AN ANALYSIS OF THE SENSITIVITY OF SOIL EROSION MODELS WITHIN A GEOGRAPHICAL INFORMATION SYSTEM

by

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In the name of Allah, Most Gracious, Most Merciful

"And We send down water from the sky according to (due) measure,
and We cause it to soak in the soil,
and We certainly are able to drain it off (with ease)."

Al-Mukminun 23:18

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ABSTRACT

Soil erosion is an important field of study due to the effects it has on the quality of soil and the environment. In the field of soil erosion modelling, the availability of data is an important factor that may influence the choice of model to be used. This is especially so in developing countries where data are scarce. Where data are available, their quality is seldom assessed, hence the level of reliability of modelled results is not known.

The importance of availability and quality of data in any work involving GIS is well understood. Data for this study are obtained from Langkawi Island, Malaysia. Malaysia is a country where development is going on at a very fast rate. Activities such as clearing of forests for development have increased the risk of erosion, hence attention is now being given to this area so that threats and problems caused by it can be managed.

This study analyses the sensitivity of two empirical models, the Morgan, Morgan and Finney (MMF) and Soil Loss Estimator for Southern Africa (SLEMSA) soil erosion models, to variations in their input variables by the use of geographical information systems. This is achieved by implementing the models in ERDAS Imagine Spatial Modeler while IDRISI is used to carry out most of the data manipulation, analysis and presentation. The study has shown that using the Spatial Modeler is a very efficient way of running the models especially when many model runs are involved.

The results of these analyses show that one of the most important input variables is slope (the other being vegetation, soil type and rainfall). An analysis is carried out to find the best slope data set that can be derived from available topographic data. This is done by generating DEMs and slope images using three GIS software packages, namely the ERDAS Imagine-ARC/INFO combination, GRASS, and IDRISI. Pixel sizes of 5m, 20m and 50m are used in the analysis. The accuracy of the slope images is compared with values derived from a topographic map. It is found that slope data derived from ERDAS Imagine at 50m resolution are the most accurate and this data set is used in the subsequent analysis.

Sensitivity analysis of the two models is carried out by using the *one-at-a-time* approach in which the model is run with the values of a single input variable being changed while keeping the other inputs at nominal values. Relative sensitivities of the model to variations in the input variables are determined by assessing the confidence limits, bench marks and sensitivity parameters of the input variables. Generally, it is found out that the MMF model can be considered to be sensitive to three categories of input variables while the SLEMSA model is sensitive to two different categories.

The results have shown that there are differences in the way the two models "react" to their various input variables, leading to the conclusion that due attention should be given to these inputs in terms of their levels of accuracy so that the results of soil erosion modelling can be interpreted in a more meaningful fashion.

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CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

Soil is a non-renewable and vulnerable resource. It constitutes the basic foundation for the economic and social development of a region. Its degradation and the need to preserve and to protect it has been of great concern to many countries where soil erosion has become a threat. Because soil erosion is a dynamic hazard and possesses both physical and socio-economic attributes, soil erosion assessments need frequent updating. Soil erosion risk assessment techniques which are needed to facilitate these frequent updates have been difficult to define. Soil erosion risk assessment is important especially in the humid tropical environment because erosion risks are very high when natural vegetation is cleared especially on steep slopes (Stocking, 1995a) and vegetation clearance is proceeding rapidly in many parts of the humid tropics in response to competing land uses for agricultural, mining and general infrastructural development (Millington, 1984). It will become increasingly important for land-use planners to have a sound understanding of the factors controlling soil erosion, how to assess its severity, predict the rates of erosion for particular areas, and how to control or prevent erosion.

