Paper presented at the 22nd Asian Conference on Remote Sensing, 5 - 9 November 2001, Singapore.

EXTRACTION OF PARAMETERS AND MODELLING SOIL EROSION USING GIS IN A GRID ENVIRONMENT

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KEY WORDS: GIS, Soil Erosion, Modelling, Watershed, USLE

ABSTRACT

Soil erosion assessment for watershed management is one of the major concerns because in reality it is not possible to conserve all areas under the threat of erosion because of the financial constraints. Geographic Information Systems are becoming a popular tool when seeking solutions to issues of these kinds, which are spread over large spatial extents. However it is of utmost importance to ensure a reasonable assessment of soil erosion because this is the core to any such decision making. Use of USLE for erosion assessment using GIS poses concerns since some parameters are polygon specific. This could be overcome easily by the use of grid-based data layers and selecting appropriate size of grids for a particular data set. The most common problem is the computation of the slope length and slope class parameters of a particular grid of a DEM. The present study describes a different methodology to compute these factors using a digital elevation model of the study area. A watershed from Sri Lanka covering an area of 23,000ha was selected for modelling. Field survey results recognised the need to calibrate the model for planning purposes. Model calibration used a weighting scheme. A comparative analysis of results for the same project area from the grid-based model and a model that did not use grid-based data indicated an almost same value of mean annual erosion level for the watershed. This paper also carries a discussion of the key issues that need to be considered when modelling in different environments. Suitably developing a model in a grid data environment provides better flexibility to compute erosion levels for different spatial scales. Grid based method also enables the meaningful use of pixel based remotely sensed land cover information for modelling soil erosion.

1. INTRODUCTION

Soil erosion is one of the most serious environmental problems in the world today because it threatens agriculture and also the natural environment. Since soil erosion affects the productivity of land and while adversely effecting downstream areas, soil conservation takes a lead role in today's development programs. In reality it is not possible to conserve all areas under the threat of erosion because of the financial constraints. The attention is given to only a few selected locations at a time to suit the constraints in acquiring sufficient funds. Therefore in practice, vulnerable area are prioritised and then undertaken for development. Though such prioritisation work needs to consider many aspects such as critical areas of soil erosion, threat to lives & property, limitations in accessibility, social constraints and political stability etc., reasonable assessment of soil erosion is the core of any such decision making. Geographic Information Systems are becoming a popular tool when seeking solutions to issues of these kinds, which are spread over large spatial extents and require a study of many alternatives. Most common method for soil erosion assessment is the use of Universal Soil Loss Equation (USLE). Many have proposed modifications to the USLE but all are woven around the same concept where rainfall erosivity, soil erodibility, slope length, slope class, land cover and land management factors are taken as directly proportional to the rate of annual erosion (Brooks et al 1991, Renard et al 1997,Morgan 1986). Though development of a GIS for soil erosion assessment based on USLE may appear as a straightforward procedure, it requires caution in computations since the slope class and slope length attributes of spatial extents are polygon specific. This needs the computation of the soil erosion assessments to be limited to the slope class and slope length polygons and hence if such land parcels are not selected in a proper manner then overlaying may cause averaging of erosion levels over the concerned polygons (Wijesekera & Chandrasena 2001). The need for averaging could be easily overcome in a raster-based approach where polygons in each layer could be selected to be of the same size. Present study describes the methodology adopted to compute these factors and a comparison of results with the polygon based study done by Wijesekera & Chandrasena (2001). In order to compare the results, same watershed used in the above reference from Sri Lanka was modelled.

2. STUDY AREA

The selected watershed of 23,000 square kilometers is located in the Kegalle district (70 13' 50"N, 800 22' 18"E) of Sri Lanka (Figure 1). This watershed receives an average annual rainfall of about 3500mm. Elevations of the watershed range from 40m to 1100mMSL. Rainfall, soil types, land cover and topographic data from the Meteorology Department, Irrigation Department and the Survey Department were available for the study area. Study area indicated the presence of seven significant land cover types and three major soil types. Department of Agrarian Services (DAS) which is the agency responsible for the management of small agricultural area throughout the island had carried out a field survey to identify the level of soil erosion experienced in the study area. Field survey conducted by DAS had used a participatory approach where the villagers and officials jointly assessed and mapped the level of soil erosion observed in the watershed (Wijesekera & Chandrasena, 2001). This indicated a qualitative assessment where identified areas had been classified as either moderately or significantly eroded (Table 1). Field survey carried out in selected area of the watershed had identified 65 spatial units that were experiencing either moderate or significant soil erosion. Land cover distribution, rainfall and soil type distribution within the study area are shown in Table 2.

