https://doi.org/10.17221/128/2019-SWR

Possibilities of including surface runoff barriers in the slope-length factor calculation in the GIS environment and its integration in the user-friendly LS-RUSLE tool

Jiří Brychta[1], Martina Brychtová[2]*

[1]Department of Geography, Faculty of Science, J. E. Purkyně University, Ústí nad Labem, Czech Republic
[2]Department of Land Use and Improvement, Faculty of Environment, Czech University of Life Sciences Prague, Prague, Czech Republic

**Corresponding author: jiri.brychta@ujep.cz*

Citation: Brychta J., Brychtová M. (2020): Possibilities of including surface runoff barriers in the slope-length factor calculation in the GIS environment and its integration in the user-friendly LS-RUSLE tool. Soil & Water Res., 15: 246–257.

Abstract: The effect of the morphology is key aspect of erosion modelling. In Universal Soil Loss Equation (USLE) type methods, this effect is expressed by the topographic factor (LS). The LS calculation in GIS is performed by a unit contributing area (UCA) method and can mainly be influenced by the pixel resolution, by the flow direction algorithm and by the inclusion of a hydrologically closed unit (HCU) principle, the cutoff slope angle (CSA) principle and the ephemeral gullies extraction (EG) principle. This research presents a new LS-RUSLE tool created with the inclusion of these principles in the automatic user-friendly GIS tool. The HCU principle using a specific surface runoff interruption algorithm, based on pixels with NoData values at the interruption points (pixels), appears to be key. With this procedure, the occurrence of overestimation results by flow conversion was rapidly reduced. Additionally, the reduction of extreme L and LS values calculated in the GIS environment was reached by the application of the CSA and EG principles. The results of the LS-RUSLE model show the prospective use of this tool in practice.

Keywords: cutoff slope angle; hydrologically closed unit; L factor; LS factor; unit contributing area

Probably the most important influence on the correctness of the evaluation, whether it is the long-term soil loss or sediment transport, is due to the terrain morphology. The influence of the morphology in the Universal Soil Loss Equation (USLE) (Wischmeier & Smith 1978) or on the revised version RUSLE (Renard et al. 1997) or also on the modified version MUSLE (Williams & Berndt 1977) is expressed by the topographic factor (LS). These methods are widely accepted over the world and, therefore, were a principle methodological source for the creation of several so-called USLE family models – RULSE2 (USDA 2008), RUSLE 3D (Desmet & Govers 1996; Mitášová & Mitáš 1999), USPED (Mitášová et al. 1996), Atlas DMT Erosion Modul (Atlas DMT 2019), CSLE (Liu et al. 2002), PERFECT (Littleboy et al. 1992), G2 (Panagos et al. 2014; Karydas & Panagos 2016), SWAT (Arnold et al. 1998), WATEM/SEDEM (Van Rompaey et al. 2001), SEDD (Ferro & Minacapilli 1995), CREAMS (Knisel 1980; Silburn & Freebairn 1992), AGNPS (Young et al. 1989), AnnAGNPS (Bosch et al. 1998), ERCN (Chlada & Dumbrovský 2000),

Supported by the Operational Programme Research, Development and Education of the Czech Republic for financing the Project Smart City – Smart Region – Smart Community (Grant No. CZ.02.1.01/0.0/0.0/17_048/0007435).

https://doi.org/10.17221/128/2019-SWR

EPIC (Williams et al. 1983). According to several authors (Moore & Wilson 1992; Desment & Govers 1996; Mitášová et al. 1996; Kinell 2008; Zhang et al. 2013), the LS factor calculation is a key aspect of the soil loss prediction accuracy.

A number of computational relationships of the LS factor have been derived. The evolution of the LS factor equation was described by Rodríguez and Suárez (2010). The original manual computational methods based on the determination of the representative flow paths on the plot subtracted from the contour maps (Wischmeier & Smith 1965, 1978; Foster & Wischmeier 1974) were replaced by a fully distributive computation in the GIS environment (Moore & Burch 1986) using the principle of replacing the horizontal slope-length by the unit contributing area (UCA). The UCA method was adopted in several studies (Desment & Govers 1996; Mitášová et al. 1996; Moore et al. 1991; Moore & Wilson 1992). The UCA is derived from the digital terrain model (DTM) by determining the flow direction and then the flow accumulation raster multiplied by the given pixel resolution. Basically, two groups of flow direction algorithms can be distinguished – the single-flow direction (SFD) (O'Callaghan & Mark 1984; Jenson & Dominique 1988; Fairfield & Leymarie 1991; Orlandini et al. 2003) and the multiple-flow direction (MFD) (Freeman 1991; Quinn et al. 1991; Tarboton 1997; Seibert & McGlynn 2007). The resulting flow direction raster is then used as the input data to the given flow accumulation algorithm (Jenson & Dominique 1988; Freeman 1991; Quinn et al. 1991; Tarboton et al. 1991; Tarboton 1997; Quinn et al. 1995; Wolock & McCabe 1995).

There are several other problems that are mainly connected with the overestimation or underestimation of the slope-length and the L factor values. Several authors adopted different principles to solve this problem. Hickey et al. (1994), Dunn and Hickey (1998) and Hickey (2000) brought the cutoff slope angle principle (CSA) as a method for the inclusion of deposition areas in the slope-length calculation. This method was modified according to the RUSLE principles by Van Remortel et al. (2001). Van Remortel et al. (2004) presented the flow path and cumulative cell length method (FCL) respecting the horizontal projection of the slope-length principle in the 2D terrain according to Wishmeier and Smith (1978). Zhnag et al. (2017) adopted the modified CSA method by Van Remortel et al. (2004) and transformed the FCL method (Van Remortel et al. 2001) to 3D conditions taking the terrain convergences into account.

The goal of the paper is to compare and discuss the abovementioned principles of reducing the extreme LS values and integrate the selected principles in a newly created GIS tool – LS-RUSLE. The goal of the created tool is to have complete automation, to speed up and simplify the time-consuming calculation of the correct LS factor values without extremes. For practical use in erosion modelling, the tool has been created with a user-friendly interface that is familiar with the most often used GIS software – ArcGIS.

METHODOLOGY

For an overview, first, the individual points of the methodology and the aims of our testing are stated:

(1) The creation model/script for the calculation of the LS factor based on the UCA (Equations (5)–(6), Figure 1) and SUCA (Equations (7)–(9)) principle using Python programming language and ArcGIS API.

(2) To analyse of the impact of the raster resolution (1 m vs. 10 m), the flow direction algorithms (D8 vs. D∞) and the HCU principle (without the HCU vs. with the HCU) on the resulting LS values and the average annual soil loss values (Table 2, Figures 4–6).