The Universal Soil Loss Equation (USLE) is the most common soil erosion model used throughout the world. Though this is so, there are weaknesses in the model which have prompted researchers to seek alternatives. The model uses six factors, which are interrelated, though the model demands them to be independent (Stocking, 1995b). Hence, factor values are only valid for the specific combination of circumstances under test at the experimental station. In practice, careful but selective extrapolation may be allowable without too many errors creeping in. However the researcher will have no control over and no knowledge of errors of extrapolation outside the experimental boundaries. Only occasionally has a researcher sought to validate USLE results. As noted by Stocking (1995b), Vanelslande et al. (1984) took just one factor, soil erodibility, and found it hopelessly and uncertainly predicted for tropical soils through the USLE nomogram. However, due to its misleading simplicity, the USLE has attracted many users including Cihlar (1987) in Canada and Roose (1976) in West Africa. In Malaysia, Buyong and Tang (1995), Baharuddin and McGuire (1995), Hashim et al. (1995), and Zainal Abidin and Tew (1997a) have also adopted the USLE in producing soil erosion risk maps.

1.2 SIGNIFICANCE OF SOIL EROSION

Quoting the 'alarming facts' about the extent, rate and impact of erosion must be done objectively for, more often than not, the figures mentioned may be misleading, especially when they involve the extrapolation of measurements taken at one scale for estimates based on an entirely different scale. Examples of these are given in Stocking (1995a) who shows that sensational statements portray the negative effects of soil erosion. In fact, much of the eroded material is redeposited close to the site and may provide input for other users. The same issue is addressed by Blaikie (1985) where the question of whether soil erosion is really a problem should be treated fairly.

In a study carried out at Cornell University, claimed to be the most comprehensive study to date on the costs of soil erosion, it is reported that soil erosion causes up to US$400 billion in damage worldwide (News & Views, 1995). In addition to substantial economic losses of nutrients and water, erosion causes significant ecological damage where plant composition is affected and soil biodiversity is depleted. Soil erosion also causes damage beyond the immediate agricultural areas, such as damage to roads and waterway infrastructure. The study also mentioned that although soil erosion has occurred throughout history, it has intensified in recent years where each year 75 billion metric tons of soil are removed from the land by wind and water erosion, with most coming from agricultural land.

Soil formation is extremely slow, especially in cold or dry climates. In areas where the climate is moist and warm, it takes thousands of years to form just a few centimetres of soil. According to the Union of International Associations (UIA, 1995), an estimated 24 billion tonnes of topsoil is lost each year, worldwide. New topsoil is being formed but at a very slow rate of about 3.4 tonnes per hectare per year. This difference between creation and loss results in an annual loss of 16.8 to 23.5 tonnes per hectare. At this rate, one-third of the world's arable land will be depleted within the next 20 years.

Sanders (1984) quotes figures to show that in the year 1981 the Food and Agriculture Organisation of the United Nations (FAO) estimated that between 5 and 7 million hectares of land were being lost annually through soil degradation. More recently, Stocking (1995a) stresses the severity of the problem when he stated that since 1945 1.2 billion hectares, an area roughly the size of China and India combined, have been eroded at least to the point where their original biotic functions are impaired. Of this area, about 9 million hectares are very severely damaged and 300 million hectares are so damaged that cultivation is all but impracticable.

An indication of the rate of soil erosion in various countries is given by Morgan (1985, 1995) as shown in Table 1.1 where the rates are grouped into those related to natural vegetation, cultivated land and bare soil. As a comparison, a soil renewal rate of 1 t/ha/yr was quoted by Morgan (1985) to be a realistic rate for most UK conditions. For the US, a rate of 11 t/ha/yr is the generally acceptable standard (Morgan, 1980). Table 1.2 shows the rates of erosion in other countries as quoted in various other studies.

Country	Rates of Erosion (t/ha/yr)		
	Natural	Cultivated	Bare
China	0.1 - 2	150 - 200	280 - 360
USA	0.03 - 3	5 - 170	4 - 90
Australia	0 - 64	0.1 - 150	44 - 87
Ivory Coast	0.03 - 0.2	0.1 - 90	10 - 750
Nigeria	0.5 - 1	0.1 - 35	3 - 150
India	0.5 - 5	0.3 - 40	10 - 185
Ethiopia	1 - 5	8 - 42	5 - 70
Belgium	0.1 - 0.5	3 - 30	7 - 82
UK	0.1 - 0.5	0.1 - 20	10 - 200

