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MODELING OF SOIL EROSION RISK UTILIZING MORPHOMETRIC ANALYSIS AND GEOSPATIAL APPROACH IN LAKE NAKURU, KENYA

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ABSTRACT

Applicability and integration of Geographic Information System (GIS) technology and Remote Sensing (RS) with morphometric analysis are essential in modeling, delineating, and predicting water-induced soil erosion risks over a vast area. Globally, water resource locations are vulnerable to soil erosion risks. There is a need to create digital maps of geologic, ground elevation, watershed network systems, and soil erosion models combined statistically in GIS to delineate areas at risk of soil erosion. The study applied ArcGIS integrated with morphometric analysis to collect data and model soil erosion risks in Lake Nakuru environs. Garmin GPS, RS, field surveys, and GIS mapping were used to collect topographic, soil type, vegetation, and land use data. The results reveal that Lake Nakuru receives significant water volume and sediments from its distributaries and littoral land as evidenced by many rills and gullies. There are significant variations in slope, aspect, drainage density, and stream order across Lake Nakuru, indicating variations in the terrain's susceptibility to erosion processes. Steeper slopes were potential erosion hotspots, experiencing surface runoff and soil erosion. The south-facing slopes exhibited higher erosion risks due to increased exposure to solar radiation and potential drying of the soil. The study recommends the implementation of erosion control measures in high-risk zones, raising awareness about sustainable land management practices, and providing training on erosion control techniques that can contribute to long-term soil conservation efforts.

Key Words: Geospatial analysis, Digital mapping, Soil erosion risks, Morphometric analysis, Erosion control measures, Sustainable land management

1. INTRODUCTION

Water soil erosion is the main cause of earth deterioration throughout the globe. The success of drainage basin management depends heavily on morphometric analysis, a scientific hydrology method of analysis. This is based on the delineation of areas at risk for soil erosion using linear, topographic, and watershed-related components of geographic information systems spatial data (GISSD). Due to rising human-induced activities, a growing population, and other naturally occurring variables, water resource locations all over the world are vulnerable to soil erosion. To decrease water contamination, adequate planning and management strategies must be documented through scientific research. The interconnectedness between uplands and downstream regions, as well as the interdependence of land use, soil, and water, are all identified by watershed management (Benzougagh, Bisen, et al., 2022; Benzougagh, Meshram, et al., 2022).

Drainage basin management is recognized to reduce natural disasters and improve sustainable development (Meshram et al. 2021). The success of drainage basin management depends heavily on scientific hydrology methods of analysis, particularly morphometric analysis. River erosion control strategies are part of basin management (Gajbhiye et al. 2015). To evaluate the risks and dangers posed by nature, the assessment is also carried out in sub-watersheds. Watershed morphometric analysis is essential in understanding the relationships between the dynamics of landforms and the hydrologic responses. This involves the delineation of areas at risk of soil erosion using linear, topographic, and watershed-related components of Geographical Information System Spatial Data (GISSD).

A morphometric study calculates the length, surface area, size, slope, and other mathematical characteristics of watersheds and stream networks (Benzougagh et al., 2017; Pande et al., 2017; Şener & Arslanoğlu, 2023). Due to rising human-induced activities, a growing population, and other variables, water resource locations all over the world are vulnerable to soil erosion. To decrease water contamination, adequate planning and management strategies must be documented through scientific research. The interconnectedness between uplands and downstream regions, as well as the interdependence of land use, soil, and water, are all identified by watershed management (Benzougagh et al. 2022; Garbowski et al., 2023).

Morphometric analysis, also known as topographic analysis, is the study of the shape and form of the land surface and can be used to identify factors that contribute to soil erosion (Newton et al., 2023). For example, steep slopes, shallow soils, and areas with poor drainage are all indicators of high erosion risk. By analyzing these factors, it is possible to identify areas that are at a higher risk of erosion and target conservation and land management practices in those areas.

