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GIS Application for Comprehensive Spatial Soil Erosion Analysis with MUSLE Model in Sandakan Town Area, Sabah, Malaysia

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ABSTRACT

Soil erosion is one of the principal causes of soil degradation in Sandakan, Sabah, Malaysia. The natural phenomenon of erosion is now accelerated by human activities that alter the natural mechanisms. This acceleration is caused by destruction of plant cover, the growing of wrong cultivations, unsuitable farming techniques etc., all of which may be prevented with correct management and land planning. Soil erosion has been identified as one of the important environmental issues and therefore, detail assessment on prediction of soil loss and its impacts has been carried out using the application of the Modified Soil Loss Equation (MUSLE) and Geographical Information System (GIS). ARC-INFO was used for the storage of the data layer on each factor controlling soil erosion. Identification of potential high-risk erosion areas was made using a thematic data layering approach to analyze risk areas. The quantitative soil loss (t ha-1 yr-1) ranges estimates by MUSLE model by a spatial information analisis approach (GIS) were computed: (a) Very High risk (>150 tons/ha/year); (b) High risk (100-150 tons/ha/year); (c) Moderate risk (50-100 tons/ha/year); (d) Low risk (10-50 tons/ha/year); and (e) Very low risk (<10 tons/ha/year). About 46.33% of the area was classified as very low, 43.50% as low, 5.23% as moderate, 4.49% as high and 0% as very high. Soil erosion hazard has been identified and found to be significant in areas with slope above 36.96o. All findings showed that integration of GIS can be used for spatial analysis in a large scale. Production of A total value maps can be applied to particular development planning areas especially for housing and agriculture developments.

1. INTRODUCTION

Soil erosion is one of the principal causes of soil degradation in Sandakan, Sabah, Malaysia. The problems provoked by erosion result in economic loss in the agricultural and forestry sectors and may directly or indirectly pose hazards to persons or property due to such events as landslides, floods, etc. The natural phenomenon of erosion is now accelerated by human activities that alter the natural mechanisms by which rocks are degraded and soil is formed. This acceleration is caused by destruction of plant cover, the growing of wrong cultivations, unsuitable farming techniques etc., all of which may be prevented with correct management and land planning.

Soil become impermeable due to several conditions: first when the rainfall intensity exceeds the absorptive capacity of the surface and second when the groundwater level is at a level parallel to the ground. Soil erosion may lead to the decrease of chance of successful regeneration and reduce soil fertility (Bockheim, et al., 1975). The process of soil erosion may indirectly result in the loss of natural resources gradually and affect long-term productivity of the land. In the tropic where poor soil cohesion, high rainfall and temperatures give rise to highly erosive soil that are very sensitive to the impacts of clearance of vegetative cover (Lal, 1981; Huang and Laflen, 1996). In addition, soil erosion also leads to deterioration of the quality of surface water or ground water due to the increase in turbidity due to sediment transport and may contribute to the occurrence of some event such landslide and flooding hazards.

Based on Baharuddin et al. (1995), under natural condition, rates of erosion have been reported as very low in Malaysia. Erosion rates increased when tree canopy and litter layer are disturbed, and when soil surface was exposed. Erosion starts with the detachment of soil particles by rainfall splash and progresses in the form of sheet, rill and gully erosion. From the past studies on soil loss in Sabah (Malmer & Grip, 1990) and other studies sites in Malaysia (Lai et al., 1994; Lai et al., 1996) soil loss from undisturbed natural forest of varying slopes from 6-30 degree varies from 0.08 to 0.77 t ha-1y-1.

