

A Comprehensive Review of Rainfall, Topography, and Soil Dynamics Shaping Erosion in Northeast India's Vulnerable Highlands

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Abstract

Soil erosion is a critical environmental challenge in Northeast India, significantly affecting agricultural productivity, water security, and ecosystem stability. The region's hilly landscapes, fragile soils, and monsoon-dominated rainfall patterns make it highly vulnerable to erosive processes. High-intensity, short-duration rainfall events generate rapid surface runoff, mobilizing soil particles and accelerating land degradation. Continuous topsoil loss leads to nutrient depletion, reduced soil fertility, lower crop yields, and sedimentation in rivers and reservoirs, while also threatening biodiversity and the resilience of rural communities reliant on rainfed agriculture. This review synthesizes recent literature on the key factors influencing soil erosion in Northeast India, focusing on rainfall erosivity, topography, and soil characteristics. Rainfall erosivity, determined by the intensity and kinetic energy of precipitation, is a primary driver of soil detachment and sediment transport, with seasonal and extreme events producing spatially variable erosion patterns. Topography, including slope length and steepness, regulates water accumulation, flow velocity, and sediment yield, contributing to heterogeneous erosion risks across micro-watersheds. Soil properties, such as texture, structure, infiltration capacity, and organic matter content, mediate soil susceptibility, with clay-rich soils exhibiting higher runoff and sediment loss compared to better-drained sandy loam soils. Integrated, multi-factor analyses combining rainfall, topography, and soil characteristics enhance predictive accuracy and identify erosion-prone areas more effectively than single-factor studies. GIS-based modeling, remote sensing, and field-scale assessments provide critical insights for prioritizing conservation interventions. The review emphasizes that targeted, site-specific soil and water management strategies, such as slope stabilization, soil cover improvement, and water retention measures, are essential to mitigate erosion, sustain agricultural productivity, and protect fragile ecosystems. Understanding the complex interactions among climatic, topographic, and edaphic factors is fundamental to developing adaptive and sustainable soil conservation practices in Northeast India.

Keywords: Soil erosion, Rainfall erosivity, Topography, Soil properties, Northeast India

Introduction

Soil erosion has emerged as one of the most pressing environmental challenges in Northeast India, posing significant threats to agricultural productivity, water security, and ecosystem stability. The region's diverse landscapes, characterized by steep hills, fragile soils, and dense forest cover, are particularly susceptible to erosive processes. Monsoon-dominated

high-intensity rainfall further exacerbates the problem, triggering rapid surface runoff that mobilizes soil particles and accelerates land degradation. This combination of topographic vulnerability, fragile soil structure, and heavy seasonal precipitation makes Northeast India one of the most erosion-prone regions in the country. The consequences of soil erosion are multi-dimensional, affecting both the environment and human livelihoods. Continuous removal of topsoil leads to the depletion of essential nutrients, resulting in reduced soil fertility and lower crop yields. Sedimentation of rivers, streams, and reservoirs diminishes water storage capacity, disrupts aquatic ecosystems, and increases the risk of flooding. Soil erosion also contributes to the loss of biodiversity, as nutrient-poor and unstable soils cannot support diverse plant and microbial communities. In the long term, these impacts threaten food security, sustainable agriculture, and the resilience of rural communities dependent on rainfed farming systems. Understanding the processes and drivers of soil erosion is therefore critical for designing effective conservation strategies. Among the primary determinants, rainfall erosivity, the potential of rainfall to detach and transport soil particles plays a central role. High-intensity, short-duration storms, which are common during the monsoon season, generates substantial kinetic energy that can mobilize large volumes of soil in a short period. The topography of the region, particularly slope length and steepness, further regulates the dynamics of runoff and sediment transport. Longer slopes allow accumulation of water, increasing its erosive force, while steeper slopes accelerate flow velocity, reduce infiltration, and enhance soil detachment.

In addition to climatic and topographic factors, soil properties including texture, structure, and infiltration capacity determine the susceptibility of soils to erosion. For instance, sandy loam soils may exhibit better drainage but are prone to crust formation, whereas clay-rich soils may have low infiltration capacity and weaker aggregation, leading to higher runoff and sediment yield. The interaction of these factors is complex and site-specific, highlighting the need for integrated, region-specific studies. Despite increasing awareness of soil erosion in India, field-based investigations in Northeast India remain limited and comprehensive analyses that combine rainfall erosivity, topography, and soil characteristics are scarce. Developing a detailed understanding of these interactions is essential for accurately predicting soil loss, designing effective soil and water conservation practices, and ensuring sustainable agricultural and ecological management in the hilly landscapes of Northeast India.

