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GIS-Based Upland Erosion Mapping

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PREFACE

The main source of sediments in reservoirs is from upland areas. Very high upland erosion rates have been observed in tropical countries around the world. For instance, Malaysia receives 2500 mm of rainfall precipitation per year and the steep mountain areas are subjected to deforestation. The corresponding erosion rates have exceeded 10,000 tons/km^2/year. The example of Cameron (C.) Highlands in Malaysia illustrates how geographic information system (GIS) can be used to examine soil erosion mapping. From this study using the Revised Universal Soil Loss Equation (RUSLE) model, the average annual soil loss rate at C. Highlands was estimated at 282,500 m^3/year in 1997 and increased to 335,000 m^3/year in 2006. The comparison of erosion rates between 1997 and 2006 shows a soil loss increase of 18.5% in less than a decade. These rapid increases in reservoir sedimentation rates are attributed to changes in land use that can be easily monitored with GIS.

16.1 Introduction

16.1.1 Upland Erosion Processes and Models

The main source of sediments in reservoirs is from upland erosion. Morgan and Davidson [22] and Julien [15,16] describe soil erosion processes and dynamics that have been studied for decades. The main factors contributing to upland erosion losses include rainfall erosivity, soil erodibility, land topography, land use, and land conservation practices [9]. Specific degradation rates in reservoirs of the United States are typically less than 2000 tons/km^2/year [18] and are primarily linked to upland erosion rates. Upland erosion losses have been estimated using well-known methods like the Universal Soil Loss Equation (USLE) from Wischmeier and Smith [34]. The USLE includes all the factors affecting upland erosion from sheet and rill erosion. Renard et al. [25] provided a modified version named the Revised Universal Soil Loss Equation (RUSLE).

The advances in geographic information system (GIS) have allowed applications of raster-based formats for the determination of the various parameters of the USLE and RUSLE. Some detailed applications at the watershed scale include Mitasova et al. [20], Molnar and Julien [21], and Kim and Julien [19]. The applicability in tropical areas represents a challenge because of the reduced availability in GIS-gridded information for topography, soil type, and land use, as well as for the evaluation of the rainfall erosivity parameter R.

In tropical regions, the early and widely accepted soil erosion models consist of relatively simple response functions to predict mean annual erosion losses. Forest Research Institute Malaysia (FRIM) [11] provided a guide for soil erosion losses on Malaysian forestland using MUSLE. Schoorl et al. [28] state that the current trend is towards replacing these by far more elaborated process-based models. Among these models include water prediction program (WEPP) of the USDA; the erosion productivity impact calculator (EPIC); chemical, runoff, and erosion from agricultural management systems (CREAMS); and European soil erosion model (EUROSEM). These models are usually event based and are more applicable to agricultural areas than mountainous watersheds. Other models can be useful in the analysis of watershed hydrology (e.g., HEC-HMS, SHETRAN, and MIKE SHE). Other programs combine hydrology and hydraulics such as InfoWork RS, SWMM, SED2D, XP-STORM, and BASINS. Ekhwan et al. [7] studied the use of InfoWork RS to determine the sediment loads and riverbed profiles at Cameron (C.) Highlands. Hartcher and Post [12] studied the mean annual conceptualization of transport and deposition processes of sediments in Thailand using SedNet. Fortuin [10] under the REACH study created Early Warning and Risk Navigation Systems (EWARNS) in order to resolve and minimize the serious soil erosion problems in C. Highlands, Malaysia. TNBR [30] studied the use of DHI's SEAGIS

(Soil Assessment Model) to estimate the sediment entering into the river systems coupled with MIKE 11 and MIKE 12 model for the rainfall and hydrological conditions. Dynamic GIS-based watershed erosion modeling studies showing the processes of upland erosion, sediment transport, and deposition include applications of CASC2D-SED [8,13,17,26]. More recent developments of dynamic simulations of sediment transport and contaminant transport and fate were reported by Velleux et al. [31,32], Caruso et al. [4], and Johnson et al. [14].

C. Highlands in Malaysia is located in the mountains of a tropical region subjected to about 2500 mm of rain every year. The area formerly developed for hydropower development has been plagued with sedimentation problems. C. Highlands has been rapidly deforested and substituted with agriculture, urbanization, and infrastructure development contributing to severe soil erosion. The increase in soil erosion is primarily attributed to agricultural expansion, while the urbanization may also contribute, but to a lesser extent [28]. Changes in land use are therefore considered to have a major effect on the soil erosion losses.

This site provides a unique example for the demonstration of the applicability of GIS techniques for the analysis of upland erosion losses in a mountain tropical watershed. The site requires an evaluation of all the upland erosion parameters using RUSLE. The analysis also demonstrates how temporal changes in land use affect the upland erosion rates. This field site of C. Highlands in Malaysia has been selected because it is one of the most highly erodible areas in the world. The changes in land use between 1997 and 2006 are highlighted in terms of impact of soil erosion.

16.1.2 Field Site Description

The C. Highlands catchment area shown in Figure 16.1 in Peninsular Malaysia is relatively high with mountains ranging from 1524 m to Gunung Brinchang standing at 2032 m. Under the C. Highlands hydroelectric scheme—stage I construction, the high head scheme supplemented by the combined flow from two major rivers, Sg. Telom and Sg. Bertam, is being conveyed to the power house through a closed tunnel. The gross head estimated between Sg. Bertam and Sg. Batang Padang was 568 m.

The application of GIS facilitates the calculations of soil erosion by enabling the integration of hardware and software for the analysis of data capturing the spatial and temporal variability of watershed characteristics of geographically referenced information. GIS allows us to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. For this study, ArcGIS version 9.3 was utilized. A raster-based approach is used here because it has proven to be more convenient and very well suited for the analysis of soil erosion at the watershed scale. Overall the simulation models are the most effective way to predict soil erosion processes and their effect by using GIS [1]. GIS provides a great advantage to analyze multilayer of data spatially and quantitatively within the basin. The estimation of soil loss in the basin using GIS is also in the ranges of other studies. GIS not only provides accurate results but also provides cost- and time-effective ways of analysis.

