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Comparative study of USLE and RUSLE model in predicting soil erosion events using GIS in Penang Island

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Abstract

Around the world, soil erosion is a major environmental concern, especially in tropical areas like Malaysia's Penang Island. In order to assess the accuracy and dependability of both models in estimating soil erosion risk, this study will use the USLE and RUSLE models to estimate soil erosion on Penang Island. Additionally, the predictions generated by the RUSLE model will be compared with site verification. Important parameters were extracted from spatial datasets and added to the models, including the rainfall erosivity factor, soil erodibility factor, slope length and steepness factor, vegetation management factor, and supporting conservation practices factor. In order to analyse and map the risk of soil erosion throughout Penang Island, the research integrated GIS technology with both the USLE and RUSLE models. The findings suggest that the RUSLE model outperforms the USLE model in detecting regions vulnerable to soil erosion. Thus, the RUSLE model demonstrates more reliable data and typically aligns well with real site verification outcomes. In general, the forecast of soil erosion through RUSLE can be effectively contrasted with the USLE model within GIS. This study's recommendation suggests gathering data for model inputs to enhance the precision of soil erosion forecasts on Penang Island.

Keywords: Land-use, GIS, mapping, RUSLE, soil erosion, USLE

Introduction

Soil erosion is a worldwide environmental issue that affects both natural ecosystems and agricultural output. Although it is a natural phenomenon, human activities like overgrazing, forest clearing, improper farming techniques can accelerate it. For sustainable land management and effective soil conservation, accurate soil erosion estimation is crucial. Soil erosion is recognized as a factor in the degradation of biodiversity, agricultural productivity, water quality, and aquatic life (Behera et al., 2023). Soil erosion is examined from various disciplines and perspectives. This book defines soil erosion as the cumulative result of all processes that dislodge and move soil from its original site over the long term (Asmamaw & Mohammed, 2019). Soil erosion is a naturally

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occurring geomorphic process, although human usage of the soil often results in rates of soil detachment and transport that are several orders of magnitude greater than naturally occurring rates. Researchers have developed numerous methods to estimate soil erosion, including process-based models like the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE). The USLE model estimates the typical soil loss resulting from splash, sheet, and rill erosion (Bernama, 2023). Created by the United States Department of Agriculture (USDA) in the 1960s, it is used globally (Adnan et al., 2021). The USLE has evolved into a valuable tool for predicting soil losses and planning control strategies by integrating GIS-based techniques for calculating factor values on a grid cell basis. Next, The RUSLE includes improvements in estimating the cover-management factor and the topographic factor, designed to overcome the shortcomings of the USLE. However, despite these advancements, there are still debates about the applicability and accuracy of the RUSLE compared to the USLE. Therefore, comparative studies are necessary to evaluate the performance of these two models under different climatic and geographical conditions. Furthermore, Geography Information System (GIS) has developed methodologies and processes for performing soil erosion studies to assess the level of soil erosion in a specific area. The aim of this study is to comparative study of USLE and RUSLE models in predicting soil erosion events using GIS in Penang Island. Soil erosion can be accelerated by intense rainfall and steep slopes, particularly in regions with these characteristics. Rainfall and stormwater activities are primary factors contributing to slope collapse and landslides at many construction sites situated on slopes in Malaysia (Mokhtar, 2006; Rahman & Mapjabil, 2017). Reported approximately 21,000 landslide-prone locations across Malaysia, with 76% of them (16,000 locations) in Peninsular Malaysia, 2,000 in Sarawak, and 3,000 in Sabah (Rahman & Mapjabil, 2017). According to sectoral studies in Malaysia, 88% of 49 documented landslide events occurred on man-made slopes JKR as depicted in Figure 1.

Source: National Slope Master Plan 2009-2023, 2019

Figure 1. Landslide prone areas in Malaysia

Literature review

One typical environmental issue that poses a harm to the ecology of Penang Island's hills is soil erosion. Events that can affect and pose a risk to people, the environment, and the economy include landslides, flooding, soil erosion, and slope collapse (Ahmad et al., 2013; Ahmad et al., 2020). The slope is particularly vulnerable to erosion and landslides in Malaysia due to the country's abundant rainfall. As a result, was shown in Figure 2 , soil erosion and slope failure caused a section of the federal road around the island, which runs from Balik Pulau road to Teluk Bahang, to become completely blocked in July 2023. Zairil Khir Johari, the chairman of the Penang Infrastructure and Transportation Committee, stated that slope breakdown was brought on by soil erosion because of a high rainfall distribution during the Public Works Department's (PWD) precursor study of the site (Bernama, 2023). Figure 2. shows the location of the slope failure at FT006 section 46.80 in Balik Pulau, Penang.

Source: Bernama, 2023

Figure 2. Slope failure at FT006 section 46.80 at Balik Pulau

Sheet erosion refers to the gradual loss of soil in thin layers due to the impact of raindrops and shallow surface movement. Soil erosion is an indigenous geological phenomenon of separation and transportation of soil particles from their origin, and their accumulation either onsite or offsite (Jain et al., 2001). It can be challenging to detect unless significant soil deposition nearby has occurred, or the erosion damage is already substantial. During sheet erosion, organic compounds and essential nutrients contained within soil particles are often removed, diminishing soil fertility over time. (Mulvihill, 2021). The most vulnerable soils to sheet erosion are those that have been overgrazed and farmed and have insufficient vegetation to cover and hold the soil. Although, the erosion problem occurs along the globe, however, countries with tropical and subtropical climates, such as Malaysia, are particularly vulnerable to soil erosion and its associated challenges due to high rainfall intensities in these regions (Abd Rahman et al., 2023). Bare spots, water puddles as soon as it rains, exposed tree roots, discernible grass roots, and exposed subsoil are all signs of sheet erosion. Sheet erosion occurs when minute particles are released from the substrate by rain splash and are then carried away, typically over short distances, by a thin, even layer of water known as sheet flow. Soil erodibility, typically termed as the K-factor, is an inherent property of soil that determines its resistance to both detachment and transport (Rehman et al., 2022). Sheet erosion is a phenomenon of modest magnitude because sheet flow transfer often happens over small distances. As opposed to a normal sheet flow, a sheet flood has a significantly higher volume and a much lower frequency. The sheet erosion occurring along the Langat River at Kuala Langat is shown in Figure 3.

