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Estimating the LS Factor for RUSLE through Iterative Slope Length Processing of Digital Elevation Data within ArcInfo Grid

A limitation of using the USLE and RUSLE soil erosion models at regional landscape scales has been the difficulty in obtaining an LS-factor grid suitable for use in GIS applications. Previous work resulted in an ArcInfo GRID AML program that allows the creation of a USLE-based LS factor grid using a DEM elevation dataset. This paper describes the additions and modifications applied to the previous AML code to produce a RUSLE-based version of the LS factor grid. These alterations included replacing the USLE algorithms with their RUSLE counterparts and redefining some of the assumptions made regarding slope characteristics. In areas of the Western USA where it was tested, the RUSLE-based AML program has produced LS values that are roughly comparable to those listed in the RUSLE Handbook guidelines.

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INTRODUCTION

The Universal Soil Loss Equation (USLE) model and its derivative, the Revised Universal Soil Loss Equation (RUSLE), are commonly used throughout the world to calculate average annual soil loss per unit land area resulting from rill and sheet (interrill) erosion. Traditionally, the two models have been used primarily for local conservation planning at an individual farmstead scale. In fact, the USLE model (Wischmeier and Smith, 1978) was originally developed for gently sloping cropland situations, although subsequent research leading to the RUSLE model (Renard *et al.*, 1997) has broadened the applicability of the models to include soil loss estimation for rangeland, forests, disturbed sites, and steep slopes. The term *soil loss* is something of a misnomer, since eroded soil could be subsequently deposited downslope on lesser sloping surfaces (Haan *et al.*, 1994). In this sense, USLE and RUSLE are primarily erosion models with some limited linkages to sediment yield models.

When using the USLE or RUSLE, the effects of topography on soil erosion are estimated by the slope length (L) and slope steepness (S) constituents of the dimensionless LS factor, where LS is one of five component factors (R, K, LS, C, and P) that are multiplied together to calculate the average annual soil loss per unit area. The LS factor is calculated as the product of the slope length and steepness constituents converging onto a point of interest (e.g., a farm field or a raster cell on a GIS grid). In mountainous regions, the use of the USLE and RUSLE for GIS-based regional landscape ecology modeling has been hampered by a lack of reliable estimates of the R factor (rainfall intensity) and LS factor values. For local conservation planning, the LS factor is usually either estimated or calculated from actual field measurements of length and steepness. Labour-intensive field measurements are obviously not feasible for modeling soil erosion on a regional scale.

To help resolve these difficulties, a procedure was developed to enhance an existing computer program that could generate a RUSLE-based grid of LS factors for landscape ecology applications using GIS. Prior work by Hickey *et al.* (1994) and Hickey (2000) had already resulted in the production of an ArcInfo™ Arc Macro Language (AML) program for creating a USLE-based LS factor grid using an input digital elevation model (DEM) (see *www.cwu.edu/~rhickey/slope/slope.html* for more information regarding this code and similar code developed for the GIS software IDRISI). The RUSLE enhancements to the USLE-based AML involved the substitution of several recently developed RUSLE algorithms and modification of a few assumptions in the AML concerning the treatment of high points, flat areas, slope breaks, and other specific slope criteria. The RUSLE algorithms derived by McCool *et al.* (1987, 1989) utilized the results of statistical analysis applied over a much broader range of slope configurations, gradients, and cover types than those modeled for the USLE, so the new algorithms are generally considered to be more comprehensive than those of the earlier model (Renard *et al.*, 1997). The RUSLE-based AML for computing the LS factor is available from the above website. A thorough review of available GIS-based methods for calculating the LS factor is included in papers by Dunn and Hickey (1998) and Hickey (2000).

BACKGROUND

Detailed erosion studies into the general behavior of soils to changes in slope characteristics have been conducted for over 50 years. Research has shown that increased slope length and steepness produces higher overland flow velocities and correspondingly higher erosion (Haan *et al.*, 1994). Also, soil loss is much less sensitive to changes in slope length than to changes in slope steepness (McCool *et al.*, 1987). Slope length has been defined as the distance from the point of origin of overland flow to the point where either the slope gradient decreases enough that deposition begins, or the flow is concentrated in a defined channel (Wischmeier and Smith, 1978). Various approaches and algorithms for quantifying slope length have been developed (Hickey, 2000), including raster grid cumulation (Hickey, 2000), unit stream power theory (Moore and Burch, 1986), contributing area (Desmet and Govers, 1996), and network triangulation (Cowen, 1993) techniques. There are also a number of methods for estimating slope steepness (Dunn and Hickey, 1998), including neighborhood, quadratic surface, maximum slope, and maximum downhill slope techniques. The algorithms described in this paper use the raster grid cumulation and maximum downhill slope methods.

