



Extension of a GIS procedure for calculating the RUSLE equation LS factor



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ABSTRACT

The Universal Soil Loss Equation (USLE) and revised USLE (RUSLE) are often used to estimate soil erosion at regional landscape scales, however a major limitation is the difficulty in extracting the LS factor. The geographic information system-based (GIS-based) methods which have been developed for estimating the LS factor for USLE and RUSLE also have limitations. The unit contributing area-based estimation method (UCA) converts slope length to unit contributing area for considering two-dimensional topography, however is not able to predict the different zones of soil erosion and deposition. The flowpath and cumulative cell length-based method (FCL) overcomes this disadvantage but does not consider channel networks and flow convergence in two-dimensional topography. The purpose of this research was to overcome these limitations and extend the FCL method through inclusion of channel networks and convergence flow. We developed LS-TOOL in Microsoft's.NET environment using C# with a user-friendly interface. Comparing the LS factor calculated with the three methodologies (UCA, FCL and LS-TOOL), LS-TOOL delivers encouraging results. In particular, LS-TOOL uses breaks in slope identified from the DEM to locate soil erosion and deposition zones, channel networks and convergence flow areas. Comparing slope length and LS factor values generated using LS-TOOL with manual methods, LS-TOOL corresponds more closely with the reality of the Xiannangou catchment than results using UCA or FCL. The LS-TOOL algorithm can automatically calculate slope length, slope steepness, L factor, S factor, and LS factors, providing the results as ASCII files which can be easily used in some GIS software. This study is an important step forward in conducting more accurate large area erosion evaluation.

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1. Introduction

Despite their shortcomings and limitations the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) are still the most frequently used equations for estimation of soil erosion. This is mainly due to the simple, robust form of the equations as well as their success in predicting the average, long-term erosion on uniform slopes or field units. Many researchers also apply them to watershed or larger areas to estimate soil erosion

(Kinnell, 2000, 2010). However extraction of the topographic factor becomes a big problem, especially the slope length.

Both the USLE and the RUSLE equations are written as follows:

$$A = RKLSCP \quad (1)$$

Where A is soil loss ($t\ ha^{-1}y^{-1}$); R is a rainfall-runoff erosivity factor; K is a soil erodibility factor; LS is a combined slope length and slope steepness factor; C is a cover management factor; and P is a support practice factor. The detail of the factors and how they affect the erosion prediction process are discussed in Renard et al. (1997, 1991).

The effect of topography on erosion in USLE/RUSLE is accounted for by the dimensionless LS factor (Van Remortel et al., 2001, 2004). The slope length factor (L) is the ratio of soil loss from the field slope length to that from a 72.6 ft length under identical conditions. The slope steepness factor (S) is the ratio of soil loss from the field slope gradient to that from a 9% slope under otherwise identical conditions (Wischmeier and Smith,

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1978). The L and S terms of the equation are often lumped together as “LS” and referred to as the topographic factor. They are calculated by slope length and slope angle. Slope length for this equation is defined as “the distance from the point of origin of overland flow to either of the following, whichever is limiting for the major part of the area under consideration: (a) the point where the slope decreases to the extent that deposition begins, or (b) the point where runoff enters a well-defined channel that may be part of a drainage network or a constructed channel such as a terrace or diversion” (Wischmeier and Smith, 1978).

Traditionally, the best estimates for slope length were obtained from field measurements, but these are not always available or practical, especially at watershed or even larger area. However, over the last 20 years procedures have been developed which allow the use of geographic information system (GIS) technology to generate both USLE and RUSLE-based validation of the algorithm used to simulate the slope length (Merritt et al., 2003; Moore and Wilson, 1992; Rodriguez and Suarez, 2010; Van Remortel et al., 2004; Wilson, 1986). Moore and Burch (1986a) recognized that higher erosion or deposition rates occur at the convergence of a catchment as also postulated in the USLE/RUSLE. These results imply that sheet flow has the lowest sediment transport capacity and that the topographic convergence or divergence in a catchment can increase or decrease the unit stream power and the sediment transport capacity. ~~The major problem is that for a 3-D hillslope where there is flow convergence or divergence, soil loss does not really depend on the distance to the point of origin of overland flow, so slope length should be replaced by the unit contributing area.~~ (Desmet and Govers, 1996; Moore and Burch, 1986a,b). Thus, the LS factor is no longer one-dimensional when applying USLE or RUSLE to large area using GIS.

Various approaches and algorithms for quantifying the LS factor have been developed.

Moore and Wilson (1992) presented a simplified equation using unit contributing area (UCA) for calculating the LS factor over three-dimensional terrain. The unit contributing area is defined as the area that drains to a specific point. It was calculated by multiplying a flow accumulation grid with the cell size. For this study the equation calculates a combined LS-factor based on the contributing area and slope steepness:

$$LS = \left(\frac{A_s}{22.13} \right)^m \left(\frac{\sin(\theta)}{0.0896} \right)^n \quad (2)$$

where

A_s = unit contributing area (m)

θ = slope in radians

m (0.4–0.56) and n (1.2–1.3) are exponents.

Desmet and Govers (1996) used a multiple-flow direction algorithm (Quinn et al., 1991) to calculate contributing areas then to calculate the LS factor in segments (Foster and Wischmeier, 1974). They compared the slope length, slope gradient and LS factor of their method with the manual approach and determined that their method generally predicted these values more closely to the manual approach. And Winchell et al. (2008) improved this method and compared several variations of the GIS approach to come up with a better method. ~~The greatest limitation of these methods is the absence of an algorithm for predicting topographically driven zones of soil deposition~~ (Winchell et al., 2008).

Consequently new models were developed to overcome this disadvantage. One approach for identifying breaks in slope length involves the evaluation of change in slope based on the concept of slope length as proposed by Dunn and Hickey (1998) and Hickey

(2000). Van Remortel et al. (2001) added subsequent RUSLE-based amendments to the USLE-based code including the substitution of several developed RUSLE algorithms and the modification of a few assumptions in a AML program. Later, Van Remortel et al. (2004) focused on the mechanisms involved in extracting key flowpath-based and cumulative cell length portions (FCL) of the original AML program and extracted a code to run in a more robust C++ executable program. DEM data is systematically analyzed using 3×3 cell windows consisting of the central cell and 8 surrounding cells. In FCL method, a single-flow direction algorithm (O’Callaghan and Mark, 1984) is used and slope breaks are considered. In recent research of Liu et al. (2011) showed that the FCL method is a more suitable calculation method than UCA method. ~~However, even with the new models, plan-concave area (i.e. zones of flow concentration), channel networks are not considered.~~ It is obvious that areas of flow convergence will have significantly greater LS-values than flat areas or areas of flow divergence, and also that slope length must stop at a channel. Therefore, inaccuracies remain in the most recent models.

The aim of this paper is to propose an algorithm that extends the FCL method (Van Remortel et al., 2001, 2004) and revises its calculation algorithm for slope length and flow convergence both based on the UCA algorithm as well as the cutoff conditions for including channel networks. Using the concept of the single-flow direction algorithms (O’Callaghan and Mark, 1984) with a focus on the calculation of slope length including channel networks, a calculation process is shown. A comparison of results for slope length and LS factor calculated with the UCA method (Moore and Wilson, 1992), the FCL method (Van Remortel et al., 2004) and the LS-TOOL method (this paper) for Xiannangou catchment is presented and also compared with the manual method. Finally, we show the relationship between slope length, cumulative area threshold and DEM resolutions.

