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Soil erosion analysis for flood disaster assessment using GIS-based RUSLE model in Kota Belud, Sabah, Malaysia

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ABSTRACT

Soil erosion is one of the significant environmental problems and main contributors to flood events, especially in the Kota Belud district of Sabah, Malaysia. A detailed assessment of soil loss prediction and its consequences was carried out in this district using the revised soil loss equation (RUSLE) model with a geographical information system (GIS). A thematic data layering method was used to analyze risk areas and identify possible high-risk erosion zones. The RUSLE model used GIS as the spatial information analysis method for calculating the amount of soil loss (tons/ac/year). Approximately 61.50% (89 ac) of the area was classified as very low risk, 2.67% (4 ac) low risk, 4.76% (7 ac) moderate risk, 3.57% (5 ac) high risk, and 27.50% (40 ac) very high risk. All the outcomes revealed that GIS integration might be used for regional spatial analysis. Total value maps can be used to plan inevitable development, such as housing, farming, and hazard and risk management.

Keywords: revised universal soil loss equation (RUSLE); soil erosion; soil loss; flood

1. INTRODUCTION

The 2015 Ranau earthquake substantially influenced the Kota Belud river basin system. Due to tremors from the earthquake and multiple aftershocks, widespread landslides in the Mount Kinabalu area resulted in flash floods and debris flows in the river basin. The landslide swept away roughly 1,500 ha (15 km^2) of soil, rocks, and timber from the slopes. Such landslides affect watersheds and contribute to debris flows during heavy rain. For example debris flows occurred in Mesilou, Kilambun, Kedamaian, and Penataran rivers a few weeks after a severe earthquake. The river basins became shallow due to debris flows and an increase in the number of flood events in this area, as the rivers could not tolerate the water capacity (Roslee et al., 2017; Roslee and Norhisham, 2018; Roslee et al., 2018; Roslee and Sharir, 2019a, 2019b; Sharir et al., 2019; Mariappan et al., 2019; Pirah and Roslee, 2021, 2022; Sharir and Roslee, 2022; Sharir et al., 2022).

Floods are the most dangerous of natural disasters, having human casualties, destruction of infrastructure, and economic consequences, particularly in areas where socioeconomic development has resulted in land-use changes (Kaffas et al., 2022). Floods can induce severe soil degradation and sediment deposition, leading to irreversible soil loss from a region, depending on critical parameters such as rainfall intensity and watershed conditions (Borga et al., 2014). Furthermore, rainfall that causes flash floods can cause deadly debris flows (NWS, 2017). Soil erosion is a major worldwide problem with severe financial and ecological consequences. Floods are among the most hazardous natural disasters, leading to human casualties, destruction of infrastructure, and significant economic consequences. These impacts are especially pronounced in areas where rapid socioeconomic development has led to extensive land-use changes (Kaffas et al., 2022). The sediment discharge of actual flood events could be close to the yearly sediment discharge since the significant burden of the discharged sediments is related to a few flood episodes (Markus and Demissie, 2006; Vanmaercke et al., 2010). Cao et al. (2016) and Kaffas et al. (2022) reported that the amount of sediment produced by a single high flood can be the same, or even more significant than the amount made in an average year.

On a local or regional scale, spatial and quantitative data on soil erosion can help sustainable management, soil protection, and environmental conservation. Defining erosion-prone areas and quantitatively measuring soil loss rates are important for developing and implementing effective erosion controls or sustainable water management strategies (Alisawi and Shahid, 2017; Shi et al., 2004). Moreover, it is important to understand the physical processes that lead to soil erosion and sedimentation for both long- and short-term adaptation and mitigation strategies (Slattery et al., 2002; Wainwright et al., 2003).

This study aims to establish a comprehensive technique for estimating baseline soil erosion and erosion in river basins. Erosion is a dynamic process that evolves through time and place. GIS can keep track of data's spatial location and gives tools for relating it using a database system (Alisawi and Shahid, 2017; Shahid et al., 2000). Incorporating the RUSLE model into a GIS platform provides the necessary tools to generate detailed and reliable maps of soil erosion-prone zones. These tools allow for the efficient transfer and application of spatial data in erosion analysis, enabling more precise land management decisions. RUSLE is a modified version of the universal soil loss equation (USLE), which has been applied at various geographic scales and is linked to a GIS framework. These maps could be used to plan land cover development and coordination in the proliferating Kota Belud River basin.

