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Soil Erosion Assessment on Hill Slopes of Jammu–Srinagar National Highway (NH-44) Using RUSLE Model

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Abstract

Soil erosion represents a critical environmental and geotechnical challenge in mountainous regions, particularly along transportation corridors such as the Jammu–Srinagar National Highway (NH-44), which traverses the fragile and tectonically active Himalayan terrain. The combined influence of steep slopes, intense monsoonal rainfall, weak geological formations, and anthropogenic disturbances significantly accelerates erosion and slope instability processes. This study presents a comprehensive assessment of soil erosion along NH-44 using the Revised Universal Soil Loss Equation (RUSLE) integrated with Geographic Information System (GIS), remote sensing, and hydrological modelling. The analysis incorporates key RUSLE parameters, including rainfall erosivity (R), soil erodibility (K), topographic factor (LS), cover management (C), and support practice (P), derived from spatial datasets such as Digital Elevation Models (DEM), land use/land cover (LULC), soil maps, and rainfall records. Runoff estimation was carried out using the Soil Conservation Service Curve Number (SCS-CN) method to evaluate the hydrological contribution to soil erosion. Additionally, geotechnical investigations were conducted to characterise colluvial and alluvial soils, which dominate the study area and exhibit low shear strength and high susceptibility to erosion. The results indicate that soil loss along NH-44 varies from 0.5 to over 40 t/ha/year, with severe erosion concentrated in Ramban, Banihal, Nashri, and Panthyal. A strong correlation between slope gradient, runoff, and erosion was observed, highlighting the dominant influence of topography and rainfall intensity. Slope stability analysis using Bishop's method yielded Factor of Safety (FOS) values ranging from 1.1 to 1.3, indicating marginally stable slopes that are highly susceptible to failure during intense rainfall events. The findings demonstrate that soil erosion and slope instability are closely interconnected processes and underscore the necessity for integrated mitigation strategies, including bioengineering techniques, structural stabilisation measures, and improved drainage systems. Overall, this study provides a robust framework for sustainable slope management and enhancing infrastructure resilience in Himalayan highway systems.

Keywords: *Geographic Information System (GIS); Himalayas; Landslide Susceptibility; NH-44; RUSLE Model; Slope Stability; Soil Erosion*

1. Introduction

Soil erosion is a major environmental and geotechnical issue affecting land productivity, ecological stability, and infrastructure performance. Global erosion rates are estimated at 12–15 t/ha/year, while significantly higher rates are observed in mountainous regions such as the Himalayas due to steep slopes, intense monsoon rainfall, fragile geology, and anthropogenic disturbances (Pimentel, 2006; Koirala et al., 2019). The Himalayan terrain ishighly dynamic and prone to erosion, landslides, and slope instability (Panagos et al., 2015). The Jammu–Srinagar National Highway (NH-44), a vital transportation corridor, traverses this fragile terrain and is frequently affected by landslides, debris flow, and severe soil erosion, particularly in sections such as Ramban, Banihal, Nashri, and Panthyal. These issues are primarily associated with weak colluvial and alluvial soils, high rainfall intensity, and slope disturbances caused by highway construction (Morgan, 2005; Wischmeier & Smith, 1978). The Revised Universal Soil Loss Equation (RUSLE), integrated with GIS and remote sensing, is widely used for spatial estimation of soil erosion (Renard et al., 1997; Ganasri & Ramesh, 2016). Hydrological modelling using the SCS-CN method enables runoff estimation, a key driver of erosion processes (Mishra & Singh, 2003), while geotechnical analysis and slope stability assessment using Bishop's method provide insight into failure mechanisms (Duncan, 1996). Despite extensive research, limited studies integrate erosion modelling with hydrological and geotechnical analyses for highway-specific conditions in the Himalayan regions. Therefore, this study develops an integrated framework combining RUSLE, GIS, SCS-CN modelling, geotechnical investigation, and slope stability analysis to assess erosion dynamics along NH-44 and identify critical zones for effective mitigation.