Geospatial techniques, such as GIS mapping and remote sensing, can be used to collect and analyze data on land use, vegetation, and soil type, which can also be used to identify areas at high risk of erosion (Kumar & Kalambukattu, 2022; Singh et al., 2023). By overlaying these data with information on topography and hydrology, it is possible to create detailed maps of erosion risk that can inform conservation and land management decisions.

Several models can also be developed to predict erosion risk in a given area (Benzougagh et al., 2020; Abu El-Magd et al., 2022; Kulimushi et al., 2023). These models can be based on a variety of factors, such as climate, land use, and soil properties, and can be used to predict the likelihood of erosion in different parts of a catchment area. This can help identify areas that are at a high risk of erosion, even before erosion has occurred, and help conservation and land management decisions. The example of these models used in mapping and forecasting soil erosion are described in the literature, which includes the Universal Soil Loss Equation (USLE), Modified Universal Soil Loss Equation (MUSLE), Morphometric Analysis, etc. (Kumar and Joshi, 2016; Meshram et al., 2020; Benzougagh et al., 2020). The use of GIS tools stands out in watershed and soil resource analysis (Jaiswal et al., 2015; Haidara et al., 2019). The study utilizes the Geographical Information System (GIS) to determine areas prone to soil erosion and to analyze various fields of the prioritized watershed area morphometric parameters. GIS has recorded success in solving siting challenges and assessing erosion vulnerability (e.g., Benzougagh et al., 2021).

In particular, Kenya has had a long problem with soil erosion in the Lake Nakuru watershed. Watersheds in Kenya offer environmental benefits to populations downstream by delivering water for household consumption, hydroelectric power production, and crop cultivation. Adversities do, however, also arise in watersheds as a result of tectonic activity and climatic extremes (Torrefranca and Otadoy, 2022). In the study of watershed morphology, surface characteristics are analyzed to explain and better understand these natural reactions of a hydrologically determined landform (Kabite & Gessesse, 2018). The lake of Nakuru lies around the West-central of the Rift Valley Kenya. The area covers approximately 11 Kilometres from Nakuru City. It is located between 0.37 south latitude and 36.08 east longitude. The novelty of this study lies in its integration of morphometric analysis and GIS to determine the soil erosion risk in the Lake Nakuru region. The morphometric analysis and geospatial approach can be a powerful tool for predicting soil erosion risk and guiding conservation and land management practices to prevent or mitigate erosion. The study was guided by specific objectives which include examining the characteristics of watersheds and identifying factors that contribute to soil erosion risk.

This study is made up of different sections. Section 1 comprises the introduction while section 2 consists of material and methods. Section 3 presents the result 4 consists of discussions. Lastly, section 5 concludes the paper.

