Sedimentation Dynamics Analysis in the Muda Dam Watershed Using the Universal Soil Loss Equation (USLE)

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Abstract: *Dam sedimentation present a significant challenge to water resource management, impacting reservoir capacity to ensure the long-term functionality and sustainability of dam infrastructure. This study presents a comprehensive approach to monitoring dam sedimentation by employing the Universal Soil Loss Equation (USLE). The USLE can provide valuable insights for predicting soil erosion processes in a watershed, and its application in the context of dam sedimentation provides a valuable tool for estimating sediment yield. Continuous monitoring of sedimentation trends allows for timely decision-making in dam management and sediment control strategies. The research involves the integration of field data, remote sensing, and GIS techniques to assess the factors contributing to sedimentation within the Muda Dam watershed. Detailed soil characteristics, land use patterns, rainfall data, and topographical information are incorporated into the USLE framework to quantify soil erosion rates. Remote sensing technologies, such as satellite imagery, are utilized to monitor land cover changes and validate the model outputs. The study examines how changes in land use within the Muda Catchment area have resulted in sediment deposition in recent years. Yearly land use from 2015 to 2021 was analysed using multi-temporal Landsat 8 OLI images. The Universal USLE approach was applied to estimate soil loss during this period. Results show that the highest soil loss, within the range of 100-150 tons/ha/year, occurred in 2016 at the sub-catchment area of Sungai Boho. In 2018, the highest soil loss was observed at the sub-catchment area of Sungai Lasor, and in 2019 at Sungai Muda 1. However, in 2021, the highest erosion was recorded at the sub-catchment area of Sungai Teliang. Bathymetric measurements reveal that the reservoir's volume decreased by nearly 13.55 million cubic meters (MCM) from 2015 to 2021, resulting in a sedimentation rate of approximately 2.26 MCM per year. The integrated approach presented in this study offers a robust framework for monitoring and predicting dam sedimentation, ultimately aiding in the development of effective sediment management strategies for reservoirs.*

Keywords:land use change, sedimentation, soil loss

Introduction

Erosion and sedimentation are natural processes that happen every day on all types of land due to the effects of wind and water. Soil water erosion is a major cause of global land degradation and soil loss (Fan, 2015) through its negative impact on the organic, physical and chemical characteristics of soils (Aslam, 2021). Soil is eroded by water through processes that vary in temporal and spatial scales. These processes are splash, interrill, rill and gully erosion, in which particles are detached by raindrop impact, unconcentrated flow or concentrated flow, and transported via rainsplash, interrill flow or concentrated flow (Cooper & Medeiros, 2012). Soil erosion has become a major environmental problem in recent years, especially in catchment areas where intensive use of land for development, including urbanization and agricultural activities is being carried out. Sediment deposition reduces the storage capacity and life span of dams as well as river flows. The amount of sediments can decrease the potential storage capacity of dams whereby approximately 0.5% to 1% of sediment depositions affect the annual loss of storage capacity of dams around the world. If these silt deposits are not cleared out, the dam will become blocked in as soon as a few decades. To meet this problem many methods were developed to measure the amount of sediment and to reduce the quantities of it.

Bathymetric survey data is widely recognized as the most accurate method for estimating dam sedimentation, but it is also costly and time-consuming. Therefore, the bathymetric survey will not always be possible to perform on a regular basis. A supplementary method is demanded to estimate sedimentation easily and economically. This might be possible to carry out by using computer modelling for the catchment area of a dam. Besides that, empirical models are generally the simplest (Merritt, 2003) and easy to use with less computational needs (Lida Eisazadeh, 2012); thus, have become the most popular and widely used for the estimation of surface erosion and sediment yield from catchment areas. Universal Soil Loss Equation (USLE) was developed in 1965 (Musgrave, 1947) (Wischmeier W. a., 1965) and improved in 1978 (Wischmeier W. a., 1978). It is the most frequently used empirical model to estimate the total amount of sediments that are eroded in a specified area. Since then, USLE has undergone substantial improvements leading to the Revised USLE (RUSLE) (Renard, 1997) Currently, RUSLE is the most widely used in Malaysia for the estimation of surface erosion and sediment yield from catchment areas because of their simple structure and ease of application. The RUSLE model follows the same formula as USLE, but it has a sub-factor for evaluating the cover management factor (C), a new equation for slope length, steepness and new conservation practice values. Many researchers have modified the USLE parameters for extended applications. Investigators developed the MUSLE to estimate sediment yield for particular storm runoff events (Williams, 1975) Sediment yield is the quantity of eroded soil that is delivered to an outlet of a watershed or a point in the watershed that is far from the source of the detached soil particles (Renard, 1997) and it is different from soil loss and soil erosion. MUSLE is a modified version of USLE and uses many of the same readily available parameters and data sets of USLE. In the MUSLE the factors made up of peak discharge and runoff variables replace the USLE's rainfall erosivity factor and it made the model to predict sediment yield, channel erosion, gully erosion, floodplain scour, and deposition which is not possible by USLE and RUSLE. In contrast to USLE/RUSLE, the MUSLE estimates sediment yield directly without the need for sediment delivery ratio. Moreover, MUSLE has an advantage over USLE/RUSLE due to its capability to predict a single storm sediment yield. The limitation of MUSLE is, that it predicts a sediment yield only and is not suited for long-term soil.

In this study, Geographic Information Systems (GIS) were integrated with the Universal Soil Loss Equation (USLE) to develop an erosion risk map and identifying soil erosion risk areas in the upper Muda catchments. The USLE was chosen due to its suitability for estimating long-term mean soil losses, particularly in areas with low-gradient slopes. Additionally, this study investigates the main factors influencing soil erosion in the study area.

Literature Review

Soil erosion is the common land degradation problem in the worldwide because of its economic use and environmental impacts. To estimate soil erosion, the calculation methods that can be used are USLE (Universal Soil Loss Equation). Base on the **(Wischmeier W. a., 1969)**, there are four calculation factors, namely the rain erosivity factor (R), the soil erodibility factor (K), the length and slope factor (LS), and the land cover factor (CP).