2. Study Area and Geotechnical Characteristics

The study area comprises the mountainous stretch of the Jammu–Srinagar National Highway (NH-44) between Udhampur and Qazigund, including critical landslide-prone zones such as Ramban, Banihal, Nashri, and Panthyal[1]. Located in the Lesser Himalayas, the region is characterised by rugged terrain, steep slopes (>30°), and highly weathered, tectonically active formations. The area experiences a monsoon-dominated climate, with approximately 70–80% of annual rainfall occurring between June and September, resulting in intense precipitation that significantly influences soil erosion and slope instability (Koirala et al., 2019). High rainfall generates rapid runoff, increases pore water pressure, and frequently triggers landslides and debris flows along the highway corridor. A comprehensive geotechnical investigation was conducted through field sampling, in-situ measurements, and laboratory testing (grain size analysis, Atterberg limits, and shear strength) as per IS standards. The soils are predominantly colluvial and alluvial in origin. Colluvial soils are loose, poorly graded, and highly permeable, with low cohesion (10–25 kPa) and friction angles of 25°–32°, making them highly susceptible to erosion and shallow landslides under saturated conditions (Morgan, 2005). In contrast, alluvial soils are stratified and moderately sorted, with cohesion values of 5–20 kPa and friction angles of 28°–35%; however, they remain prone to erosion due to fine particle composition and weak bonding (Wischmeier & Smith, 1978). The geotechnical properties of these soils strongly influence erosion processes, as low cohesion and loose structure facilitate detachment, while high permeability enhances infiltration and runoff. Consequently, colluvial soils exhibit higher erosion susceptibility, particularly during monsoon conditions (Koirala et al., 2019). These conditions lead to frequent slope failures, debris flow, and road blockages along NH-44. Critical zones include Ramban (colluvial failures), Banihal (saturation-induced instability), Nashri (runoff-driven erosion), and Panthyal (combined failure mechanisms). To mitigate these risks[2], integrated stabilisation measures are required, including structural interventions (retaining walls, rock bolting, soil nailing), bioengineering techniques (vegetation cover, turfing, hydroseeding), and effective drainage systems (surface and subsurface drainage). Such measures are essential for reducing erosion, improving slope stability, and ensuring the long-term resilience of infrastructure in this fragile Himalayan environment[3].

3. Methodology

This study adopts an integrated and multidisciplinary framework to assess soil erosion and slope instability along the Jammu–Srinagar National Highway (NH-44). The methodology combines the Revised Universal Soil Loss Equation (RUSLE), Geographic Information System (GIS) and remote sensing techniques, hydrological modelling using the Soil Conservation Service Curve Number (SCS-CN) method, detailed geotechnical investigation, and slope stability analysis using Bishop's simplified method. The approach is designed to capture the complex interaction between topographic conditions, rainfall characteristics, soil properties, vegetation cover, and anthropogenic disturbances associated with highway construction[4].

3.1.Data Collection

The analysis begins with the collection of spatial and non-spatial datasets required for soil erosion modelling and geotechnical assessment. Digital Elevation Model (DEM) data from SRTM/Cartosat were used to derive slope, flow accumulation, and other terrain parameters. Rainfall data obtained from the India Meteorological Department (IMD) were utilised to compute rainfall erosivity. Soil maps from FAO and NBSS & LUP were used to determine soil properties relevant to erodibility. Satellite imagery (Landsat) facilitated the generation of land use/land cover (LULC) maps and vegetation indices. Additionally, field investigations were carried out to collect disturbed and undisturbed soil samples for laboratory testing. These datasets provided the essential foundation for subsequent spatial analysis and modelling[5].

3.2. Data Pre Processing

All datasets were pre-processed to ensure spatial accuracy and consistency. DEM data were corrected for sinks and depressions to enable reliable flow routing and slope derivation. Georeferencing and projection were applied to maintain a uniform coordinate system across all layers, while raster resampling was performed to standardise spatial resolution. Satellite imagery was processed using supervised classification to generate land use/land cover (LULC) maps, and vegetation indices such as NDVI were derived to quantify vegetation cover. These preprocessing steps ensured data consistency and minimised errors in subsequent GIS-based analysis[6 – 10].

3.3.RUSLE-Based Soil Erosion Modelling

The Revised Universal Soil Loss Equation (RUSLE) was employed to estimate average annual soil loss:

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

where A is the soil loss (t/ha/year), Ris rainfall erosivity, Kis soil erodibility, LS is the slope length and steepness factor, C is a cover management factor, and P is a support practice factor. All factors were converted into raster layers and integrated using GIS-based raster algebra to generate spatial soil erosion maps[11].

