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Methodology for estimating the topographic factor LS of RUSLE3D and USPED using GIS

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ABSTRACT

In the RUSLE3D (Revised Universal Soil Loss Equation–3D) and USPED (Unit Stream Power-based Erosion Deposition) models, the effects of topography on soil loss are represented by the combined factor *LS*, where *L* is the slope length factor and *S* the slope gradient factor. The problems with measuring slope gradient and length over large areas are i) they are not always estimated correctly, and ii) different ways are used for their calculation. GIS (Geographical Information Systems) software has several algorithms for estimating topographic parameters included in the equations of *LS*. The objective of this research was developing a methodology for *LS* calculation using GIS, in order to define the most accurate algorithm for each parameter. For the estimation of *S* and upslope contribution area (~*L*), the Zevenbergen and Thorne algorithm and the Deterministic Infinity algorithm, respectively, were selected.

1. Introduction

1.1. Background

Water erosion is a severe and extended issue affecting all European countries, although with different intensities. The European Mediterranean countries are particularly prone to erosion, because they are subject to prolonged dry periods followed by heavy erosive rains falling on steep slopes characterized by fragile soils (Terranova et al., 2009). The process of soil erosion leads to sediment transport and consequent deposition. Sediment is detached from the soil surface by both raindrop impact and the shearing force of flowing water. The detached sediment is transported downslope primarily by flowing water, although there is also a small amount of downslope transport by raindrop splash (Walling, 1988). Once runoff starts over the surface areas and in the streams, the quantity and size of material transported increases with the velocity of the runoff. At some point, the slope may decrease, resulting in a decreased velocity and hence a decreased transport capacity (Haan et al., 1994). The sediment is then deposited, starting with the large primary particles and aggregates. Smaller particles are transported further downslope, resulting in the enrichment of fines. The amount of sediment load passing the outlet of a catchment forms its sediment yield (Jain and Kothyari, 2000).

Geomorphological research has played an important role in the development and implementation of soil erosion assessment tools. To be useful for decision makers, soil erosion models must have simple data requirements, must consider spatial and temporal variability in hydrological and soil erosion processes, and must be applicable to a variety of regions with minimum calibration (Renschler and Harbor, 2002).

The Universal Soil Loss Equation, USLE, is the most widely used and accepted empirical soil erosion model for water erosion assessment. It was developed for sheet and rill erosion based on a large set of experimental data from agricultural plots (Wischmeier and Smith, 1978), for detachment capacity limited erosion with negligible topographic curvature and deposition, and for representing soil loss averaged in space and time (Mitasova et al., 1996a). The USLE is:

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

where T = average annual soil loss per unit area predicted by the model (t acre^{-1} year^{-1}); R = rainfall–runoff erosivity factor (the rainfall erosion index); K = soil erodibility factor, the soil loss rate per erosion index unit for a specified soil on a standard plot, which is defined as a 72.6-ft. (22.13 m) length of uniform 9% slope in continuous clean-tilled fallow; L = slope length factor, the ratio of soil loss from the field slope length to soil loss from a 72.6-ft length under identical conditions; S = slope steepness factor, the ratio of soil loss from the field slope gradient to soil loss from a 9% slope under otherwise identical conditions; C = cover-management factor, the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow; and P = support practice factor, the ratio of soil loss with a support practice such as

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contouring, strip-cropping, or terracing to soil loss with straight-row farming up and down the slope.

L and S in Eq. (1) are computed as follows:

$$L = \left(\frac{\lambda}{22.13}\right)^m \tag{2}$$

$$m = \frac{\beta}{(1+\beta)} \tag{3}$$

$$\beta = \left\{\frac{\left(\frac{\sin\theta}{0.0896}\right)}{\left[3(\sin\theta)^{0,8} + 0.56\right]}\right\} \times r \tag{4}$$

$$S = 10.8\sin\theta + 0.03;\quad \text{for terrain slope} < 9\% \tag{5}$$

$$S = 16.8\sin\theta - 0.05;\quad \text{for terrain slope} > 9\% \tag{6}$$

where λ = slope length (m); m = variable exponent according to β; β = the ratio of erosion in rills to that in inter-rills; θ = slope steepness angle (degrees); and r = coefficient equal to 0.5 for forest land, 1.0 for agricultural land, and 2.0 for construction sites.

The USLE has been enhanced during the past 30 years by a number of researchers. For example, MUSLE (Williams, 1975), RUSLE (Renard et al., 1991, 1997), ANSWERS (Beasley et al., 1989), and RUSLE3D (Mitasova et al., 1996a,b; Mitasova and Mitas, 1999) are based on the USLE and represent its improvement. The use of USLE and its revisions is limited to the estimation of gross erosion, and lack the capability to compute deposition along hillslopes and depressions or in channels. Moreover, the fact that erosion can occur only along a flow line without the influence of the water flow itself restricts direct application of the USLE to complex terrain. This one-dimensional structure means that the equation cannot handle converging and diverging terrain, i e., real 3-D landscapes (Moore and Wilson, 1992).