The USLE equation is expressed by Equation 1 [**(Wischmeier W. a., 1978)**

$$Ea = R\ K\ LS\ CP \qquad (1)$$

with: Ea = A = amount of eroded soil (tonnes/ha/year)

R = rain erosivity factor (Kj/ha)

K = soil erodibility factor

L = slope length factor
S = slope factor
P = conservation action factor
C = land cover crop factor

Numerous studies reported USLE as the best model and is being used worldwide for the estimation of surface erosion **(Ying Zhang, 2024) (Dimitrios D. Alexakis, 2012) (Perović, 2013) (Chatterjee, 2014) (Kourgialas, 2016)**. Moreover, there has been widespread application Geographical Information System (GIS) coupled with Remote Sensing (RS) data in mapping soil characteristics **(F Khairunnisa, 2020) (Ishtiyaq Ahmad, 2013)**, land use patterns **(Kapatamoyo et al, 2023) (Afrin S, 2019) (Zarco-González, 2021) (Nawaz, 2016) (Sarah Hanim Samsudin*, 2020)** and rainfall data **(Aafaf El Jazouli, 2017) (Hasmida Mustaffa, 2023)** in USLE. Guided by the result from USLE approach, predicted soil erosion which may lead to sedimentation issues in dam can be calculated **(Zhu, 2015) (C.P. Devathaa*, 2015) (Tran Thi Phuong*, 2014) (Sujaul Islam Mir, 2010) (Sindu Nuranto, 2023) (Perović, 2013) (F Khairunnisa, 2020) (Khabat Khosravi, 2023) (Ishtiyaq Ahmad, 2013) (Chatterjee, 2014) (Perović, 2013)** ultimately aiding in the development of effective sediment management strategies for dams.

Methodology

a. Study Area

Muda Dam is located at latitude 6°06'49" N and longitude 100°51'9" E in the Sik district of Kedah, Malaysia. Constructed in 1969, the dam's primary purpose is to serve as an irrigation water storage dam under the Muda Irrigation Scheme, which supports agricultural development and the rice sufficiency policy. Muda Dam has a large catchment area of 984 km^2 and a storage capacity of 160 million m^3. However, the dam has been experiencing water quality degradation due to forest activities, which has implications for both domestic water supply and irrigation in the northern area. The Muda catchment area has been divided into five sub-catchments: Sungai Boho, Sungai Lasor, Sungai Muda 1, Sungai Muda 2, and Sungai Teliang.

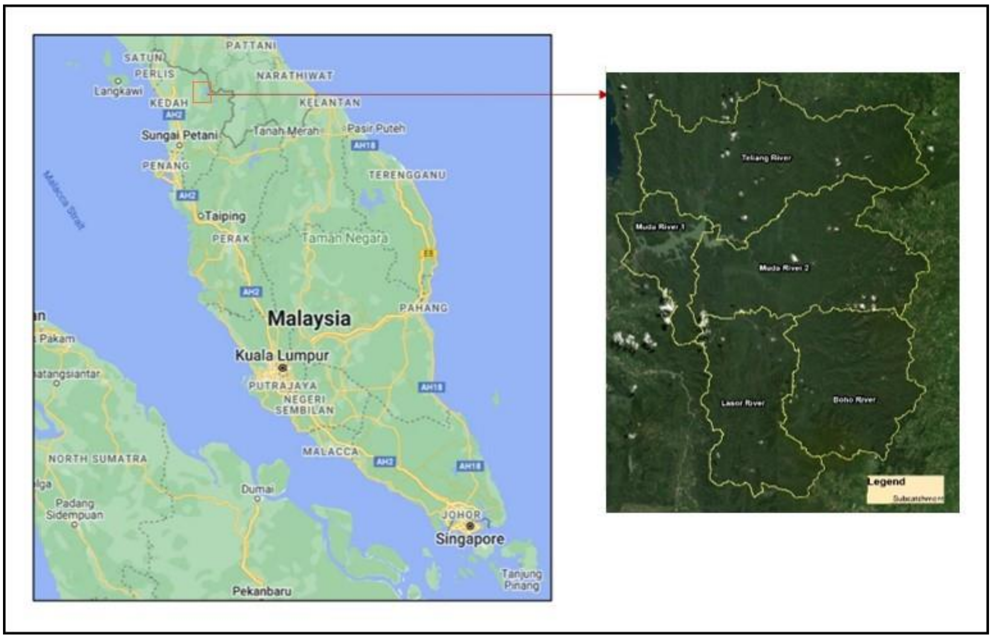


Figure 1: Study Area

a. Data Sources

The collection of spatial data is crucial at the preliminary stage of developing a soil loss risk map. Data from various agencies, such as the Department of Agriculture Malaysia, the Department of Survey and Mapping Malaysia, the Department of Irrigation and Drainage Malaysia, and others, were acquired, collated, and cleaned to produce the erosion risk map. The geospatial data collected in this study include the Digital Elevation Model (DEM), soil properties, and land use/land cover data for the study area (Table 1). This information will be formatted and organized into an integrated database for ease of use and reference in later stages of the study. Gaps and discrepancies between these data will be identified and rectified accordingly. Finally, the spatial data were input into ArcGIS 10.5, digitized into shapefile format, and projected to Kertau RSO Malaya (meter) for tabulation and/or graphical representation for significant analysis.

