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Sediment Transport Capacity Performance Assessment Based on a RUSLE and Sediment Delivery Ratio Model-Article One

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ABSTRACT

Surface soil erosion occurs when soil, rocks, and sediments are exposed to the atmosphere and pushed over time by natural forces such as rainfall, wind, and gravity. Surface erosion in high highland locations has resulted in sediment accumulation and an increase in catchment water levels. It has also lowered water quality and had a negative impact on the marine ecology. The Revised Universal Soil Loss Equation (RUSLE) model and sediment delivery ratio (SDR) equation were used in this study to compute and analyse the spatial distribution of soil erosion and sediment yield (SY) in the Universiti Pertahanan Nasional Malaysia (UPNM) catchment. In order to finalise the soil erosion map, input parameters such as soil erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover (C), and land management practises (P) were developed using ArcGIS. The SY was then computed by merging the final soil erosion map with the SDR equation. The results reveal that soil erosion in the UPNM catchment ranges from 0 to 0.9507 t/ha/year in 2016 and from 0 to 0.3338 t/ha/year in 2021. While the SY distribution in 2016 and 2021 ranged from 0 to 0.3993 t/ha/year, respectively. Furthermore, the very high erosion contributes around 20% in the research area. Overall, the results present the spatial distribution of soil erosion and SY in UPNM catchment. As a result, our study proposes immediate attention to soil and water conservation initiatives in heavily degraded areas particularly in the UPNM catchment.

1. Introduction

Nowadays, soil erosion is seen to be one of the biggest problems with the river system since it degrades the soil, water quality, and aquatic life [1]. It is one of the slowest and barely detectable processes, occurring primarily as a result of human interventions as opposed to climatic inputs and natural hazards. Due to inert human activities on the surface of the earth, which has a substantial influence on the permanent vegetation cover.

Eroded soil is problematic because it causes persistent soil degradation, from which natural restoration processes may not be able to restore the soil for decades. In addition, other off-site damages are caused by eroded chemical-sediments resulting from the deposition of materials at adjacent sites, which may also impact the surface water system [2]. Since the limitations of direct

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measurements of soil loss over limited areas where hydraulic conditions must be considered, monitoring erosion processes is challenging. The destructive effects of land cover type on watershed ecosystems have been a universal concern. For instance, agricultural clearing can obstruct water flow, thereby increasing the quantity of surface runoff and sediments it carries. Since Malaysia has a tropical climate with an average annual precipitation, the frequency and magnitude of floods will change and sedimentation will occur when the natural vegetation is irrevocably converted to agriculture [3].

The Revise Universal Soil Loss Equation (RUSLE) was used to measure erosion in different land-use trends and to plan for conservation. Physical modelling and information that is combined with other in-situ datasets are used to figure out how much sediment has been washed away. This helps conservation plans work better. RUSLE is an empirical model that is used to figure out how much soil is lost on average every year at the catchment scale and to describe soil erosion. Since the spatial distribution of soil erosion must be taken into account, remote sensing and geographic information system (GIS) are used a lot with the RUSLE model because of the amount of data needed and the ability of these methods to handle this type of data [4].

GIS is a tool for organising, analysing, and displaying information in the form of maps. It connects information to maps by integrating various types of descriptive data with location-specific data [5]. Case studies rely on mapping and analysis constructed on this basis to identify and address issues. It is possible to comprehend interconnections and spatial contexts with the aid of a GIS [6]. The benefits include the ability to model and estimate the final product efficiently using spatial analysis, as well as the capacity to make explicit comparisons between data layers and analytical results. This research utilised ArcGIS 10.8 as the GIS software because it has satellite image processing capabilities, allowing it to employ the RUSLE parameters and predict the soil erosion rate in the Universiti Pertahanan Nasional Malaysia (UPNM) catchment.

This research aims: (1) compute surface soil erosion and sediment yield by integrated GIS with the RUSLE and sediment delivery ratio (SDR); (2) analyze the sediment yield and annual spatial soil erosion in UPNM catchment.

2. Methodology

2.1 Study Area

The UPNM catchment covers 2.0 km^2 inside the Royal Military Camp, Sungai Besi, between 3.0507236 latitude and 101.7267928 longitude. Several streams and a rill divide the Royal Military College and UPNM catchment. Tropical acrisols with significant clay build-up, high weathering, and leaching are the main soil type in this catchment. Soil is low-fertile and sensitive to erosion, especially for agricultural practices [7]. The catchment has deciduous and evergreen trees. There are 33% undisturbed forests in this catchment, and some of the slopes are rather steep. Selected outputs have been assessed for sediment yield.