To provide an automatically calculated result for policy makers and soil and water managers, we developed the calculation support application LS-TOOL. This user-friendly application is developed in Microsoft’s .NET environment using C# language through array-based processing of digital elevation data. This algorithm will save time and automatically calculate LS factor using ASCII DEM data.

2. Materials and methods

2.1. The model theory

LS calculation is based on the following expressions of McCool et al. (1989) used in RUSLE:

$$LS = L \cdot S \quad (3)$$

$$L = (\lambda/22.13)^m \quad (4)$$

$$m = \beta/(1 + \beta) \quad (5)$$

$$\beta = (\sin \theta)/[3 \cdot (\sin \theta)^{0.8} + 0.56] \quad (6)$$

$$\begin{aligned} S &= 10.8 \cdot \sin \theta + 0.03 & \theta < 9\% \\ S &= 16.8 \cdot \sin \theta - 0.5 & \theta \geq 9\% \end{aligned} \quad (7)$$

where

λ is the length of the slope

m is a variable length-slope exponent

β is a factor that varies with slope gradient, and

θ = slope angle

Desmet and Govers (1996) considered that in a two-dimensional situation, slope length should be replaced by the unit contributing area and used unit contributing area algorithm to calculate slope segment as:

$$L_{ij} = \frac{A_{S_{ij-out}}^{m+1} - A_{S_{ij-in}}^{m+1}}{(A_{S_{ij-out}} - A_{S_{ij-in}}) \cdot (22.13)^m} \quad (8)$$

where

- L_{ij} = slope length factor from the grid cell with coordinates (i,j)
- $A_{S_{ij-out}}$ = unit contributing area at the outlet of the grid cell with coordinates(i,j)(m²/m)
- $A_{S_{ij-in}}$ = unit contributing area at the inlet of the grid cell with coordinates(i,j)(m²/m)

If the slope length starts from a high point or a slope length cutoff, a new slope length start, $A_{S_{ij-in}} = 0$, then

$$L_{ij} = \left(\frac{A_{S_{ij-out}}}{22.13}\right)^m \quad (9)$$

Further,

$$A_{S_{ij-out}} = \frac{A_{ij-out}}{D_{ij}} \quad (10)$$

and the grid data has the same cell size, so $\lambda_{ij} \times D_{ij} = A_{ij-out}$
Comparing Eqs. (4) and (9), Eq. (8) may be rewritten:

$$\lambda_{ij} = \frac{A_{ij-out}}{D_{ij}} \quad (11)$$

where:

- A_{ij-out} =contributing area at the outlet of grid cell with coordinates (i,j) (m²)
- D_{ij} =the effective contour length (m) (Shown in Fig. 1 (Gallant and Hutchinson, 2011))
- λ_{ij} =slope length (m)

In order to calculate the unit contributing area, the contributing area of a cell is divided by the effective contour length. The length of the contour line within the grid cell equals the length of the line through the grid cell center and perpendicular to the

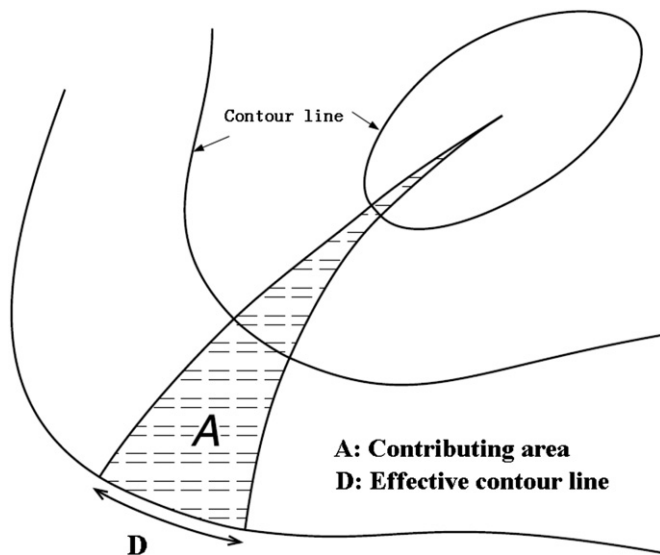


Fig. 1. Schematic representation of specific catchment area (Gallant and Hutchinson, 2011).

aspect direction, and is calculated as (Desmet and Govers, 1996):

$$D_{ij} = Cellsize \cdot (\sin\theta_{ij} + \cos\theta_{ij}) \quad (12)$$

θ_{ij} =aspect direction for the grid cell with coordinates (i,j)

The contributing area of each cell can be represented as the sum of the contributing areas of the surrounding eight cells which flow into it. Eq. (11) can therefore be rewritten:

$$\lambda_{ij} = \sum_{x=0,y=0}^{x=i,y=j} \sum_{k=1}^m \lambda_{x,y} \quad (13)$$

where

k =the code of the surrounding eight cells of coordinates (x,y)
 $\lambda_{x,y}$ can be seen as the cell slope length (CSL) of each grid and,

if we use the D8 algorithm of O'Callaghan and Mark (1984), $\lambda_{x,y} = Cell\ size$ when the aspect direction is E, S, W, N (east, south, west and north) as shown in Fig. 2, and $\lambda_{x,y} = Cell\ size \cdot \sqrt{2}$ when the aspect direction is SE, SW, NW, NE (southeast, southwest, northwest, northeast) as shown in Fig. 2.

When convergent flow occurs, the slope lengths of all the surrounding cells which flow into the current cell should be added to the length of that cell, instead of just using the longest of the surrounding cells. This is a point where the FCL approach of Van Remortel et al. (2004) is integrated in our method. Using our new approach, slope length here is not limited to its original meaning in USLE/RUSLE in 1-D terrain, but can reflect the convergence and divergence flow in 3D terrain. We can call it the distributed watershed erosion slope length (DWESL).

2.2. The model structure

The methodology for calculating the L and S factors is illustrated in Fig. 3.

The flowchart shows an overall view of the process:

- Step 1:** Input a DEM data,
- Step 2:** Analyze the DEM data to determine if suitable data is available for use in the model,
- Step 3:** If suitable data is available, fill any spurious single-cell nodata cells and sinks within the source data by using an iterative routine,
- Step 4:** Use the D8 (O'Callaghan and Mark, 1984) method for assignment of slope angle, slope aspect and outflow direction,
- Step 5:** Calculate cutoff point,
- Step 6:** Compute the CSL by using slope aspect,
- Step 7:** Use a forward-and-reverse traversal method to compute accumulated area,
- Step 8:** Calculate DWESL using outflow direction data, CSL data, and accumulated area threshold value,

NW 32	N 64	NE 128	} Cellsize
W 16	C	E 1	
SW 8	S 4	SE 2	

Fig. 2. The cell code for a 3 × 3 window used in Eq. (13), C: current calculated cell, E: east, SE: southeast, S: south, SW: southwest, W: west, NW: northwest, N: north.

