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ESTIMATION OF UPLAND EROSION USING GIS

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Abstract—The Universal Soil-Loss Equation (USLE) is a widely used method for calculating annual soil erosion losses, based on rainfall, runoff, slope, runoff length, soil type, and landuse parameters. The equation was originally developed on small agricultural plots, but has since been adopted for evaluating erosion from large watersheds under a wide range of landuses. This study was designed to compare USLE calculations in a GIS environment at grid sizes ranging from 30 × 30 m up to 6 × 6 km. The analysis of two watersheds in Mississippi shows that large grid sizes tend to underestimate soil losses. At grid sizes exceeding 100 × 100 m, a correction factor must be included in the calculations. With the use of the correction factor, the USLE can be applied directly at macroscales, providing an important tool for studies of basin-wide upland erosion rates. The proposed method is shown to be applicable for large watersheds under different climates. © 1998 Elsevier Science Ltd. All rights reserved.

Key Words: Soil erosion, Geographic information system, Upland erosion, Sediment source, Sediment yield.

INTRODUCTION

Soil erosion from upland areas is a large source of sediment transported in rivers (Meyer, 1971). The extent of sheet and rill erosion is controlled by factors such as climate, topography, soil type, and landuse. Erosion rates in upland areas depend on erosive forces from raindrop impact and runoff, and on soil resistance to detachment and transport. Numerous physical processes are involved in the detachment of soil and its subsequent transport downslope, and this complexity makes it difficult to evaluate upland erosion.

A study by Musgrave (1947) gave rise to a first approximation of the relationship between major causal factors and the resulting rate of erosion. Musgrave determined that the primary factors influencing the rate of erosion are rainfall, flow characteristics of surface runoff, soil characteristics, and vegetation. Work by Wischmeier and Smith (1965, 1978) led to the definition of the Universal Soil Loss Equation (USLE) as a relationship to calculate the long-term average soil loss as the product of the parameters R, K, L, S, C and P, where average long-term soil losses are calculated in annual tons acre^{-1}, R is a rainfall erosivity factor, K is a soil-erodibility factor, L is a slope-length factor, S is a slope-steepness factor, C is a cropping-management factor, and P is a conservation practice factor. The determination of sediment yield from upland sediment sources is summarized in Shen and Julien (1993).

The USLE is used by soil conservationists around the world in predicting the average annual soil loss due to sheet and rill erosion. Yet the equation was derived on small agricultural plots, and is thus only valid up to 1 ha (0.01 km^2). In the 1980s, Julien and Frenette (1987) performed studies on the Chaudière basin in Canada, in order to examine the applicability of the USLE on large areas. They were able to extend the applicability of the USLE to large watersheds by applying a correction factor. This method can be used for simple and straightforward calculations of upland erosion losses on large watersheds, based on average watershed characteristics. The method has also been applied in Spain by Julien and Gonzalez del Tanago (1991).

Today, the data required for USLE calculations are readily available in a Geographic Information Systems (GIS) format. GIS has the unique capability of representing watershed characteristics within a grid cell environment at fine resolutions. The USLE is theoretically applicable only at grid sizes less than 100 × 100 m (0.01 km^2). The accuracy of USLE calculations using larger grid sizes can be studied within the GIS environment by applying the equation at a wide range of cell sizes. Increasing grid size leads to a loss of information that must be accounted for if the equation is to be applied at grid sizes larger than 100 × 100 m.

The purpose of this study is to use GIS in calculating soil loss rates at various grid sizes, and thus to be able to draw conclusions regarding the applicability of the USLE at macroscales. The following objectives are defined: (1) erosion mapping at a 30-m resolution and evaluation of mean annual soil loss; and (2) application of the USLE at grid sizes ranging from 30×30 m to 6×6 km and determination of grid-size correction factors.

EROSION MAPPING IN THE GIS GRASS ENVIRONMENT

USLE calculations at a 30-m resolution

The analysis was performed using GRASS (Geographic Resources Analysis Support System) capabilities for the display and manipulation of GIS data. GRASS is a tool that can be used in aggregating GIS data and in performing calculations on raster values of individual cells. The Goodwin Creek watershed in Mississippi was used in the analysis because it has been extensively monitored by the United States Department of Agriculture. Over 10 years of runoff and sediment transport measurements are available (Blackmarr, 1995; Shields, Knight and Cooper, 1995; Alonso, 1996). Goodwin Creek covers an area of 21.6 km^2 and is located in north-western Mississippi.

The USLE determines soil loss as the product of the factors R, K, L, S, C and P. The original GIS raster maps used in establishing the required parameters were: (1) a digital elevation map (DEM) generated by the United States Geological Survey; (2) a soil map generated by the Soil Conservation Service; and (3) a landuse map developed by the Agricultural Research Service in Oxford, Mississippi. The DEM at a 30-m resolution is shown in Figure 1, with the channel network overlaid on the elevation map.

The average annual value of the rainfall erosivity factor, R, was estimated from an iso-erodent map of R factors for the United States (Wischmeier and Smith, 1965). The factor R indirectly accounts for variations in rainfall intensity-duration-frequency, specific to different geographic locations. A uniform value of 330 was selected as representative of the Goodwin Creek basin.

