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Assessment of the impact of the accuracy of the DMR on the calculation of soil erosion using the USLE and USLE-2D models

Tatiana KOHUTOVÁ, Matúš TOMAŠČÍK, Michaela DANÁČOVÁ*, Kamila HLAVČOVÁ

Slovakia has recorded a potentially significant increase in water erosion, especially after consolidating the plots of hundreds of hectares of agricultural area with monocultures of marketable crops. This is also due to large blocks of land being created on sloping sites. Due to its simplicity, the Universal Soil Loss Equation (USLE) is most commonly used to calculate potential soil erosion. This study compares the classical USLE and the USLE-2D methods, which consider the combined spatially variable slope length and steepness. The slope length is replaced in USLE-2D by the contributing area based on a raster digital model relief model. Data from Tulčík cadastre in east Slovakia demonstrates the results of water erosion on 26 plots used as agricultural areas. As expected, differences were found, which were further analysed concerning slope lengths and steepness. Comparing the grid size (1, 10 and 20 m) for the USLE-2D model showed that more significant differences were obtained for plots with a smaller area and a higher slope. It was confirmed that at a lower pixel resolution, the results are overestimated.

KEY WORDS: soil erosion, DMR, LS-factor, USLE, USLE-2D

Introduction

Over the past few decades, technological progress has dramatically increased the "human landscape" at the expense of the natural environment. The result is that the landscape is losing its biological and cultural richness. One area where it is possible to reduce the consequences of human activity on natural ecosystems is the rural landscape (Bonfanti et al., 1997). Humans have significantly changed the natural structure of the environment into an agricultural landscape, which differs from the original and natural layout in its character and diversity as well as the duration of continuous vegetation cover on the land throughout the years. The effective use of the landscape along with the morphological features of the relief affects the development of the soil degradation process (Morgan, 2005; Nosko et al. 2019).

Since humankind began agriculture, erosion by wind and water has been the main threat to soil. Soil erosion is a natural process. However, its acceleration is most often caused by human activity in the countryside, and this causes problems that must be solved (Podhrádzka, 2010; Petlušová et al., 2017). It was confirmed that by soil erosion there are transported soil sediment and nitrogen which contributes to surface water contamination (Siman and Velisková, 2020).

Therefore, the rural landscape has become the subject of our interest. Our top priority is to reduce the impact of water soil erosion caused by agricultural activity. Many mathematical models categorized as empirical, conceptual, physically based, or process-oriented are available to estimate soil erosion on different spatial and temporal scales (De Vente and Poesen, 2005; Morgan, 2005). Due to its relatively simple analysis of the data and parameters input, the Universal Soil Loss Equation (USLE) was developed to calculate the average annual soil loss from an area (Wischmeier and Smith, 1978). However, the application of process-based physical models (e.g., Erosion 3D, WEPP, or PESERA) does not necessarily result in lower degrees of uncertainty compared to more simply structured empirical models such as USLE-type algorithms (Alewel, et al., 2019). The accuracy of the data input and the methodologies used to compute each factor have a direct impact on the quality of the final computations (Michalopoulou et al., 2022; Semari and Korichi, 2023).

The main objective of the study was to assess the intensity of soil erosion on the parcels of the Tulčík Cadastre. The results of the study should determine the issue of how important the resolution of the digital model relief (DMR) input data in calculating the joint topographical LS factor (LS-factor) is. To answer this question, algorithms for calculating the LS-factor according to various authors were also tested. This topographical factor is key in calculating the average annual soil loss using USLE-2D. The second part of the article compares the values obtained by the USLE-2D and the classic USLE methods. In the conclusion, the advantages and disadvantages of these methods of determining the average annual soil loss on plots of different sizes and slope ratios are evaluated.

Methodology and data

Study area

The study area is the cadastral territory of Tulčík, located in eastern Slovakia in the northern part of Prešov (Fig 1.) The foothills of the Čergov range extend into the cadastral territory. There are clay soil types on the land from the north part of the village. The type of soil on the land is clay. The area of the cadastral territory is 12.9 km^2, and more than 70% of the total area is agricultural land (Fig. 1). The altitude ranges from 264 to 560 m a.s.l., and the maximum slope is 59 percent.
The location of the Tulčík study area in Slovakia is presented in Fig. 1, and the DMR and the map of the slopes are shown in Fig. 2. The input data of land use and DMRs are a product of ZBGIS (provider: Geodetic and Cartographic Institute Bratislava – GKÚ Bratislava). The geospatial data was processed in the open-source QGIS (Quantum Geographic Information System).