2. MATERIALS AND METHODS

2.1 Study area

The research area is part of the Kota Belud district, sitting on Sabah's west coast, facing the South China Sea (Figure 1). Kota Belud is 70 km from Sabah's capital, Kota Kinabalu. The district's size is estimated to be 1,385.6 km^2. There are three primary river basins in the district: the Tempasuk River basin, with an area of 122 km^2; the Kedamaian River basin, with an area of 445 km^2; and the Wariu River basin, with an area of 343 km^2.

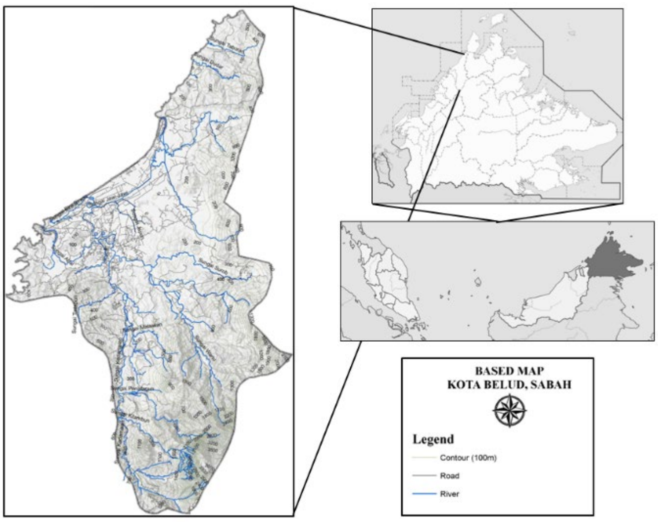

Figure 1. Location of study area

2.2 Geological settings

The research region comprises various geological units, such as Ophiolite rock, Trusmadi Formation, Crocker Formation, Wariu Formation, igneous intrusion rock of granitoid rocks, and alluvium deposits (Figure 2). As basement rocks, the Ophiolite of the Cretaceous age is the oldest lithologic unit in the study area. It is composed of sheared serpentinite, gabbro, and dolerite with the appearance of radiolarian chert. It can be observed in the center of the study area's southern and eastern parts. During the Palaeocene to Middle Miocene, the Trusmadi Formation was formed before being overlain by the younger Crocker formation (Jacobson, 1970). The Trusmadi Formation experienced regional metamorphism with slate and phyllite and some siltstone and sandstone. This formation is prone to instability because it is made up of argillaceous rocks. It is in the southern part of the research area.

The Crocker Formation is a turbidite deposition aged from the Late Eocene to Early Miocene periods and covers approximately 51% of the study area (Collenette, 1958). It was formed by a thick sandstone unit, sandstone-shale bedding unit, and shale unit. Most of the slopes in the research area are part of the Crocker Formation, which has a high degree of weathering and a deep soil profile. The Wariu Formation, also known as the Melange, is characterized by a mixture of slump breccia and mudstone dating to the Middle Miocene.

The Wariu Formation is found in the study area's central region and is characterized by brecciated boulders and fragments of various sizes. It is prone to failure movement due to its weak structure and unconsolidated layout. Mount Kinabalu's batholith is found in the southeast corner of the research area. The Pliocene intrusion consists of felsic, acidic, and intermediate igneous rocks.

The batholith is made up of biotite quartz monzodiorite and hornblende quartz monzonite. The study area's principal rivers, such as Sg. Kadamaian, Sg. Panataran, and Sg. Wariu, are all fed by Mount Kinabalu. Terrace sand, gravel, pebble, and coral from the Pleistocene era are predominantly found in the northern half of the study region and along the main rivers. It consists of a flat deposition of alluvium particles of varied sizes. Most of the deposition occurred on low topography. Recent-age deposition of coastal and riverine alluvium is the youngest rock unit in the study area. Bars, plains, and levees are standard flat features seen along the coast and rivers.

