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A Synergistic Approach to Soil Erosion Management: Geospatial Morphometric Analysis Coupled with Soil Erosion Modelling

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ABSTRACT: Soil erosion is a persistent environmental challenge, particularly in agricultural and hilly regions, where it contributes to land degradation, reduces soil productivity and enhances sedimentation in water bodies. In contemporary research, geoinformatics technologies such as Geographic Information Systems (GIS) and Remote Sensing (RS) are extensively utilized, both nationally and globally, for morphometric analysis and soil erosion modelling within watershed management. Key factors influencing soil loss includes slope, drainage density, relief and land use land cover. Integrating morphometric parameters with soil erosion models enhances the accuracy of identifying vulnerable areas and assists in the prioritization of sub-watersheds for conservation interventions. Erosion rates can range from less than 1 to more than 1000 tons/ha/year, depending on topography and land-use practices. This study underscores the effectiveness of using GIS-based modelling and morphometric analysis as a cost-efficient, scalable and reliable approach to support soil conservation planning, promote sustainable watershed development and resource management.

Keywords: Geoinformatics, Morphometric analysis, Soil conservation, Soil erosion models, Watershed management.

INTRODUCTION

Soil erosion and land degradation have become some of the most pressing environmental challenges of the 21st century, particularly in regions where agriculture forms the backbone of local economies (Gammoudi *et al*., 2025; Tully *et al.*, 2015). These issues are especially severe in hilly and mountainous areas, where steep slopes, fragile soil structures and intense rainfall contribute to rapid loss of topsoil (Lawmchullova & Lalrinkimi 2024). Globally, erosion not only threatens soil fertility and crop productivity, but also degrades water quality, reduces reservoir capacity and diminishes biodiversity (Pandey *et al.*, 2009). It is estimated that more than 75 billion tons of soil are lost annually from agricultural lands worldwide, severely impacting food security and the health of terrestrial ecosystems. Soil degradation results in reduced agricultural outputs, land abandonment and rising vulnerability to climate change and extreme weather events (Teku & Workie 2025).

Soil erosion is primarily influenced by both natural and anthropogenic factors (Othman *et al*., 2023). Natural factors include rainfall intensity, soil texture, topography, slope length and gradient, while human-induced causes encompass deforestation, overgrazing, shifting cultivation, unregulated construction and improper land management practices. Regions in Asia, Africa and South America report the highest erosion rates, with annual soil loss estimated between 30 to 40 tons per hectare, resulting in extensive land degradation and significant economic setbacks (Pandey *et al.*, 2009; Ananda & Herath 2003). Particularly concerning is the loss of topsoil, the uppermost and most biologically active layer, which contains essential nutrients and organic matter critical for plant growth and ecosystem health. Over the past 150 years, nearly 50% of the world's topsoil has been degraded (Chandra Pal & Chakrabortty 2018), with water-induced erosion recognized as one of the leading contributors.

Kamat and Priyanka Raj (2017) focuses on detailing out how erosion can act as an underlying cause of other primary disasters, and that planners should take these into account in any disaster management planning.

To accurately evaluate, predict and manage soil erosion, various models have been developed over time. Among them, the Revised Universal Soil Loss Equation (RUSLE) has gained global prominence due to its relative simplicity, adaptability to diverse conditions and minimal data requirements (Al-hasn *et al.,* 2024; Richi, 2025). RUSLE is a widely used empirical model designed to estimate long-term average annual soil loss based on multiple interacting factors. The standard RUSLE formula is:

$$A = R \times K \times LS \times C \times P$$

Each parameter in the RUSLE model reflects a key physical or land management component influencing erosion. Rainfall erosivity (R) captures the impact of raindrop energy and runoff. Soil erodibility (K) reflects soil susceptibility to detachment and transport. The topographic factor (LS) accounts for slope length and gradient, while the cover management (C) and support practice (P) factors represent the protective role of vegetation and conservation measures like contour farming, respectively (Richi, 2025). Together, these variables allow researchers and planners to model soil loss risk under different environmental and land-use scenarios.

The integration of soil erosion models with Geographic Information Systems (GIS) and Remote Sensing (RS) technologies has significantly advanced the accuracy, efficiency and scalability of soil erosion assessments (Ahmed *et al.*, 2025). GIS enables spatial analysis and mapping of erosion-prone zones across large and complex terrains, while RS provides up-to-date, high-resolution data on land cover, vegetation, slope and hydrology. By overlaying thematic layers-such as digital elevation models (DEMs), rainfall distribution, soil types and land use maps-GIS-based RUSLE modelling allows for precise identification of erosion hotspots and the prioritization of sub-watersheds for conservation planning (Nawaiseh, 2020). Globally, studies report that up to 80% of total eroded soil, or nearly 20 billion tons annually, eventually reaches oceans and water bodies, contributing to sedimentation and loss of reservoir capacity, while also affecting soil physical and chemical characteristics (Alsaihani & Alharbi 2024).