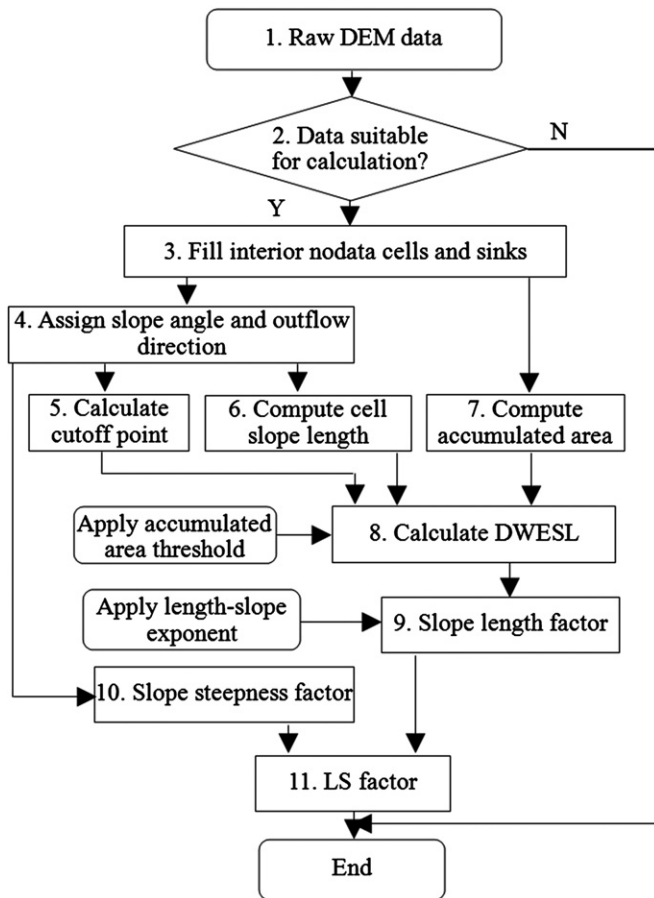


Fig. 3. Flowchart illustrating the process of calculating distribution watershed erosion slope length (DWESL), slope steepness and distributed LS factor values in the algorithm.

Step 9: Determine slope length factor by using the DWESL and length-slope exponent,

Step 10: Determine slope steepness constituent using the slope angle,

Step 11: Compute the LS factor.

2.2.1. Raw DEM data

We calculate the LS factor from a flowpath-based algorithm using the existing of DEM (an ASCII file with header information) data. The requirement for the algorithm is a depressionless and high quality DEM data for its accuracy and resolution affect the generation of surface runoff (slope gradient, slope aspect and slope length) (Liu et al., 2011; Raaflaub and Collins, 2006; Vaze et al., 2010).

We selected the Xiannangou catchment (44.85 km²), located in the Loess Plateau of China, as an example for the validation of the LS-TOOL. We used Hc-DEM (Yang et al., 2007) which greatly improves DEM quality. The resulting DEM is hydrologically correct in that the river network defined from it is connected without spurious small parallel streams being introduced. The data unit is meters. We chose to use high resolution 5m-DEM because it matches the real terrain well and has a short run time for LS-TOOL.

The raw DEM and all the intermediate results are read as a matrix into the memory. Therefore it is necessary to ensure the memory size is at least 6 times bigger than the size of the raw data.

We analyze the existing DEM data with respect to nodata cells per 3×3 window. Occurrence of 3 or more nodata cells per 3×3 window will cause the program execution to be ended, otherwise the program can continue.

2.2.2. Fill interior nodata cells and sinks

If any interior nodata cells exist, the program fills them with data. Previously the program defaulted to a fill value equal to that of the lowest surrounding cell as described by Hickey et al. (1994). If the nodata cells fill with the lowest surrounding, it will easily appear as a large flat area where it is difficult to have continuity of a channel network (Martz and Garbrecht, 1992; O'Callaghan and Mark, 1984; Tarboton et al., 1991). So in LS-TOOL the user also has the option to select the average value of all the surrounding cells.

2.2.3. Assign slope angle and outflow direction

Once the production of depressionless DEM data procedure has been completed, the cell downhill slope angle and outflow direction can be calculated using the Deterministic 8 (D8) algorithm from O'Callaghan and Mark (1984). The outflow direction refers to the direction of the neighboring cell with the maximum downward slope angle. The max downhill slope angle for the surrounding eight directions is the cell slope angle, meanwhile, as previously mentioned the direction of this cell is the outflow direction.

2.2.4. Calculate cutoff point

When we calculate the slope length and accumulated area using the D8 algorithm, the outflow direction should be extracted with the cutoff point considered.

The end of slope length in this paper is determined by two factors which define the slope length: (a) the slope cutoff point and (b) the channel network. For our purposes, the *cutoff point* where the sediment will be deposited is defined as the ratio of the slope angle of the central cell to that of the outflow direction cell. For example if the elevation of the central cell is higher than outflow direction cell, and the change of slope angle between the central cell and the outflow direction cell is great than 50% (slope decreasing by 50% or greater), then the outflow direction is the *cutoff direction*, the outflow direction cell is the *cutoff point*, and the next cell cannot accumulate the slope length from this direction. We use factors 70% (0.7) and 50% (0.5) for slope gradients of less than and greater than 5% respectively (Van Remortel et al., 2004). Actually, the appropriate ratio value for slope cutoff point is best set by an expert who has knowledge of the research area in question. Therefore a cell is supplied in the user interface of our program for setting of this parameter by the user. Furthermore, slope length is limited by the *channel network* extracted from digital elevation data using Tarboton et al. (1991) method and a value must be set which defines channels as pixels exceeding an accumulated area threshold.

2.2.5. Compute CSL

CSL, the slope length of each grid, is calculated from Eq. (12), and is decided by outflow direction.

2.2.6. Compute accumulated area

The channel network is extracted from the fixed DEM data. There are a lot of methods for deriving channels or rivers from DEM data (Ames et al., 2009; Fairfield and Leymarie, 1991; Merwade et al., 2008; O'Callaghan and Mark, 1984; Tarboton et al., 1991). Here, we used the procedure for identifying channels suggested by Tarboton (1991) because it can be easily integrated

in our algorithm easily: (a) First, calculation of the accumulated area array matrix. This procedure is almost the same as the flow accumulation command in ArcGIS. This procedure makes use of the flow direction data to create the flow accumulation data, where each cell is assigned a value equal to the number of cells that flow to it. (b) Second, definition of the channels matrix, as pixels exceeding an accumulated area threshold.