2. MATERIALS AND METHODS

1.1 Descriptive of the Study Area

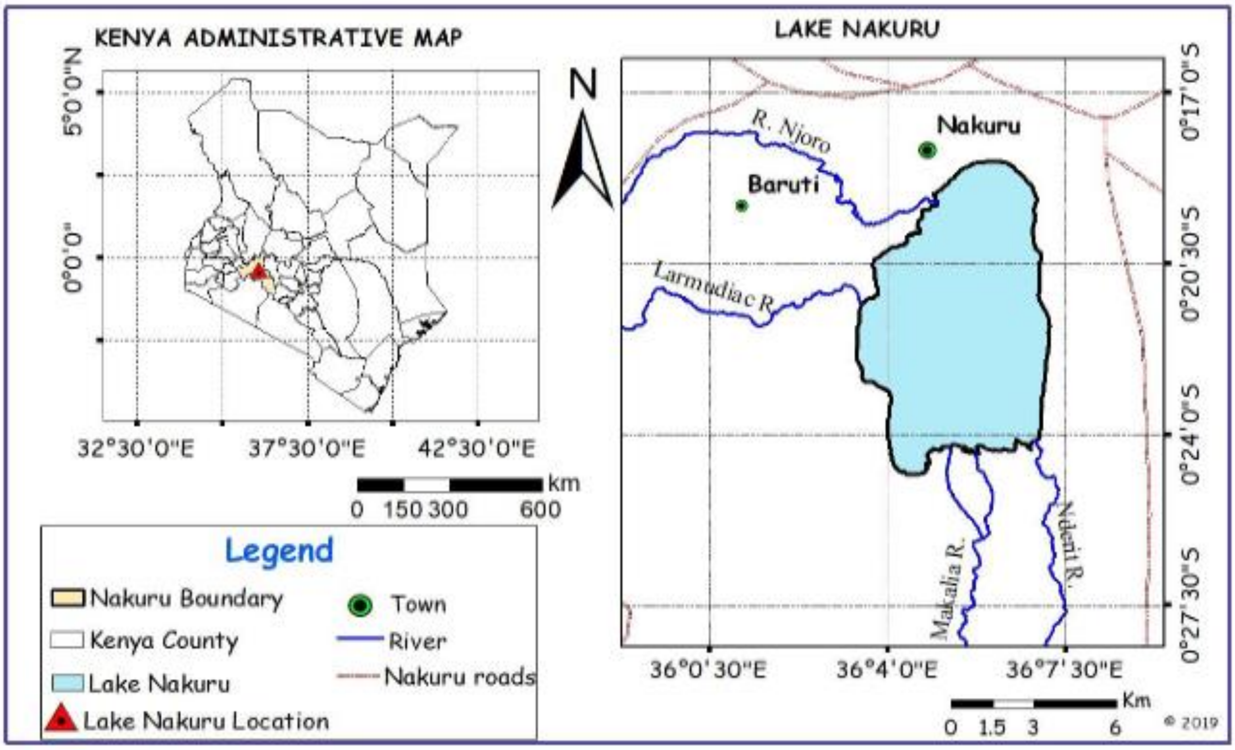

Figure 1: Lake Nakuru Location Map (Iradukunda & Nyadawa, 2021)

1.2 Morphometric Analysis and Geospatial Methodology

Morphometric analysis and geospatial approach were used to model soil erosion risk by analyzing the topographic features of a given area, such as slope, aspect, and drainage patterns, and incorporating this information with data on soil type, vegetation, and land use. This can help identify areas that are at a higher risk of erosion and inform conservation and land management practices to prevent or mitigate erosion in those areas. GIS technology and remote sensing were used to effectively collect and analyze geospatial data, and models were developed to predict erosion risk in a given area.

The methodology for morphometric analysis (Figure 1), typically includes the following steps:

a) Data collection: The first step is to collect topographic data, such as digital elevation models (DEMs), contour maps, or lidar data, as well as data on soil type, vegetation, and land use. This data can be collected using various techniques such as remote sensing, field surveys, and GIS mapping.

b) Data processing: The collected data is then processed using GIS software to create detailed maps of the area. This includes creating a digital elevation model (DEM) of the area, which can be used to calculate various topographic parameters such as slope, aspect, and drainage patterns.

c) Calculation of morphometric parameters: Using the processed data, various morphometric parameters are calculated. These include slope, aspect, relief, stream frequency, stream length, stream order, drainage density, and bifurcation ratio. These parameters provide information on the topographic characteristics of the area and can be used to identify areas at high risk of erosion.

d) Mapping and interpretation: The calculated morphometric parameters are then mapped and interpreted. This includes creating maps of slope, aspect, and drainage patterns, as well as overlaying these maps with data on soil type, vegetation, and land use. This can help identify areas at high risk of erosion and inform conservation and land management decisions.

e) Modeling: After the morphometric parameters have been calculated and interpreted, models can be developed to predict erosion risk in a given area. These models can be based on a variety of factors, such as climate, land use, and soil properties, and can be used to predict the likelihood of erosion in different parts of a catchment area.

f) Validation: The model developed using morphometric analysis should be validated using field data. This will help to check if the predictions made by the model are accurate or not.

