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Soil erosion assessment and its correlation with landslide events using remote sensing data and GIS: a case study at Penang Island, Malaysia

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Abstract In this paper, an attempt has been made to assess, prognosis and observe dynamism of soil erosion by universal soil loss equation (USLE) method at Penang Island, Malaysia. Multi-source (map-, space- and ground-based) datasets were used to obtain both static and dynamic factors of USLE, and an integrated analysis was carried out in raster format of GIS. A landslide location map was generated on the basis of image elements interpretation from aerial photos, satellite data and field observations and was used to validate soil erosion intensity in the study area. Further, a statistical-based frequency ratio analysis was carried out in the study area for correlation purposes. The results of the statistical correlation showed a satisfactory agreement between the prepared USLE-based soil erosion map and landslide events/locations, and are directly proportional to each other. Prognosis analysis on soil erosion helps the user agencies/decision makers to design proper conservation planning program to reduce soil erosion. Temporal statistics on soil erosion in these dynamic and rapid developments in Penang Island indicate the co-existence and balance of ecosystem.

Keywords Soil erosion · Frequency ratio analysis · GIS · Landslides · Land use/cover · Remote sensing · USLE · Malaysia

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Introduction

Soil from the world's croplands is being swept and washed away 10–40 times faster than it is being replenished. Soil erosion is second only to population growth as the biggest environmental problem the world is facing. The United States is losing soil 10 times faster than the natural replenishment rate, while China and India are losing soil 30–40 times faster (Pimentel 2006). As a result of erosion over the past 40 years, 30% of the world's arable land has become unproductive. Around 60% of eroded soil ends up in rivers, streams and lakes, making waterways more prone to flooding and to contamination from fertilizers and pesticides. Erosion also reduces the ability of the soil to store water and support plant growth, thereby reducing its ability to support biodiversity (Pimentel 2006).

Land is a scarce resource which is much sought after in Penang Island, Malaysia. This is because Penang Island is largely made up of steep topography, including hilly areas, and much of the lowland areas are already developed. Penang is one of the many rapidly industrialising states in Malaysia with a large urban population. In recent decades, industrialisation efforts and the development of other economic sectors have been intensified, leading to greater urbanisation and subsequent pressures on land. Although land reclamation has eased the pressures somewhat, it is not enough to satisfy the high demand for land on the island. With this situation, developers have turned to the remaining hill land on the island. Many hilly areas are already being developed and some other hill development projects are in the pipeline for future developments (Ahmad 1992; Cheng et al. 2008; Pradhan and Lee 2010a, b, c; Pradhan 2010a; Oh and Pradhan 2010). As a result, Penang Island is under constant pressure for various agricultural and urban developments. This has led to many environmental problems such as deforestation, decimation of water catchments, destruction of endangered fauna and flora, soil erosion, landslides, water pollution, sedimentation and downstream flooding (Ahmad et al. 2006; Pradhan and Lee 2009).

The environmental hazard caused by hill land development is that of high rates of soil erosion which has occurred in many parts of the hill slopes in Penang Island. Over the last decades, it has led to landslides (Pradhan 2010a, b; Pradhan and Buchroithner 2010; Pradhan and Lee 2010a; Pradhan and Pirasteh 2010; Pradhan and Youssef 2010). In Penang Island, the natural elements, particularly the weather elements, are highly erosive (Goh 1982). Geomorphological processes such as rain splash erosion and surface run-off erosion have been shown to be extremely high in wet equatorial areas (Pradhan 2010a; Lim and Lee 1992). Given the high intensity of tropical rainfall within short durations, the erosivity of rain and run-off are main causes for loosening the soil, weakening slopes and ultimately leading to mass movements of solid and semi-solid materials such as soil creep, landslips and landslides (Brunsden and Prior 1984; Lim and Lee 1992). Deforestation carried out in hilly areas, especially steep slopes of more than 20°, can be a catalyst to erosion and landslides. Controlled deforestation with immediate replanting can curb erosion and landslides but when it is carried out at a rapid non-sustainable rate, it can weaken slopes and bring about landslides. Deforestation is closely related to hill development as hills are usually densely forested before they are developed (Chan 1998a, b). Furthermore, unpaved roads have been built by the squatters to improve accessibility and many also farm illegally on the slopes (Chan 1998a). All these activities have destroyed the natural forest cover and exposed steep slopes to erosion. Highway construction through the dense equatorial forests has also been a major cause of soil erosion and landslides. There have been numerous incidents of minor landslides along highways in Malaysia before the major landslide which occurred along the North–South Highway near Bukit Lanjan in Kuala Lumpur in 21 October 2003 (Pradhan 2010a).