3.4.GIS-Based Spatial Analysis

GIS techniques were extensively used to integrate multiple spatial datasets and perform erosion modelling. Each RUSLE factor was represented as a raster layer, and overlay analysis was performed using a raster calculator to compute soil loss. Spatial analysis enabled the identification of erosion-prone zones and visualisation of erosion patterns along NH-44. The GIS environment also facilitated terrain analysis, slope classification, and correlation studies between erosion and environmental variables[12 – 15].

3.5.Hydrological Modelling (SCS-CN Method)

Hydrological analysis was conducted using the SCS-CN method to estimate surface runoff and understand rainfall–runoff–erosion relationships. Curve Number (CN) values were assigned based on soil type and land use conditions. The potential maximum retention (S) and runoff (Q) were calculated using standard SCS equations. This analysis provided insights into runoff generation and its influence on soil erosion, particularly during high-intensity rainfall events[16 – 20].

3.6.Geotechnical Investigation

A detailed geotechnical investigation was carried out to characterise the engineering properties of soils along NH-44. Field investigations included visual soil classification, in-situ density measurement, and sample collection. Laboratory tests were conducted as per IS standards, including grain size analysis, Atterberg limits, and shear strength determination. Based on these analyses, soils were classified into colluvial and alluvial types. Their mechanical behaviour, including cohesion, friction angle, and permeability, was evaluated to understand their role in erosion and slope instability[20 – 25].

3.7.Slope Stability Analysis (Bishop's Method)

Slope stability was analysed using Bishop's simplified method, which involves dividing the slope into vertical slices and evaluating equilibrium conditions. The Factor of Safety (FOS) was computed by considering resisting and driving forces acting on each slice. This method accounts for pore water pressure effects and provides a reliable estimate of slope stability under different conditions. The analysis was particularly useful in identifying critical slopes prone to failure along the highway[25 – 30].

3.8.Results Analysis and Validation

The results obtained from RUSLE, hydrological modelling, and geotechnical analysis were integrated to evaluate the relationship between slope, runoff, and soil erosion. Statistical and spatial analyses were performed to identify trends and correlations. The results were validated through comparison with existing Himalayan studies and field observations, ensuring the reliability and applicability of the model.

3.9.Methodological Significance

The integrated methodology adopted in this study provides a comprehensive framework for analysing soil erosion and slope instability in mountainous terrains. Unlike conventional approaches, this method combines surface erosion modelling with subsurface geotechnical behaviour and hydrological processes, enabling a more realistic assessment of hazard conditions along NH-44. The overall workflow is illustrated in Figure 1.

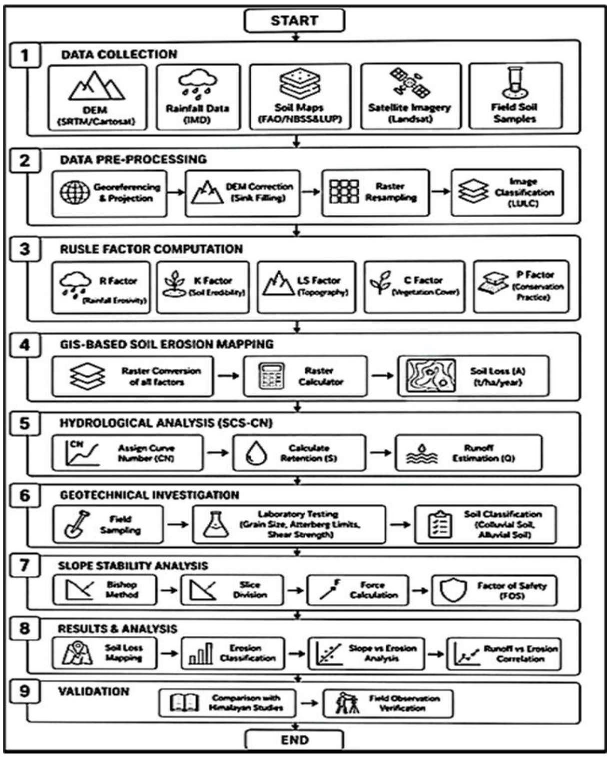

Figure 1 **Simplified methodological framework for soil erosion assessment along NH-44 integrating RUSLE, GIS analysis, hydrological modelling, geotechnical investigation, and slope stability analysis**