In our method, the accumulated area was determined through an iterative procedure. This started with the flow accumulation matrix being initialized to value one. The accumulated area can be calculated by a forward-and-reverse traversal accumulation algorithm operation using the initial accumulated area matrix and

outflow direction matrix. This algorithm is illustrated in Fig. 4, and works as follows:

- (1) The accumulated area matrix is created with an initial value of one assigned to all cells in the matrix (shown in Fig. 4c). Cells having a flow accumulation value of one (to which no other cells flow) generally correspond to the pattern of ridges.
- (2) Using a forward traversal method beginning with the top left cell moving cell by cell to the bottom right cell of the array matrix, sum the accumulated area of the surrounding 8 cells which flow into that cell. If the sum value plus the initial accumulated area matrix of the cell is greater than the current value then a new value replaces the current cell value. In this

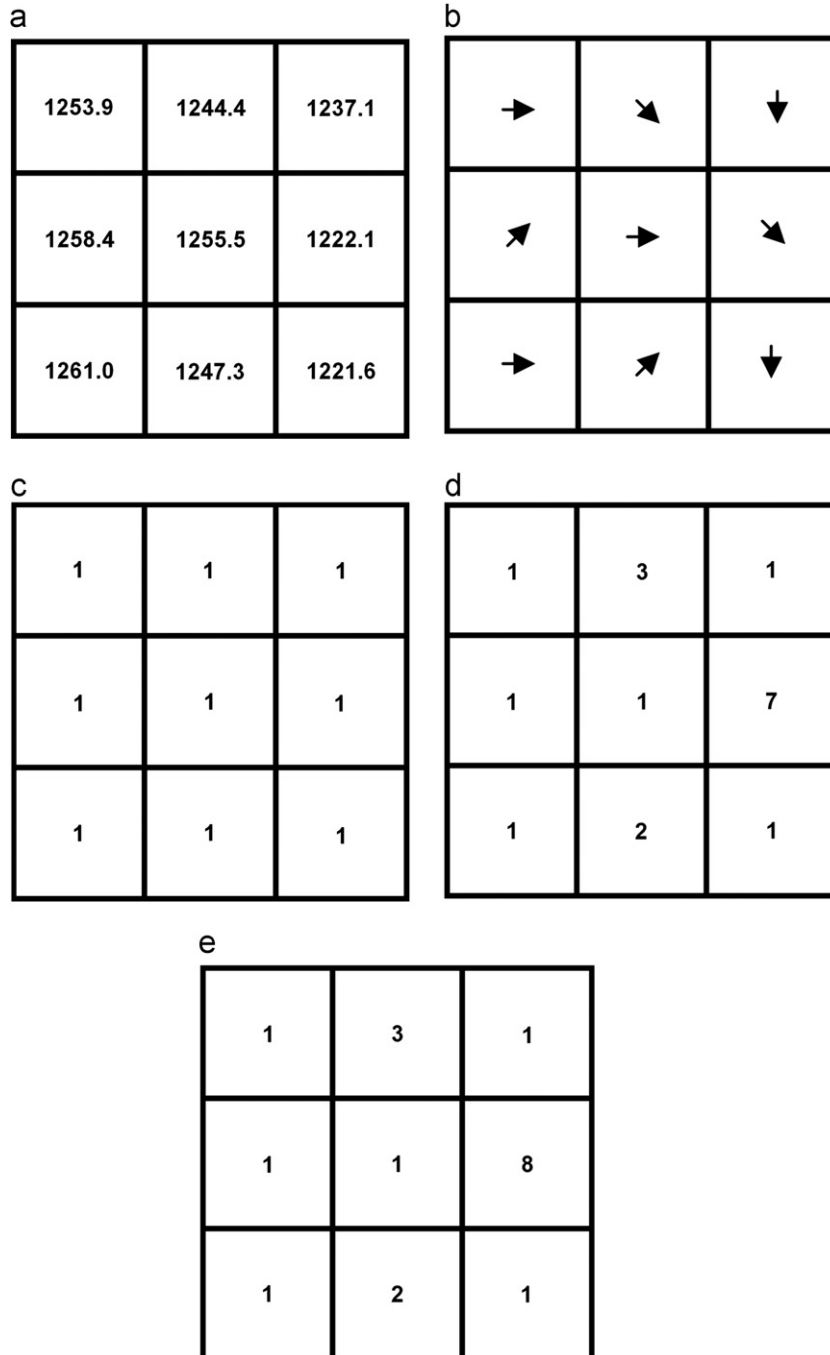


Fig. 4. The process of computing accumulated area. (a) Original DEM elevation (m). (b) Outflow direction of each cell. (c) Initial accumulated area. (d) Accumulated area value after the forward traversal in the first iteration. (e) Accumulated area value after the reverse traversal in the first iteration.

way, the forward direction traverse accumulates all possible flowpath cells flowing in an easterly or southerly direction (shown in Fig. 4d).

- (3) A reverse traversal method is run from the bottom right to the top left. The method accumulates all possible flowpath cells flowing in a westerly or northerly. As with the forward method, smaller values are replaced by larger values (shown in Fig. 4e).
- (4) The forward-and-reverse traversal method is run iteratively until there are no additional changes in the cumulative area value of any grids.

We would point out that: (a) for efficient use of memory, we define each cell's initial value as one square meter, without considering the actual cell size. This means that before using the accumulated area information, the final cell value needs to be multiplied by the cell's actual area. As previously noted, the appropriate accumulated area threshold value is best set by an expert who has knowledge of the research area in question, so we provide a cell in the user interface for setting the area threshold. (b) It is not necessary to consider whether the drainage paths are connected or not in extracting the channel networks from DEMs, this is because a disconnected channel will be a flat area where the downhill slope angle is zero, and there is a cutoff point. The drainage paths are cutoffs for accumulated slope length, the gaps are also cutoffs for accumulated slope length, and the consequences are same.

2.2.7. Calculate the distribution watershed erosion slope length (DWESL)

The algorithm for calculating the DWESL is quite similar as the one used for computation of accumulated area, with the cutoff direction and channels also taken into consideration.

Cumulative slope length can be calculated using the CSL, outflow direction, and accumulated area data. This is done by simply summing the CSL along the outflow direction pathways initiated from the beginning point of a particular slope.

The process of calculating DWESL is:

- (1) Request dynamic memory from the operating system to allow the allocation of a float matrix to accommodate user-defined DWESL,
- (2) The initial DWESL value is the CSL,
- (3) Start the forward traversal from the top left cell,

- (4) If the current cell is not the cutoff point, and the surrounding eight cells have outflow directions to the current cell, and the accumulated area value of these cells is less than the threshold value, then the current cell's DWESL is the sum of the CSL and the slope lengths of the surrounding cells which flow to the current cell,
- (5) If the new DWESL is greater than the previous DWESL value, then the current cell's DWESL changes,
- (6) Continue the forward traversal cell by cell and repeat 4 and 5 until reaching the bottom right hand cell,
- (7) Start the reverse traversal from the bottom right proceeding cell by cell, and repeat the procedures in step 4 and 5 until reaching the top left cell,
- (8) Continue the forward reverse and traversal process until there are no more changes in cell values,
- (9) Make all cells where the accumulated area is greater than the threshold equal to "0". We set "0" here in following reasons: (a) DEM data have values at that position, LS factor should have values, (b) the LS layer finally will time other factors (R, K, C, P), it is an appropriate way to set LS value as value "0". So if LS value is 0 at somewhere, which means: our model cannot have a LS value at that position.

2.2.8. Determine slope length factor, slope steepness factor and LS factor

Various suggestions exist in the literature regarding how to represent the LS factor of the USLE/RUSLE. We use McCool et al.'s (1997) Eqs. (3)–(7) to calculate slope length factor, slope steepness factor and LS factor respectively.

