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USING GIS FOR FACILITATING EROSION ESTIMATION

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ABSTRACT. *Geographic Information System (GIS) combined with soil loss models can enhance the evaluation of soil erosion estimation. ARC/INFO geographic information system with the Revised Universal Soil Loss Equation (RUSLE) was used to estimate soil erosion on a portion of the Walnut Gulch experimental watershed in southeast Arizona. Spatial data from different sources provided input for four alternate GIS based procedures in computing the combined slope length and steepness factor in RUSLE for determining soil erosion estimates. Results of GIS based RUSLE erosion estimates from the four procedures are compared with actual sediment yield observed on the experimental watershed for the period 1973 through 1989. Results indicate GIS based RUSLE predicted soil erosion estimates are less than the observed measured sediment yield in most years. Application of a sediment delivery ratio which varies with watershed area is addressed as possible explanation for the differences in estimated erosion and measured sediment yield. GIS can be used with RUSLE to get a good estimate of soil erosion but care has to be taken in interpreting the result and comparing it to measured sediment yield. The results from this study clearly show the need for more work in using GIS and RUSLE for soil erosion estimation.*

Keywords. *Erosion, Geographic information system, GIS, Soil loss, Water.*

Reduction of soil erosion by water requires identification of excessive soil loss areas and estimation of soil loss using predictive erosion models. One of the most widely used erosion prediction models is the Universal Soil Loss Equation (USLE). Recently this model was revised by incorporating new materials that have become available through 40 years of additional research. The revised version, known as the Revised Universal Soil Loss Equation (RUSLE), is also able to include computational algorithms that enhance its capability to predict soil erosion. RUSLE is an erosion model designed to predict the longtime average annual soil loss carried by runoff from specific field slopes in specified cropping and management systems as well as rangeland (Renard et al., 1997). It was derived from theory of erosion processes combined with 10,000 plot-years of data from natural runoff plots and about 2,000 plot-years of rainfall simulator data. RUSLE estimates soil loss from sheet and rill erosion caused by rainfall and its associated overland flow. Like most erosion models, it is based on detachment limiting conditions designed to evaluate hill-slopes. In contrast to process-based models that consider erosion processes individually, RUSLE has a lumped equation structure that does not explicitly consider runoff, processes of detachment, transport or deposition individually, but rather as a combination (Renard et al., 1991, 1994).

The algorithms used in computing RUSLE factors are somewhat complex and are linked to each other and are difficult unless used with computers. RUSLE's utility can only be enhanced by using models with a high degree of computational performance. Even though the algorithms with which to estimate RUSLE factors are more extensive, the regression form of the factors that are used in RUSLE remain the same as the USLE. This relationship for RUSLE is given by:

$$A = R\ K\ L\ S\ C\ P \qquad (1)$$

where A is the amount of erosion for the specific field slope measured in tons/ha/year (tons/acre/year); R is a rainfall runoff erosivity factor; K is a soil erodibility factor; LS is a combined slope length and steepness factor; C is a cover management factor; and P is a support practice factor. The detail of the factors and how they effect the erosion prediction process are discussed in Renard et al. (1991, 1997).

Since computers are able to process larger amounts of data, recent research has been directed towards automation of erosion prediction by integrating the models with Geographic Information Systems (GIS) to save time, money, and field work. GIS is designed to store, retrieve, manipulate, and display large volumes of spatial data derived from a variety of sources. Input data such as the United Sates Geological Survey (USGS) quadrangle maps, orthophoto contours and a Digital Elevation Model (DEM) are data sources that GIS can spatially process for development of length and slope steepness values. The GIS used to analyze data was PC ARC/INFO (Environmental Systems Research Institute, 1992), a vector based GIS in which features are represented by

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Cartesian geometry. The primary role of the GIS was to obtain slope lengths and steepness and for spatially displaying estimated erosion on the entire watershed. The advantage of GIS is that large quantities of data can be processed in less time than could be done by the traditional approach of using topographic maps.

Linkage of GIS and erosion is made possible by the spatial format in which RUSLE factors are presented. These factors can be stored in GIS for each unit area inside a watershed for further calculation and graphical presentation of erosion. Examples of this linkage have been attempted by Hession and Shanholtz (1988), where a GIS for targeting non-point source agricultural pollution combined with USLE was used to evaluate sediment loading to streams from agricultural lands. The GIS data base could be readily accessed for correcting or updating data, while the manual approach was not as flexible.