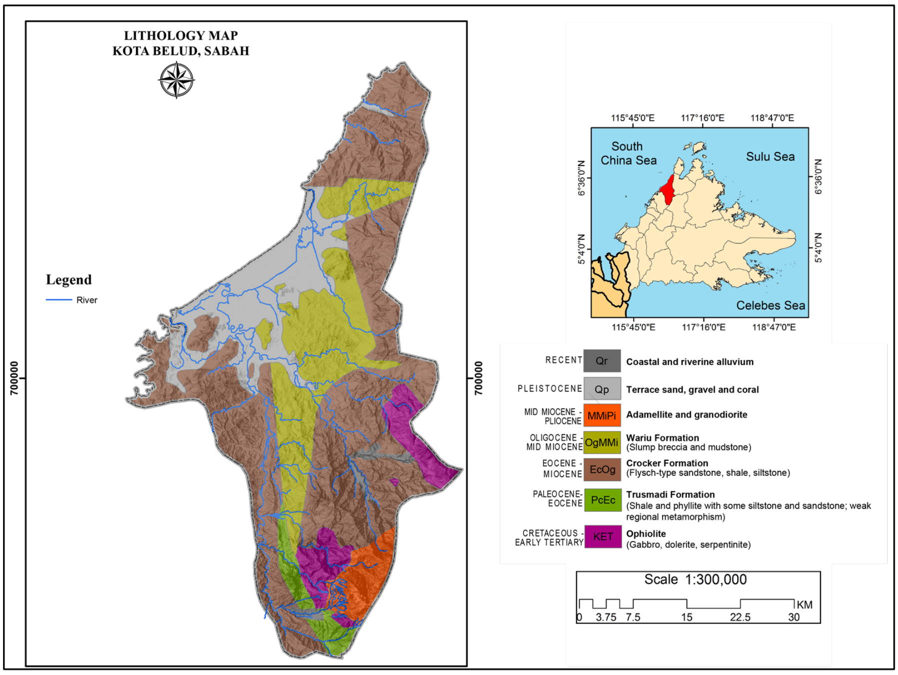

Figure 2. Lithology of study area

2.3 Soil erosion study

The amount of soil erosion was predicted using soil erosion modeling. Multiple simulations can act as indicators. The universal soil loss equation (USLE) is the most widely used and reliable method for quantifying soil loss (Wischmeier and Smith, 1978). The rainfall factor of the original USLE was replaced by the rainfall erosivity factor in RUSLE (Fernandez et al., 2003; Sharir and Roslee, 2022; Shi et al., 2004). The model reflects soil erosion risk by considering six parameters and developing an equation to assess soil loss. GIS raster format was used to map all these attributes. Equation 1 was used to express it.

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

where:
A = estimated average annual soil loss (ton/ha/year),
R = rainfall erosivity factor (MJ mm/ha/year),
K = soil erodibility factor (ton/ha/year),
L = slope length factor,
S = slope gradient factor,
C = vegetation cover-management factor,
P = support practices.

2.3.1 Rain erosivity factor (R)

The level of soil loss is proportional to the ability of precipitation to penetrate the topsoil layer and cause surface runoff (Moore and Burch, 1986; Morgan, 1974). Morgan (1974) proposed a method for determining R values using yearly average precipitation and intensity data for 30 min at each gauge station. The R factor computes the volume and velocity of runoff by assessing the impacts of precipitation (Gelagay and Minale, 2016). R was determined using Equation 2 and rainfall data from the Malaysia Meteorological Department (METMalaysia).

$$R = \mathrm{E} \times \frac{\mathrm{I30}}{100} \tag{2}$$

where:
R = annual average rainfall (mm)
I_{30} = peak 30-minute intensity of rainfall (cm/h)
E = total kinetic energy of rainfall (J/m^2)
Expanding further:

$$E = \sum_{i=1}^{n} Ei$$

where:
n = number of rainfall segments,
Ei = kinetic energy of the i-th segment of rainfall (Equation 3).

$$Ei = (206 + 87 \log I_{si}) \times His \quad (3)$$

where:
I_{si} = intensity of the i-th segment of rainfall (cm/h),
H_{si} = rainfall amount in the i-th segment (cm).

The calculation was selected based on prior studies demonstrating its suitability for tropical countries such as Malaysia. The location coordinates of the rainfall station have been entered into the GIS environment. Each rainfall station's average data has been saved as a GIS attribute (Figure 3).

Inverse distance weighting was used to analyze and interpolate the input data's mean yearly rainfall to provide continuous raster precipitation data for the study area.