The soil-erodibility factor, K, is a measure of the intrinsic ability of a soil to erode, and thus varies as a function of soil type. A table from Schwab *et al.* (1981) was used in determining the K factor, in tons $acre^{-1}$, corresponding to each soil type. The GRASS command *r.reclass* was then used to reclassify the raster soil map into a map representing the spatial distribution of K (Fig. 2), based on a soil survey performed by Galberry (1960).

The slope-length factor, L, accounts for increases in runoff volume as downslope runoff lengths increase. The value corresponding to Goodwin Creek was assumed to be 100 m, as determined by the drainage density of the basin.

The slope-steepness factor, S, accounts for increased runoff velocity as slope steepens. The DEM (Fig. 1) was a key component in evaluating the S factor. Based on elevations in the DEM, the GRASS command *r.slope.aspect* was used to generate a raster map showing the spatial distribution of slopes at a 30-m resolution. Slopes in the Goodwin Creek watershed ranged from less than 1% to 23%, as shown in Figure 3.

For direct application of the USLE, a combined slope-length and slope-steepness (LS) factor was evaluated for each cell as (Wischmeier and Smith, 1965):

$$LS = l^{0.5}(0.0076 + 0.0053s + 0.00076s^2), \quad (1)$$

where l = runoff length in feet, and s = slope (per cent).

The cropping-management factor C is a function of landuse conditions such as vegetation type, before and after harvesting, crop residues, and crop sequence. Values of C range from zero to one. The Goodwin Creek landuse map was reclassified according to tables in Wischmeier and Smith (1965) and Meyer (1971). Cropping management factors corresponding to Goodwin Creek landuse categories are shown in Figure 4.

The conservation practice factor, P, is determined by the extent of conservation practices such as strip cropping, contouring, and terracing practices, which tend to decrease the erosive capabilities of rainfall and runoff. Values of P range from zero to one. Since such methods are not used in the Goodwin Creek basin, the value of P was assumed to be 1.

Having specified the values for all parameters, on a cell-by-cell basis, the USLE was applied using the GRASS command *r.mapcalc*. Soil loss for every 30×30 m cell was calculated as the product of the factors R, K, LS, C, and P corresponding to that particular cell. At the 30 m resolution, annual soil-loss rates in Goodwin Creek ranged from 200 tons $acre^{-1}$ to 0.0 tons $acre^{-1}$ as shown in Figure 5.

USLE calculations at grid sizes beyond 30 m

In evaluating soil erosion losses at grid sizes larger than the original 30-m resolution, it was first necessary to aggregate the 30-m input data. Matrix aggregation within GRASS can be performed for matrices of 3×3, 5×5, 7×7,... up to 23×23. The 30-m data were therefore aggregated into cell sizes ranging from 90×90 m to 690×690 m.

Since the rainfall erosivity factor, R, the slope-length factor, L, and conservation factor, P, were considered to be constant throughout the watershed, their values were not affected by increases in grid size. In contrast, the soil erodibility factor, K, the crop management factor, C, and slope-steepness factor, S, differed spatially throughout the watershed and therefore were affected by increased grid

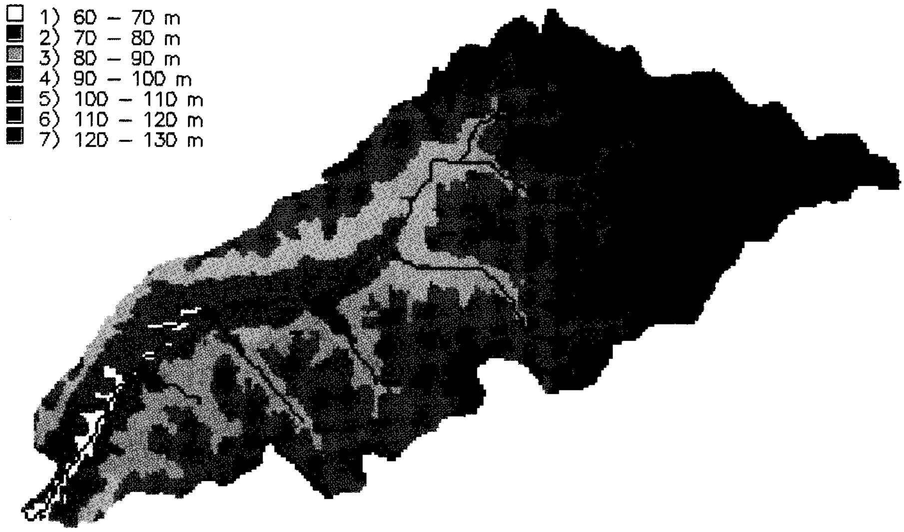

Figure 1. Goodwin Creek elevations.