Source: Abidin et al., 2017

Figure 3. Sheet erosion along Langat River at Kuala Langat

Rill erosion is a form of erosion that creates shallow, curved, parallel channels in the soil. These channels, initially small, are referred to as micro-rills. Over time, with repeated water flow, they can enlarge and deepen, depending on the frequency and volume of water passing through them (Rollo & Dunn, 2022). Rill erosion is most noticeable on hillsides, where it manifests as a group of parallel, perhaps convergent channels that range in depth from 0.3 to 3.9 inches. These channels are formed as runoff water concentrates and flows down a slope. The distinctive flow pattern of rill erosion suggests that water moves in predictable, if disjointed, parallel channels.

Moreover, rills happen when the capacity of surface runoff to separate soil particles outweighs the soil's resistance to a force applied perpendicular to its surface. Erosion begins when water breaks up soil particles and moves them down the slope. Rills can occur on any surface and are closely tied to the steepness of the hillside slope. Not all surfaces are suitable for the creation of rills, and steep slopes are necessary because gravity limits the water's capacity to produce the perfect conditions needed for rills to form. Because the strength of the water is controlled by gravity, the sexual atmosphere required to create rills is exclusive to steep slopes and cannot occur on any other surface (Rollo & Dunn, 2022). Figure 4 shows the rill erosion occurring along Langat River at Hulu Langat.

Source: Abidin et al., 2017

Figure 4. Rill erosion along Langat River at Hulu Langat

Method and study area

This research delineates the comprehensive methodology utilized in comparing the RUSLE and USLE models for predicting soil erosion in the study area. The methodology comprises four main sections: data collection, data processing, data analysis, and visualization of the soil erosion risk map. Figure 1 shows research methodology. In the data collection phase, four types of data were gathered: satellite imagery, DEM data, soil maps, and rainfall data. The processing phase involved utilizing NDVI, land use, slope, and flow accumulation data to evaluate relevant factors and calculate average annual soil loss using appropriate formulas. Data analysis included comparing prediction results from both models and conducting on-site verification. Accuracy assessment was integral to this section, focusing on comparing the accuracy of predictions between the USLE and RUSLE models (Figure 5).