Parallel to erosion modelling, morphometric analysis has emerged as a crucial tool for understanding watershed behaviour, especially in ungauged or data-scarce basins (Ghodke *et al.*, 2025). Morphometry refers to the quantitative assessment of the shape, size, drainage pattern and relief characteristics of a watershed (Mehwish *et al.*, 2024; Thakural *et al.*, 2025; Varma *et al.*, 2020). Parameters such as drainage density, stream frequency, bifurcation ratio, elongation ratio, circularity ratio, relief ratio are derived from DEMs and satellite imagery to describe the structural and functional aspects of a drainage basin. These parameters help estimate runoff generation, peak flow characteristics and erosion potential of the watershed (Teku & Workie 2025).

The use of geospatial techniques for morphometric analysis allows for the rapid and accurate delineation of watershed boundaries, stream networks and slope gradients, which are essential for hydrological modelling and conservation planning (Thakural *et al.*, 2025; Panika *et al.*, 2023). For instance, high drainage density and steep relief are often associated with higher runoff potential and greater soil erosion risk, while elongated or irregularly shaped basins may indicate longer flow paths and delayed peak discharge. Therefore, morphometric characterization not only provides insight into geomorphic processes but also supports sub-watershed prioritization, allowing decision-makers to focus interventions in the most erosion-prone areas (Mathewos *et al.*, 2024).

When combined, RUSLE modelling and morphometric analysis offer a comprehensive framework for soil erosion risk assessment (Mohammed *et al.*, 2025). This integrated approach enables stakeholders-such as planners, researchers and conservationists-to visualize soil loss patterns, evaluate landscape vulnerability and implement targeted land management practices such as contour farming, terracing, vegetative barriers and watershed treatments. In tropical and subtropical countries, where data availability is often limited and terrain complexity is high, the integration of these geospatial methods provides a cost-effective, scalable and reliable solution for sustainable land resource planning (Sohal & Kaushal 2023).

This paper explores the scientific principles, global applications and methodological advancements of soil erosion models and morphometric analysis using GIS and remote sensing for effective soil erosion modelling and sustainable natural resource management.

Morphometric analysis of watersheds through geospatial technology

Mishra and Nagarajan (2010) conducted a morphometric analysis of a Tel River basin watershed in Odisha using RS and GIS, covering 1515.45 km². Twelve sub-watersheds (SWS-1 to SWS-12) ranged from 30 to 202 km² in area. Drainage density varied between 1.09 and 3.36 km/km², while elongation ratios (0.6-0.8) indicated steep slopes. Circularity ratios (0.34-0.80) reflected varying topographic maturity, with SWS-11 showing the highest value. Erosion susceptibility was ranked using compound parameters, where SWS-1 had the highest priority due to its lowest score (4). The study helped identify erosion-prone zones for conservation planning.

Pal *et al.* (2012) analysed morphometric parameters of the Watut watershed (5410.74 km²) in Papua New Guinea using topographic maps, Landsat ETM+ imagery and GIS techniques. Key parameters included absolute and relative relief, dissection index, average slope, drainage density and ruggedness index. The watershed had a drainage density of 0.5 km/km², indicating moderate to low drainage. The average slope was 31%, reflecting moderately steep terrain. These characteristics influence runoff and erosion. The study emphasized the role of morphometric analysis in understanding watershed hydrology and erosion potential.

Romshoo *et al.* (2012) assessed morphometric parameters of five watersheds (W1-W5) in the upper Indus basin using DEM and geospatial tools. Parameters included drainage density, bifurcation ratio, stream frequency, elongation ratio and infiltration number. W5 had the highest drainage density (4.50 km/km²) and stream frequency (19.74 km^{-2}), indicating high runoff and low infiltration. Its bifurcation ratio (5.89) and basin relief (887 m) further suggested flash flood susceptibility. SWAT simulations showed highest runoff in W5 (11.17 mm/year). The study highlighted W5 as the most hydrologically active and vulnerable watershed.

Rai *et al.* (2017) analysed morphometric parameters of the Narmada basin (98,796 km²) using ASTER DEM and GIS to evaluate drainage and hydrological characteristics. The bifurcation ratio (2-9) suggested structural control, while drainage density (0.81 km/km²) reflected moderate infiltration. Basin relief was 1321 m with a relief ratio of 0.53, indicating steep terrain and high runoff. An elongation ratio of 0.14 and circularity ratio of 0.084 indicated an elongated basin with delayed peak flow. Sinuosity index (1.58) confirmed a meandering river pattern. The study showed notable hydrological differences between upper and lower sub-basins.