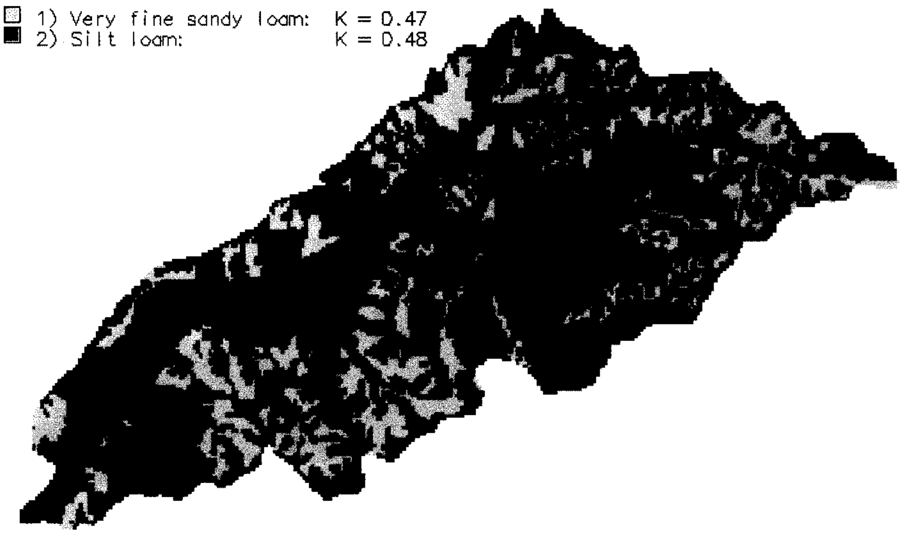

Figure 2. Goodwin Creek soil types and K values.

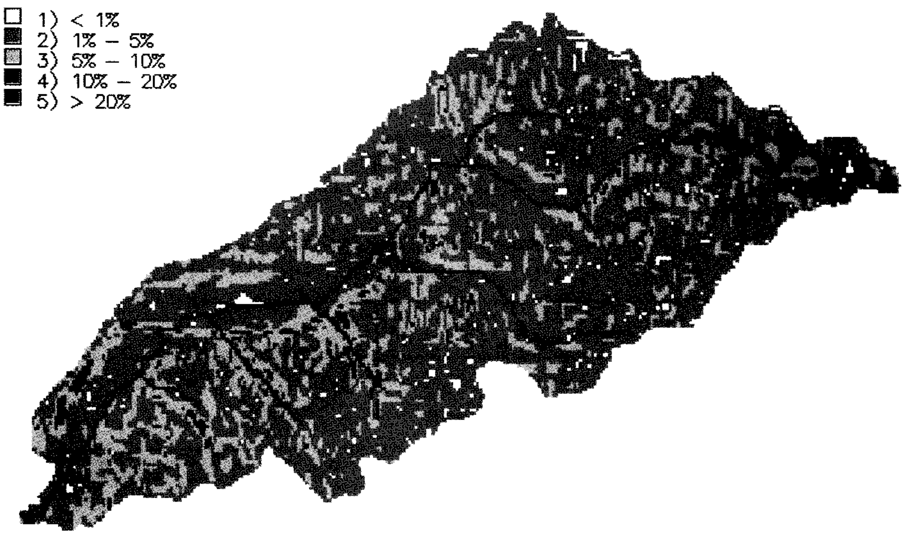

Figure 3. Goodwin Creek slopes.

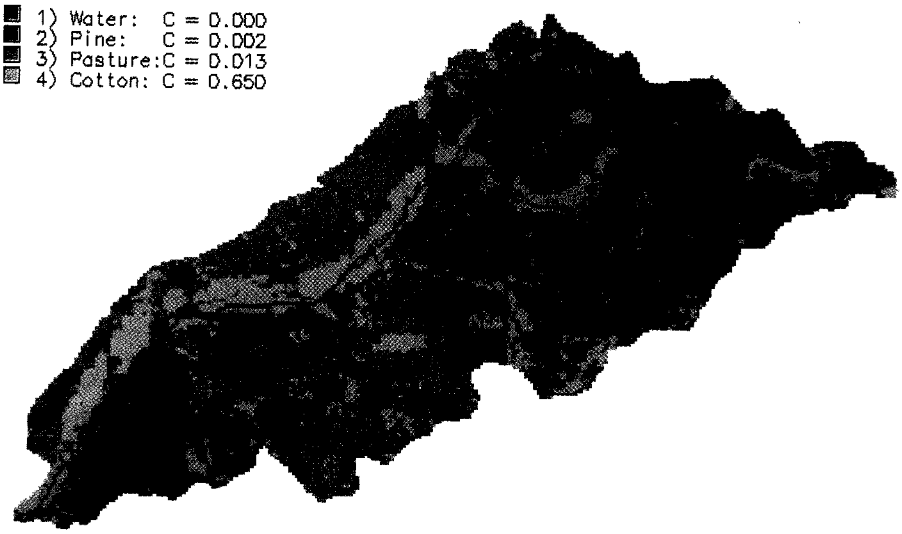

Figure 4. Goodwin Creek landuse and C values.