The boundary shape files of C. Highlands were obtained from the Department of Agriculture (DOA), Malaysia, shown in Figure 16.2. These shape files were added as data into ArcGIS. The total drainage area of C. Highlands scheme is 183 km^2 comprising of 111 km^2 for Telom and 72 km^2 for Bertam.

16.2 Upland Erosion Parameters

The well-known and widely used model used to estimate soil erosion losses from the upland areas is the USLE developed by the USDA Wischmeier and Smith [33,34]. The model was later modified and

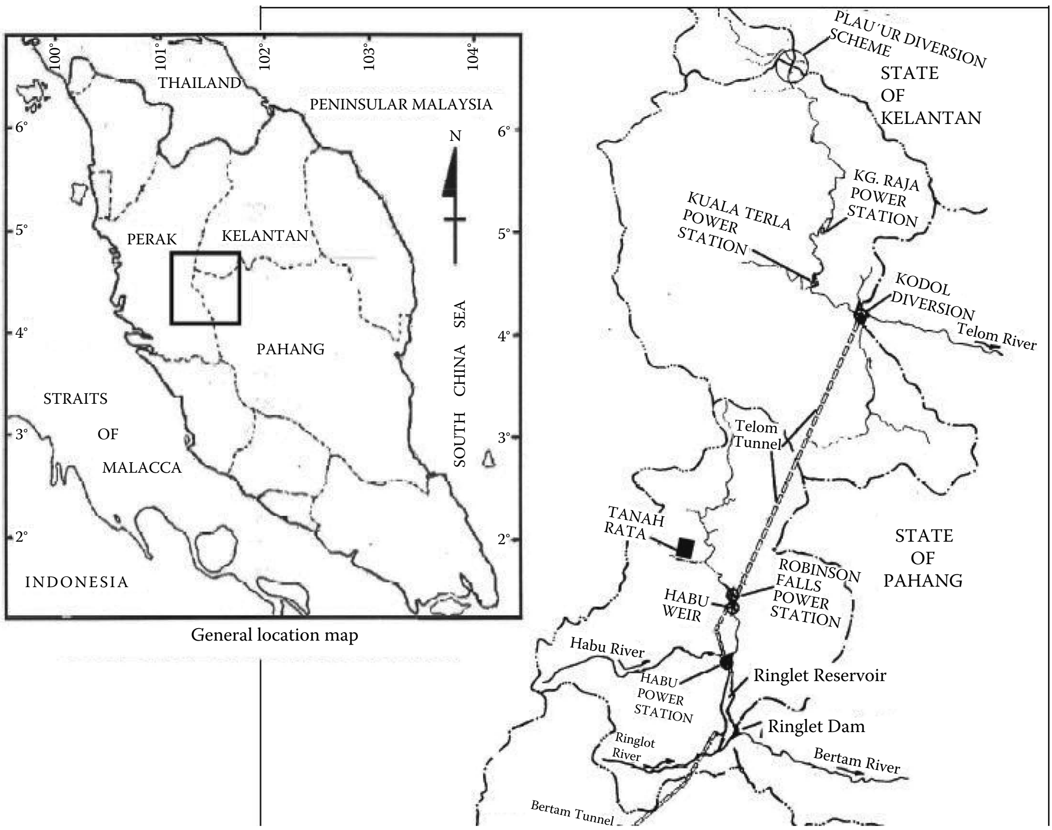

FIGURE 16.1 C. Highlands area.

renamed RUSLE by Renard et al. [25]. More details can be found in Pitt et al. [24] and Blaszczynski [2]. The USLE equation combines six parameters as described in Equation 16.1:

$$\mathbf{A = RKLSCP} \tag{16.1}$$

where

- **A** is the upland erosion loss in tons per acre per year
- **R** is the rainfall erosivity factor
- **K** is the soil erodibility factor
- **L** is the slope length factor
- **S** is the slope steepness factor
- **C** is the cropping and management factor
- **P** is the conservation practice factor

A flow chart for the calculation of soil erosion losses is presented in Figure 16.3. The calculation details for this study can be found in Teh [28].

16.2.1 Rainfall Erosivity

In earlier studies at C. Highlands, the mean annual rainfall precipitation was observed to be approximately 2620 mm fairly evenly distributed over the year with somewhat heavier rainfall periods in April and November. This estimate decreased slightly in recent years where the mean annual rainfall reached

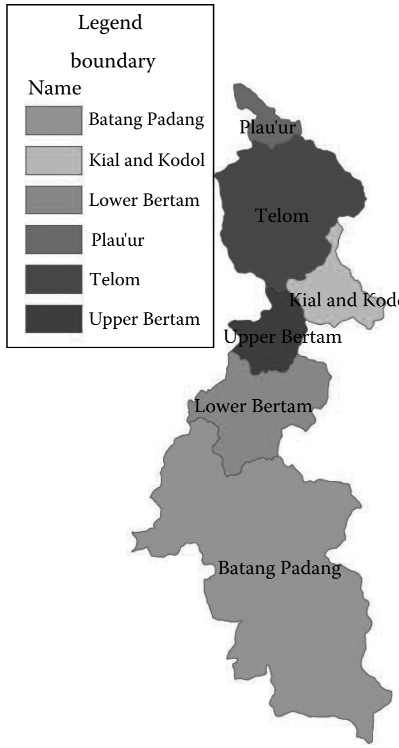

FIGURE 16.2 Boundary map, Department of Agriculture, Malaysia.