4. Results

The results indicate that soil loss along the Jammu–Srinagar National Highway (NH-44) varies from 0.5 to over 40 t/ha/year, reflecting moderate to severe erosion across the study area. Severe erosion is concentrated in Ramban and Banihal, where steep slopes and high rainfall intensity significantly enhance soil detachment and transport. Higher erosion rates are observed in barren and agricultural lands due to reduced vegetation cover, whereas forested areas exhibit comparatively lower erosion owing to root reinforcement and surface protection (Koirala et al., 2019). Slope stability analysis reveals Factor of Safety (FOS) values between 1.1 and 1.3, indicating marginally stable conditions, particularly in cut slopes influenced by anthropogenic disturbances (Duncan, 1996). The spatial distribution of RUSLE factors highlights their combined control on erosion patterns. The rainfall erosivity factor (R) ranges from 350 to 550 MJ mm ha^{-1} h^{-1} year^{-1}, with higher values in the Ramban–Banihal stretch, confirming rainfall as a primary driver of erosion. The soil erodibility factor (K) ranges from 0.014 to 0.023, with higher values associated with fine-grained alluvial soils and lower values with coarser colluvial deposits. The topographic factor (LS) exhibits the greatest variability (5 to >50) and is the dominant parameter, particularly for steep cut slopes. The cover management factor (C) ranges from 0.01 to 0.45, indicating strong dependence on vegetation cover, while the support practice factor (P) varies from 0.55 to 1.0, reflecting limited conservation measures along most highway sections. Erosion classification reveals a wide range of intensity, from slight (0–5 t/ha/year) in forested areas to severe (>40 t/ha/year) in landslide-prone zones. Moderate to high erosion (5–20 t/ha/year) is associated with agricultural and transitional slopes, while very high erosion (20–40 t/ha/year) occurs in exposed cut slopes. Spatially, severe erosion is concentrated in Ramban, Banihal, and Panthyal, whereas Nashri exhibits moderate to high erosion. Overall, the findings demonstrate that soil erosion along NH-44 is primarily controlled by slope steepness, rainfall intensity, and vegetation cover, with the LS factor identified as the most dominant parameter. The relationship between slope angle (θ) and soil erosion is highly significant, as increasing slope enhances runoff velocity, thereby increasing shear stress and sediment transport capacity. This produces a scientifically meaningful relationship because soil erosion generally increases with slope steepness as shown in figure 2. A strong positive linear relationship is observed between slope and soil loss ($R^2 = 1.00$), indicating a near-proportional increase under the given conditions Mechanistically, steeper slopes increase the gravitational force component acting parallel to the surface, reduce infiltration time, and elevate runoff energy, leading to greater soil detachment and transport. Rainfall acts as the primary driver of soil erosion through raindrop impact and surface runoff. A strong positive relationship between rainfall and soil loss is observed (Figure 3), indicating that higher rainfall intensity significantly enhances erosion. When rainfall intensity exceeds soil infiltration capacity, Hortonian overland flow is generated, resulting in increased detachment and sediment transport. The cover management factor (C) as shown in figure 4 further highlights the role of vegetation in controlling erosion. A strong relationship between C and soil loss ($R^2 = 0.95$) is observed, with slightly greater variability compared to physical factors[31]. Lower C values (=0) correspond to well-protected surfaces with dense vegetation, whereas higher values (approaching 1.0) indicate bare or disturbed land with maximum erosion potential.Shown as Figure 2 Relationship between slope and soil erosion along NH-44 with regression and confidence intervals. Figure 3 Relationship between rainfall and soil erosion along NH-44 with regression and confidence intervals, Figure 4 Relationship between vegetation (C factor) and soil erosion along NH-44 with regression and confidence intervals[32]

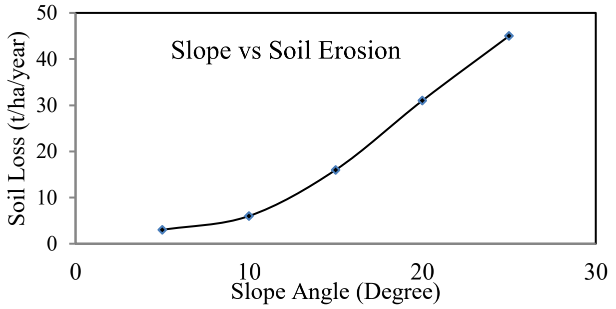

Figure 2 **Relationship between slope and soil erosion along NH-44 with regression and confidence intervals**