Note that the specific steps and techniques used in morphometric analysis may vary depending on the specific study and the data available. But the overall process remains the same.

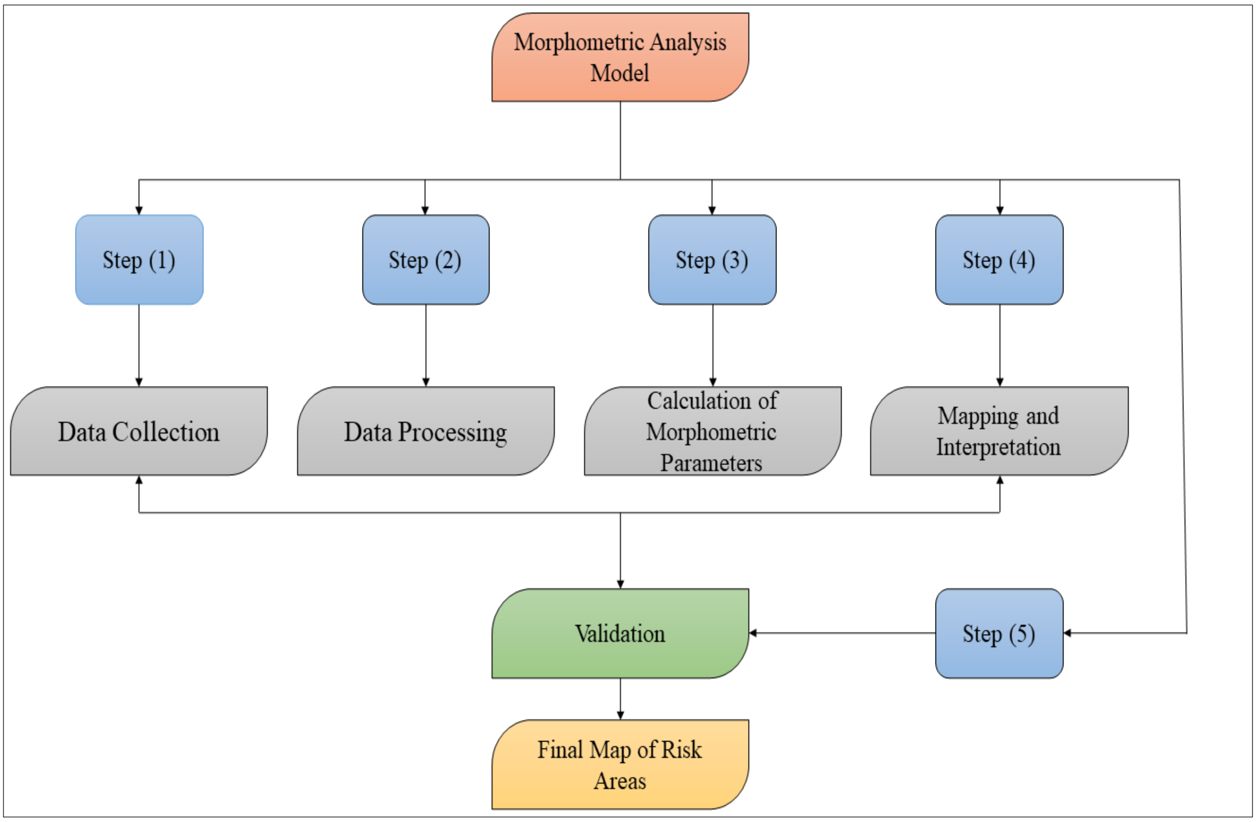

Figure 2: The steps of the Morphometric Analysis methodology.

Step (4) Requires the calculation of morphometric parameters, which are summarized in **Table 1**.