Geographic Information Systems (GIS) are the most important tool for seeking solutions to issues related to soil erosion. One of the most common methods used for soil erosion assessment is the Universal Soil Loss Equation (USLE). Research topics related to soil erosion has its own history and scientific basis underlying all been researched for decades. However recently, continue to review progress and are increasingly focused on the topic in more detail about the modeling mechanisms. In general, there are three types of soil scientific basis underlying all been researched for decades. However recently, continue to review progress and are increasingly focused on the topic in more detail about the modeling mechanisms. In general, there are three types of soil erosion models (modified from Merritt et al., 2003) in different research that (1) Empirical model (Musgrave Equation – Musgrave, 1947; Pacific Southwest Interagency Committee (PSIAC) - Pacific Southwest Interagency Committee, 1968; Dendy-Boltan Method Flaxman Method – Flaxman, 1972; Equation (MUSLE) Sediment – Renfro, 1975; Delivery Ratio Method – Dendy & Boltan, 1976; Universal Soil Loss Equation - Wischmeier & Smith, 1978; Soil Loss Estimation Model for South Africa (SLEMSA) – Elwel, 1978), which represents the natural environment or that are based on statistical observations of the empirical (Nearing et al., 1994). This model is often used for modeling complex process, particularly useful to identify the source of sediment (Merritt et al., 2003). (2) Physical-based model (Sediment Concentration Graph – Johnson, 1943; Erosion Kinematic Wave Models – Hjelmfelt et al., 1975; Renard-Laursen Model – Renard & Laursen, 1975; Quasi-Steady State - Foster. Meyer and Onstad, 1977; Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) – Beasley et al., 1980; Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) – Knisel, 1980; Water Erosion Prediction Project (WEPP) – Laflen et al., 1991; European Soil Erosion Model (EUROSEM) – Morgan, 1998) represent the natural processes that describe each system by consolidating individual physical processes of more complex models. The equations in the model formula are illustrated by natural processes such as stream flow or sediment transport (Merritt et al., 2003). Perfection in this model can explain the spatial variability of its most important features found on the soil surface as topography, aspect, slope, vegetation, soil, climate and various other parameters including precipitation, temperature, precipitation and evaporation (evaporation) (Legesse et al., 2003). (3) Conceptual model is a mixture of empirical and model-based physical model (Unit Sediment Graph – Rendon-Herrero, 1978; Instantaneous Unit Sediment Graph – Williams, 1978; Sediment Routing Model – Williams & Hann, 1978; Discrete Dynamic Models – Sharma & Dickinson, 1979; Agricultural Catchment Research Unit (ACRU) – Schulze, 1995; Hydrologic Simulation Programme, Fortran – Walton & Hunter, 1996) and its application more applicable to answer general questions related to catchment processes (Beck, 1987 and Merritt et al., 2003).

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2. Description of The Study Area

Location of the study area is located in Sandakan Town, Sabah. The rapid development since the eighties (80's) had a spill over effect in the Sandakan town area where lands was cleared for the construction of highways, high-rise buildings, industrial, housing area and several other heavy infrastructures. These activities had, besides spurring economic growth, also caused environmental management problems, such as streams were polluted with pesticides, flash flood, fertilizers and siltation. There was also widespread erosion in the cleared areas, slope failure and land subsidence had frequently occurred. Climate plays an important role in affect substantially the runoff on slopes, especially in research and modeling soil erosion mechanism. The study area experienced equatorial climate is hot and humid all year round.
The aim of this paper is to assess the soil erosion due to land-use planning in Sandakan Town area. The objective is to generate a GIS-assisted soil erosion map of the study area as a means of providing information to various levels in the decision-making process