No	Data	Description	Resolution	Sources
1	DEM	Digital Elevation Model	20 m	Department of Survey and Mapping Malaysia (JUPEM)
2	Landuse	Landsat 8 OLI	30 m	Malaysian Space Agency (MYSA)

No	Data	Description	Resolution	Sources
3	Soil	Soil properties	30 m	Department of Agriculture Malaysia (DOA)
4	Weather	Rain	Annual Precipitation	Muda Agricultural Development Authority (MADA)
5	Dams	Bathymetry (m)	2015 and 2021	Muda Agricultural Development Authority (MADA)
6	Validation	Sedimentation Rate (MCM)	2015 and 2021	Muda Agricultural Development Authority (MADA)

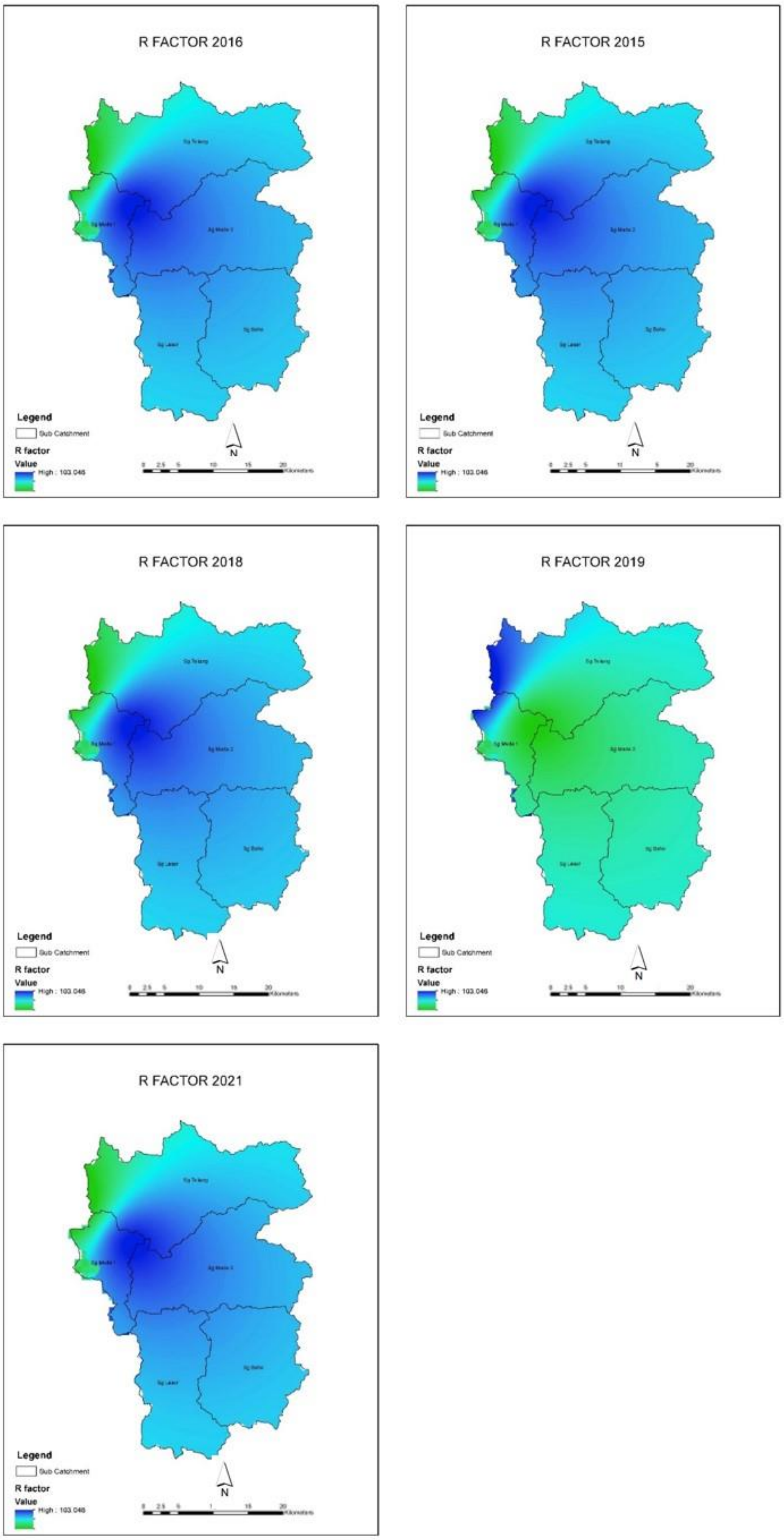
b. Data Preparation and Modelling

i) Rainfall Erosivity Factor (R)

The Rainfall erosivity index was calculated based on **(Hurni, 1985)** According to Hurni (1985) an empirical equation to estimate the R-value based on annual total rainfall for specific catchments. For this study, the relationship between mean annual rainfall and rainfall erosivity established for Muda Catchment condition based on the analysis of monthly rainfall data of different stations **(Hurni, 1985)** was used. Annual rainfall data acquired over the last from 2015 until 2021 years from the nearest rainfall stations of each catchment were used in this study. The equation used is:

$$R=-8.12+0.562PR \qquad (2)$$

R is the rainfall erosivity factor and P is the mean annual rainfall (in mm). Muda Agricultural Development Authority (MADA) provided the mean annual rainfall data. Using this equation, the R-value corresponding to the mean annual rainfall of the watershed was calculated. Estimates of rainfall erosivity for the years 2015 until 2021 are illustrated in the rainfall erosivity maps for the Muda Dam Catchment. (Figure 2).



R FACTOR 2016

R FACTOR 2015

R FACTOR 2018

R FACTOR 2019

R FACTOR 2021

Figure 2: R factor of Muda Catchment from 2015-2021.

ii) Soil Erodibility Factor (K)

Soil erodibility refers to the soil's ability to resist both detachment and transport, and is influenced by various factors such as topography, slope gradient, and human activities. However, the most critical factor is the soil's intrinsic properties, including its texture, aggregate stability, shear strength, infiltration capacity, and organic and chemical composition. Larger soil particles are generally more resistant to being transported, while finer particles tend to be more cohesive. As a result, fine sand and silt are the least resistant to erosion.

The K factor represents the influence of soil properties and profile characteristics, such as soil texture, aggregate stability, shear strength, infiltration capacity, and organic and chemical content, on soil loss. According to the guideline **(DID, 2010)**, the Tew Equation and Nomograph are recommended methods for estimating the K factor for Malaysian soil series. Table 1 illustrates the range of soil erodibility for various soil types in the Peninsular Malaysia soil series. The soil data provided by the Department of Agriculture Malaysia (DOA), with a resolution of 30 meters, is then converted into a raster file for use in soil loss and erosion analysis, specifically for the K factor, as shown in Figures 3 and 3.1.