Soil erosion is the main cause of land sliding in this area; its control becomes essential in order to prevent landslides. By adjusting the factors which are responsible for soil erosion like land use/cover, etc. the rate of soil erosion can be minimised. Therefore, in this study, area soil erosion spatial assessment is needed. GIS is an efficient tool to integrate various datasets and assess any dynamic system such as soil erosion. There have been many studies of soil erosion by various methods (ranging from rule-based- to empirical- to process-based systems) using GIS (Adinarayana et al. 1999; Lee 2004; Millward and Mersey 1999, 2001; Beatriz et al. 2002; Huffman et al. 2000; Mati et al. 2000; Bissonnais et al. 2002; Martínez-Casasnovas et al. 2002; Renschler and Harbor 2002; Martínez-Casasnovas 2003; Youssef et al. 2009). However, use of universal soil loss equation (USLE) index model is very popular in both agricultural and hilly watersheds owing to its ease of obtaining parameters.

Keeping in view the importance of studying one of the major environmental threats of soil erosion in Penang Island, it is proposed to assess the dynamic soil erosion and correlate with another equally important and related threat of landslides in this fragile ecosystem. In particular, the objectives of the study are to:

- Assess soil erosion and prognosis and its dynamism.
- Correlate with landslide events/locations in the absence of ground data/ungauged ecosystems.

Study area

Penang Island is undergoing rapid development with land clearing for housing estates, hotels, and apartments causing erosion and landslides. The study area is depicted in Fig. 1 (a—Penang island in Malaysia; and b—Penang island as seen by SPOT image of January, 2005). Penang is one of the 13 states of the Federal territory of Malaysia and is located on the northwest coast of the Peninsula Malaysia. It is bound to the north and east by the state of Kedah, to the south by the state of Perak, and to the west by the Straits of Malacca and Sumatra (Indonesia). Penang consists of the island of Penang and a coastal strip on the mainland, known as Province Wellesley. The island covers an area of 285 km^2, and is separated from the mainland by a channel. The study area is located approximately between latitudes 5°15′ N to 5°30′ N and longitudes 100°10′ E to 100°20′ E. The slope of the area ranges from 25° to as much as 87°. The relief of the study area varies between 0 and 420 m above mean sea level (msl) and consists of coastal plains, hills and mountains.

According to the Malaysian Meteorological Department data, the temperature of the northern part of Penang ranges between 29°C and 32°C and the mean relative humidity between 65% and 70%. The highest temperature is during April to June while the relative humidity is lowest in June, July and September. Rainfall on Penang Island averages between 2,670 and 6,240 mm; and 58.6 and 240 mm (Lee and Pradhan 2006) per annum and month, respectively.

Geologically, the study area is located on the western flank of the Main Range, which is composed of granite. The granite in Penang Island is classified on the basis of the proportion of alkali

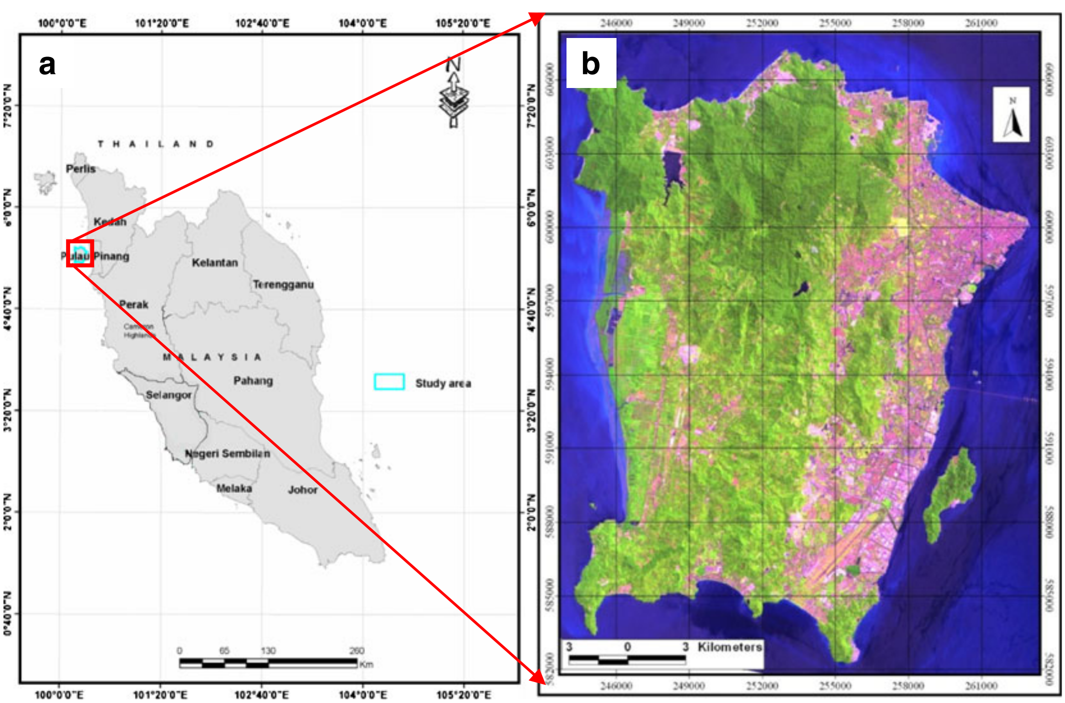


Fig. 1 **a** Map of Peninsular Malaysia showing location of study area; **b** Penang Island as seen by SPOT image (January, 2005)

