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Rainfall Erosivity And Topographic Influences On Runoff And Soil Loss In Contrasting Soils In Chandel District Of Manipur

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Abstract
Soil erosion remains one of the most pressing environmental challenges in hilly agro-ecosystems, threatening agricultural productivity, water quality, and ecological sustainability. This study examined the combined influence of rainfall erosivity, slope length, and slope steepness on runoff and soil loss in red sandy loam and dark clay loam soils of Chandel District, Manipur, during 2015-2016. Field experiments were conducted using runoff plots of varying slope lengths (5 m, 10 m, and 15 m) and slope gradients (0%, 2%, and 5%), with erosive storms monitored for runoff volume and soil loss. Rainfall characteristics were quantified using the EI_{30} index, with mean rainfall intensity recorded at 18.4 mm h^{-1} and mean erosivity at 645 MJ • mm • ha^{-1} • h^{-1}. Results demonstrated a strong positive relationship between slope length and runoff, indicating that longer slopes facilitated greater water accumulation and surface flow. Similarly, soil loss increased markedly with slope steepness, showing nonlinear behaviour under 5% slopes, which suggests threshold responses that intensify erosion risks. Soil type played a critical role, with dark clay loam soils exhibiting consistently higher runoff and soil loss compared to red sandy loam soils, due to their lower infiltration capacity and weaker structural stability. These findings highlight the synergistic effects of climatic, topographic, and soil factors in driving erosion. The study underscores the need for slope-specific and soil-specific conservation strategies, such as terracing, contour bunding, and vegetative barriers, to mitigate land degradation. Incorporating localized rainfall erosivity data into predictive models can further strengthen erosion management in fragile hill ecosystems.
Keywords: *Soil erosion, rainfall erosivity, slope length, slope gradient, runoff*

INTRODUCTION

Soil erosion has emerged as one of the most pressing environmental challenges of the 21st century, threatening agricultural productivity, water security, and ecological balance worldwide. The problem is particularly acute in tropical and subtropical regions, where fragile soils, steep terrains, and intense seasonal rainfall combine to accelerate land degradation. Globally, erosion leads to the depletion of soil fertility, sedimentation of rivers and reservoirs, biodiversity loss, and reduced resilience of farming systems. In India, where nearly 60 percent of agriculture is rainfed, the vulnerability is even greater. Erosion not only diminishes crop yields but also degrades water quality and weakens ecosystem stability, thereby posing a serious barrier to food security and sustainable rural development. Rainfall characteristics play a decisive role in driving soil erosion. High-intensity, short-duration storms are particularly destructive, as they generate rapid surface runoff that carries away significant quantities of soil in a short time. The erosive potential of rainfall is often measured using indices that combine kinetic energy and rainfall intensity, which together determine the detachment and transport of soil particles. In monsoon-dominated regions such as Northeast India, rainfall erosivity is therefore a dominant factor shaping soil erosion dynamics.

Topography further regulates the process of erosion. Slope length influences how much water accumulates and flows downslope, while slope steepness affects runoff velocity and infiltration. Longer slopes generally allow more water accumulation, increasing the erosive force, whereas steeper slopes enhance runoff speed and reduce water infiltration, resulting in greater soil detachment and sediment yield. Understanding these interactions is crucial for identifying vulnerable landscapes and designing conservation measures. Equally important are the inherent properties of soils, which mediate how they respond to rainfall and runoff. Factors such as texture, structure, and infiltration capacity determine whether soils are resistant or susceptible to erosion. In the hill districts of Northeast India, red sandy loam and dark clay loam soils present contrasting behaviours under erosive conditions. While red sandy loam soils are more prone to crusting, they generally exhibit better drainage, which can reduce runoff. Dark clay loam soils, on the other hand, tend to have lower infiltration capacity and weaker aggregation, leading to higher runoff volumes and soil loss. These contrasts highlight the need to study erosion processes across different soil types. Regardless of growing attention to soil erosion research in India, region-specific studies in Northeast India remain limited. Chandel District of Manipur, with its hilly terrain, fragile soils, and high rainfall variability, provides an important case for investigation. This study seeks to fill this gap by analysing the combined effects of rainfall erosivity, slope length, and slope steepness on runoff and soil loss. The findings are expected to strengthen erosion prediction models and contribute to the development of effective soil and water conservation practices tailored to hill agricultural systems of the region.