2.2 Data Source

Table 1 shows details the data sources used for this research. All satellites images were download from the Earth Explorer website of the United States Geological Survey (USGS) and the framework reprocessed the Digital Elevation Model (DEM) to identify the UPNM catchment and generate slope using ArcGIS.

Table 1
Data Sources for parameters

Parameters	Year	Dataset	Source
Erosivity factor, R	2016 & 2021	Rainfall data	UPNM weather station
Soil Erodibility factor, K	2016 & 2021	DMSW data	FAO
Topographic factor, LS	2016 & 2021	Aster DEM	USGS
Cover Management factor, C	2016 & 2021	Landsat 8 and DEM	USGS
Support Practice factor, P	2016 & 2021	Aster DEM	USGS

2.3 RUSLE Factor

The RUSLE is applied to the UPNM catchment by representing the catchment as a polygon shape and calculating soil erosion in the shape. RUSLE compute the average annual erosion expected on field by the expression as below [8]:

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

where *A* is the average annual soil erosion rate (t/ha/year); *R* is the erosivity factor (MJ mm/ha/h/year); Erodibility factor is *K* (t ha h/ha/MJ/mm); *LS* is a topographic factor; *C* represents the effects of vegetation cover and crop management practises; and *P* represents soil conservation practise effects.

2.4 Erosivity Factor (R)

Since erosion is dependent on water, erosivity might be considered a key component of erosion [8]. The *R* factor measures how much soil is being worn away by the rain. The more intense and long-lasting the rain, the more soil it wears away [2]. Wishcmeier *et al.*, [8] came up with an empirical formula to figure out the *R* factor using only monthly and yearly rainfall. This formula was the common way to estimate the factor with unit MJ mm/ha/h/yr:

$$R = \sum_{1}^{12} 1.735 \times 10^{\left(1.5\, log\left(\frac{Pi}{P}\right) - 0.08188\right)} \tag{2}$$

where *Pi* represent monthly rainfall (mm) and *P* represents the annual rainfall (mm). *R* factor was calculated from the rainfall data from weather station in the study area of UPNM between 3.048946 latitude and 101.721904 longitude. The results were then interpolated to make a map of *R* factor for the catchment by using the inverse distance weighting (IDW) method [2].

2.5 Soil Erodibility Factor (K)

Soil erodibility is the long-term average influence of soil profile structures and features such texture, size, thickness, organic content, clay type, permeability, and human impacts on soil. The biophysical and chemical qualities of a soil determine its erodibility, which is intrinsic. The *K* factor also determines soil textures vulnerability to extreme rainfall and detachment. Department of Irrigation and Drainage Malaysia (DID) guideline has recommended for the calculation of the factor is Tew Equation and Nomograph. It was shown to provide the most accurate estimation of *K* factor for Malaysia soil series as follows:

$$K = f_{csand} * f_{ci-si} * f_{orgc} * f_{hisand} \tag{3}$$

$$f_{csand} = (0.2 + 0.3 * \exp[-0.256 * m_s * (1 - \left(\frac{m_{sil}}{100}\right))]) \tag{4}$$

$$f_{cl-si} = \left(\frac{m_{sil}}{m_c + m_{sil}}\right)^{0.3} \tag{5}$$

$$f_{orgc} = \left(1 - \frac{0.25 * orgc}{orgc + \exp[3.27 - 2.95 * orgc]}\right) \tag{6}$$

$$f_{hisand} = \left(1 - \frac{0.7 * \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left[-5.51 + 22.9 * \left(1 - \frac{m_s}{100}\right)\right]}\right) \tag{7}$$

where m_s is the content of sand fraction ($0.05 < \phi < 2.00$ mm, diameter) [%]; m_{silt} is the content of silt fraction ($0.002 < \phi < 0.05$ mm, diameter) [%]; m_c represents the content of clay fraction ($\phi < 0.002$ mm, diameter) [%]; *orgc* is the content of organic carbon [%].

2.6 Slope Length and Slope Steepness Factor (LS)

LS factor combines the effects of the slope length factor (*L*) and the slope steepness factor (*S*) to show how topography affects soil erosion. Generally, longer slopes lead to greater soil erosion. This is because as the length of the slope increases over time, more water flows downhill. As slope steepness gets higher, water runs off faster and erodes more [9].