One of the first procedures to become widely accepted involving length and slope extraction using a DEM was evaluated by Spanner et al. (1983). In a similar investigation, Blaszczynski (1992) used the same criteria where regional soil loss was predicted using a RUSLE/GIS interface. Both found that by using GIS based data, standardization of automated derivation of slope gradients and slope lengths from DEMs can remove the subjective element usually present in determination of LS factors.

A method of LS extraction from a DEM using overland flow theory has been proposed by Moore and Wilson (1992). They proposed a simple soil-erosion index which accounts for major hydrological and terrain factors affecting erosion. This index is considered to be equivalent to the LS factor in RUSLE. Results of previous applications show use of GIS with a soil erosion model can enhance management decisions for land use planning and provide an essential role in using data from many formats.

This research presents results of application of GIS based factors in RUSLE for erosion estimation for a given watershed, with major focus on the different algorithms used to calculate length and slope steepness factors in RUSLE.

METHODS

THE EXPERIMENTAL WATERSHED

Experimental data was collected on a 4.5-ha (11.2-acre) sub-watershed located within the USDA Walnut Gulch experimental watershed in Tombstone, Arizona (fig. 1). The dominant vegetative cover is characterized by desert brush with scattered grasses. Although the intended land use is as rangeland, it has not been grazed since 1962. Little change in vegetation type, density, and surface groundcover has been measured since the watershed was fenced (Simanton et al., 1993). Slopes of the watershed range from 1 to 15%. The soil falls in the series Rillito-Laveen which is a gravelly loam with medium and moderately coarse texture soil formed in calcareous old alluvium. Gullies in the watershed are not prevalent and the existing ones are not deeper than 0.6 m (2 ft.). Three rain gages evenly distributed within the watershed have been operational for over 20 years. Records indicate average annual rainfall of about 279 mm (11 in.). This is assumed to be uniform over the entire 4.5-ha (11.2-acre) watershed. Most of this precipitation comes from air-mass thunderstorms between the months of July and September. As a result, precipitation in these months accounts for 95% or more of the annual runoff. Measured sediment yield values were obtained by on site sampling techniques which are discussed in detail by Simanton et al. (1993). Erosion was estimated for years 1973 through 1989 using parameters developed specifically for the watershed and computed by RUSLE. The parameters used by RUSLE were computed following the procedures below. Figure 2 represents a flow diagram of the RUSLE/GIS interface for data and processing used in this study.

Rainfall-runoff Factor (R). The rainfall-runoff erosivity factor (R) is one the most important parameters in erosion estimation by RUSLE. The value of R requires converting on-site rain gage data to an energy intensity (EI) value which represents total storm kinetic energy (E) times the maximum 30-min intensity (I_{30}) as:

$$EI = (E)(I_{30}) = \left(\sum_{r=1}^{m} e_r \Delta V_r\right) I_{30} \qquad (2)$$

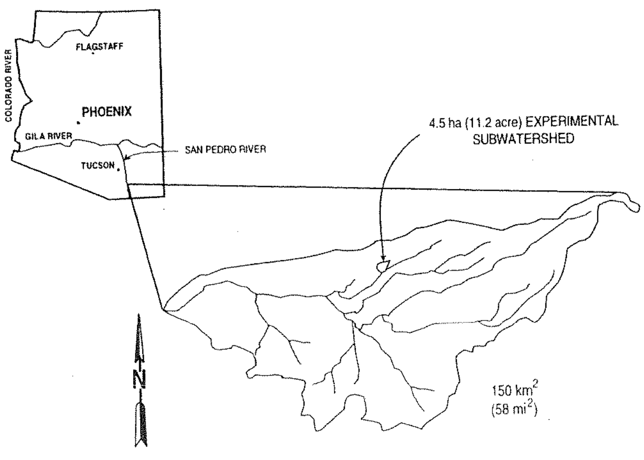

Figure 1–Walnut Gulch Experimental Watershed, Tombstone, Arizona.