The USLE model

One of the most widely used methods for estimating water erosion is the "Universal Soil Loss Equation", (USLE) empirical model (Wischmeier and Smith, 1978). This method is used in Slovakia, mainly due to its simplicity. The USLE is used for assessing the long-term average soil loss by water erosion from agricultural lands in a given type of climate zone. It considers the given type of soil with a particular slope and the length of the slope and a specific system of growing crops, cultivating soil, and applying anti-erosion measures. Intense short-term rain plays an important role in the method (Impact of Changes in Short-Term Rainfall, e.g., Földes et al. 2022). The equation cannot be used for a period shorter than one year and also not for calculating soil loss from an individual rainfall or runoff from melting snow.
The USLE model is used to calculate the erosion risk:

$$G = R.K.L.S.C.P \tag{1}$$

where G is the average annual soil loss [t ha^{-1} year^{-1}]; R is the rain erosion efficiency factor, expressed as a function of the maximum 30 min intensity and kinetic rainfall energy [MJ ha^{-1} cm h^{-1}]; K is the soil erodibility factor expressed as a function of the topsoil's texture and structure, organic matter content, and permeability [t ha^{-1} year^{-1}]; L is the length factor expressing the effect of an uninterrupted length of slope on the amount of soil loss due to erosion [-]; S is the slope factor expressing the effect the steepness of the slope on the amount of soil loss due to erosion [-]; C is the factor of the protective influence of the vegetation cover, depending on the development of the vegetation and the agricultural technology used [-]; and P is the impact factor of any anti-erosion measures [-].
The quality of the resulting calculations is directly dependent on the accuracy of the R, K, C, and P factors input and the methods used to calculate the L and S factors.

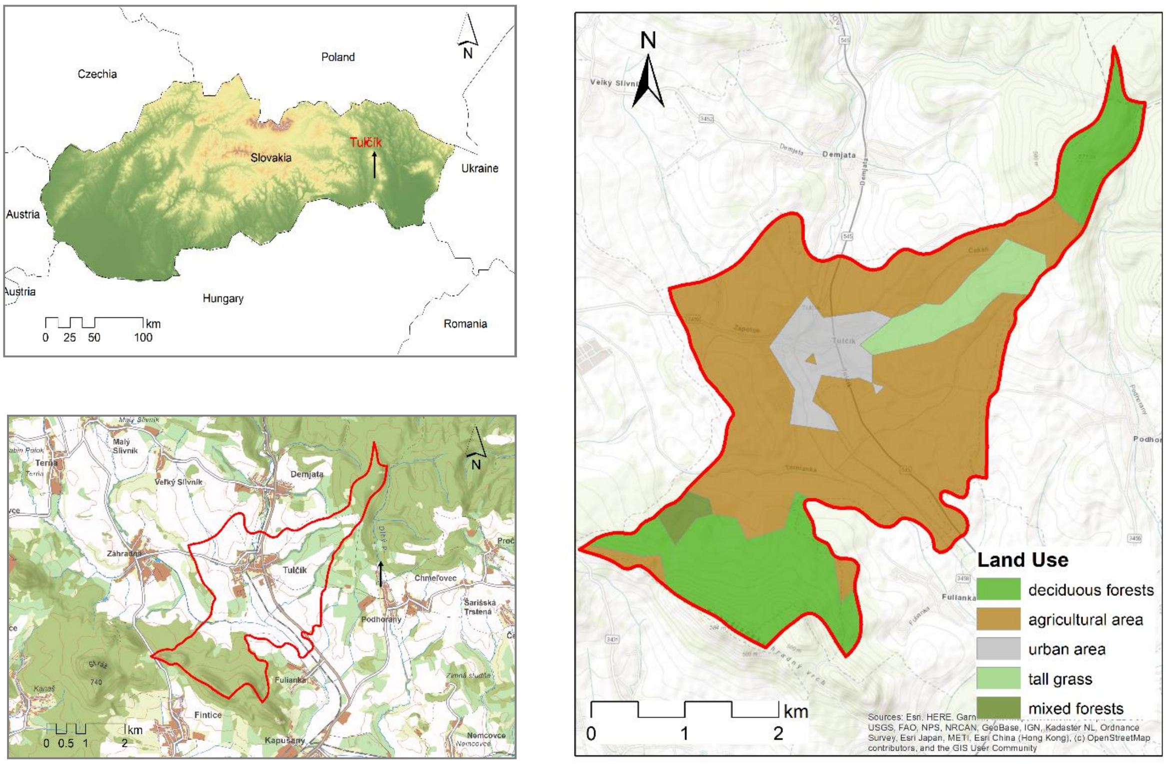


Fig. 1. Location of the Tulčík study area (Prešov region, Slovakia), sources: GKÚ Bratislava; Esri.