3. MODELLING SOIL EROSION

In order to carryout a comparative analysis model development was done similar to work of Wijesekera & Chandrasena (2001). Estimation of soil erosion by water in the study area was modelled using the USLE. USLE estimates the average annual soil loss (A) by using a functional relation of several factors expressed as A=RKLSCP where R is the rainfall erosivity, K is the soil erodibility, L & S are slope length and slope angle factors, C is the crop management factor and P is the erosion control practice factor. Modelling in the present study used a raster based approach where a square cell of 25 meters was chosen. It was taken that this resolution would be suitable for a reasonable accuracy considering that the original data were mostly from 1:50,000 maps. Grids of rainfall, soil land use and elevation data created using ArcInfo software were used for the computation for the USLE. Rainfall spatial averaging done using Thiessen polygons were converted to coverages of selected cell size. Rainfall erosivity factor for each cell was determined from the average annual rainfall value for that using a correlation developed for Sri Lanka by Premalal in 1986 (Gunawardene 1995). In this the rainfall erosivity was equated to (972.75+9.95xAnnual Rain)/100. Spatial distribution of soils converted to each cell was taken for computation of erodibility using values presented by Joshuwa (1977) for Sri Lankan soils.

USLE is an equation that estimates average annual soil loss by sheet and rill erosion on those portions of landscape profiles where erosion but not deposition is occurring. Also it does not look at gully erosion (Kenneth et al 1991). Slope length is defined as the horizontal distance from the origin of overland flow to the point where either the slope gradient decreases enough that deposition begins or runoff becomes concentrated in a defined channel. As such for a land parcel of a smooth surface, the slope length could be identified as the length of slope of that particular cell along the maximum slope direction. In this cell based study no attempt was made to identify either the surrounding flow accumulation or drainage networks in order to determine the slope length since flow accumulation is closer to concerns of gully formation. Therefore the approach to calculate the slope length in the present work differed from other cell-based studies such as Spanner (1983) or Satya & Ryosuke (1998) and looked at a single cell as an individual entity reflecting only its own annual soil loss as conceptualised by USLE.

Digitised contours of the study area were interpolated using a linear triangular irregular network . A 3x3 cell window was used to compute steepest slope and direction at the centre of a cell which were subsequently used for the computation of L and S factors. Other parameters of L and S factors were taken as described by Brooks et al (1991). Slope length factor was taken as $(\lambda/72.6)^m$ where λ is slope length and m a slope dependent parameter. Value for m was taken as 0.3 for slopes less than 5%, 0.6 for slopes greater than 10%, and 0.5 for slopes in-between. Slope gradient factor (S) is equal to $(0.43+0.3s+0.043s^2)/6.613$ where s is the slope gradient in percent. Initial C factors of the model were taken from published information related to land cover of the study area. Conservation practice (P) factors were determined using prevalent soil conservation land use practices in Sri Lanka. Since conservation practices of land use could be easily correlated with land cover, the P factor values for each land cover could be identified by field inspection. Values of C & P factors taken from literature and used for initial computations are in Table 2. Four data layers in the GIS namely rainfall, soil, slope and land cover, having cells of equal size were overlaid to compute the annual soil erosion at each cell.

4. MODEL CALIBRATION AND VERIFICATION

Model computations done using minimum crop management values cited in the literature had a variation of annual soil loss values between 0-887 tons/ha/year. Average value was 29.7 tons/ha/year with a standard deviation of 39.4, indicating that the high values reaching three figures were only in a limited number of cells. Acceptable soil loss tolerances from literature range from 2.5-12 tons/ha/year (Malcolm, 1992) (Soil & Water 1993). Comparison computations present an impression that 45% of the watershed area is experiencing a soil loss greater than 10 tons/ha/year. In contrast, field survey results showed that the watershed was not experiencing such a poor state of degradation. For model to be compatible with values cited in literature, outputs had to be much lower but since parameters used for USLE computations already used minimum values suggested in literature, model outputs could not be lowered further. As such for meaningful use, the GIS model outputs require calibration using filed survey data.