Specific effects of topography and hydrology on soil loss, in the USLE and its revisions, are estimated by the non-dimensional *LS* factor, as the product of *L* and *S*. According to Wischmeier and Smith (1978), λ, included in the *L* factor equation (Eq. (2)), is defined as the distance from the point of origin of overland flow to either 1) the point where the slope decreases enough to promote deposition or 2) the point where runoff enters a well-defined channel of a natural or artificial network (Wischmeier and Smith, 1965). The concept of Wischmeier and Smith (1978) is common to the RUSLE and USLE. The main difference between the two equations is the estimation of λ in Eq. (2). The RUSLE equations have been improved for their application in watersheds, in contrast to the USLE designed for agricultural plots (Garcia Rodríguez and Gimenez Suarez, 2010a).

Estimation of the *LS* factor poses more problems than the other factors in the USLE (Renard et al., 1991), particularly in applications to real landscapes. Some of these problems stem from implicit assumptions concerning runoff generation and sediment transport, notably uniform runoff generated over a catchment, runoff via the infiltration excess mechanism (i.e., Hortonian overland flow) without saturation overland flow, and no representation of sediment deposition even at the lower ends of concave slopes (Moore and Wilson, 1992).

While the USLE is designed for straight slope sections, Foster and Wischmeier (1974) developed a procedure to calculate the average soil loss on complex slope profiles by dividing an irregular slope into some segments to take slope profile shape into account. This is important as slope shape influences erosion (D'Souza and Morgan, 1976; Desmet and Govers, 1996a). Using manual methods the USLE was already applied on a watershed scale (Williams and Berndt, 1977; Wilson, 1986; Griffin et al., 1988). Williams and Berndt (1977) represented a watershed by a limited number of points from which the average watershed slope was calculated. The watershed slope length was determined for the watershed as a whole, based on the catchment area and the total length of the drainage lines. Wilson (1986) represented a watershed by a limited number of profiles on which the methodology for irregular slopes was applied. Griffin et al. (1988) compared various manual methods and concluded that there was no obvious 'best' method. However, they observed that the uniform slope method consistently underestimated *LS* values when compared to the irregular slope method or the point method. The point method, on the other hand, was more sensitive to the density of the sample grid than the irregular slope method (Desmet and Govers, 1996b). Basically, all the methods described above calculate the *LS* value for a sample of points or profiles in the area under study. The results are then considered to be representative for the whole area. A fundamental problem may arise: although measuring the local slope from a contour map is relatively straightforward, measuring slope length at a given point is more difficult.

In a manual analysis, the distance from the point under consideration to the divide is measured and considered as the slope length for that point. A difficulty with this approach is that it is not always easy to define clearly the location of the divide. The accuracy of where breaks for *L* and *S* values in a given farm field are located relies on the experience of the field operator on how to partition the field into homogeneous *LS* units (Lewis et al., 2005). However, the major problem is that in a two-dimensional situation, slope length should be replaced by the unit contributing area, *A*, i.e. the upslope drainage area per unit of contour length. According to Desmet and Govers (1996b), in a real two-dimensional overland flow and the resulting soil loss do not really depend on the distance to the divide or upslope border of the field, but on the area contributing runoff per unit contour length (Ahnert, 1976; Bork and Hensel, 1988; Moore and Nieber, 1989). The latter may differ considerably from the manually measured slope length, as it is strongly affected by flow convergence and/or divergence. Thus, although manual methods account for the effect of profile shape on erosion, they do not account for planform shape, i.e. the degree of convergence (Desmet and Govers, 1996a).

The solution in these situations would be the use of GIS. With advances in GIS, erosion models tended to adopt a more explicit representation of the area on which erosion occurs using spatially distributed parameters, providing outputs showing the spatial variability of the process (Feng et al., 2010). GIS-based approaches provide one of the few means available for systematically examining the role of spatial variability in soil properties, rock types and numerous other geologic and climatic properties in the evolution of a landscape. The spatially explicit nature of GIS analyses and their emphasis on incorporating real-world data make GIS a powerful tool for building insight into the evolution of complex landscapes and landscape processes (Finlayson and Montgomery, 2003; Wilson, 2011).

To minimize subjectivity in calculating the *LS* factor, calculations based on digital elevation models (DEMs) and GIS procedures have been developed (Desmet and Govers, 1996b; Mitasova et al., 1996a,b; Mitasova and Mitas, 1999; Van Remortel et al., 2004; Garcia Rodríguez and Gimenez Suarez, 2010a). Desmet and Govers (1996b) as well as Mitasova et al. (1996b) focused on a grid-cell-based evaluation of *LS* in a multi-flow context (Lewis et al., 2005). A simplified method of estimating *LS* in the RUSLE is presented by Desmet and Govers (1996b) that can be easily extended to estimating soil loss in complex 3-D terrain. It may also help distinguish areas experiencing net erosion and those experiencing net deposition.

1.2. Spatial modeling with RUSLE3D

In the 1980s, the implementation of the *LS* factor was unfeasible in a watershed scale, because the variation of λ in Eq. (3) was difficult to represent. The RUSLE uses the same empirical principles as the USLE; however, it includes numerous improvements such as monthly factors, incorporation of the influence of profile convexity/concavity using segmentation of irregular slopes, and improved empirical