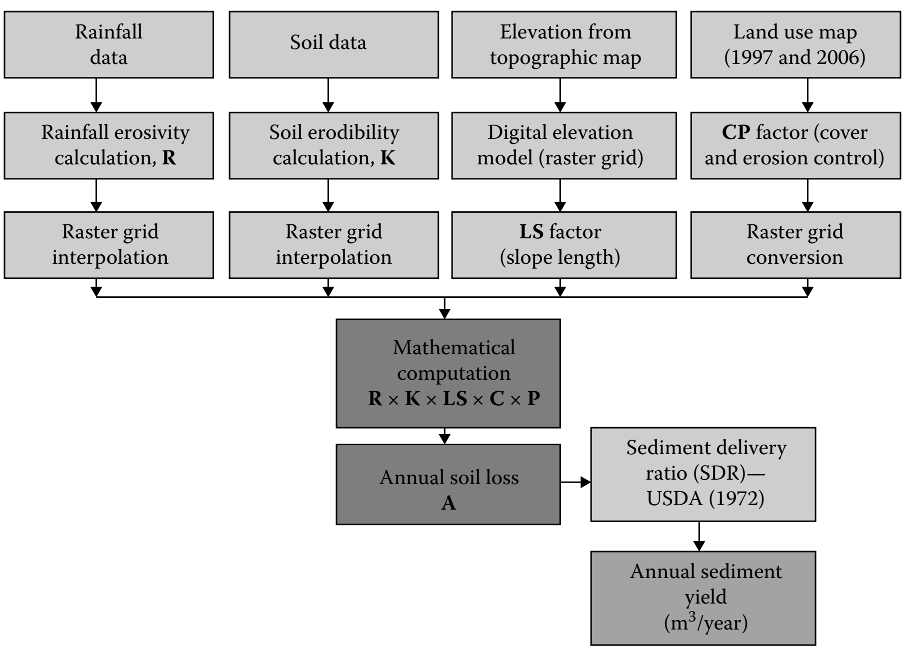

FIGURE 16.3 GIS-based upland erosion flow chart.

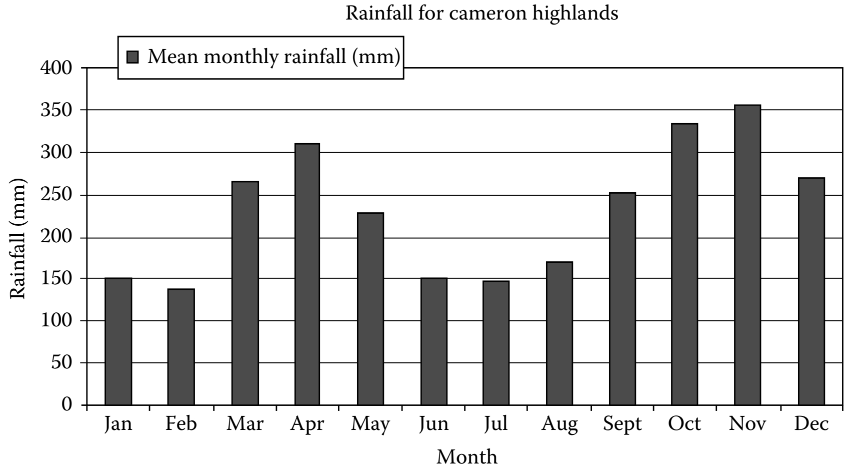

FIGURE 16.4 Mean annual rainfall measured at C. Highlands.

2550 mm. Higher rainfall precipitation occurs twice in a year, as shown in Figure 16.4, during the months of April through May and October through November.

The rainfall erosivity factor **R** describes that the rainstorm energy of the rainfall, which varies with climate and location within a certain region. In Malaysia, the Department of Irrigation and Drainage provided a Design Guides Report (DID) [6] to compute the annual EI_{30} and averaged **R** factor equal to 9068 for Pahang State at Gunung Brinchang. This value is excessively high and had to be discarded. Other studies in Southeast Asia have also suggested relationships for the factor **R**. In Indonesia, Bols [3] provided an equation for the calculation of the **R** value based on an empirical study of the mean annual precipitation **P** in mm:

$$\mathbf{R} = \frac{2.5\mathbf{P}^2}{100(0.073\mathbf{P} + 0.73)} \tag{16.2}$$

In Thailand, Hartcher and Post [12] investigated hillslope erosion. The rainfall erosivity factor was determined using the following Hartcher equation [12]:

$$\mathbf{R} = 38.5 + 0.35\mathbf{P} \tag{16.3}$$

Therefore, the values of the factor **R** at C. Highlands could be estimated from the rainfall precipitation from the 1999 to 2006 rainfall record. Several equations were compared in Table 16.1. Both the methods of Hartcher and Bols [3,12] provided comparable values of **R** factor with 993 and 941, respectively.

Based on isohyets, a map of the rainfall erosivity factor **R** was developed from the equation of Bols [3]. The GIS map in Figure 16.5 shows the distribution in factor **R** for the RUSLE model.

16.2.2 Soil Erodibility

The soil erodibility factor **K** describes the ability of a soil to erode under rainfall. The **K** factor is defined as a unit of mass per area per unit time. It quantifies the amount of soil erosion as a function of soil type, soil texture, and composition. The **K** factor values can be estimated using the soil erodibility

TABLE 16.1 Computed Rainfall Erosivity **R** at C. Highlands

ID	Stn_Name	Lat	Long	Unit	P_99-06	R_99-06[a]	R_99-06[b]	R_99-06[c]	R_99-06[d]
9001	Blue Valley Tea Estate at C. Highlands, Pahang	4.5861	101.4194	mm	2216.300	804.205	814.205	1108.150	755.598
9002	Kg. Raja at C. Highlands, Pahang	4.5514	101.4167	mm	2604.814	940.185	950.185	1302.407	888.648
9003	Telom Intake at C. Highlands, Pahang	4.5422	101.4250	mm	2067.800	752.230	762.230	1033.900	704.743
9004	Sg. Palas Tea Estate at C. Highlands, Pahang	4.5167	101.4167	mm	3146.700	1129.845	1139.845	1573.350	1074.223
9006	Sg. Ruil at C. Highlands, Pahang	4.4944	101.4250	mm	2937.786	1056.725	1066.725	1468.893	1002.678
9007	Kajiklim T. Rata at C. Highlands, Pahang	4.4667	101.3833	mm	2960.486	1064.670	1074.670	1480.243	1010.452
9008	Mardi C. Highlands at Pahang	4.3833	101.3833	mm	2989.229	1074.730	1084.730	1494.614	1020.295
9009	Kajiklim Habu at C. Highlands, Pahang	4.4181	101.3833	mm	2746.957	989.935	999.935	1373.479	937.327
9010	Boh Tea Estate(factory), C. Highlands, Pahang	4.4514	101.4250	mm	2574.700	929.645	939.645	1287.350	878.335
9111	C. Highlands at (Tanah Rata), Pahang	4.4667	101.3667	mm	3339.343	1197.270	1207.270	1669.671	1140.196
				Total Average	2758.411	993.944	1003.944	1379.206	941.249