2.3. Comparison of the model

In order to compare DWESL and LS values calculated by LS-TOOL with manual methods, we followed the methods of McCool et al. (1997) and Griffin et al. (1988) to finish field work. Since it is very difficult to have slope lengths and slope gradients for the whole catchment, we selected 200 sample places (as shown in Fig. 5, right picture). Red dots are mainly hilltops, ridges, or local high points; green dots are channels, gully, or roads. Blue points are gently rolling areas.

In order to compare LS-TOOL with existing methods, we applied the three GIS methods in the Xiannangou catchment, China (Fig. 5). The comparison focused on operating of the model.

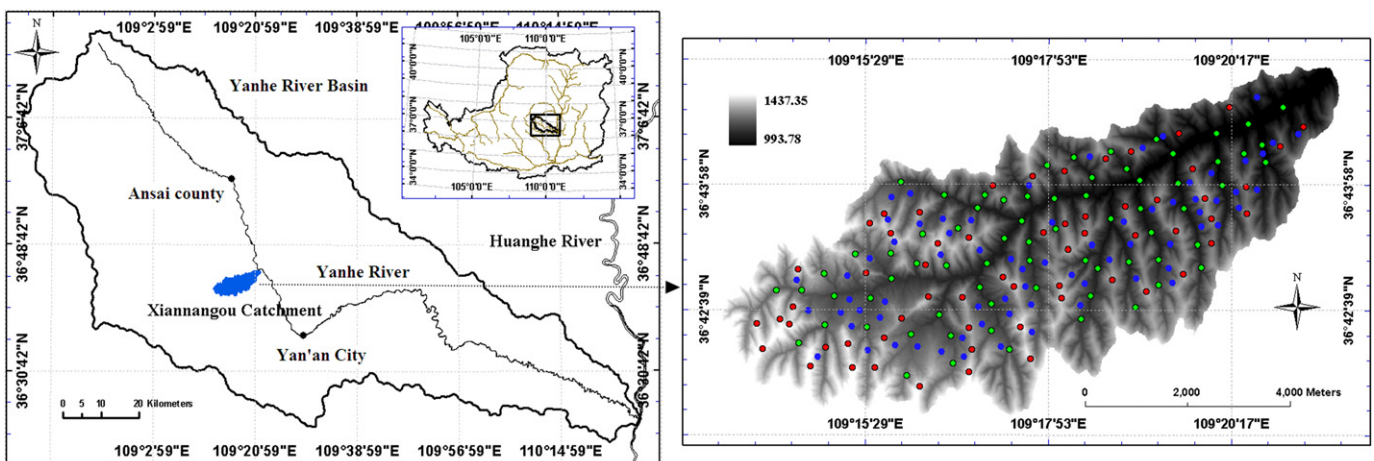


Fig. 5. The left main map shows the location of the Xiannangou catchments (light green shading) in the Loess Plateau in the middle reaches of the Yellow River basin. The inset map shows the location of the Loess Plateau in the middle reaches of the Yellow River basin, China. The right map shows the 5-m DEM of the study site. The elevation from 993.78 meter (white) to 1437.36 meter (black). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The three GIS methods, UCA (Moore and Wilson, 1992), FCL (Van Remortel et al., 2004) and LS-TOOL were compared by calculating the slope length and LS values.

With the UCA, because there is an upper bound to the slope length which usually does not exceed 1000 feet (304.8 m) (Renard et al., 1997). We chose to use Eq. (2) ($p=0.4$, $q=1.3$) following Jabbar's approach (2003), with a maximum accumulation of 60 grid cells, and using the spatial analyst tools in ArcGIS.

The FCL method was implemented using C++ program (Van Remortel et al., 2004).

In applying of LS-TOOL, we selected an accumulated area threshold of 40 00 m², because this threshold corresponded well to the real channels. LS-TOOL is developed in Microsoft's.NET

environment using C#. Three design aspects were clearly identified: (1) Easy to use. LS-TOOL needed to be designed as a simple, user-friendly application. (2) Expandability and standalone capability. It must be easy to increase additional functions and also not require other software to support. (3) Reusability and maintainability. In order to be easy to maintain, the application should be developed using common criteria.

The graphical user interface (GUI) of LS-TOOL is shown in Fig. 6.

3. Results and discussion

3.1. Comparison of the LS factor value- using manual, LS-TOOL, FCL and UCA methods

The calculated DWESL are shown in Fig. 7. It can be seen that DWESL values are very low at hilltop, ridge, and local highland points, for these places are the start of the slope length. The DWESL increased along the flow path, and increased rapidly when convergence flow occurred, with its accumulated high value being just before its arrival at the channel position along the flow path where it became zero.

The calculated LS values are shown in Fig. 8. Because the slope gradient is the major factor influencing the LS factor, the areas with high slope gradients have a greater LS-factor. LS values are also higher along the flow path, and increased faster at zones of flow concentration.

The contour map and the calculated channel networks based on the LS-TOOL method are shown in Fig. 9 (For greater clarity, we clipped a part of the research area to illustrate the result). It can be seen that the channel networks correspond very well to the topography. When compared with the channel sample zones (green points in Fig. 5), we found that this method has its limitations. It cannot estimate the width of channels, rather it always estimates the channel networks as a line, with the width being equal to cell size. Also notable is that when DWESL keep increasing, slope length in manual method already stopped at the edge of the channel.

We compared the slope length values, L factor, S factor and LS factor calculated by LS-TOOL and the manual method respectively. The linear regression r^2 and regression line for this evaluation are shown in Fig. 10. There is a strong relationship between the manual method and LS-TOOL. The regression relation for the S factor is better than that for L factor, slope length and LS factor.

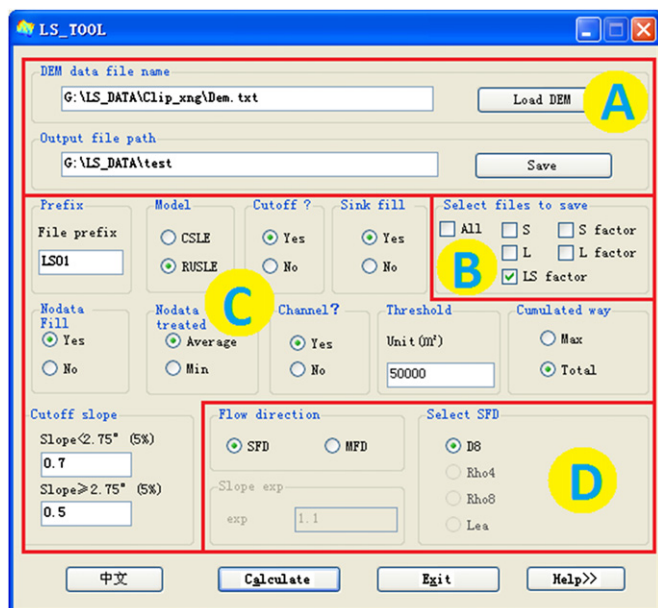


Fig. 6. The graphical user interface (GUI) of LS-Tool. The areas denoted by the blue letters A, B, C and D are referred to in the text where details are provided. Area A: Selection of the DEM file and output file path, Area B: Selection of which file(s) to save, S: slope steepness, L: slope length, S factor, L factor or ALL, Area C: Calculation options. Including file prefix, models, use of the cutoff or not, whether to fill nodata or sink cells, how to fill nodata cells (average value or minimum value of surrounding eight cells), consider channel or not, threshold of accumulated area, set cutoff slope value, Area D: Algorithm options, single-flow direction (sfd) or multiple-flow direction (mfd). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