Though, to figure out the *LS* map factor, the digital elevation model (DEM) of study area with a spatial resolution of 12.5 m was corrected geometrically and extracted using ArcGIS 10.8. The DEM was used with the spatial analyst extension in ArcGIS to figure out important steps like flow accumulation, flow direction, and fill [10]. The *LS* factor may be calculated with the ArcGIS raster calculator by utilising equation below:

$$LS = \left(\frac{\lambda}{\Psi}\right)^m * (0.065 + 0.046s + 0.0065s^2) \tag{8}$$

where λ is sheet flow path length (m); Ψ is 22.13; s represents the average slope gradient in percent (%); m is 0.2 for $s < 1$, m is 0.3 for $1 \le s < 3$, m is 0.4 for $3 \le s < 5$, m is 0.5 for $5 \le s < 12$ and m is 0.6 for $s \ge 12\%$.

2.7 Cover Management Factor (C)

C factor evaluates vegetation density, primary agricultural system efficiency, and soil management [2]. It also indicates the rate of soil loss from diverse land surfaces when the land stays uncovered by plants and other means to avoid soil erosion [10]. Ghosal *et al.*, [11] found that plant growth and canopy cover diminish raindrop intensity before hitting topsoil. Vegetation type, growth, and density effect cropping and land-cover [11].

The *C*-factor ranges from 0 to 1. A value close to 1 indicates bare fallow soil due to lack of vegetation, while a value close to 0 denotes for fully covered soil. However, for this study, to determine the *C* values, satellite image was utilized to compute an index of vegetation abundance by using Normalized Difference of Vegetation Index (NDVI). First, the NDVI was generated from a satellite images red and near-infrared spectral reflectance difference. Higher values indicate more vegetation which ranges from -1 to +1 [2]. Second, the NDVI vegetation index is a ratio of red (*R*) and near-infrared (NIR) band values, reflecting the fraction of photo-synthetically active energy absorbed [2]. Therefore, the expression given:

$$NDVI = \frac{(PIR-R)}{(PIR+R)} \tag{9}$$

For Landsat 8 images:

$$NDVI = \frac{(Band5-Band4)}{(Band5+Band4)} \tag{10}$$

Since, the study region is in a tropical climate, the following regression connection is utilized to determine the *C* factor [12]:

$$C = \frac{(1-NDVI)}{2} \tag{11}$$

2.8 Support Practice Factor (P)

P-factor represents the impact of practices that lessen water runoff, which in turn lessens soil erosion. This factor defined by Kim, [13] is the ratio of soil loss with a particular support practice to the corresponding soil loss with straight row upslope and downslope tillage, and it is dependent on the slope. It ranges from 1 to 0, where 0 represents very excellent practices that reduce soil erosion and 1 represents no practices. Therefore, any land cover besides agricultural land has a value of one, unless there are management practices such as terracing. The support practice factor was determined using DEM with the spatial analyst extension and referring to the RUSLE model criteria by Wischmeier *et al.*, [8] as shown in Table 2.

Table 2
P-factor value

Slope (%)	Contouring	Strip cropping	Terracing
0.07 to 7.0	0.554	0.275	0.106
7.0 to 11.3	0.604	0.305	0.126
11.3 to 17.6	0.804	0.405	0.166
17.6 to 26.8	0.904	0.455	0.186
>26.8	1.004	0.505	0.206

2.9 Sediment Delivery Ratio and Sediment Yield

According to Vanoni, [14] sediment yield is the quantity of sediment actually discharged from the catchment area. The three components of the erosion process are detachment, transport, and sedimentation. Runoff as a transports of the eroded soil particles downslope, and some of these particles are categorized as suspended sediments until the runoff reaches the basin outlet. The sediment measured at the discharge point (the lowest point within the catchment area). The sediment yield has an inverse relationship with the area of drainage, and numerous factors (such as the annual precipitation, stream capacity, and soil erosion rate) control sediment yield; consequently, there are numerous formulas that link sediment yield to soil erosion. The most prevalent formula for defining the sediment delivery ratio as the ratio of sediment yield to total annual soil loss of the catchment as below [1]:

$$SDR = (0.42A)^{-0.125} \tag{12}$$

where A is catchment area in hectare (ha).