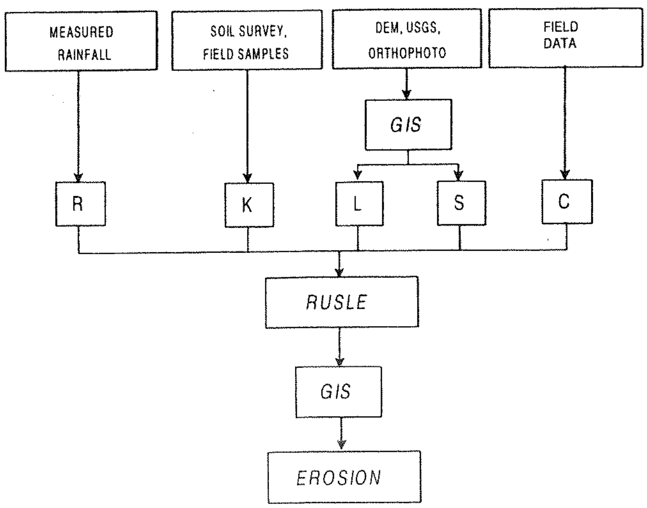

Figure 2–Flow diagram of data and processing.

In equation 2, ΔV_r is depth of rainfall for the *rth* increment of the storm hyetograph which is divided into "m parts" each with essentially constant rainfall intensity (mm, in.), e_r is rainfall energy per unit depth of rainfall per unit area. I_{30} is twice the maximum amount of rain falling in 30 consecutive minutes. The R value for each year is the sum of the $EI_{(30)}$ values for all storms within that year. R values range from a low of 306 MJ·mm/ha·h·yr (18 hundreds of foot·tonf·in./acre·h·yr) in 1989, to a high of 3149 MJ·mm/ha·h·yr (185 hundreds of foot·tonf·in./acre·h·yr) in 1975. This demonstrates the importance of accurate rainfall records near the site of interest. The effect of doubling the R value is to double predicted erosion; similarly halving the R value will reduce erosion by half.

Soil Erodibility Factor (K). The soil erodibility factor is related to the integrated effect of rainfall, runoff, and infiltration on soil loss. Input to soil erodibility factors were obtained by direct measurements in the field and are summarized in table 1. The soil erodibility nomograph (Wischmeier and Smith, 1978) method was used to compute an erodibility factor from soil characteristics found by sampling. The nomograph is comprised of five soil and soil profile parameters: percent silt and very fine sand (<0.1 mm), percent modified sand (0.1-2mm), percent organic matter (OM), and codes for structure (S) and permeability (P).

The average annual value obtained for K by the nomograph method in RUSLE's program is 0.01765 ton·ha·h/ha·MJ·mm (0.134 ton·acre·h/100 acre·ft·tonf·in.). Sensitivity of K stems from problems such as soils that are rarely homogeneous over large areas, but many times are treated as homogeneous for standard mapping procedures. In this sense, soils are difficult to characterize in terms of specific attributes needed for RUSLE's K routine. For example, on a watershed hilltop, silt and fine sands can be 18%; whereas, at the toe of hillslopes, silt and fine sands of 25% may be present. Field sampling and testing of the site of interest are the best methods available. In this research, soil samples were taken across the watershed but the average values of the input to the RUSLE soil nomograph routine (table 1) were used to estimate an average K value. Silt and very fine sand percentage was the most sensitive input to the RUSLE K factor routine.

Cover Management Factor (C). Table 2 summarizes field input data which are required for the RUSLE C factor routine. Field data obtained by line transect observation and sampling were input to RUSLE's cover management factor routine quantifying percent cover, rock, bare ground, and data such as fall height, and above and belowground biomass. For the period from 1973 to 1989 there may have been some differences from year to year but such data were not available and as a result a constant value was assumed.

Table 1. Data for input to RUSLE's soil nomograph routine

% Silt and very fine sand	20.8%
% Modified sand	54.6%
% OM	0.4%
% Clay	5.0%
Structure	2 (fine granular 1-2 mm)
Permeability	3 (moderate, 5-20 mm/h)(0.2-0.8 in./h)
RUSLE computed K factor = 0.134	

Table 2. Summary of input values for the RUSLE C factor routine, ver. 1.02

Roughness value	0.8
Bare ground (%)	28
Canopy cover (%)	26
Average fall height	0.305 m (1 ft)
Root mass in top 10 cm (4 in.)	4285 Kg/ha (3,822 lb/acre)
Aboveground biomass	3065 Kg/ha (2,730 lb/acre)
Ratio below/aboveground biomass	2.5
Belowground biomass (%) found in top 10 cm (4 in.)	56
Plant community code	12 (South Desert shrub)
RUSLE computed C factor	**0.013**

A cover management factor of 0.013 for the watershed was calculated.