Table 1.1: Rates of erosion in selected countries (source: Morgan, 1995),

Country	Soil Erosion Rates (t/ha/yr)
Queensland	47 - 505
Philippine	100 - 200
Sri Lanka	9 - 15
Sweden	1 - 120
Java	5 - 25
Idaho	12 - 26
Quebec	13 - 24
Germany	14 - 84
Chile	6 - 12
Algeria	20 - 500

Table 1.2: Rates of erosion in selected countries (sources: Prove, 1995; Paningbatan, 1995; Samarakoon, 1995; Alstrom, 1992; Heusch, 1993; Busacca, 1993; Cao, 1993; Clemens, 1994; Oyarzun, 1995; and Prinz, 1994)

Zachar (1982) gives soil erosion values at various continents as shown in Figure 1.1. The rate is in t/ha/yr while the corresponding depth is in cm, absolute is the absolute soil erosion in 10^6 tons while area is the area of the continents in 10^6 km^2. These estimates are considered to be very high as there are large areas of the world where erosion is minimal or where deposition is taking place.

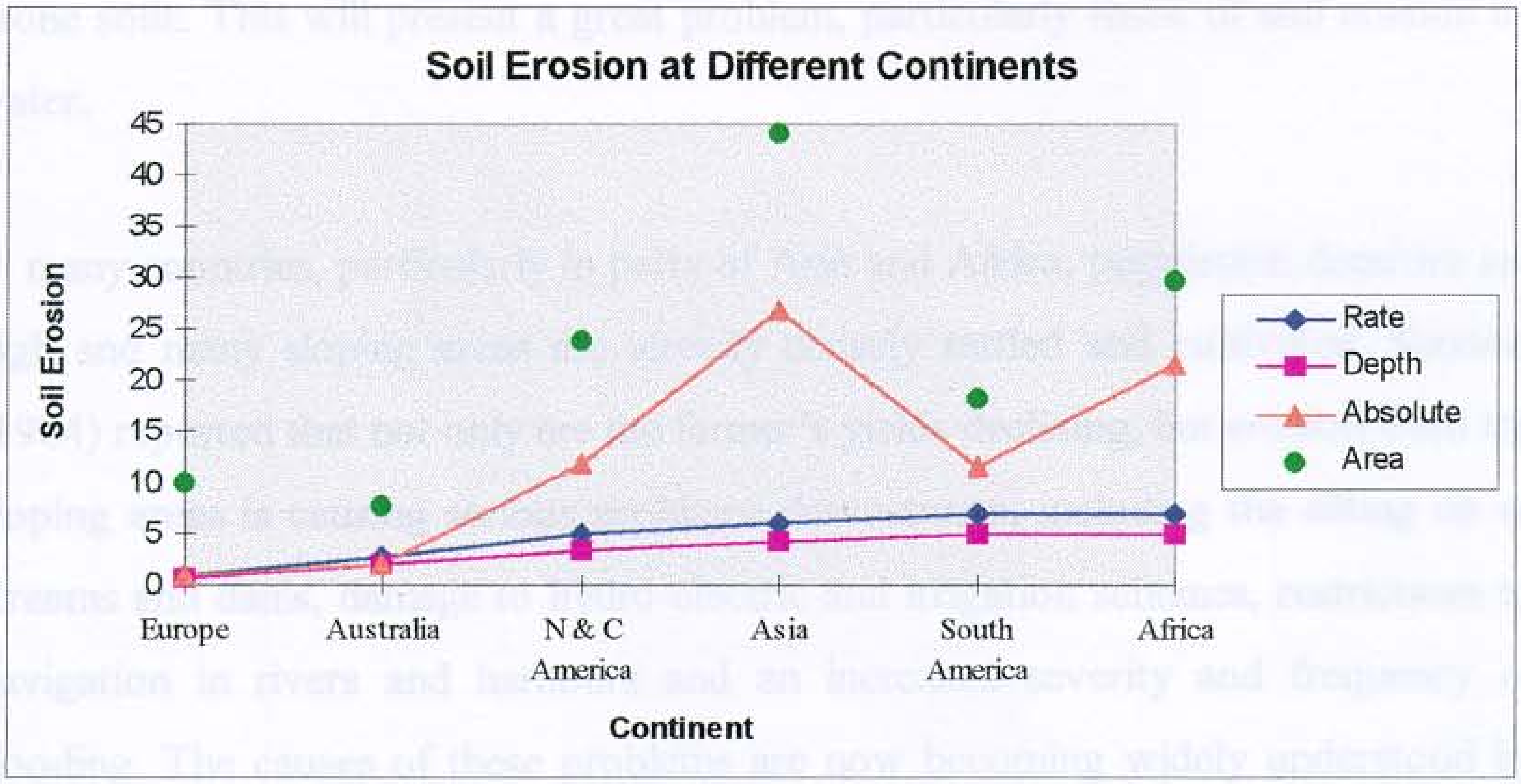

Figure 1.1: Soil erosion rates of various continents (Zachar, 1982)

A report by the US Environmental Protection Agency in 1988 indicated that the nation's water quality problems were largely due to pollution from agricultural activities. About 50% to 70% of the surface water surveyed was affected by nonpoint source pollution, from soil erosion, sedimentation, and chemical application. Sediments cover up spawning areas and stunt the growth of aquatic vegetation. Nutrients (primarily nitrogen and phosphorus) from runoff create the opposite effect, spawning algae that deplete oxygen in water bodies. Pesticides and other toxic materials are taken up in the food chain, posing a threat to both aquatic life and to humans, and affecting water quality. In addition, the annual in-stream damage from soil erosion and sedimentation is estimated at between \$3.2 and \$13 billion nationwide (Liao and Tim, 1994).