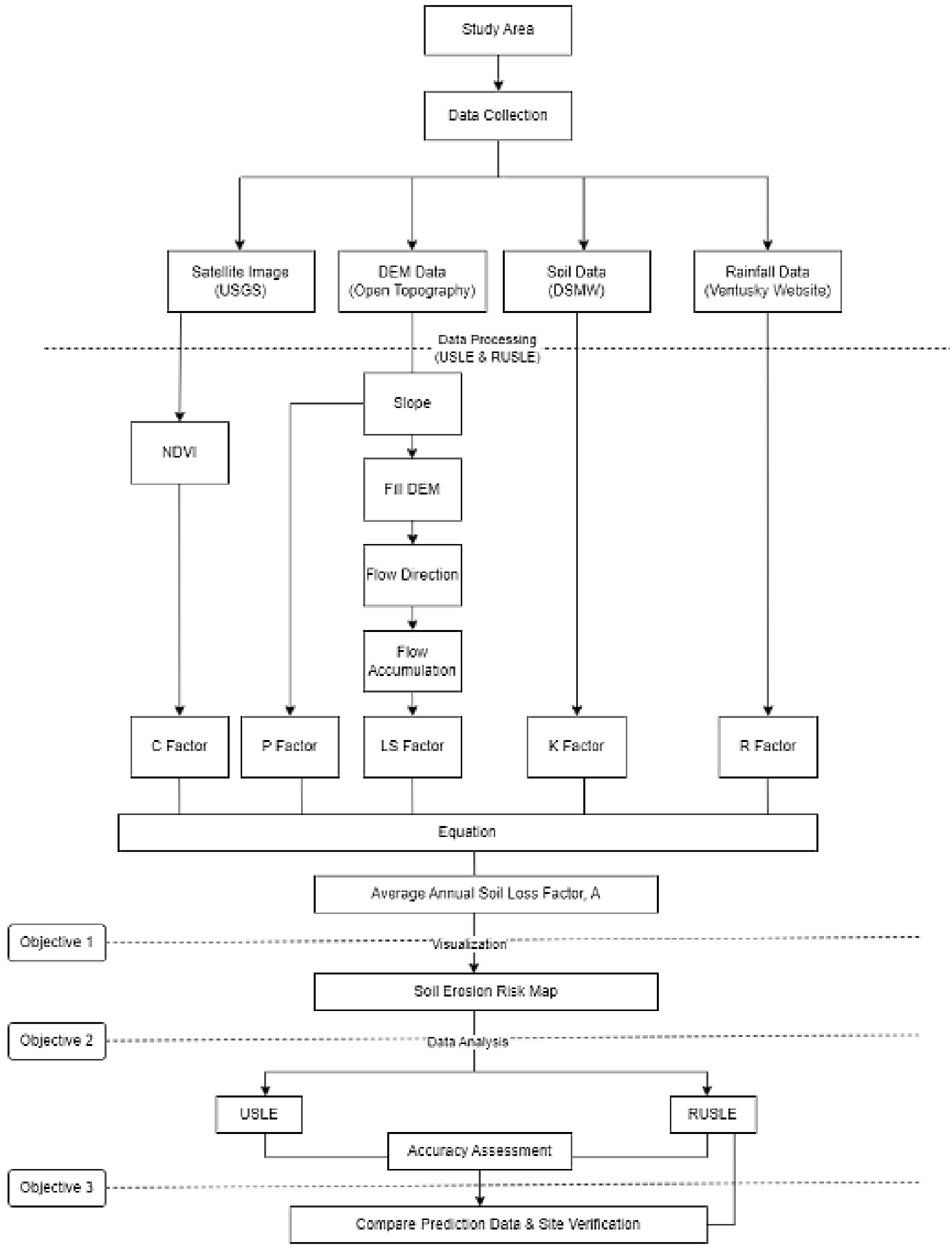

Figure 5. Flowchart of research methodology

Data acquisition

Table 1. Description of the datasets used in this study

Data	Resolution	Year	Source
Landsat 8	30m	2024	United States Geological Survey (USGS)
DEM data	90m	2023	Open Topography
Soil data	-	2023	Digital Soil Map of World (DSMW)
Rainfall data	-	2023	Ventusky

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The predicted soil erosion of the study area was identified in this research study using ArcGIS 10.8.2 software and using data from remote sensing raster data (images from Landsat 8). The USLE and RUSLE are empirical models used for predicting soil erosion. The USLE and RUSLE is an empirical soil model that was created by Wischmeier and Smith in 1978. Equation (1) was used to calculate the A value.

$$A_{\frac{USLE}{RUSLE}} = R \times K \times LS \times C \times P \qquad \text{Eq.1}$$

where A is the estimated average soil loss, R is the rainfall erosivity, K is the soil erodibility, LS is slope length and steepness, C is vegetation management and P is supporting conservation practices. The equation of R factor and K factor was the same used for both models, but factor C and LS are using the difference equation. The slope of Penang Island is used to perform the process of the P factor of both models. (Table 2) showed the comparative study of the models used in the study area.

Table 2. Comparative study of the models

Factor	USLE & RUSLE model	
R	$38.5 + 0.35P$	
K	$K_{USLE/RUSLE} = f_{csand} \times f_{ci-si} \times f_{orgC} \times f_{hisand}$	
	USLE model	**RUSLE model**
LS	$LS_{USLE} = \left(flow\ accumulation \times \frac{cell\ value}{22.14}\right)^{0.4} \times \left(\frac{sin\ sin\ (slope)}{0.0896}\right)^{1.4}$	$LS_{RUSLE} = \left(flow\ accumulation \times \frac{cell\ value}{22.1}\right)^{m} \times (0.065 + 0.045S + 0.0065 \times S^2)$
C	$C_{USLE} = exp\left(-\alpha \times \frac{NDVI}{\beta - NDVI}\right)$	$C_{RUSLE} = 0.9167 - NDVI \times 1.1667$

The accuracy of the predicted risk levels from both the USLE and RUSLE models. Then, compared by RUSLE model with actual site verification data. Additional verification evidence was required. Eight locations were selected for on-site verification, representing various areas within the study site and offering a diverse set of conditions for assessing soil erosion risks. The actual soil erosion risk levels at these locations were determined through on-site verification and observations. Penang Island is in Northwest Peninsular Malaysia at latitudes 5°22'11" N and longitudes 100°15'38" E using the WGS84 coordinate system, has an average height of 118 meters above sea level. There are 301.27 km^2 in the Penang Islands overall, with 126.4 km^2 in the northeast and 174.87 km2 in the southwest. The Department of Statistics Malaysia (DOSM) states that Penang Islands has one of the highest rates of urbanization, following Kuala Lumpur and Selangor, which have rates as high as 90.8%. Penang Island is also seeing constant economic growth, and because of extensive industrialization, rapid technological advancements, and the greatest rate of urbanization to accommodate population increase, high-risk geohazard zones have been created (Figure 6). For example, the high terrains of Bukit Bendera (738 meters) and Bukit Western (833 meters) in these two places have had multiple landslide incidents in the past few years.

Source: Google Earth, 2024

Figure 6. Study area

Results and discussion

This chapter describes the concepts of the USLE and RUSLE models along with techniques to estimate the annual average soil loss rate using the USLE and RUSLE equations. In this study, only one software was used to process the data: ArcGIS software.

Rainfall erosivity factor

Penang Island is experiencing high rainfall rates that can lead to soil erosion. Increased rainfall, sloping terrain, and insufficient vegetation cover can accelerate the erosion process. This water erosion can damage infrastructure and cause the loss of productive soil and sediment in rivers and oceans. Raindrops, upon hitting the ground, are the primary source of energy for soil separation. In this study, the annual average rainfall data obtained was used to calculate the value of rainfall erosivity (Mg/ha/year). The monthly anomaly precipitation data in 2023 was obtained from six rainfall stations from Ventusky. The spatial interpolation of all data points was conducted using the IDW method. The value of R was calculated based on the formula in Equation (2) that was introduced by Morgan in 1974. where P is mean annual rainfall in mm (2023). R factor map in Figure 7 indicates that the values range between 230.3 and 258.9 mm/ha h year.

$$R = 38.5 + 0.35P$$

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Eq. 2

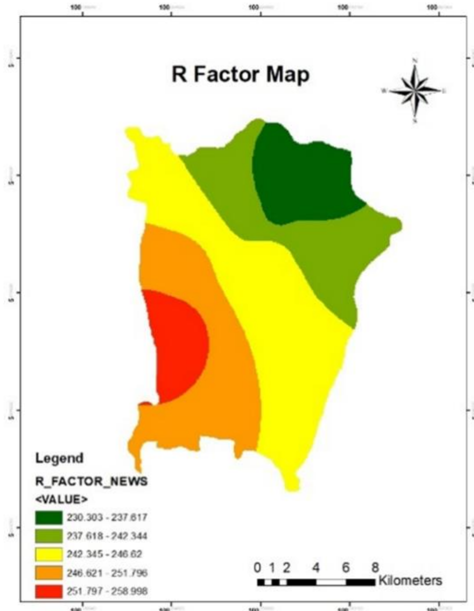

Figure 7. R factor map

Soil erodibility factor

There is one predominant soil unit known as Orthic Acrisols (AO). Orthic Acrisols are characterized by a clay-enriched subsoil horizon and are typically found in tropical regions. The K factor depends on four parameters: sand, clay, silt, and organic matter percentages, which determine the soil's susceptibility to erosion. The K factor value was calculated using Williams' (1995) Equations (3) to (7).