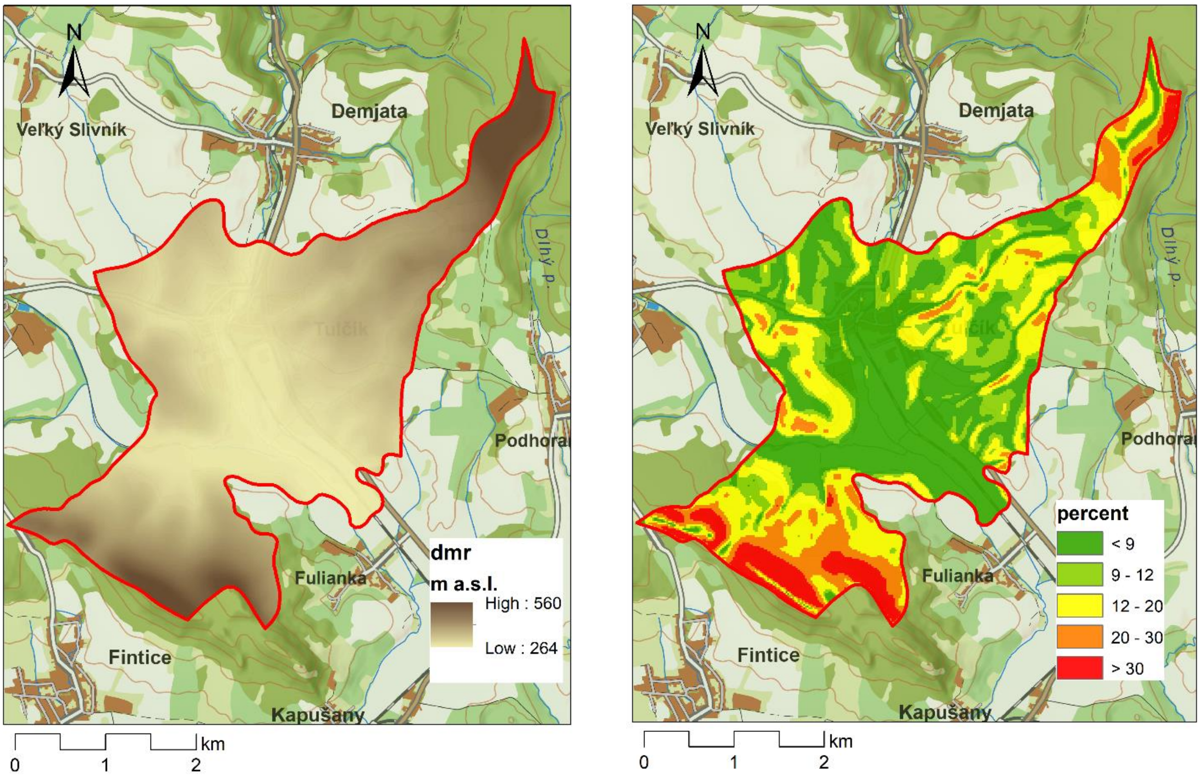


Fig. 2. Digital relief model (DMR) and the map of the slopes of the Tulčík study area (sources: GKÚ Bratislava; Esri).

Two of the most important parameters that affect soil loss are the slope (*S*) and the length of the slope (*L*), i.e., the length of the surface flow until it reaches a natural or artificial recipient.

USLE-2D model

The calculation of the risk of erosion by the USLE-2D model is based on the universal equation of the soil using the topographical factor (LS-factor). Specifically, the LS-factor is of great interest because of the variety of equations applied in the literature to calculate it and because these equations require the use of digital relief models.
The LS-factor is created from a digital model of the terrain and the layer of the land parcels distributing the area into partial surfaces.

LS – factor
We decided to compare the effect the topographic LS-factor (which will replace the *L* and *S* factors we calculated) will have on the resulting soil loss values. The LS-factor is calculated based on an algorithm using the formula:

$$LS = \sum_{j=1}^{N} \frac{S(i,j).\lambda(i,j)_{outlet}^{m+1} - S(i,j).\lambda(i,j)_{inlet}^{m+1}}{(\lambda(i,j)_{outlet} - \lambda(i,j)_{inlet})\,.\,22.13^{m}} \qquad (4)$$

where:
LS – topographic factor in USLE-2D for one plot,
$\sum_{j=1}^{N}$ – the sum of all cells from *i* to *j* for the plot,
$\lambda(i,j)_{outlet}$ – length of slope at the output for *i*, *j* cell [m],
$\lambda(i,j)_{inlet}$ – length of slope at the input for *i*, *j* cell [m],
$S(i,j)$ – slope factor for *i*, *j* cell,
m – slope length exponent.

The slope factor for the individual cells is expressed by algorithms according to several authors (Van Oost, Govers, 2000).