feldspar to total feldspars (Ahmad et al. 2006; Ong 1993). Ahmad et al. (2006) reported that some of the granite and associated micro-granite are further divided into two main groups: the North Penang Pluton and the South Penang Pluton. In the northern part of the island, the alkali feldspars that generally do not exhibit distinct cross-hatched twining are orthoclase to intermediate microcline in composition. In the southern region, they generally exhibit well-developed cross-hatched twining and are believed to be microcline (Ong 1993). The dominant granite geology, granitic soils and boulders, and hillside development in the study area give rise to distinct landslide and rockfall problems (Tan 1990). The land use and land cover pattern in the study area is mainly peat swamp forest, plantation forest, inland forest, scrub, grassland and ex-mining area, urban land, water body and barren land (Pradhan 2010c; Pradhan et al. 2010a, b). Owing to limited land size and the highly industrialized nature of Penang's economy, agriculture is given low emphasis.

Soil erosion assessment by USLE model

In this study, the USLE model was used to estimate the average annual soil loss, which is expressed as mass per unit area per year (tons/ha/year). USLE is an index method and interplay of how climate, soil, topography, and land use affect soil erosion caused by raindrop impact and surface runoff (Arnoldus 1981; Lee 2004). In general, erosion depends on the amount and intensity of rainfall and runoff, the protection provided to the soil by land use against the direct forces of raindrop impact and surface runoff. The susceptibility of the soil to erosion as a function of intrinsic soil properties and soil properties modified by land use, and the topography of the landscape as described by slope length, steepness, and shape (Lee 2004).

The USLE was applied in a GIS medium to determine the average annual soil loss and its distribution in the study area. The USLE (Eq. 1) predicts soil loss for a given site as a product of six major factors whose values at a particular location can be expressed numerically (Lee 2004). The values of these erosion factors vary considerably about their means from storm to storm but hopefully the effects of these fluctuations average out in the end. Thus, the USLE is suitable for predicting long-term averages. In USLE model, soil loss rate is calculated as:

$$A = R \times K \times \mathrm{LS} \times C \times P \tag{1}$$

R Rainfall runoff erosive factor

Rainfall data was obtained from the Bayan Lepas weather station belonging to Malaysian Meteorological Services Department. The monthly average rainfall data of 20 years (1985–2004) was used to calculate the R factor. In the proposed study, the formula recommended by Arnoldus (1981) was used (Eq. 2):

$$R\text{ann} = \left[4.17 \times \sum_{i=1}^{12} \left(\frac{p_i^2}{p}\right)\right] - 152 \tag{2}$$

Where, P_i is the monthly average rainfall (mm) for the month i, P is the annual average rainfall (mm) and R_{ann} represents the annual average R. When P and P_i values are substituted from rainfall data in the above equation, the resultant value of R can be obtained. R factor was obtained from Bayan Lapas weather station and calculated using Eq. 2 which, for Penang Island, is 652.81 MJmm/ha.h. This constant factor was used for the entire island.

K soil erodibility factor

It is a function of percentage of silt and coarse sand, soil structure, permeability of soil and the percentage of organic matter. K factor is based on the soil types. The soil map was obtained from the Malaysian Irrigation and Drainage Depart-

Table 1 Soil types and their *K* factor values

Soil series (types)	*K* factor
Serong	0.1144
Selangor kangkong association	0.07
Rengam	0.09
Kuala-kedah permatang association.	0.1125
Steep land	0.1100
Rengam bukit temiang association	0.1159
Local alluvium–colluvium association	0.1137
Urban land	0.1102

ment (IDD) in hard copy format and was digitized (Pradhan 2010a). There are eight classes of soil types and the *K* values (Table 1) for these classes were extracted from the Agricultural Handbook (Shamshad et al. 2008). Soil map was considered as a basic layer to derive the *K* factor layer. Vector soil map was converted into raster format using spatial analyst tool in Arc Info 9.2. Then, the value field of the soil layer was reclassified by respective values of *K* factor, using the reclassify tool of Spatial Analyst extension in Arc Info 9.2 and subsequently raster layer of *K* factor was generated (Fig. 2). Considering different properties of soil such as texture, organic matter and permeability, *K* values were obtained. These values were validated with previous researchers (Shamshad et al. 2008).