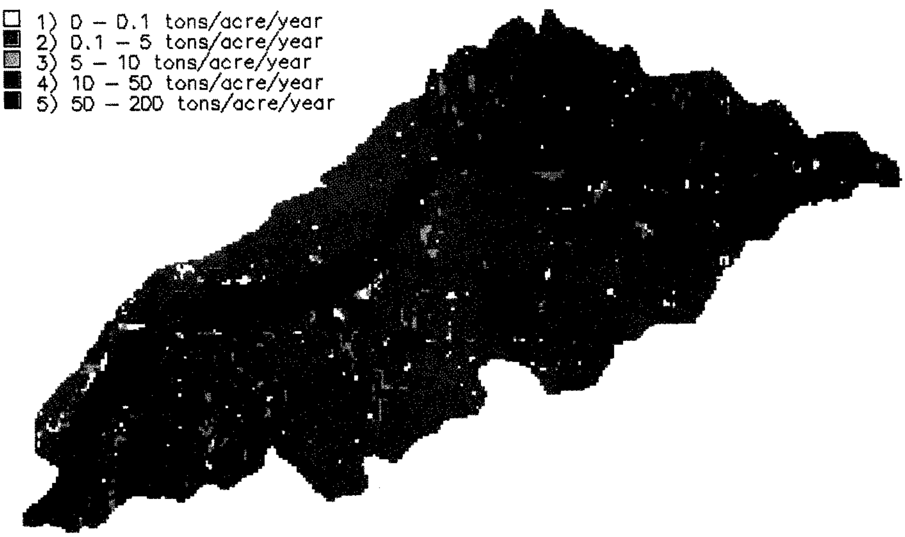

Figure 5. Goodwin Creek soil loss rates.

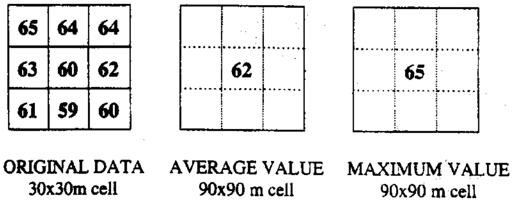

Figure 6. Matrix aggregation.

sizes. At coarser resolutions, the factors *K*, *C* and *S* were evaluated, based on matrix aggregation of the original 30-m input data.

Matrix aggregation was performed using the GRASS command *r.neighbors*, which allows the user to select the average, minimum, or maximum value of aggregated cells as the value corresponding to the larger grid size (Fig. 6). *K* and *C* values at grid sizes larger than 30 × 30 m were determined as the average value corresponding to the matrix of 30-m cells. For example, parameters corresponding to a 90 × 90-m cell were obtained by applying a 3 × 3 matrix to the original 30 × 30 m data, with the *K* and *C* values determined as averages of the nine 30 × 30 m cells contained within one 90 × 90 m cell.

The GRASS command *r.neighbors* was also used in evaluating the slopes corresponding to larger grid sizes. Maximum and minimum elevations were specified within each matrix aggregation, allowing for the calculation of grid slopes as:

$$s = \frac{Z_{\max} - Z_{\min}}{\sqrt{A}}, \qquad (2)$$

where s = slope, in m m^{-1}; $Z_{\max,\min}$ = maximum or minimum grid cell elevation, in m; and A = area of grid cell, in m^2. The combined slope-length and slope-steepness factor (*LS*) was then evaluated using Equation (1).

The *LS* factor is clearly affected by changes in scale. As cell size is increased from 30 × 30 m to 690 × 690 m, the distribution of slopes is smoothed out and tends toward a lower mean slope for the entire watershed. The cumulative distribution function corresponding to Goodwin Creek slopes, as affected by changes in grid size, is shown in Figure 7. At coarser grid resolutions, slopes decrease significantly. The maximum grid cell slope corresponding to a 30-m resolution is 23%, whereas the maximum slope corresponding to a 690-m resolution is only 16%.

Having defined the parameters *R*, *K*, *LS*, *C* and *P* corresponding to cell sizes greater than 30 × 30 m, the USLE was applied on a cell-by-cell basis. A wide range of grid sizes was used, based on aggregated cell matrices. Annual soil-loss rates were determined for every cell within the basin. The cumulative distribution function of estimated annual erosion rates is shown in Figure 8, for cell sizes ranging from 30 m to 690 m. Clearly, the distribution of slopes at increasing grid sizes has an important effect on the distribution of erosion rates as grid size is increased. At a 690-m resolution, the maximum erosion rate is approximately 30 tons acre^{-1}, in contrast to a maximum value of 200 tons acre^{-1} at a 30-m resolution. In addition, at