REVIEW OF LITERATURES

Soil erosion has been widely recognized as a complex process influenced by climatic, topographic, and edaphic factors. Early studies emphasized rainfall as the dominant driver of erosion. Renard et al. (1997) highlighted that high-intensity, short-duration storms disproportionately contribute to annual soil loss compared to longer rainfall events, a view reinforced by Kinnell (2010), who showed that the kinetic energy of raindrops enhances soil particle detachment and transport. Similarly, Lal (2019) stressed that rainfall erosivity is a central factor determining the degradation of rainfed agricultural lands, particularly in tropical and subtropical regions. Topography has also been extensively studied for its role in shaping erosion dynamics. Zhang et al. (2003) demonstrated that slope length directly affects water accumulation, thereby increasing runoff volume and erosive power. Nearing et al. (2017) further observed that steeper slopes intensify runoff velocity, reduce infiltration, and exacerbate sediment yield. Ghosh et al. (2015) confirmed this relationship in Indian contexts, where slope-induced runoff accelerates land degradation in hilly regions. Earlier, Morgan (2005) had already conceptualized the significance of slope gradient and length in soil erosion models, noting that even minor increases in slope steepness drastically alter runoff and soil detachment processes.

Soil properties play an equally important role. Singh et al. (2009) found that red sandy loam soils, though prone to crusting, allow better drainage compared to dark clay loam soils, which have weaker structural stability and lower infiltration. Mandal et al. (2016) supported this by showing that clay-rich soils in Northeast India produced higher runoff and sediment yields under erosive rainfall conditions. Liu et al. (2014) added that soil texture, aggregation, and organic matter significantly mediate erosion responses to rainfall intensity, while Pimentel and Burgess (2013) emphasized that soil fertility decline due to erosion directly reduces agricultural productivity worldwide. Quantifying rainfall erosivity has been a key focus in erosion research. The EI30 index, proposed and popularized by Renard et al. (1997), remains the most widely used method for estimating erosive potential, as it integrates storm energy and maximum 30-minute rainfall intensity. Sharda et al. (2016) applied this index across different agro-ecological zones of India, demonstrating its effectiveness in predicting soil loss. Kannan, Srinivasan, and Purohit (2014) also validated the EI30 approach in watershed-scale studies, reinforcing its suitability for monsoon-dominated regions.

In recent years, Nearing et al. (1999) emphasized the importance of combining rainfall erosivity with field-based soil loss measurements to improve erosion prediction models. Das et al. (2016) examined rainfall variability in Northeast India and linked it with erosion risks, underscoring the vulnerability of hilly districts such as Chandel. Similarly, Sharma and Singh (2010) reported that more than 70% of annual rainfall in Northeast India occurs during the monsoon season, creating concentrated erosive forces that threaten agricultural lands. Despite these advances, gaps remain in regional studies. Most investigations have been conducted at broader scales, with limited attention to field-based assessments in Northeast India. Specifically, the integration of rainfall erosivity, slope length, and slope steepness in contrasting soils of Manipur, particularly in Chandel District, remains understudied. Addressing this gap is crucial for developing region-specific conservation practices and refining erosion models tailored to the fragile hill ecosystems of Northeast India.

Objectives

The primary objective of this study is to analyse the combined influence of rainfall erosivity, slope length, and slope steepness on runoff and soil loss in red sandy loam and dark clay loam soils of Chandel District, Manipur. Specifically, the research aims to estimate rainfall erosivity through the EI30 index during erosive storm events, evaluate the effect of slope length on runoff and sediment yield across contrasting soil types, and assess the role of slope steepness in soil detachment and transport processes. Further, it seeks to compare runoff and soil loss between red sandy loam and dark clay loam soils, thereby identifying the distinct erosion responses of these soil groups under varying topographic and rainfall conditions. Finally, the study intends to provide practical recommendations for erosion modeling and sustainable soil conservation strategies in hill agricultural systems of Manipur, where soil degradation poses serious challenges to productivity and land management.

MATERIALS AND METHODS

The study was carried out in erosion-prone agricultural lands of Chandel District, Manipur, situated in the hill ranges of Northeast India and characterized by a subtropical monsoon climate, undulating terrain, and fragile soils. The district receives an average annual rainfall of 1,700-2,000 mm, of which more than 70% occurs during the monsoon season, creating favourable conditions for soil erosion. Two dominant soil types, red sandy loam and dark clay loam, were selected for the experiment owing to their contrasting physical properties such as texture, aggregation, and infiltration capacity. To examine the influence of slope length and steepness, runoff plots of 5 m, 10 m, and 15 m were established on both soil types, and three slope gradients (0%, 2%, and 5%) were tested. Each treatment was replicated three times following the standard erosion plot methodology to ensure statistical accuracy. The plots were bounded with galvanized iron sheets to prevent lateral inflow and facilitate the collection of surface runoff and sediment. Rainfall data were monitored using automatic rain gauges installed at the site, and rainfall intensity was calculated as the ratio of rainfall depth to storm duration. Rainfall erosivity was estimated using the EI30 index, derived by multiplying total storm kinetic energy (E) with the maximum 30-minute rainfall intensity (I30). Runoff generated after each erosive storm was collected in calibrated tanks connected to the plots, while sediment samples were oven-dried at 105 °C until constant weight was attained. Soil loss was then calculated and expressed in tonnes per hectare per year following established protocols. This systematic design enabled the evaluation of the interactive effects of rainfall erosivity, slope length, and slope steepness on runoff and soil loss under contrasting soil conditions of Chandel District.