Prasad *et al.* (2020) carried out a morphometric analysis of the Dada watershed (1491.1 ha) in the lower Shivalik's of Punjab using 12.5 m ALOS PALSAR DEM. The watershed exhibited a 5th order drainage system with 377 streams and a total length of 71.98 km. Drainage density was 4.83 km/km², indicating high surface runoff. The mean bifurcation ratio (4.97) reflected moderate structural influence. A circulatory ratio of 0.22 and elongation ratio of 0.586 suggested an elongated basin with moderate runoff potential. The study provided insights into watershed behaviour and erosion susceptibility.

Singh *et al.* (2021) analysed the Dudhnai watershed (483.76 km²) in Assam using SRTM DEM and an ArcGIS-based morphometric toolbox. The 6th order basin had a total stream length of 1327.6 km and an average bifurcation ratio of 4.75, indicating a well-dissected drainage network with low flood risk. Drainage density was 2.76 km/km² and a ruggedness number of 1.77 pointed to high erosion susceptibility. The infiltration number (15.92) suggested low infiltration and high runoff potential. Overland flow averaged 0.18 km, indicating dominant channel erosion. Chil sub-watershed was most erosion-prone, followed by Manda and Sarangma.

Haokip *et al.* (2022) analysed eight sub-watersheds (SW-1 to SW-8) in the Teesta river basin, Sikkim, using morphometric parameters and Sentinel-2A based LULC data. The 6th order river system had drainage density ranging from 0.43 to 0.68 km/km², with SW-4 showing the highest value, indicating greater erosion risk. Elongation (0.58-0.64) and circularity ratios (0.35-0.68) suggested elongated shapes with varying runoff potential. Relief reached 4558 m, with total relief of 2008 m. SW-4 and SW-5 had the highest erosion susceptibility (Cp = 3.39 and 4.00). LULC showed dense forests (31.73%), sparse forests (31.15%) and barren land (12.08%), with SW-4 and SW-5 most erosion-prone.

Panika *et al.* (2023) carried out morphometric analysis of Mawai watershed in Madhya Pradesh, India, using GIS and remote sensing techniques. The watershed, covering 512.67 km², was delineated from DEM data and analyzed for linear, areal and relief aspects. Results showed the basin as 6th order with a dendritic drainage pattern. The bifurcation ratio averaged 3.89, indicating limited structural control, while the drainage density (2.53 km/km²) suggested moderate permeability and runoff potential. Form factor (0.39), elongation ratio (0.70) and circulatory ratio (0.47) indicated an elongated basin shape with lower flood susceptibility. Relief ratio (0.023) and relative relief (2.27%) reflected moderate relief characteristics. Overall, the morphometric indices highlighted moderate runoff, elongated basin geometry and the need for soil and water conservation measures to manage erosion and sustain groundwater recharge.

Kumar *et al.* (2024) analysed the Barakar river basin using 12.5 m ALOS PALSAR DEM and ArcGIS Pro 3.0.1 to derive morphometric parameters like slope, relief, drainage density and stream order. The basin reached a maximum stream order of 5, indicating a well-integrated drainage system. A hypsometric integral (HI) of 0.50 reflected a mature geomorphic stage with balanced erosion and uplift. Shape and elongation ratios pointed to moderate erosion susceptibility. Morphometric indices identified zones vulnerable to sediment transport and flooding. The study aids in understanding hydrological behaviour and risk management.

Mani *et al.* (2024) conducted a morphometric analysis of the Nayar watershed (1956.33 km²) using DEM data, multispectral imagery and SOI toposheets for sustainable watershed management. Elevations ranged from 428 m to 3102 m and the drainage pattern was parallel to dendritic with 1426 streams. The mean bifurcation ratio of 4.05 indicated moderate structural control. LULC analysis (2008-2019) showed 57.60 km² of agricultural land and 57.15 km² of forest converted to wasteland, increasing erosion and landslide risk. An additional 110.03 km² of forest turned into agriculture, raising deforestation and biodiversity concerns.

Role of land use and land cover dynamics in soil erosion

Alkharabsheh *et al.* (2013) analysed the impact of land use/land cover changes on soil erosion in Northern Jordan's agricultural zones from 1992 to 2009. Using meteorological data, soil surveys, topographic maps, Landsat images and literature, soil erosion maps were generated. Soil loss slightly declined from 9.53 t/ha in 1992 to 8.97 t/ha in 2009. Overlay analysis revealed that converting rainfed cropland to rangeland significantly reduced erosion. The study emphasized how land cover change influences erosion rates. It highlighted the need for sustainable land management to protect fragile ecosystems.