Parameters	Symbol	Formula	References
Linear Aspects			
Basin Length	LB	Lb = 1.312×$A^{0.568}$	Sreedevi et al. (2005)
Basin perimeter	P	P = Outer boundary of drainage basin measured in Km	Sreedevi et al. (2005)
Stream Order	U	Hierarchical rank	Strahler (1964)
Stream Length	Lu	Length of the stream in each order	Horton (1945)
Mean Stream Length	Lsm	Lsm = Lu/Nu, Where Lu = Total stream length of order'u', Nu= Total no. of stream segments of order 'u'	Strahler (1964)
Stream Number	Nu	No. of Streams in each order	Sreedevi et al. (2013)
Stream Length ratio	Rl	RL = Lu/Lu-1, Where Lu= The total stream length of the order 'u' Lu-1 = Total stream length of its next lower order	Horton (1945)
Bifurcation ratio	Rb	Rb = Nu/Nu+1, Nu= Total no. stream segments of order 'u', Nu+1 = Number of segments of the next higher-order	Schumn (1956)
Mean Bifurcation ratio	Rbm	Average of bifurcation ratios of all orders	Strahler (1964)
Areal Aspects			
Drainage Density	Dd	Dd = Lu/A where Lu= Total stream length of all orders and A = Area of the basin (Km2)	Horton (1932)
Drainage texture	Dt	Dt= Nu/P, Where, Nu= Total No. of streams of all orders, P = Perimeter (Km)	Smith (1950)
Stream Frequency	Fs	Fs= Nu/A, where Nu= Total no. of streams of all orders, A = Area of the basin (Km2)	Horton (1945)
Elongation ratio	Re	Re = 2/Lb ×(A/π)0.5 Where, A= Area of the basin, Lb= Basin length (Km)	Schumm (1956)
Circulatory ratio	Rc	Rc = 4×π× A/P2, Where, π= 3.14, A= area of the basin, P2 = Square of the perimeter (km)	Strahler (1956)
Form factor	Rf	Rf = A/Lb2, Where A= Area of the basin (Km2), Lb2= Square of basin length	Horton (1945)
Infiltration Number	In	In = Dd×Fs Where. Dd= Drainage density and Fs=Drainage frequency	Faniran (1968)
Compactness coefficient	Cc	Cc = 0.2821 x P/A0.5, P=Perimeter of the basin, A= Area of the basin	Horton (1945)
Length of overland flow	Lg	Lg = 1/2 Dd, Dd= Drainage density	Horton (1945)

3. RESULTS

3.1 Morphometric Parameters of Lake Nakuru Watershed

Watershed/Reservoir Parameters	Unit	Water Storage Value	Sediment Storage Value
Maximum Thickness	m	8.38	0.91
Mean Thickness	m	6.68	0.44
Modal Thickness	m	7.42	0.36
Median Thickness	m	6.98	0.41
Volume of Storage	x 10^6 m^3	320.84	38.28

3.2. Linear Aspect of Lake Nakuru Watershed

The analysis of linear characteristics provides insights into hydrological connectivity, watershed characteristics, and potential influences on water volume, sediment transport, and nutrient input for the watershed (Asfaw & Workineh, 2021; Torrefranca and Otadoy, 2022). We begin with the basin length which refers to measuring the longest distance from the headwater source to the lake outlet (Sreedevi et al., 2005). It indicates the size and extent of the watershed that contributes water to Lake Nakuru. Lake Nakuru likely has a relatively long basin length, indicating a larger catchment area and potential influence from multiple water sources. The basin perimeter on one hand measures the total length of the boundary around the lake’s catchment area. The basin perimeter of Lake Nakuru might be irregular and convoluted, suggesting a complex shoreline with diverse habitats and ecological niches. This basin length contributes to the overall water volume and sediment load entering the lake from the different regions while the intricate perimeter enhances the scenic beauty of the lake and provides various ecological zones.