Table 1: Range of Soil Erodibility for Soil Type of Peninsular Malaysia Soil Series

No.	**Soil Series**	**K factor (tonnes.ha) × (ha.h $MJ^{-1}mm^{-1}$)**
1	Clay	0.042 – 0.065
2	Clay loam	0.030 – 0.047
3	Sandy Clay	0.031 – 0.043
4	Sandy Clay Loam	0.028 – 0.059
5	Sandy Loam	0.004 – 0.036
6	Silt Loam	0.014 – 0.027
7	Silty clay loam	0.032

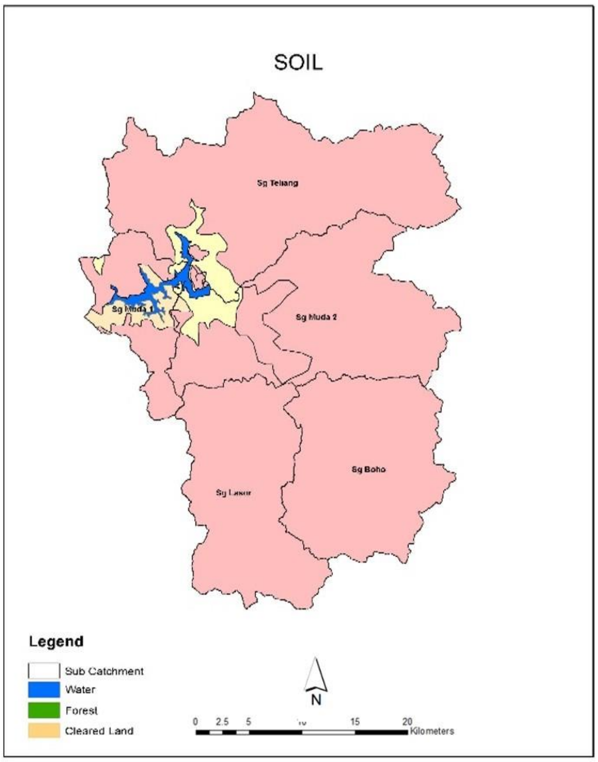


Figure 3: Soil Map of Muda Catchment

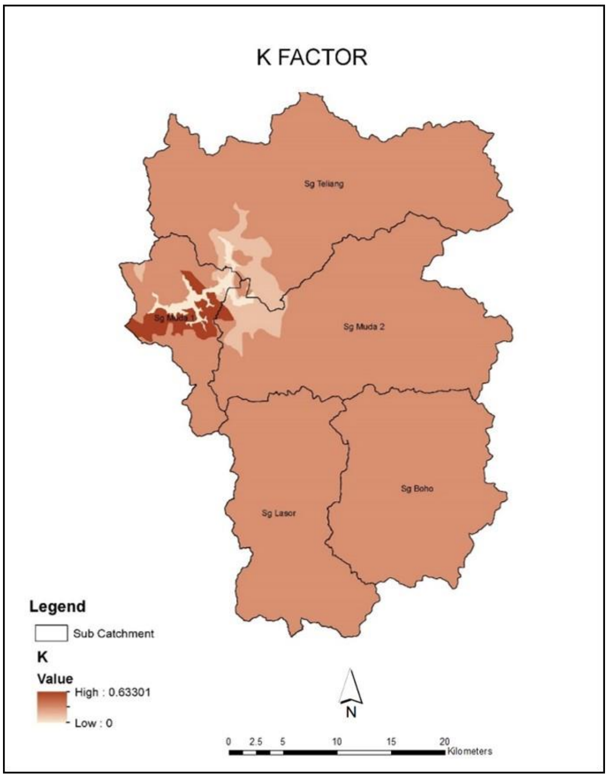


Figure 3.1: K factor of Muda Catchment

iii) Slope Factor (LS)

The rate of soil erosion by water is very much affected by both slope length (L) and slope steepness (S) in terms of gradient/ percent slope. (Wischmeier W. a., 1978) defined slope length (L) as the horizontal distance from the point of origin of overland flow to either of the following, whichever is limiting for the major part of the area under consideration:

a) The point where the slope decreases enough that deposition begins, or
b) The point where runoff becomes concentrated in a defined channel

$$L= [FA*\text{cell size})22.13)^{m} \text{ (Moore, 1992)} \qquad (3)$$

Where, FA is flow accumulation, cell size is the size of DEM and m ranges from 0.2-0.6

$$S = [\sin\beta * 0.001745)/0.09]^{n} \qquad (4)$$

Where β is slope angle in percentage, n ranges from 1.0-1.3

$$LS= (L*S)/100 \qquad (5)$$

Figure 4 presents the Digital Elevation Model (DEM) of the study area, while Figure 4.1 illustrates the slope. The length and steepness factors (LS) were calculated using the DEM derived from a topographic map provided by the Department of Survey and Mapping Malaysia (JUPEM) with a resolution of 20 m × 20 m. The classification of the LS factor indicates that the range is approximately 0 - 96.86%.

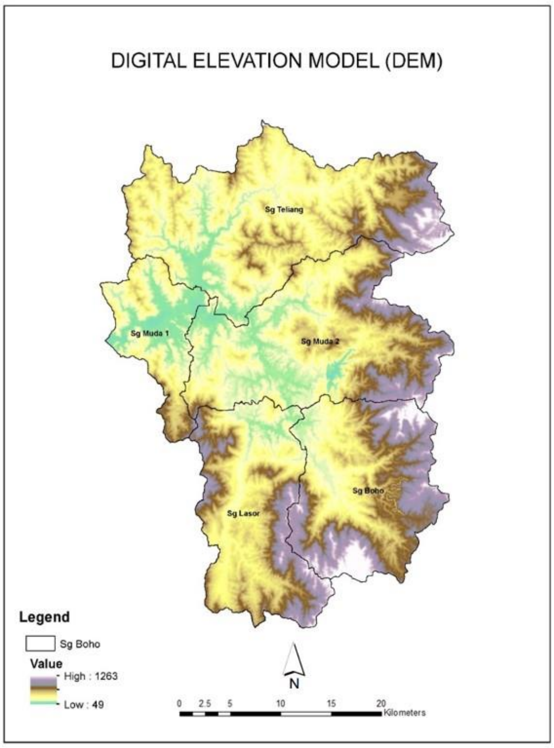


Figure 4: Digital Elevation Model (DEM) Muda Catchment.