Mallupattu and Reddy (2013) studied land use/land cover changes in Tirupati, India, from 1976 to 2003 using SOI toposheet 57O/6 and IRS-1D LISS III and PAN satellite imagery. The region was classified into eight LULC categories. Built-up area increased significantly from 5.91 km² to 18.34 km² due to rapid urbanization, while agricultural land decreased from 68.23 km² to 21.45 km². Dense forest declined sharply (22.35 km² to 4.25 km²) and plantation areas grew from 0.79 km² to 21.80 km². Open forest and mining areas emerged by 2003 and water spread areas reduced from 12.09 km² to 9.91 km² due to encroachment.

Aboelnour and Engel (2018) examined land use and land cover (LULC) changes and their effect on land surface temperature (LST) in Egypt's Greater Cairo region from 1990 to 2016 using Landsat 5 TM and Landsat 8 OLI imagery. LULC classifications showed high accuracy (over 90%), with urban areas expanding by 128%, replacing 55,491 ha of barren land and 17,665 ha of vegetation. This urban growth led to a steady increase in LST, with mean values rising from 38.4°C (1990) to 42.1°C (2016). Urban areas alone saw a 4.91°C temperature rise due to vegetation loss and increased impervious surfaces.

Chowdhury *et al.* (2020) analysed land use/land cover changes in the Halda watershed, Bangladesh, from 1978 to 2017 using Landsat imagery and GIS techniques. The watershed was classified into five categories: settlements, water bodies, vegetation, agricultural land and bare soil. Vegetation cover declined significantly from 64.62% to 41.93%, while agricultural land increased from 22.93% to 42.03%. Water bodies reduced sharply by 85.47% and settlement areas expanded by 182.49%, replacing vegetation and farmland. Supervised classification was applied with an accuracy of 89.22%, ensuring the study's reliability. The results highlight rapid urbanization and ecological degradation.

Tewabe and Fentahun (2020) analysed land use/land cover changes in Ethiopia's Lake Tana basin from 1986 to 2018 using Landsat TM data, ENVI and ArcGIS. Six land cover types were classified, showing major expansion in agricultural land (37.6% to 50.5%, +1,954 km²) and residential areas (4.6% to 13.7%, +1,370 km²). In contrast, bushland and grassland declined by 9.8% and 10%, while forest cover reduced from 5.9% to 3.6%. Classification accuracies ranged from 84.21% to 90.36%, with high kappa values. The study highlighted agricultural growth and urbanization as key drivers affecting the basin's ecosystem and hydrology.

Digra and Kaushal (2021) analysed land use/land cover (LULC) changes to understand spatial and temporal landscape variations using multi-spectral satellite imagery and techniques like supervised/unsupervised classification, NDVI and Google Earth Engine. Supervised classification was found most effective for accurate LULC mapping. In Jahlma watershed (1991–2001), agricultural land increased while grassland decreased. In Kodaikanal (1969–2008), forest cover dropped from 70% to 33%, with built-up land rising from 3% to 21%. In Rupnagar (1989–2006), cropland, forest and water bodies declined, while settlements expanded by 93.5 km².

Abebe *et al.* (2022) analysed land use/land cover (LULC) changes in Gubalafto district, Northeastern Ethiopia, over a 30-year period (1986–2016) using Landsat imagery. Five LULC types were identified: cultivated and settlement, forest cover, grazing land, bush land and bare land. Cultivated and settlement areas rose from 45.6% to 49.5%, while forest cover declined sharply from 8.9% to 2%. Grazing land dropped from 11.1% to 5.7%, whereas bush land and bare land increased, indicating land degradation. The classification showed an overall accuracy of 86.96% with a kappa coefficient of 0.754.

Guder and Kabeta (2025) assessed LULC changes in Ethiopia's Holota watershed from 2000 to 2020 using Landsat imagery and projected future changes to 2050 with the CA-Markov model. Five LULC types were analysed: forest, cropland, built-up areas, shrubland and grassland. Results showed increasing soil erosion rates, from 13.3 t/ha/year (2020) to 15.9 t/ha/year (2050), with peak rates rising to 6,626.3 t/ha/year. Built-up areas and cropland contributed most to erosion, while forest and shrubland reduced it. Built-up land is projected to rise from 12% to 20%, generating 38.7 t/ha/year erosion, whereas forests showed the lowest rate (1.2 t/ha/year).

Roba *et al.* (2025) examined land use/land cover changes and their impact on soil erosion in Ethiopia's Dumuga watershed from 1993 to 2023 using Landsat imagery. The study incorporated key erosion factors such as rainfall erosivity, soil erodibility, slope, cover management and conservation practices. Cultivated land increased significantly from 62.3% (915.3 km²) to 77.0% (1,132.0 km²), while forest cover declined from 13.3% (196.0 km²) to 3.8% (56.2 km²). These changes intensified soil erosion and sediment yield, highlighting the environmental impact of agricultural expansion and forest loss.