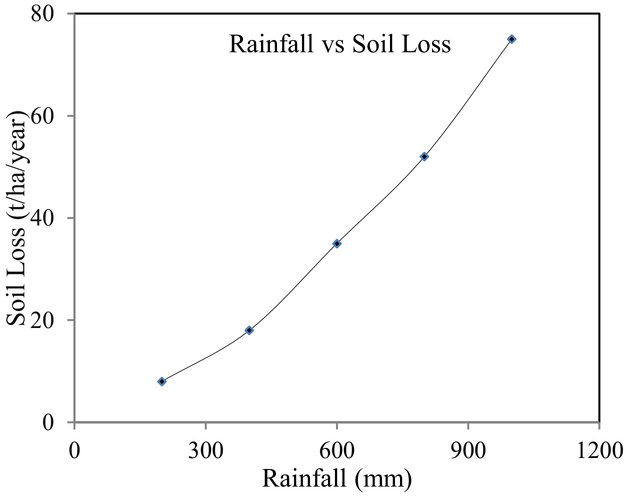

Figure 3 **Relationship between rainfall and soil erosion along NH-44 with regression and confidence intervals**

A strong positive relationship between slope gradient and soil erosion is observed, indicating that erosion rates increase exponentially with slope. Areas with slopes <10° exhibit minimal erosion (2–5 t/ha/year), while slopes of 10°–20° show moderate erosion (5–15 t/ha/year). Steeper slopes of 20°–30° experience high erosion (15–30 t/ha/year), and slopes >30° exhibit severe erosion (>40 t/ha/year), particularly in disturbed and cut-slope regions. Hydrological analysis using the SCS-CN method indicates that runoff plays a critical role in controlling erosion processes. Estimated runoff ranges from 400 to 1800 mm, with a strong correlation between runoff and soil loss ($R^2 \approx 0.80$). High runoff zones are associated with intense rainfall, poor drainage, and steep slopes, confirming that erosion along NH-44 is strongly hydrologically driven. Soil type also significantly influences erosion dynamics. Colluvial soils, dominant in Ramban and Banihal, exhibit higher erosion rates due to their loose structure, low cohesion, and susceptibility to shallow landslides. In contrast, alluvial soils, typically found near drainage channels, show moderate erosion rates but higher sediment transport potential due to finer particle composition. Slope stability analysis using Bishop's method indicates Factor of Safety (FOS) values between 1.1 and 1.3, suggesting marginally stable conditions. Slopes with FOS <1.3 are particularly vulnerable to failure under saturated conditions, with critical zones identified in Ramban (FOS = 1.1) and Banihal (FOS = 1.2). These findings confirm that soil erosion and slope instability are closely interlinked processes[33]. Based on the integrated analysis, Ramban, Banihal, and Panthyal are identified as high-risk zones, Nashri as moderate risk, and forested regions as low risk. The estimated erosion rates are consistent with Himalayan studies reporting average values of =25 t/ha/year and >80 t/ha/year under extreme conditions, thereby validating the applicability of the RUSLE-GIS model. Overall, the results highlight that soil erosion along NH-44 is primarily controlled by topography (LS factor), with significant contributions from runoff and soil properties, while slope stability analysis indicates critical conditions requiring immediate engineering intervention[34].

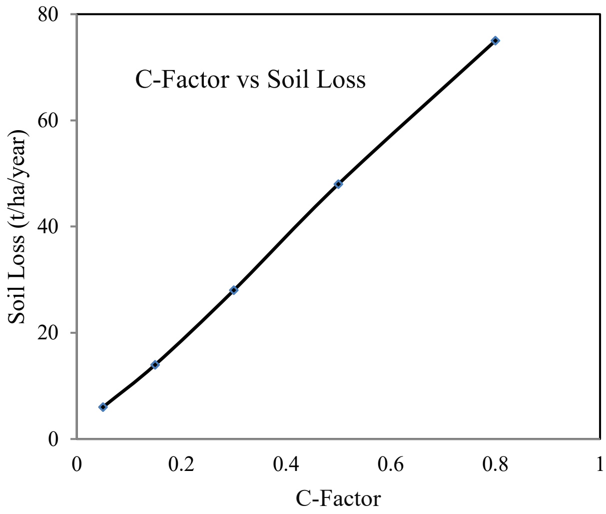

Figure 4 **Relationship between vegetation (C factor) and soil erosion along NH-44 with regression and confidence intervals**