The basic input for generating an LS factor grid in GIS is a DEM dataset of suitable scale that has been clipped to encompass the zone of interest, usually a topographically defined catchment or watershed. To avoid edge effects, this clipped region should be slightly larger than the area of interest. In addition, the output from any calculations (slope or slope length) should be closely examined to ensure that the calculations are being applied properly and that there are no significant format problems with the input DEM data. If processing difficulties occur with the use of a floating-point format, truncating or rounding to an integer format may be necessary to ensure successful computer runs. Many DEM product suppliers will not attest to the significance of decimal digits in their data sets. However, any change from floating point to integer format may result in unwanted *stair-step* features (i.e., wedding-cake effect). The presence of horizontal or vertical stippling, corn-rowing, or edge-matching errors in the DEM can result in erratic or discontinuous slope length features. There are smoothing algorithms available that may essentially *correct* some of the DEM irregularities, but will also result in unwanted smoothing or generalization of other DEM elevation cells that did not require any such correction. If utilized, DEM-enhancement algorithms should be well-documented and applied with caution to avoid gross over-extension of slope lengths.

The LS factor methodology for the RUSLE-based analysis reported in this paper was primarily derived from Version 2 of the USLE-based AML code (Hickey, 2000), which distinguished among multiple possible flow paths and made provisions for uniquely identifying and treating both high points and essentially flat areas within the input DEM. The Arc and GRID modules from the ArcInfo™ Version 7.2 software (a product of ESRI, Redlands, California, USA) for UNIX platforms were used to perform the analysis.

The relationships between real-world slope microrelief and the DEM grid cell size are not examined in this paper, so it is assumed that, for erosion and deposition purposes, a grid cell resolution of 100 m^2 or 900 m^2 area (for 10-m or 30-m DEM data, respectively) represents the natural microrelief of the slopes being modeled. If this assumption is erroneous and the actual topography reflects slope breaks that are more or less frequent than the fixed cell size, then any estimates of the LS factor from this DEM analysis can be expected to deviate accordingly. Previous research suggests that most measured slope lengths are less than 120 m and that slope lengths generally do not exceed 300 m (McCool *et al.*, 1997). However, very little research on slope length has been conducted in extremely mountainous terrain to confirm the validity of this suggestion for such diverse and complex landscapes. It is important to note that data accuracy is always relative to the database specifications, and that the quality of an output product cannot exceed that of its lowest quality input layer. Given that erosion data is never 100 percent accurate and the RUSLE was developed primarily for use in agricultural lands, results generally should be treated qualitatively, not quantitatively. In short, erosion models are typically very good at deriving patterns of erosion, but not necessarily the actual rates of erosion. For more information regarding terrain modeling and DEM accuracy, see Holmes *et al*. (2000), Endreny *et al*. (2000), Walker and Willgoose (1999), Acharya and Chatruvedi (1997), Wolock and Price (1994), or Zhang and Montgomery (1994).

METHODOLOGY

In order to derive LS-factor values, a series of DEM-derived grids are produced by running the LS-factor AML program and are subsequently used in the final calculations. Figure 1 contains a flow chart that shows an overall view of the process.