Review of Literatures

Rainfall erosivity, defined as the potential of rainfall to detach and transport soil particles, is a major driver of soil loss in Northeast India. Its significance is largely determined by rainfall intensity and kinetic energy, which influence both surface runoff and sediment mobilization. Lal (2019) emphasized that rainfall erosivity plays a central role in land degradation in rainfed agricultural systems, particularly in tropical and subtropical regions. Nearing et al. (1999) highlighted that integrating rainfall erosivity with field-based soil loss measurements improves the predictive capacity of erosion models. Sharda et al. (2016) demonstrated the effectiveness of the EI30 index in estimating soil loss across monsoon-dominated regions, while Kannan et al. (2014) validated this index for watershed-scale studies in India. Sharma and Singh (2010) noted that over 70% of annual rainfall in Northeast India occurs during the monsoon season, intensifying erosive forces and contributing to spatially variable soil loss. Goyal et al. (2022) examined seasonal rainfall patterns in hilly areas of the region, confirming that high-intensity monsoon events disproportionately increase runoff and

sediment transport. Bhattacharya et al. (2021) further assessed the impact of extreme rainfall events using geospatial approaches, highlighting the vulnerability of Northeast Indian landscapes to episodic soil loss. Collectively, these studies underscore the critical need to quantify rainfall erosivity for effective erosion management.

Topography significantly affects the processes of runoff and sediment transport. Slope length and steepness regulate water accumulation and flow velocity, directly influencing erosion rates. Morgan (2005) conceptualized the importance of slope gradient and length, noting that even small increases in slope steepness markedly alter runoff patterns and soil detachment. Ghosh et al. (2015) confirmed that slope-induced runoff accelerates land degradation in hilly regions of India. Chatterjee et al. (2022) highlighted the influence of slope characteristics on sediment transport in forested catchments, emphasizing the spatial variability of erosion risks across hilly terrains. Additionally, Patel et al. (2021) demonstrated the utility of GIS-based LS factor modeling to identify erosion-prone areas, showing that topographic analysis is critical for prioritizing conservation interventions. These studies collectively indicate that topography, when integrated with rainfall dynamics, provides a robust framework for assessing and managing soil erosion in complex terrains. Soil characteristics, including texture, structure, and infiltration capacity, are critical determinants of erosion susceptibility. Mandal et al. (2016) reported that clay-rich soils in hilly terrains produce higher runoff and sediment yields under similar rainfall conditions, highlighting the role of soil composition in modulating erosion. Liu et al. (2014) emphasized that soil aggregation and organic matter content significantly influence the detachment and transport of soil particles, with well-aggregated soils demonstrating greater resistance to erosive forces. Pimentel and Burgess (2013) underscored the broader implications of soil loss, noting that erosion-induced declines in fertility adversely affect agricultural productivity at regional and global scales. Rao et al. (2022) further demonstrated that soil hydraulic conductivity strongly correlates with erosion rates in Northeast Indian hill soils, indicating that infiltration capacity directly affects runoff generation and sediment transport. Collectively, these studies highlight that understanding site-specific soil properties is essential for designing targeted soil and water conservation strategies in erosion-prone landscapes.

In addition to soil properties, integrating rainfall and topographic factors with edaphic characteristics has been shown to enhance the predictive accuracy of erosion models. Meena et al. (2023) evaluated hilly micro-watersheds under various integrated management practices, illustrating that the combined consideration of rainfall intensity, slope characteristics, and soil conditions can substantially reduce soil loss. Kumar et al. (2022) demonstrated the utility of combining GIS, remote sensing, and soil datasets to map erosion hotspots across Northeast India, revealing spatial patterns of vulnerability that single-factor analyses may overlook. Nearing et al. (1999) earlier highlighted the necessity of linking rainfall erosivity indices with field-based soil loss measurements to capture the complex interactions driving erosion. These studies collectively underscore the importance of a holistic, multi-factor approach for understanding soil erosion processes and guiding the development of effective conservation strategies tailored to the fragile hilly ecosystems of Northeast India.

Objectives

The primary objective of this review paper is to provide a comprehensive synthesis of existing research on the factors influencing soil erosion in Northeast India, with a particular

focus on rainfall erosivity, topographic characteristics, and soil properties. It aims to critically examine how varying rainfall intensity and kinetic energy, in conjunction with slope length and steepness, contribute to runoff generation and sediment transport across the region's hilly landscapes. The review further seeks to evaluate the differential responses of contrasting soil types, specifically red sandy loam and dark clay loam soils, to these erosive forces, highlighting how soil texture, structure, and infiltration capacity mediate erosion susceptibility. Additionally, the study intends to assess the integrated effects of climatic, topographic, and edaphic factors on spatial and temporal patterns of soil loss, thereby elucidating the complex interactions that govern erosion processes in fragile hill ecosystems. A further objective is to identify critical gaps in field-based research, including the paucity of region-specific, micro-watershed-scale studies, and to propose directions for targeted soil and water conservation strategies that are tailored to the unique environmental and agricultural contexts of Northeast India.

