of calibration. This study aims to assess the applicability of the Erosion 3D model for erosion risk assessments at the landscape scale, and to evaluate the impact of erosion mitigation measures.

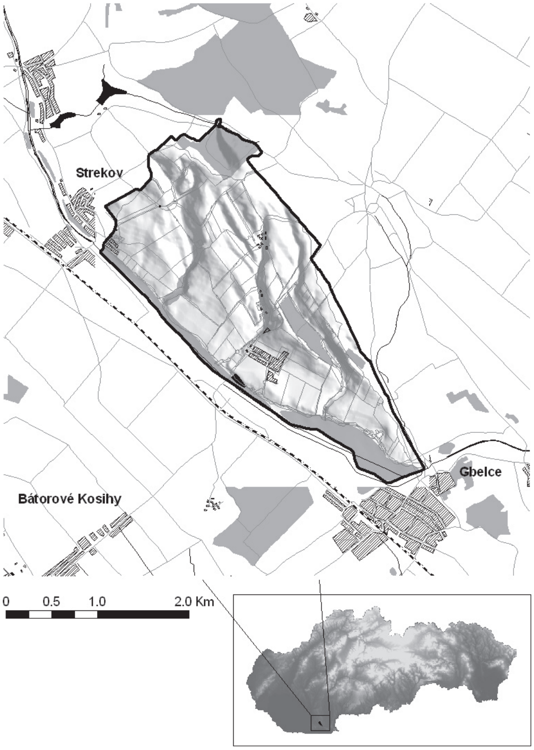

Fig. 1. Location of the sample area.

Materials and methods

Sample area

The sample area is a typical region of loess plateau situated in the south-western part of Slovakia. According to the morphogenetic soil classification system of Slovakia, the prevailing soil types can be characterized as Chernozems located mostly on moderate slopes and plateau covered by loess (Šály, 2000), while Haplic Luvisols and Regosols prevail on steeper slopes. The topography is slightly moderate with a prevailing slope of 4%, reaching 8–12% in some places. Since high-quality soils prevail, agriculture is well developed. This fact significantly influenced the landscape structure, with arable land dominating the landscape. This region is oriented to intensive agricultural production, since there is an absence of industrial facilities in the catchment. The total size of the sample area is 210 ha and it is delineated by a small watershed representing the typical landscape type in this region.

Erosion modelling

To predict soil loss in the sample area, the physically-based soil erosion model Erosion 3D was used. This model calculates the amount and the direction of overland flow by taking into account the slope and the exposition of

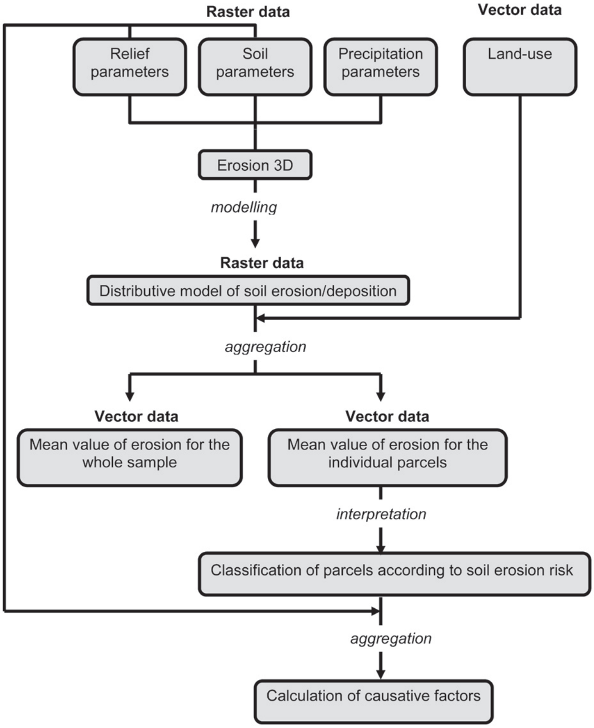

Fig. 2. The methodology of erosion risk assessment.