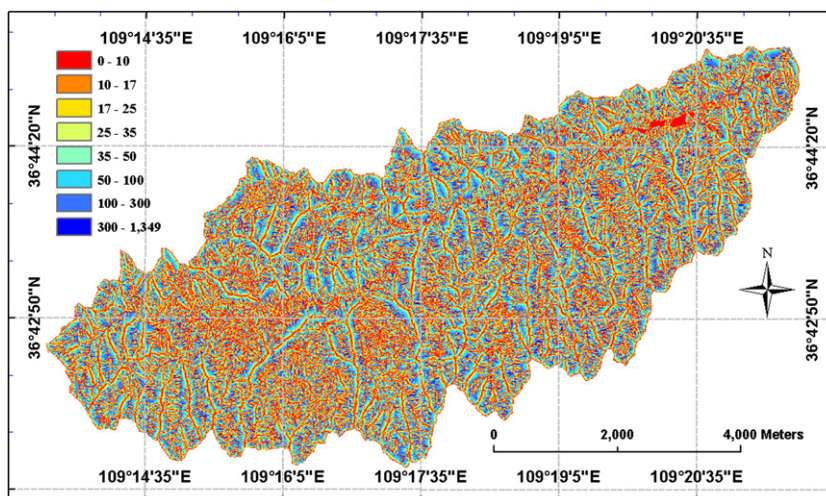


Fig. 7. Spatial pattern of the DWESL values calculated by LS-TOOL.

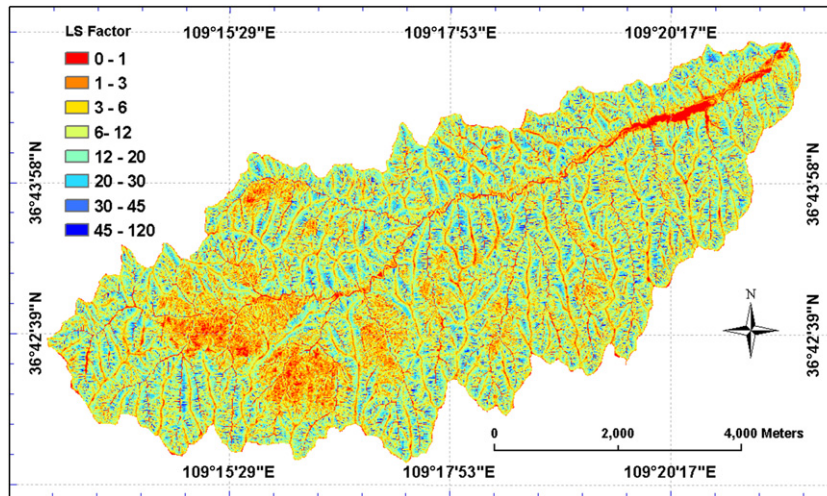


Fig. 8. Spatial pattern of the LS factor value calculated by LS-TOOL.

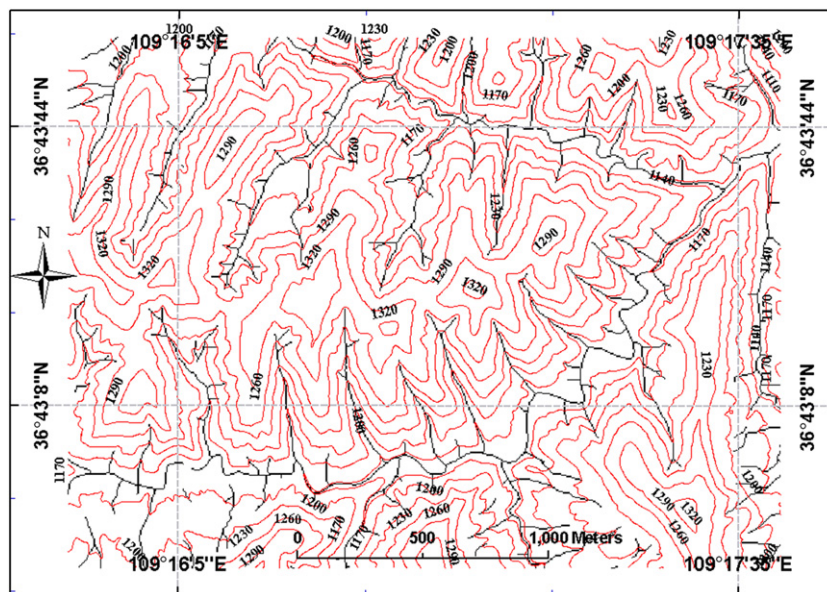


Fig. 9. The contour line with Channel networks calculated by LS-TOOL (clipped from Xiannangou Catchment).

A possible reason is that the error in calculating slope gradient was not accumulated, it only exits for one grid, while for slope length, error was accumulated from the start point along the flow path until the end of the grid. Another likely reason is that DWESL is very sensitive to elevation which decides the flow direction in LS-TOOL method, so a different flow direction means a different length. The manual method does not have that disadvantage.

We also compared the LS factor calculated by UCA and FCL method with the manual method respectively. The linear regression r^2 and regression line for these evaluation are shown in Fig. 11. Compared LS factor among LS-TOOL, UCA and FCL method, LS-TOOL can calculate more in line with other two methods.

3.2. Comparison of LS factor values—correlation for three methods

We compared the calculated LS-values based on the UCA approach to those generated with FCL and LS-TOOL, by using all non-zero cells (LS values in channels are zero in LS-TOOL). The linear regression r^2 and regression line LS values for this evaluation are shown in Fig. 11a (FCL and UCA), 11b (LS-TOOL and UCA) and 11c (LS-TOOL and FCL). An important objective of this

study was to gain an understanding of how the existing GIS-based LS-factor values estimation methods compare with LS-TOOL. It can be seen that the distribution of LS-factor values estimated using the LS-TOOL correlates more closely to those approximated by the UCA method. As the slope gradient increased, the differences of LS factor values also increased. There is clearly a stronger correlation between the UCA method and LS-TOOL at lower slope gradients.

For flat slopes, the three GIS methods provide almost the same value. When convergence flow occurred, both the UCA method and LS-TOOL method are able to take that into consideration and therefore the LS-factor values have the same growth trends. However with the FCL method the factor value also increased but more slowly than the other two methods. This is because its algorithm does not account for the convergent flow.