5. Discussion

5.1. Dominant Control of Topography (LS Factor)

The results clearly indicate that topography is the most influential factor governing soil erosion along NH-44, as represented by the LS factor in the RUSLE model. The highway traverses steep Himalayan slopes, often exceeding 30°, which significantly increases the velocity of surface runoff and enhances the detachment and transport capacity of soil particles. The exponential relationship between slope gradient and soil loss observed in this study is consistent with established geomorphological principles (Qiu et al., 2018). As slope increases: Flow velocity increases, Shear stress on soil surface increases, Sediment transport capacity increases In NH-44, road cutting operations artificially steepen slopes beyond their natural angle of repose, further amplifying the LS factor. This explains the concentration of high erosion zones in Ramban and Banihal, where steep cut slopes dominate. Additionally, the DEM-based LS factor may underestimate micro-topographic variations, suggesting that actual erosion rates in localised zones may be even higher than predicted.

5.2. Rainfall–Runoff Interaction and Hydrological Control

Rainfall erosivity (R factor) plays a crucial role in controlling soil erosion, particularly in monsoon-dominated regions like Jammu & Kashmir. Approximately 70–80% of annual precipitation occurs during the monsoon season, leading to intense rainfall events that generate high runoff. The integration of SCS-CN runoff modelling demonstrates a strong correlation ($R^2 = 0.8$) between runoff and soil erosion, confirming that erosion is primarily hydrologically driven. High-intensity rainfall contributes to: Raindrop impact (soil detachment), Surface runoff (soil transport), and Increased pore water pressure (slope instability). This is particularly critical in Nashri and Panthyal, where drainage congestion and inadequate slope protection exacerbate runoff-induced erosion. Furthermore, short-duration, high-intensity storms typical of Himalayan climates produce flash runoff, which is not fully captured by average-annual models, indicating a potential underestimation of peak erosion events.

5.3. Influence of Land Use and Vegetation Cover (C Factor)

Vegetation plays a critical role in mitigating soil erosion by intercepting rainfall, reducing runoff velocity, increasing infiltration, and enhancing soil cohesion through root reinforcement. The study shows that areas with dense vegetation cover exhibit significantly lower erosion rates compared to barren or disturbed slopes. This is consistent with previous findings that vegetation can reduce erosion by up to 80–90% (Zhou et al., 2006). However, along NH-44, Road construction leads to deforestation and the removal of vegetation. Cut slopes remain exposed for long periods. Natural revegetation is slow due to harsh terrain. This results in high C-factor values, particularly in freshly cut slopes, leading to severe erosion. The adoption of a vegetation-based C-factor model in this study improves accuracy by accounting for spatial variability in vegetation density, which is often overlooked in conventional RUSLE applications.

5.4.Geotechnical Behaviour of Colluvial and Alluvial Soils

A key contribution of this study lies in the integration of geotechnical properties into soil erosion assessment along NH-44, enabling a more realistic interpretation of slope instability processes in the Himalayan terrain. The colluvial soils encountered in the study area are typically loose, poorly graded, highly permeable, and characterised by low cohesion, rendering them inherently unstable. These properties significantly increase their susceptibility to both erosion and slope failure. During rainfall events, rapid infiltration into these permeable soils leads to a rise in pore water pressure, which reduces effective stress and consequently decreases shear strength. This progressive loss of shear resistance destabilises the slope mass and facilitates failure mechanisms such as shallow landslides and debris flows. Such conditions are particularly pronounced in the Ramban and Banihal sections, where steep slopes combined with intense rainfall further exacerbate instability. These findings underscore the critical role of geotechnical characteristics in controlling erosion-induced slope failures in Himalayan highway environments. In contrast, alluvial soils, typically found near drainage channels along NH-44, exhibit distinct behaviour due to their fluvial origin. These soils are generally stratified and moderately sorted, with relatively higher strength compared to colluvial deposits; however, they remain loosely structured and weakly bonded. Their finer particle composition makes them highly susceptible to detachment and transport under flowing water conditions. Moreover, the high permeability of alluvial soils promotes rapid infiltration and contributes to increased surface runoff during intense rainfall events. This process enhances sediment transport capacity and accelerates channel erosion, particularly in areas of concentrated flow. As a result, alluvial soils play a significant role in sediment mobility, channel degradation, and downstream deposition processes along the highway corridor. Overall, the contrasting behaviour of colluvial and alluvial soils highlights the dual mechanism of slope instability and sediment transport along NH-44, emphasising the need for integrated geotechnical and hydrological considerations in erosion assessment and slope management.