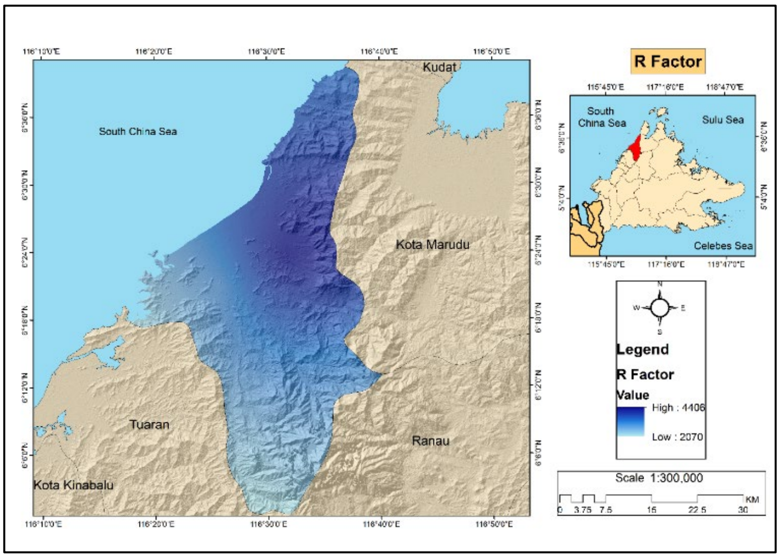

Figure 3. R factor map

2.3.2 Soil erodibility factor (K)

The soil erodibility factor (K) assesses the vulnerability of a topography or soil component to erosion, the transport of sediment, and the volume of runoff for each rainfall input using a standard form. The Department of Agriculture Sabah released the K factor values according to their soil type classification. All information was entered into attribute tables in spatial vector format and then transformed to spatial raster format using conversion tools (Figure 4).

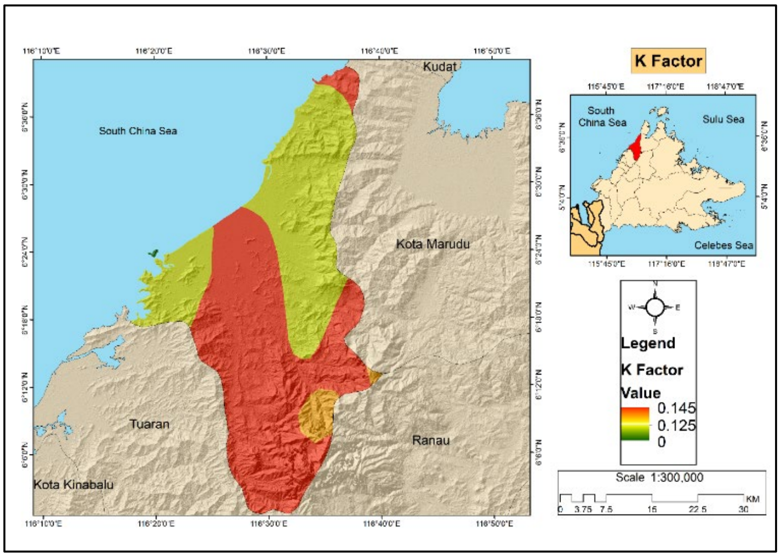

Figure 4. K factor map

2.3.3 Slope length and steepness factor (LS)

The topographic component, slope length and steepness (LS), is the soil loss ratio under specified conditions to slope length and steepness criteria. This calculation can be altered depending on the location—the slope LS factor results in high runoff from the surface and flows velocity. The cumulative flow grid was characterized as a grid of multiple pixels, with the cell size corresponding to the length of pixels in the grid theme (Roslee and Sharir, 2019a). The slope length and steepness factors were calculated using the hydrological tools available in ArcGIS ArcToolbox. The slope length and steepness on the topographic map were produced using a digital elevation model (DEM) with 10-m contour gaps. For further study, the DEM was transformed into a spatial raster format. The DEM data required many steps to construct the letter L, such as the creation of the fill DEM, flow direction, and flow accumulation. Similarly, the steepness of the slope was determined from DEM data. The LS factor was estimated from both raster data using Equation 3 in the raster calculator (Figure 5).

2.3.4 Vegetation cover management factor (C)

The importance of vegetation cover management (C) is determined by the type of land use in the research area, soil cover, management strategies, and the growth stages of vegetation. This factor is crucial as it influences the soil's susceptibility to erosion during rainfall events. (C) (Wischmeier and Smith, 1978). The importance of this component is determined by the soil cover, management strategies, growth, and the fact that rain might trigger erosion at any time. The C value is determined by the type of land use in the research area (Figure 6). Following the digitization process, this data was transformed from vector to raster.