Field observations were clustered in to seven groups and out of these four groups were used for calibration and other three were used for verification. Modelled soil loss values were grouped to obtain the best match with field survey data. Since the distribution of erosion level in cells did not vary much from the cited polygon based study the weighting scheme in optimisation used the same weights of 15, 35 and 50 tons/ha/year for insignificant, moderate and severe erosion levels to ensure better comparison. Mean Ratio of Absolute Error which is $(1/n)\Sigma\{|Eo-Ec|/Eo\}$ where E,o,c,n are for erosion level, observed, calculated and for number of samples respectively, was used as the objective function. Matching process with direct matching of cell values did not converge automatically. Hence a semi-automated methodology using both the MRAE and a visual pattern comparison was adopted. A visual comparison was necessary for optimisation since the USLE computed long time average soil loss whereas field investigations observed actual situations that reflected the influence of localised effects of features and gully erosion as well. Computations optimised the threshold values between insignificant, moderate and severe erosion classes as of 33 and 48 tons/ha/year with a calibration error of 0.0792 and a verification error of 0.0752.

5. COMPARISON

Comparison of computed spatial distribution of erosion levels from both methods is in Figure 2. Modelling results showed that about 16% of watershed could be ranked in the severe erosion level category. Polygon based USLE values had a mean value of 33 tons/ha/year, a standard deviation of 26 and varied between 0-156.. Study using slope polygons grouped slope classes into six in which slopes greater than 45% were grouped as one. In the present study, slopes were not grouped and hence unconstrained. This could have been a reason for indicating a higher upper limit. Investigation of the individual cell values showed that 3.5% of the area had resulted in annual soil loss values greater than 156. Both methods resulted in similar values through model calculations.

Calibration of USLE values in the polygon-based method had 26 and 45 tons/ha/year as threshold values between insignificant, moderate and severe erosion classes. Averaging of computed annual soil loss estimate values in slope-averaged polygons would have resulted in comparatively lower value of thresholds in the polygon based method. Though the values from both methods do not drastically differ from one another, it is prudent to be cautious of the averaging effect over spatial extents when model computations are used for planning purposes.

Creation of DEM from 20m interval contour data indicated issues such as flat valley bottoms and ridge tops. Investigation of computations at each cell showed that in most cases such flat area represented insignificant soil erosion zones as expected in nature. However, in most ridge tops and in some valley bottoms, it is necessary to identify spot heights to evade this masking effect of the steeper zones because masking may hide some significant erosion level zones. This deficiency was noted in both methodologies.

A comparison of area in zones having severe, moderate and insignificant soil erosion levels from both methods is shown in Table 3. Percentage of extents classified under moderate level of erosion in polygon based computation shows a reduction in the raster-based approach. Comparison shows that there had been a tendency for values of polygon approach to move from the moderate category to the insignificant category when raster approach is used. This suggests that polygon-based approach may lead to an over estimation of extents that require precautionary measures. However it is noted that a careful selection of manageable polygon sizes may look after this concern. Comparison shows that both methods estimated similar annual erosion levels for approximately 70% of the watershed with a well matched spatial distribution. Estimations were quite close in the severe category indicating the greater emphasis on this category when using a weighted function for optimisation.

6. CONCLUSIONS

1. Modelling USLE in a raster GIS using cell gradient and aspect for slope length factor computations resulted in very satisfactory out puts thus indicating the potential of GIS Model for planning purposes.
2. Field verification of outputs indicated the importance of calibrating the erosion model to avoid deviation from reality reflecting alarming situations.
3. Optimisation techniques need to consider objective functions supported by weighting schemes combined with visual comparisons to ensure matching of both magnitude and spatial variation.
4. Calibration of raster based model indicated 33 and 48 tons/ha/year as the threshold values between insignificant, moderate and severe values for the watershed. These were quite similar to the values obtained

from polygon method and hence could be used as guidance for uncalibrated watershed of similar nature. However due consideration to the deviation should be given with respect to the intended usage.

5. Grid based approach could reduce the effect of spatial averaging effect of slope class polygons experienced in the polygon based method.
6. DEM generation for similar work need to make every attempt to incorporate additional spot heights to avoid masking of steep terrain during computations.

