Soil erosion prediction and sediment yield estimation: the Taiwan experience

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Abstract

Estimating watershed erosion using geographic information systems coupled with the universal soil loss equation (USLE) or agricultural non-point source pollution model (AGNPS) has become a recent trend. However, errors in over-estimation often occur due to the misapplication of parameters in the equation and/or model. Because of poor slope length calculation definitions for entire watersheds, the slope length factor is the parameter most commonly misused in watershed soil loss estimation. This paper develops a WinGrid system that can be used to calculate the slope length factor from each cell for reasonable watershed soil loss and sediment yield estimation.

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1. Introduction

Universal soil loss equation (USLE) is the standard soil loss prediction model in the Soil and Water Technical Regulations published by the Council of Agriculture, Taiwan government. Technicians in Taiwan need a suitable computer program that can easily determine slope length and cover-management factors. The USLE was derived with data from small agricultural plots. Although some authors have reported on extensive use of the USLE for large basins (Nisar Ahamed et al., 2000), the task enlarging the USLE applications from small plots to larger areas, such as watersheds and determining the correct values for the six major equation factors is still a challenge.

There are a number of implicit assumptions involved in runoff generation and sediment transport embedded in the USLE. Erosion from saturated overland flow is not explicitly considered and the sediment deposition is not represented. For these and other reasons, applying this model to landscapes is more difficult than applying it to simple hillslopes. The second assumption represents a major practical problem because the model does not distinguish the hillslope areas that experience net deposition from those that experience net erosion.

The data required for the USLE calculations might be available in a geographic information systems (GIS) format so that GIS-based procedures can be employed to determine the factor values for

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predicting erosion in a grid cell via the USLE (Kinnell, 2001). Most attempts to use GIS in conjunction with the USLE to model spatial changes in soil loss have often proceeded without addressing the problems related to the assumptions that are incurred in scaling up the USLE applications from plots to large areas. The GIS/USLE application by Ventura et al. (1988) and Hession and Shanholtz (1988), for example, failed to mention the need to distinguish areas experiencing net erosion and net deposition before applying this equation. Furthermore, the definitions for slope gradient and length used by Ventura et al. (1988) are unclear and probably different from those specified in the original USLE. Therefore, an automatic extraction for the slope length spatial distribution at watershed scale in conjunction with the USLE is necessary to avoid the above-mentioned problems.

2. Methods and materials

2.1. Predicting soil loss with the USLE for plots

Most erosion assessments performed in North America during the past two decades have used the USLE (Hession and Shanholtz, 1988; Ventura et al., 1988; Wilson, 1989). This model was derived empirically from approximately 10,000 plot-years of data (Wischmeier and Smith, 1978) and may be used to calculate erosion at any point in a watershed that experiences net erosion. The USLE is written as follows:

\[ A = R \times K \times L \times S \times C \times P \]  

where

- \( A \) is the average annual soil loss (t/ha per year),
- \( R \) the rainfall erosivity factor (MJ/ha mm h),
- \( K \) the soil erodibility factor (t/MJ h mm),
- \( L \) the slope length factor,
- \( S \) the slope steepness factor,
- \( C \) the cover-management factor and
- \( P \) is the supporting practice factor.

Climate erosivity is represented by \( R \) and can be estimated from the rainfall intensity and amounts data. The soil erodibility nomograph (Wischmeier et al., 1971) can be used to predict the \( K \) value. The topography and hydrology effects on soil loss are characterized by the \( L \) and \( S \) factors. For direct USLE applications, a combined \( LS \) factor was evaluated for each land cell as (Wischmeier and Smith, 1978)

\[ LS = \left( \frac{\lambda}{27.01} \right)^{m} (65.4 \sin^{2} \beta + 4.56 \sin \beta + 0.0654) \]  

where
- \( m \) takes the values 0.5, 0.4, 0.3, and 0.2 for \( \tan \beta > 0.05, 0.03 < \tan \beta \leq 0.05, 0.01 < \tan \beta \leq 0.03 \) and \( \tan \beta \leq 0.01 \), respectively (\( \lambda \) is the slope length in m, \( \beta \) the slope angle in degrees). Land use and management are represented by \( CP \) and can, with some difficulty, be inferred using remote sensing combined with ground-truthing.

2.2. Erosion estimation for watersheds

Estimation of the \( L \) factor for a watershed contains a particular problem in applying it to real complex landscapes as part of GIS. Slope lengths for a given land area should not be different when grid size is changed. Areas experiencing net soil loss should be specified during development methods for automated slope length delineation in a watershed.