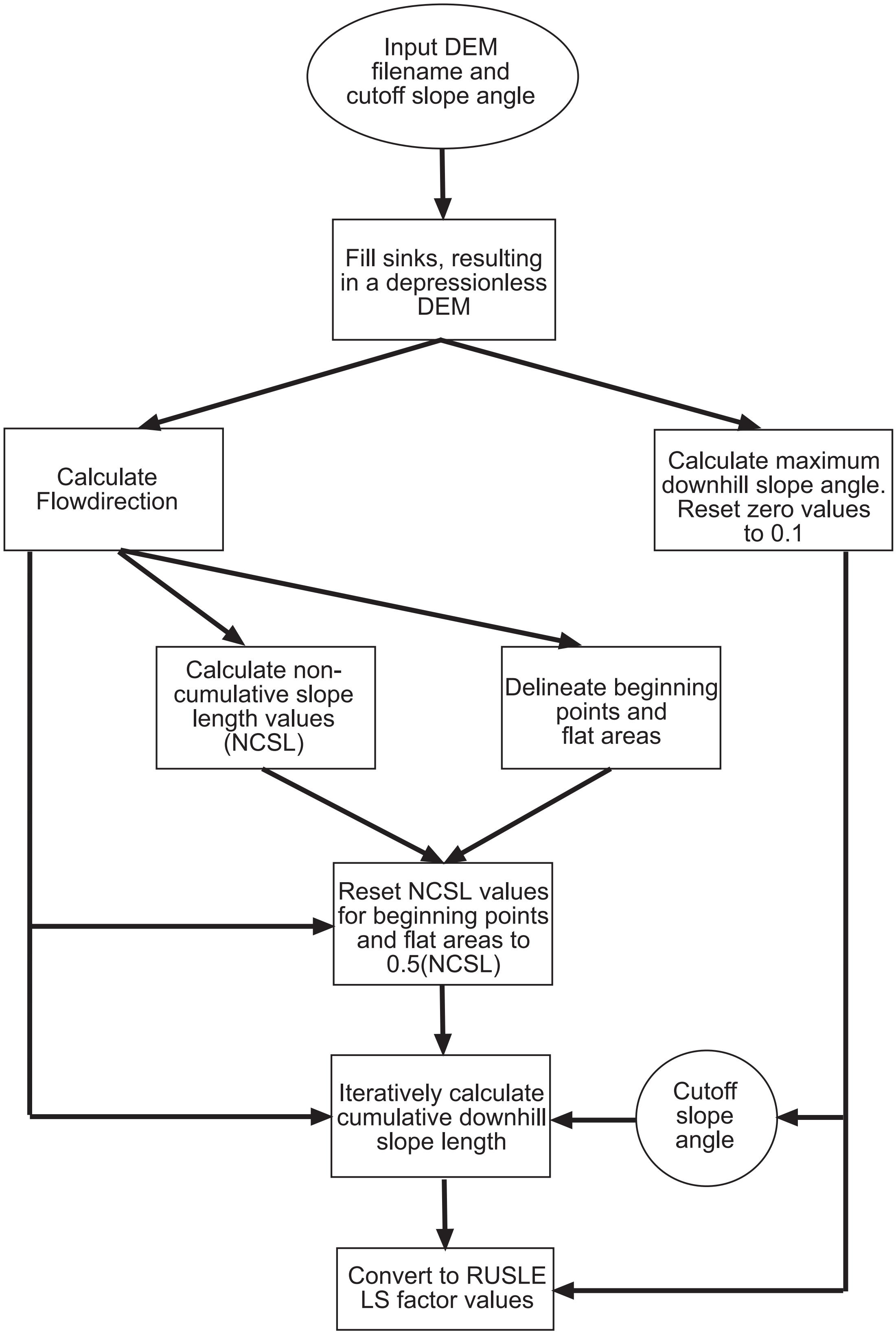

Figure 1. *Flowchart illustrating the process of calculating cumulative downhill slope length (and LS values) for use in the RUSLE.*

As the first step in the AML run, any spurious single-cell sinks within the source DEM are filled using an iterative routine that has been demonstrated to produce better results than using the standard *fill* command in ArcInfo GRID (Hickey *et al.*, 1994). In this process, individual sink elevations are flattened to correspond with surrounding cells. The flow directions in and out of each DEM cell are then calculated using the ArcInfo GRID commands *focalflow* and *flowdirection*, respectively. The outflow grid indicates the cardinal (i.e., orthogonal) or half-cardinal (i.e., diagonal) direction to which each cell is outwardly flowing, as determined by the highest elevational gradient among the *in* and *out* cells. Groups of cells with outflow values other than cardinal or half-cardinal are considered to be flat areas (e.g., benches, terraces) lacking a single defined outflow direction. For the inflow grid, each cell adopts a coded value identifying the direction(s) of all cells that could possibly be flowing into that cell. This is done by examining all surrounding cells of higher elevation and selecting only those whose outflow direction indicates flow into the selected cell.