ANALYSIS AND RESULTS

The rainfall characteristics recorded during 2015-2016 provide clear evidence of the erosive potential of storm events in the study area. Rainfall intensity varied from 6.7 to 32.6 mm h^{-1}, with a mean of 18.4 mm h^{-1}, indicating that most storms were of moderate to high intensity (Table 1). Such short-duration, high-intensity storms are particularly effective in generating overland flow, since rainfall rates frequently exceed the infiltration capacity of hill soils, thereby accelerating surface runoff and soil particle detachment. Rainfall erosivity, expressed in $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$, ranged from 250 to 1120, with an average of 645, reflecting substantial variability in storm energy. The higher end of this range corresponds to storms with enough kinetic energy to initiate rill formation and transport significant volumes of sediment downslope. A total of 20 erosive storms were recorded during the study period, suggesting that while erosive storms were not frequent, their intensity and erosivity values were high enough to exert considerable influence on soil loss and landscape degradation. These findings underscore that rainfall erosivity is a dominant driver of soil erosion in monsoon-dominated hill regions such as Chandel District. The observed mean erosivity values align with thresholds known to cause accelerated erosion in fragile agro-ecosystems, emphasizing the importance of incorporating rainfall intensity and EI_{30} indices into erosion prediction models. Furthermore, the variability across storms suggests that extreme rainfall events contribute disproportionately to annual soil loss, highlighting the necessity for site-specific soil and water conservation strategies to buffer against high-energy storms.

Table 1: Rainfall characteristics of erosive storms during 2015-2016

Parameter	Range	Mean
Rainfall intensity (mm h^{-1})	6.7-32.6	18.4
Rainfall erosivity ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$)	250-1120	645
No. of erosive storms	20	-

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Figure 1 demonstrates the relationship between slope length and surface runoff, highlighting slope length as a key geometric factor governing water accumulation and flow dynamics in hilly agricultural landscapes. Generally, a positive relationship is observed, where runoff volume increases with slope length due to greater contributing area, prolonged flow concentration, and reduced infiltration opportunity. The shape of the response curve provides further insight into underlying hydrological processes. A near-linear increase suggests proportional scaling of runoff with slope length, whereas a convex or accelerating trend indicates threshold processes such as rill initiation or soil crusting that amplifies runoff disproportionately. In contrast, a plateauing trend would imply limits imposed by soil storage capacity, infiltration recharge, or lateral water redistribution, where additional slope length contributes little extra runoff. These hydrological responses are strongly influenced by rainfall intensity, as high-intensity storm events with greater erosivity can shift the curve upward, accelerating soil detachment and transport. The relationship is further modulated by site-specific factors including soil type, slope steepness, and vegetation cover. Coarse-textured soils such as red sandy loam, with higher drainage capacity, typically produce less runoff compared to finer-textured dark clay loam soils, which exhibit lower infiltration and greater runoff volumes. Similarly, steeper slopes amplify runoff velocity, decreasing infiltration time and enhancing erosive potential. Vegetation cover and surface residues mitigate these effects by increasing surface roughness and infiltration, thereby dampening runoff growth with slope length. Scientifically, the observed trend underscores the importance of slope length management through soil conservation practices such as contour farming, terracing, and grassed waterways to reduce erosion risk. Nonlinear or threshold behaviours, if present, signal potential for rill or gully formation on long slopes, necessitating structural interventions. To strengthen interpretation, regression modeling of runoff–slope length relationships, stratified analyses by soil type and gradient, and normalization using runoff coefficients are recommended. Overall, the figure emphasizes that slope length significantly governs runoff dynamics, but its effects are context-dependent, shaped by interacting soil, topographic, and rainfall characteristics, which must be accounted for in conservation planning.