L and *S* Terrain factors

Terrain factors represent the slope length (*L*) and slope steepness (*S*). The amount of erosion increases as the slope length increases (Wischmeier and Smith 1978; Desmet and Govers 1996; Renard et al. 1997). The slope length is defined as the distance, along the flow path, from the origin of overland flow to the point where deposition begins to occur (on concave slopes) or to a concentrated flow channel. The *L* and *S* factors jointly represent the effect of slope length, steepness and shape on sediment production. USLE represents the combined effects of rill and inter-rill erosion. Rill erosion is primarily caused by surface runoff and increases in a downslope direction because the runoff increases in this direction. Inter-rill erosion is caused primarily by raindrop impact and is uniform along a slope. Therefore, the *L* factor is greater for those conditions where rill erosion tends to be greater than inter-rill erosion. Erosion increases with slope steepness but, in contrast to the *L* factor representing the effects of slope length, the USLE makes no differentiation between rill and inter-rill erosion in the *S* factor that computes the effect of slope steepness on soil loss. These factors are typically calculated together for input into the equation as:

$$\mathrm{LS} = \left(\text{Flow accumulation} \times \frac{\text{Cell size}}{22.13}\right)^{0.4} \times \sin\left(\frac{\text{Slope}}{0.896}\right)^{1.3} \qquad (3)$$

The LS factor raster grid was calculated using the ArcInfo Spatial Analyst tool. The digital elevation model, drawn from 10-m contour intervals and survey-based points (spot heights) from 1:25,000 topographical sheets (Pradhan 2010a), were the sources for the LS factor. The technique for esti-

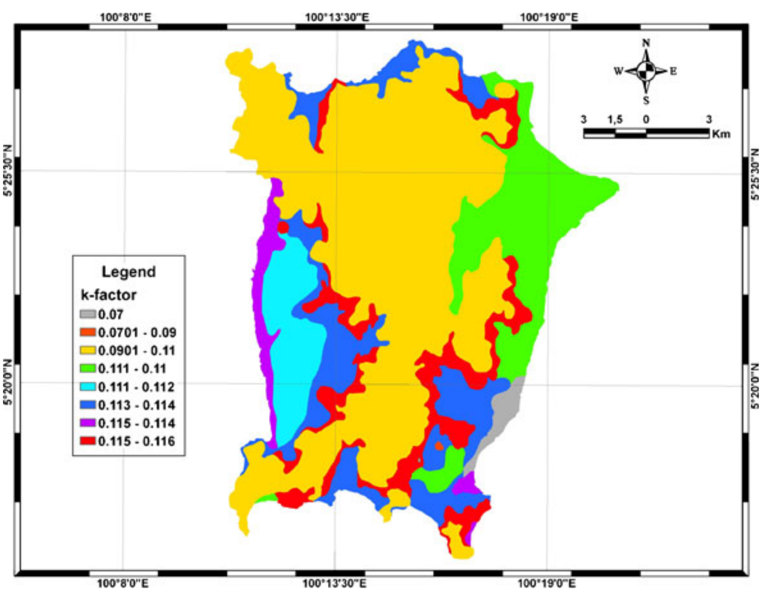


Fig. 2 *K* factor layer of study area

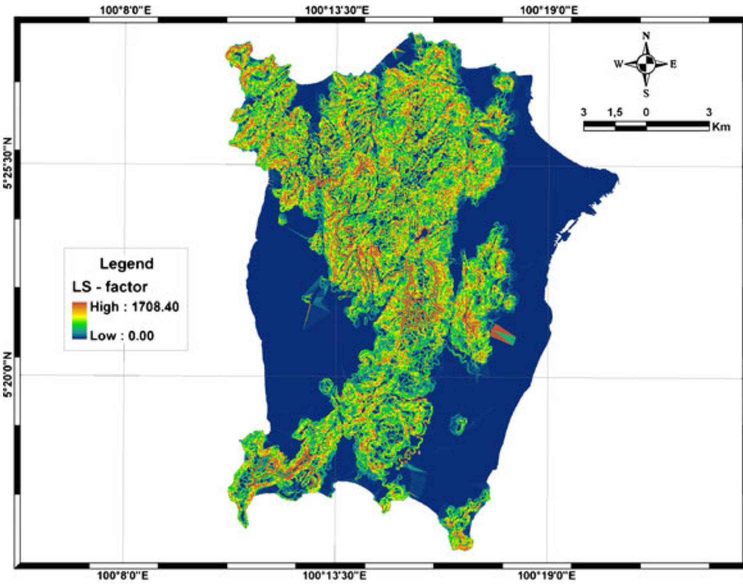


Fig. 3 LS factor layer of study area

mating the LS factor was proposed by Moore and Burch (1986a, b). The technique for computing LS requires a flow accumulation and the slope steepness. Using Eq. 3, LS factor were calculated and is shown in Fig. 3.

