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A new RUSLE slope length factor and its application to soil erosion assessment in a Loess Plateau watershed

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ABSTRACT

The Universal Soil Loss Equation and Revised Universal Soil Loss Equation have been widely used in watershed scale soil erosion assessments. However, the influences of the coupled effects of upslope topography and vegetation cover on flow accumulation and the downslope soil erosion are not fully considered in the current methods. In this study, a new calculating method for slope length factor (L), named the modified grid formula based on upslope contributing areas (L_M), was established by adding a new parameter, the effective contributing area ratio, to the existing L calculating method, the grid formula based on upslope contributing areas (L_G). A small watershed on the Loess Plateau was selected to evaluate the effects of the L_M on watershed soil erosion assessment. The soil erosion was estimated via the Revised Universal Soil Loss Equation using with two L calculating methods: L_M and L_G. Then, the soil loss of various land use types estimated from the two L methods were compared with the corresponding observed values from the nearby runoff plots, and the sediment yields based on the two L methods were estimated using the Sediment Delivery Distributed model and compared with measured values at the hydrologic station in the outlet of the watershed. The results indicated that, compared with L_G, 1) the L values obtained via the L_M were lower, contributing to a substantial decrease in soil erosion estimated at the watershed scale; 2) the average annual soil erosion estimated via the L_M for slope farmland, forestland and grassland in the watershed were closer to the observed values from local runoff plots; 3) the average annual sediment yield of the watershed estimated via the L_M was only ± 5% relative to the measured values, implying that the values estimated via L_M was more accurate than the current methods. Overall, the L_M has accounted for the effect of vegetation hydrologic process and erosion process, which can improve the estimation accuracy of soil erosion assessments at the watershed scales and limit the risk of overestimating.

1. Introduction

The land degradation caused by soil erosion is one important threat to soil resources worldwide. Every year, 25–40 billion tons surface soils are removed globally due to soil erosion, causing approximately 400 billion dollars' worth of direct economic losses, such as declines in crop production (FAOUN, 2015; Montanarella, 2015). Water erosion causes the loss of water, soil and nutrient resources (Chen et al., 2007; Lal and Pimentel, 2008; Haregeweyn et al., 2008), reduces the soil quality (Stocking, 2003), causes sediment deposition (Haregeweyn et al., 2006) and water pollution (Gafur et al., 2003), threatens human society with floods and debris flows (Pimentel, 2006). Thus, soil and water conservation are of great concerns for many countries. Soil erosion prediction is considered as a prerequisite for the scientific application of soil conservation measures, an important basis for accurately assessing controlling effects, and the frontier of soil erosion studies (Nearing et al., 1994). Specifically, soil erosion predictions at the watershed and regional scales are usually regarded as the scientific basis for land management decision-making.

Model simulations are the basic methods for soil erosion prediction, usually there are two types of prediction models: physically-based models and empirical models (Merritt et al., 2003). Physically-based

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models theoretically have a greater transferability than empirical models, are more likely to achieve sound predictions (Wainwright and Mulligan, 2013). However, in some regions, the complex parameters in physically-based models cannot be easily and precisely quantified, making the expected ideal results difficult to obtain (Kinnell, 2000; Perrin et al., 2001), thus the empirical models are still widely used for soil erosion assessment both on the watershed and regional scale. Of all the empirical models, the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) are probably the most widely used empirical models for water erosion assessment worldwide. However, in the USLE and RUSLE, the slope length factor (L) remains controversial, and this ambiguity has limited the application of the USLE and RUSLE at the watershed scale (Van Remortel et al., 2001).

For a uniform slope with finite length, the flow accumulation and erosion increase linearly as the slope length increases (Zingg, 1940 ; Wischmeier and Smith, 1978 ; McCool et al., 1989). Thus, the relationship between the length of the flow accumulation and soil erosion can be directly established based on the slope length. In a watershed with complex terrain, water and sediment from upslope areas affect the erosion processes in downslope segments (Zheng et al., 1998), So slope segments are actually considered as open hydrological units, the flow accumulation and the erosive power of certain slope segment are not controlled primarily by rainfall and the underlying surface conditions but also by the upslope flow accumulation. Changes in upslope flow accumulation due to the coupled effects of upslope topography and vegetation cover can be reflected in the downslope erosion. Thus, an L calculating method based on the contributing area is more suitable for soil erosion assessments at the watershed scale (Moore and Nieber, 1989 ; Desmet and Govers, 1996). The upslope contributing area is greatly influenced by the land use and vegetation cover along the flow path. Various land uses and vegetation patterns, such as terraces, drainage ditches and different vegetation types (Black, 1968; Lin and Lin, 2001; Rose et al., 2003; Winchell et al., 2008; Yang et al., 2009; Cao et al., 2015), can reduce the downslope soil erosion by intercepting slope runoff and reducing the erosive power. Therefore, these factors should be considered into the parameters of the soil erosion models to improve the assessing accuracy of models at the watershed scale, which should be incorporated into the L since only L can reflect the connections of flow or runoff between different slope segments by either the flow length or the upslope flow accumulation area, while all the other factors in USLE and RUSLE are independent for each slope segment. However, this effect is not fully considered currently for the widely used four L calculating methods in soil erosion assessments at both the watershed and regional scales in many countries (Table 1), which are: the slope formula based on slope length (Wischmeier and Smith, 1978; McCool et al., 1989), the segmented formula based on upslope flow length (Foster and Wischmeier, 1974), the grid formula based on upslope unit contributing areas (Mitasova et al., 1996), and the grid formula based on upslope contributing areas (GFBUCA, L_G) (Desmet and Govers, 1996).