2.3. Flow direction of a watershed

A watershed can be described with respect to the surface runoff as being the locus of points within an area where runoff produced inside the area perimeter will move into a single watershed outlet. Information about the flow direction is recorded as an attribute of each spatial unit within the watershed to represent the flow direction. In this study, a 3 × 3 moving window was used over a digital elevation model (DEM) to locate the flow direction for each cell. The steepest descent direction from the center cell of the window to one of its eight neighbors was chosen as the flow path. This neighbor is called the cell downstream of the center cell. This method is also called the D8 (deterministic-eight node) algorithm. D8 remains the most frequently used method for determining contributing areas, although it cannot model the flow dispersion (Gallant and Wilson, 1996). Fig. 1 provides an example of a DEM, and the flow directions are indicated with arrows.

A variety of methods have been developed to process DEMs automatically to delineate and measure the...
properties of drainage networks and drainage basins (Mark, 1983; Band, 1986; Jenson and Domingue, 1998; Tarboton et al., 1991; Martz and Garbrecht, 1992). An approach that has been widely used to compute the flow directions and delineate watersheds was presented by Jenson and Domingue in 1988. It used a depression-filling technique for the treatment of flat areas and depressions. However, two problems were encountered when this method was applied to realistic, complex landscapes. The first is that in some cases there might be more than one outflow point from a depression or flat area after the area is filled. The second is that looping depressions located on a flat surface cannot be solved. Martz and Garbrecht (1998, 1999) proposed a complicated breaching algorithm for the treatment of closed depressions in a DEM. Based on Jenson’s method, a modified method in this study was developed to effectively improve dead-end problems in depressions and flat areas. Fig. 2 shows the difference between both methods in flow direction extraction.
2.4. Channel networks in a watershed

Channel networks are traditionally obtained by tracing stream channels manually from maps or airborne photos. With increasing computer power and the availability of DEMs, attempts have been made to extract networks from DEMs via computer programs. The “catch-number” method was used to calculate the catchment number for each cell, i.e. the number of cells that contribute surface flow to any particular cell. Cells with catchment numbers greater than a given threshold are considered to be on the flow path. All cells with catchment numbers greater than the threshold delineate and define the network channels. The beginning point of a channel depends on how the channels are defined. If the beginning point of a channel is defined at the place where a defined amount of water has accumulated on the surface and starts to flow downhill, the upper extent of a channel will change with the variation in precipitation. The variable nature of the starting points can be modeled by adjusting the threshold according to the hydrological factors, such as rainfall intensity. The distribution and the extent of the networks in reality can be more closely represented with channels extracted with a proper threshold. Fig. 3 shows that the smaller the chosen threshold, the more detailed the channels obtained.

2.5. Delineation of slope length

As indicated by Kinnell (2001), the impact of variations in runoff from upslope caused by factors other than space is ignored if slope length is determined from nothing more than the drainage area as in the current practice when the USLE is applied to grid cells. To distinguish between overland and channel flow, thresholds are employed to determine the proper slope lengths. Fig. 4 depicts the overland flow path that is derived after extracting the channel flow using a specified threshold. The threshold for channel flow extracted in a specific watershed depends on the hydrological and geological factors of the watershed. Lower infiltration rate and/or higher rainfall intensity areas are more vulnerable to gully erosion. Hence, a lower threshold sufficient to initiate the beginning point of a channel can be expected. In other words, areas with higher infiltration rates will express longer slope lengths under the same rainfall intensity. Generally, overland flow paths seldom exceed 100 m due to the interception of natural depressions, flat areas, or ditch construction. A threshold of 100 m can be used as a default value to initiate the beginning point of a channel for delineating the slope length in a watershed in most areas. If observed data exists in practice, the threshold can be further adjusted for the model to fit the real world. The revised universal soil loss equation

Fig. 3. Channel networks of the Dafuko watershed inferred from DEM as the threshold changed.
Fig. 4. Spatial distribution of overland flow illustrating portions of watershed with net erosion.

(RUSLE) (Renard et al., 1996) also indicated that surface runoff will usually concentrate in less than 400 ft. Slope length is best determined using pacing or field measurements. In this study case, the on-site investigation indicated that 100 m was the better average value.