A) Relationship according to Wischmeier and Smith (1978):

$$S(i,j) = 65.41.\sin 2\, \theta i,j + 4.56.\sin \theta i,j + 0.065 \qquad (5)$$

B) The relationship according to McCool (1989), which is also used in RUSLE:

$$S(i,j) = 10.8.\sin \theta i,j + 0.03, \text{ where } \theta i,j \leq 9\% \qquad (6)$$

$$S(i,j) = 16.8.\sin \theta i,j - 0.5, \text{ where } \theta i,j > 9\% \qquad (7)$$

C) Govers' relationship was based on field data from 1991:

$$S(i,j) = (\tan \theta i,j \ / \ 0.09)1.45 \qquad (8)$$

D) Nearing (1997) proposed a simple function for the slope factor:

$$S = -1.5 + \frac{17}{(1+e^{[2.3-6.1\sin(\Theta)]})} \qquad (9)$$

Results and discussion

DMR and slope values

The property of the DMR was assessed using descriptive statistics (min, max, mean, standard deviation, range (min-max)); the values are summarized in Table 1. From the statistical analysis, the elevation values from each DMR examined have a substantial degree of similarity. The quality assessment should include the examination of the vertical accuracy. Ground control is considered the most accurate method and is, therefore, suitable for comparing DMR elevation values. This comparison is missing in the study as we did not have the available data. Comparing the DMR with different cell sizes may provide some important information regarding the accuracy of these elevation data (Polidori and Hage, 2020). In this study, the slope angle for each grid cell is calculated using a specific numerical method known as the Deterministic-8 method in ArcGIS. A comparison of both DMRs shows a high degree of divergence. The descriptive statistics for the slope values calculated are presented in Table 1.

It was confirmed that the maximum slope values for the DMR decreases with increases in the cell size, meaning that the higher the DMR resolution, the higher the maximum slope value calculated. The minimum slope value is zero for all the DMR data. The maximum slope value is noted in the southern and northern study DMR areas (DMR 1, grid size 1x1m); it is equal to approximately 87% (see Table 1). The standard deviation and mean of the slope values were compared for all DMR resolution. Results show minimal difference.

Comparison of the LS - factors

Different algorithms were used to examine the impact of the LS-factor on the soil loss results obtained by the USLE-2D model. The first one is based on the equation that was suggested by Wischmeier and Smith (W-S, equation 5); the second one uses the equation from the RUSLE model (McCool, equations 6 and 7); the third one is based on field data (Govers, equation 8); and the fourth one was suggested by Nearing (Nearing, equation 9). The descriptive statistics were calculated for the LS-factors for each DMR resolution (see Table 2).

The highest LS-factor values were obtained using the Govers method for all DMR resolutions. The lowest LS-factor values were obtained using to the W-S method (approximately 2 times lower than the Govers method). This study shows that the higher the resolution of the DMR data, the higher the maximum LS values, except for the W-S based method. This observation also applies to the mean values. The following figure shows the difference between the calculated mean values of LS-factors using all of the approaches examined (Fig. 3).

It can by seen that the LS values (mean) from the DMR 20 (grid size: 20x20m), DMR 10 (grid size: 10x10m), are much higher than the DMR 1 (grid size: 1x1m) for all the algorithms (Fig. 3). The lowest mean LS for the DMR 20 is calculated from the W-S, while the highest mean

Table 1. The descriptive statistics of the DMR files and the slope values [%] in the study area

	DMR 20 (grid size 20m)	DMR 10 (grid size 10m)	DMR 1 (grid size 1m)	Slope 20 [%]	Slope 10 [%]	Slope 1 [%]
MIN	264.8	265	261.8	0	0	0
MAX	560.5	574.7	581.0	58.95	71.8	87.2
MEAN	340.8	341.1	340.1	12.4	12.9	17.1
STD DEV.	70.2	70.5	70.0	9.15	9.9	15.1
RANGE	295.7	309.8	319.2	58.95	71.8	87.2

Table 2. The descriptive statistics of LS-factor for DMR with resolution pixel sizes of 1m, 10m and 20m

Method	LS - factor											
	W-S			McCool			Govers			Nearing		
	DMR 20 (20x20)	DMR 10 10x10)	DMR 1 (1x1)	DMR 20 (20x20)	DMR 10 (10x10)	DMR 1 (1x1)	DMR 20 (20x20)	DMR 10 (10x 10)	DMR1 (1x1)	DMR 20 (20x20)	DMR 10 (10x 10)	DMR 1 (1x1)
MIN	0	0	0	0	0	0	0	0	0	0	0	0
MAX	27	26	65	29	31	65	56	65	65	29	29	65
MEAN	1.469	1.411	0.402	1.583	1.522	0.383	**3.084**	**2.88**	**2.505**	1.519	1.458	0.383
STD DEV.	2.711	2.691	1.825	2.969	2.958	1.901	**5.964**	**2.834**	**4.207**	2.854	2.835	1.855
RANGE	27	26	65	29	31	65	56	65	65	29	29	65

value is calculated from Gover's approach.
The input data on the relief is very important for the USLE-2D method. When calculating the LS-factor, the resolution of the pixel with the altitude data plays a key role (Fijałkowska, 2021; Michalopoulou et al., 2022). A high resolution (1x1m) resulted in very low LS-factor values in this case. This is probably due to the overly complicated terrain for this type of process. Wang et al. (2020) studied the effect of the DMR resolution on the LS-factor by implementing two DMRs (5x5m and 30x30m grid size). This study highlighted the increase in the L factor and the decrease in the S factor with coarser DMR resolutions. Regarding the LS-factor, the results showed an increase in areas with a large relief and a decrease in smaller relief areas.