Tahir *et al.* (2025) analysed land use/land cover changes in Lahore, Pakistan (1994–2024) and projected trends for 2034 and 2044 using Landsat imagery, supervised classification and the CA-Markov model. Classification accuracy exceeded 90% with a kappa coefficient of 0.92. Results showed major urban expansion, with built-up areas increasing by 359.8 km², while vegetation and barren land declined by 198.7 km² and 158.5 km², respectively. Projections indicated built-up land will rise to 61.6% by 2044, while vegetation and barren land will decrease to 37.0% and 0.41%. Water bodies remained largely unchanged throughout the period.

Soil erosion models

Raclot and Albergel (2006) evaluated soil erosion in Tunisia's Kamech catchment (245 ha) using the WEPP model over a 7-year period (1995–2002). The area, with 70% cereal crops and 30% rangeland, received an average annual rainfall of 600 mm and 11 runoff events per year. WEPP simulations showed runoff overestimation by +10% and underestimation by -3% under different scenarios. Sediment yield predictions varied widely, with errors from -64% to +279%, though the best estimate was 32,963 m³ (–10%). Peak discharge prediction showed low reliability, with NSE values below 0.51, indicating limited model accuracy.

Baigorria and Romero (2007) assessed soil erosion hotspots in the La Encañada watershed, Peruvian Andes, using the WEPP model integrated with GIS through the GEMSE tool. The 6,000 ha watershed had elevations from 2,950 to 4,000 m and slopes up to 65%. Rainfall data (717.3–801.0 mm/year) and maximum intensity (147 mm/h) were used for simulations. Results showed 80% of the area had runoff below 5 mm/year, 15% had 5–20 mm and 5% exceeded 20 mm. Soil loss was under 10 Mg/ha/year in 58% of the area, but over 150 Mg/ha/year in 10%, particularly in steep regions with slopes above 40°.

Zhang *et al.* (2009) evaluated soil erosion risk in Black Hawk County, Iowa, using ArcMUSLE, an ArcGIS-based tool integrating the Modified Universal Soil Loss Equation (MUSLE). The 24.2 km² watershed was 93% agricultural, dominated by hay and corn/bean crops. A

2-year, 24-hour rainfall event (80.3 mm) generated 765,370 m^3 runoff and a peak discharge of 3.62 m^3/s. Sediment yield was estimated at 6,669 tons. High erosion occurred in areas with LS-factor > 3.14 and curve numbers between 30–92. Steep slopes and sparse vegetation contributed most to sediment delivery.

Tibebe and Bewket (2011) assessed soil erosion in Ethiopia's Keleta watershed (1,060.4 km^2) using the SWAT model, with elevations ranging from 1,320 to 4,180 m and slopes over 25%. Model calibration (1990–2000) achieved an NSE of 0.789 and R = 0.831. The long-term average annual soil loss was 4.3 t/ha/year, with 80% of the area facing low to moderate erosion (<8 t/ha/year). However, 1.2% experienced severe erosion (>12 t/ha/year), especially on steep cultivated lands with Eutric Cambisol and Chromic Vertisol soils. Six sub-watersheds were prioritized for conservation measures like terracing, reforestation and contour bunding.

Demirci and Karaburun (2012) assessed soil erosion risk in the Buyukcekmece lake watershed, Istanbul, using the RUSLE model integrated with GIS (ArcGIS 9.3). RUSLE factors were derived from meteorological, soil, topographic and satellite data. Erosion rates were categorized into five classes: low (<1 t/ha/year), slight (1–3), moderate (3–5), high (5–10) and severe (>10). Results showed 54% of the area had low erosion risk, 19% slight, 11% high and 5% severe, highlighting the need for targeted soil conservation measures.

Ganasri and Ramesh (2016) assessed soil erosion in the 3,128 km^2 Nethravathi basin, Western Ghats, India, using the RUSLE model integrated with GIS and remote sensing data (LISS-3 and Carto DEM). Key RUSLE factors were calculated, estimating an annual potential soil loss of 473,339 t/year. The results closely matched measured sediment yield, with agricultural expansion contributing an additional 14,673.5 t/year. A probability zone map showed that most of the basin falls under low erosion risk, while only a small area faces high erosion susceptibility.

Roslee *et al.* (2017) evaluated soil erosion risk in Sandakan, Sabah, Malaysia using the MUSLE model integrated with GIS and ARC-INFO software. Soil erosion was categorized into five risk levels based on thematic data layers. Results showed that 46.33% of the area had very low erosion risk, 43.50% low, 5.23% moderate and 4.94% high, with no area in the very high-risk class. Erosion-prone zones were mainly on steep slopes (>36.96°) and uplands. Rainfall erosivity was estimated using Thiessen polygon interpolation with data from multiple rain gauges.