Next, the maximum downhill slope angle of each cell is calculated from the filled DEM on an individual neighboring-cell basis (Dunn and Hickey, 1998). The cell slope angle is based on each cell's outflow direction and allows for both cardinal and half-cardinal directional flow. In the original USLE AML code, a cell with outflow to a cell of the same elevation was assigned a slope angle of zero degrees, as were multi-cell sinks that may have come through the fill process intact. This approach was modified slightly based on the assumption that *all* land-based cells inherently exhibit a slope angle that is greater than zero degrees, even though the cell resolution may not be sufficient to reflect this gradient. For these essentially flat cells, a 0.1-degree slope angle is assigned which allows the cells of an occasional multi-cell sink (for instance, along a canyon streamcourse or hillslope bench) to maintain slope connectivity with adjacent sink cells while constraining any erosion calculated for the cells to remain within the sink.

A grid containing the cell slope length, or non-cumulative slope length (NCSL) of each grid cell, is calculated from the slope angle and flow direction grids as either the cardinal or half-cardinal length of that cell according to its outflow direction (i.e., the centre-to-centre cell length of each *from/to* cell combination). In order to correspond with USLE and RUSLE guidelines, the NCSL value is calculated in x,y space (i.e., the horizontal projection of the grid) instead of x,y,z space (i.e., the surface of a natural landscape). From the NCSL grid, beginning points are defined which represent the beginning cells for every flow path. These points include those cells having outflow direction but no inflow cells (e.g., ridgelines, benches, mesas, etc.) as well as cells associated with flat areas (undefined outflow direction), and are assigned slope lengths of one-half of their NCSL values.

Prior to initiating the slope length cumulation process, provisions must be made for distinguishing areas on the input DEM in which deposition, not erosion, is the dominant process. The AML code addresses this by including a mechanism for specifying slope cutoff factors that define areas dominated by deposition. When considering sediment-laden water flowing across the earth's surface, at some point the flow velocity will decrease enough that the sediment carried will begin to deposit rather than erode more sediment.

Defining the parts of the landscape in which this will happen is not a simple task. Deposition is primarily a function of slope gradient (which largely determines the velocity) and the sediment concentration within the flow. If the flow is fully saturated with sediment, any decrease in velocity will result in deposition rather than erosion. Conversely, if the flow is relatively unsaturated, it will take a very significant decrease in slope (possibly to near zero) to result in deposition. The slope cutoff factor is a user-input value which considers the erosion/deposition conundrum. The cutoff factor is defined as the change in slope angle from one cell to the next along the flow direction pathway. This value ranges from 0 to 1 and is applied wherever the slope angle decreases from one cell to the next. A cutoff value of zero will cause the slope length to reset with any decrease in slope angle, whereas a value of 1.0 will prevent the slope length from ever resetting.

Ideally, appropriate values for the cutoff factor would be set by an expert having knowledge of the particular area in question. As this may not always be feasible, a value closer to 0.5 (slope decreasing by 50% or greater) may be appropriate based on assumptions made in other studies (Griffin *et al.*, 1988; Wilson, 1986). Only the nearest upslope cell is considered for the cutoff calculations, and the user is prompted at the outset to enter separate cutoff factors for slopes less than or greater than 5 percent. For slope gradients of 5 percent or greater, a user response of 0.5 is recommended. For slopes less than 5 percent, a 0.7 value is suggested because it is generally easier to initiate deposition on lesser gradient slopes. Nonetheless, where possible, these values should be set by an expert familiar with the particular study site.

At this point, cumulative slope length can be calculated using the NCSL, slope angle, beginning points, and flow direction grids. This is done by simply summing the NCSL values along flow direction pathways initiated from the beginning points. An intensive, iterative routine fuels the downward cell-by-cell slope length cumulation process. The cumulative slope lengths for each of the eight possible flow source directions are calculated separately, and each cell associated with a particular flow direction is assigned a slope length only if several conditions are satisfied:

- The possible flow source cells (as indicated by the inflow direction grid) must also have an outflow direction into the cell of interest,
- The flow source cell must already have a cumulative slope length assigned,
- The slope angle from the flow source cell to the cell of interest must not decrease by more than the relevant slope cutoff value.