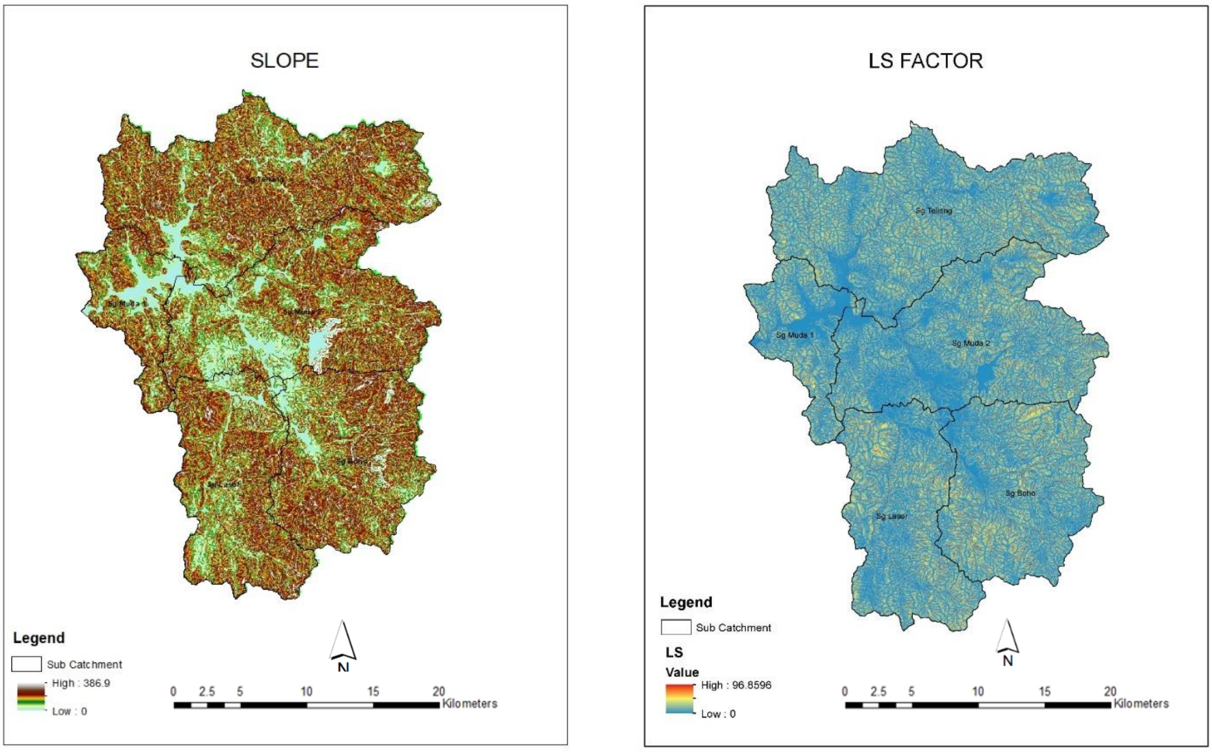


Figure 4.1: Slope map and LS Factor Map of Muda Catchment

iv) Cover Management Factor (C) and Conservation Practice Factor (P)

This study uses remote sensing data, specifically from Landsat 8 OLI, to distinguish between natural forests and plantations through supervised classification. The images that have been used to extract the land cover are from 2015 until 2021. This is crucial for accurately monitoring natural forest loss and plantation expansion, particularly in sensitive areas such as the Muda Catchment. The ability of remote sensing technologies to differentiate between these two land cover types plays a vital role in environmental management, conservation efforts, and assessing the impacts of land-use changes. The cover management factor (C), as part of the Universal Soil Loss Equation (USLE), is key in controlling soil loss at specific sites. It accounts for various management techniques, including;

a) Ground cover such as mulch or organic matter that can reduce the erosive impact of rainfall,

b) Vegetation, which is the plants acting as a natural shield, preventing soil detachment and promoting infiltration, and;

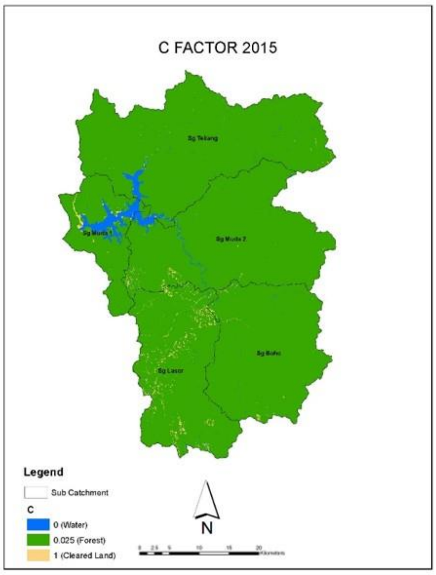
c) Pavements or hard surfaces that can mitigate erosion by preventing soil exposure but can also lead to increased runoff.