The sediment delivery ratios can be generated from the previous expression by multiplying the average annual potential soil erosion of the catchment. This ratio can then be used to analyze the sediment load that comes from hillslopes and smaller sub-areas to the channel. The sediment yield (SY) was determined for the study area as follow:

$$SY = SDR \times A \tag{13}$$

where A is the annual soil loss for the observation site. SDR is the sediment delivery ratio, which ranges from 0 to 1.

3. Results and Discussion

3.1 R Factor

The intensity and length of the rainfall have a major impact on the *R*-factor. Soil erosion increases as the rainfall erosivity factor rises [15]. This is especially true during the first two phases of soil erosion (detachment and transportation). The erosivity of rainfall in two different years is between 412.67 MJ mm/ha/h/yr and 160.661 MJ mm/ha/h/yr respectively, shown in Figure 1 and Figure 2. To observed, in the 2016 has higher values of erosivity compare to 2021 may be a result of climate change. When temperatures increase, more water evaporates into the air, leaving plants and soil with less moisture. Due to this, dry periods last longer than they would if temperatures were cooler. Therefore, the likelihood that precipitation will cause soil erosion is reduced, as is the capacity of runoff to transport eroded soil.

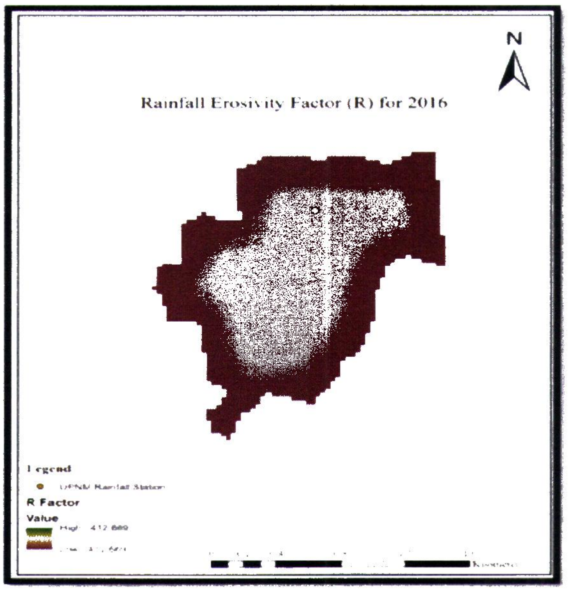


Fig. 1. Map of R factor for year 2016

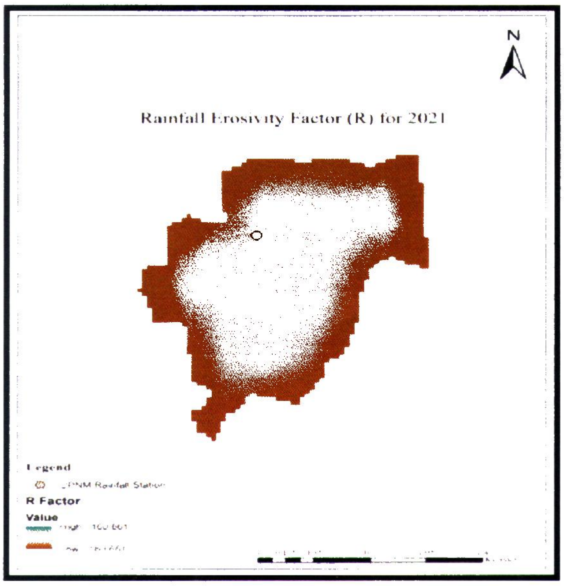


Fig. 2. Map of R factor for year 2021

3.2 K Factor

The structure, permeability, organic matter concentration, and particle size of the soil all influence the soil erodibility factor [3]. Acrisols comprised 100 percent of the sample area but with two different phase, which Ao 108-2ab with 48 percent and Ao 90-2/3 with 52 percent. The only type of soil that contains more than 50 percent sand for both phase; sandy soils typically have low K values due to low discharge and high infiltration rates. Therefore, the dominant erodibility factor was 0.0201, which was associated with Acrisols soil types (purple) in south area and was followed by (K factor) value 0.0185, which was associated with Acrisols soil Phase 2 types (green) in north area (Figure 3).