C factor Land cover and management factor

C factor measures the combined effect of all the interrelated cover and management variables, (Wischmeier and Smith 1978). It was derived from a land use/cover classification from the satellite data. A land use/cover map was prepared using SPOT 5 images (10 m spatial resolution) of 2005. A supervised classification method was applied to the SPOT image followed by field survey verification (Pradhan 2010a). According to land use/land cover classification map of study area, *C* factors were assigned to different classes and the values were drawn from the work carried out by Emrah et al. (2007; Table 2 and Fig. 4). Similarly, land use/cover classification was also carried out for 2010 using Landsat ETM+ data of 10 m resolution to understand the dynamism of soil erosion. Subsequently, *C* factor map was produced using the land use/cover map of 2010 and is shown in Fig. 5.

Table 2 *C* factor values for each land use classes in the study area (Source: Emrah et al. 2007)

Sr. no.	Land use	*C* factor
1	Water body	0
2	Settlement	0.003
3	Forest	0.004
4	Urban	0
5	Bare land	1
6	Agriculture	0.40

P factor Conservation practices factor

The supporting practice *P* factor describes the effects of practices such as contouring, strip cropping, concave slopes, terraces, sediment basins, grass hedges, silt fences, straw bales and subsurface drainage. The value for *P* is taken by using practices analogy since the data is not readily available for study area. Therefore, in the absence of conservation practices data in this study area, *P* factor was assumed as 1.

Soil erosion mapping

Arc Info Spatial Analyst extension and raster calculator was used to calculate *A* (in t/ha/y). The soil erosion intensity map was then classified into five zones of soil erosion for visual interpretation: very low, low, moderate, high and very high (Fig. 6). The erosion intensity index was classified into five classes of total soil erosion (highest 10%, sec-

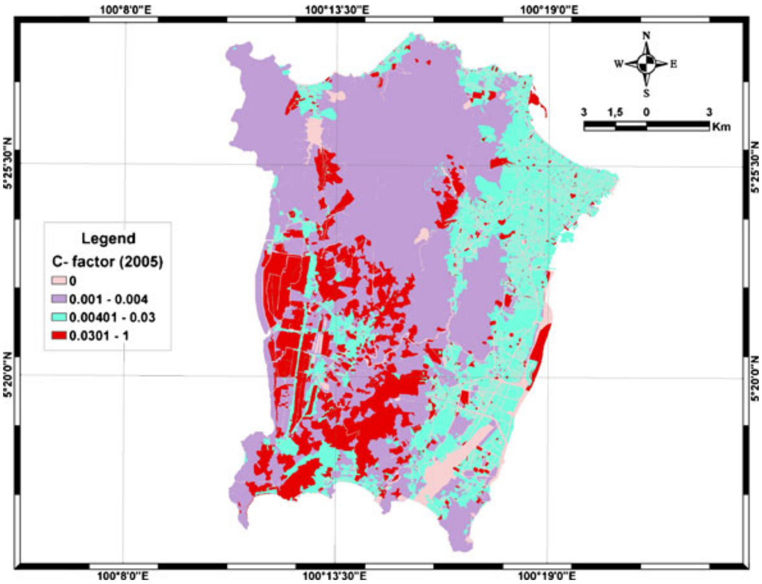


Fig. 4 *C* factor layer of 2005 of study area

ond 10%, third 20% and remaining 60%) based on equal area classification for visual and easy interpretation.

Prognosis

Prognosis means actual vs. potential soil erosion (Adinarayana 2010). Potential soil erosion risk is defined as the inherent risk of erosion, irrespective of current land use or vegetation cover. It is calculated by USLE as:

$$A = R \times K \times \mathrm{LS} \tag{4}$$

Whereas actual soil erosion is calculated with crop management factor (CP) in USLE.