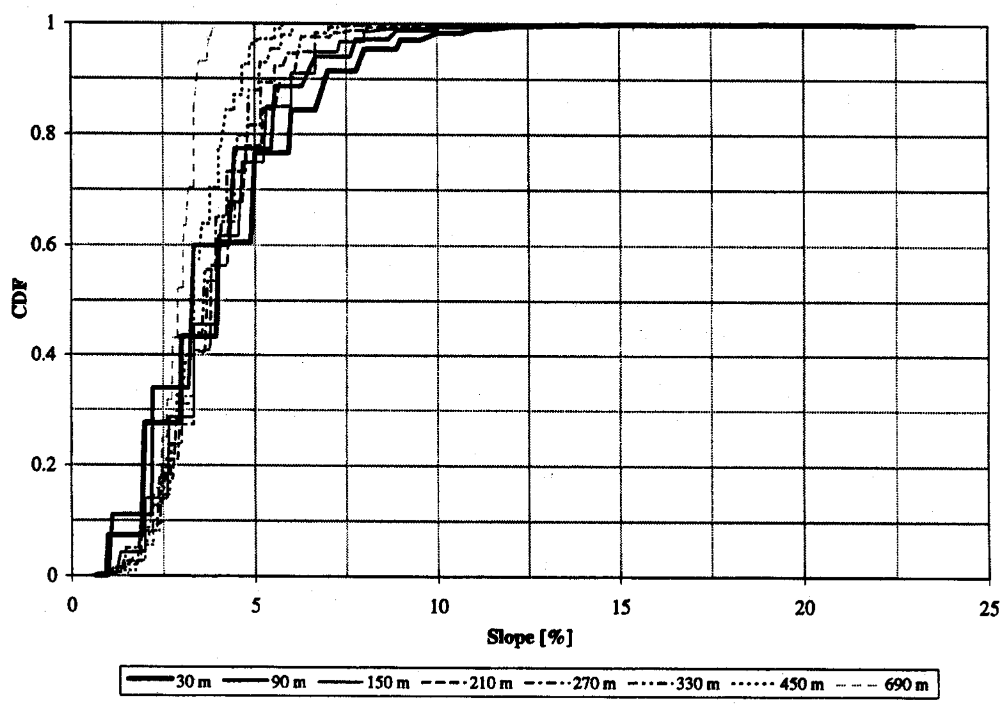

Figure 7. Goodwin Creek distribution of slopes with increasing grid size.

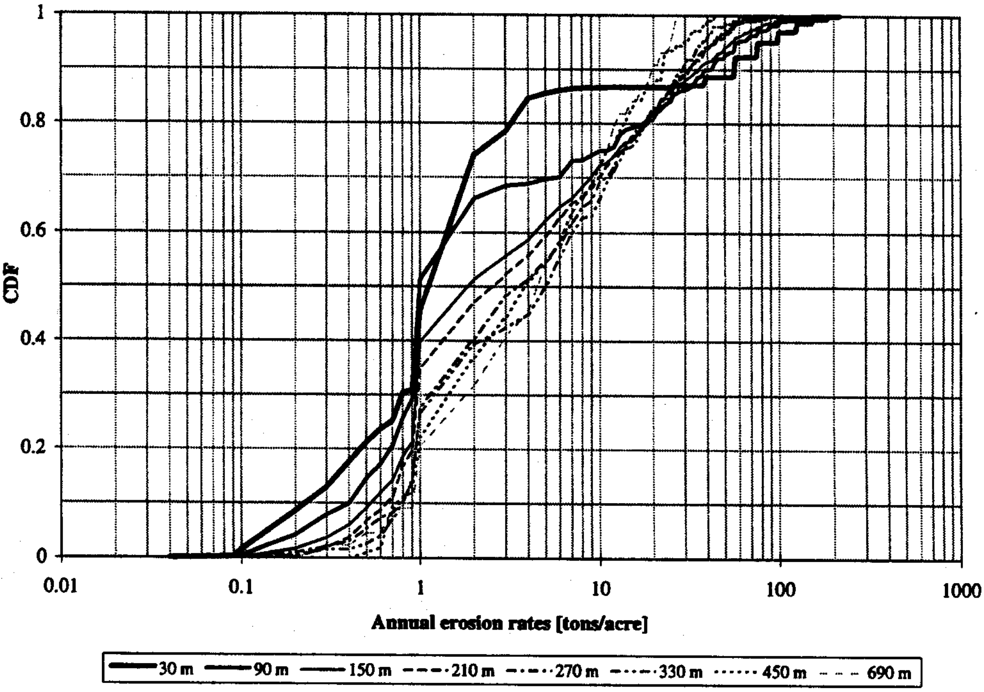

Figure 8. Goodwin Creek distribution of soil erosion rates with increasing grid size.

a 690-m resolution, 90% of the basin has erosion rates less than 20 tons acre^{-1}, whereas at a 30-m resolution, 90% of the basin has erosion rates less than 70 tons acre^{-1}. The coarser resolution will result in a reduced estimation of erosion losses for the entire basin.

GRID SIZE ANALYSIS

Selected range of grid sizes used in the study

The range of grid sizes used in the analysis was selected, based on GRASS capabilities for matrix aggregation. Using the original 30-m input data, the largest possible aggregation (23 × 23) resulted in a 690 × 690 m cell size. In order to extend the analysis beyond 690-m, it was therefore necessary to re-aggregate the 90-m and 150-m data. A 23 × 23 matrix applied to the 150-m Goodwin Creek data resulted in a maximum cell resolution of 3450 × 3450 m. At this point, due to the potential loss of information resulting from multiple aggregations of original input data, it was decided that a second watershed should be included in the analysis. A sub-basin of the Hickahala Basin, also located in north-western Mississippi, was selected. With an area of 304.5 km^2, this sub-basin allowed for the grid analysis to be extended to cell sizes up to 6 × 6 km.