5.5.Slope Stability and Factor of Safety (FOS)

Slope stability analysis using Bishop’s simplified method indicates that the Factor of Safety (FOS) values range from 1.1 to 1.3, representing marginally stable slope conditions along the NH-44 corridor. These values suggest that while slopes may remain stable under dry conditions, they are highly vulnerable to failure during periods of saturation. The increase in pore water pressure during rainfall events significantly reduces effective stress and, consequently, the shear strength of soil, acting as a primary triggering mechanism for slope failure. This behavior clearly demonstrates that soil erosion and slope instability are closely interconnected processes rather than independent phenomena. Furthermore, the combined influence of a high topographic factor (LS), weak and loosely structured soil materials, and elevated pore water pressure creates critical instability conditions along the highway. These factors collectively contribute to frequent slope failures, particularly in steep, engineered cut slopes, emphasising the need for integrated geotechnical and hydrological mitigation strategies in the NH-44 region.

5.6.Comparison with Himalayan Studies

The results obtained in this study are consistent with findings from regional Himalayan studies, which report average soil erosion rates of approximately 25 t/ha/year (Koirala et al., 2019) and values exceeding 200 t/ha/year under extreme conditions. The erosion range observed along NH-44, varying from 0.5 to over 40 t/ha/year, falls within the moderate to high erosion category, thereby validating the applicability and reliability of the RUSLE-GIS model in mountainous terrain. However, in contrast to large-scale watershed-based studies, the highway-specific analysis presented here reveals distinct characteristics. Notably, erosion along NH-44 exhibits higher localised intensity, primarily driven by anthropogenic disturbances such as slope cutting, excavation, and vegetation removal associated with road construction. Additionally, a greater spatial variability in erosion rates is observed due to heterogeneous slope geometry, varying soil conditions, and uneven distribution of rainfall and runoff. These findings highlight the importance of site-specific assessments for linear infrastructure projects, where localised factors play a more dominant role compared to broader watershed-scale processes.

5.7.Limitations of the Study

Despite the robustness of the integrated methodology adopted in this study, several limitations must be acknowledged. Firstly, the RUSLE model, being empirical in nature, does not account for complex erosion processes such as gully erosion and mass movement, and it assumes relatively uniform slope conditions, which may not fully represent the heterogeneous terrain of the Himalayan region. Secondly, data-related limitations may influence the accuracy of results; for instance, the rainfall data used may not adequately capture short-duration, high-intensity storm events that significantly impact erosion, while the resolution of the Digital Elevation Model (DEM) can affect the precision of the LS factor estimation. Thirdly, geotechnical variability introduces uncertainty, as soil properties such as cohesion, permeability, and shear strength vary spatially, and limited field sampling may not fully represent this heterogeneity. Finally, the hydrological analysis based on the SCS-CN method involves simplifications, as it assumes a uniform watershed response and does not explicitly account for spatial variability in infiltration and runoff processes. These limitations highlight the need for incorporating higher-resolution data, advanced process-based models, and extensive field investigations in future studies to improve the accuracy and reliability of erosion assessment along mountainous highway corridors.

5.8.Engineering Implications and Practical Significance

The findings of this study have important implications for the design, construction, and maintenance of highway infrastructure along the NH-44 corridor. The analysis identifies key risks, including slope failure during monsoon seasons, debris flow–induced road blockages, and long-term infrastructure degradation due to continuous erosion. These challenges are driven by steep slopes, weak soil conditions, and intense rainfall, which collectively destabilise the terrain. To address these issues, an integrated mitigation approach is required. Structural measures such as retaining walls, rock bolting, and slope benching provide mechanical stability and reduce driving forces. Bioengineering techniques, including grass turfing, hydroseeding, and vegetative barriers, help reduce surface erosion by improving soil cohesion and limiting runoff velocity. In addition, effective drainage systems—both surface and subsurface—are essential to regulate water flow, lower pore water pressure, and prevent saturation-induced failures. The combined implementation of these measures is crucial for enhancing the long-term stability, safety, and resilience of highway infrastructure in the fragile Himalayan environment[35].