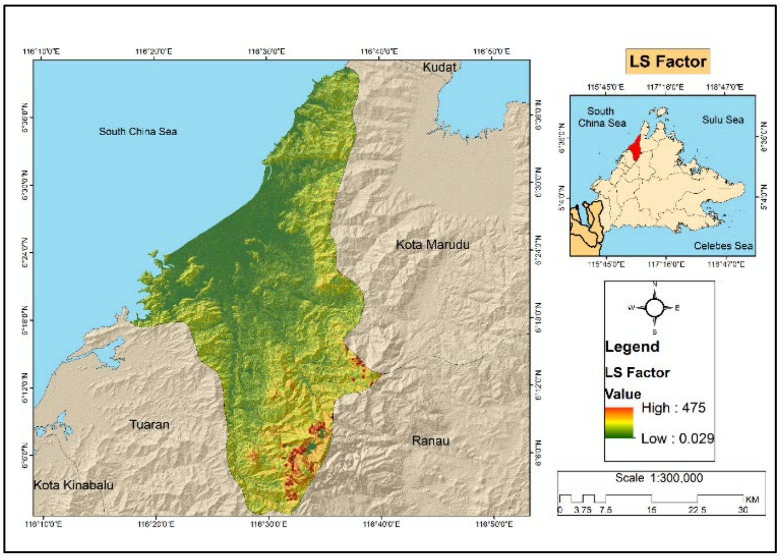

Figure 5. LS factor map

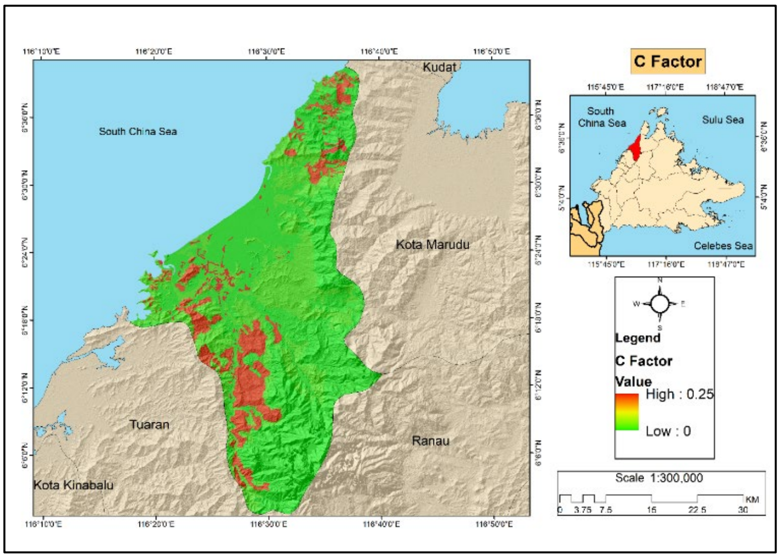

Figure 6. C factor map

2.3.5 Supporting conservation practice factors (P)

P values in the research area range from 0 to 1 and are impacted by land management practices. This study computed the P value for each soil type based on the classification of land-use categories (Moore and Burch, 1986) (Figure 7).

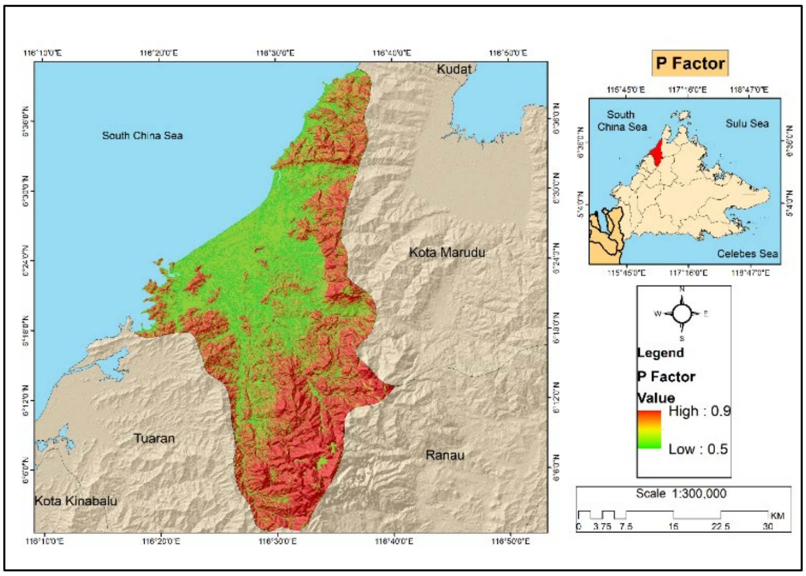

Figure 7. P factor map

3. RESULTS

The parameters required for assessing soil erosion were established in the early stages of this study. The distribution of several elements in the Kota Belud River basin is shown below.