Annual Soil Loss Comparison – USLE-2D

The average annual soil loss of the study area was estimated by acquiring the USLE-2D and multiplying the rainfall erosivity factor (R), soil erodibility factor (K), slope length and steepness factor (LS-factor), cover management factor (C), and the anti-erosion measures factor (P).
The LS-factor was calculated based on Mc Cool's algorithm (equations (6), (7)). The soil erosion rates were estimated for three of the DMRs examined. The R-factor was calculated using the interpolation method according to Onderka and Pecho (2019). The background vector layer of the bonified soil-ecological unit's boundaries was used to calculate the *K*-factor. The value $P = 1$, which is often employed in practice was used. Only if there are no anti-erosion measures on the plots treated.
The results obtained based on DMR with a pixel resolution of 10 x 10m (range 0–79.3 t ha^{-1} year^{-1}, Fig. 4) and DMR with a pixel resolution of 20 x 20m (range 0 – 68.2 t ha^{-1} year^{-1}) were compared. The average annual soil loss was calculated on 45 plots of agricultural area. A soil loss value of more 4 t ha^{-1} year^{-1} (Act no. 220/2004) is marked in red in Fig. 4, where 11 plots are potentially at risk.
From the total number of 45 plots, we selected plots with

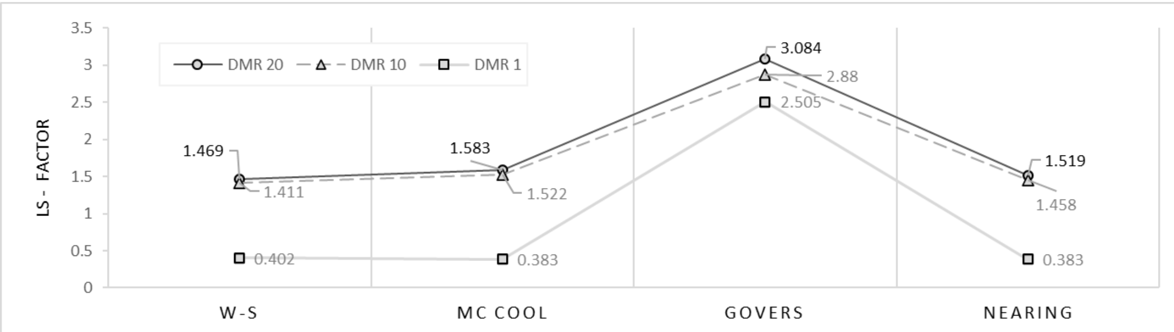


Fig. 3. LS factor values (average) obtained by all the methods for all the DMR resolutions (grid size: 1, 10, 20m).

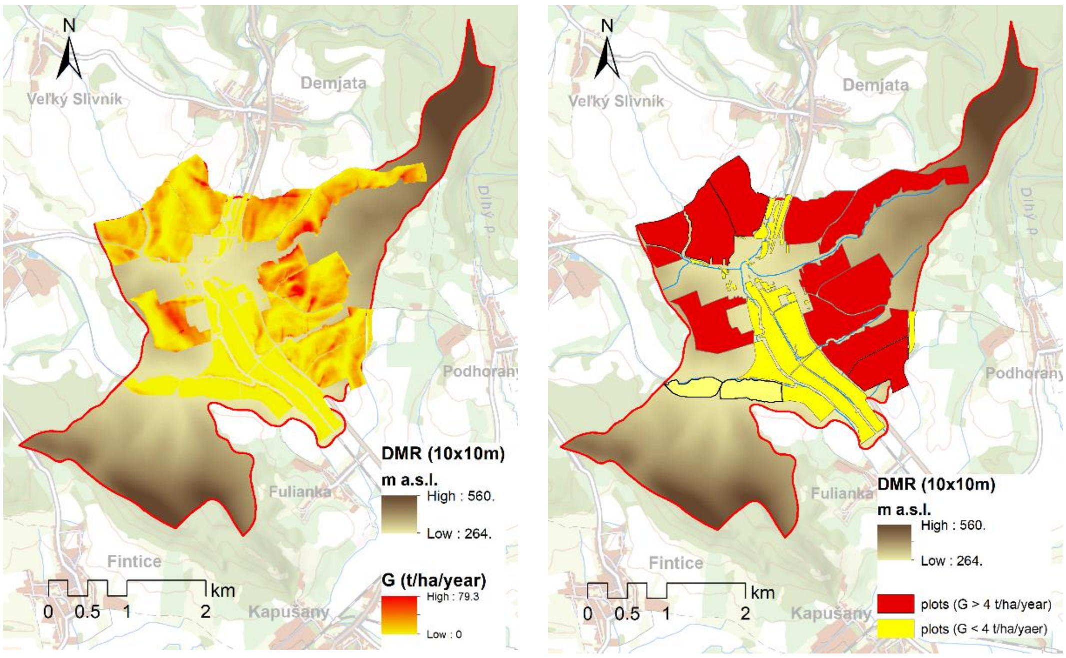


Fig. 4. Agriculture area (yellow plots) in the cadastral territory of Tulčík, on the right side are red plots with soil losses of more than 4 t ha^{-1} year^{-1} (USLE-2D model).

a greater length than 100 m. In the next part, the soil erosion values on 26 plots are compared.