the considered land surface, and the infiltration rate which is estimated by an infiltration sub-routine based on the approach of Green and Ampt (1911). The algorithm for calculating the spatial distribution of flow paths employs a raster-based digital elevation model, as in Schmidt, Werner (2000). The application of Erosion 3D requires information on the site specific relief and soil and rainfall conditions. The model acquires this information from the following parameters:

- Relief parameters:
  - Digital Elevation model (regular squared tessellation/matrix)
- Soil parameters:
  - bulk density (kg.m^{-3})
  - initial soil moisture content (%)
  - organic carbon content (%)
  - erodibility (N.m^{-2})
  - coefficient of roughness (Manning n)
  - canopy cover grade (%)
  - grain size distribution (fine clay to coarse sand, as in DIN classification) (%)
  - correcting factor for hydraulic conductivity
  - related precipitation measuring points
- Precipitation parameters:
  - duration of precipitation (min)
  - intensity of precipitation (mm.min^{-1}).

The temporal resolution of the model depends on the rainfall data available, and it can range from 1 to 15 minutes. Values of all input parameters are assumed to be spatially uniform below the scale of grid resolution.

Simulation scenarios

The erosion model was applied to simulate soil loss under 3 main land cover scenarios. These scenarios were designed to describe the spatial and temporal variability of land-cover, soil properties and the related erosion processes throughout the entire vegetation period. The assessment of these scenarios was based on the actual crop rotation system and representative precipitation data. Relief parameters and textural classes were set as constants, and all parameters related to impermeable surfaces, such as settlements and roads and forest vegetation, were also set as constants because they show little spatial and temporal variation. In total, there were 15 scenarios assessed. The 3 main scenarios represented the land-cover for April (scenario A), June (scenario B) and October (scenario C), and 12 partial scenarios represented hypothetical situations, wherein the whole area would be covered by one crop from the actual crop rotation system. These consisted of summer barley (scenarios A1, B1, C1), winter wheat (scenarios A2, B2, C2), wide-sown crops (A3, B3, C3) and oil rape (A4, B4, C4). These partial scenarios could then be used to determine the most suitable location for individual crops.

Scenario A – this scenario represent land cover corresponding to April. In this period, most agricultural fields are characterized by insufficient vegetation cover. This makes the soil more susceptible to erosional processes, and their occurrence is more frequent especially during long or extreme rainfall on the unprotected soil surfaces, combined with snowmelt surface flow. In early spring, the soil is also more saturated by water which decreases its infiltration capacity. This effect can be partly alleviated by agro-technical measures, which improve the soil's physical properties by decreasing values of soil bulk density, increasing values of surface roughness and erosional potential, and infiltration, thus minimizing the impact of rainfall.

Scenario B – scenario B represents land cover corresponding to June. In this period, the agricultural crops are characterized by high soil cover. Now, the effect of spring agro-technical measures has decreased and processes such as compaction and soil aggregate disintegration prevail. Despite these facts, the occurrence of erosion events is rather low due to the highly developed soil cover.

Scenario C – scenario C represents land cover corresponding to October. During this period, the soil cover decreases due to harvesting activities, but compared to the spring period the vegetation residues remaining on the surface or root zone play an important role in compensating for the negative effect of the unfavourable soil physical properties caused by heavy machinery. After the application of agro-technical measures following harvesting, the situation becomes similar to scenario A, with the only differences being the absence of snowmelt water, and a lower intensity but higher frequency of rainfall following the drier summer period.