[a] Harper, 1987, Thailand.
[b] Hartcher, 2005, Thailand.
[c] Morgan, 1974, Malaysia.
[d] Bols, 1978, Indonesia.

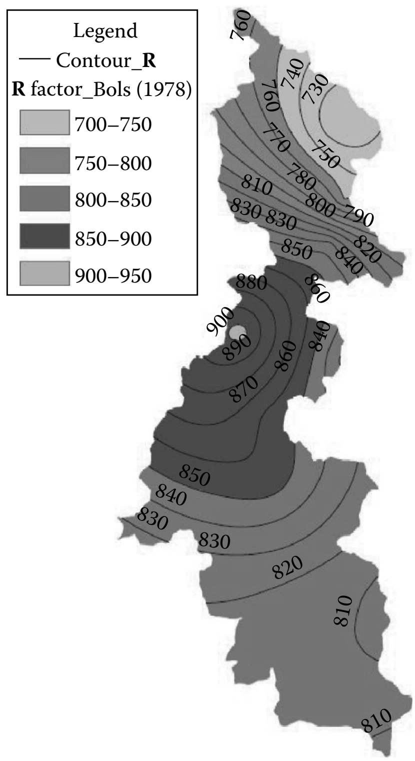

FIGURE 16.5 Rainfall erosivity map, **R**, ranging from 700 to 950 using Bols (1978) method.

nomograph method that depends on soil properties such as the percentage of silt, clay, and fine sand, percentage of organic matter (OM), soil structure code, and permeability class. The Wischmeier et al. [35] equation is

$$\mathbf{K} = \frac{2.1\times10^{-4}\left(12-\mathbf{OM}\right)\mathbf{M}^{1.14} + 3.25\left(\mathbf{S}_1 - 2\right) + 2.5(\mathbf{P}_1 - 3)}{100} \tag{16.4}$$

where

$\mathbf{M}$ = (%silt + %very fine sand) × (100 − %clay)
%silt is 0.002–0.05 mm
%very fine sand is 0.05–0.1 mm
%sand is 0.1–2 mm
%clay is <0.002 mm
OM is the % of **OM**
$\mathbf{S}_1$ is the structure index
$\mathbf{P}_1$ is the permeability

From laboratory sampling conducted in 2010, the particle size distribution for sediments at C. Highlands consists of an average composition of 13% sand, 60% silt, 25% clay, and 2% **OM**. For applications in Malaysia, Tew [29] proposed the following slight modification to the following method:

$$\mathbf{K} = \frac{\left[1.0\times10^{-4}\left(12-\mathbf{OM}\right)\mathbf{M}^{1.14}+4.5\left(\mathbf{s}-3\right)+8.0\left(\mathbf{p}-2\right)\right]}{100} \tag{16.5}$$

where
K is the soil erodibility factor (tons/ha)(ha hr/MJ mm)
M = (%silt + %very fine sand) × (100 − %clay)
OM is the % of **OM**
s is the soil structure code
p is the permeability code

Using the Wischmeier et al. [35] formula, the **K** value for C. Highlands was determined to be 0.052, while Tew [29] provided 0.033. Meanwhile, the soil erodibility map for **K** factor developed using the GIS method obtained a higher value of 0.0659. On the other hand, findings from the NREM [23] by the Ministry of Natural Resources and Environment, Department of Environment, Malaysia, for C. Highlands reveal that the soil erodibility factors in the study area range from 0.1 to 0.2. For this study, the values of **K** are assumed to be uniform and are adopted from the DOA. Therefore, the **K** factor used for steep, urban, and mined land was 0.066.

16.2.3 Slope Length and Steepness Factors

The two factors **L** and **S** describe the slope length and steepness factors, respectively. They can be determined from the topography of the area under study. In most studies, both factors are combined together to form the slope steepness factor **LS**. For the C. Highlands area, the topographic factors **L** and **S** were obtained from the topographic information provided by the digital elevation model (DEM) derived from the NASA Shuttle Radar Topographic Mission (thereafter SRTM) dataset. A DEM of scale 1:50,000 was obtained for this study whereby the slope length and slope steepness can be used in a single index, which expresses the ratio of soil loss as defined mathematically by Wischmeier and Smith [34]. Using the raster calculator function under spatial analyst, the **LS** factors were obtained. The slope of the DEM in percentage and the flow accumulation were calculated at a cell size of 20 m. Using the available data from ArcGIS, the slope map is shown in Figure 16.6 and the slope length and steepness for **LS** factor was calculated, and the **LS** map is shown in Figure 16.7.

16.2.4 Cropping Management and Conservation Practice

The cropping management factor represents the ratio of soil loss under a given crop to that of a bare soil freshly tilled in the drainage direction [33]. The cover factor **C** relates to land use characteristics. Based on the previous studies and available land use maps, the values on Table 16.2 from the Ministry of Natural Resources and Environment, Department of Environment, for the **C** factor were used for this study.

As expected, the land use changes have been quite significant since the year 1946. Figure 16.8 shows the forested area reduction is almost all sub-catchment. The average percentage of reduction in forested area is 35% from 1946 to 1997. The Lower Bertam sub-catchment recorded the lowest percentage in 1997 at 30% for the forested area.