If all three conditions are satisfied, the cell of interest receives a value by adding the NCSL of its flow source cell to the cumulative slope length of the flow source cell. A composite cumulative slope length is then determined by adopting the maximum cumulative slope length from the eight directional grids and the initial cumulative slope length grid. In areas of converging flows, the longest cumulative slope length takes precedence (Hickey *et al.*, 1994; Hickey, 2000). The AML program iteratively cycles through these steps until every downslope cell is eventually assigned a cumulative slope length by incrementally working its way from the beginning points downslope to the watershed pour point. Once completed, the units of the final cumulative slope length grid are converted to feet, if necessary, to be consistent with the RUSLE reporting units. The slope length and slope angle calculations are then converted to LS-factor values.

The RUSLE algorithm for calculating the L constituent (McCool *et al.*, 1997) serves to reference the erosion estimate for a horizontally projected slope length (HPSL) to the experimentally measured erosion for a 22.1-m (72.6-foot) reference slope length (RSL), raised to the power of a designated slope-length exponent (*m*) value. In this way, L is equal to: $(HPSL / RSL)^{m}$. The dominant land cover types for our study areas were assumed to be rangeland or woodland with a low susceptibility to rill erosion. Therefore, a graduated range of RUSLE slope length exponents was adopted that is consistent with a low ratio of rill to interrill erosion over a wide range of slope gradients (McCool *et al.*, 1997). It was also assumed that actual slope lengths are always longer than 4.6 m (15 feet) such that rilling is likely to be an active component of the erosion. This assumption allows a single L-constituent algorithm with multiple exponents to be applied across the entire slope range (McCool *et al.*, 1987; 1997). As required for use in USLE and RUSLE, the AML program assigns L-constituent values with respect to the x,y horizontal projection of the grid, not the true x,y,z surface of a natural landscape.

The S constituent is calculated directly from the slope angle grid using two RUSLE algorithms (McCool *et al.*, 1987, 1997) that are differentially applied according to a break point at the experimentally modeled 9 percent gradient (Wischmeier and Smith, 1978). For slopes of less than 9 percent gradient, S is equal to: *10.8 * sin (slope_angle + 0.03*). For slopes of 9 percent or steeper, S is equal to: *16.8 * sin (slope_angle - 0.50).* The LS factor is subsequently calculated as the product of the L and S constituents.

EXAMPLE RUN

One of our tests of the RUSLE-enhanced AML was conducted for the Lamoille Creek watershed in northeastern Nevada, USA. The catchment drains northward from high-elevation forests of the Ruby Mountains through broad sagebrush plains and empties into a floodplain along the upper reach of the Humboldt River. A grid containing 30-m resolution DEM data was purchased from the United States Geological Survey (USGS) National Elevation Dataset (NED) source. The map extent used for the DEM input grid consisted of the intended watershed study area plus a 10-cell buffer strip surrounding the study area.

The Lamoille Creek watershed occupied a raster grid space of 1284 rows by 613 columns, and elevations ranged from 1597 to 3450 m. Approximately 54 percent of the watershed has slopes of 5 percent gradient and steeper, while approximately 47 percent of the watershed has slopes steeper than 9 percent. Slope angles calculated by the AML program ranged from 0.1 to 77.8 degrees, with a mean of 14.7 degrees and a standard deviation of 13.7 degrees. As a result of applying a slope cutoff factor of 0.5, slope lengths ranged from 15 to 3050 m, with a mean of 125 m and a standard deviation of 183 m. As shown in Figure 2, the L and S constituent values for the Lamoille Creek watershed were multiplied to create the final LS factor grid. Figure 3 shows a zoomed-in view of the flow direction for individual cells within a portion of the input DEM grid. Figure 4 shows a zoomed-in view of the LS-factor grid values with respect to the same area.

Figure 2. *Grids of the L constituent, S constituent, and LS factor, respectively, for the Lamoille Creek watershed in northeastern Nevada, USA.*