(3) The integration of the mentioned methods for reducing the extreme values (HCU-LPIS, HCU, CSA, EG3, EG5) in the created LS factor model using Python and ArcGIS API (Figures 2–3). Each principle was integrated particularly by itself and then gradually combining them together. It means that several variants of the model were created and tested.

(4) To perform analyses of the spatial comparisons of several variants of the computation – inclusion of each principle of reducing the extreme values and their combinations. To respectively analyse the impact of the given variants to the resulting L and LS values (Table 3).

(5) To create a final LS-RUSLE tool with the integrated selected principles for reducing the extreme values as an ArcGIS tool with a user-friendly interface and the automation of all the time-consuming calculations (Figures 7–8). Examples of the resulting raster values generated by the model are shown in Figure 9.

The basic form of the Equations for the LS-RUSLE calculation (1)–(4) according to McCool (1987) and Renard et al. (1997) are:

https://doi.org/10.17221/128/2019-SWR

$$\mathrm{L} = \left(\frac{\lambda}{22.13}\right)^m \quad (1)$$

$$\mathrm{S} = 10.8 \sin(s_1) + 0.03 \quad (2)$$

$$\mathrm{S} = 16.8 \sin(s_2) - 0.5 \quad (3)$$

where:
LS – the topographic factor,
λ – the horizontal projection of the uninterrupted slope length,
s_1 – the slope (rad) < 9%,
s_2 – the slope (rad) ≥ 9%,
m – the exponent determined by Equation:

$$m = \frac{\beta}{(\beta+1)}\text{, where: } = \frac{\left(\frac{\sin s}{0.0896}\right)}{3(\sin s)^{0.8}+0.56} \quad (4)$$

These are the basic equations used for the creation of the GIS tool LS-RUSLE. Its user interface and structure are shown in Figures 7 and 8 and its principles are described below. Next, the attention is given to the L factor, particularly to the horizontal projections of the uninterrupted slope length (λ). λ was calculated by several different methods based on the flow accumulation algorithm:

(1) The unit contributing area – UCA (Moore & Burch 1986; Moore & Wilson 1992; Desment & Govers 1996; Zhang et al. 2013, 2017),
(2) The simplified unit contributing area – SUCA (Mitášová et al. 1996, 1998),
(3) The hydrologically closed unit principle – HCU (Atlas DTM 2019, Van Oost & Govers 2000),
(4) The cutoff slope angle principle – CSA (Dunn & Hickey 1998; Hickey 2000; Van Remortel et al. 2001)
(5) The ephemeral gullies extraction principle – EG3, EG5.

Two different flow direction algorithms D8 (Jenson & Dominique 1988) and D∞ (Tarboton 1997) were compared to generate the flow accumulation raster. The high precision (up to 0.18 m) LiDAR DMR 5G (CUZK) was used as the altitude data. This precision enabled the creation of the DEM with resolutions of 1 and 10 m. The relevant characteristics of the model area are summarised in Table 1. In this table, the characteristics of the model are compared, the watershed – all the watershed, solved hydrologically closed units (HCU – see second paragraph below) and the LPIS land block (Trojáček & Kadlubiec 2004). These parameters give the basic overview of the testing terrain conditions.

Unit contributing area principle (UCA, SUCA). The L factor equation by Foster and Wischmeier (1974) was transformed by Desment and Govers (1996) for the DEM surface subdivided into a number of segments represented by grid cells (GC):

$$\mathrm{L}_{x,y} = \frac{As_{x,y}^{m+1} - As_{x,y-1}^{m+1}}{\left(As_{x,y} - As_{x,y-1}\right)(22.13)^m} \quad (5)$$

where:
$\mathrm{L}_{x,y}$ – the L factor for the GC with the coordinates x, y,
$As_{x,y}$ – the UCA at the outlet of the GC with the coordinates x, y (m^2/m),
m – the variable slope-length exponent.

The assumption is that the slope length starts from the ridges and peaks, $As_{x,y} = 0$ and then Equation (5) can be transformed as follows:

$$\mathrm{L}_{x,y} = \left(\frac{As_{x,y}}{22.13}\right)^m\text{, where: } As_{x,y} = \frac{A_{x,y}}{D_{x,y}}\text{,}$$

$$\text{where: } D_{x,y} = R\left(\left|\sin\alpha_{x,y}\right| + \left|\cos\alpha_{x,y}\right|\right) \quad (6)$$

where:
$A_{x,y}$ – the contributing area for the GC with the coordinates x, y (m^2),
$D_{x,y}$ – the effective contour length for the GC with the coordinates x, y (m),
R – the raster resolution, the GC size respectively (m),
α – the aspect direction for the GC with coordinates x, y (rad).

For these transformations, Desment and Govers (1996) used the concept of the UCA (Figure 1) (Moore & Burch 1986; Moore & Wilson 1992).

Table 1. The representative parameters of the model area compared with the watershed of level III

Parameters	Watershed				HCU				LPIS			
	Ø	SD	min	max	Ø	SD	min	max	Ø	SD	min	max
Elev. (m.a.s.l.)	276.3	85.9	161.5	836.5	275.5	85.9	161.5	565.5	273.9	40.9	201	416.5
Slope (°)	6.5	7.6	0	61.9	6.3	5.2	0	36.7	4.3	2.7	0	19.2
Curvature (–)	0.01	1.4	–11.2	9.8	0.01	1.2	–6.4	6.2	0	0.5	–2.2	3.3

HCU – parameters within the hydrologically closed unit; LPIS – land blocks; curvature – terrain surface curvature (Moore et al. 1991); SD – standard deviation

https://doi.org/10.17221/128/2019-SWR

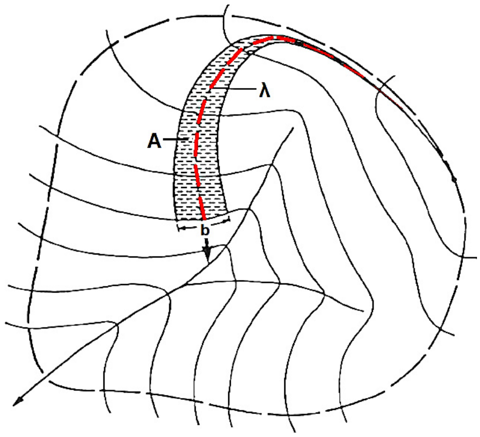

Figure 1. The principle of the UCA method (adapted from Moore & Burch 1986)

λ – the horizontal projection of the uninterrupted slope length; A – the upslope contributing area; b – the effective contour length

Moore and Wilson (1992) simplified the given equation as:

$$L = \left(\frac{As}{22.13}\right)^m \tag{7}$$

and Mitášová et al. (1996) in accordance with Griffin et al. (1988) simplified the given equation with the assumption that $D = R$ as:

$$L = (m+1)\left(\frac{As}{22.13}\right)^m \text{ or } L = (m+1)\left(\frac{\text{flowacc}\cdot R^2}{22.13\cdot R}\right)^m \text{ or} \tag{8}$$

$$L = (m+1)\left(\frac{\text{flowacc}\cdot R}{22.13}\right)^m \tag{9}$$

where:

L – the L factor,

flowacc – the flow accumulation raster,

D – the effective contour length,

R – the GC size,

m – the variable slope-length exponent.