Proposals

A set of anti-erosion measures was used to minimize the impact of soil erosion on the most susceptible landscape types identified in the previous step. The proposal was based on practices recommended in the literature (Janeček, 1992; Demo, 1998; Fulajtár, Janský, 2001; Jambor, 2002; Uhlířová, 2005) and also in the existing legislation (Act No. 220/2004). The proposal for minimizing the impact of erosion consisted of the following measures:

Spatial optimalization of landcape structure

The optimalization of landscape structure is based on rearrangement or adjustment of the size and shape of parcels and their localization according to shape, inclination and orientation of the relief. The main goal is to decrease the slope length of the parcels and thus minimize the destructive effect of erosional processes and simultaneously preserve the parcels' minimal economical size and also their accessibility. Optimal recommended parameters are also recommended by technical standard STN 75 4501, (2000) (Table 1).

Table 1. Proposed parcel size and parameters according to technical standard STN 75 4501.

Slope	**Length (m)**	**Width (m)**	**Size (ha)**	**Erosion**
0°–3°	750	400	30	no erosion
3°–7°	550	250	10–20	medium
7°–12°	400	250	5–10	strong
> 12°	delimitation to meadows and pastures		arbitrary	extreme

Parameter	**Units**
Parcel size for lowland	30–50 ha
Parcel size for inclined relief	5–10 ha
Minimal economical parcel size	2 ha
Optimal length	400–500 m
Minimal length	200 m
Minimal width	50 m

Source: Modified according to STN 75 450

Organizational measures

The main principle of organizational measures is the most suitable localization of agricultural crops and the application of agro-technical measures to minimize the impact of soil erosion in the model area. This method is based on differing erosion mitigating effects of agricultural crops. One of the most effective crops is thick-sown crops. The alfalfa-grassland mix mitigates erosion up to 1/100 and alfalfa itself up to 1/50. Cereals mitigate the erosion from up to 1/5 to 1/20 depending on the sowing and harvest times. Broad-sown crops and root crops mitigate the erosion effect only up to 1/2 and thus the cultivation of these crops is recommended on flat parcels and on parcels with little inclination (< 3°). For parcels which have a higher inclination between 3° and 7°, it is recommended to increase the erosion mitigation effect of broad-sown and root crops by applying a protective crop rotation system or by cultivating different crops, such as cereals. For parcels with an inclination higher than 10°–12°, arable cultivation should be replaced by meadows.

Agro-technical measures

Agro-technical measures represent the set of mechanization and construction measures such as contour cultivation, minimal agro-technique, interception vegetation strips and buffer strips. The proposed measures created a basis for implementation of the erosion mitigation scenario. Emphasis was placed on optimalization of spatial structure, mainly the modification of parcels shape and orientation as passive soil erosion measures, since these factors were identified as the main causes of erosion in the model area. The main goal was modification of continuous slope length and effects of higher slope inclination by orientation of parcels along contour lines. The goal was to preserve the actual parcel size to ensure the efficiency of agricultural mechanization. Where the above-mentioned measures could not be applied, agro-technical measures in the form of 5–7 m vegetation and infiltration strips were proposed concurrently with completion of vegetation borders and buffer strips. Active protection measures were also proposed on some parcels to delimit meadows or forests and for conversion to crops with better erosion mitigating effects such as thick-sown and fodder crops. This proposed structure formed the basis for the set of erosion mitigation simulations for rainfall events with a return period of 100 years. No scenarios were proposed for other rainfall events since their output values could be predicted from previous results.

Model outputs

The model produces raster-based, quantitative estimates of soil loss, soil deposition and sediment delivery into the surface water system. The following data is provided for each grid cell:

Parameters related to area:

- erosion and deposition for a chosen grid cell (t.ha^{-1}),
- erosion, deposition and net erosion for the watershed draining into a chosen grid cell (t.ha^{-1}).

Parameters related to cross-section of flow:

- runoff (m^3.m^{-1}),
- sediment delivery (kg.m^{-1}) and sediment concentration (kg.m^{-3}).

A total number of 725 simulations were run based on criteria for implementation of this scenario. The result of each simulation was exported in the form of a grid model representing the net erosion for each grid element. These results were then aggregated and the mean value of net erosion was calculated for the entire sample area.