Most of the world's land that has so far been brought into production is on flatter areas, on the deeper, more fertile and easy to work soils. For obvious reasons, farmers have avoided as far as possible the steep lands and the harder to work, shallow, erosion-prone areas. In future more areas of new land will be developed. As the tendency has been to develop the more fertile, flatter land first, agriculture can be expected to extend to areas of steeper slopes with poorer, more erosion prone soils. This will present a great problem, particularly those of soil erosion by water.

In many countries, particularly in parts of Asia and Africa, population densities are high and many sloping areas are already densely settled and cultivated. Sanders (1984) reported that not only are the farmer's yields declining, but erosion from the sloping areas is causing serious problems downstream, including the silting up of streams and dams, damage to hydro-electric and irrigation schemes, restrictions to navigation in rivers and harbours and an increased severity and frequency of flooding. The causes of these problems are now becoming widely understood by politicians, administrators and the public in general.

1.3 SOIL EROSION IN MALAYSIA

A number of studies on soil erosion have been made in Malaysia, where the site selected for this study is situated, as reported by Morgan (1979). These date back as far as 1939 and are associated mainly with mining, agricultural and urban activities. All the data available were derived from studies of sediment concentrations in rivers and, because much of the sediment removed from hillsides was deposited before it reached the rivers, the data almost certainly underestimate the rates of soil loss. These data do not permit more than the most generalised judgements on erosion risk to be made.

Morgan (1979) has produced a reconnaissance erosion risk map of the whole country as shown in Figure 1.2. This was derived by superimposing maps of p^2/P and erosivity where p is the highest mean monthly precipitation, P is the mean annual precipitation and erosivity is obtained from the equation:

$$\text{Erosivity} = 9.28P - 8838.15$$

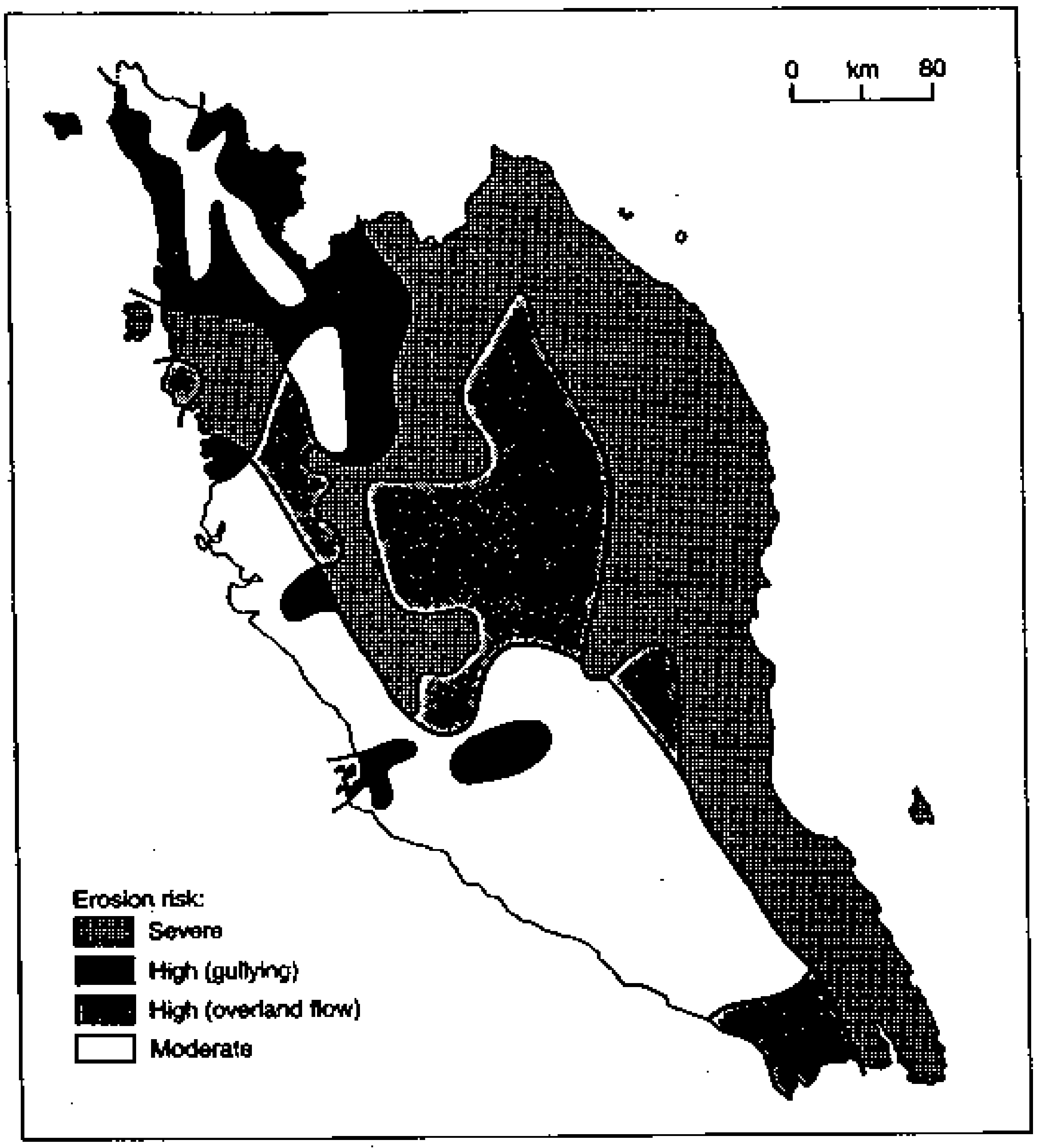

Figure 1.2: Reconnaissance survey of soil erosion risk in Peninsular Malaysia
(source: Morgan, 1979)

More recently, the topic of soil erosion has been given more attention and widespread coverage due to the very serious threat and problem it has caused (Zainal Abidin and Tew, 1997b). Recent studies on erosion in Malaysia were carried out especially on hillsopes due to the many landslides tragedies that have occurred. This, many believe, has resulted from the rapid development undergone by the country as a result of land clearing, reclamation and rehabilitation activities. Studies by Zainal Abidin and Tew (1995, 1996 and 1997b) and Mohd. Kassim et al. (1995) have all looked at the frequency, intensity and risk of soil erosion at various highland areas using the USLE soil erosion model.

The new national development policy gives less emphasis to agriculture, which results in the conversion of land close to urban areas to uses other than agriculture.

As economic activity and population increased, agricultural activities have spread rapidly to the uplands, and has increased the problems of soil erosion and degradation, sedimentation and river pollution. There are strong indications that subsequent generations of crops are yielding less due to deterioration of soil properties. As a result of this, planters and agriculturists have lately developed greater interest in soil and water conservation (Hashim et al., 1995).