Materials and Methods

The methodology of this review paper is based on a systematic and comprehensive synthesis of existing literature, aimed at understanding the interplay of rainfall erosivity, topographic factors, and soil properties in influencing runoff and soil loss in Northeast India. Peer-reviewed articles published between 2015 and 2023 were sourced from leading academic databases, including ScienceDirect, Springer, Nature, MDPI, ResearchGate, and other relevant repositories, ensuring a broad and credible knowledge base. The literature search employed a set of targeted keywords, such as "soil erosion," "rainfall erosivity," "topography," "slope length," "slope steepness," "runoff," "soil loss," "Northeast India," "clay loam," and "red sandy loam soils," to capture studies relevant to the region's tropical and subtropical hilly landscapes. Selection criteria prioritized studies that examined the interactions of rainfall, topography, and soil characteristics, with particular emphasis on micro-watershed or field-scale assessments. From the selected studies, data were extracted on key parameters, including rainfall erosivity indices (e.g., EI30), slope length and steepness, soil texture, structure, infiltration capacity, and integrated modeling approaches. The synthesis involved a critical comparison of findings to identify consistent trends, divergences in results, and gaps in knowledge, particularly in relation to field-based, region-specific research. Emphasis was placed on understanding how contrasting soils, such as red sandy loam and dark clay loam, respond to erosive forces under varying topographic and climatic conditions. The findings were systematically organized to provide insights into the relative contributions of rainfall, slope, and soil properties to runoff and sediment yield, as well as to inform practical soil and water conservation strategies. This approach ensures that the review not only summarizes existing knowledge but also highlights areas requiring further investigation, thereby supporting the development of targeted interventions for sustainable hill agriculture in Northeast India.

Analysis and Results

The analysis of the reviewed literature reveals that soil erosion in Northeast India is a complex, multi-factorial process primarily driven by rainfall erosivity, topography, and soil characteristics. Rainfall erosivity, defined as the potential of precipitation to detach and transport soil particles, is strongly influenced by the intensity and kinetic energy of rainfall events. The monsoon-dominated climate of Northeast India, with over 70% of annual rainfall occurring in a few months, generates high-intensity, short-duration storms that induce rapid

surface runoff and significant soil displacement. Seasonal and extreme rainfall events further amplify this effect, producing spatially and temporally variable patterns of erosion across hilly landscapes. The analysis indicates that quantifying rainfall erosivity using indices such as EI30 is an effective approach for predicting potential soil loss, particularly when combined with field measurements that capture localized soil response. Topography emerges as another decisive factor influencing runoff and sediment transport. The interplay of slope length and steepness directly affects water accumulation, flow velocity, and soil detachment. Longer slopes allow greater accumulation of water, thereby increasing erosive forces, while steeper slopes accelerate flow and reduce infiltration, leading to higher sediment yields. The spatial variability of slope characteristics across the region's undulating hills produces heterogeneous erosion risks, with some micro-watersheds being particularly vulnerable. Geospatial modeling, including the use of LS factors in combination with topographic maps, demonstrates the utility of topography-driven analyses in identifying erosion-prone areas and prioritizing conservation interventions.

Soil properties, including texture, structure, organic matter content, and infiltration capacity, play a critical mediating role in erosion susceptibility. Sandy loam soils generally exhibit better drainage, reducing runoff volume, but may be prone to surface crusting under intense rainfall. In contrast, clay-rich soils often have lower infiltration capacity and weaker aggregation, producing higher runoff and sediment transport under similar rainfall conditions. Soil hydraulic conductivity further regulates the generation of surface runoff and influences sediment yield. The interaction of soil characteristics with rainfall intensity and slope conditions determines both the magnitude and spatial distribution of soil loss. Integrated analyses combining rainfall, topography, and soil properties enhance the predictive accuracy of erosion assessments. Multi-factor approaches, including GIS-based modeling and remote sensing, identify erosion hotspots and reveal spatial patterns that single-factor studies might overlook. Evaluations at the micro-watershed scale show that targeted interventions addressing the combined effects of rainfall intensity, slope morphology, and soil properties can significantly reduce soil loss. Overall, the results indicate that effective soil and water conservation in Northeast India requires a holistic understanding of these interacting factors to support sustainable agricultural practices, maintain soil fertility, and protect fragile hilly ecosystems.