The UCA method cannot reflect the channel networks because the cutoff factor is not considered in this method, resulting in LS factor values being too high at channels. The FCL method explicitly addresses the deposition issues by evaluating changes in slope, but without considering channel networks or accommodating convergence flow. When in a convergence topography,

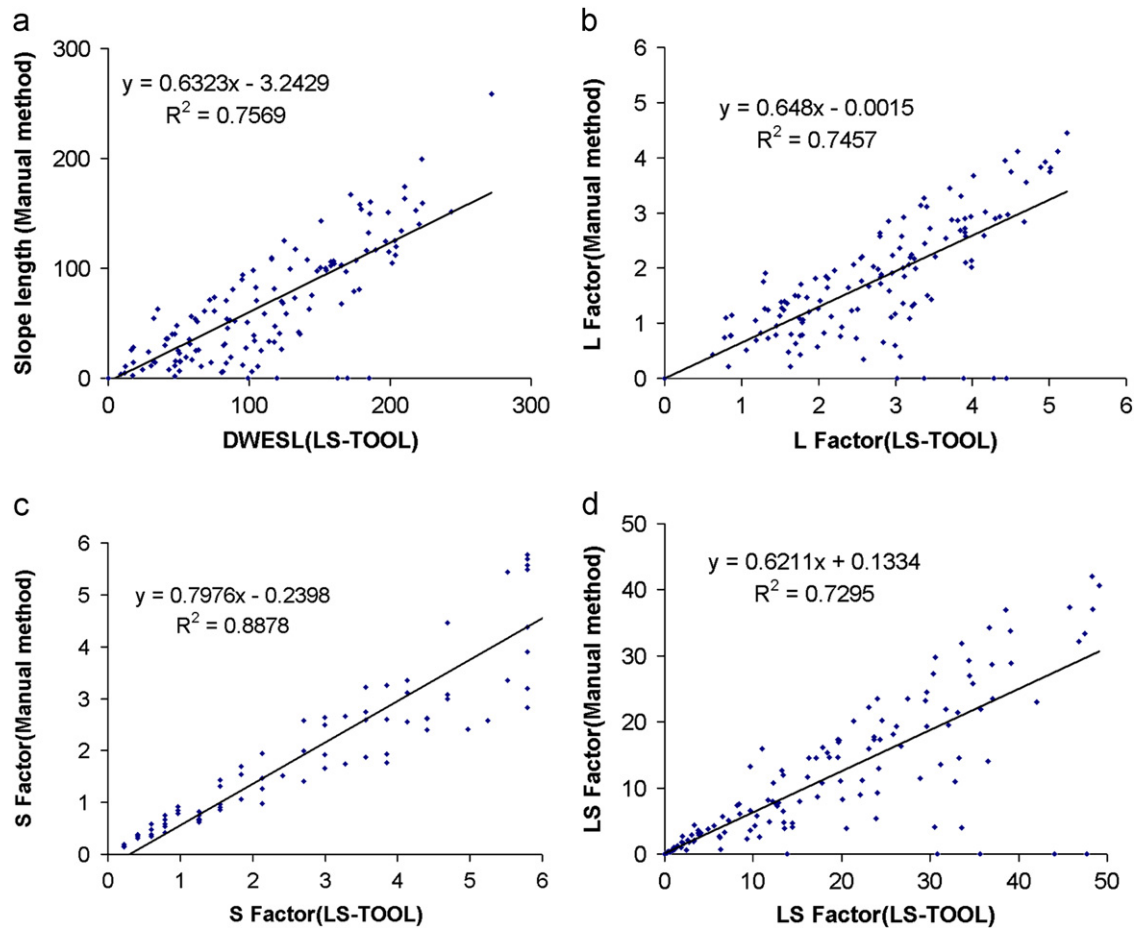


Fig. 10. Comparison of DWESL, L factor, S factor and LS factors between manual and LS-TOOL methods. (a) Slope length. (b) L factor. (c) S factor. (d) LS factor.

convergence flow will occur, however the FCL method just adds the longest slope length to the current cell, and does not consider the other cells which also flow into it. These are the main differences between the three methods.

3.3. Relationship between DWESL, accumulated area threshold and DEM resolution

We compared the maximum slope length and average slope length, under different DEM resolutions and different accumulated area thresholds. As shown in Fig. 12, for a given resolution, maximum and average slope length increased with the increase of the accumulated area threshold. The change in slope length is more significant when accumulated area threshold is smaller, and levels out at the threshold increases. Since with high-resolution DEM, the cutoff points are obvious, the maximum and average results were lower than with the low resolution data. Based on the location of the first cutoff point, the maximum and average slope lengths reach a certain value, no longer increasing even if the accumulated area threshold significantly increases. As accumulated area threshold increased channel network density becomes sparse and maximum slope length again increases. Fig. 13.

The comparison of our GIS-based LS factors calculation method, LS-TOOL, with previous studies produced encouraging results. Rodriguez and Suarez (2010) suggest use of the contributing area concept instead of slope length due to the difficulty of calculating slope length. Our results clearly show good correlation between the LS-TOOL generated values and the UCL generated values.

In addition, LS-TOOL identifies breaks in slope length, by involving the evaluation of change in slope, channel networks and convergence flow. LS-TOOL needs more validation in the future for only a few watersheds were used to estimate soil erosion.

We found that most of the results (DWESL, L factor, slope gradient, S factor, LS factor) calculated by LS-TOOL were greater than those generated by the manual method. From a theoretical viewpoint, LS-TOOL can calculate complex areas, especially the convergence area, which the manual method does not take into account. These need empirical exercise to prove when RUSLE is applied to watershed or larger area in the future work.

The accumulated area threshold decides the channel network density (Tarboton, 1997, 1991). The current study suggests that the accumulated area threshold be estimated using the maximum slope length divided by cell size to replace the actual accumulated area threshold. Several other authors also suggested new methods to estimate channel networks or streams more accurately (Ames et al., 2009; Merwade et al., 2008; Muttiah et al., 1997). We plan to investigate these issues in future work.

Another area for future development of LS-TOOL involves use of a multiple-flow direction (mfd) algorithm in place of a single-flow direction algorithm. Desmet and Govers (1996) think that single-flow direction (sfd) algorithms, which transfer all matter from the source cell to a single cell downslope, allow only parallel and convergent flow, while mfd algorithms can accommodate divergent and convergence flow. Others have shown that the mfd method gives a better representation of real terrain than sfd algorithms (Butt and Maragos, 1998; Wilson et al., 2007; Wolock and McCabe, 1995). And Winchell et al. (2008) used the slope