Linear Parameters of Lake Nakuru Watershed		
Linear Parameter	**Unit**	**Measured Value**
Length of the Lake	Km	16.46
Width of the Lake	Km	10.58
Length of the Shoreline [2022]	Km	38.24
Length of the Shoreline [2023]	Km	40.78
Surface Area of the Lake [2022]	Km^2	64.98
Surface Area of the Lake [2023]	Km^2	69.45

According to Strahler (1964), stream order is a hierarchical ranking given to different segments of a river network based on their position within the overall drainage system. The order is determined by the number of tributaries flowing into a particular stream segment. Higher-order streams have more tributaries and represent larger channels. The stream order of Lake Nakuru can help identify its position within the overall river network. Higher-order streams indicate larger tributaries contributing to the lake's water supply, potentially impacting its hydrology and nutrient input.

Stream length refers to the distance measured along the centerline of a stream from its origin to the point where it enters Lake Nakuru. It provides information about the overall length and extent of the streams flowing into the lake, which is important for estimating water volume, sediment transport, and nutrient input (Horton, 1945). Longer stream lengths can indicate a larger and more interconnected watershed. The streams length of Lake Nakuru signifies the distance that water travels before entering the lake. Its longer stream length indicates a larger and more interconnected watershed, which can influence water volume, sediment transport, and nutrient load.

According to Strahler (1964), mean stream length is calculated by dividing the total stream length by the number of streams within the watershed. Stream number represents the total count of individual streams or tributaries flowing into the lake (Sreedevi et al., 2013). Higher stream numbers suggest a more intricate and branched drainage system, indicating potential variations in flow patterns, water sources, and ecological conditions within the lake. Lake Nakuru has a notable stream number, indicating a complex river network within its watershed. Higher stream numbers imply a dense and interconnected system of tributaries, contributing to the lake's water supply. The mean stream length provides an average measure of the length of streams flowing into Lake Nakuru for this study. This metric helps understand the typical length of the streams and their distribution pattern within the catchment area. The mean stream length of Lake Nakuru gives an average measure of the length of streams within its catchment area. This metric helps understand the typical length and distribution pattern of the streams, reflecting the overall drainage network.

The stream length ratio reveals the relative contribution of tributaries compared to the main river or primary stream flowing into Lake Nakuru. A higher stream length ratio suggests a substantial presence of smaller tributaries, affecting the hydrological dynamics and sediment transport patterns within the lake. On the other hand, the bifurcation ratio is the ratio between the number of higher-order streams (Nu) and the number of lower-order streams (Nu+1) within the river network (Schumn, 1956). A higher bifurcation ratio indicates a more dendritic and interconnected drainage system, which can influence the flow dynamics and distribution of water and sediment within Lake Nakuru. As a final linear aspect, the mean bifurcation ratio represents the average bifurcation ratio across the entire river network within the catchment area (Strahler, 1964). It provides a summary measure of the overall branching pattern and network structure. Comparing the mean bifurcation ratio with other river systems helps to identify unique characteristics or similarities in the branching patterns of Lake Nakuru.

In summary, Lake Nakuru has a relatively long basin length, suggesting a larger catchment area and influence from multiple water sources. Its basin perimeter is irregular and convoluted, contributing to a complex shoreline with diverse habitats. The lake exhibits a notable stream number and high bifurcation ratio, indicating a dense and interconnected river network. Longer stream lengths and a higher mean stream length reflect a larger and well-connected watershed. These characteristics suggest that Lake Mutanda receives significant water volume, sediment, and nutrients from its tributaries. Overall, the linear aspects highlight the hydrological connectivity and potential ecological importance of Lake Nakuru within its catchment area.