2.6. Predicting sediment yield

The sediment delivery ratio concept, DR, is most commonly defined as the ratio of sediment yield to total soil loss. Equation may be expressed in non-dimensional terms as

\[ DR = \frac{S_y}{T} \]  (3)

where \( S_y \) is the sediment yield (mass/area/time) at the watershed outlet or point of interest, and \( T \) the total soil loss (mass/area/time) defined as the total eroded sediment on the areas eroding above the watershed outlet. Conceptually, Eq. (3) is a convenient way to estimate the sediment yield at a downstream point of interest such as a reservoir site or a detention basin. Soil loss estimation is usually conceptualized and computed in the context of the universal soil loss equation. This also introduces a limitation because USLE does not consider gully erosion, riverbed or bank erosion, or sediment deposition. With these exclusions, USLE is most properly applied on steeper (where the slope shape is not concave and sufficiently steep to ensure net soil detachment) field portions, commonly with slope lengths on the order of \( 10^3 \) to \( 10^4 \) m in length. The amount of sediment delivered from upland to the stream or watershed outlet can be determined by multiplying the soil erosion rates against a delivery ratio. The relationship is given by

\[ L_s = \sum (A_s)_i \times DR_i \]  (4)

where \( L_s \) is the total amount of upland sediment delivered to the perennial stream (t per year), \( (A_s)_i \) the annual soil loss (t per year) for a given cell, and \( DR_i \) the upland sediment delivery ratio of the cell \( i \). The upland sediment delivery ratio (DR) depends upon the land cover, slope and distance to the stream channel. As pointed out by Wolman (1977), DR provides a cover for the actual physical storage processes as well as for errors in estimates of the amount eroded and for temporal discontinuities in the sediment delivery process. Data from Taiwan’s reservoirs and watersheds indicates that the major sediments are fine particles such as silt and clay. Taiwan’s torrents and gullies are over constructed by conservation structures or retaining works, which is why slope erosion is much more important than the riverbed contribution.
Because coarse particles cannot be estimated by the USLE and a simplified calculation is needed for Taiwan’s watersheds, this paper considers sediments from sheet erosion transported by overland flow until it reaches the channels. The channel flows then carry the sediments to reservoirs or watershed outlets. Generally, DR decreases as the overland flow length increases because it is more difficult for sediments to reach the channels over longer traveling distances. We verify this assumption in the example applications and with examples from Taiwan’s major reservoirs and watershed (Fig. 5). The DR for a given cell $i$ can be calculated from the receiving drainage length ($LR_i$) ratio to total drainage length ($L_i$):

$$DR_i = \frac{LR_i}{L_i}$$

### 2.7. System architecture

Successful watershed modeling for non-point pollution control depends upon how large volumes of input data are managed and manipulated. The function used to summarize and display the model results in a variety of forms and presentation styles that require highly flexible data management. We developed the WinGrid spatial analysis software to generate and organize the input parameters required by the USLE model. In the WinGrid system, the basic data storage unit can be represented as a single layer in a map that contains information about the location features. The WinGrid system consists of several separate program components (e.g. GRIDDING, SPATIAL, WATERSHED, MODULES, UTILITY, DISPLAY, and IMPORT/EXPORT). Each component performs a separate task.

The USLE modeling database generated for this study included both spatial and non-spatial information. The spatial information consisted of digital elevation data for characterizing the slope and aspect; imagery data for the land use/land cover classification and soil information. The non-spatial information included field-monitoring data, which could be used in the model calibration and other land-related information collected during farmer surveys. These data were processed and spatially organized at a 40 m × 40 m grid cell resolution. The parameter values required by the model were extracted from the WinGrid database for each cell grid.

### 2.8. Example application

The study area chosen for the upland soil loss and sediment yield evaluation was the Dafuko watershed. This 1209.6 ha watershed is located at the headwaters of Peikang Creek, one of the major rivers in central Taiwan. The study watershed is characterized by mudstone resulting in poor infiltration and strong erosion potential at the bare areas. There are several gullies that empty into the Dafuko Creek, a tributary of Peikang Creek. The soil texture in the watershed consists mainly of silt and/or clay, with slopes ranging from very gentle to moderately steep. Agriculture is predominant in 24.3% of the area and a hardwood forest covers the remaining 75.7%. Only a negligible portion of this area is occupied by other utilization. The major crops in this area are bamboo, areca, tea and citrus. The climate in this watershed is humid and sub-tropical. The drought season is from October to April. The long-term (1986–1999) average annual rainfall is around 1877 mm, with the highest monthly value at 380 mm, occurring in August. Because of the high rainfall intensity and soil erosion potential, farmers in the watershed are required to implement the best management practices (BMPs) to control excessive soil loss.
2.9 Parameters required and manipulation