3.1 Factor maps

The results showed that the rainfall erosivity factor (R) values ranged from 2070 to 4406 mm/ha. year (Figure 3). In addition, the soil erodibility factor (K) values were from 0 to 0.145 (Figure 4), the topographic factors (LS) value were from 0.029 to 475 (Figure 5), the cover management factor (C) values were from 0 to 0.25 (Figure 6), and the support practice factor (P) values for the entire area were from 0.5 to 0.9 (Figure 7).

3.2 Erosion map using RUSLE

The RUSLE model was multiplied across thematic map layers to provide the final spatial analysis output. The RUSLE parameter maps (R, K, LS, C, and P) were integrated within the ArcGIS environment to generate composite maps of the estimated erosion loss in the study area. Figure 8 shows the produced map for this model. The soil loss data were divided into five categories: very low, low, moderate, high, and very high. The quantitative soil loss (ton/ac/year) ranges calculated using the RUSLE model and a geographical information system (GIS) are as follows: (a) extremely high risk (>15 tons/ac/year), (b) high risk (10–15 tons/ac/year), (c) moderate risk (5–10 tons/ac/year), (d) low risk (3–5 tons/ac/year), and (e) extremely low risk (3 tons/ac/year).

4. DISCUSSION

Water erosion is one of the most severe environmental issues today (Yusof et al., 2019). It is critical to understand the rate of soil erosion around drainage systems to determine where sediment deposits originated. The revised universal soil loss equation (RUSLE) approach was used to assess soil erosion rates throughout the Kota Belud district. The data from multiple inputs analyzed by ArcGIS resulted in six-factor maps: R, K, LS, C, and P. These raster data were combined within the ArcGIS environment to generate composite maps of the estimated erosion loss in the study area using the RUSLE relation. The soil erosion rate is classified into six classes based on the severity of the erosion. The soil erosion rate map (A) suggests that 61.50%, 2.67%, 4.76%, 3.57%, and 7.50% of the study area was categorized as very low risk, low risk, medium risk, high risk, and very high risk, respectively.

Most of the soil erosion potential in the Kota Belud district is rated as very low risk, with a proportion of 63.29% for a total area of 87,657 ha. In comparison, very high erosion risk represents 26.17% (36,245 ha) of the entire district. Medium risk represents 4.52% (6,260 ha), low risk is 3.69% (5,111 ha), and high erosion risk is 2.33% (3,227 ha) of the area. Most of the very high category can be found near the riverbank in the southern part of the research area. This considerable soil loss is caused by the strong link between the LS parameters. The mean erosion rate is significant in barren areas; hence, this area must be prioritized. The LS factor, which features steep slopes surrounding the foot of Mount Kinabalu, increases the risk of soil erosion in the southwestern section of the Kota Belud district, where the Kadamaian River basin is located.

Furthermore, some areas in this district have a significant erosion rate, particularly around the main riverbanks, such as Sungai Wariu, Sungai Tempasuk, and Sungai Abai. The high rate of soil erosion along the riverbanks will increase the presence of sediment in the riverbed. The sediment load caused by riverbank erosion is likely to disrupt the drainage system, causing the river to be incapable of holding the water discharge volume. Hence, it will be more susceptible to flooding, especially during the rainy season.

5. CONCLUSION

This study used RUSLE in a GIS framework to estimate the annual sediment erosion in the Kota Belud River basin. According to RUSLE, the annual average soil erosion loss in the Kota Belud River basin ranges from 0 to 15 tons/ac/year. Moreover, the study reveals that the LS is essential in determining the basin's soil erosion susceptibility, followed by supporting conservation practices factors. The most flood-prone places were generally found at riverbanks and plains in the south of the research area, where most of the very high soil erosion rate can be found. As a result, improving flood alerts and safety measures in these areas should be prioritized.

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