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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.

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:

$$A = RKLSCP \tag{1}$$

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:

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

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:

$$LS=L\cdot S \tag{3}$$

$$L=(\lambda/22.13)^m \tag{4}$$

$$m=\beta/(1+\beta) \tag{5}$$

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

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

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