Validation

The process of validation is generally based on comparison of simulated and measured data. Since there were no direct measurements for the sample available, only qualitative assessment could be made. These methods included comparison of soil profiles located on erosion susceptible slopes which were identified during the erosion simulation. Each slope transect included 3 points located at the top, middle and the bottom of a given slope. A total of 5 transects were designed. Using a simple hand auger, the thickness of soil diagnostic horizons and stratification of soil profile was examined. The presence or absence of diagnostic horizons, their thickness and transformation of the total horizon stratification should reflect the impact of erosion or deposition processes.

Results

The following results were obtained:

1. The highest mean values of erosion were recorded for rainfall events with a return period of 100 years, with a maximum value for the 15 minute duration rainfall of 25.2 mm and

an intensity of 1.68 mm.min^{-1} (Fig. 3). The lowest values were recorded for rainfall events with a return period of 1 year (Fig. 5).

2. The highest mean value of erosion of 2.51 t.ha^{-1} was recorded for rainfall events with a return period of 100 years, with maximum value for the rainfall which endured for15 minutes and partial scenario A 1, in April with summer barley (Fig. 3).
3. The maximum value of erosion of 43.24 t.ha^{-1}, with a standard deviation of 3.47, was recorded for rainfall events with a return period of 100 years, with a maximum value for the rainfall with duration of 15 minutes and also in partial scenario A 1 in April with summer barley (Fig. 4).

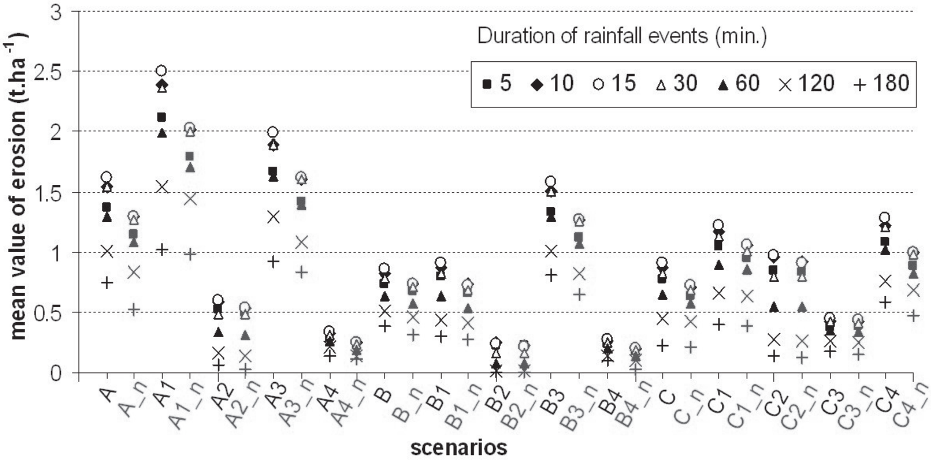

Fig. 3. Mean values of erosion for rainfall events with a return period of 100 years.

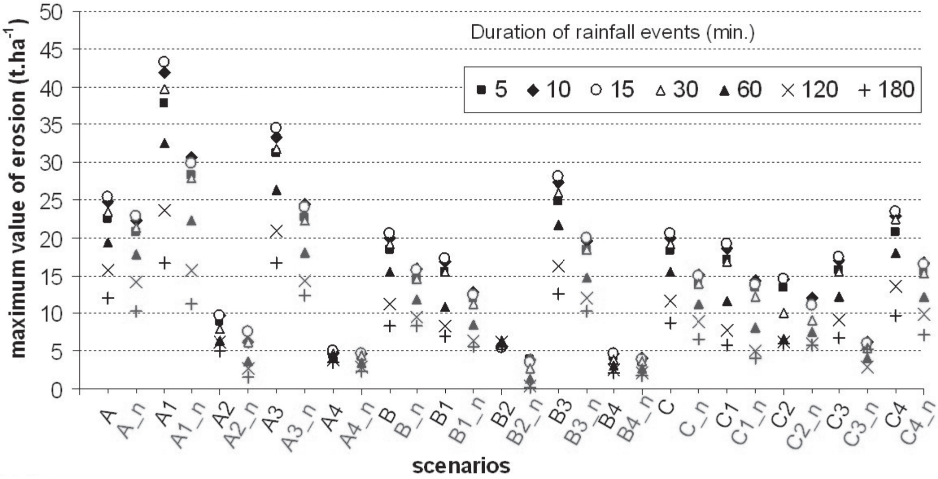

Fig. 4. Maximum values of erosion for rainfall events with a return period of 100 years.