7. REFERENCES

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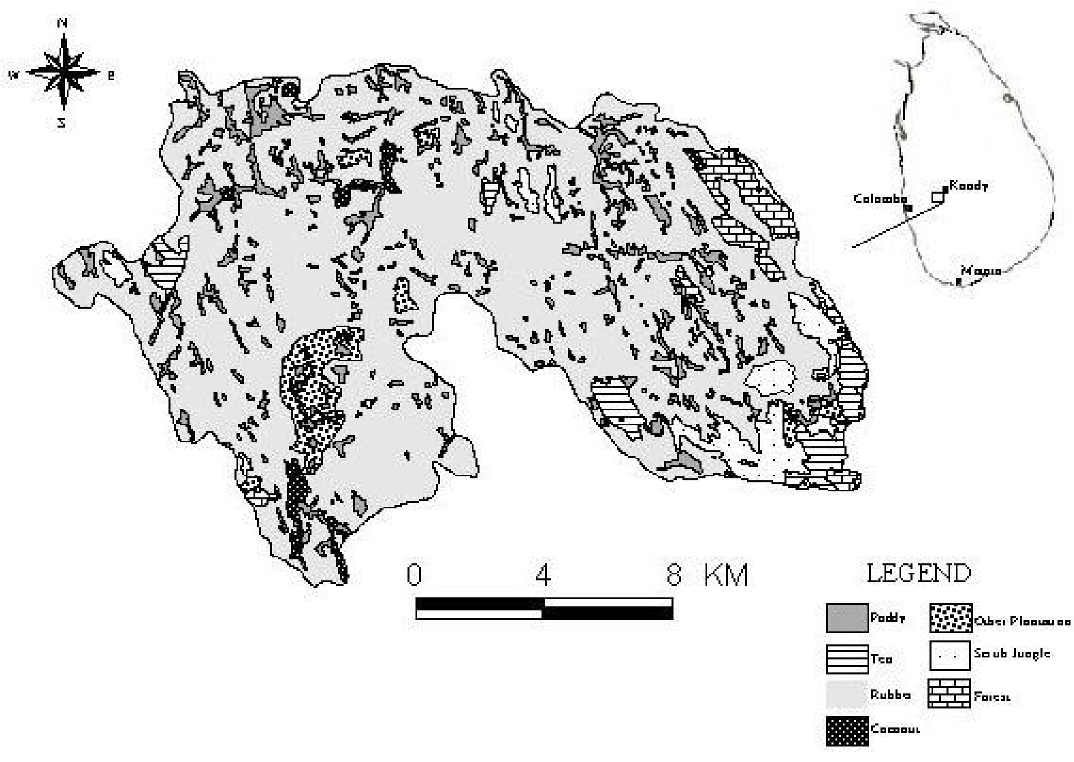

Figure 1: Location and Major Land Cover of Study Area

Table 1: Field Assessment of Erosion Level

Erosion Level	Identification
No Significant Erosion	Erosion is not considerable / No apparent soil erosion / loss of top soil is slight or not significant
Moderate Erosion	Dissection of runoff channels or gullies / moderate loss of top soil clearly visible and the loss is less than 25cm / slight exposure of tree roots
Severe Erosion	Severe erosion, complete truncation of soil profile / subsoil exposed / Deep channels or Gullies, Loss of Top Soil is greater than 25 cm

Table 2: Rainfall, Soil, Land Cover Distribution of Study Area and Associated Erodibility, C& P Factors

Land Cover Distribution in the Watershed and Associated C & P Factors

Land Cover	Distribution (%)	C Factor	P factor
Paddy	9.7	0.1 – 0.2	0.15
Tea	3.2	0.1 – 0.4	0.35
Rubber	75.3	0.2 – 0.3	0.35
Coconut	1.1	0.1 – 0.2	0.6
Other Plantation	3.4	0.1 0.2	1
Scrub Jungle	4.6	0.002 – 0.02	1
Forest	2.7	0.001 –0.01	1

Soil and Rainfall Distribution in the Watershed

Soil Type and Erodibility	Distribution (%)
Red Yellow Podzolic (0.22)	74.6
Reddish Brown Latazolic (0.17)	24.5
Immature Brown Loam (0.33)	0.9

Annual Rainfall (mm)	Distribution (%)
2423	27.3
3724	9.3
3381	63.4

Table 3: Comparison of Polygon Based and Grid Based Results

Polygon Based Estimation	Grid Based Estimation			Total
	Severe	Moderate	Insignificant	
Severe	11.4 % (2605 ha)	4.3% (991 ha)	5.9% (1360 ha)	21.6% (4980 ha)
Moderate	3.3% (761 ha)	3.2% (738 ha)	13.8% (3113 ha)	20.3% (4681 ha)
Insignificant	1.2% (230 ha)	1.5% (346 ha)	55.3% (12796 ha)	58% (13,373 ha)
Total	15.9% (3666 ha)	9.0% (2075 ha)	75.0% (17,293 ha)	100%