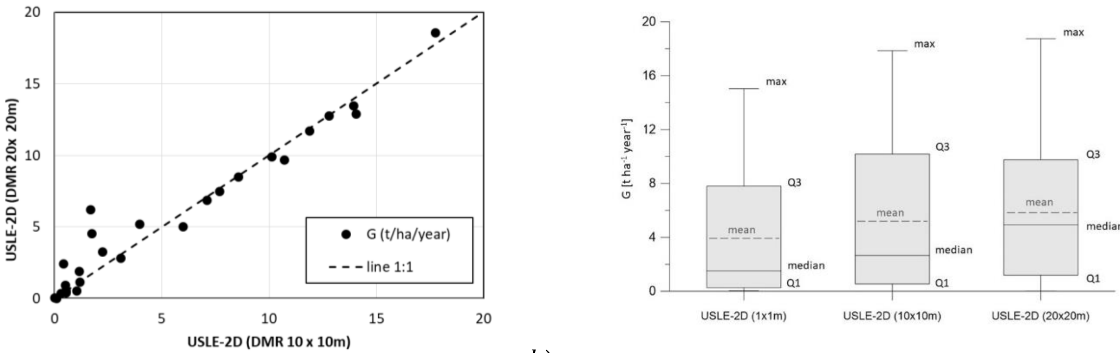
For a direct comparison, the results of the average annual soil loss calculated for the DMR resolution (10m and 20m) are shown in Figure 5a. As can be seen, there are slight deviations throughout the range. The higher deviations were indicated at lower values of soil loss.

The descriptive statistics (box plot, Fig. 5b) of the relative values of the erosion loss show a significant median difference (for the 20x20m resolution, it is 4.6 t ha^{-1} year^{-1}; for the 10x10m resolution, the value is lower, i.e., 2.2 t ha^{-1} year^{-1}, and for the 1x1m resolution, it is 1.1 t ha^{-1} year^{-1}). The values of the 25th percentile or 75th (boundaries Q_1, Q_3), are very similar in case resolutions G10 (resolution 10x10m) and G20 (resolution 20x20m). The value of the average soil loss is 6.0 versus 5.5 t ha^{-1} year^{-1}.

Comparison of the USLE and USLE-2D methods

The difference between the USLE (classic method) and USLE-2D (resolution 10x10m) is evident. Both methods yield similar results in mapping relative erosion risks. However, there appear to be important differences in the absolute values. Although both methods provide identical slope values, the effect of flow convergence needs to be considered using the classic method.

In the case of the USLE method, the slopes and the lengths of the parcels were obtained manually from the map. Equations 2 and 3 were used to calculate the *L*-factor and *S*-factor. The values obtained of the annual soil loss ranged from 0.95 to 18.59 t ha^{-1} year^{-1}. Parcels with a soil loss value of more 4 t ha^{-1} year^{-1} are marked in red (Fig. 6). Twelve plots with a potential high threat of water erosion were identified.



a) *b)*

Fig. 5. The impact of the accuracy of the DMR on the calculation of the annual soil erosion a) regression b) box plot.