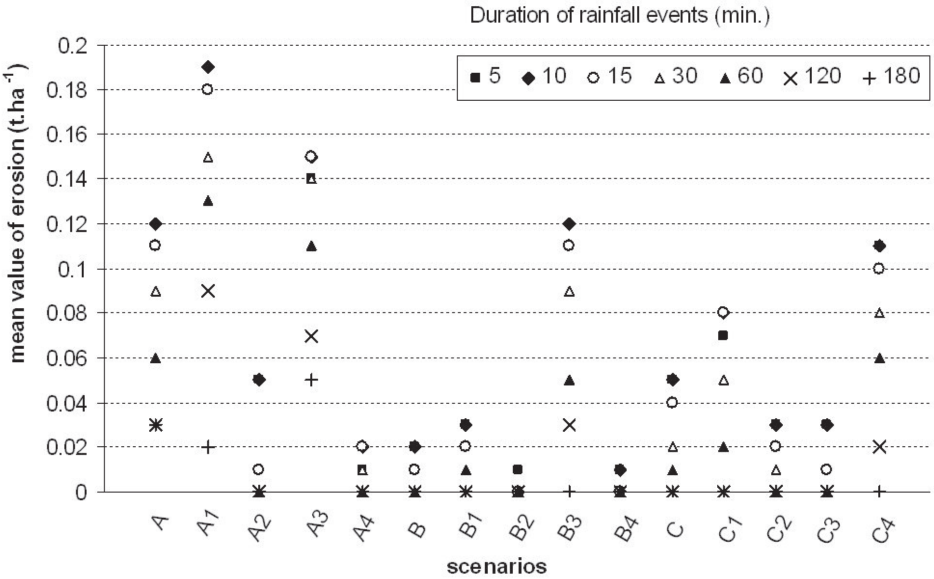

Fig. 5. Mean values of erosion for rainfall events with a return period of 1 year.

Note: Scenarios

A–April	B–June	C–October
A1–Summer barley April	B1–Summer barley June	C1–Summer barley October
A2–Winter wheat April	B2–Winter wheat June	C2–Winter wheat October
A3–Wide-sown crops April	B3–Wide-sown crops June	C3–Wide-sown crops October
A4–Oil rape April	B4–Oil rape June	C4–Oil rape October

_n – scenarios with application of erosion mitigation measures

Using the basic zonal statistics tools involving the calculation of the mean net erosion value for each parcel, the most erosion susceptible parcels were identified (mean value of net erosion > 5 t.ha^{-1}). The weighting coefficient of 1 was assigned to each parcel with a value > 5 t.ha^{-1}. This calculation was applied to all the main and partial scenarios. After summation of the weighting coefficients (with results ranging from 1 for small to 10 for high susceptibility to soil erosion) all the parcels were classified according to erosion risk. The proportion of areas in the given erosion risk classes is shown in Fig. 6.