$$K_{USLE/RUSLE} = f_{csand} \times f_{ci-si} \times f_{orgC} \times f_{hisand}$$

Eq.3

$$f_{csand} = \left(0.2 + 0.3 \times exp\left[-0.256 \times m_s \times \left(1 - \frac{m_{silt}}{100}\right)\right]\ \right)$$

Eq.4

$$f_{ci-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3}$$

Eq.5

$$f_{orgc} = \left(1 - \frac{0.25 \times orgC}{orgC + exp[3.72 - 2.95 \times orgC]}\right)$$

Eq.6

$$f_{hisand} = \left(1 - \frac{0.7 \times \left(1 - \frac{m_s}{100}\ \right)}{\left(1 - \frac{m_s}{100}\right) + exp\left[-5.51 + 22.9 \times \left(1 - \frac{m_s}{100}\ \right)\right]}\right)$$

Eq.7

where $K_{USLE/RUSLE}$ is the erodibility factor, m_s is the % sand, m_{silt} is the % silt, m_c is the % clay, and Org_c is the % organic carbon. Soil erodibility factor, K refers to the ability of soil to be displaced by the rainfall forces (Asmamaw & Mohammed 2019; Jazouli et al. 2019). The results in Figure 8 show that the values of the K factor are 0.160, indicating a moderate to high susceptibility to erosion.

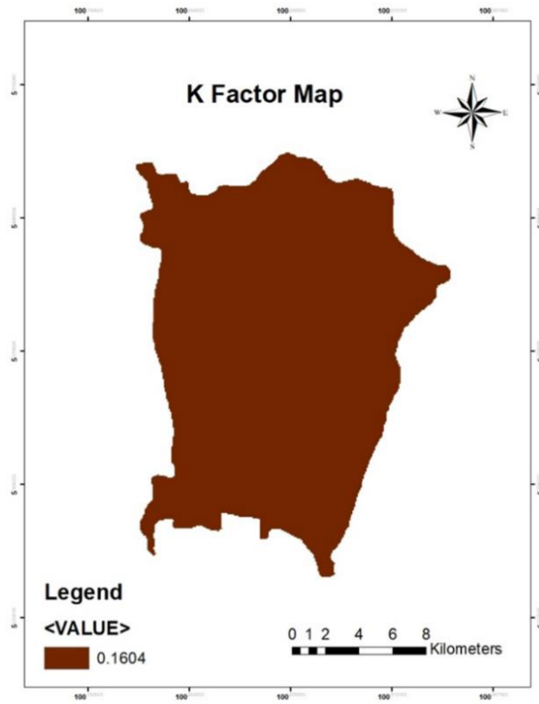

Figure 8. K factor map

Slope length and steepness (LS)

The LS factor in both USLE and RUSLE equations reflects the combined effect of slope length and steepness on soil loss. This factor has the greatest influence on soil erosion in the study area. To calculate the LS factor for both models, DEM data was processed to create flow direction, flow accumulation, and slope raster datasets. Flow accumulation was derived from the flow direction, and both flow accumulation and slope raster data were utilized in the LS calculation. Both images show a similar spatial distribution of LS values, with high values concentrated in similar areas. The RUSLE model appears to show more detailed variation within the high LS compared to the USLE model. Equation (8) and Equation (9) for USLE and RUSLE models has been given as:

$$LS_{USLE} = \left(flow\ accumulation \times \frac{cell\ value}{22.14}\right)^{0.4} \times (sin(slope)/0.0896)^{1.4}$$

Eq.8

$$LS_{RUSLE} = \left(flow\ accumulation \times \frac{cell\ value}{22.1}\right)^{m} \times (0.065 + 0.045S + 0.0065 \times S^2)$$

Eq.9

where S is slope in % and m is parameter related slope class in (Table 3).

Table 3. Value m relative to each class of slope

m value	Slope (%)
0.5	>5
0.4	3-5
0.3	1-3
0.2	<1

Source: Mondal et al., 2018

The results of the processed DEM and LS factor in the Penang Island area are shown in Figure 9 to Figure 10 for both models. The result of the analysis shows that the high value LS of the USLE model is 1628.69, while the high value LS of the RUSLE model is 302.166.