We called this simplification the simplified unit contributing area method (SUCA).

Hydrologically closed unit principle (HCU). In addition to the terrain convergence and raster resolution, the LS overestimation in the GIS is also caused by disregarding the surface runoff barriers. This leads to extreme slope-lengths up to a few kilometres. This is a common mistake in GIS erosion analyses. However, the original USLE methodology considers the individual plots as hydrologically closed units (HCU). This principle is integrated in the created GIS tool LS-RUSLE. It is also integrated in the USLE2D model and Atlas DMT module in a similar way (Van Oost & Govers 2000; Atlas DMT 2019). See other details in the 2nd paragraph of the results and discussion sections. A common problem in calculating the LS in the GIS is also setting too low resolution, which, even in the case of HCU inclusion, may result in the joining of two or more HCUs and, thus, lengthening the slope. This problem is caused by the conversion of the vector polygon layers into raster layers and the joining of their pixels (Figure 2). These problems are solved in the presented model LS-RUSLE by generating a grid with NoData values for the pixels at the intersections with surface runoff barriers. Because raster arithmetic operations do not allow the inclusion of NoData in the calculations (NoData × 1 = NoData, NoData + 1 = NoData), it was also necessary to develop a script for extracting the slope values into categories < 9% and ≥ 9%, by replacing the NoData values with 0 and then calculate the S factor values separately according to Equations (2) and (3).

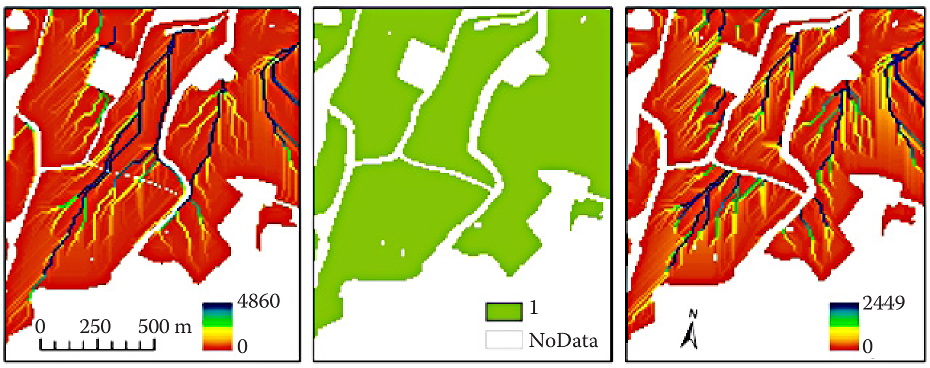

Figure 2. An example of generating an incorrect flow accumulation grid (left) and the correct way (right) using an algorithm with the NoData values, the pixels at the intersections of the surface runoff interruptions (centre) integrated in our LS-RUSLE model

https://doi.org/10.17221/128/2019-SWR

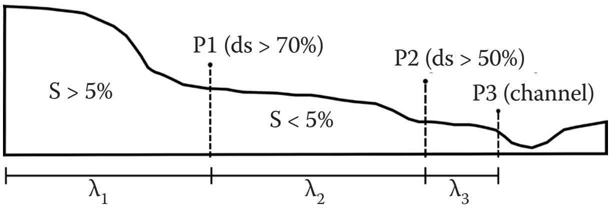

Figure 3. A demonstration of the CSA principle
P1–P3 – cutoff points; S – slope (%); ds – slope gradient change; λ_1–λ_3 – slope-length

Cutoff slope angle principle (CSA). Wischmeier and Smith (1978) defined the slope-length as the distance from the point of the surface runoff origin to the point where the slope gradient decreases enough that the deposition begins, or the flow is concentrated in a defined channel or where the surface runoff barriers are located. Hickey (2000) include the deposition areas in the slope-length calculation using the cutoff slope angle (CSA) method. This method was modified according to the RUSLE principles by Van Remortel et al. (2001). The CSA method is based on the assumptions: (1) for slopes > 5%: if the slope decreases by more than 70% then the deposition begins, (2) for slopes < 5%: if the slope decreases by more than 50% then the deposition begins, the slope-length (λ_1) is interrupted and the new slope-length (λ_2) begins (3) when the runoff enters into a channel (λ_3). The CSA principle is described in Figure 3.

Ephemeral gullies extraction principle (EG3, EG5). According to the abovementioned definition by Wischmeier and Smith (1978), we extended the UCA method by another assumption of the exclusion of larger ephemeral gullies (EGs) defined by Dumbrovský et al. (2020). This assumption is based on the original principles of USLE/RUSLE which only enable the calculation of sheet and rill erosion. The EGs represent a border when the rills transform into gullies and, at least, the larger gullies, the valleys and the channels should be excluded. According to Dumbrovský et al. (2020), the contribution area of the EG is 3–5 ha, therefore, when the resolution is 10 m, then the contributing area represents 300–500 grid cells. Similar to Tarboton's et al. (1991) methodology for the channels are identified the gullies as the grid cells exceeding the threshold values of the accumulated area array matrix. We tested the threshold values of 300 and 500 grid cells contributing an area of 3 ha (EG3) and 5 ha (EG5), respectively.