3.3. Areal Aspect of Lake Nakuru Watershed

The analysis of areal aspects provides valuable information about the shape characteristics, hydrological connectivity, and potential ecological dynamics within Lake Nakuru and its surrounding watershed. It can assist in understanding the water flow patterns, sediment transport, and overall functioning of the lake ecosystem. We begin by analyzing the drainage density. Drainage density refers to the total length of all streams within the watershed divided by the total area of the watershed. It indicates the overall density of the stream network in the area (Horton, 1932). Higher drainage density values suggest a more interconnected and dense drainage pattern, which can affect water flow and sediment transport in Lake Nakuru. The drainage texture of Lake Nakuru provides us insights into the heterogeneity and connectivity of the stream channels, which may influence water flow and nutrient distribution. This refers to the spatial arrangement and pattern of the stream network within its watershed Smith (1950). A fine-grained or intricate drainage texture suggests a higher density of smaller streams and channels, resulting in a more complex and interconnected network. This can contribute to enhanced water flow, sediment transport, and ecological diversity within the lake.

Stream frequency represents the number of streams that intersect a given unit area within the watershed. It provides information about the density of the stream network and the likelihood of surface water accumulation (Horton, 1945). A higher stream frequency indicates a denser and more interconnected stream network in the vicinity of Lake Nakuru. This can influence the overall hydrological characteristics of the lake, such as the volume and rate of water inflow, as well as sediment transport patterns. The elongation ratio measures the extent to which the lake's shape deviates from a perfect circle. A higher elongation ratio closer to 1 suggests a more elongated or irregular shape for Lake Nakuru. This influences factors such as shoreline development, ecological niches, and sediment deposition patterns within the lake. On the other hand, the circulatory ratio characterizes the degree of irregularity or tortuosity of the lake's shoreline. It provides information about the density of the stream network and the likelihood of surface water accumulation (Strahler, 1956). A higher circulatory ratio indicates a more convoluted or indented shoreline for Lake Nakuru. This higher circulatory ratio implies a more irregular shoreline, indicating potential variations in habitats and ecological niches within Lake Nakuru. According to Horton (1945), the form factor represents the compactness or roundness of the lake's shape. It is calculated as the ratio of the lake's surface area to the square of its perimeter. A form factor closer to 1 suggests a more circular shape, while values further from 1 indicate a more irregular shape. A higher form factor indicates a more circular shape, while lower values suggest a more elongated or irregular shape. The form factor influences factors such as lake mixing, sedimentation rates, and the potential for wave action within the lake.

The infiltration number relates to the soil permeability and the capacity of the watershed to absorb and retain water. It is calculated as the ratio of the total area of the watershed to the perimeter squared (Faniran, 1968). A higher infiltration number suggests that the Lake Nakuru watershed has a greater potential for water infiltration, which can impact groundwater recharge, baseflow, and overall hydrological processes.

The compactness coefficient measures the compactness or dispersion of the lake's shape. It is calculated by dividing the area of the lake by the area of a circle with the same perimeter. A higher compactness coefficient indicates a more compact shape, while a lower value suggests a more irregular shape for Lake Nakuru. This coefficient influences factors such as shoreline development, the distribution of littoral zones, and the potential for wave energy dissipation. The length of overland flow on the other hand refers to the total length of land surface over which water flows before reaching the lake (Horton, 1945). A longer length of overland flow for Lake Nakuru indicates increased potential for sediment transport, nutrient runoff, and surface water interactions within the watershed. It provides insights into the pathways and potential sources of water and sediment entering the lake. Lake Nakuru exhibits a dense and interconnected stream network, as indicated by its high drainage density and stream frequency. The irregular shape of the lake, reflected in its elongation ratio and circulatory ratio, contributes to a varied shoreline and potential for diverse habitats. The compactness coefficient suggests a relatively compact shape for the lake. The infiltration number indicates a good capacity for water absorption and groundwater recharge in the Lake Nakuru watershed. The length of overland flow helps us understand the path water takes before reaching the lake and its potential for sediment transport. Overall, Lake Nakuru's areal aspects highlight its hydrological connectivity, shape characteristics, and potential for habitat diversity.