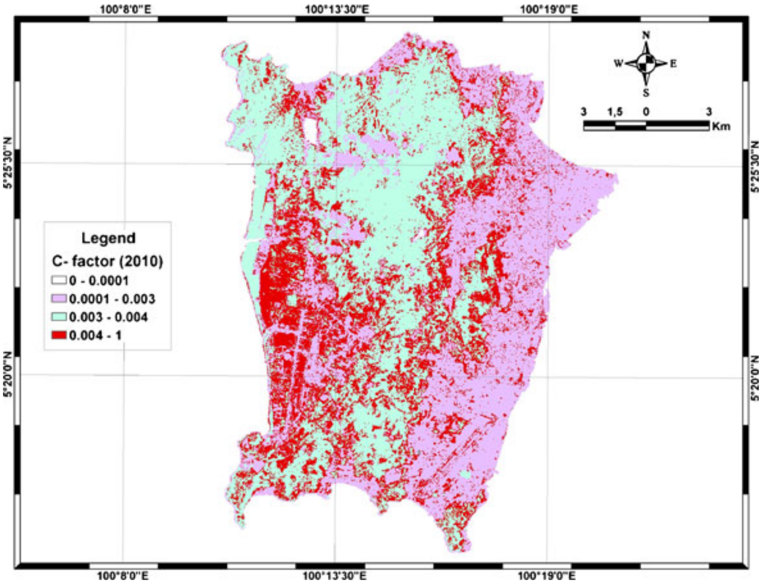


Fig. 5 *C* factor layer of 2010 of study area

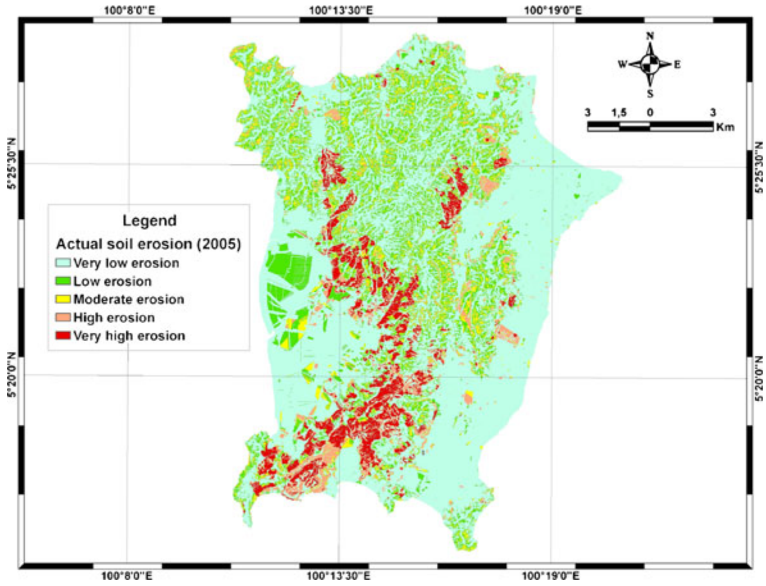


Fig. 6 Actual soil erosion prone zone map (2005) of Penang Island

Temporal assessment of soil erosion

This exercise was carried out keeping in view of the dynamic changes in land use/cover patterns, developments in urbanization, industrialization and infrastructure and its consequent effect on soil erosion in this sensitive ecosystem. Keeping all relatively static RKLS factors in 2005 constant, the dynamic *C* factor of 2010 were replaced in USLE and generated the current soil erosion map. SPOT 5 of January 2005 (Fig. 7) and Landsat ETM+ of March 2010 (Fig. 8) images were the inputs for land use/cover pattern changes and the corresponding temporal *C* factors.