Support Practice Factor (P). Support practice factor represents the ratio of soil loss with a support practice like contouring, strip cropping, or terracing to soil loss with straight-row farming up and down the slope. For ungrazed, undisturbed southwest rangeland that best characterizes the experimental watershed, the support factor P equal to 1 for RUSLE was used.

Slope Steepness and Length Factor (LS). The LS factor characterizes the effect of topography on erosion in RUSLE. Slope steepness and length factors were computed by GIS using four different methods. The first two approaches use vector data input while the third and fourth use raster data input. The first LS factor was derived by a photogrammetric corrected orthophoto with 0.305 m (1 ft) elevation contour intervals. The analysis included subdividing the 4.5-ha (11.2-acre) watershed into 38 unit areas. The lengths and slopes were measured and recorded by digitizing each area in the GIS. Slope steepness and length values were input to the RUSLE software LS routine to calculate LS factors on the watershed.

The second algorithm used a Tombstone, Arizona, USGS topographic 7.5-min quadrangle map with 7.6-m (25-ft) elevation contour intervals to derive the LS factor. The 7.6-m (25-ft) contours on the hard copy were digitized using GIS to obtain lengths and slopes for input to RUSLE's LS factor routine. Slope steepness and length were computed based on the 7.6-m (25-ft) contours and average flow length of each area. The scale of input data is greater than the first algorithm.

The third was derived from a DEM with a resolution of 15 × 15 m (49.2 × 49.2 ft) requiring roughly 200 grids covering the 4.5-ha (11.2-acre) watershed. Methods used in calculating lengths and slopes using the DEM, were adapted from Spanner et al. (1983) and Blaszczynski (1992). Slope steepness and lengths derived by GIS were input to RUSLE to compute LS factors for the entire watershed.

The fourth used a DEM algorithm adapted from Moore and Wilson (1992), using an erosion index thought to be similar to the LS factor in RUSLE. Using the same 15 m × 15 m DEM, this technique differs from Spanner (1983) in that it modeled overland flow from a DEM where Spanner's algorithm computed length based on existing slope steepness. The idea of extending the LS factor to three-dimensional form, to include topographic effects is important in erosion estimation when using DEMs. The erosion index is given by:

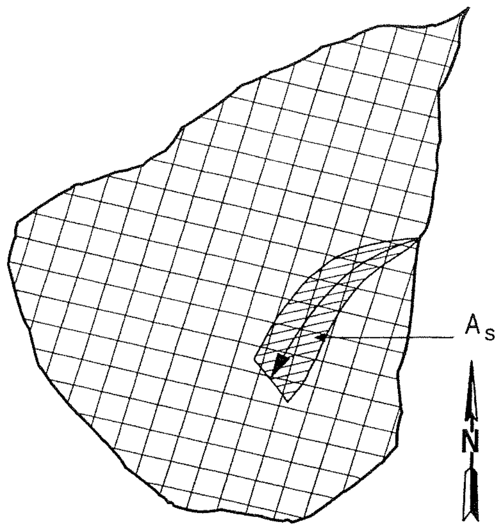

Figure 3–Moore's A_s — specific area.

$$T_c^* = \left(\frac{A_s}{22.13}\right)^m \left(\frac{\sin\theta}{0.0896}\right)^n \quad (3)$$

where T_c^* is a sediment transport index substituted directly in RUSLE in place of the LS factor. A_s is the contributing upland sloping area (specific area) including the area for which erosion was calculated (fig. 3); θ is the slope angle in degrees; m is 0.6 and n is 1.3 (Moore and Wilson, 1992). The specific area can be rewritten as:

$$A_s = \sum_{i=1}^{j} \frac{\mu_i a_i}{b_i} \quad (4)$$

where μ_i is a weighting coefficient dependent on the runoff generation mechanism and soil properties; a_i is the area of the *ith* cell; b is the width of each cell; and i = 1,j represent all of the i cells hydraulically connected to cell j. Here we assumed $\mu_i = 1$ for all cells which means rainfall excess is generated uniformly over the entire catchment area. As figure 3 illustrates, the A_s reflects the contributing area from various grids to be used in the T_c^* calculation.