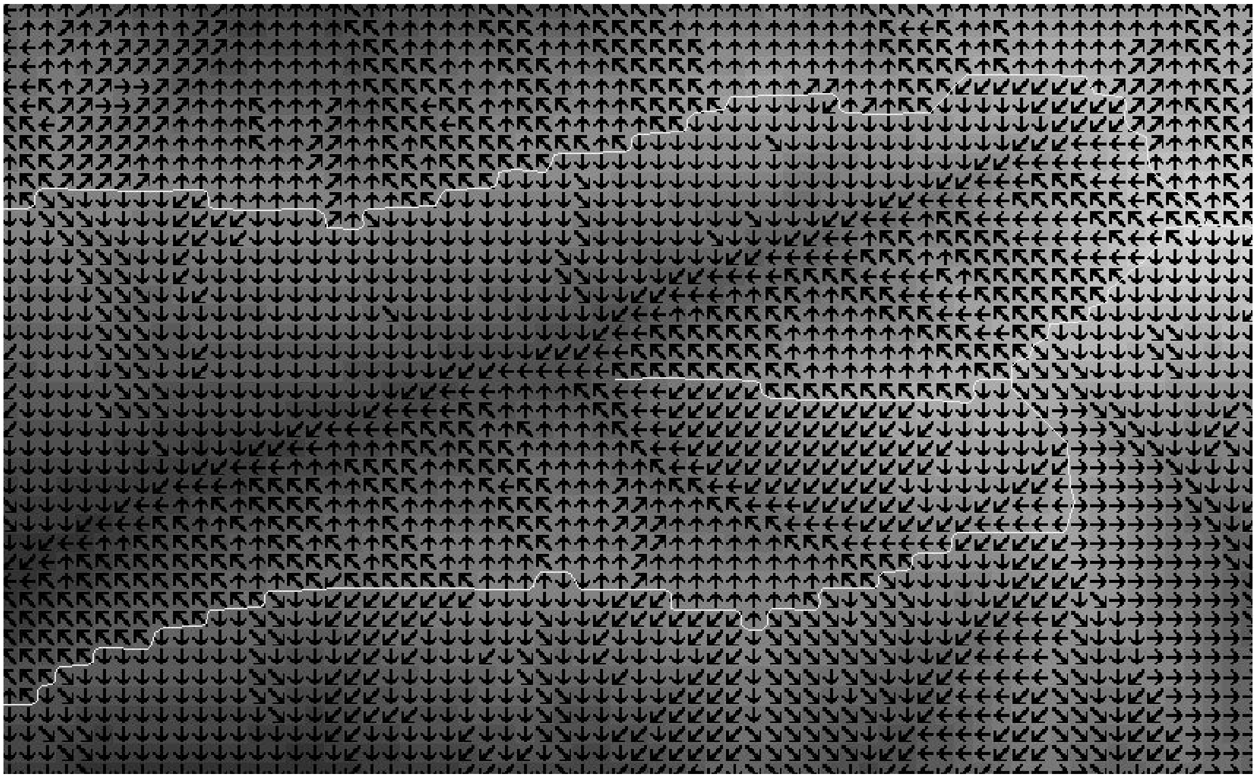

Figure 3. *Black flow direction arrows overlying the 30-m DEM grid for a zoomed-in portion of the study area (white line denotes principal ridgetops).*