RESULTS AND DISCUSION

The results and connected discussion sections are arranged according to the first paragraph of the capture methodology. First of all, the influence of the flow direction of D8 (Jenson & Dominique 1988) and D∞ (Tarboton 1997), and the resolution of 1 and 10 m, were tested within the LPIS land blocks and without any surface runoff interruptions as opposite extremes: D8 vs. D∞, 1 m vs. 10 m, HCU-LPIS vs. without the HCU. The resulting LS values of this comparison are summarised in Table 2. The LS values calculated with the 10 m resolution and the HCU-LPIS principle application ranged from 0 to 29.1 (Figure 4, left). If no HCU principle was applied, the LS reached extreme values in places of increased runoff accumulation (Figure 4, right). According to the LPIS database (Trojáček & Kadlubiec 2004), the average land block area of the Czech Republic (CR) is 12.1 ha, but also extreme sizes exceeding 30 ha occur. If we accept the hypothesis that this size approximately corresponds with the size of the HCU, we can set the limits – the maximum and average values of the slope-length

Table 2. The results of comparing the approaches of the LS calculation

Resolution (m)	Flowdir	HCU	Ø	Max	SD	LS > 30 (%)	LS ≤ 1 (%)
10	D8	no	4.07	1 499	14.42	1.74	53.89
10	D8	no*	2.33	243.59	5.19	0.48	59.6
10	D8	yes	1.59	29.1	1.8	0	70.84
10	D∞	yes	1.77	22.33	1.45	0	66.79
1	D8	no	2.2	4 011	12.54	0.76	72.59
1	D8	no*	0.73	933.33	4.69	0.3	79.32
1	D8	yes	0.7	472.6	2.39	0.08	81.74
1	D∞	yes	1.51	143.86	1.92	0.02	69.77

Flowdir – flow direction method; HCU – hydrologically closed unit; *comparison at same pixel location only within the HCU (pixel by pixel); LS – topographic factor; SD – standard deviation

https://doi.org/10.17221/128/2019-SWR

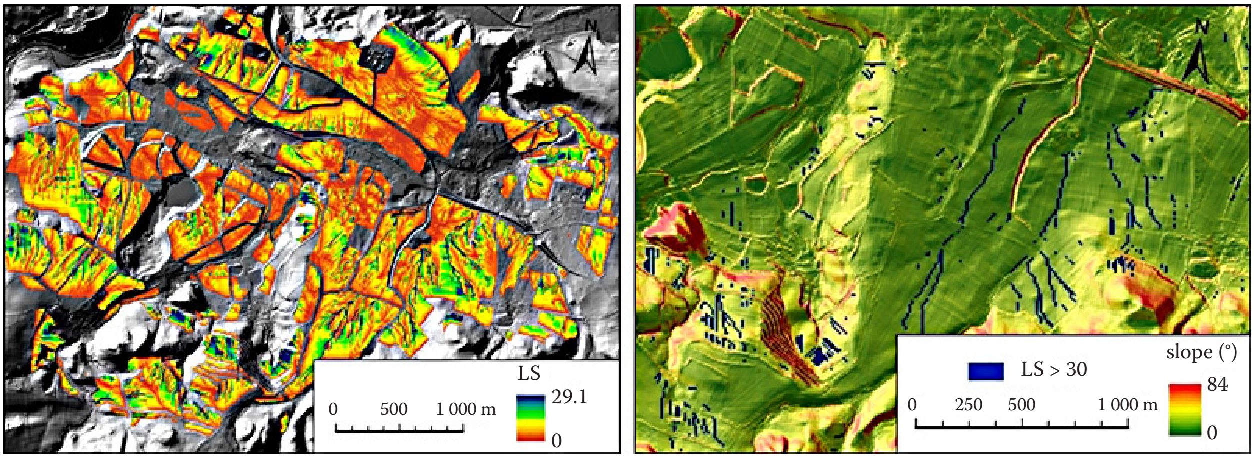

Figure 4. The topographic factor (LS) values within the land blocks (LPIS) (left) and the comparison with the extreme values without the hydrologically closed unit (HCU) application (right)

and the subsequent L factor for comparisons and controlling the resulting values. Land blocks of 12 ha approximately correspond to λ = 850 m, L = 6.2 and land blocks of 30 ha correspond to λ = 1500 m and L = 8.3. According to the analyses of the DMR 4G of the CR, the average slope of the agricultural land is 5.24%, which corresponds to S = 0.5. If we choose an extreme combination of 25% slope and λ = 1500 m, we approximately get an LS = 30. For a combination of the average λ = 850 m and slope 5% then the average LS = 4.2. The extreme value LS = 30 was not exceeded if the HCU-LPIS was applied and, in the case of no HCU, the values were 0.3–0.48% higher when compared at the same pixel locations within the HCU and 0.76–1.74% higher when compared to the entire evaluated area. The testing was carried out for a resolution of 1 and 10 m. The results in Table 2 confirm the key role of the HCU application – the extreme values are < 0.1% in comparison with the non-HCU cases, where the extreme values are 0.3–1.74%. The LS calculated with the D8 (Jenson & Dominique 1988) and D∞ (Tarboton 1997) algorithms and with a resolution of 10 m and 1 m show differences of 3.75–8.85% (Figure 5). The pie charts (calculated for the tolerance limit of LS = 2) show that red means D8 > D∞, grey means D8 = D∞ and blue means D8 < D∞. Using the D∞ algorithm, a smoother spatial distribution of the LS values was achieved. The effect of these values on the resulting annual average soil loss values calculated by the standard USLE-GIS procedure is shown in Figure 6.

These results confirmed the assumption of the correct use of the HCU principle and the D∞ algorithm (Tarboton 1997) and, therefore, were integrated to the created script/model using the ArcGIS API and Python programming language. In the first version of the model, the SUCA method (Moore & Wilson 1992; Mitašová et al. 1996, 1998) with and without the

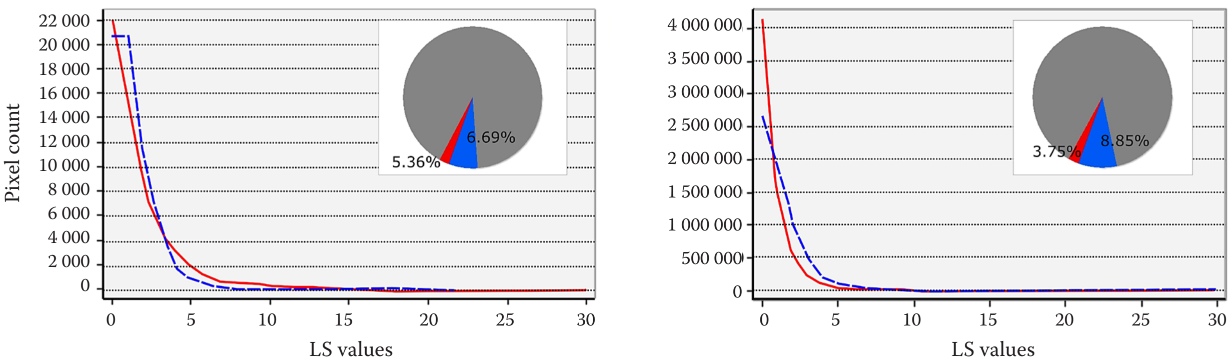

Figure 5. The comparison of the topographic factor (LS) results calculated with the D8 (red curve) and D∞ (blue curve) algorithms for the 10 m (left) and 1 m (right) resolutions