Comparison of the resulting LS factors calculated using each method over the entire 4.5-ha (11.2-acre) watershed are presented in table 3. It should be clear that the combined LS factor, not separate L and S, was used because of the use of DEMs specifically in the third and fourth algorithm.

Results and Discussion

Results (table 3) showed that different sources of field data for calculating length and slope factors on the same experimental area had significant effects on RUSLE's erosion estimation. In comparing Spanner's algorithm (using 15 × 15 m resolution elevation data), with Moore's algorithm (using the same 15 × 15 m resolution elevation data), two different procedures with the same source data resulted in one computing an LS factor nearly double that of the other. This resulted in doubling of predicted erosion rates.

Table 3. Average LS factors per unit area for four LS estimation methods

LS Estimation Method	LS Factor
0.304 m (1 ft.) contour	1.95
USGS 7.62 m (25 ft.) MAP	1.82
Spanner 15 m (49.2 ft) DEM	1.22
Moore 15 m (49.2 ft) DEM	2.19

Table 4. Summary of RUSLE calculations

R $\left(\frac{MJ \cdot mm}{ha \cdot h \cdot yr}\right)$ $\left[\frac{100 \cdot ft \cdot tonf \cdot in.}{acre \cdot h \cdot yr}\right]$	K $\left(\frac{ton \cdot ha \cdot h}{ha \cdot MJ \cdot mm}\right)$ $\left[\frac{ton \cdot acre \cdot h}{100 \cdot acre \cdot ft \cdot tonf \cdot in.}\right]$	LS *	C	P	A Predicted Erosion tons/ha (tons/acre)
1055	0.01765	1.95	0.013	1	0.471 (0.21)
(62)	(0.134)	1.82			0.448 (0.20)
		1.22			0.292 (0.13)
		2.19			0.538 (0.24)

* DEM estimates from table 3.

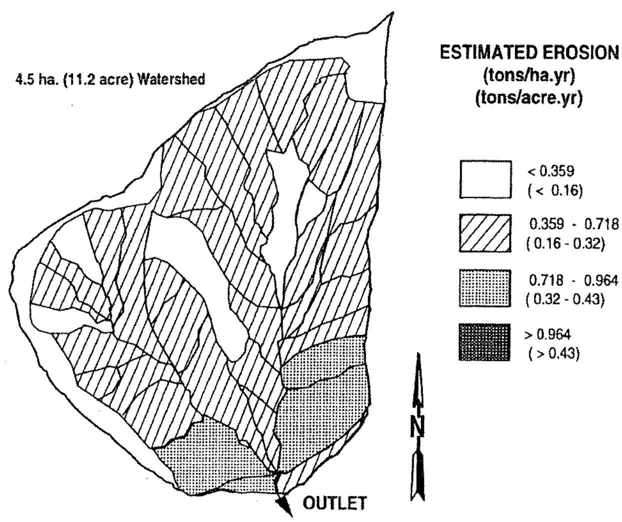

Figure 4–Erosion calculated by RUSLE derived from the 0.305 m (1 ft) contour orthophoto map.

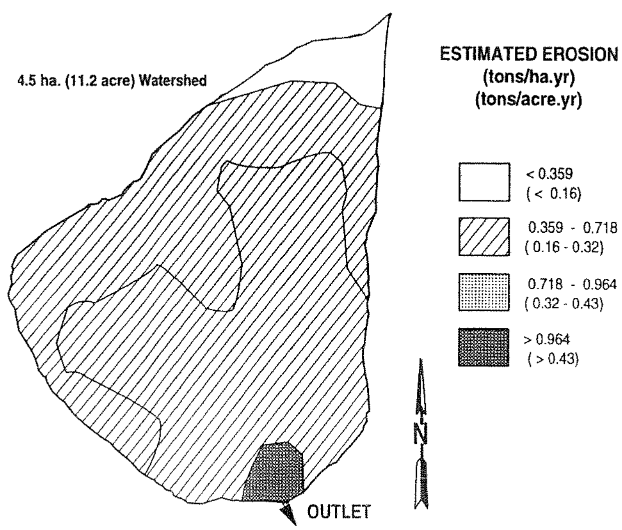

Figure 5–Erosion calculated by RUSLE derived from the USGS 7.6 m (25 ft) contours.