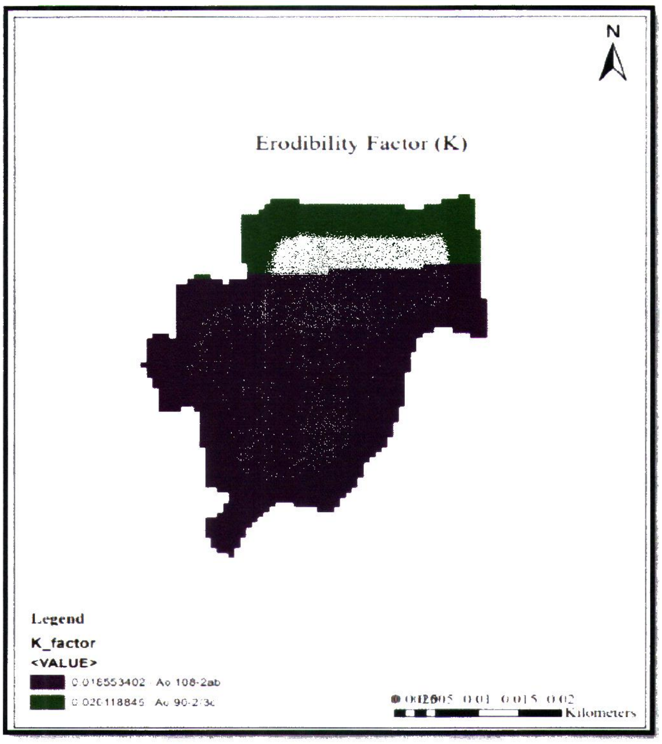


Fig. 3. Map of K factor

There are a variety of soil types, each of which offers varying degrees of protection against erosion [16]. The most important factor is the texture of soil. Erosion is greatest in fine sand, clay, or silt. Sand and loam soil resist erosion better [17]. Aside from the way the soil looks and feels, factors like the soil's structure, how well it lets water through, and how much organic matter it has also affect how easily the soil will wash away. Soils that are porous, which means they let more water pass through them, and soils with more organic matter are less likely to wash away. Wind erosion is less likely to happen on soils that have a rough surface.

3.3 LS Factor

LS is the influence of slope gradient and slope length on soil erosion. Erosion is more severe as slope length and slope gradient increase. The *LS*-factor ranges from 0 to 0.33, an increase in the *LS*-factor increases erosion because the discharge was more rapid, thereby increasing its energy.

According to Figure 4, North-East (green) regions are of particular concern, with high *LS* values since the place has not been explored or used by people yet.

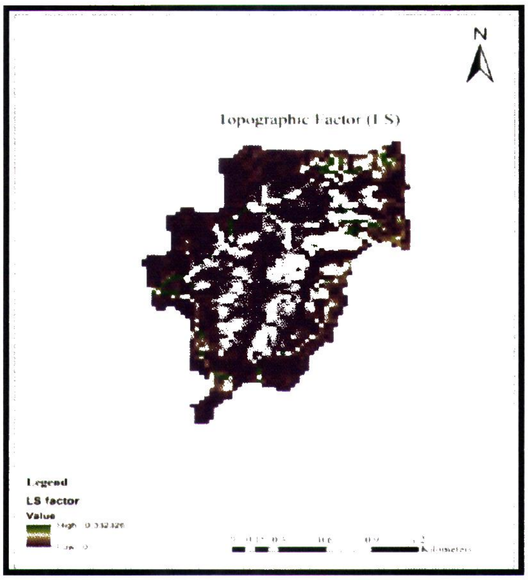


Fig. 4. Map of LS factor

3.4 C Factor

Vegetation cover was a major consideration to show how crops and management practises affect the rate of soil erosion [18]. Figure 5 and Figure 6 shows the results in two distinct years range of *C*-factor is 0.27004 to 0.516374 for 2016 and 0.273523 to 0.524646 for 2021 respectively. Erosion resistance increases as *C*-factor decreases. In urban and bare areas were found the highest value due to a lack of vegetation (blue), while the lowest values were found on the margins of the main channel (brown). There is also some vegetation cover in middle of region, resulting in a bit yellowish colour.