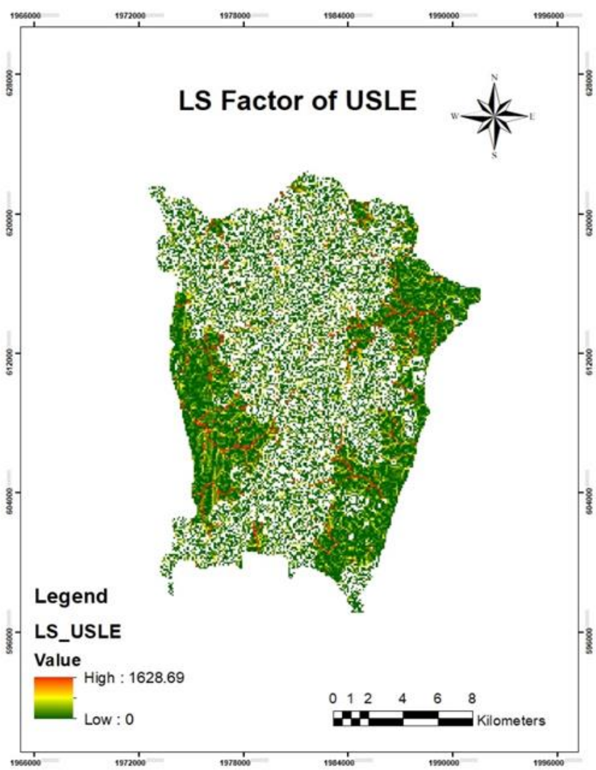

Figure 9. LS factor of USLE

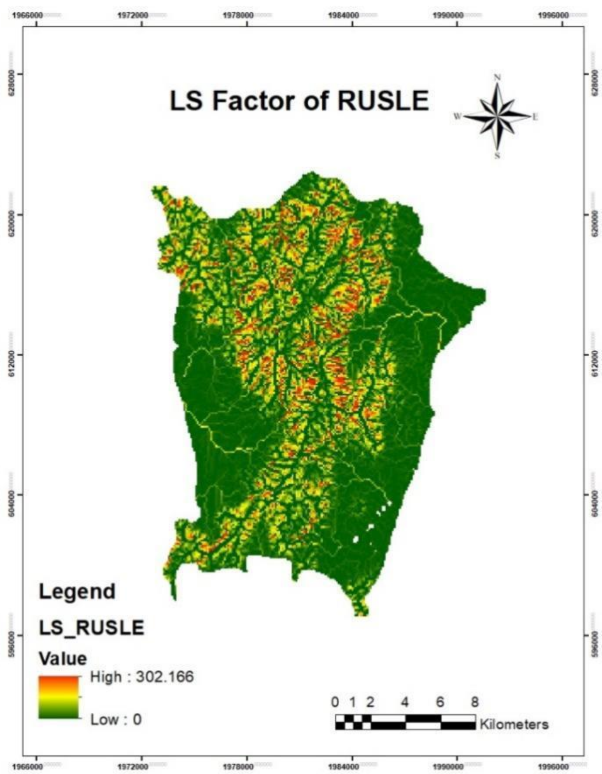

Figure 10. LS factor of RUSLE

Cover and management (C)

For the NDVI (Normalised Difference Vegetation Index), the effects of available vegetation covering any ground surface, either agricultural practices or not, in reducing soil erosion are numerically represented by the C factor. In this research study, the Landsat 8 images were used in Equation (10) to calculate the NDVI. The NDVI calculation required an appearance of both bands in the Landsat 8 images, as band 4 was associated with red (R) and band 5 with infrared (IRC) [3].

$$NDVI = \left(\frac{NDVI\ - RED}{NDVI\ + RED}\ \right)$$

Eq.10

where NIR is near infrared band of the satellite image and R is red band of the satellite image. The NDVI values found in the study area range from −0.12 to +0.53. Figure 11 shows the result of the NDVI.

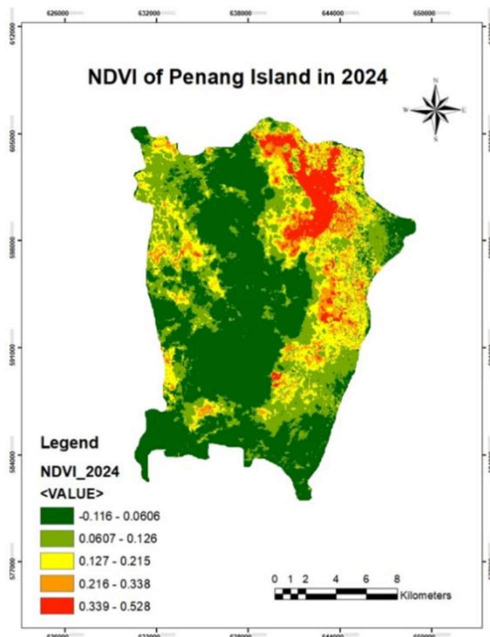

Figure 11. NDVI of Penang Island

As a result, the effect of vegetation cover is included in the C factor in soil erosion. However, the C factor values of the USLE model are calculated here and range from 0.1 to 1.0, while the RUSLE model ranges from 0.30 to 1.05. According to the RUSLE model's C factor, a low value of 0.30 is covered with dense vegetation or forested areas, which help in reducing soil erosion. However, the high value of 1.05 has less vegetative cover or more disturbed land, which increases the susceptibility to soil erosion. The NDVI values were used in different regression equation in USLE and RUSLE models. The regression equation of the USLE model was as defined by Vander Knijff, et al., (1999) based on Equation (11) while the Equation (12) used for the RUSLE model.

$$C_{USLE} = exp\left(-\alpha \times \frac{NDVI}{\beta\ - NDVI}\right)$$

Eq.11

$$C_{RUSLE}\ = 0.9167 - NDVI \times 1.1667$$

Eq.12

where alpha and beta were defining the shape of the curve, where $\alpha = 2 \; and \; \beta = 1$. The C factor map for the USLE and RUSLE is depicted in Figure 12 and Figure 13.