Pham *et al.* (2018) evaluated soil erosion in the Sap river basin, Central Vietnam, using the USLE model integrated with GIS. Results showed that 34% of the area experienced high erosion rates (>10 t/ha/year), while 47% had low rates (<1 t/ha/year). Natural forest areas were most affected, with erosion reaching 19 t/ha/year. Topographic factors were the dominant cause, followed by support practices, soil erodibility, crop management and rainfall erosivity. The study recommended intercropping and planting broadleaf trees to mitigate erosion.

Tesfaye *et al.* (2018) used a GIS-based USLE model to estimate soil erosion and prioritize nine sub-watersheds in the Somodo watershed, southwestern Ethiopia. Soil loss was calculated using a 30 m × 30 m grid in ArcGIS, yielding a mean annual rate of 18.69 t/ha/year. Over 75% of the area exceeded 20 t/ha/year, surpassing the tolerable threshold of 11 t/ha/year. Sub-watersheds SW-4, SW-6 and SW-7 had slight erosion; SW-2, SW-3 and SW-8 had moderate levels. SW-1 showed high erosion, while SW-5 and SW-9 exhibited very high severity (>30 t/ha/year), highlighting urgent conservation needs.

Atoma *et al.* (2020) evaluated soil erosion in the Huluka watershed, central Ethiopia, using the RUSLE model integrated with GIS, based on Landsat 5 TM and Sentinel imagery from 1998 to 2018. The study revealed a maximum soil loss rate of 400 t/ha/year. Severe erosion impacted 6% (1,115 ha) of the area, high to very high erosion risk covered 21% (4,032 ha) and low to moderate risk spanned 73% (13,424 ha). Critical sub-watersheds with average soil loss between 14.4 and 27 t/ha/year were identified and prioritized for conservation efforts.

Nawaiseh (2020) applied the RUSLE model integrated with GIS and remote sensing to estimate soil loss and prioritize sub-watersheds in Wadi Ziqlab, Northern Jordan. Using DEM, LANDSAT imagery, soil survey data and rainfall records, five erosion risk classes were mapped. Results showed that soil loss ranged from 0.0 to 1707 tons ha^{-1} $year^{-1}$, with an average of 46.76 tons ha^{-1} $year^{-1}$. Approximately 60% of the watershed area was classified under high to extremely high erosion risk, mainly in the middle and upper catchments. Sub-watershed prioritization indicated that five sub-basins (10, 15, 16, 25 and 27) fall under very high priority, requiring immediate conservation. Recommended measures include terracing, afforestation with drought-resistant species, rangeland management and rehabilitation of old soil conservation structures.

Karakoyun and Kaya (2022) assessed soil erosion in the Murat river basin, Turkey (17,865 km^2), using the SWAT model calibrated and validated with data from two gauging stations. Elevations ranged from 1,239 to 4,033 m, with an average slope of 12.6%. NSE values for streamflow calibration were 0.57 and 0.77 and 0.50 and 0.75 for validation. Sediment yield NSEs were 0.54 and 0.69 for calibration and 0.62 and 0.35 for validation. Spatial analysis showed 3.9% of the basin faced very severe erosion (>20 t/ha/year) and 21.3% had severe erosion (>10 t/ha/year), mainly in barren lands and steep sub-watersheds. Sub-watersheds 74 and 76 had the highest sediment yields (32.57 and 24.62 t/ha/year).

Yousuf *et al.* (2022) evaluated soil erosion and sediment yield in the Takarla dam watershed, Kandi region, Punjab, India, using the RUSLE model integrated with GIS and sediment delivery ratio (SDR). A 12.5 m resolution DEM, meteorological data (2010–2020) and field-based soil sampling were used to calculate RUSLE factors. The study reported an average annual soil loss of 12.79 t/ha/year, with a total erosion of 248,872 tonnes over 20 years, of which 142,604 tonnes were deposited in the dam, indicating significant sedimentation. These results are critical for erosion mitigation and sustainable reservoir management.

Sharma *et al.* (2023) assessed soil erosion in the Sutlej river basin, Indian Punjab, using the RUSLE model integrated with remote sensing and GIS. The study utilized IMD rainfall grids, FAO soil maps, ALOS PALSAR DEM and LULC data to derive key RUSLE factors. Results showed average annual soil loss ranging from 1.26 to 25 t/ha/year, with a total estimated loss of 2,441,639 tonnes. While 94.4% of the basin experienced very slight erosion, 0.11% faced very severe erosion, predominantly in the Shivalik foothills.