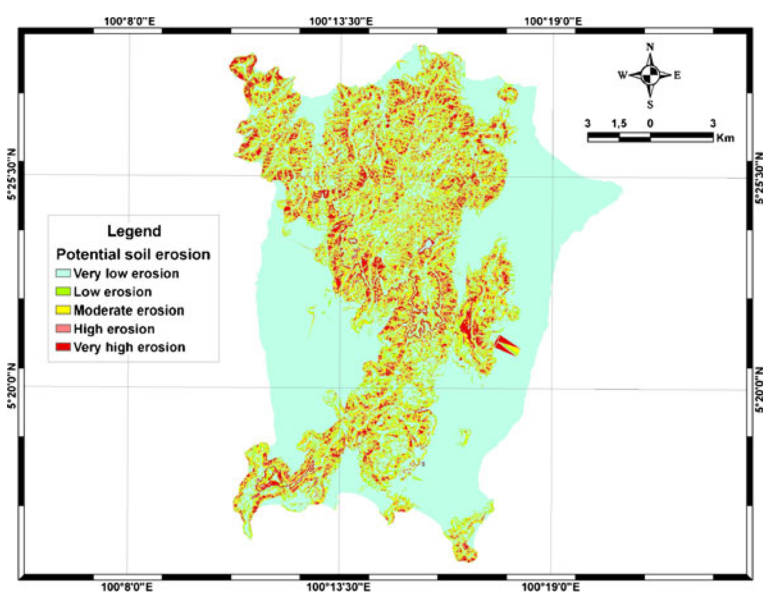


Fig. 7 Potential soil erosion prone zone map (2005) of Penang Island

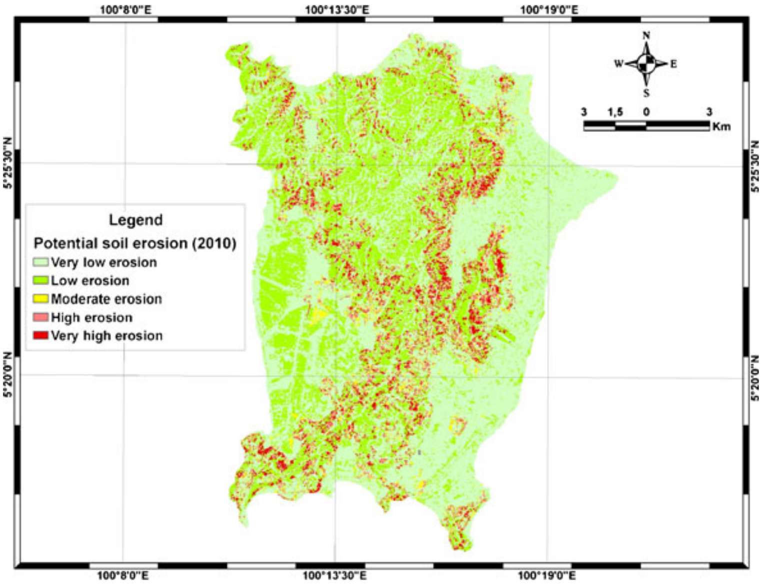


Fig. 8 Soil erosion prone zone map (2010) of Penang Island

Results and discussion

Prognosis

Comparison of actual soil erosion prone (Fig. 6) and potential soil erosion prone (Fig. 7) maps reveals that potential soil erosion is more than the actual soil erosion (Fig. 9), owing to the absence of CP. This will help the decision makers to (a) know the maximum erosion that can take place in an area, and (b) generate scenarios with changes in land use/cover for better conservation management. In general, the following measures of landslide control appear effective and are recommended for the study area: (1) replanting of trees, shrubs, grass and other cover vegetation in exposed areas on hill slopes, i.e. adopt a sustainable logging policy whereby trees felled must be replanted by enforcing tree plantation campaign; (2) stricter monitoring of deforestation and better enforcement of the law must be carried out; (3) better maintenance of roads, highways and other communication structures in hilly areas in order to prevent of soil erosion; (4) ensure that developers build retaining walls after cutting hill slopes; (5) relocate squatters on hill slopes and regenerate these areas with forest and or proper development planning with respect to hill land areas.

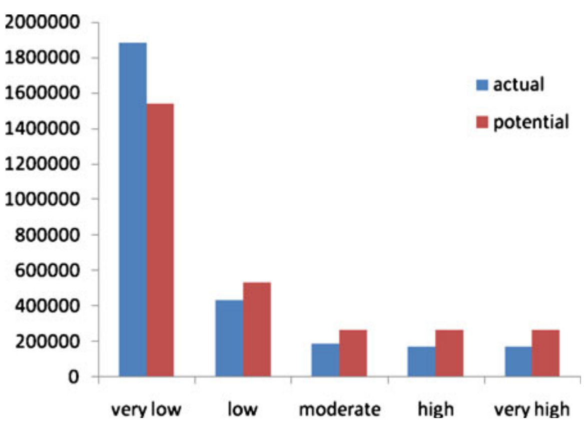
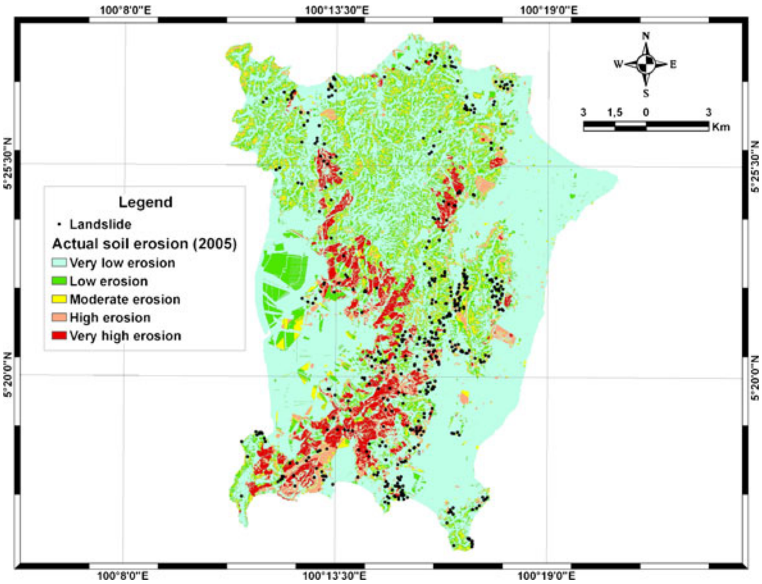


Fig. 9 Graph showing Prognosis

Correlation of soil erosion map

As there is no facility/infrastructure to validate soil erosion intensity values in the study area, landslides locations maps, generated from aerial photographs, previous inventory and extensive field survey, was used to correlate the soil erosion intensity map. Landslide locations, occurred

Fig. 10 Soil erosion map of 2005 with landslides locations



during the past 20 years, are overlaid with the actual soil erosion map of 2005 and is shown in Fig. 10.