The results show that approximately 58% of the sample area can be classified as low erosion risk (classes 1 to 3), 37% can be classified as moderate erosion risk (classes 4 to 7) and 5% are classifiable as high erosion risk (classes 8 to 10). For parcels identified as susceptible to erosion, the set of soil and geo-morphological parameters was extracted by aggregating the mean and maximum values of these parameters within each parcel. Based on these results,

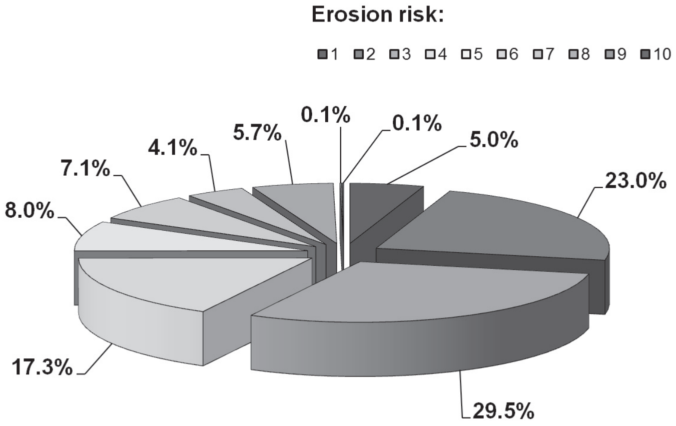

Fig. 6. Proportion of the total sample area according to erosion risk classes.

the most susceptible landscape types are characterized by the following combination of soil and geo-morphological parameters:

- maximum slope length: 1000–1500 m,
- slope inclination: 7°–12°,
- soil cover: from 0–10%,
- surface roughness: 0.015– 0.2 s.m $^{-1/3}$,
- erosion susceptibility: 0.023–0.038 N.m^{-2}.

The ability and effectiveness of the proposed measures in mitigating soil erosion was assessed by calculating the difference between the values for the main scenarios and the values of the erosion mitigation scenarios. The maximum difference for the main values of erosion reached 0.48 t.ha^{-1} in scenario A1. This was for summer barley with rainfall duration 15 minutes and a return period of 100 years.This scenario produced a reduction in soil loss of 18.94%. Regarding the maximum value, the difference was 13.30 t.ha^{-1} in this same scenario, thus representing a reduction of 59.06%.

Discussion

Application of the mathematic-physical modelling approach of (Erosion 3D) to the modelling of soil erosion in the model area.

Erosion 3D represents an ideal compromise in combining the demands for less input parameters and desired quality of simulation of hydrological and erosion processes. Based on publication records (Michael et al., 2005; Schmidt et al., 1999; Schmidt, 2000; Schob et al., 2006; Weigert, Schmidt, 2005), this model provided good results in the localization of erosion prone areas as sources of sediments entering the surface waters. Its main advantages are:

- it is an adequate tool on which landscape planners can base figures required in discussions on important protection efforts,
- input parameters can be obtained from literature or they can be easily estimated here in comparison to other models,
- it takes into account the deposition of eroded sediments.

Some disadvantages and limitations concerning the application of the Erosion 3D model have been described in the following works (Wickencamp et al., 2000; Schmidt, 1996; Schmidt et al., 1999).

Modelling outputs and their interpretation

This model produces raster-based, quantitative estimates of soil loss, soil deposition and sediment delivery into surface water systems. To achieve this, the net erosion measured in t.ha^{-1} was calculated for each grid cell, and.from this data, the mean value, the maximum value and the standard deviation were calculated. The highest values were identified for the April and October scenarios, especially where crops are characterized by low canopy cover (A1 – in April with summer barley, A3 – wide-sown crops, C4 – oil rape.). In this period of the year, the important determining factor for soil erosion is the high water saturation of the soil complex. The lowest erosion values were recorded in simulations of the summer period (B2 – in June with winter wheat, B4 – June for oil rape, etc.). During this period, the soil cover reaches its highest values, the soil is rather dry and thus most of the precipitation is infiltrated. Low values were also recorded for scenarios related to April and October, but only for crops with high soil cover (A4 – April oil rape, A2 – April winter crops and C3 – October wide-sown crops).