5.9.Overall Interpretation

The findings of this study demonstrate that soil erosion along NH-44 is governed by a complex interaction of topographic, hydrological, vegetation, and geotechnical factors. The integration of the RUSLE model with geotechnical analysis provides a more realistic understanding of slope behaviour in fragile Himalayan terrains, where surface erosion and subsurface instability processes coexist. The results indicate that no single factor acts independently; rather, the combined effects of steep slopes, intense rainfall, weak soil structure, and limited vegetation cover drive erosion and slope failure along the highway corridor. These findings highlight the need for an integrated slope management approach that incorporates engineering, environmental, and hydrological strategies. The use of real-time monitoring systems, such as rainfall thresholds and slope movement sensors, can enhance early warning and risk mitigation[36]. Additionally, sustainable practices—including bioengineering measures, efficient drainage systems, and environmentally sensitive stabilisation techniques—are essential for improving long-term infrastructure resilience. Overall, the study underscores the importance of a multidisciplinary and proactive approach to ensure the safety and sustainability of mountainous highway systems like NH-44.

Conclusion

This study presents a comprehensive assessment of soil erosion along the hill slopes of the Jammu–Srinagar National Highway (NH-44) using an integrated framework that combines the Revised Universal Soil Loss Equation (RUSLE), Geographic Information System (GIS), hydrological modelling (SCS-CN), and geotechnical analysis. The findings demonstrate that soil erosion in the study area is governed by a complex interplay of topographic, hydrological, and geotechnical factors. The estimated soil loss ranges from 0.5 to over 40 t/ha/year, with severe erosion concentrated in critical zones such as Ramban, Banihal, Nashri, and Panthyal. Among the RUSLE parameters, the topographic factor (LS) emerged as the most influential, highlighting the dominant role of steep slopes and road-cut geometries in accelerating erosion processes. Rainfall was also identified as a key driver, with monsoon-induced precipitation generating high runoff and enhancing soil detachment. The strong correlation between runoff and soil loss confirms that erosion along NH-44 is predominantly hydrologically controlled. Geotechnical investigations revealed that the slopes are primarily composed of colluvial and alluvial soils, which are inherently weak, loosely structured, and highly susceptible to erosion and instability. Colluvial soils, due to their low cohesion and heterogeneous composition, are particularly prone to shallow landslides and debris flow during rainfall events. In contrast, alluvial soils, although relatively more stable, exhibit higher sediment transport potential due to their finer particle composition and stratified structure. Slope stability analysis using Bishop's simplified method indicated Factor of Safety (FOS) values between 1.1 and 1.3, suggesting marginal stability across several sections. These values indicate that even moderate increases in pore water pressure during rainfall can trigger slope failure. The study further establishes that soil erosion and slope instability are closely interconnected processes, with erosion acting both as a trigger and a consequence of slope failure. The incorporation of vegetation-based C-factor modelling highlights the critical role of vegetation in reducing erosion, as areas with dense cover exhibited significantly lower soil loss. These findings reinforce the importance of bioengineering techniques in slope stabilisation. Overall, the results are consistent with Himalayan-scale erosion studies and validate the applicability of RUSLE-GIS modelling for highway-specific analysis. However, certain limitations exist, particularly the inability of RUSLE to account for gully erosion and mass movement processes, indicating the need for more advanced and integrated modelling approaches in future research. From an engineering perspective, the study underscores the urgent need for sustainable slope management practices along NH-44. Recommended measures include structural stabilisation (retaining walls, rock bolting, slope benching), bioengineering techniques (hydroseeding, turfing, vegetation cover), and efficient drainage systems to control runoff and reduce pore water pressure. In conclusion, this study provides a scientifically robust and practically applicable framework for understanding and mitigating soil erosion along mountainous highways. The outcomes can support engineers, planners, and policymakers in developing effective erosion control and slope stabilisation strategies, thereby enhancing the safety, sustainability, and resilience of critical infrastructure in the Himalayan region.

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