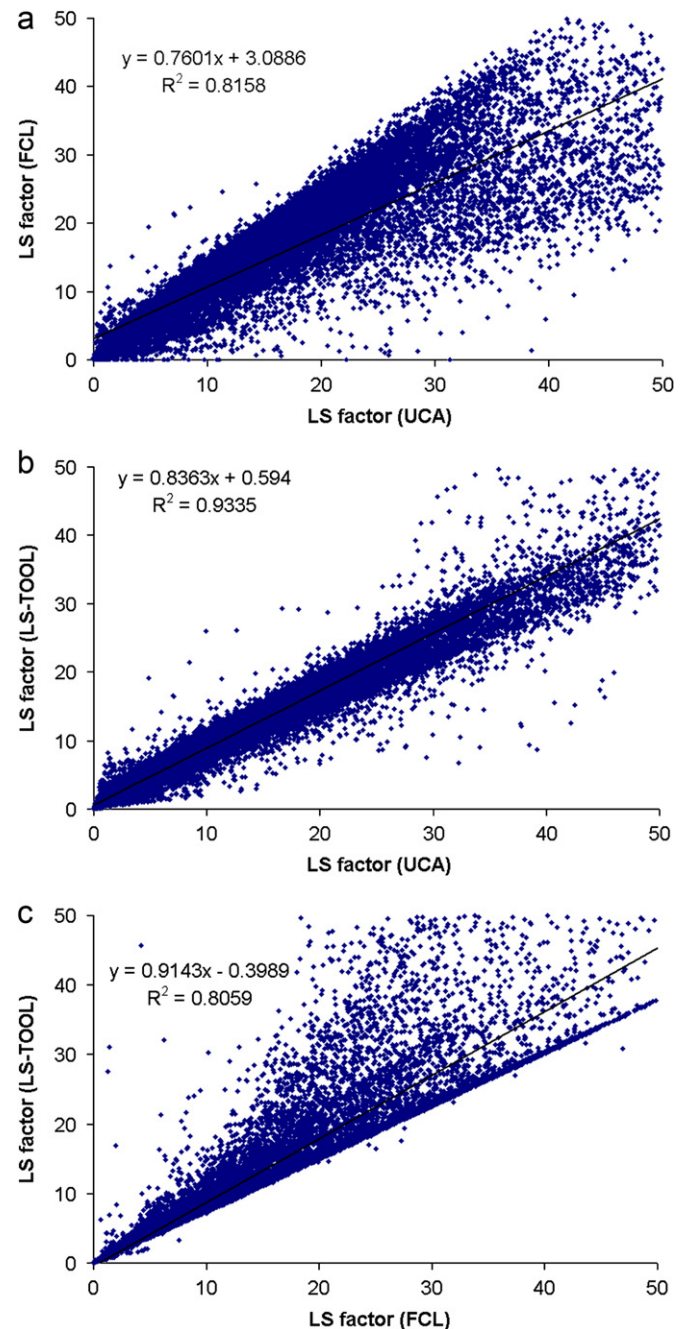
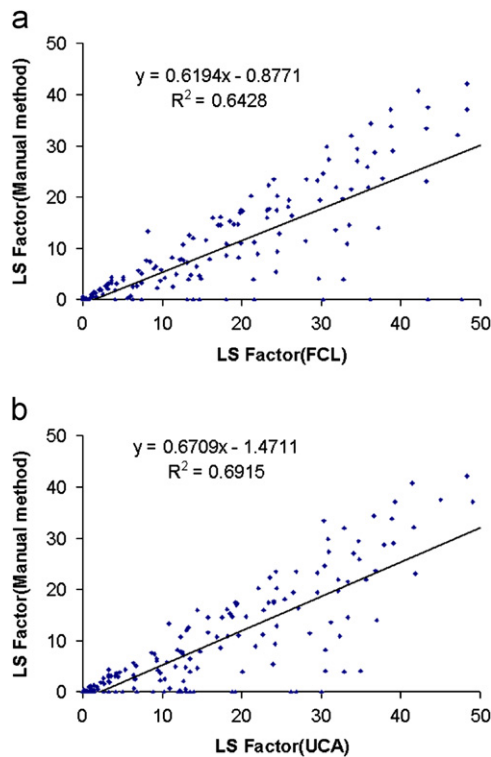


Fig. 11. Linear regression relationship of LS factors between UCA, FCL and LS-TOOL. (a) FCL and UCA methods. (b) LS-TOOL and UCA methods. (c) LS-TOOL and FCL methods.

segment calculation method (Desmet and Govers, 1996; Foster and Wischmeier, 1974), a mfd algorithm (Tarboton, 1997) which considers irregular slopes, and got improved results. However, using the mfd method to calculate slope length with cutoff conditions considered is a very complex procedure, even though it can accommodate convergence and divergence flow. To facilitate the use of mfd, the LS-TOOL algorithm should be improved by incorporating mfd algorithms and Winchell's method.

In this paper, slope length along a given flow path can be measured pixel by pixel, considering whether the neighboring pixels are diagonal or orthogonal neighbors, which roughly corresponds to real slope length. Butt and Maragos (1998) proposed the values of distance which are 0.96194 in the orthogonal direction and 1.36039 in the diagonal direction. Paz et al. (2008) tested the values in estimation of river length and improved the quality of calculated length of rivers. Errors in slope lengths calculated by the D8 method occurs for a variety of reasons, including horizontal DEM resolution and vertical DEM accuracy. So the need for high-resolution DEM data in our method, and the difficulty in setting some of the parameters in LS-TOOL, may be the greatest limitations of this method.

4. Conclusions

An automated three-dimensional GIS-based approach to generating high resolution, spatially distributed LS-factor datasets for large watersheds or regional area has been presented, LS-TOOL. Evaluation of the results shows that there is a positive relationship between the field data and LS-TOOL. This approach generates more similar results to manual method than previously existing algorithms. The FCL method has a lower LS-value for concave areas, because the effect of flow convergence cannot be considered. Although it is well known that the slope length should stop

Fig. 12. Fig. 11. Linear regression relationship of LS factors between UCA and FCL, UCA and LS-TOOL, FCL and LS-TOOL.

at channel networks, the FCL method and UCA method do not take this into consideration LS-TOOL considers soil deposition zones, channel networks and flow convergence, overcomes the disadvantage of the UCA and FCL method. The LS-TOOL algorithm was integrated as a tool which can automatically calculate slope length, slope steepness, L factor, S factor, and LS factors, providing the results as ASCII files which can be easily used in some GIS software. The applicability of the proposed LS-TOOL algorithm may be significantly improved in the future by including procedures to extract the concave and convex slope and apply multiple-flow direction algorithms based on GIS. None the less this is an important step toward conducting large area erosion evaluation, it overcomes the limitations of the UCA method, and improves the cutoff conditions in FCL.

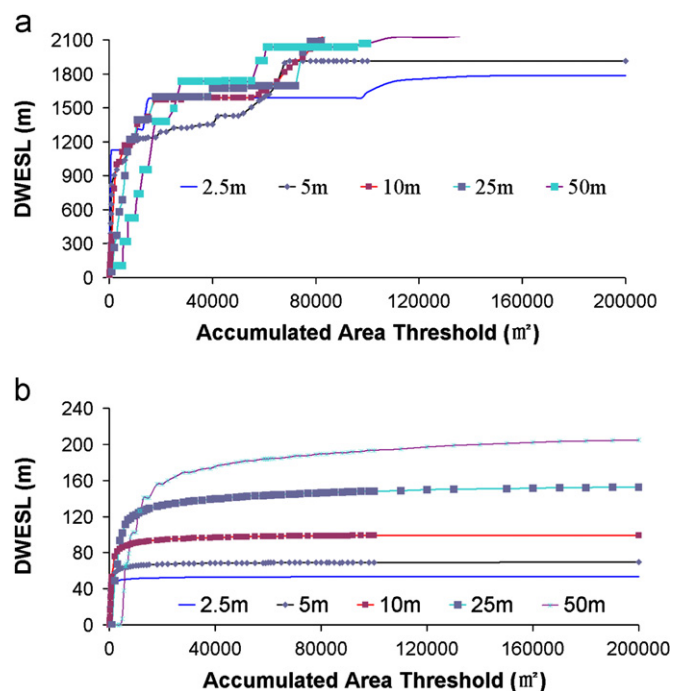


Fig. 13. The relationship of slope length, resolution (cell size) and accumulated area threshold computed by LS-TOOL. (a) Maximum slope length of different resolution with accumulated area threshold curves. (b) Average slope length of different resolution with accumulated area threshold curves.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.cageo.2012.09.027>.

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