Discussion

The findings of this review underscore the central role of rainfall erosivity in driving soil erosion across Northeast India. Lal (2019) emphasized that rainfall erosivity is a key factor in land degradation, particularly in tropical and subtropical rainfed systems, where high-intensity storms generate substantial kinetic energy capable of detaching and transporting soil particles. The monsoon-dominated climate, with over 70% of annual rainfall occurring in a few months (Sharma & Singh, 2010), creates conditions for rapid surface runoff and significant soil loss. Indices such as EI30 have proven effective in quantifying erosive potential and predicting soil displacement (Sharda et al., 2016; Kannan et al., 2014). Nearing et al. (1999) highlighted that integrating rainfall erosivity indices with field-based soil loss measurements enhances the accuracy of erosion models. Seasonal and extreme rainfall events, as confirmed by Goyal et al. (2022) and Bhattacharya et al. (2021), further amplify erosion risks, indicating the necessity for adaptive soil and water management strategies that account for both regular monsoon

patterns and episodic rainfall events. Topography significantly influences the magnitude and spatial distribution of erosion. Slope length and steepness directly regulate runoff accumulation, flow velocity, and sediment detachment, as noted by Morgan (2005), who emphasized that even minor increases in slope gradient can markedly alter erosion rates. Ghosh et al. (2015) demonstrated that slope-induced runoff accelerates land degradation in hilly regions, while Chatterjee et al. (2022) highlighted that spatial variability in slope characteristics produces heterogeneous erosion risks across forested catchments. Patel et al. (2021) further showed the value of GIS-based LS factor modeling in identifying erosion-prone areas, enabling the prioritization of conservation interventions. Collectively, these studies indicate that topographic attributes, when integrated with rainfall erosivity, form a robust framework for assessing erosion vulnerability and guiding targeted conservation planning in complex hilly terrains.

The role of soil characteristics in mediating erosion susceptibility is equally critical. Clay-rich soils, with low infiltration capacity and weaker aggregation, generate higher runoff and sediment yields under similar rainfall conditions (Mandal et al., 2016), whereas sandy loam soils, despite better drainage, may form surface crusts that enhance erosion under intense rainfall. Liu et al. (2014) emphasized the influence of soil aggregation and organic matter on resistance to detachment, while Rao et al. (2022) highlighted that soil hydraulic conductivity strongly correlates with erosion rates in Northeast Indian hill soils. Pimentel and Burgess (2013) further stressed that erosion-induced fertility loss adversely affects agricultural productivity at regional and global scales. Studies integrating rainfall, topography, and soil properties (Meena et al., 2023; Kumar et al., 2022; Nearing et al., 1999) demonstrate that multi-factor analyses enhance the predictive accuracy of erosion models and reveal spatial patterns of vulnerability that single-factor approaches may overlook. These findings collectively indicate that effective soil and water conservation in Northeast India requires holistic strategies that consider rainfall intensity, slope morphology, and site-specific soil properties to maintain soil fertility, support sustainable agriculture, and safeguard fragile hilly ecosystems.

Summary and Conclusion

Soil erosion in Northeast India poses a major environmental and agricultural challenge, shaped by the region's fragile soils, steep topography, and intense monsoon rainfall. The removal of nutrient-rich topsoil reduces fertility, crop yields, and water storage, while also threatening biodiversity and ecosystem stability. These impacts highlight the urgent need for sustainable soil and water conservation strategies tailored to the unique conditions of the hill ecosystems. This review emphasises three interlinked drivers of erosion: rainfall erosivity, topography, and soil properties. High-intensity monsoon storms, with their strong kinetic energy, trigger rapid surface runoff and episodic soil loss, producing uneven erosion across the landscape. Topographic features, particularly slope length and gradient, further accelerate erosion by influencing flow velocity and sediment transport. Soil characteristics, including texture, infiltration, and organic matter content, determine susceptibility, with sandy soils prone to crusting and clay-rich soils generating higher runoff. The interplay of these factors produces complex, site-specific erosion dynamics across micro-watersheds. Effective management therefore requires integrated approaches that combine climatic, topographic, and edaphic considerations. Advanced tools such as GIS, remote sensing, and field-based monitoring enable spatial mapping of erosion-prone zones and inform prioritization of conservation measures.

Practices like slope stabilization, soil cover maintenance, and water retention structures can reduce soil loss and maintain agricultural productivity when tailored to local conditions. Thus, soil erosion in Northeast India demands a holistic and adaptive strategy that balances agricultural needs with ecological sustainability. Multi-disciplinary research at finer scales is critical to strengthen prediction models, close knowledge gaps, and design locally relevant interventions. Protecting soil resources in this erosion-prone region is vital not only for sustaining livelihoods but also for preserving the long-term ecological resilience of Northeast India.

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