Using the basic zonal statistics tools, via the calculation of mean net erosion value for each parcel, most erosion-susceptible parcels were identified and a map was produced to highlight the susceptibility of cultivated parcels to soil erosion. For these parcels, the set of soil and geo-morphological parameters was extracted and the following results were achieved:

- The parcel size had no significant impact on the occurrence of erosion processes. Most of the erosion-susceptible parcels had an optimal size (0–5 ha) from an erosion mitigation point of view. The most threatened parcels were characterized by a higher inclination of 7°–12° and slope length of 500–1,500 m. Based on these results, we can conclude that the parcel's shape and orientation are more significant determining factors than parcel size.
- Considering vegetation cover, the most threatened parcels were identified as having low vegetation cover of 0–10%, but some of the parcels fell within the category of 50–70 vegetation cover. Factors in addition to the degree of vegetation cover were considered for these parcels.
- Similarly, for erosion susceptibility and surface roughness, although most susceptible parcels were characterized by low values, some were also noted to have higher values for these parameters.
- Considering bulk density, threatened parcels were characterized by values varying from low to higher numbers (1 340 to 1 644 kg.m^{-3}) Based on this, we can conclude that soil

bulk density did not have a significant impact on soil erosion. This statement is also supported by the fact that the measured values of bulk density are within the optimal limit for clayed soil at 1400–1700 kg.m^{-3}.

A set of anti-erosion measures was instituted to minimize the impact of soil erosion on the most susceptible landscape types identified in the previous step. This set consisted of passive measures including consolidation of the parcel shape, orientation and size, infiltration, vegetation strips and grassed waterways, combined with the active measures such as land-use/cover delimitation. This proposed structure thus formed the basis for the set of erosion mitigation simulations which were compared with main and partial scenario simulations without the application of erosion mitigation measures. The results of this comparison supported the fact that the proposed measures effectively reduced the impact of soil erosion without significant modification to the parcel's accessibility and cultivatability. The most effective measures were especially the modification of spatial structure of the agricultural landscape and modification of parcel size, orientation and shape. These results also demonstrated that simulation models such as Erosion 3D can provide the information necessary for the appropriate localization and extent of site-specific measures.

Validation

Using the methodology of evaluation of soil horizons stratification transformation, we verified the presence of erosion depositional processes. The eroded forms on the steeper slopes were characterized by continuous transformation of Luvisols to Regosols. This process resulted in the absence of the surface A horizon with a high content of organic matter and denudation of the light coloured subsurface B horizon. On the bottom of the slopes, the soil profiles were characterized by the absence of pedogenetic material and other diagnostic horizons, with the exception of the dark thick surface horizon created by continuous accumulation of fine soil material. Eroded and accumulated forms both exhibited poor discrimination in the diagnostic horizons and homogenization of the soil profile. Although this presented method can successfully validate the presence of eroded and accumulated forms, it cannot sufficiently prove whether these forms occurred as a result of erosion processes, or by the combined action of erosion and tillage activities.

Conclusion

This paper presents a methodology of evaluation of erosion risk on a sample area using a physically based modelling approach. To capture the spatial and temporal variability of erosion processes, simulations were based on modelling scenarios designed so that they reflect the variability of soil vegetation cover, soil properties and the impact of erosion mitigation measures throughout the vegetation period. The simulation results showed a significant decrease in erosion values, especially in the case of scenarios with the highest soil loss. Based on the mutual comparison of individual scenarios, we were able to demonstrate their impact on soil erosion in the sample area. The simulation results were also used to classify the sample area according to erosion risk and for the calculation of its main causative factors.

Results of such erosion modelling should be validated using experimental data. This validation is based on the comparison of experimental (measured) and simulated data. Since there was no quantitative experimental data available for the sample area, we had to use the so called indicative method to validate results. Therefore, the simulation outputs could be used only for assessment of erosion risk and not for the precise quantification of eroded soil. The indicative method was based on assessment of the transformation of the soil profile. However, this method could not prove sufficiently whether the erosion/accumulation forms were created by water erosion alone or also by tillage.

Despite these limitations, this model provided adequate information, necessary for the optimal localization and extent of site-specific measures and also for the assessment of their impact on soil erosion.

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