2.1 Geology

The exposed rocks in the study area and its surrounding vary in types and ages, from Late Eocene-Early Miocene, Neogene's clastic sediment of the Garinono Formation, the Sandakan Formation and Volcanic Facies to vary recent Quaternary alluvial materials which are still being deposited. The Garinono Formation consists mainly of slump breccia and includes sequences of intebedded mudstone, tuff, tuffite and minor sandstone and calcarenite. The slump breccia of the Garinono Formation is made up of fragments and blocks of assorted rock types in a mudstone matrix. The fragments and blocks consists mainly sandstone, limestone, chert, basalt, serpentinite and gabbro. Mudstone, sandstone, tuff and tuffite form interbedded sequences at different stratigraphic horizons in the Garinono Formation (Lee, 1970). The Sandakan Formation was deposited in a shallow marine, deltaic and partly fluvatile environment. The lithological sequence includes sandstone, carbonaceous mudstone and conglomerate (Lee, 1970). The Sandakan Formation consists of sedimentary succession which has been dated to the Miocene and Pliocene age. These outcrops are usually well persevered and exhibit a mud-dominated sand-shale alternations. The Volcanic Facies has a thickness of about 25 to 45 metres and has a greyish to black colouration. Grain sizes in fine and can be found at the Buli Sim Sim area. The formation of the volcanic facies is believed to have its origin in the Dent Volcanic of the Early Miocene (Lee, 1970). Pliocene to Quaternary sediments rests on top the Sandakan Formation. These deposits consist of high-level alluvium and recent alluvium. High-level alluvium is found around the coast and consists of unconsolidated deposits older than the recent alluvium. Recent alluvium is deposited along major river valleys and deltas and consists mainly of clay, silt and gravel. The alluvium soft, compressible and may be prone to excessive settlement.

3. Materials and Method

3.1 Modified United Soil Loss Equation (MUSLE)

GIS applications are often used in the work of soil erosion analysis. Modelling soil erosion is often considered difficult because of the relatively complex interactions. Generally there are four factors to consider; soil, topography, land use and climate (Wischmeier & Smith 1978). Overall approach of this paper will involve the use of models of universal soil loss equation (USLE), which was introduced by Wischmeier & Smith (1978). Although this model was found to have a lot of constraints and uncertainty, but it's very popular widely used throughout the world to date, especially in the tropics because it has the simplicity and relative robustness and uniform approach (Aniya, 1985; Balamurugan, 1991 ; Kerte'sz, 1993; Gokceoglu & Aksoy, 1996; Lenzi & Luzio, 1997; Larsen & Torres-Sanchez, 1998; Turrini & Visintainer, 1998; Guzzetti et al., 1999; Sharma et al., 1999 Huffman et al ., 2000; Jibson et al., 2000; Brazier et al., 2001; Millward & Mersey, 2001; Beatriz et al., 2002; Bissonnais et al., 2002; Martı'nez-Casasnovas, 2003; Huabin et al. , 2005; etc.). Precipitation, topography, soil type and land use as a database that will be used in the analysis. Each developed vector data will be converted into raster data. For raster data, the space is divided evenly into pixels in a square shape that has the same size. Value is stored for each pixel determines the type of an object or situation that is available in every location. Thus, in the approach to raster data, the space occupied by a number of uniform pixels, each of which has different values (Figure 1).

4. Results

In this study, the USLE is used to estimate the total value of A is expressed as mass per unit area per year (t / ha / year) (Equation 1). MUSLE equation (Equation 2) was used in the GIS environment to determine the total value of A and its distribution. This equation predict the loss of land for an area based on six parameters such as rainfall erosivity factor (R), soil erodibility factor (K), slope length factor (L), slope steepness factor (S), cultivation and management factor (C) and conservation support practice factor (P) which are all evaluated numerically.

igure 1.: Research Framework and Methodology

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

Since the USLE was designated for agricultural lands, the soil loss was estimated using the modified model to suit for forest environmental conditions called modified soil loss equation (MUSLE) (Warrington et al., 1980). In MUSLE model, soil cover management factor (C) and soil conservation practice factor are replace by vegetation management (VM). It written as:

$$A = R * K * L * S * VM \quad (2)$$

Factors controlling soil erosion such as steepness, slope length, rainfall, soil erodibility, and vegetation management factors have been identified within the project area and mapped. Subsequently, the various factors maps were overlain to determine erosion levels of each identified watershed in the study area, based on the MUSLE using GIS in a grid cell format. Scanning, digitization and geo-referencing were done in the input module. The output of this module was used as the base for the analysis module to integrate and process on logical combinations and knowledge-base rules. The rules were constructed form the knowledge of the terrain parameter of the study area. Integration of these rules was carried out with graphic (spatial) database in the analysis module. Using the query support, the spatial database was analyzed and the final soil erosion map was produces. The erosion-risk levels (very low, low, moderate, high and very high) were identified and marked on the map for further analysis.