$R$ varies on a regional scale. It can be checked on the Taiwan rainfall erosivity map given by Huang (1979). The soil erodibility nomograph can be used to predict the $K$ value. The nomograph of Taiwan’s $K$ values was interpolated or measured from county soil surveys by sampling more than 113 sites (Wann, 1984). Kriging was applied to grid the $R$ and $K$ values for the application site. In the WinGrid system two thresholds are needed to determine the overland flow, intermittent flow and perennial flow for the watershed. A threshold of 100 m was used to separate the overland flow and channel flow. Another threshold was used to extract the perennial flow from the channel flow for the delivery ratio calculation. The overland flow path can then be delineated and assumed as the slope length experiencing net erosion in the watershed (Fig. 6). Land use and land cover information was obtained from remote sensing data. The normalized difference vegetation index (NDVI) was used to calculate the spectral ground-based data, which shows the highest correlation with the above-ground biomass (Lin, 1997). After a reversal linear transformation derived from training samples, the relationship between $C$ and NDVI can be established as $C = (1 - \text{NDVI})/2$, where the $C$ value in each land cell can be specified (Fig. 7). Fig. 8 depicts the $c$ factor from the NDVI calculation compared with the land cover information. It is highly
correlated with Taiwan’s Soil and Water Technical Regulations. A more accurate C factor requires an on-site investigation. Because artificial erosion control practices are nearly absent, a P factor is usually assigned to each land cell with a value of 1.0 in the watershed. The watershed sediment yield can be estimated using the sediment delivery spatial distribution ratio (Fig. 9) generated from the DEM calculation.

3. Results and discussion

The simulation results for the Dafuko Creek watershed are summarized in Figs. 10 and 11. Which indicate the soil loss and sediment yield spatial distribution. According to the Hydrological Yearbook of Taiwan, the average annual sediment yield for Peikang Creek is about $2.35 \times 10^6$ t measured at a sampling station with a watershed area of 645.21 km$^2$. A 2.6 mm average annual deposition depth can be derived from the 1.4 t/m$^3$ bulk density calculation in the topsoil at the Peikang Creek watershed. Because Dafuko Creek is one of the upstream tributaries of Peikang Creek, we obtained a similar erosion depth calculation via this module. Using the overland flow path as the slope length, the annual erosion depth is in the range of 2.2–2.7 mm at the bridge sites taken at the sub-watershed outlet along the Dafuko Creek.
Simanton et al. (1980) applied the USLE to four small watersheds on Walnut Gulch located in southeastern Arizona, USA. Two of the watersheds had no gullies or significant alluvial channels and represented somewhat reasonable applications of the USLE model. USLE application to two other small watersheds with significant gullies and alluvial channels represented a gross misapplication of the USLE model. Wilson (1989) pointed out that the USLE should be applied only to those parts of the landscape that experience net erosion. The software developed

### Table 1

<table>
<thead>
<tr>
<th>Watershed outlet</th>
<th>Erosion depth (mm per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paddy no. 1</td>
<td>2.7</td>
</tr>
<tr>
<td>Sen-Man</td>
<td>2.2</td>
</tr>
<tr>
<td>Kan-Sun</td>
<td>2.5</td>
</tr>
<tr>
<td>Kan-Kuan</td>
<td>2.6</td>
</tr>
<tr>
<td>Kan-Huo</td>
<td>2.2</td>
</tr>
</tbody>
</table>
in this study scales up USLE applications from the slope to the watershed.

4. Conclusion

Soil erosion involves complex and heterogeneous hydrological processes. The USLE has been the official calculation algorithm used by Taiwan’s government. This method has been widely used to calculate erosion at any point in a landscape that experiences net erosion. It is simple to use and conceptually easy to understand. The DEM is a fundamental input for spatially distributed models and can provide primary spatial information on elevation, slope and watershed aspect in the modeling process. The DEM can be integrated within the watershed system to model the effects of these parameters upon soil erosion over the entire watershed. This study successfully introduced a simple method for automated spatial distribution extraction for overland flows in conjunction with the USLE to produce a reasonable estimation for soil erosion and sediment yield at the watershed scale.

References