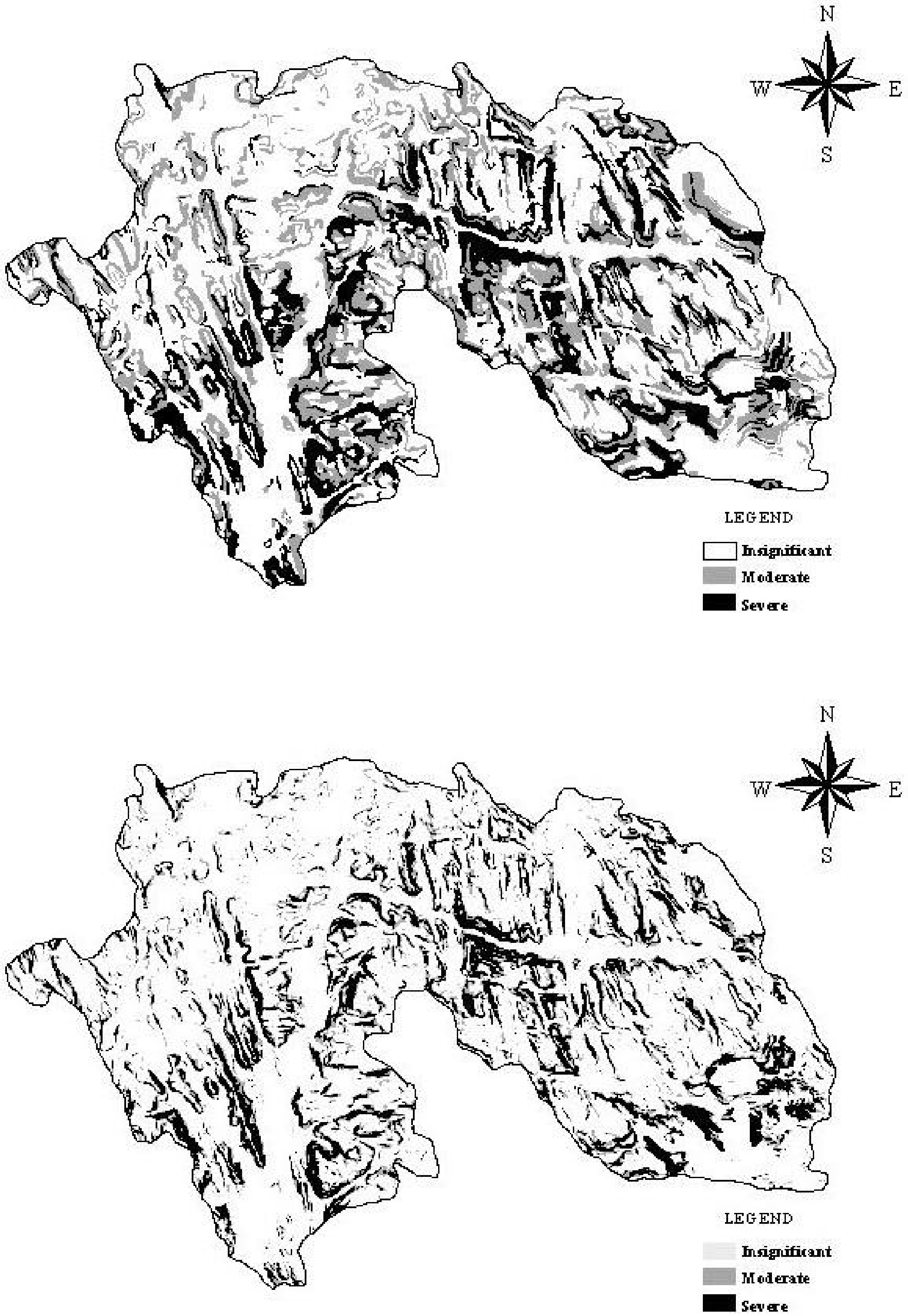

Figure 2: Comparison of Polygon Based (Top) and Grid Based (Bottom) Results