The grid size analysis was performed using two categories of cells. The cells serving as original data for matrix aggregations were defined as cells with area A_o. The original 30-m grid size was defined as having an area of A_o[1]. The cell sizes resulting from matrix aggregations were defined as cells with area A. Comparisons of erosion loss rates at different grid sizes depended on the relationships between areas A_o and A. As shown in Table 1A and B, the cells with area A_o were 30 × 30 m, 90 × 90 m, and 150 × 150 m for Goodwin Creek and 30 × 30 m, 92 × 92 m, and 274 × 274 m for Hickahala. The maximum grid size used on Goodwin Creek was a 3450 × 3450 m cell corresponding to an area A of 11.90 km^2. The maximum grid size used on Hickahala was 6310 × 6310 m, with an area, A, of 39.80 km^2. N was defined as the ratio of A/A_o, serving as an indicator of the number of cells A_o within any matrix aggregation.

Determination of the grid size correction factor Q_e

In order to understand the effect of grid size on USLE calculations, a relationship relating soil loss estimates calculated at various grid sizes was established. The relative correction factor Q_e^* was thus defined as:

$$Q_e^* = \frac{\text{total loss calculated for the watershed subdivided into grid size A}}{\text{total loss calculated for the watershed subdivided into grid size A}_o}. \quad (3)$$

The values of Q_e^* resulting from USLE calculations are shown for Goodwin Creek and Hickahala in Table 1A and B, respectively. The relative correction

Table 1. Relative correction factor Q_e^* for (A) Goodwin Creek and (B) Hickahala sub-basin

Grid area A_o (km^2)	Grid area A (km^2)	N (A/A_o)	Number of cells	Total area (km^2)	Total loss (tons)	Average soil loss (tons acre^{-1})	Q_e^*
			(A) Goodwin Creek				
0.0009 (30 m × 30 m)	0.0009	1	23 770	21.39	65 986	12.48	1.00
	0.0081	9	2672	21.64	58 966	11.03	0.89
	0.0225	25	966	21.74	63 060	11.74	0.96
	0.0441	49	490	21.61	56 011	10.49	0.85
	0.0729	81	299	21.80	57 846	10.74	0.88
	0.1089	121	198	21.56	56 385	10.58	0.85
	0.2025	225	108	21.87	45 399	8.40	0.69
	0.4761	529	44	20.95	39 908	7.71	0.60
0.0081 (90 m × 90 m)	0.0081	1	2672	21.64	58 966	11.03	1.00
	0.0729	9	299	21.80	27 728	5.15	0.47
	0.2025	25	108	21.87	24 995	4.63	0.42
	0.9801	121	23	22.54	23 022	4.13	0.39
	2.3409	289	9	21.07	25 362	4.87	0.43
	4.2849	529	4	17.14	18 663	4.41	0.32
0.0225 (150 m × 150 m)	0.0225	1	966	21.74	63 060	11.74	1.00
	0.2025	9	108	21.87	24 983	4.62	0.40
	0.5625	25	39	21.94	27 687	5.11	0.44
	2.7225	121	9	24.50	20 933	3.46	0.33
	6.5025	289	4	26.01	33 351	15.19	0.53
	9.9225	441	3	29.77	12 335	1.68	0.20
	11.9025	529	2	23.81	16 035	2.73	0.25
			(B) Hickahala sub-basin				
0.0009 (30 m × 30 m)	0.0009	1	322 894	299.98	1 017 102	13.72	1.00
	0.0084	9	30 031	251.10	838 189	13.51	0.82
	0.0753	81	3903	293.71	825 739	11.38	0.81
	0.2090	225	1438	300.59	707 878	9.53	0.70
	0.4097	441	740	303.18	620 780	8.29	0.61
	0.4915	529	618	303.72	608 037	8.10	0.60
0.0084 (92 m × 92 m)	0.0084	1	30 031	251.10	838 189	13.51	1.00
	0.0753	9	3200	240.80	482 375	8.11	0.58
	0.2090	25	1169	244.36	414 965	6.87	0.50
	0.4097	49	616	252.38	375 181	6.02	0.45
	0.6773	81	396	268.20	359 801	5.43	0.43
	1.8813	225	155	291.60	295 418	4.10	0.35
	4.4231	529	69	305.19	276 764	3.67	0.33
0.0753 (150 m × 150 m)	0.0753	1	3903	293.71	825 739	11.38	1.00
	0.6773	9	396	268.20	360 303	5.44	0.44
	1.8813	25	155	291.60	262 274	3.64	0.32
	9.1054	121	33	300.48	168 542	2.27	0.20
	16.9316	225	17	287.84	133 294	1.87	0.16
	39.8080	529	7	278.66	156 006	2.27	0.19

factor Q_e^* is plotted as a function of N in Figure 9, with three series corresponding to Goodwin Creek and three series corresponding to Hickahala. As grid size increases, values of Q_e^* decrease significantly, indicating that the USLE tends to underestimate soil loss rates when large cell sizes are used. Demonstrated trends in Q_e^* can be traced back to effects of increasing grid size on the cumulative distribution function of slopes and erosion losses. The loss of information at larger grid sizes can be generalized by considering the effects of A and A_o on the relative correction factor Q_e^*. The following relationship is defined:

$$\log Q_e^* = a + b \log A + c \log \frac{A_o}{A_o[1]}, \qquad (4)$$

where a, b and c = constants, $A_o[1]$ = area of original raster map data cell (30 × 30 m), A_o = cell area before aggregation; and A = cell area after aggregation.