https://doi.org/10.17221/128/2019-SWR

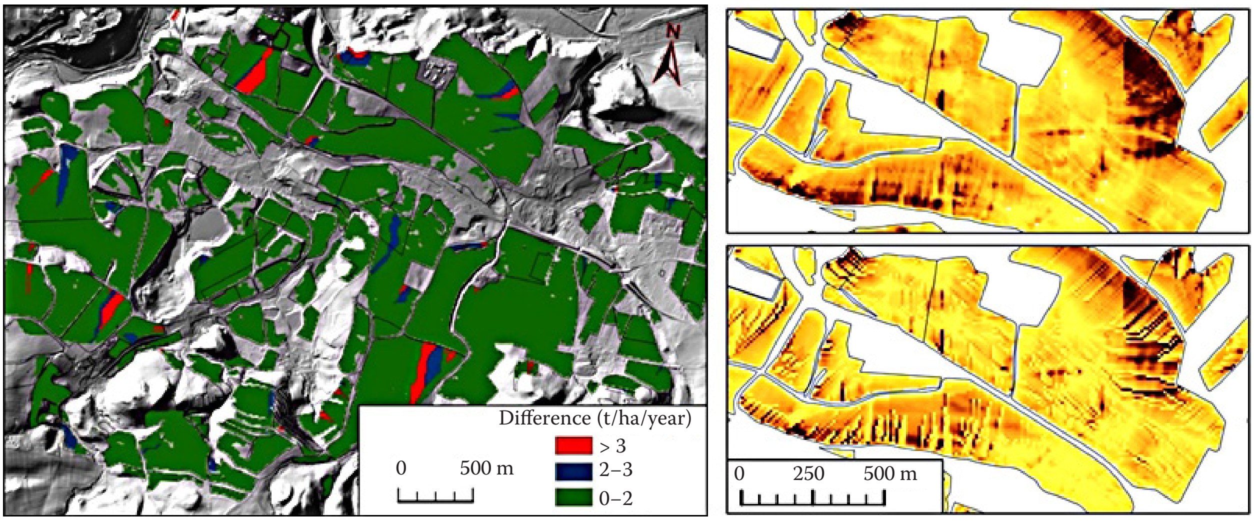

Figure 6. The long-term soil loss differences calculated using the D8 (bottom) and D∞ (top) algorithms

HCU-LPIS principle was tested. The main advantage of the SUCA method or the SUCA with HCU-LPIS is its simplicity and computing speed. However, the simplification led to the resulting values being 88.87% over the average LS value (LS = 4). Application of the LPIS land blocks (Trojáček & Kadlubiec 2004) as the HCU can lead to the underestimation in several cases where the border of the land block does not interrupt the surface runoff. We can see the reducing values in Table 3 – only 55.67% > 4. We overcame this problem by using the HCU principle in similar way as Van Oost & Govers (2000). Van Oost and Govers (2000) created the model USLE2D for the LS factor calculation. USLE2D requires a quite time-consuming creation of a parcel layer and converting it to a raster to an ASCII format then to an RST format and then the resulting values back in the same way to ASCII and next to GRID. An alternative simpler creation of a parcel layer provides the Atlas DMT erosion module which requires the vector polygon layer as input – by the manual polygon editing or by importing the land block vector layer from the LPIS database (Trojáček & Kadlubiec 2004). However, as explained above, the border of the LPIS land block does not represent the surface runoff barriers in all the cases. The HCU is defined as the land parcel or plot where no foreign water flows into it (Wishmeier & Smith 1978). For the calculation of the LS factor using the GIS environment, the surface runoff barriers should be determined and defined on the basis of a detailed survey together with the use of the geodetic survey of the actual state. Our created and presented final version of the LS-RUSLE tool provides another possibility of the overland flow interruption and enables the vector polygon and/or line layer as the input data as well, which represents

Table 3. The summary of the comparisons of the used principles

Method				L			LS			LS < 4	LS > 25
UCA/ SUCA	HCU/ HCU-LPIS	CSA	EG	Ø	SD	max	Ø	SD	max	(%)	
SUCA	–	–	–	1.97	3.47	26.42	2.33	5.19	243.59	21.13	0.48
SUCA	HCU-LPIS	–	–	1.5	1	8.74	1.77	1.45	22.33	44.33	0
UCA	HCU	–	–	1.84	1.56	13.4	2.3	3.04	28.93	75.8	0.25
UCA	HCU	CSA	–	1.84	1.53	11.52	2.27	2.96	28.82	76.1	0.22
UCA	HCU	CSA	EG5	1.36	1.28	10.04	2.21	2.77	22.12	76.8	0.18
UCA	HCU	CSA	EG3	1.29	1.21	8.9	2.16	2.7	19.1	77.9	0.12

UCA – unit contributing area; SUCA – simplified unit contributing area; HCU-LPIS – boarders of LPIS land blocks usd for delineation of HCU; HCU – hydrologically closed unit; CSA – cutoff slope angle; EG – ephemeral gullies; LS – topographic factor; SD – standatd deviation

https://doi.org/10.17221/128/2019-SWR

the surface runoff barriers without any other settings. It was solved with the emphasis of a user-friendly approach when the user defines any features and input as one or more layers without dealing with the topological imperfections. This approach brought a simplification and sped up the calculation of the LS factor values. The usual used resolution in the land use planning process is 5–10 m. So, in many cases, the line features are sufficient for several line erosion control measures. In comparison with USLE2D (Van Oost & Govers 2000), the LS-RUSLE has surface runoff barriers and interrupting features automatically defined as the NoData values. In the USLE2D model, the whole "parcel layer" has to be created by the user and the user also has to manually define the 0 values to each surface runoff barrier. The zero value have different computational rights in comparison to the NoData values. It can bring discrepancies when zonal statistics algorithms are used for averaging the soil loss values – respectively the average of the 0 and 1 values = 0.5 and the average of the NoData and 1 = 1. If the HCU principle was applied, it reduced the LS values to 24.2% > 4. USLE2D has not integrated other principles such as CSA and EG (see below).

We particularly integrated each principle according to Table 3 for purposes of their comparison and discussion. As confirmed above, the HCU principle is an essential part of the calculation. When the CSA principle was applied for the model area, it led to a slight decreasing of the higher LS values (only 23.9% > 4). The CSA principle was also adapted by Liu et al. (2002) in the CSLE with turning point of 10% due to the Chinese morphology with higher slopes. Panagos et al. (2015) used the CSA for the European LS factor map. The EG5 and EG3 principles tested in these papers have a higher LS value impact. The application of the EG5 and EG3 led to the decreasing extreme slope-length values caused by the flow concentration and the increasing of the LS values lower than 4 (only 23.2 and 22.1% > 4). Defining the threshold values for the EG identification can differ according to the morphology conditions. We used the upslope contributing area of 500 and 300 grid cells according to the research by Dumbrovský et al. (2020). A similar approach was used by Zhang et al.