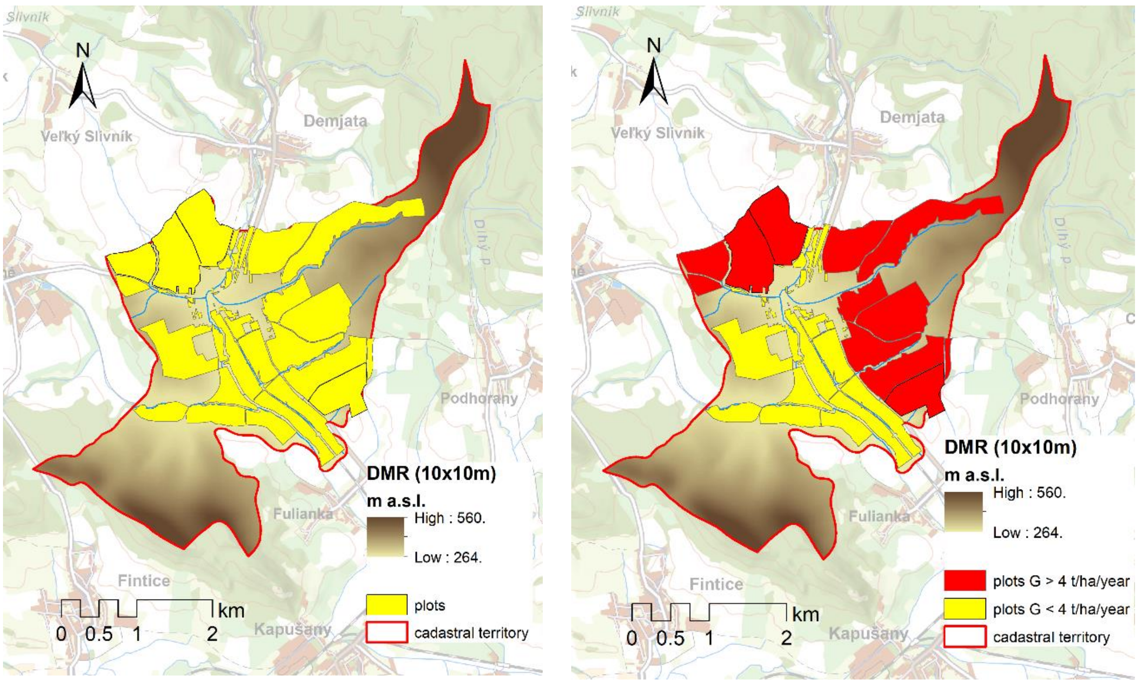


Fig. 6. Agricultural area (yellow plots) in the cadastral territory of Tulčík; on the right side are red plots with potential annual soil loss of more than 4 t ha^{-1} year^{-1} (USLE model).

We selected parcels (26) based on the slope lengths for a complex comparison of the soil erosion between USLE and USLE-2D. Table 3 shows the results of the annual soil erosion, and the assumed differences are demonstrated.

The soil loss results using the above methods are fairly consistent (see Table 3). The differences between the empirical methods are not significant (Fig. 7a). A total of 26 plots were evaluated, 50% of which exceeded the permissible soil loss value for medium-deep soils according to both methods.

During the evaluation, the impact of the slope of the plot (Fig. 7b) and the length of the slope (Fig. 7c) were directly analyzed. The values concerning the length, and the slope of the plot were taken from the manual determination for the calculation of USLE. The land area was obtained from a GIS environment. The steepness of the slope confirmed the high degree of sensitivity.

Both methods yield similar results in mapping relative erosion risks compared to the classical method. However, there appear to be significant differences in the absolute values. Although both methods provide similar slope values, the USLE method is needed to show an overestimation of the erosion risk clearly. According to USLE, only the overvalued plots had a low slope (up to 3%), a small area of up to 10 ha, and a slope length of up to 500m.

Figure 8 shows the specific values of the average annual soil loss for the 26 compared plots. Again, as is seen in the individual plots; the difference is fundamental in the USLE method (see plots 1–3, 15–17, 20, and 26).

Table 3. Comparison of soil erosion between USLE and USLE-2D (DMR with a pixel resolution of 10x10m), L_d is the length of the slope

Plot No.	L_d [m]	G – USLE [t ha^{-1} year^{-1}]	G – USLE-2D [t ha^{-1} year^{-1}]	Plot No.	L_d [m]	G – USLE [t ha^{-1} year^{-1}]	G – USLE-2D [t ha^{-1} year^{-1}]
1	663	**11.82**	**10.12**	14	768	**10.26**	**7.1**
2	384	**9.95**	**10.71**	15	611	**12.81**	**12.79**
3	780	**11.07**	**11.89**	16	410	**14.71**	**17.75**
4	232	0.75	0.53	17	627	**18.59**	**13.92**
5	488	1.96	1.011	18	538	**6.76**	5.97
6	231	1.93	1.16	19	545	3.74	3.94
7	128	1.90	0.41	20	872	**9.64**	**14.04**
8	156	1.51	0.53	21	282	2.58	3.06
9	219	1.62	0.49	22	169	2.52	1.12
10	1320	**4.99**	**7.68**	24	113	3.22	1.72
11	495	**7.29**	**8.55**	26	132	**4.64**	1.67
12	128	0.95	0.07	28	158	1.61	2.21
13	240	2.25	0.29	29	191	1.12	0.00