The terrain within the study area can be classified according to the slope category as defined by the DOA, Malaysia. The terrain and topography classification is then used in the erosion practice factor, **P** as in Table 16.3, where it considers the best practices to reduce source erosion such as contouring and terracing. The values proposed are dependent on the terrain slope.

Two sets of land use maps from the DOA were available for this study, as shown in Figure 16.9a and b for years 1997 and 2006, respectively. The **C** and **P** factors were generated the same way as the **K** factor

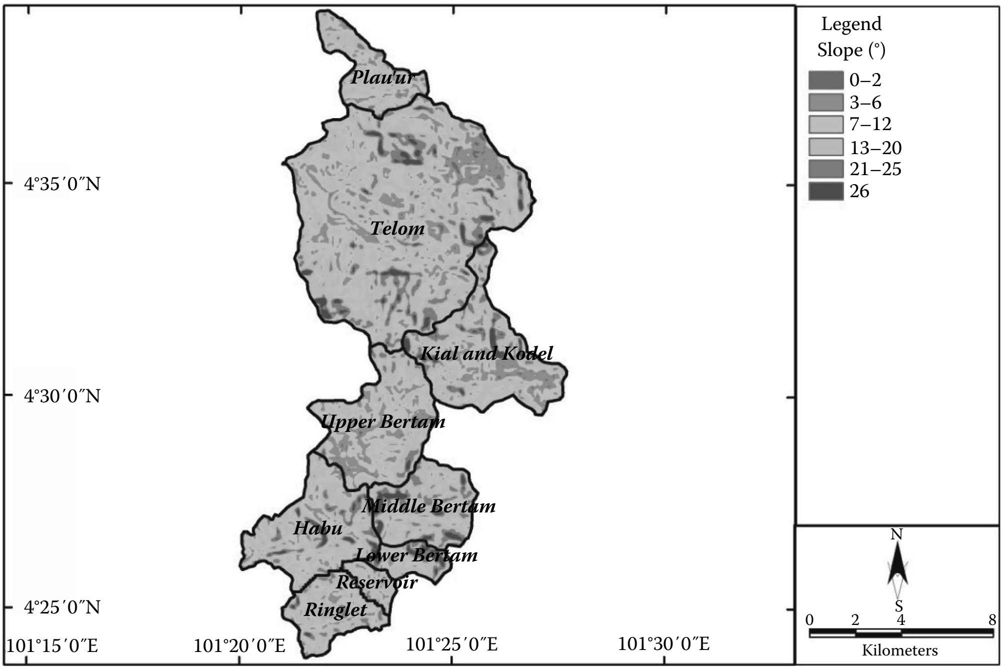

FIGURE 16.6 Slope map derived from DEM.

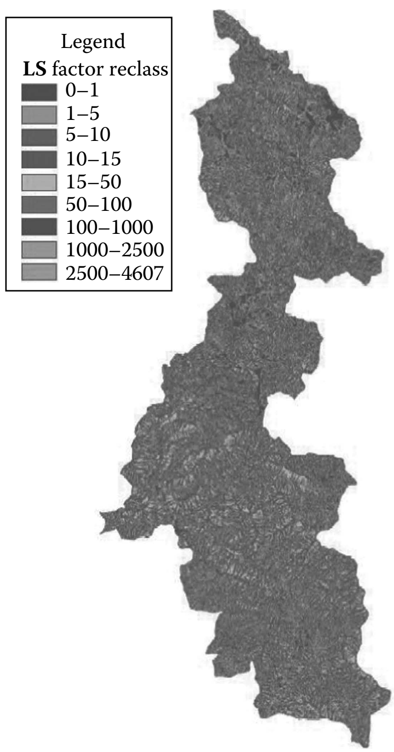

FIGURE 16.7 **LS** factor for C. Highlands.

TABLE 16.2 Land Use Cover Factor, **C** (DOA)

Land Use Type	C Factor
Agriculture experimental stn.	0.600
Associated areas	0.350
Bare land	1.000
Forest	0.010
Grassland	0.015
Market gardening	0.350
Mine	1.000
Mixed agriculture	0.350
Orchard	0.250
Residential area	0.003
Scrub forest	0.010
Shifting cultivation	0.250
Sundry nontree cultivation	0.250
Tea	0.350
Urban	0.500
Water body	0

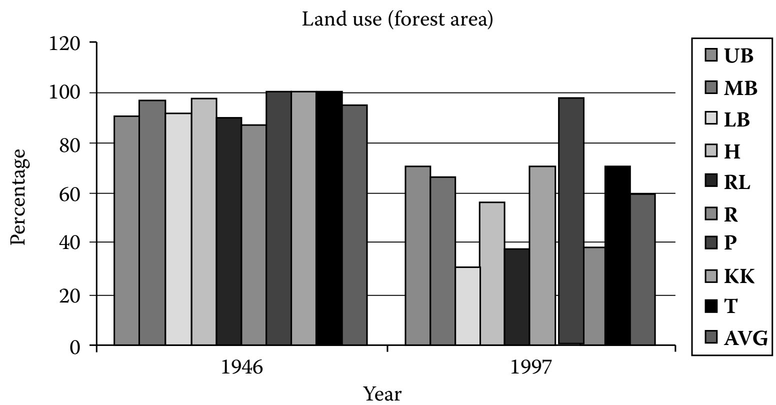

FIGURE 16.8 Comparison of forested areas by subwatersheds between years 1946 and 1997.