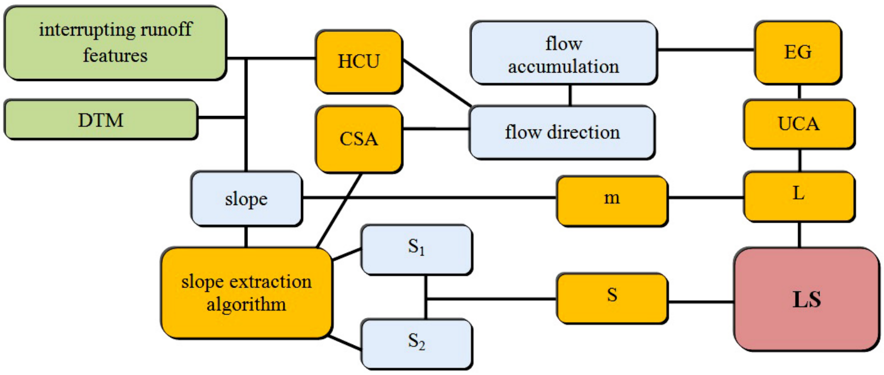

Figure 7. The structure of the LS-RUSLE model (green – input data; orange – extended procedures: hydrologically closed unit (HCU), utoff slope angle (CSA), ephemeral gullies (EG), unit contributing area (UCA) and its adaptation in the GIS environment by the authors; blue – intermediate calculations and procedures; red – output)

Procedure explanation: input data – digital terrain model (DTM) and vector polygon and/or line data representing the surface runoff barriers → processes A, B, C, D:

Process A: based on the HCU algorithm, the pixels intersected with the surface runoff barriers are extracted as NoData from the DTM → CSA (inputs: result from procedure C) → flow direction algorithm D∞ (from corrected DTM) → flow accumulation algorithm → identification and extraction of the ephemeral gullies and valleys as NoData from the flow accumulation raster based on the EG3 algorithm → UCA raster = the input for the L calculation according to Equation (6)

Process B: slope algorithm (from input DTM) → the exponent "m" calculation according to Equation (4) = input for the L calculation according to Equation (6)

Process C: slope algorithm (from input DTM) → slope extraction algorithm for the extraction given the slope categories according to Figure 3 (the result is the input for the CSA algorithm in process A and Equations (2)–(3) → the inputs for the S calculation according to Equations (2) and (3)

Process D: calculation according to Equations (2), (3), (6) → the raster values with L, S and LS values

https://doi.org/10.17221/128/2019-SWR

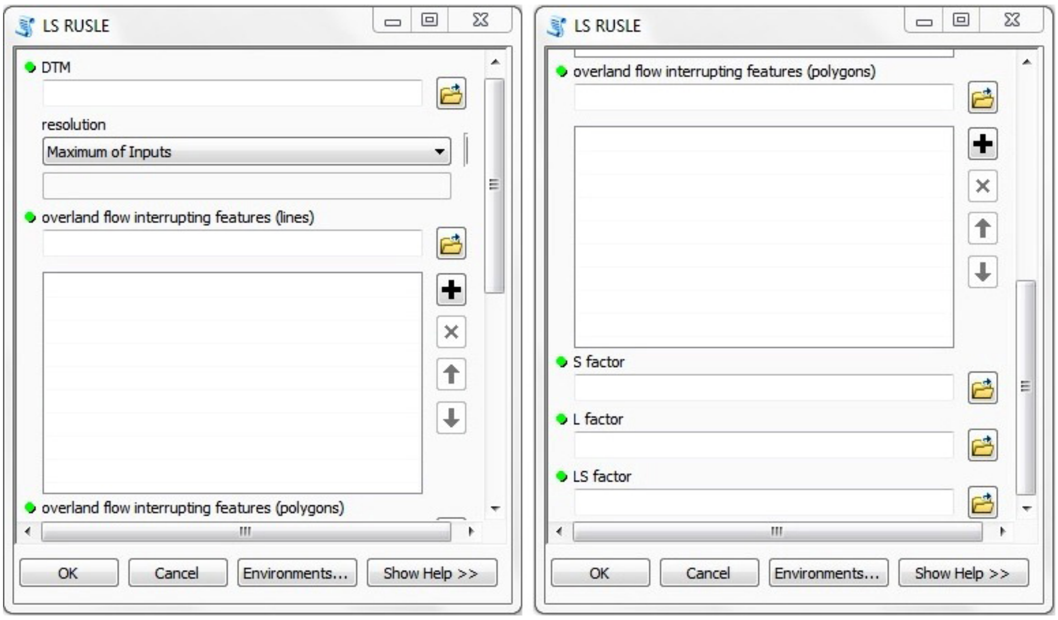

Figure 8. The LS-RUSLE tool user interface

(2017) for excluding large valleys. If the principles of the HCU, CSA and EG3 were applied, then only 0.12% of the LS values > 25. These extremes usually occur in ephemeral gullies and valleys. The specific question is setting the limits of the UCA when the ephemeral gullies begin. Ephemeral gullies should be excluded from the USLE calculation and solved by the hydraulic methods or empirical methods proposed by Dumbrovský et al. (2020). As in the case of the HCU algorithm, all the pixels identified by the CSA and EG algorithms were automatically changed to the NoData values and excluded from the other calculations.

The final version of the LS-RUSLE tool was created using the ArcGIS API and Python programming language, which works on the same principle as the ArcGIS tool. Its inputs are a DTM with an optional resolution and any number of line or polygon features which represent the surface runoff barriers. The user interface is shown in Figure 7. The tool enables to generate the correct LS values with respect to the original methodological principles. The output is a raster layer with the LS (and the L and S factor values separately) for each pixel of a selected size or it is automatically set according to the input DTM resolution. The structure of the model is shown in Figure 8. The above described principles of UCA, HCU, CSA and EG3 are integrated in the tool. More detailed research is needed to compare the resulting values in the different morphological conditions and mainly by the terrain measurements and