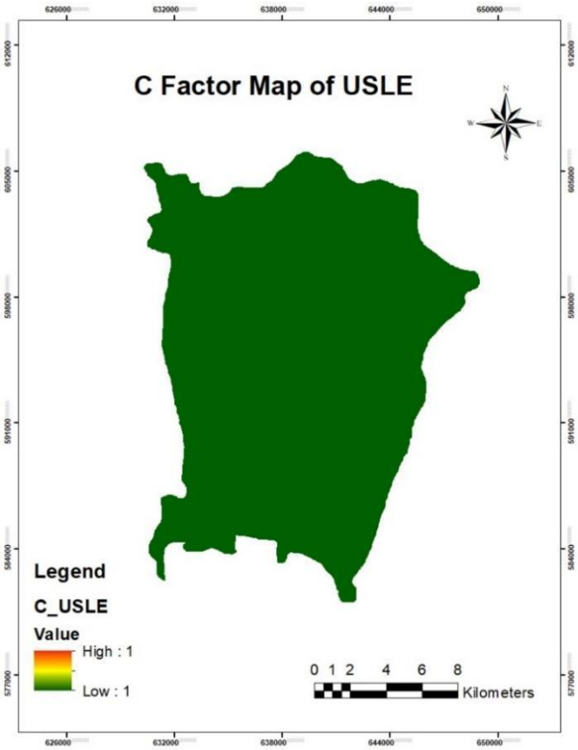

Figure 12. C factor of USLE

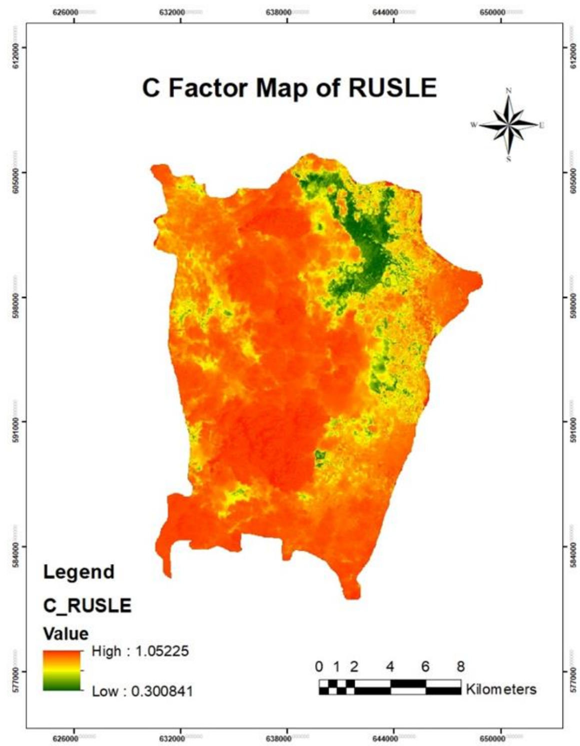

Figure 13. C factor of RUSLE

Support conservation practices (P)

In this study, the slope of Penang Island is used to perform the process of the P factor of both models. These areas have a P factor close to 1, indicating a higher potential for soil erosion, while values close to 0.55 indicate a lower erosion potential. The concentration of high P factor places indicates that the risk of erosion is higher in these areas due to either ineffective conservation techniques, steeper slopes, or more severe rainfall. Next, low P factor values are indicative of less heavy rainfall, flatter topography, or better land management techniques, all of which lower the risk of erosion. According to Table 4, the P factor was shown to depend on the slope.

Table 4. P factor depending on slope

Slope (%)	Contouring
0.0 - 7.00	0.55
7.00 - 11.3	0.60
11.3 - 17.6	0.80
17.6 - 26.8	0.90
26.8 >	1.00

Source: DOA, 2010

The P factor map for the USLE and RUSLE is depicted in Figure 14.

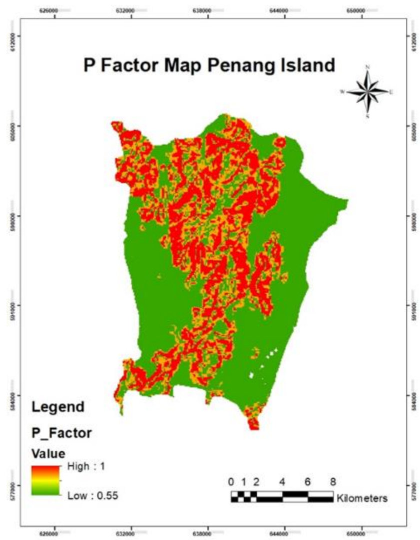

Figure 14. P factor map Penang Island

Soil erosion risk map

The study analysed soil erosion risk maps generated using both the USLE and RUSLE models on Penang Island. The results show that the RUSLE model is more effective than the USLE model in pinpointing areas vulnerable to soil erosion. This difference arises because the soil erosion risk assessments in both models utilize distinct regression equations to calculate the C and LS factors. Then, the results of all five factors were calculated using models based on the Equation (1). Next, the results were reclassified into five classes which were very low risk, low risk, moderate risk, high risk and very high risk. Figure 15 shows the result of the soil erosion risk map of the USLE model, while Figure 16 shows the result of the RUSLE model.