TABLE 16.3 Erosion Control Factor, **P** (DOA)

Category	Topography	Slope Range (°)
1	Flat	0–2
2	Undulating	2–6
3	Moderate hilly	6–12
4	Hilly	12–20
5	Moderate steep	20–25
6	Steep	>25

Slope (%)	P Factor
1.1–2.0	0.60
2.1–7.0	0.50
7.1–12.0	0.60
12.1–18.0	0.80
18.1–24.0	0.90

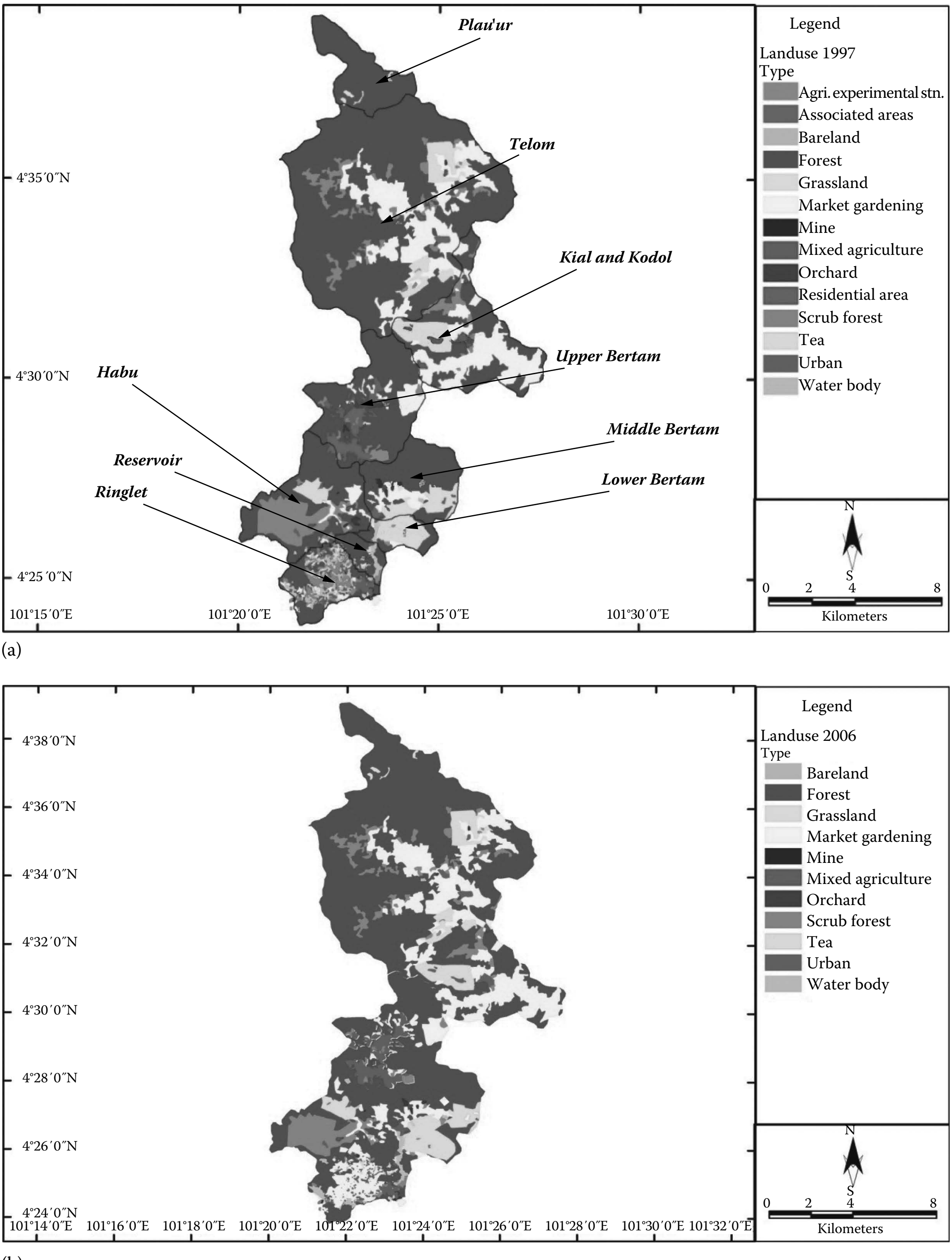

FIGURE 16.9 Land use maps for (a) year 1997 and (b) year 2006 (DOA).

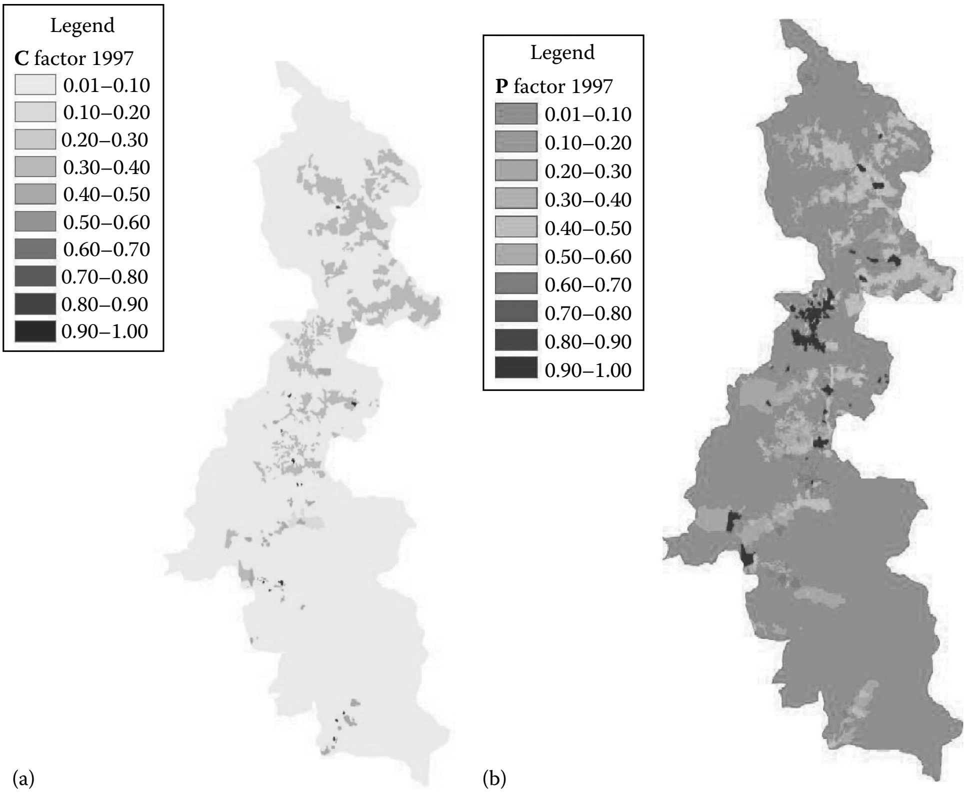

FIGURE 16.10 Computed (a) **C** factor and (b) **P** factor for 1997 using ArcGIS.

by cross-referencing the attribute table to ArcGIS. For this study, **P** values were chosen based on the land use instead of management practice. The GIS converted the information from a vector-based format to a raster-based format at a cell size of 20 m.