4.1 Rain Erosivity Factor (R)

The rate of soil erosion is associated with rain seepage strength to break the soil surface and cause surface runoff (water runoff) occurs (Morgan et al., 1998). R values were calculated based on the equation that was introduced by Morgan (1974), by referring to the annual average rainfall and intensity data for 30 minutes at a maximum for each rain gauge stations in Sandakan Town, which obtained from the Malaysian Meteorological Department, Kota Kinabalu branch. Equation (3) by Morgan (1974) was chosen because it has been proven successful in several previous studies to tropical countries, especially in Malaysia.

$$R = [(9:28 * P) - 8838] * 0.075 \quad (3)$$

Where,
P = annual average rainfall
I_{30} = rainfall intensity for 30 minutes (75mm)

The rain gauge stations in the study area have been registered into the GIS map format by entering the coordinate position. The average rainfall for each rainfall station will be used as input into the file attributes in the GIS (Figure 2). Based on the input, the estimated rainfall for the Sandakan Town area is done by using the Thiessen polygon method which is a better method than the method of calculation Aritmetrik rainfall areas (Chow et al., 1988). K is the soil-erodibility factor which measure erodibility for a standard condition. This standard condition is the unit plot, which is an erosion plot

72.6 ft (22.13 meters) long on a 9 percent slope, maintained in continuous fallow, tilled up and down hill periodically to control weeds and break crust that form on the surface of the soil. The plots are plowed, disked and cultivated the same for a row crop of corn or soybeans except that no crop is grown on the crop.

Soil erodibility factor represents both susceptibility of soil to erosion and the rate of runoff, as measured under the standard unit plot condition. Soils high in clay have low K values, about 0.05 to 0.15, because they resistant to detachment. Coarse textured soils, such as sandy soils, have low K values, about 0.05 to 0.2, because of low runoff even though these soils are easily detached. Medium textured soils, such as the silt loam soils, have moderate K values, about 0.25 to 0.4, because they are moderately susceptible to detachment and they produce moderate runoff. Soils having high silt content are most erodible of all soils. They are easily detached; tend to crust and produce high rates of runoff. Values of K for these soils tend to be greater than 0.4. Organic matter reduces erodibility because it reduces the susceptibility of the soil to detachment, and it increases infiltration, which reduce runoff and thus erosion. Addition or accumulation of increased organic matter through management such as incorporation of manure is represented in the C factor rather than the K factor. Extrapolation of the K factor nomograph beyond on organic matter of 4% is not recommended or allowed in MUSLE. In MUSLE, factor K considers the whole soil and factor Kf consider only the fine-earth fraction, the material of <2.00mm equivalent diameter. For most soil, Kf = K.

Soil structures affect both susceptibility to detachment and infiltration. Permeability of the soil profile affects K because it affects runoff. Although a K factor was selected to represent a soil in its natural condition, past management or misuse of a soil by intensive cropping can increase a soil's erodibility. The factor K may need to increase if the subsoil is exposed or where the organic matter has been depleted, the soil's structure destroyed or soil compaction has reduces permeability.

In this study, the K factor for each soil type data obtained from the State Department of Agriculture based on the parent material. After the entry of all data attributes carried out for each soil type in the spatial database in vector format, it was later converted into a spatial raster format using the Conversion in Arc tool Box on raster pixel size of 10 x10 square meters (Figure 2).

4.3 Slope Length and Steepness Factor (LS)

The LS can be used in an index (Wischmeir & Smith, 1978). Emprikal equation calculating the LS was introduced by USDA Agriculture Handbook No. 537 (Offline. Wischmeier & Smith, 1978). This equation can be changed according to the suitability of an area. In this study, the formula used is based on the equations introduced by Moore & Burch (1986) (Equation 4).