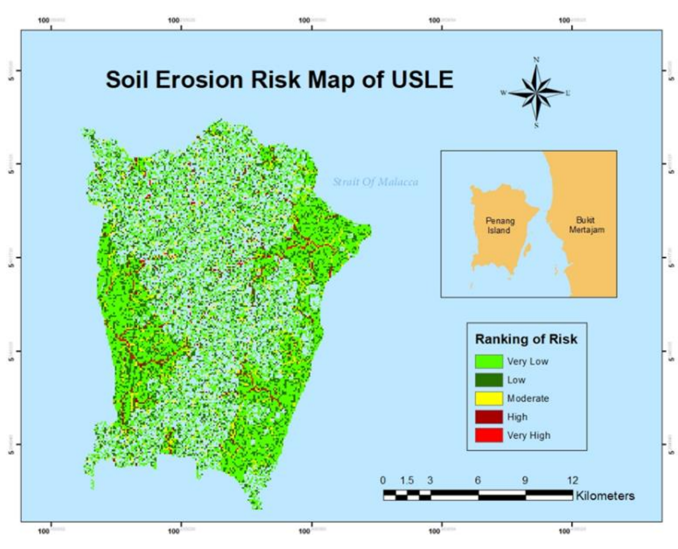

Figure 15. Soil erosion risk of USLE

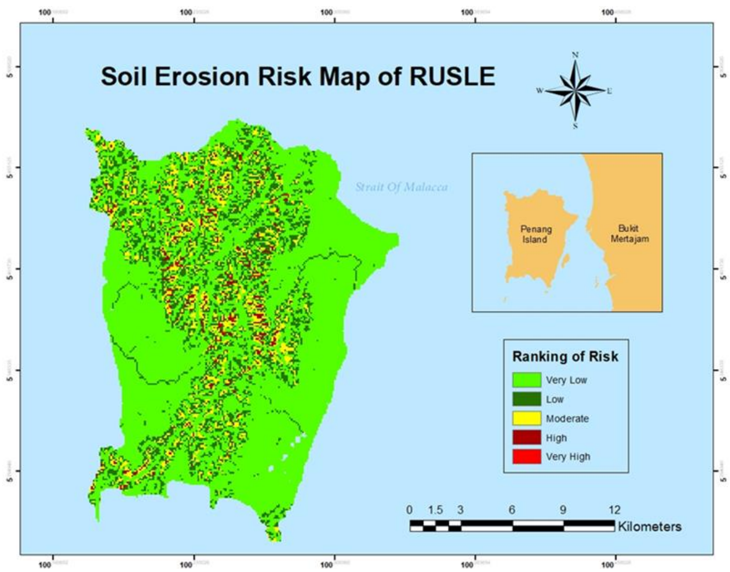

Figure 16. Soil erosion risk of RUSLE

Accuracy and reliability of both models (USLE vs RUSLE)

Table 5 shows the result of compares actual site verification data with the predicted risk levels from the USLE and RUSLE models at various locations. K factor is a crucial marker of soil erosion susceptibility (Wang et al., 2013) and is a vital parameter employed in various soil erosion estimation models influencing the extent of soil loss (Zhang et al., 2013; Huang et al., 2022). Based on Table 5, the RUSLE model shows more consistent data and generally correlates well with actual site verification results. The USLE model also predicts accurately but lacks data for several locations, suggesting occasional gaps in its reliability for predicting soil erosion. Therefore, various studies have been focused on developing empirical models to estimate soil erodibility based on physical and chemical properties, including mathematical, graphical, and instrumental methods (Zhao et al., 2018). Consequently, the RUSLE model is deemed more reliable and accurate in estimating soil erosion risk compared to the USLE model. In Penang, Malaysia, soil erosion studies have primarily utilized the Universal Soil Loss Equation (USLE) within GIS frameworks to map and analyze erosion-prone areas, particularly in the island's steep and rapidly urbanizing regions.

One notable study assessed the relationship between soil erosion and landslide risk in Penang using a GIS-based USLE model, revealing that high erosion potential is strongly correlated with hilly terrain, vegetation clearance, and unplanned development (Roslee et al., 2020). However, the study also highlighted limitations in USLE's ability to account for complex slope dynamics and seasonal land cover variation, which are characteristic of Penang's tropical environment. While research applying the Revised Universal Soil Loss Equation (RUSLE) specifically within Penang remains limited, RUSLE has been successfully applied in nearby regions with similar topographical and climatic conditions. For example, a study in the Pansoon sub-basin in Selangor demonstrated that RUSLE, when integrated with GIS, provided more accurate predictions of soil erosion, with a high correlation to observed sediment yield ($R^2 = 0.97$), outperforming traditional USLE-based methods (Hafizan et al., 2019). Furthermore, regional comparative research conducted across Southeast Asia affirms that RUSLE's enhanced slope length and cover-management factor algorithms result in more reliable erosion estimates in steep, humid tropical environments such as those found in Penang (Ahmad et al., 2024). These findings suggest that while USLE has provided foundational insights into erosion risks in Penang, the implementation of RUSLE supported by remote sensing and GIS technologies would significantly improve spatial accuracy and model responsiveness to land use dynamics and terrain variability.

Table 5. Actual site verification data with predicted risk levels from USLE and RUSLE

No	Location	Coordinate		Actual site verification	Level risk by USLE	Level risk by RUSLE
		Latitude	Longitude			
1	Jalan Bukit Kukus	5°21'34.98"	100°16'29.15"	Medium	No data	Very Low
2	Jalan Tun Sardon 1	5°21'20.16"	100°16'12.60"	Low	No data	Low
3	Jalan Tun Sardon 2	5°20'59.48"	100°15'17.81"	Very Low	Low	Very Low
4	Jalan Tun Sardon 3	5°20'52.34"	100°14'25.73"	Very Low	No data	Very Low
5	Jalan Balik Pulau (Kek Lok Si Temple)	5°24'0.73"	100°16'26.00"	Medium	High	Medium
6	Jalan Teluk Bahang 1	5°25'24.54"	100°13'9.18"	Medium	Very low	Medium
7	Jalan Teluk Bahang 2	5°25'23.10"	100°13'8.51"	Medium	No data	Low
8	Jalan Teluk Bahang 3	5°25'36.50"	100°13'6.96"	Medium	Medium	Medium

Estimation of soil erosion risk

This section describes the comparisons of the predictions produced by the RUSLE model with site verification. The temperatures range from 31°C to 33°C, which are relatively consistent and typical of a warm climate. Researchers have came to devise simple indices and empirical models to estimate soil erodibility. Amongst these thorough empirical studies, the Tew equation has been identified to yield appropriate estimates of the soil erodibility for Malaysian soil series. There are eight locations taken for location verification with varying risk levels throughout Penang Island. Referring to Table 6 provides detailed information about soil erosion risk at specific locations based on the RUSLE model. Figure 17 shows the map location of verification.