As the economic growth rate of the country increases, the need for better information on soil erosion and related fields is becoming more widely recognised. Under the Environmental Quality Act, 1974 (Amendment) 1985, most developments require environmental impact assessments to be conducted and have the results presented in the form of reports. Handling environmental data manually is almost impossible, especially when analysis is needed. In the area of soil erosion assessment and analysis, there exists a number of problems, the most important of which are:

- A demand for the generation of soil erosion risk maps for Environmental Impact Assessment in view of the rate of Malaysia's economic development.
- The need for soil erosion risk maps to be produced in a very fast and yet economic manner without compromising the quality of its information.
- Manually assessing and analysing the environmental data for the production of the erosion risk map is not feasible (Buyong and Tang, 1995).

The leaders of Malaysia have established Vision 2020, a set of aims which is laid out to turn Malaysia into a modern and developed country by the year 2020. One of the prime activities in achieving these aims is the development of land and its usage. Hence, soil erosion problem should be addressed seriously and an efficient and practical means of producing the erosion distribution is sought for.

1.4 STATEMENT OF THE PROBLEM

There is no single soil erosion methodology which can be applied universally in the tropics. Instead several alternatives exist with potential and limitations which have not been fully explored. Manrique (1993) reviews two main approaches to soil erosion assessment, empirical and physically driven models, in terms of their scope and rationale, structural framework, computational procedures, data requirements, limitations and potentials for use in the tropics. From this review, it is seen that alternative approaches to the USLE produce reliable soil loss estimates from limited and incomplete data, and have higher likelihood of usage than the USLE. These physically driven models are based on the fundamental principles of erosion mechanics, sediment transport, flow hydraulics, and hydrology. These kinds of erosion model often require: i) extensive and detailed data which are seldom available in the tropics, and ii) on-site calibration and field testing which may further preclude their use in areas with no history of field experimentation and/or limited climatic data gathering capabilities. Under optimal conditions, however, these models provide estimates of runoff, soil losses, and chemical movement and transport which are sufficiently close to reality to satisfy planners' needs.

Therefore the user is faced with a dilemma of selecting the most appropriate model to be used in investigating rates of soil erosion for his particular study area. The use of a 'simple' model such as the USLE may not give reliable results. On the other hand, the use of a more complicated model will present the user with the problem of the availability of the data and field testing as mentioned above. In studies of erosion over large areas, using remote sensing and GIS, empirical models have been used because physically based models require a large number of parameters and are thus difficult to apply over large areas (Drake et al., 1995).

The use of GIS in environmental modelling including soil erosion modelling is widespread. The continuing rapid improvements in the size, speed and general availability of modern computers has made this possible. GIS are especially used in the preparation and manipulation of the data, analysis, and the display of the output. Most of the data that are used in a soil erosion model are related to climate, vegetation, soil and topography. The first three groups of data can be managed by a GIS but it will not have any direct influence on their accuracies. However the fourth group, especially slope, can be directly produced from elevation data using a GIS, hence an analysis of methods of generating slope maps is necessary so that the accuracy of the slope data is sufficient for the requirement of the model.

The importance of data in any GIS related study cannot be denied. In a study such as soil erosion modelling, it is not only the case that the data characteristics are important but the level of effect that each input data set has on model behaviour is also significant and should be given due consideration. This level of influence, which can be assessed through a sensitivity analysis, should be given emphasis because it is critical to model validation and it also serves to guide future research efforts and model implementations. Sensitivity analysis is the study of the variation of model output resulting from a variation in model input. As noted by Janssen (1994) sensitivity analysis is an important part of the modelling process, and contributes substantially to a reliable and efficient development, assessment and application of the model.

1.5 PURPOSE OF STUDY

The main aim of this study is to investigate the sensitivity of two empirical models to variations in their inputs. Sensitivity analysis is used to measure the response of the model to variations of each of its input variables. It is expected that the results of the analysis will be useful in defining the sensitivity of each of the inputs used in the models which will give the user an indication of the relative importance of the