LS = (flow accumulation cell size * / 22.13)0.4 * (sinslope / 0.0896)1.3 (4)

Flow accumulation was the theme of the accumulated flow grid described as the number of pixels grid, while the cell size is the length size of pixels in the grid theme. ArcGIS 9.3 application that is used to get the LS is through instruction in Hydrology tools and surface tools. To obtain the values for L and S, the digital elevation model (DEM) in advance will be generated from the topographic map contour gaps of 10 meters. The DEM is converted into raster format. To get the L, DEM data produced requires several stages of the generating process as fill DEM, flow direction and flow accumulation. While for the S, generation steepness also made by DEM data. After the process of generating the values of L and S is complete, the calculation / multiplication will then be made based on the Equation (5) by Moore & Burch (1986) using the raster calculator in Spatial Analyst extension (Figure 3). Figure 2 show the map of LS value of the study area.

LS = Pow ([Flow accumulation] * 10 / 22.13, 0.4) * Pow (Sin ([slope] * 0.01745 / 0.0896, 1.4) * 1.3 (5)

4.4 Vegetation Management Factors (VM)

The VM value is used to evaluate effects of cover and land management practices on surface erosion over the entire slope length where the LS factor was calculated. The VM factor of the MUSLE is a combination of vegetation cover and soil surface conditions into a single factor (Figure 2). It is a product of three sub-factors which is canopy cover, mulch or ground vegetation, and bare ground with fine roots. Landsat scenes were used to output the land cover layer.

4.5 Average Annual Soil Loss Value Analysis (A)

Soil erosion risk was determined by multiplying the respective MUSLE model interactively in Arc/Info GRID using equation (2). The soil loss values obtained were consequently grouped into four categories using a frequency distribution analysis namely very low, low, moderate, high and very high.

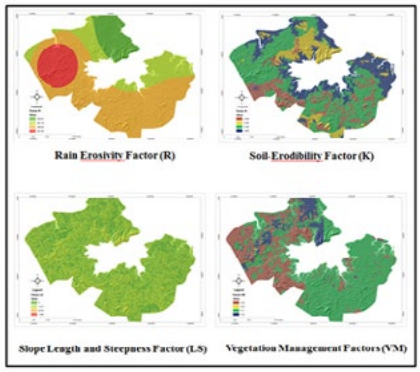

Figure 2: MUSLE factors using in Annual Soil Loss Value Analysis (A) determination

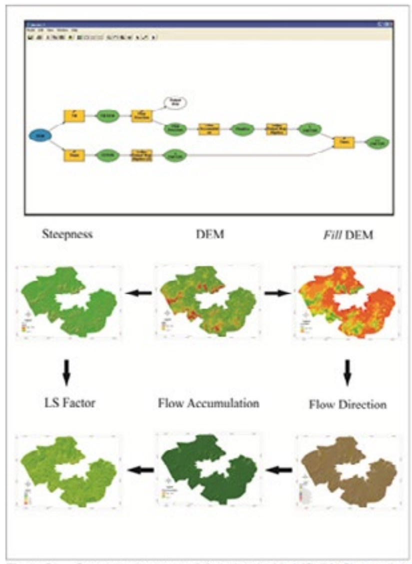

Figure 3: Geoprocessing approach by using the ModelBuilder™ to produse new maps for LS factor

Figure 3: Geoprocessing approach by using the ModelBuilder™ to produse new maps for LS factor

5. Disscussion

5.1 Average Annual Rate of Land Loss (RKLSCP)

Calculation of the total value of A was carried out based on the risk classification of soil erosion as introduced by Lam (2000) (Table 1). This classification is done by using reclassify techniques and for the purpose of statistical analysis, it uses the zonal attributes. For the purpose of conversion of land into acres, each number of pixels (count) will be multiplied by 100 (10 * 10 square meters) and then divided by 10,000. In terms of soil erosion risk classification (Figure 4), the calculation of the RKLSCP (total value of A) for the study area suggests 46.33% (1 074.1 hectares) as Very Low Risk, 43.5% (1008.6 hectares) as Low Risk, 5.23% (121.2 hectares) as Medium Risk, 4.94% (114.6 hectares) as High Risk and 0% as Very High Risk (Table 2). In general, the risk was "very low" to "low" refers to the slope of the horizontal (<15o) or moderately steep (16o - 25o). Conversely, areas with "high" to "very high" represent segments steep slopes (> 25o), upland areas and the banks of the creek. As a result of this decision emphasizes the importance of the potential impacts of soil erosion in the study area, which can be considered to represent a large part of the Sandakan town area.