While the C-factor is not static and changes depending on seasonal conditions, either the weather fluctuations, such as dry or rainy seasons, can influence vegetation cover and ground conditions. The management practices are that the implementation of soil conservation measures over time can reduce the C-factor by improving land cover. By integrating remote sensing data and assessing the C-factor, this approach can help identify areas where soil erosion is more likely to occur and guide land management strategies in the Muda Catchment area. The classification into the C factor using the classification method outlined by **(Renard, 1997)** as shown in **Table 2.**

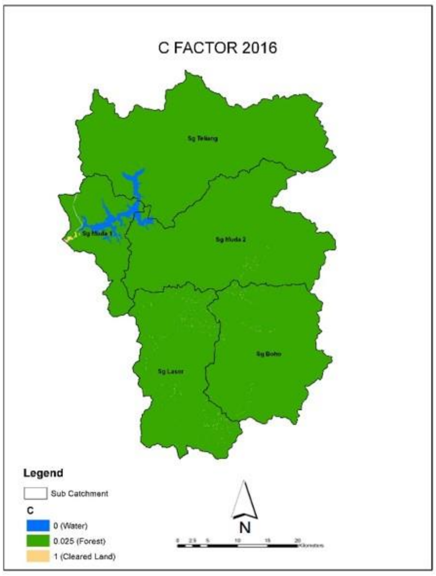
LULC Class Number	Class Name	C Value
1	Water	0
2	Trees	0.025
3	Grass	0.02
4	Flooded Vegetation	1
5	Crops	0.05
6	Shrubs	0.4
7	Built Area	1
8	Bare Ground	1

Table 2: Classification of LULC for C Factor.

The P factor depends on the conservation measure applied to the study area. In Malaysia, the most common conservation practice is contour terracing in rubber and oil palm plantations. In this study, it was assumed that agricultural activities were given a value of 1, assuming no conservation practices were adopted.



C FACTOR 2015



C FACTOR 2016

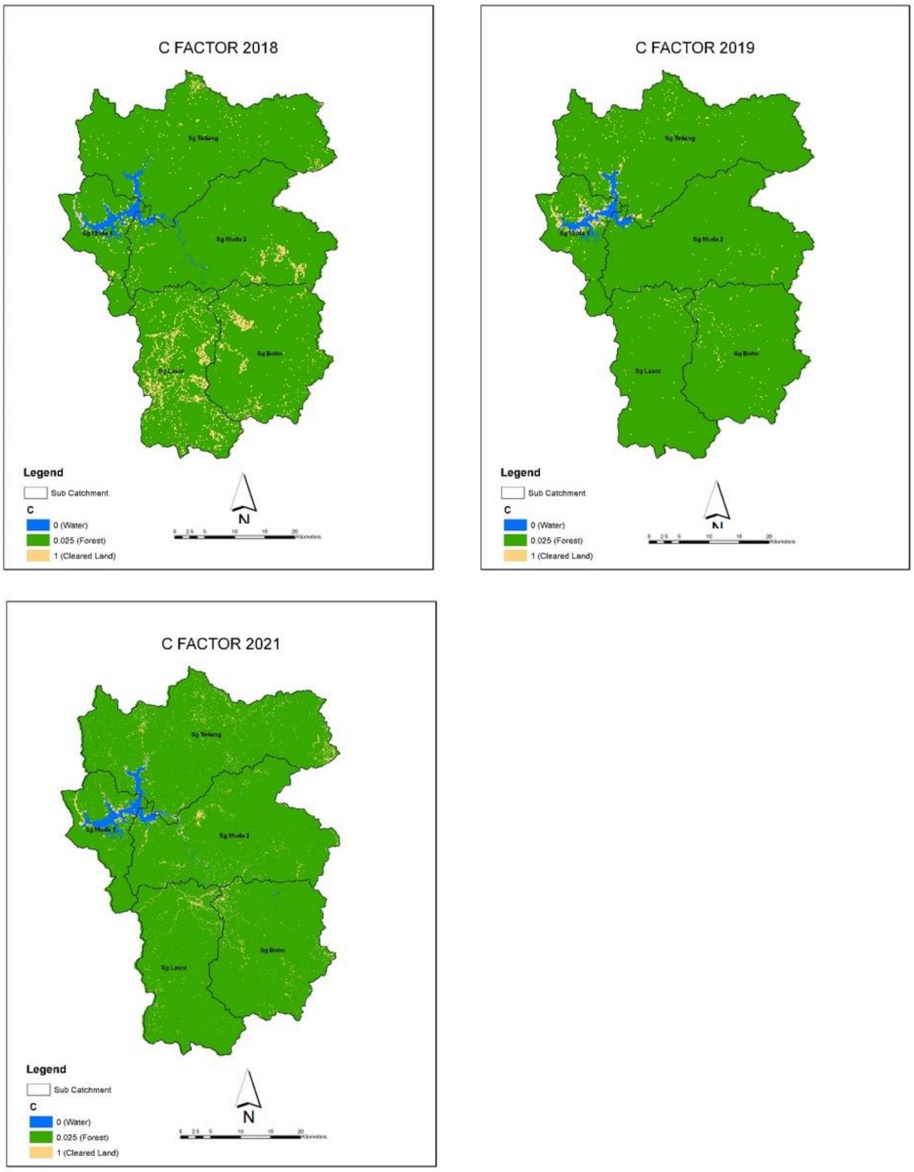


Figure 5: C Factor Map of Muda Catchment from 2015-2021

c. USLE Modelling

The Universal Soil Loss Equation (USLE), developed by **(Wischmeier W. a., 1978)** is the most widely utilized—though sometimes misapplied—equation for estimating soil loss globally. The equation predicts the long-term average annual soil loss (A) due to sheet and rill erosion by incorporating six key factors related to climate, soil, topography, vegetation, and management practices. The USLE is commonly expressed as:

$$A = R \times K \times LS \times C \times P \qquad (6)$$

where A - Annual soil loss, in tonnes ha-1 year-1.

R - Rainfall erosivity factor, an erosion index for a given storm period in MJ.mm.ha h-1 year-1.

K - Soil erodibility factor, the erosion rate in (tonnes.ha) × (ha.h MJ-1mm-1).

LS - Topographic factor, which represent the slope length and slope steepness.

C - Cover management factor, which represents the protective coverage of canopy and organic material in direct contact with the ground. It is measured as the ratio of soil loss from land cropped under specific conditions to the corresponding loss from tilled land under clean-tilled continuous fallow (bare soil) conditions.