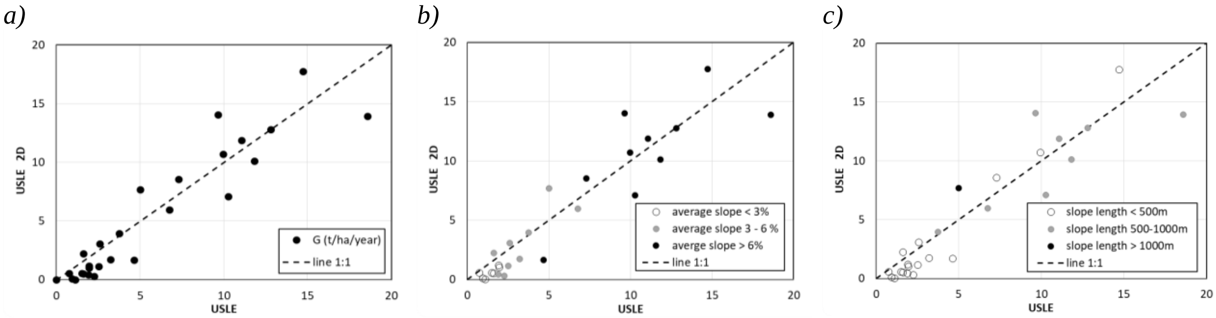


Fig. 7. Comparison of soil erosion G (t ha^{-1} year^{-1}) between the classic USLE and USLE-2D models (resolution 10x10 m), with the plots by b) average steepness of the slope c) slope length.

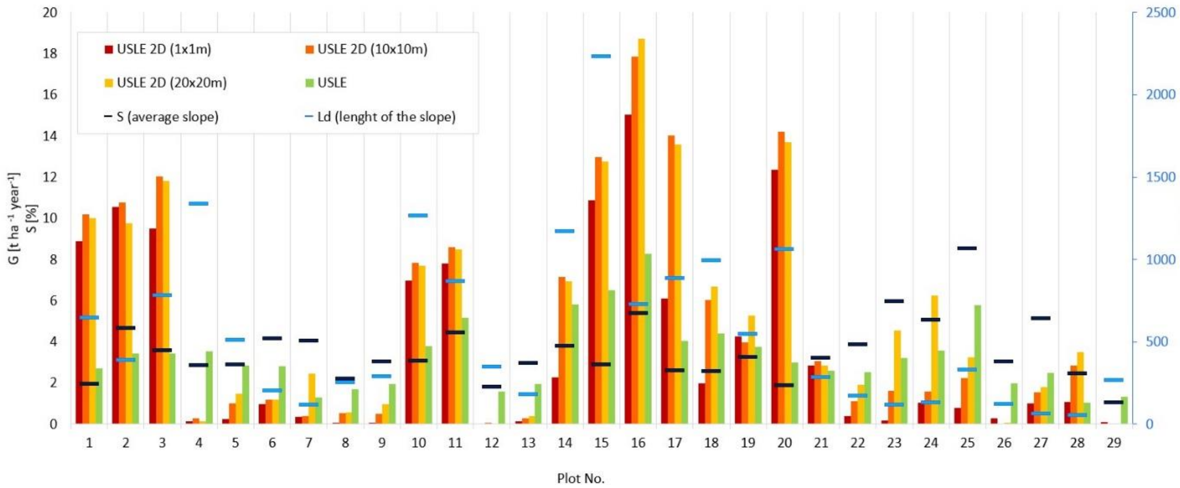


Fig. 8. Values of the annual average soil loss from 26 plots according to USLE and USLE-2D (resolution 1x1 m, 10x10 m, and 20x20 m DMR), the blue line is the length of the slope, and the black line is the average steepness of the slope.

Conclusion

In the cadastral territory of Tulčík, an estimate of the water erosion of the soil was made. Two simple models were used to calculate the soil loss, i.e., the USLE universal soil loss equation and the USLE 2D model with the LS-factor calculation algorithm, according to McCool (1978). The calculations were made in a GIS environment for the individual plots.

With the USLE method, the overestimation of the results was not confirmed, as pointed out by several authors. In this study, it was manifested on plots with a low intensity of erosion (up to 4 t ha^{-1} $year^{-1}$), which was the case only for plots with a small slope, short runoff length, and small plot size. A possible reason is the distinct fragmentation and shape of the individual plots' and the sensitivity of determining the runoff path using the classic USLE method. Both models are based on empirical and conceptual relationships, which may result in possible uncertainties concerning the results. During the evaluation, the impact of the slope of the plot, the length of the slope, and the plot's area were directly analyzed. The slope of the plot was the most pronounced. Comparing the grid size for the USLE-2D model showed that more significant differences were obtained for plots with a smaller area and a higher slope. It was confirmed that at a lower pixel resolution, the results are overestimated.

From the results obtained and a comparison of the LS-factor, it is advisable to consider using a detailed DMR with a resolution of 1x1m. Spatial data are available, but their applicability in fragmented and larger territories can be limited too (complicated for processes). It is advisable to supplement this study with further testing of other resolutions; it provides a useful reference for soil erosion study, particularly to develop model parameter assessment.

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Ing. Tatiana Kohutová
Ing. Matúš Tomaščík
Assoc. Prof. Ing. Michaela Danáčová, PhD. (*corresponding author, e-mail: michaela.danacova@stuba.sk)
Prof. Ing. Kamila Hlavčová, Ph.D.
Department of Land and Water Resources Management
Faculty of Civil Engineering
Slovak University of Technology in Bratislava
Radlinského 11
810 05 Bratislava
Slovak Republic