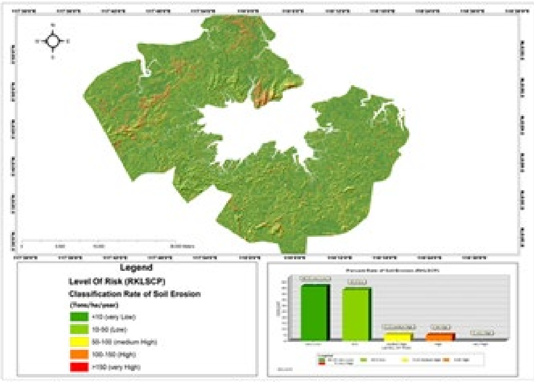

Figure 4: Map of average annual soil loss (RKLSCP) of the study area

Table 1: Classification of average soil loss risk (Lam, 2000)

Total soil loss erosion (tons/ha/year)	Risk Level
<10	Very Low
11- 50	Low
50-100	Moderate
101-150	High
>150	Very High

Table 2: Average annual soil loss rate (RKLSCP)

Class Of Average Soil Loss Risk	Total soil loss erosion (tons/ha/year)	Area Wide (Meter^2)	Area Wide (Hectare)	(%) Soil Loss
Very Low	<10	10,740 815	1,074.1	46.33
Low	11- 50	10,085 623	1,008.6	43.50
Moderate	50-100	1,212 168	121.2	5.23
High	101-150	1,146 222	114.6	4.94
Very high	>150	3	0.0003	0
Total		**23,184 831**	**2318.5**	**100**

5.2 Potential Impacts of Climate Change on Soil Erosion

5.2 Potential Impacts of Climate Change on Soil Erosion

Quantifying the impacts of climate change on soil erosion has important implications to the understanding of their environmental impacts. The rate of erosion depends on many factors including precipitation intensity, soil characteristics, topography of the terrain, and land cover type. The MUSLE equation depends on five factors related to climate (rainfall runoff erosivity (R), soil type (erodibility factor, K), topography (slope steepness and length factor, LS) and vegetation management (VM). The first factor is a sole function of rainfall frequency and intensity; both are influenced by climate change.

Change in total rainfall amount at a given location may occur in different ways, primarily either due to an increase in the number of precipitaion (wet) days or due to increased average precipitation per wet day. Coressponding to a change in the average amount of rainfall during wet days is generally a change in rainfall intensities. In other words, the distribution of rainfall amounts per day is generally correlated to the distribution of rainfall intensities in the study area. These two factors of rainfall change will influence runoff and erosion in different ways.

Long term investigations of soil erosion require information about the way in which climate change influences the resilience and stability of terrain topography and land cover type. it is, therefore, necessary to identify and monitor indicators of terrain topography and land cover type resilience and stability. an important element of climate change – soil erosion relationships is establishing how rapidly such key indicators respond to change. this can be done, for example, by following changes occurring after fire, grazing or land abandonment on slopes having different aspects.

6. Conclusion

The total value of A shows that the result of the RKLSCP is estimated as 46.33% of soil loss (1074.1 hectares). In terms of average soil erosion risk classification, for the class of very low to low, the results for the total RKLSCP showed the highest value of 46.33% and 43.50% with an area of approximately 2,082.7 hectares. The findings prove that integration of GIS spatial analysis is able to scale the region. The maps of total value of A produced can be used as a reference for development planning area, particularly agricultural and residential development.

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