P - Conservation practice factor, which represents the soil conservation operations or other measures that control the erosion, such as contour farming, terraces, and strip cropping. It is expressed as the ratio of soil loss with a specific support practice to the corresponding loss with up and-down slope culture.

Results and Discussion

a) Annual Average Soil loss

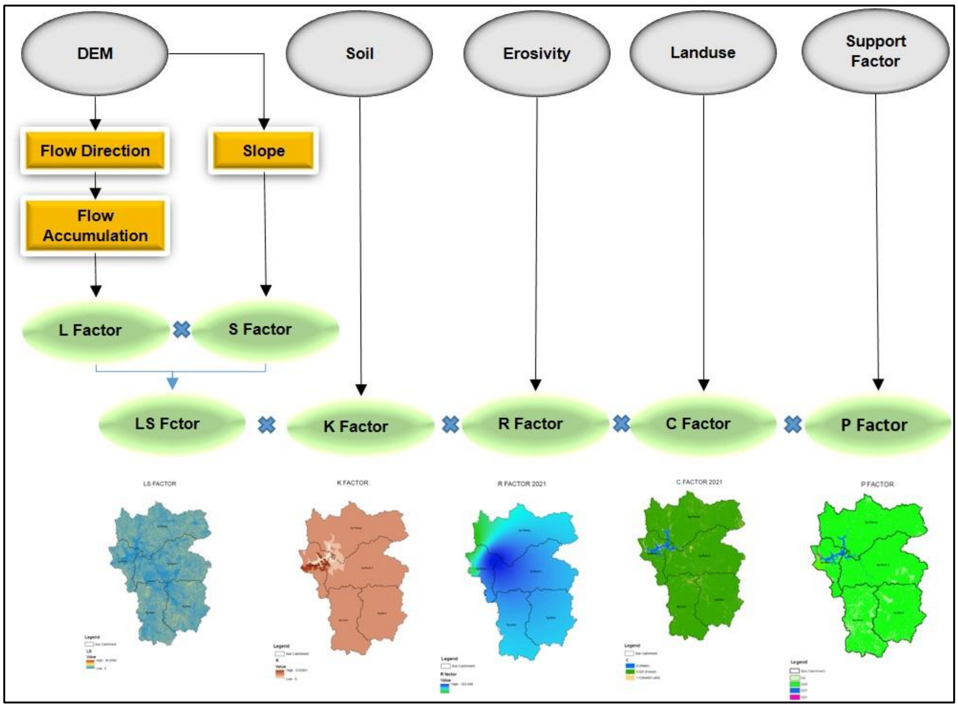
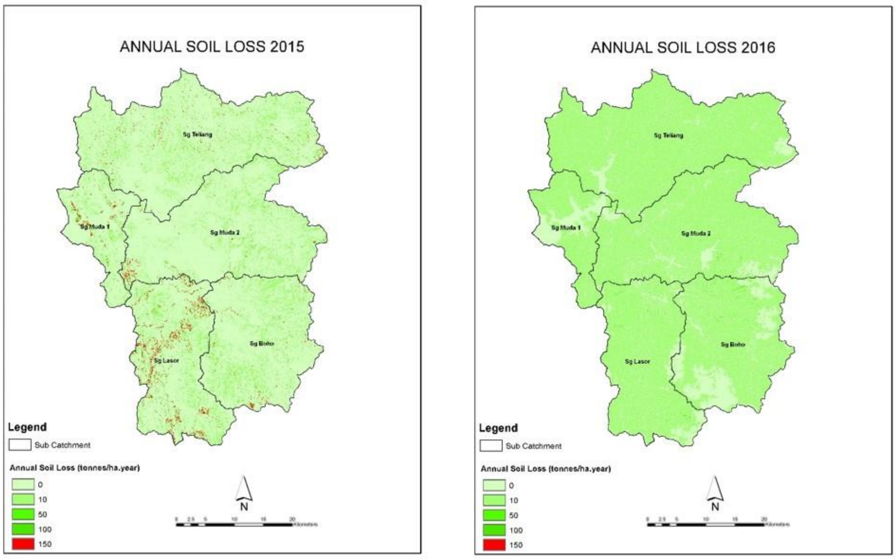


Figure 6: The Workflow Diagram of USLE in Muda Catchment.

All parameters in the USLE model were computed using the ArcGIS software. The subsequent sections designate the computation of all five factors in the USLE equation using the data obtained from various sources. The spatial resolution of the data was set at 30m x 30m. The workflow diagram is presented in Figure 6 where R factor, K factor, LS factor, and CP factor is derived from the data. The unit of annual average soil loss, A is tons/ha/year. Based on the literature review **(Mohd Amirul Mahamud, 2022)** the permissible soil loss for any situation of soil degradation is 11.2 tons/hectares/year. By using that as a benchmark, A-factor calculated from this study is categorised into soil loss class category as presented in **Table 3. Figure 6.1** shows the estimated amount of annual soil loss for each sub catchment in the study area where within the range of 100-150 tons/ha/year, occurred in 2016 at the sub-catchment area of Sungai Boho. In 2018, the highest soil loss was observed at the sub-catchment area of Sungai Lasor, and in 2019 at Sungai Muda 1. However, in 2021, the highest erosion was recorded at the sub-catchment area of Sungai Teliang.