At both the watershed and regional scales, the L is usually calculated from regular DEM (digital elevation model) grid cells, where each cell is considered as a slope segment. The slope formula based on slope length method was primarily designed for uniform slopes to predict erosion on straight slope sections, which limited its application in the natural conditions. Compared with the slope formula based on slope length method, the segmented formula based on upslope flow length method, to some degree, considers the effects of upslope flow accumulation on soil erosion and can identify differences in soil erosion between different segments. However, this method still can’t effectively characterize the relationship between complex irregular terrain and soil erosion. For example, the soil erosion of a grid cell where multiple flow paths converge should be estimated based on all the upslope cells along the flow paths, but the segmented formula based on upslope flow length method only considers the effect of the longest flow path on soil erosion and generally ignores the effects of other flow paths. More importantly, in both methods, the L is calculated based on the one-dimensional flow length. However, in the real situation, overland flow and the resulting soil erosion does not depend on the distance to the divide or the upslope border of the field but instead depends on the area per unit of contour length contributing runoff to that point (Desmet and Govers, 1996). In the grid formula based on upslope unit contributing areas and L_G method, the one-dimensional flow length has been replaced by the two-dimensional contributing area, which has broken through the traditional relationships between the slope length and L, and can describe the mechanics by which an increase in contributing area leads to an increase in surface runoff and soil erosion. Therefore, these two methods are more suitable for soil erosion assessments at both the watershed and regional scales.

Both the grid formula based on upslope unit contributing areas method and L_G method for calculating L values are based on the theoretical upslope contributing area quantified by DEM. However, the upslope contributing area was estimated based on the unit contour width, making it difficult to reflect the actual flow and transport process. For L_G method, which was the most widely used L calculating method in watershed and regional scale soil erosion assessment, the flow paths are determined according to the flow direction based on DEM. Then, the contributing area is calculated by multiplying the number of grid cells along the flow path by the area of each grid cell, indicating that the contributing area in the L_G represents the theoretical maximum contributing area and does not reflect the influence of vegetation cover on flow accumulation, thus the influences of land use and/or vegetation cover on flow accumulation and downslope soil erosion are not taken into consideration. Since vegetation can influence water inputs and runoff, many researches focused on the spatial variations in vegetation and how this is related to hydrologic processes (Cammeraat and Imeson, 1999; Ludwig et al., 2005). For example, Van Oost et al. (2000) indicated that the landscape structure, or the spatial organization of different land units, has an impact on soil erosion. In this situation, the L_G will inevitability overestimate the actual L value because it assumes that all upslope grid cells contribute the same to downslope surface runoff and soil erosion.

Generally speaking, the upslope flow accumulation is not only influenced by the contributing area determined by the upslope topography but also by land use or vegetation cover changes along the flow paths because the surface runoff can be retained and reduced by the rainfall redistribution induced by vegetation canopies. Rational and reliable soil erosion assessment can be only acquired if the coupled effects of upslope topography and vegetation cover on downslope soil erosion are fully considered in the models. In USLE and RUSLE, this coupled effect of upslope topography and vegetation cover can’t be reflected by the cover and management factor (C) since the C can only represent the effect of vegetation cover on soil erosion in the independent slope segments (Qin et al., 2010), thus this coupled effects can be only reflected by L since only L can reflect the connection of flow or runoff between different slope segments.

The objectives of this study are: 1) to establish a new L calculating method named as the modified formula based on upslope contributing areas (L_M) by improving the widely used L_G in order to reflect the coupled effects of upslope topography and vegetation cover on downslope soil erosion; 2) to evaluate the applicability of the new L calculating method by comparing the estimated soil erosion and sediment yield of the watershed with the corresponding measured data in a typical watershed. This work is taken for the following steps: first, soil erosion of the watershed were estimated using the RUSLE and two L calculating methods, the L_M and L_G; second, the integrative application of the Sediment Delivery Distributed (SEDD) model (Ferro and Porto, 2000) and RUSLE were used to estimate the sediment yield of the watershed; third, the estimated soil erosion for different land use types were compared with the corresponding observed values with field runoff plots, and the estimated sediment yield of the watershed were