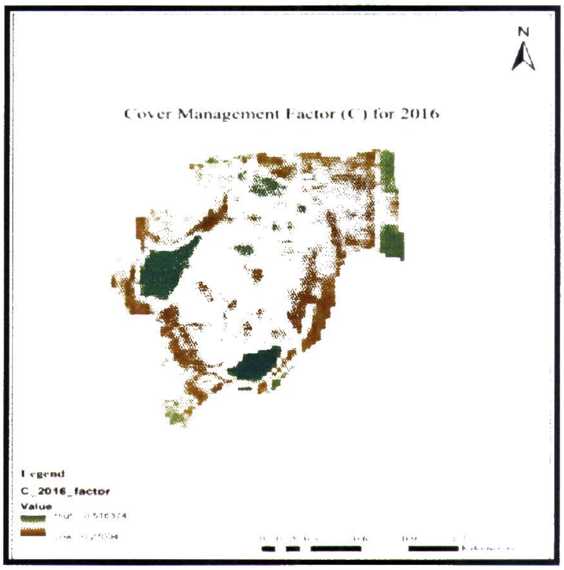


Fig. 5. Map of C factor for year 2016

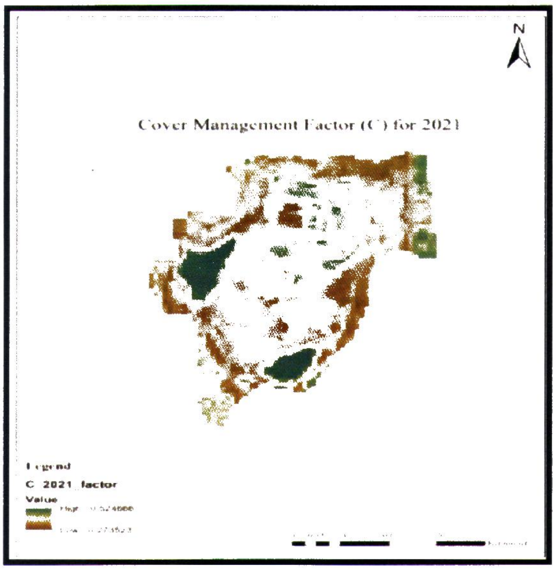


Fig. 6. Map of C factor for year 2021

3.5 P Factor

According to Ganasri *et al.*, [19] these practises typically alter the quantity, flow pattern, velocity, or direction of surface water. This region's *P*-factor value is derived from a data table with four distinct categories: slope, contouring, strip cropping, and terracing. The majority of the area depicted in the Figure 7 (urban area, vegetation, undeveloped land, and aquatic body) is not covered by steep slopes, resulting in a lower P-value except agricultural areas has a value of one, as the support factor depends on the slope.

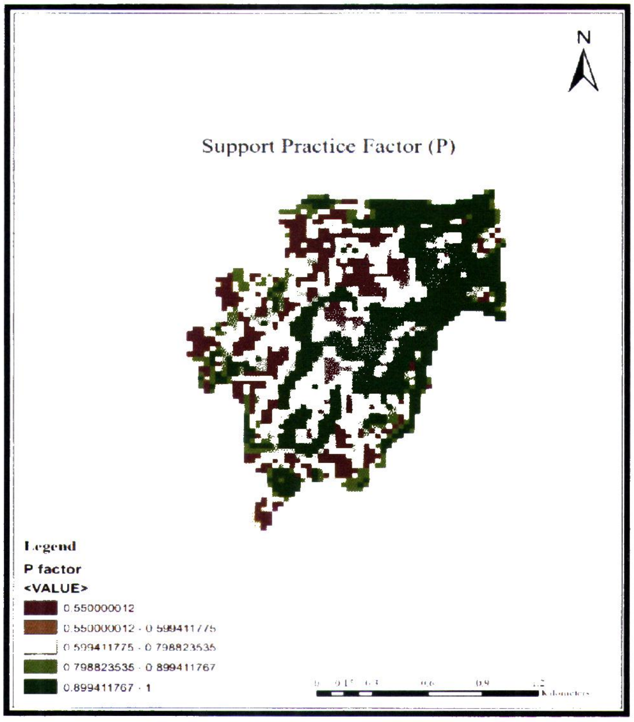


Fig. 7. Map of P factor

Adopting these supportive conservation practises, such as improved drainage and fewer agricultural activities in high-risk areas, reduces the *P*-factor value because they reduce discharge volume and velocity and increase sediment deposition on the surface of hill slopes. The soil erosion control practice is more effective the lower the *P*-factor.

3.6 Annual Average Soil Loss Rate (A)

In ArcGIS's raster calculator tool, the RUSLE parameters raster grids were multiplied by five parameters to figure out A for the UPNM area in 2016 and 2021. Figure 8 and Figure 9 show the average yearly rate of soil loss in 2016 and 2021, respectively. In 2016, the average soil loss was calculated to be 0.950689 t/ha/yr, and 0.333783 t/ha/yr in 2021.