Soil erosion map was correlated with the help of frequency ratio-based statistical analysis. Frequency ratio approaches are based on the observed relationships between distribution of landslides and soil erosion intensity to reveal the correlation between these two related phenomena in the study area (Pradhan and Lee 2010a; Pradhan 2010a, b). The frequency was calculated from the analysis of the relationship between landslides and the attribute factors as given in Table 3. The frequency ratios of each soil erosion ranges were calculated from their relationship with landslide events. In the relationship analysis, the ratio is that of the area where landslides occurred to a particular area of erosion prone zone. A value of 1 is an average value. If the value is greater than 1, it means a higher correlation, and a value lower than 1 means lower correlation of occurring soil erosion.

Frequency ratio computed for Penang Island is shown in Table 3. The relationship between soil erosion and landslides occurrence shows that very high erosion zone has higher probability of landslides. For very low erosion zone, frequency ratio is 0.529, which indicates it has very low probability of landslide occurrences. For high and very high erosion zones, frequency ratio are found

Table 3 Frequency ratio values of landslide occurrences vs. soil erosion intensity map of 2005

Soil erosion levels	Pixels in domain	Pixel %, (a)	Landslide occurrence points	Landslide occurrence points, %, (b)	Frequency ratio, (b/a)
Very low (60%)	1884775	66.21	162	35.06	0.529
Low (20%)	433189	15.22	121	26.19	1.72
Moderate (20%)	186474	6.55	56	12.12	1.85
High (10%)	172521	6.06	58	12.55	2.07
Very high (10%)	169624	5.96	65	14.08	2.36
Total	2846583	100	462	100	1

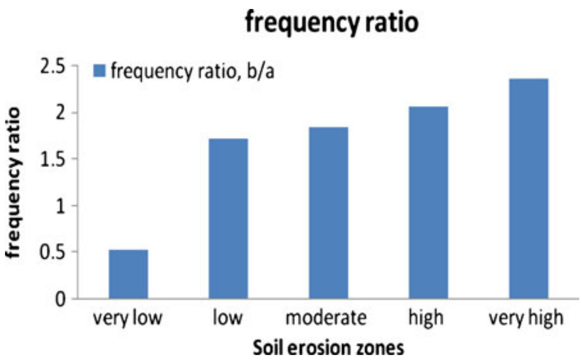


Fig. 11 Frequency ratio analysis of soil erosion map of 2005 with landslides

to be >2, which indicates they have more probability of landslide occurrences. Figure 11 shows the graphical representation of frequency ratio to each soil erosion prone zone. Perusal of the graph indicates a linear relationship between frequency ratio and soil erosion zones. This correlation result shows satisfactory agreement between the erosion map and the landslide events/location data.

Satellite-based temporal changes of land use/cover over 5 years in this fragile ecosystem (Table 4) indicates significant reduction in forest area (about 11.51%), increase in urban and agriculture areas (5.91% and 6.11%, respectively) and almost stable in case of barren land. These developments indicate the urbanization, industrialization at the cost of forest ecosystem and demand for food in the island. Overall, mean annual soil erosion of the study area was increased from 75.71 t/ha/yr in 2005 to 92.54 t/ha/year in 2010.

Table 4 Changes in areal extent of land use/ land cover from 2005 to 2010

Sr. no.	Land use/cover	% area covered in 2005	% area covered in 2010
1	Agriculture	15.23	21.34
2	Forest	50.14	38.63
3	Bare land	2.06	3.49
4	Settlement	30.29	36.2
5	Water body	2.38	0.34

Concluding remarks

Penang Island area is very susceptible to soil erosion and landslides, therefore there was a need to study the soil erosion prone zones of this area. The study demonstrates the integration of USLE with GIS to model soil erosion quantitatively and to predict the erosion hazard over a large area. The soil erosion map was compared to the landslide events/locations map and verified using the location of landslides by frequency ratio analysis. The results of this correlation showed a satisfactory agreement between the soil erosion intensity map and landslide events data.

Potential soil erosion map helps the decision makers to know the maximum erosion that can take place in the island and design land use/cover systems to reduce this non-point source pollution. Application of the USLE has many advantages: it provides quantitative data for comparison with qualitative assessments in erosion studies; data requirements for USLE are not too complex or unattainable and are compatible with GIS and easy to implement and understand from a functional perspective.

While the erosion map can be used to shadow the landslide hazard map, it was difficult to account for actual C and P factors. The true C and P values require further investigation in this region. Results can be used as basic data to assist in slope management and land use planning, but the methods used in the study are valid for generalized planning and assessment purposes. Developmental aspects in the island had a bearing on soil erosion as evidenced by time-series analysis over 5 years.

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