4. DISCUSSION

This section presents an analysis of the modeling of soil erosion risk. The analysis focuses on the results obtained from the application of morphometric analysis, highlighting the implications for soil erosion management and the understanding of landscape dynamics in Lake Nakuru, Rift-valley Kenya. This analysis provides us valuable insights into the characteristics and properties of landforms, aiding in the assessment of erosion vulnerability in the Lake Nakuru region. By analyzing various morphometric parameters such as slope, aspect, drainage density, drainage aspect, basin length, basin parameter, stream length ratio, drainage texture, etc., we gain a comprehensive understanding of the terrain's susceptibility to erosion processes. The results of the morphometric analysis in Lake Nakuru reveal significant variations in these parameters, indicating areas of higher and lower erosion risk. The analysis of morphometric parameters revealed significant variations in slope, aspect, drainage density, and stream order across Lake Nakuru. These findings indicate variations in the terrain's susceptibility to erosion processes. Steeper slopes were identified as potential erosion hotspots, as they are more prone to surface runoff and soil erosion. The aspect of the landforms also plays a role, with south-facing slopes generally exhibiting higher erosion risk due to increased exposure to solar radiation and potential drying of the soil. The identification of contributing factors to soil erosion in Lake Nakuru is an essential outcome of the analysis. The results indicated that intensive agriculture, deforestation, and inadequate soil conservation practices were major contributors to erosion risk in specific areas. Such information is vital for formulating sustainable land management practices and implementing measures to mitigate erosion. Effective land use planning, reforestation initiatives, and the promotion of sustainable farming techniques can help reduce erosion risks and preserve the soil resources of Lake Nakuru. The geospatial approach complements the morphometric analysis by integrating spatial data and advanced mapping techniques to assess soil erosion risk across the study area. Geospatial analysis allows for the identification and delineation of erosion-prone areas based on factors such as land cover, land use, proximity to water bodies, and slope gradients. The geospatial analysis, incorporating land cover, land use, proximity to water bodies, and slope gradients, further enhanced the understanding of soil erosion risk. The generated soil erosion risk map identified areas with varying degrees of erosion susceptibility. High-risk zones were concentrated in areas with steep slopes, sparse vegetation cover, and close proximity to water bodies. These findings are crucial for prioritizing erosion control measures and implementing targeted land management strategies to mitigate erosion risks in Lake Nakuru.

Furthermore, the analysis enables the identification of potential contributing factors to soil erosion in Lake Nakuru. The morphometric analysis and geospatial approach reveal the influence of topography, land use practices, and natural features on erosion patterns. Steeper slopes, intensive agriculture or deforestation activities, and inadequate soil conservation practices are identified as significant contributors to erosion risk in specific areas. This information is crucial for designing targeted interventions and land management strategies to mitigate soil erosion and promote sustainable land use practices.

5. CONCLUSIONS

The results of the modeling of soil erosion risk using morphometric analysis and a geospatial approach provide valuable insights into erosion vulnerability and landscape dynamics in Lake Nakuru, Rift Valley Kenya. The findings contribute to the development of targeted erosion control strategies and sustainable land management practices. By understanding the spatial distribution of erosion-prone areas and identifying contributing factors, policymakers and land managers can take proactive measures to mitigate erosion risks, preserve soil resources, and promote sustainable development in the region. The findings of this study have significant implications for soil erosion management and conservation in the study area. By incorporating morphometric analysis and geospatial techniques, decision-makers and land managers can develop targeted interventions to protect erosion-prone areas and promote sustainable land use practices. This includes implementing erosion control measures such as terracing, contour plowing, and reforestation in high-risk zones. Additionally, raising awareness among local communities about the importance of sustainable land management practices and providing training on erosion control techniques can contribute to long-term soil conservation efforts.

It is important to acknowledge certain limitations of the study. The analysis relied on available data and assumptions related to parameters such as soil characteristics and erosion processes. Further research and field validation are needed to refine the models and improve the accuracy of erosion risk assessments. Additionally, the study focused on Lake Nakuru and its immediate surroundings, and the findings may not be directly applicable to other regions. Local contextual factors should be considered when implementing erosion control measures in different areas.

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