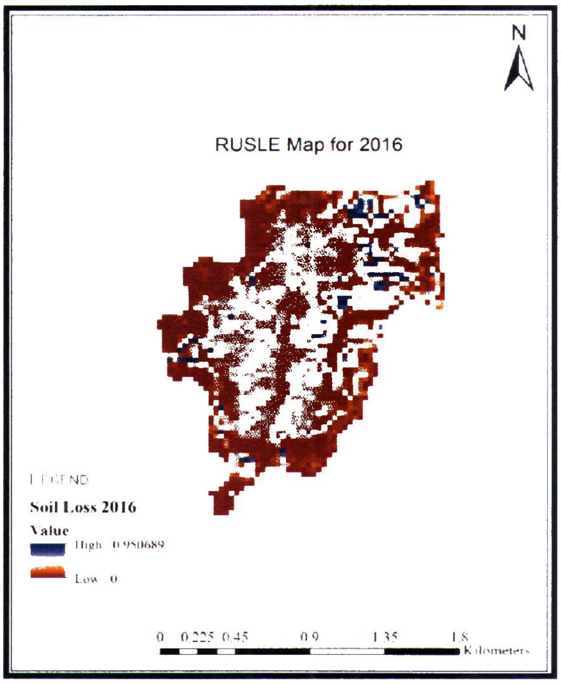


Fig. 8. Soil loss for year 2016 map

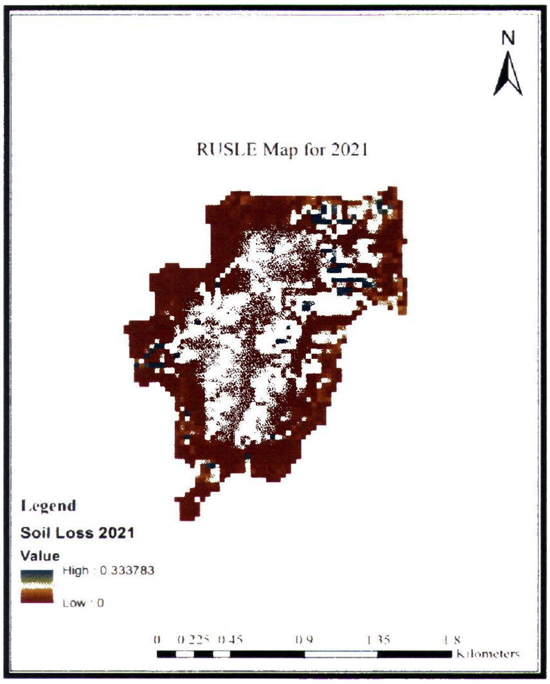


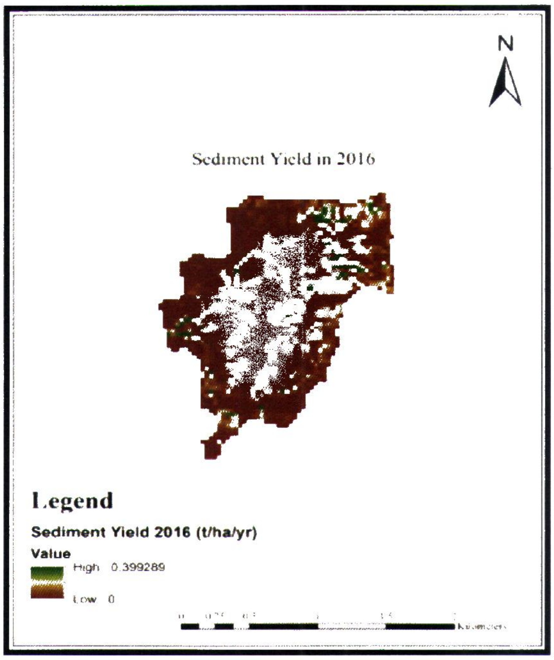
Fig. 9. Soil loss for year 2021 map

Both figures show the affected areas are in the steep slope, built-up surface area, and degraded vegetative cover with no soil support control, while the low-risk part of the catchment is mostly flat with low slopes, where soil deterioration may have little direct impact. Erosion estimates coloured the catchment from low (brownish) to very high (blue). 20% of the UPNM catchment was highly erodible, needing prompt action to minimize soil erosion and sediment loss.