A summary of the six RUSLE factor calculations (R, K, LS, C, P) are given in table 4. Four average predicted erosion values are presented resulting from the 4 methods of LS estimation procedures, and an average R value is presented.

Figures 4 and 5 show as the resolution of elevation contours increased (7.6 m-0.305 m) (25 ft-1 ft), the greater detail gave the ability to map hill-slopes more accurately. The 0.305-m (1-ft) contour elevation data indicated where the LS factor may be high within the watershed. Although, for computing an average LS factor per unit area on the entire watershed, there is little difference between 0.305-m (1-ft) contour LS factors and LS factors computed using 7.6-m (25-ft) contour intervals at least for this illustration.

Figures 6 and 7 show the two algorithms, i.e., Spanner's and Moore's, are able to identify spatial areas of high estimated erosion similarly, but the Spanner 15-m DEM algorithm is consistently lower than the Moore 15-m DEM algorithm. This stems from the procedure used for calculating overland flow processes, and the different algorithm used by each for determining the flow length. As it can be observed from the figures, the spatial variations in length-slope factors by the different procedures have significant effects on the total erosion calculation.

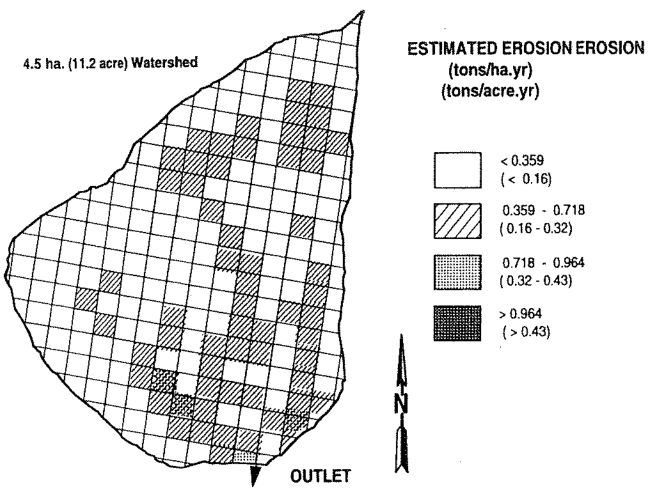

Figure 6–Erosion calculated by RUSLE using Spanners algorithm on the 15 m DEM.

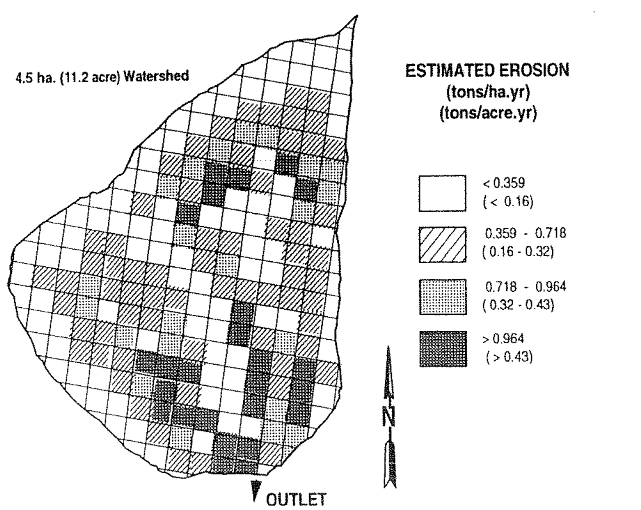

Figure 7–Erosion calculated by RUSLE using Moore's algorithm on the 15 m DEM.