Table 6. Information of site verification and level risk by RUSLE

No	Time (PM)	Temperature	Location	Coordinate		Level risk by RUSLE
				Latitude	Longitude	
1	12.36	32°	Jalan Bukit Kukus	5°21’34.98”	100°16’29.15”	Very Low
2	13.01	32°	Jalan Tun Sardon 1	5°21’20.16”	100°16’12.60”	Low
3	13.54	31°	Jalan Tun Sardon 2	5°20’59.48”	100°15’17.81”	Very Low
4	14.01	31°	Jalan Tun Sardon 3	5°20’52.34”	100°14’25.73”	Very Low
5	13.21	33°	Jalan Balik Pulau (Kek Lok Si Temple)	5°24’0.73”	100°16’26.00”	Medium
6	14.46	32°	Jalan Teluk Bahang 1	5°25’24.54"	100°13’9.18”	Medium
7	14.50	32°	Jalan Teluk Bahang 2	5°25’23.10"	100°13’8.51"	Low
8	14.54	32°	Jalan Teluk Bahang 3	5°25’36.50"	100°13’6.96"	Medium

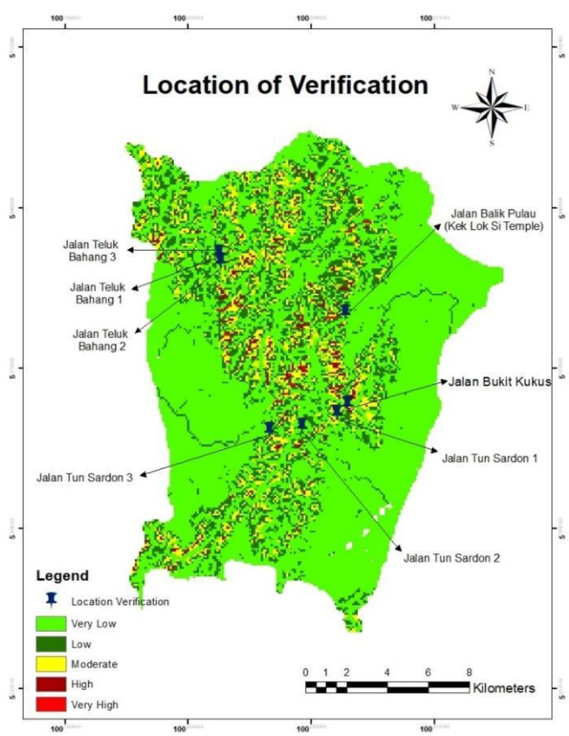

Figure 17. Map of location verification

Conclusion

The comparative study of USLE and RUSLE models in predicting soil erosion events in Penang Island using GIS has provided valuable insights into their efficacy and reliability. The estimating soil erosion of five factors namely R, K, LS, C, P are produced and from the combination of all factors are produced A, soil loss map from the USLE and RUSLE models. The results imply that the RUSLE model is superior to the USLE model in identifying areas prone to soil erosion. This difference arises because the soil erosion risk assessments in both models utilize distinct regression equations to calculate the C and LS factors. Soil textural composition is an important characteristic in governing the soil infiltration and water retention properties and significantly affecting the capacity of soil to hold essential nutrients (Amooh et al., 2015). RUSLE models have more consistent data and generally align well with actual site verification while USLE model also provides accurate predictions but lacks data for several locations.

This indicates that the model is highly reliable and provides accurate predictions of soil erosion. Fine textured soils tend to have higher percentages of OM than sandy or loamy soils, as indicated in the previous studies by Gupta et al. (2010), Mallick et al. (2016), and Gyamfi et al. (2016). So, the RUSLE model performs much better compared to the USLE model of accuracy and reliability to estimate soil erosion risk. Additionally, site verification of the RUSLE model's predictions affirmed its robustness in estimating soil erosion. Soil particles smaller than 20 µm (or 0.002 mm) tend to develop cohesive forces that counter the particle separation, while particles larger than 200 µm (or 0.2 mm) are hard to detach and transport under the influence of erosion drivers due to their mass (Rehman et al.2022). The spatial distribution of erosion predicted by the RUSLE model quite matched the observed erosion patterns in the field. This consistency underscores the model’s practical utility for soil erosion assessment and its potential for guiding effective land management practices on Penang Island. Overall, the RUSLE model demonstrated a higher level of accuracy and reliability in predicting soil erosion events compared to the USLE model. The study highlights the significance of employing advanced models such as RUSLE for assessing soil erosion, to aid in sustainable land use planning and soil conservation efforts. There is high accuracy, obtained between prediction model and measured sample from field observation. The use of GIS was very effective in evaluating factors contributed to soil erosion and helped monitoring erosion in large area.

From 2020 to 2025, multiple studies have reaffirmed that while both the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE) follow the same empirical framework, RUSLE offers greater precision and flexibility, especially in complex tropical environments such as Penang, Malaysia. USLE, originally developed for temperate agricultural regions, is limited in capturing the effects of steep slopes, urban expansion, and rapid land use change, which are significant in Penang’s mixed terrain of coastal plains and hilly interiors. In contrast, RUSLE incorporates improved slope algorithms and dynamic vegetation factors, making it more suitable for the island's topographic variability and increasing development pressure. For instance, similar to findings in India’s Kodar River basin (Di Stefano et al., 2024), RUSLE can better represent soil erosion risks in Penang’s hilly catchments such as Bukit Bendera and Teluk Bahang, especially when combined with GIS and remote sensing. Waseem et al. (2023) highlighted how RUSLE produced high-resolution erosion risk maps in the Jhelum watershed, an approach applicable to Penang for erosion-sensitive areas around infrastructure corridors and agro-tourism sites. Studies from Ethiopia and other tropical regions have shown RUSLE’s effectiveness in data-scarce contexts (Tesfaye & Tibebe, 2025; Mekuria, 2022), similar to many sites in Penang where localized erosion data is limited. Overall, recent evidence supports RUSLE's adaptability and accuracy in Penang's tropical, mixed-use landscape, while USLE remains too simplistic for such complex environmental conditions.

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