Using the ArcGIS, the cover management factor **C** and erosion control factor **P** were developed using the method described previously for 1997 in Figure 16.10 and 2006 in Figure 16.11. The maps produced for 2006 exclude the sub-watershed of Plau'ur due to unavailability of data. The comparison of these maps reflects the impact of the change in land use that has been taking place on the watershed within less than 10 years.

16.3 Upland Erosion Mapping

The maps obtained from RUSLE for C. Highlands are obtained from the product of the six parameters of Equation 16.1. The values of erosion potential were divided into seven classes as shown in Table 16.4. Figure 16.12 shows the upland erosion maps for 1997 and 2006, respectively.

Two separate sub-watersheds Habu and Ringlet were further investigated to examine the rate of increase in soil loss. Using the soil maps for Habu on Figure 16.13, the RUSLE model showed an increase in soil loss from 32,000 m^3/year in 1997 to 50,600 m^3/year in year 2006, which corresponds to a 58.1% increase. Meanwhile the Ringlet area shown in Figure 16.14 also showed a 100% increase in soil loss from 25,600 m^3/year in 1997 to 50,900 m^3/year in year 2006.

These increases in upland erosion losses reflect directly on the increased sedimentation rates measured in these reservoirs. The C. Highlands hydroelectric scheme was planned and constructed from 1959 to 1964. The main feature of the scheme was to harness the Ringlet Falls with Sultan Abu Bakar

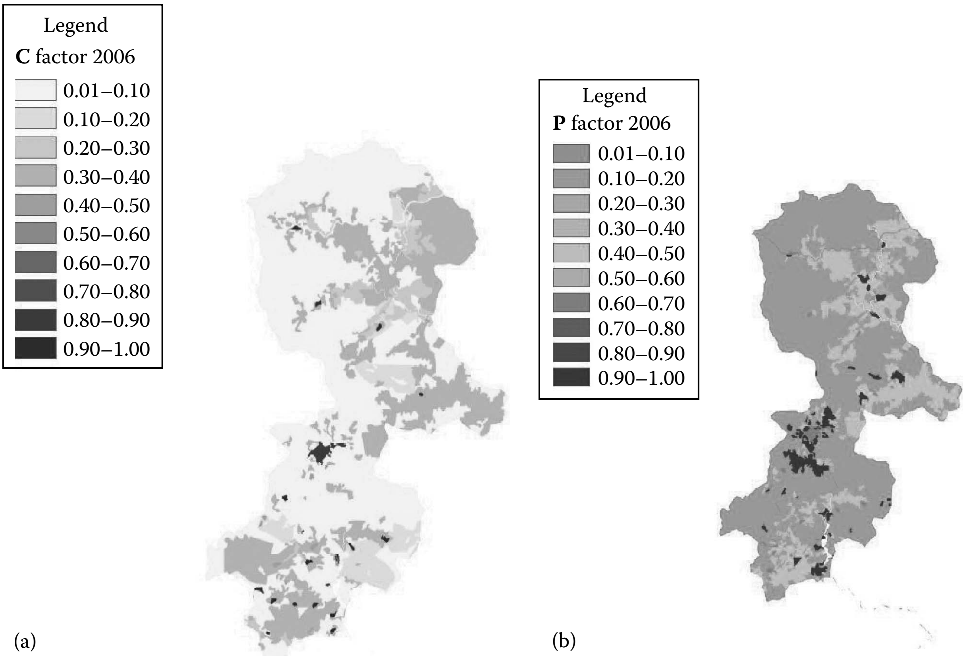

FIGURE 16.11 Computed (a) **C** factor and (b) **P** factor for 2006 using ArcGIS.

TABLE 16.4 Derivation of the Ordinal Categories of Soil Erosion Potential

Erosion Class	Numeric Range (tons/ha/year)	Erosion Potential
1	0–1	Very low
2	1–5	Low
3	5–10	Moderate
4	10–20	High
5	20–50	Severe
6	50–100	Extreme
7	>100	Exceptional

Dam that stands at 40 m height with concrete buttresses fitted to four (4) gated spillways. The reservoir elevation at full supply level is 1070.7 m and has a surface area of 60 ha. The reservoir receives water from three rivers (Sg. Habu, Sg. Bertam, and Sg. Ringlet) and other minor tributaries. Ringlet Reservoir was designed for a gross storage of 6.7 million m^3, of which 4.7 million m^3 is the active/live storage and 2.0 million m^3 is inactive/dead storage. The dead storage was designed for a useful lifespan of approximately 80 years that translates to a design sediment inflow of 20,000 m^3/year [5]. From the bathymetric survey data the sediment rate of 40,000 m^3/year was recorded immediately after construction. The data showed an increase of almost 100% from the designed storage requirement, which means that the dead storage would be filled up after 40 years of operation and not meeting the design life expectancy. Since these earlier studies, the rate of sedimentation increase is directly related to the increase in the upstream activities such as deforestation, uncontrolled farming, residential, and other rapid changes in land use on the contributing watershed areas. The main difference with earlier studies is that GIS has now become a very important tool in the analysis of the prospective changes in reservoir sedimentation rates based on changes in land use.