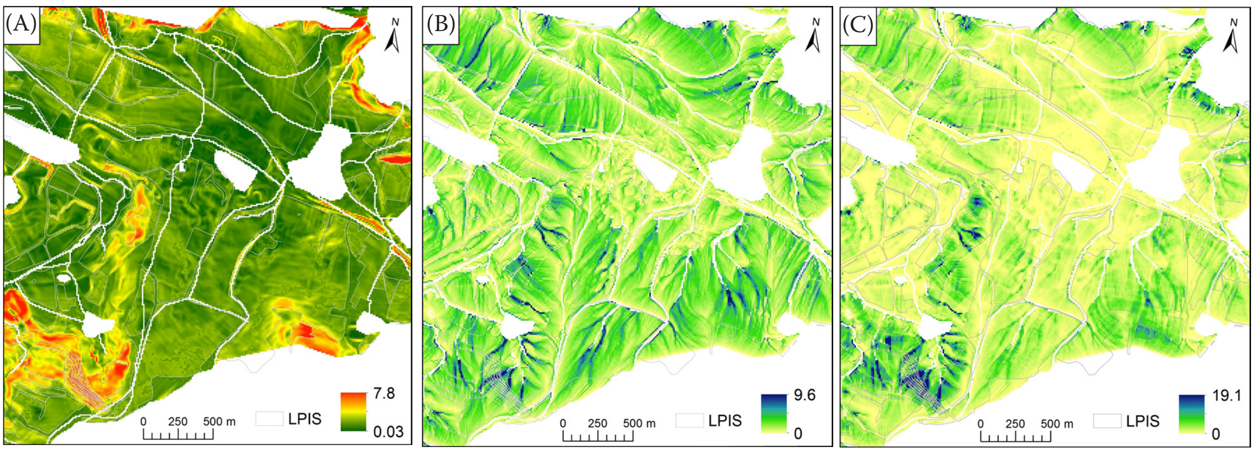

Figure 9. The resulting values of the S (A), L (B), and LS factors (C) generated by the created LS-RUSLE model

https://doi.org/10.17221/128/2019-SWR

the direct impact on the soil loss values. Hrabalíková and Janeček (2017) performed these comparisons by simulated rainfalls, but this method does not enable the evaluation of the terrain convergences and slope curvatures, but the way can be to use a specific sampling method for the larger areas by Pathak (1991). The resulting values of the S, L and LS factor generated by the LS-RUSLE model are shown in Figure 9.

CONCLUSION

This research was focused on the automatic calculation of the topographic factor in the GIS. The DTM resolution and flow direction algorithms were analysed. For a local scale, the D∞ algorithm (Tarboton 1997) shows a better spatial distribution of the LS values. However, when comparing the results of the average annual soil loss, the differences were not significant. The LS-RUSLE tool was created based on McCool's et al. (1997) equation used in RUSLE and the UCA method. In particular, consideration of the elements of the overland flow interruption according to the principle of the HCU in accordance with the original methodology appears to be key. This principle is integrated in the LS-RUSLE model using a specific overland flow interruption algorithm, based on pixels with NoData values at the interruption points (pixels). With this procedure, the occurrence of the results overestimation due to the pixel joining when converting the land parcels polygons vector data to raster values was reduced. Additionally, reducing the extreme L and LS values was reached by the application of the CSA and EG principles. The results of the LS-RUSLE model show the prospective use of this tool in practice.

REFERENCES

Arnold J.G., Srinivasan R., Muttiah R.S., Williams J.R. (1998): Large area hydrologic modelling and assessment Part I: model development. JAWRA Journal of the American Water Resources Association, 34: 73–89

Atlas DMT (2019): Erosion Module Atlas DMT. Available at: http://www.atlasltd.cz/eroze.html

Bosch D., Theurer F., Bingner R., Felton G., Chaubey I. (1998): Evaluation of the AnnAGNPS water quality model. In: Parsons J.E., Thomas D.L., Huffman R.L. (eds.): Agricultural Non-Point Source Water Quality Models: Their Use and Application. Florida, CSREES and EWRI: 45–54.

Chlada F., Dumbrovský M. (2000): Program ERCN, Ver. 2.0. VÚMOP, Prague. (in Czech)

Desmet P.J.J., Govers G. (1996): A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. Journal of Soil and Water Conservation, 51: 427–433.

Dumbrovský M., Drbal K., Sobotková V., Uhrová J. (2020): An approach to identifying and evaluating the potential formation of ephemeral gullies in the conditions of the Czech Republic. Soil and Water Research, 15: 38–46.

Dunn M., Hickey R. (1998): The effect of slope algorithms on slope estimates within a GIS. Cartography, 27: 9–15.

Fairfield J., Leymarie P. (1991): Drainage networks from grid digital elevation models. Water Resources Research, 27: 709–717.

Ferro V., Minacapilli M. (1995): Sediment delivery processes at basin scale. Hydrological Sciences Journal, 40: 703–717.

Foster G.R., Wischmeier W. (1974): Evaluating irregular slopes for soil loss prediction. Transactions of the ASAE, 17: 305–309.

Freeman T.G. (1991): Calculating catchment area with divergent flow based on a regular grid. Computers and Geosciences, 17: 413–422.

Griffin M.L., Beasley D.B., Fletcher J.J., Foster G.R. (1988): Estimating soil loss on topographically nonuniform field and farm units. Journal of Soil and Water Conservation, 43: 326–331.

Hickey R. (2000): Slope angle and slope length solutions for GIS. Cartography, 29: 1–8.

Hickey R., Smith A., Jankowski P. (1994): Slope length Calculations from a DEM with in ARC/INFO GRID. Computers, Environment and Urban Systems, 18: 365–380.

Hrabalíková M., Janeček M. (2017): Comparison of different approaches to LS factor calculations based on a measured soil loss under simulated rainfall. Soil and Water Research, 12: 69–77.

Jenson S.K., Dominique J.O. (1988): Extracting topographic structure from digital elevation data for geographic information system analysis. Photogrammetric Engineering and Remote Sensing, 54: 1593–1600.

Karydas G.Ch., Panagos P. (2016): Modelling monthlysoil losses and sediment yields in Cyprus. International Journal of Digital Earth, 9: 766–787.

Kinnell P.I.A. (2008): Sediment delivery from hillslopes and the universal soil loss equation: some perceptions and misconceptions. Hydrological Processes, 22: 3168–3175.

Knisel W.G. (1980): Creams: A Field Scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems. Conservation Research Report No. 26, US Departement of Agriculture.

Littleboy M., Freebairn D.M., Hammer G.L., Silburn D.M. (1992): Impact of soil-erosion on production in crop-

https://doi.org/10.17221/128/2019-SWR

ping systems simulation of production and erosion risks for a wheat cropping system. Australian Journal of Soil Research, 30: 775–788.

Liu B.Y., Zhang K.L., Xie Y. (2002): An empirical soil loss equation. In: Proc. 12th ISCO, Beijing, May 26–31, 2002: 143–149.

McCool D.K. (1987): Revised slope steepness factor for the universal soil loss equation. Transactions of the ASAE, 30: 1387–1399.

McCool D.K., Foster G.R., Weesies G.A. (1997): slope length and steepness factors (LS). Chapter 4. In: Renard K.G. (ed.): Predicting Soil Erosion by Water : A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Washington, D.C., USDA, Agricultural Research Service: 101–141.