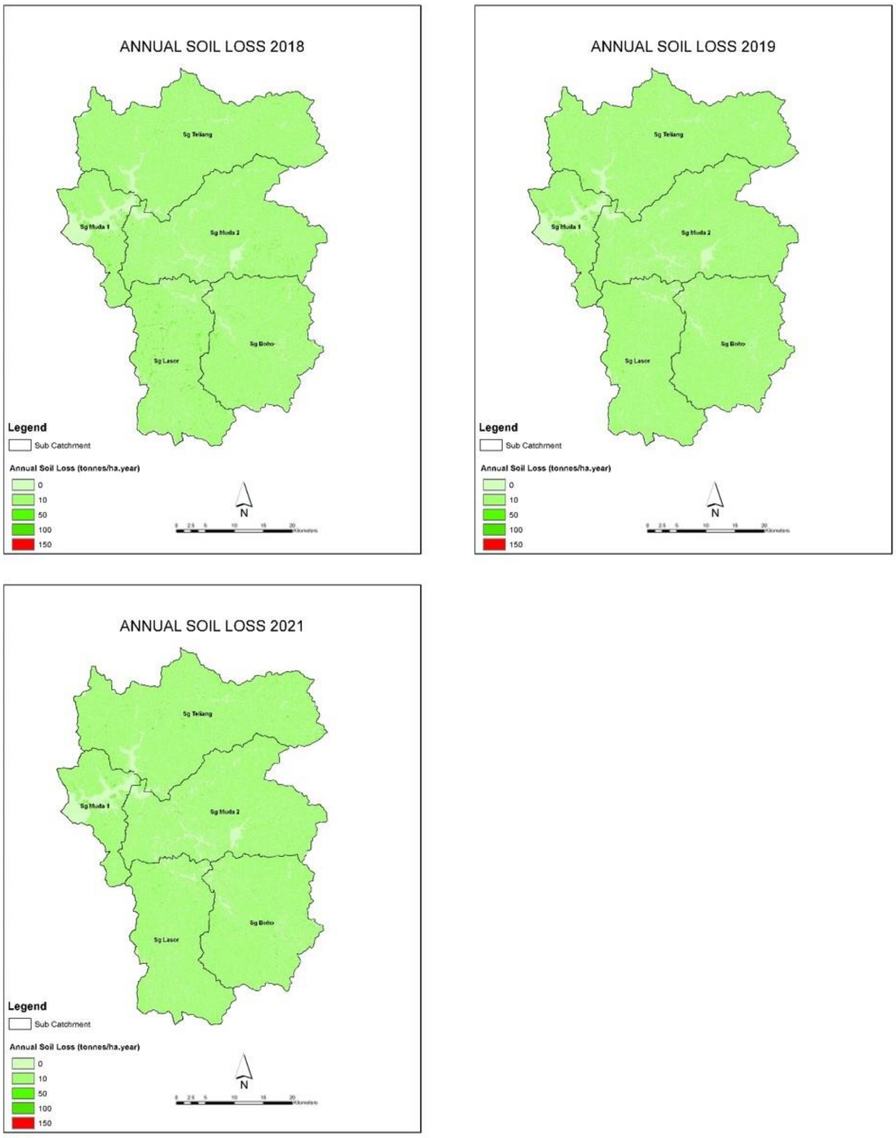


Figure 6.1 : Soil Erosion of Muda Catchment from 2015 to 2024.

Table 4: Soil Loss Class Category

Soil Loss, A **(tonnes ha^{-1} year^{-1})**	**Category**
≤ 10	Very low
10 – 50	Low
50 – 100	Moderate high
100 – 150	High
≥ 150	Very high

b. Sediment Delivery Ratio (SDR)

Annual sediment inflow into the Muda Dams is calculated based on the Sediment Delivery Ratio equation calculation. Sediment delivery ratio (SDR) is the ratio of sediment delivered at the catchment outlet to gross erosion within the basin (Jr., 1954). In this study, the average annual sediment yield for the Muda Dam's sub-catchments was determined based on a predictive (Vanoni, 1975) equation as follows:

$$SDR = 0.42\ A^{-0.12} \qquad (7)$$

where,

A - drainage area in mile^2 (1 mile^2 = 2.59 km^2)

The equation (7) was developed by (Vanoni, 1975) which used data from 300 watersheds throughout the world to develop SDR model by the power function. The Muda dam catchment SDR values is 0.21. Based on our findings, the total sediment yield for the Muda catchment is 1,485,147.65 tonnes, with an average annual yield of 297,029.53 tonnes. Finally, the total sediment yield at the Muda Dam is estimated about 0.38 million cubic meters (MCM).

c. Summary of Sedimentation Assessment

Land cover data from Landsat 8 OLI imageries from the years 2015, 2016, 2018, 2019, and 2021 were extracted and classified into two categories: cleared land and forest. Deforestation in the Lasor River and Muda River 1 sub-catchments has been expanding from 2018 to 2022 has led to the creation of open areas or cleared land within the catchment, which has increased soil erosion and contributed to a reduction in dam volume. Soil erosion rates vary considerably based on deforestation activities for effective soil conservation and mitigation of downstream effects. This study highlights that cleared land, especially on steep slopes, contributes significantly higher rates of soil loss compared to other land use and land cover categories. Identifying and managing these high-risk areas is crucial for soil resource conservation and reducing sedimentation impacts on water bodies. Both natural and anthropogenic landscape alterations are well known to significantly influence soil loss rates. Increased erosion due to activities such as deforestation can lead to downstream impacts on freshwater and estuarine ecosystems by altering hydrological processes (Pattanayak, 2007).

Conclusion and Recommendation

In conclusion, this study successfully utilized GIS techniques combined with the USLE method to estimate soil erosion and sediment yield within the Muda catchment. By incorporating spatial analysis in ArcGIS, key parameters of the USLE equation (R, K, LS, C, and P) were accurately computed, leading to the determination of a sediment yield of approximately 297,000 tonnes. Furthermore, the analysis of bathymetric surveys from 1969 and 2021 revealed an estimated annual soil loss rate of 282,000 cubic meters for the Muda Dam. These findings highlight the significance of soil erosion in the region and underscore the importance of continuous monitoring and implementation of effective soil conservation measures to mitigate future impacts on the dam and surrounding catchment areas. The assessment of soil loss rates in the MUDA Dam catchments conducted in this study provides essential data for authorities and policymakers, particularly for developing sediment management strategies for the Muda Dam. This includes urgent actions to control deforestation, as the Muda Dam is crucial for irrigation and water supply. Implementing effective sediment control measures is essential to prevent excessive annual soil loss rates.

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