Based on calculated values of Q_e^*, the constants a, b and c were evaluated using a multiple linear regression analysis. The correction factor, Q_e, was then determined using the procedure of Julien and Frenette (1987), whereby Q_e is defined as:

$$Q_e = \tilde{a} A^{\tilde{b}} \qquad (5)$$

where $\tilde{a}$, $\tilde{b}$ = constants, and A = cell area.

The maximum value of Q_e is defined as $Q_{e_{max}}$. The values of the parameters a, b and c in Equation (4), and parameters $\tilde{a}$ and $\tilde{b}$ in Equation (5) are listed in Table 2 for Goodwin Creek, Hickahala, and the Chaudière basin. The analysis was performed separately for Goodwin Creek and Hickahala, yielding similar results. The correction factor equation shown in Table 2 must be used whenever grid sizes are larger than 100 × 100 m (0.01 km^2). When grid sizes are smaller than 100 × 100 m, Q_e is constant and is equal to $Q_{e_{max}}$.

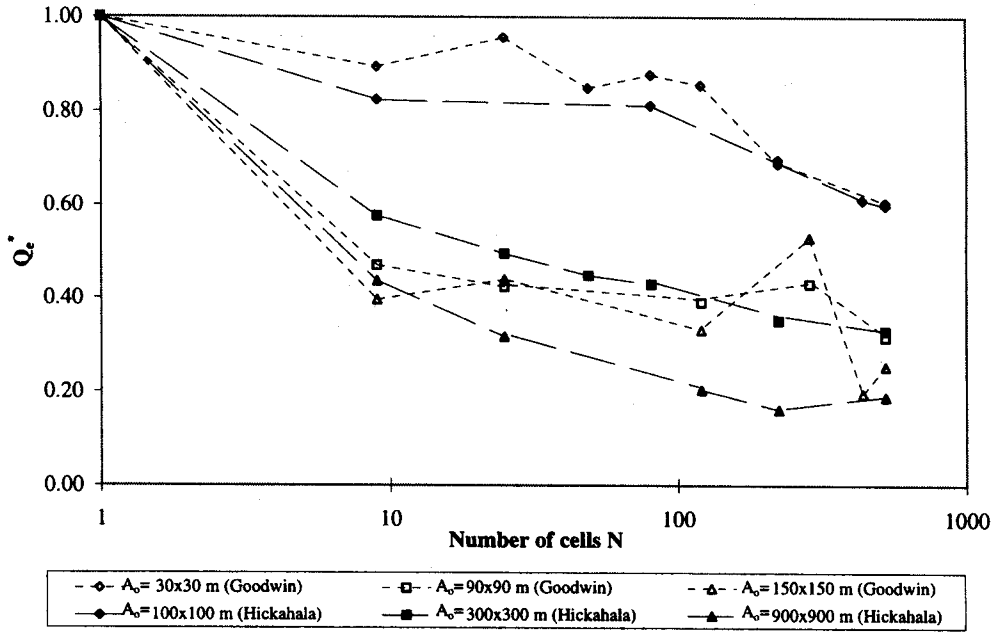

Figure 9. Relative correction factor Q_e^* as function of N.

As shown in Figure 10, by evaluating the correction factor in terms of the relative effects of A_o and $A_o[1]$, points plotted in Figure 9 now collapse more or less along a single line. The correction factor equations for Goodwin Creek and Hickahala, located in Mississippi, are similar to that of the Chaudière basin, which is located in Canada.

Total upland erosion losses using the correction factor method

The advantage of the correction factor method is that it allows for soil loss calculations to be made, assuming that a watershed can be represented by a single grid cell. According to the correction factor method, actual soil loss can be estimated as:

$$\text{Soil loss} = \frac{\bar{R}\,\bar{K}\,\bar{L}\,\bar{S}\,\bar{C}\,\bar{P}}{Q_e}, \qquad (6)$$

where $\bar{R}\,\bar{K}\,\bar{L}\,\bar{S}\,\bar{C}\,\bar{P}$ = estimated soil loss using average watershed characteristics, and Q_e = correction factor corresponding to the watershed area.

The method is applied to Goodwin Creek and Hickahala. An estimated value of annual soil loss is first calculated using average watershed characteristics, assuming the watershed is represented by a single cell. The correction factor Q_e corresponding to each watershed is then determined as a function of the total basin area, using the equations shown in Table 2. Finally, actual soil loss is calculated according to Equation (6). Table 3 summarizes the calculations made in applying the correction factor method to Goodwin Creek and to Hickahala.

As shown in Table 3, the average annual basin soil-loss rates calculated using the correction-factor method are similar to the values estimated using individual grid cell calculations. Yet, at a 30-m resolution, the application of the USLE on Goodwin Creek required calculations for 24 000 individual cells, whereas on Hickahala, calculations for 300 000 cells were required. When the correction factor method is used, calculations are needed for only one cell.