Table 5. Comparison of measured sediment yield and predicted erosion by RUSLE using the four different LS estimation procedures (tons/ha)

Year	R $\left(\frac{MJ \cdot mm}{ha \cdot h \cdot yr}\right)$	Measured Sediment Yield	Estimated Erosion by Method: Ortho-photo	USGS	Spanner DEM	Moore DEM
1973	1021	0.785*	0.471	0.426	0.292	0.516
1974	1157	1.682*	0.516	0.493	0.314	0.583
1975	3148	3.184*	1.413	1.323	0.874	1.592
1976	425	0.695*	0.202	0.179	0.112	0.224
1977	1293	2.982*	0.583	0.538	0.359	0.650
1978	681	0.179†	0.314	0.292	0.202	0.336
1979	391	0.000†	0.179	0.157	0.112	0.202
1980	306	0.224†	0.135	0.135	0.090	0.157
1981	885	0.000‡	0.404	0.381	0.247	0.448
1982	833	1.166†	0.381	0.359	0.224	0.426
1983	1140	0.359†	0.516	0.471	0.314	0.583
1984	2332	4.282†	1.054	0.964	0.650	1.166
1985	1072	0.359†	0.493	0.448	0.292	0.538
1986	1481	0.000‡	0.673	0.628	0.404	0.740
1987	494	0.000†	0.224	0.202	0.135	0.247
1988	851	0.740†	0.381	0.359	0.247	0.426
1989	306	0.000†	0.135	0.135	0.090	0.157
Average	1055	0.987	0.471	0.448	0.292	0.538
Std. dev.	714	1.300	0.336	0.314	0.202	0.381

* Depth integrated pump sampler used for sediment measurement.
† Flows in these years were smaller than the depth required to activate the sampler.
‡ Sampler problem.

Total annual sediment values measured on the experimental watershed are summarized in table 5 for years 1973 through 1989. The sediment yield values were calculated from recorded sediment yield measuring devices on site. Discussion regarding methods and equipment can be found in Simanton et al. (1993).

It is important to note that sediment yield and erosion are two different terms that are not interchangeable. Sediment yield for a watershed includes the erosion from slopes, channels, and mass wasting, minus the sediment that is deposited after it is eroded but before it reaches the point of interest. Sediment delivery ratios (SDR) have been proposed (Branson et al., 1981) to explain differences between sediment yield and predicted erosion estimation for area-wide studies (fig. 8). This was developed because RUSLE estimates erosion for individual hill-slopes; whereas, sediment yield is measured on a watershed consisting of many hill-slopes with a collecting channel and its erosion source. When many hill-slopes are combined, effects such as deposition and channel-gully erosion may increase or decrease sediment yield.

Figure 9 shows scatter of estimated erosion using the four methods. For each year all methods seem to under estimate average annual soil erosion, in years of normal and high erosion, compared to the observed measured sediment yield. In years of low or no measured sediment yield the estimated erosion by RUSLE was greater in most cases. If years of zero sediment yield were excluded from the measured sediment yield data, the average would be 1.39 tons/ha/year (0.62 tons/acre/year). In this watershed it is possible to have no sediment yield years due to mainly low rainfall such that the sampler was not able to reach a threshold depth to detect sediment. In some years the

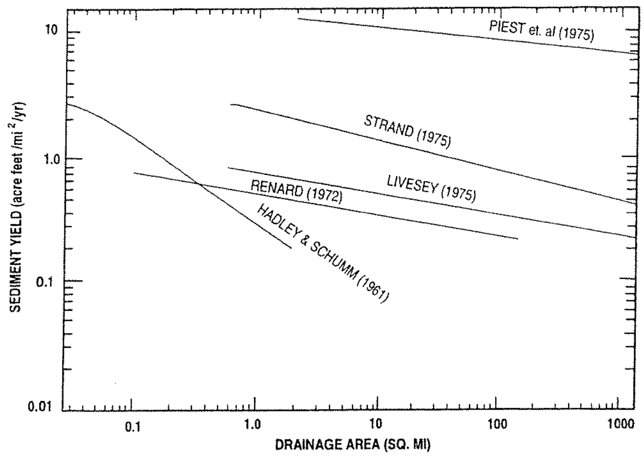

Figure 8–Examples of the relationship of sediment yield for various sizes of watershed. Data reported as tons was converted to volume assuming 1441.7 kg/m³ (90 lbs/ft³) (adapted from Branson et al., 1981).