Sharma *et al.* (2023) applied the SWAT model to evaluate water balance components in the lower Sutlej sub-basin (8,620.40 km²), India. The model was calibrated for 2011–2016 and validated for 2017–2021, showing strong agreement between observed and simulated discharge with $R^2 = 0.76$ and NSE = 0.76 for calibration and $R^2 = 0.75$ and NSE = 0.67 for validation. During calibration, surface runoff, lateral flow, base flow and evapotranspiration contributed 31.52%, 7.1%, 9.40% and 50.22% of annual rainfall, respectively. In the validation period, these components accounted for 30.48%, 6.55%, 7.73% and 49.98%. Average annual water yield was 469.31 mm (48.41%) during calibration and 420.71 mm (46.39%) during validation.

Geospatial technologies in soil erosion mapping and monitoring

King *et al*. (2005) demonstrated the significance of geoinformatics for hydrological and erosion studies in the Haute Normandie watershed, France. The study integrated optical remote sensing data from SPOT, Landsat TM, ASTER, Ikonos and QuickBird to classify bare soils, vegetated areas and land-use changes influencing runoff generation. Additionally, Radarsat radar imagery was used to estimate surface roughness. By incorporating these remote sensing-derived soil surface characteristics into deterministic storm runoff models, the study improved runoff and sediment transport predictions. Ground validation confirmed that remote sensing enhances erosion risk assessment through spatially and temporally detailed soil surface information.

Pandey *et al.* (2011) applied geoinformatics to prioritize 26 sub-watersheds of the Ret watershed, India, for effective watershed management. Using ArcGIS, morphometric parameters such as bifurcation ratio, drainage density, stream frequency, form factor, circularity ratio, elongation ratio and drainage texture were calculated. Based on erosion susceptibility, sub-watersheds were ranked, identifying six sub-watersheds (66.5 km²) as very high priority and five (61.7 km²) as high priority. Additionally, 11 potential sites for check dams were identified by analysing stream order, slope, LULC and soil type. Sub-watersheds with drainage density >3 km/km² and stream frequency >6 streams/km² were found to be most erosion-prone.

Mhangara *et al*. (2012) applied geoinformatics-based soil erosion modelling in the Keiskamma catchment, South Africa, using the GIS-integrated Sediment Assessment Tool for Effective Erosion Control (SATEEC) with the Revised Universal Soil Loss Equation (RUSLE). The study incorporated spatially distributed Sediment Delivery Ratio (SDR) and GIS-derived parameters-R (rainfall erosivity), K (soil erodibility), LS (slope length and steepness), C (cover management) and P (support practice) factors. Results showed that 35% of the catchment faced high to extreme erosion (>25 t ha^{-1} $year^{-1}$), while 65% experienced low to moderate erosion (<25 t ha^{-1} $year^{-1}$). Object-oriented classification in GIS identified erosion hotspots, especially gully erosion and valley infill sedimentation areas, primarily attributed to overgrazing in ephemeral stream zones.

Gunawan *et al.* (2013) used geoinformatics to estimate soil loss in the Manjunto watershed, Bengkulu Province, Indonesia, by integrating NDVI from satellite imagery and slope data derived from DEM-SRTM. The study revealed a substantial increase in soil erosion, with average annual soil loss rising from 3.00 t ha^{-1} $year^{-1}$ in 2000 to 27.03 t ha^{-1} $year^{-1}$ in 2009. The most erosion-prone zones were soil mapping units 41, 42 and 47, classified under very heavy erosion. GIS-based spatial analysis showed that land use changes, especially deforestation and unsustainable agricultural practices, significantly contributed to the increase in soil erosion across the watershed.

Gaubi *et al.* (2017) demonstrated the application of geoinformatics in soil erosion modelling in the Lebna watershed, Cap Bon, Tunisia, by integrating the RUSLE model with GIS and remote sensing. The study employed SPOT5 imagery, DEM and thematic maps to derive RUSLE factors-R, K, LS, C and P. GIS-based analysis estimated an average soil loss of 24 t ha^{-1} $year^{-1}$, which closely matched bathymetric sedimentation rates of 29 t ha^{-1} $year^{-1}$ in the Lebna dam. High erosion risk was associated with steep slopes (>36°), marly-clay lithology and sparse vegetation. Simulations of conservation measures like contour benches and terracing suggested a reduction of 2.5 t ha^{-1} $year^{-1}$, underscoring geoinformatics' value in erosion control planning.

Suryawanshi and Chandramohan (2018) utilised geoinformatics and the USLE model to estimate soil erosion in the Vamanapuram river basin, Kerala, India. The study employed thematic layers such as slope, rainfall and land use derived from ASTER DEM with 30 m resolution, processed using ArcGIS tools to delineate erosion-prone zones. The observed average soil loss was 2.29 t/ha/season, while the predicted average was 3.29 t/ha/season. The results indicated that over 34% of the basin faced severe erosion risk, highlighting the susceptibility of critical zones to soil degradation and the need for effective conservation planning.