Comparison with field measurements of sediment yield lends itself to the following analysis. The dominant source of sediment on Goodwin Creek has been observed to be supplied from channel ero-

Table 2. Correction factor values for three watersheds

	Goodwin Creek	Hickahala	Chaudière Basin
Parameter a	−0.278	−0.353	−0.123
Parameter b	−0.135	−0.174	−0.137
Parameter c	−0.092	−0.043	+0.083
Parameter $\tilde{a}$	0.665	0.577	0.853
Parameter $\tilde{b}$	−0.135	−0.174	−0.137
Correction factor equation	$Q_e = 0.665 \times A^{-0.135}$	$Q_e = 0.577 \times A^{-0.174}$	$Q_e = 0.853 \times A^{-0.137}$
Maximum correction factor	$Q_{e\_max} = 1.26$	$Q_{e\_max} = 1.30$	$Q_{e\_max} = 1.13$

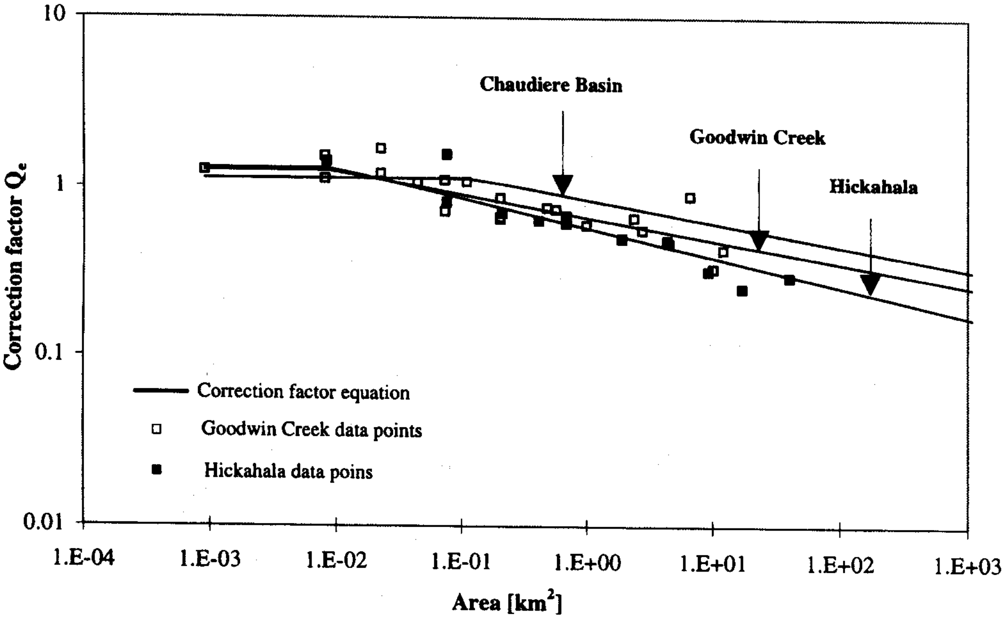

Figure 10. Correction factor Q_e as function of grid area A.

Table 3. Annual soil loss rates

Parameter	Description of parameter	Goodwin Creek	Hickahala
A	Area of basin	21.6 km^2	304.5 km^2
Q_e	Correction factor	0.439	0.213
$\bar{R}$	Rainfall-erosivity factor	330	320
$\bar{K}$	Soil-erodibility factor	0.48 tons $acre^{-1}$	0.45 tons $acre^{-1}$
$\bar{L}$	Slope length factor	100 m	100 m
$\bar{S}$	Slope steepness factor	0.014	0.005
$\bar{C}$	Cropping-management factor	0.098	0.101
$\bar{P}$	Conservation practice factor	1.0	1.0
$\bar{R}\,\bar{K}\,\bar{L}\,\bar{S}\,\bar{C}\,\bar{P}$	Soil loss using average values	4.62 tons $acre^{-1}$	2.77 tons $acre^{-1}$
Soil loss	Assuming one grid cell	10.53 tons $acre^{-1}$	12.97 tons $acre^{-1}$
Soil loss	Assuming 24 000 grid cells	12.48 tons $acre^{-1}$	
(30-m resolution)	Assuming 300 000 grid cells		13.72 tons $acre^{-1}$

sion (Alonso, 1996; Kuhnle and others, 1996). Approximately 30% of the total gross erosion comes from upland sources. With a measured sediment yield averaging 5 tons acre-$year^{-1}$ and a sediment delivery ratio of about 0.16, the mean annual upland erosion loss from the measured sediment yield can be estimated at about $5 \times 0.3/0.16 =$ 9.4 tons acre-$year^{-1}$. This value compares well with the calculated values, i.e. 10–12 tons acre-$year^{-1}$, for Goodwin Creek in Table 3.

CONCLUSIONS

The usefulness of GIS for the analysis of physical processes in large watersheds is demonstrated in this study of upland erosion. Large databases describing watershed characteristics were analyzed for Goodwin Creek (21.6 km^2) and the Hickahala sub-basin (304.5 km^2) within the GIS GRASS environment.

Analysis led to an increased understanding of the effect of grid size on soil-loss calculations. It is determined that the effect of grid resolution on the slope-steepness factor, S, plays a major role. As grid size increases, slope values for individual cells decrease, which ultimately leads to an underestimation of soil loss. By comparing annual soil-loss rates for Goodwin Creek and Hickahala at a range of grid sizes, a correction factor was determined to compensate for the underestimation of soil loss at larger grid sizes. The correction factor method is a simple technique that can be used in estimating erosion losses from large basins with minimal input data.

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