3.7 Sediment Yield

The Vanoni, [14] equation was used to calculate the SDR in the UPNM catchment. ModelBuilder in ArcGIS automated the input parameters and Vanoni equation. The hilliest regions of the catchment produce the most sediment, while the average slope drops as the catchment grows and sediment production per unit area decreases. The research region main channel sediment delivery ratio was evaluated at 0.42. Net sediment mapping and RUSLE model sediment deposition and erosion mapping were used to create the UPNM catchment sediment yield map. 2016 and 2021 sediment yield distributions ranged from 0 to 0.399289 and 0 to 0.140189 t/ha/year respectively shown in Figure 10 and Figure 11.

These relatively low sediment yield estimates show that a lot of sediment from the highland parts of the basin is stuck in grass, bushes, and trees on flood plains along UPNM's tributaries. The particle size distribution of damaged soil may help explain the 2021 UPNM catchment sediment output drop.



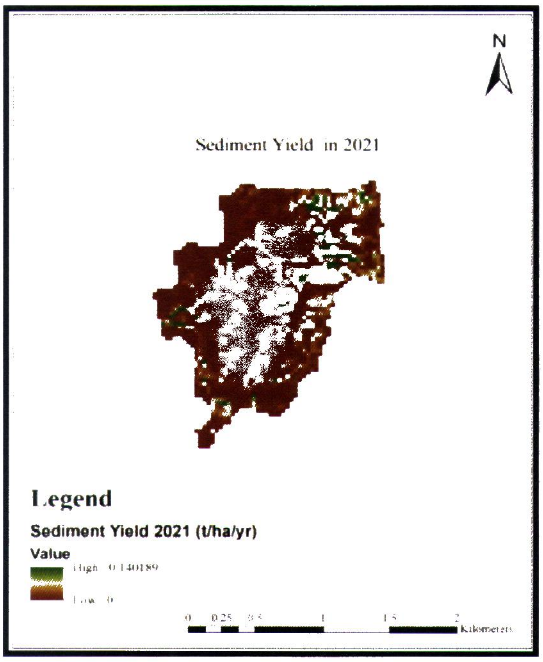


Fig. 10. Map of sediment yield for year 2016

Fig. 11. Map of sediment yield for year 2021

3.8 Validation of RUSLE/SDR model

According to Ouadja *et al.*, [2] the use of high-resolution Google Earth imagery to determine erosion risk classes in the final soil loss map revealed erosion problems in the study area, and the estimated soil loss rate was comparable to that of previous studies. Figures 12 presents the accuracy of the RUSLE model-based map of water-caused soil erosion using qualitative techniques based on visual inspection. As validation data, this method utilizes high-resolution photographs and images from Google Earth. With the increasing clarity of the images from year to year, it is possible to approximate the rate at which sediment is being washed away [20]. On the basis of a comparison between SY and a Google Earth image, it has been proven that areas with steep slopes and gullies tend to be more susceptible to erosion.

Using the Total Suspended Solid (TSS) testing, sediment concentration and flow discharges observed in 2021 by previous researcher on the same study area. This study analyzes about the total suspended solid occur by doing laboratory testing, then the researches used this study to make a clear comparison and do validation with field data.

Fig. 12. Comparison of Google Earth image and sediment yield map for year 2016 and year 2021

4. Conclusions

Water-accelerated soil erosion has global economic and environmental impacts. Deforestation and indiscriminate land clearance for agriculture, urbanization, and informal settlements in the UPNM catchment have generated widespread soil erosion and significant sediment yield [21]. ArcGIS and RUSLE were used to estimate annual soil loss rates and their geographical distribution under different land uses. Based on the annual average soil loss rate and study area in the UPNM in 2016 and 2021, the SDR was estimated and analyzed for tropical regions, there are several significant conclusions could be obtaining:

i. To assess UPNM catchment soil loss. As indicated in Fig. 6A and 6B, the 2016 soil loss rate was 0.950689 t/ha/year (95.07 t/km^2) and the 2021 rate was 0.333783 t/ha/year (33.38 t/km^2). The soil loss rate in forested, hilly, and steep slope areas was risky. The watershed landscape was divided into several categories based on erosion estimations, from low (brownish) to very high (blue). 20% of the UPNM watershed had very high erosion intensity, requiring immediate action to prevent soil erosion and sediment loss.

ii. Input parameters and Vanoni equation into ArcGIS ModelBuilder to investigate SDR at the UPNM catchment. As the watershed develops, silt output per unit area reduces and the average slope drops. Research region main channel sediment delivery ratio was 0.42. Since the watershed is small, SDR variation is unlikely.

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