Aslam *et al.* (2021) applied geoinformatics-based multi-criteria decision analysis (MCDA) using GIS and the Analytical Hierarchy Process (AHP) to map soil erosion susceptibility in the Chitral district, Pakistan. Eleven factors including lithology, slope, elevation, curvature, land cover, aspect, rainfall, drainage density, NDVI and NDWI were weighted using AHP and integrated in GIS to produce a soil erosion susceptibility map. The study classified the region into five erosion risk categories, identifying 13% of the area as very high risk and 18% as high risk. Elevation, slope, rainfall and NDWI were found to be the most influential factors. Thematic maps revealed that areas with steep slopes (>40°), high rainfall (>600 mm) and bare lands exhibited the greatest erosion susceptibility.

Kolekar et al. (2021) used geoinformation techniques to identify suitable areas for water conservation measures in the districts of West Midnapur, Purulia and Bankura, West Bengal, India. The study employed Landsat 7 imagery, ASTER DEM (30 m resolution) and daily precipitation data from 2011 to generate thematic layers for land use/land cover (LULC), soil type, slope and drainage network. The Soil Conservation Service Curve Number (SCS-CN) method was used to estimate runoff potential and a Water Conservation Potential Index (WCPI) was developed using weighted overlay analysis in ArcGIS. The results identified 479 potential sites for percolation ponds, 1,884 for farm ponds, 1,400 for check dams, 808 for contour bunding and 140 for contour trenching. Areas with high runoff coefficients (>0.4) and steep slopes (>15%) were marked as erosion-prone, highlighting the need for targeted conservation measures.

Umar and Abdullahi (2021) applied geoinformatics techniques to evaluate erosion susceptibility and groundwater management in the river Amba watershed, Central Nigeria. The study integrated LANDSAT imagery, digital elevation models (DEM), geological mapping and rainfall intensity data to generate an erosion hazard map and assess groundwater flow patterns. Key factors contributing to erosion included elevation (31.49%), land use (21%), slope (14%), geology (12.52%), rainfall intensity (10.5%) and flow accumulation (10.5%). GIS-based analysis classified the watershed into five erosion risk zones: very high, high, moderate, low and very low, with the southwestern region identified as most susceptible. Groundwater levels ranged between 4.0 and 28.5 meters, with groundwater flow directed toward the Amba River and nearby springs, which serve as vital water sources for Lafia and neighboring areas.

Polovina *et al.* (2024) demonstrated the application of geoinformatics in soil erosion modelling by integrating remote sensing and GIS to enhance the Erosion Potential Model (EPM) in the Balkan Peninsula. The study employed Landsat 7 ETM+ and Landsat 8 OLI/TIRS imagery (2010-2020), processed via Google Earth Engine (GEE), to develop a novel erosion coefficient (φ) for identifying erosion processes. The use of Bare Soil Index (BSI) and fractional bare soil cover enabled precise delineation of erosion-prone zones. Model validation using 190 field samples yielded an overall accuracy of 85.79%, with user accuracy ranging from 33% to 100% and producer accuracy from 50% to 100%. Results showed that 35% of the study area was affected by surface erosion, with high-risk zones concentrated in steep, sparsely vegetated terrains.

Wang *et al.* (2024) studied the application of geoinformatics in soil erosion dynamics and mitigation strategies in China. The research integrated data from Landsat, Sentinel and UAV systems to analyse soil, vegetation, topography and land use using models such as the Revised Universal Soil Loss Equation (RUSLE) and the China Soil Loss Equation (CSLE). The study effectively identified erosion hotspots, predicted soil loss rates and assessed regional variations with high spatial accuracy. By leveraging high-resolution imagery and advanced modelling techniques, the study offered critical insights into soil erosion patterns and informed effective conservation strategies. The findings highlighted the pivotal role of geoinformatics in supporting sustainable land management and ecosystem protection.

CONCLUSIONS

This study concludes the crucial role of morphometric analysis and the soil erosion models in understanding watershed characteristics and soil erosion dynamics. These tools supported by remote sensing and GIS, provide effective means for assessing erosion risk and prioritizing conservation efforts. Integrating these approaches enhances sustainable watershed management and informs better planning for soil and water conservation strategies. Studies across diverse regions consistently demonstrate that parameters like slope, drainage density and land use significantly influence erosion potential. The synergy of morphometric indicators with empirical models improves prediction accuracy and spatial prioritization. Remote sensing data ensures updated and large-scale analysis, reducing the need for extensive fieldwork. As land degradation intensifies due to climate change and human pressure, these techniques offer cost-effective and scalable solutions.

FUTURE SCOPE

The promising hybrids identified in this study can be exploited commercially to increase silk quality and quantity with increase in production of cocoon.

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Conflict of Interest. None.

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