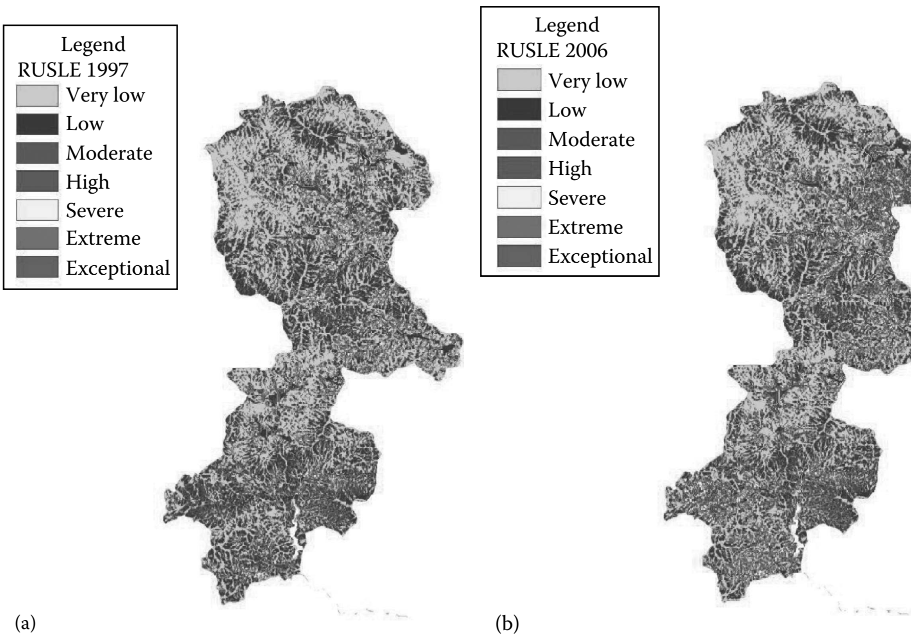

FIGURE 16.12 Computed soil erosion map for (a) 1997 and (b) 2006 using ArcGIS.

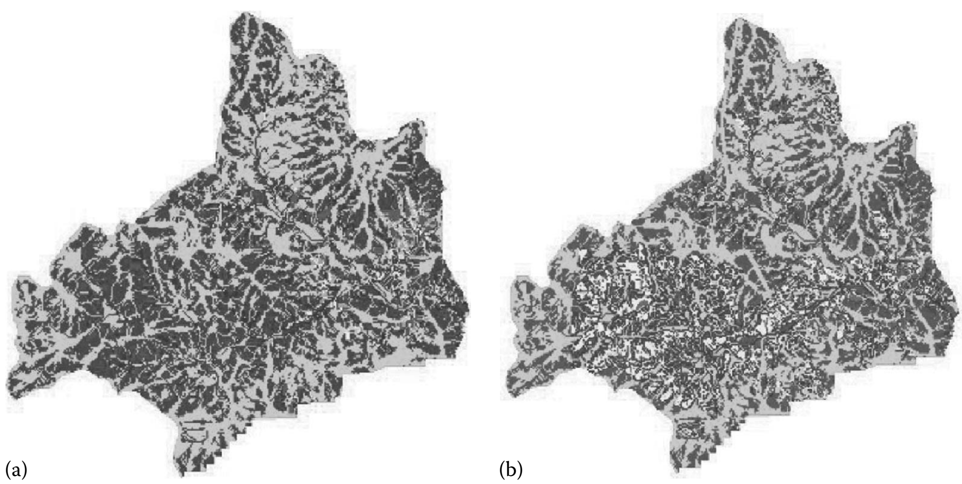

FIGURE 16.13 Soil erosion map for Habu (a) in 1997 and (b) in 2006.

16.4 Summary and Conclusions

Very high upland erosion rates have been observed in tropical countries around the world as a result of deforestation. GIS technology can be used to assess the changes in upland erosion rates from updated monitoring of land use. The USLE and RUSLE are well suited for upland erosion mapping. The methods include the effects of rainfall erosivity from rainfall records, soil erodibility from soil maps, slope length and steepness from surface topography and DEM, cropping management, and conservation practice from land use maps. This example of C. Highlands in Malaysia illustrates how GIS can be used to generate soil erosion maps at different times. Malaysia receives 2,500 mm of rainfall precipitation per year

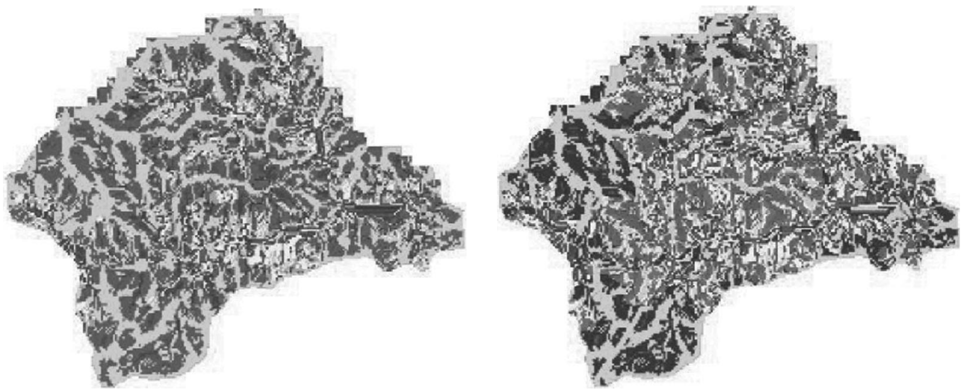
(a) (b)

FIGURE 16.14 Soil erosion map for Ringlet (a) in 1997 and (b) in 2006.

and the steep mountain areas are subjected to erosion rates in excess of 10,000 tons/km^2/year. From this study using the RUSLE model, the average annual soil loss rate at C. Highlands was estimated at 282,500 m^3/year in 1997 and increased to 335,000 m^3/year in 2006. The comparison of erosion rates between 1997 and 2006 shows a soil loss increase of 18.5% in less than a decade. These rapid increases in upland erosion rates result in similar increases in reservoir sedimentation rates. These can be attributed to changes in land use that can be easily monitored with GIS.

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