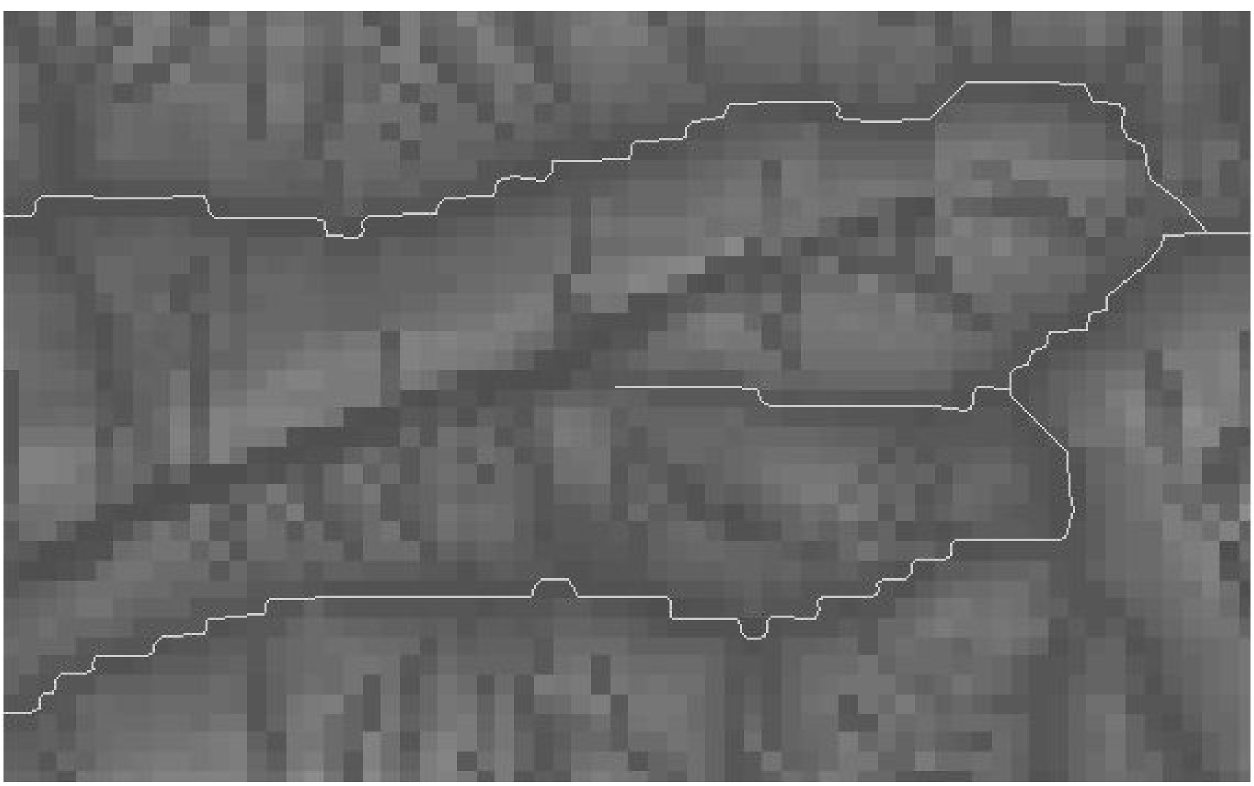

Figure 4. *RUSLE LS-factor grid for a portion of study area. The whitest cells denote the highest LS values (white line denotes principal ridgetops).*

RESULTS AND CONCLUSIONS

Results of test runs using high quality 10-m and 30-m DEMs suggest that the RUSLE-based LS factor estimates generated by the AML program are comparable to the ranges of LS values summarized in the literature (McCool *et al.*, 1997), although ground-truthing of the results has not yet been conducted. A significant drawback of the LS-factor grid iteration process presented here is that the AML runs are extremely resource-intensive. In our experience, each run of a DEM for a small (100 km by 100 km; 3333 by 3333 pixel) subregion may require as long as three days to one week to complete on a 300-Mhz UNIX workstation. The primary limitation is the time required for reading and writing files to and from the hard drive, as each iteration requires a number of such operations. In terms of processing efficiency, the use of a fast local hard drive is generally beneficial. Potential users should note that efforts are underway to initiate a C language version of this AML that can be expected to markedly increase the speed of the iterative processing to accommodate grid production for large watershed areas. Much faster run times can be expected in C as the DEM is loaded into an array and run in memory, assuming the RAM limits of the computer are not exceeded. When the computer must rely on virtual RAM on the hard drive, performance suffers.

Our test runs of the program have also demonstrated that a high-quality DEM input grid is the key element for ensuring a reliable LS-factor output grid. Errors in the DEM may result in erratic and discontinuous slope length features and will likely produce low slope length values. Conversely, efforts to smooth such errors in the input DEM will probably result in gross over-extensions of slope lengths and should be avoided where possible.

As with the original USLE-based AML program, the RUSLE-based version assumes that high points identified within the DEM correspond to true terrain high points. This normally requires that the input DEM be wholly contained within a topographically defined watershed so that erroneous beginning-point artifacts are not created along DEM boundaries within the study area of interest. The judicious use of buffer cells around the desired watershed study area can help to ensure that this watershed requirement is satisfied. Both partial watershed or subwatershed approaches can be effectively undertaken if care is taken with the initial buffer creation and subsequent clipping of the LS run results with a high resolution mask grid of the actual watershed boundary. In this event, every final LS-factor cell within the masked output grid must be traceable within the grid to a *summit* source high point having no upslope inflow cells.

The RUSLE-based AML program is available for general distribution as a text file either upon request to R. D. Van Remortel *(rvanremo@lmepo.com)* or it can be downloaded from *http://www.cwu.edu/~rhickey/slope/slope.html*. Users of the AML program are advised that it represents a prototype implementation of a method for calculating slope length and steepness from a DEM grid and should not be construed as the definitive solution for calculating the LS factor within a GIS framework.

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