Mitášová H., Mitáš L. (1999): Modelling Soil Detachment with RUSLE 3D Using GIS. University of Illinois at Urbana-Champaign. Available at: http:// skagit.meas.ncsu.edu/~helena/gmslab/erosion/usle.html

Mitášová H., Hofierka J., Zlocha M., Iverson L.R. (1996): Modelling topographic potential for erosion and deposition using GIS. International Journal of Geographical Information Systems, 10: 629–641.

Mitasova H., Mitas L., Brown W.M., Johnston D. (1998): Multidimensional Soil Erosion/Deposition Modeling and Visualization Using GIS. Final report for USA CERL. Urbana-Champaign, University of Illinois.

Moore I.D., Burch G.J. (1986): Physical basis of the length-slope factor in the universal soil loss equation. Soil Science Society of America Journal, 50: 1294–1298.

Moore I.D., Wilson J.P. (1992): Length-slope factors for the revised universal soil loss equation: simplified method of estimation. Journal of Soil and Water Conservation, 47: 423–428.

Moore I.D., Grayson R.B., Landson A.R. (1991): Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. Hydrological Processes, 5: 3–30.

O'Callaghan J.F., Mark D.M. (1984): The extraction of drainage networks from digital elevation data. Computer Vision, Graphics and Image Processing, 28: 323–344.

Orlandini S., Moretti G., Franchini M., Aldighieri B., Testa B. (2003): Path-based methods for the determination of non-dispersive drainage directions in grid-based digital elevation models. Water Resource Research, 39: 1144–1151.

Panagos P., Christos K., Cristiano B., Ioannis G. (2014): Seasonal monitoring of soil erosion at regional scale: An application of the G2 model in Crete focusing on agricultural land uses. International Journal of Applied Earth Observation and Geoinformation, 27: 147–155.

Panagos P., Borrelli P., Meusburger K. (2015): A new european slope length and steepness factor (LS-Factor) for modeling soil erosion by water. Geosciences, 5: 117–126.

Pathak P. (1991): Runoff sampler for small agricultural watersheds. Agricultural Water Management, 19: 105–115.

Quinn P., Beven K., Chevallier P., Planchon O. (1991): The prediction of hillslope flowpaths for distributed hydrological modelling using digital terrain models. Hydrological Processes, 5: 59–79.

Quinn P., Beven K., Lamb R. (1995): The in(a/tan/β) index: How to calculate it and how to use it within the topmodel framework. Hydrological Processes, 9: 161–182.

Renard K.G., Foster G.R., Weesies G.A., McCool D.K., Yoder D.C. (1997): Predicting Soil Erosion by Water : A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Agricultural Handbook No. 703, Washington, D.C., USDA, Agricultural Research Service.

Rodriguez J.L.G., Suarez M.C.G. (2010): Methodology for estimating the topographic factor LS of RUSLE3D and USPED using GIS. Geomorphology, 175: 98–106.

Seibert J., McGlynn B.L. (2007): A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models. Water Resources Research, 43: W04501.

Silburn D.M., Freebairn D.M. (1992): Evaluations of the CREAMS model. III. Simulation of the hydrology of vertisols. Australian Journal of Soil Research, 30: 547–564..

Tarboton D.G. (1997): A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resources Research, 33: 309–319.

Tarboton D.G., Bras R.L., Rodriguez-Iturbe I. (1991): On the extraction of channel networks from digital elevation data. Hydrological Processes, 5: 81–100.

Trojáček P., Kadlubiec R. (2004): Detailed mapping of agricultural plots using satellite images and aerial orthphoto maps. In: Goossens R. (ed.): Remote Sensing in Transition. Rotterdam, Millpress: 253–257.

USDA (2008): Draft Science Documentation: Revised Universal Soil Loss Equation Version 2 (RUSLE2) Washington, D.C., USDA – Agricultural Research Service. Available at: http://www.ars.usda.gov/Research/docs.htm?docid=6028

Van Oost K., Govers G. (2000): Usle2D: Online Manual. Leuven, Katholieke Universiteit Leuven. Available at: http://www. geo.kuleuven.be/geography/modelling/erosion/usle2d/

Van Remortel R., Hamilton M., Hickey R. (2001): Estimating the LS Factor for RUSLE the slope length processing of DEM elevation data. Cartography, 30: 27–35.

Van Remortel R.D., Maichle R.V., Hickey R. (2004): Computing the LS Factor for the revised universal soil loss

https://doi.org/10.17221/128/2019-SWR

equation through array-based slope processing of digital elevation data using a C++ executable. Computers and Geosciences, 30: 1043–1053.

Van Rompaey A.J.J., Verstraeten G., Van Oost K., Govers G., Poesen J. (2001): Modelling mean annual sediment yield using a distributed approach. Earth Surface Processes and Landforms, 26: 1221–1236.

Williams J.R., Berndt H.D. (1977): Sediment yield prediction based on watershed hydrology. Transactions of the ASAE, 20: 1100–1104.

Williams J.R., Renard K.G., Dyke P.T. (1983): Epic: A new method for assessing erosion's effect on soil productivity. Journal of Soil and Water Conservation, 38: 381–383.

Wischmeier W.H., Smith D.D. (1965): Predicting Rainfall – Erosion Losses from Cropland East of the Rocky Mountains: Guide for Selection of Practices for Soil and Water Conservation. Washington, D.C., USDA, Agricultural Research Service.

Wischmeier W.H., Smith D.D. (1978): Predicting Rainfall Erosion Losses: a Guide to Conservation Planning. Washington, D.C., Science and Education Administration, USDA.

Wolock D., Mccabe G. (1995): Comparison of single and multiple flow direction algorithms for computing topographic parameters in TOPMODEL. Water Resources Research, 31: 1315–1324.

Young R.A., Onstad C.A., Bosch D.D., Anderson W.P. (1989): AGNPS – A nonpoint-source pollution model for evaluating agricultural watersheds. Journal of Soil and Water Conservation, 44: 168–173.

Zhang H., Yang Q., Li R., Liu Q., Moore D., He P., Ritsema C.J., Geissen V. (2013): Extension of a GIS procedure for calculating the RUSLE equation LS factor. Computers and Geosciences, 52: 177–188.

Zhang H., Weia J., Yangb Q., Baartmanc J.E.M., Gaia L., Yang X., Lia S.Q., Yua J., Ritsemac C.J., Geissenc V. (2017): An improved method for calculating slope length (λ) and the LS parameters of the revised universal soil loss equation for large watersheds. Geoderma, 308: 36–45.

Received: September 30, 2019
Accepted: March 23, 2020
Published online: May 20, 2020