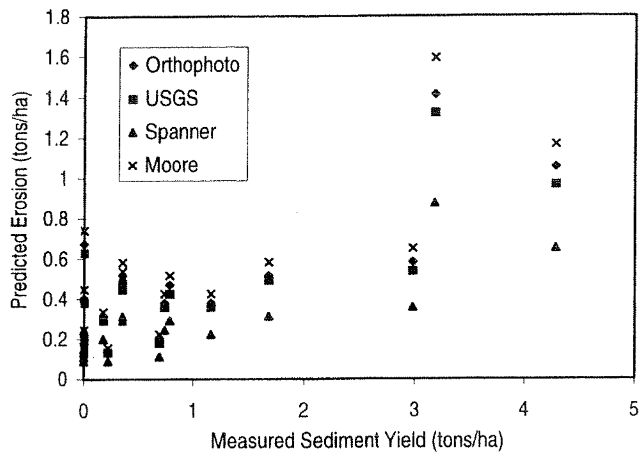

Figure 9–Measured sediment yield vs predicted erosion.

sampler had mechanical problems and was not measuring sediment even though there was reasonable rainfall. There were 5 years, (1979, 1981, 1986, 1987, 1989) without significant measurable sediment transport through the watershed outlet in the 17-year record.

Contribution by tributary gullies as pointed out by Osborn and Simanton (1989) may be one reason for the higher values found by sediment yield measurements. In most cases, years with higher rainfall runoff produced more measured sediment yield than what was estimated using RUSLE. This may be explained by coarse sediment reaching the basin outlet only during high flow years, indicating the theory of a sediment delivery ratio was not adequate in explaining the difference in measured versus predicted values on a yearly basis (Simanton et al., 1993). It is also important to note other factors such as history of erosion events, temporal changes of the soil on the landscape, and morphology of the drainage system can influence the difference between the predicted erosion and the measured sediment yield.

A sediment delivery ratio (SDR) has been used to explain differences between sediment yield and predicted soil erosion. Previous research has used the SDR to explain higher sediment yield on smaller watersheds, and decreasing sediment yield with increasing watershed size. This in general is a true relationship, but did not adequately explain results reflected by our data. For example, we have some years where zero sediment yield was measured and at the same time RUSLE predicted some erosion. It is difficult to select a ratio which accurately explains the difference between measured sediment yield and predicted erosion. For instance, in low runoff years $0 < SDR < 1$, but in normal and high runoff years $SDR > 1$, channel erosion increased yield for most cases. This shows that it is inappropriate to use SDR effectively because it changes from year to year due to changes in flow.

The concept of a SDR was evaluated by Branson et al. (1981) in which different researchers found variation in SDR based on location to be so wide on a case by case basis, it causes difficulty in selecting an appropriate value. This is reflected in figure 8, where all research shows a decreasing sediment yield with increasing watershed size, which makes the SDR theory generally hold true, but variation is so large that selection may be impossible.

Based on the unsatisfactory explanation of the data by a SDR, some insight may be gained on the problems experienced on the experimental watershed by considering deposition and channel erosion. It is proposed that in a watershed, sediment yield (Sy) can be expressed as:

$$Sy = \text{RUSLE predicted erosion}$$
$$+ \text{Channel erosion} - \text{Deposition}$$

Thus, instead of applying a new sediment delivery ratio each year, difference in sediment yield and RUSLE predicted erosion can be explained by channel erosion and deposition. Measurements and recording of these two items pose an additional problem, but with some initial effort it may be possible to explain annual difference observed with data such as that used herein.

Conclusions

GIS based erosion estimations using RUSLE were less than field sediment yield values in normal and high rainfall years. Estimated erosion was consistently higher in years where low and zero sediment yield was measured. It was assumed that the measured sediment yield based on the sampling techniques were sufficient to estimate total watershed sediment yield. Utilizing RUSLE with GIS to predict erosion on watersheds still requires quantifying channel erosion and deposition to achieve accurate results. To this end, more field work to measure these components and improve RUSLE's ability to predict erosion and deposition is needed. Caution should be used in applying a SDR, for it only explains the difference in predicted erosion and sediment yield for average annual conditions. The difference between wet and dry year RUSLE estimates and measured sediment can only be explained by channel deposition.

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