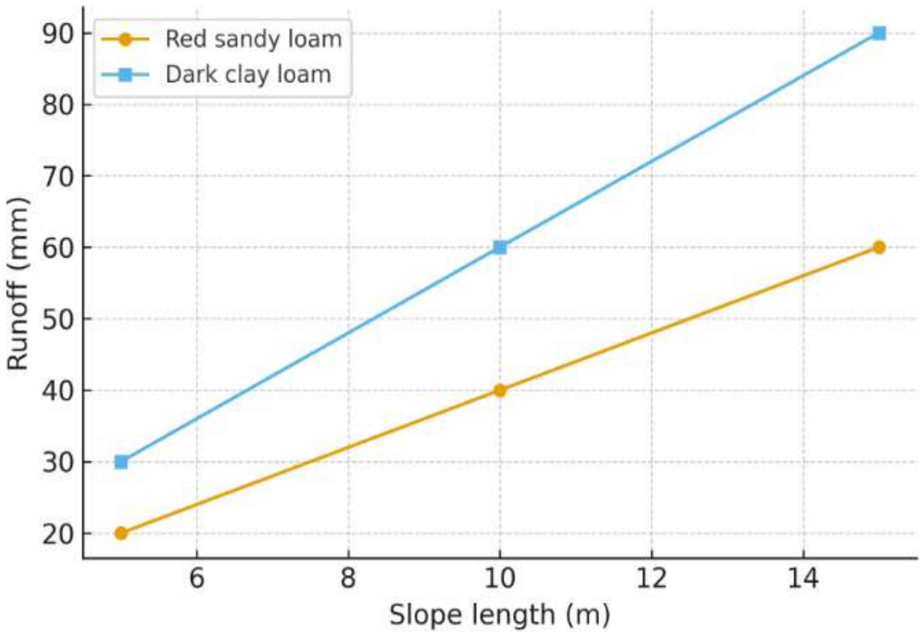

Figure 1: Relationship between runoff and slope length

The results presented in Table 2 clearly indicate a strong positive relationship between slope gradient and soil loss across both soil types. In red sandy loam soils, soil loss increased from 3.7-21.7 t ha^{-1} yr^{-1} at 0% slope to 15-48 t ha^{-1} yr^{-1} at 2% slope, and further to 32-91 t ha^{-1} yr^{-1} at 5% slope. A similar but more pronounced trend was observed in dark clay loam soils, where losses ranged from 6-29.7 t ha^{-1} yr^{-1} at 0% slope, increased to 22-67 t ha^{-1} yr^{-1} at 2% slope, and escalated to 43-124 t ha^{-1} yr^{-1} at 5% slope. These results suggest that even slight increases in slope gradient significantly amplify soil detachment and transport, with higher slopes producing disproportionately greater soil loss. Comparing the two soil types, dark clay loam consistently exhibited greater soil loss than red sandy loam under all slope gradients. This can be attributed to the weaker structural stability, higher runoff generation, and lower infiltration capacity of clay-rich soils, which make them more vulnerable to erosion under intense rainfall and steep topography.

In contrast, red sandy loam soils, though susceptible to crusting, have better drainage properties that reduce runoff volumes relative to clay loam. The observed ranges also highlight variability likely linked to storm intensity, duration, and antecedent soil moisture conditions. Scientifically, these findings confirm that slope gradient acts as a critical driver of erosion, with soil type modulating its magnitude. The disproportionately higher soil losses at 5% slope signal threshold behaviour, where accelerated runoff velocity and sediment transport dominate. This underscores the urgent need for slope-specific soil conservation measures such as terracing, contour bunding, and vegetative barriers, particularly in clay loam-dominated hill agricultural systems where erosion risks are highest.

Table 2: Soil loss under different slope gradients

Soil type	0% slope (t ha^{-1} yr^{-1})	2% slope (t ha^{-1} yr^{-1})	5% slope (t ha^{-1} yr^{-1})
Red sandy loam	3.7-21.7	15-48	32-91
Dark clay loam	6-29.7	22-67	43-124

Figure 2 illustrates the relationship between slope gradient and soil loss, highlighting slope steepness as a dominant topographic factor influencing erosion processes. The overall trend suggests a positive and nonlinear relationship, where soil loss increases sharply with increasing slope gradient. At lower slopes, soil detachment remains relatively modest, as runoff velocity is insufficient to mobilize large quantities of sediment. However, as slope steepness increases, both the velocity and erosive power of surface runoff intensify, leading to greater detachment, transport, and downslope deposition of soil particles. The curvature of the relationship implies that small increments in slope gradient can produce disproportionately higher soil losses, indicating threshold behaviour in erosion dynamics. The magnitude of soil loss is further influenced by soil type and rainfall erosivity. Coarse-textured soils such as red sandy loam, with higher infiltration and drainage capacity, generally exhibit lower soil loss compared to fine-textured dark clay loam soils, which have reduced infiltration and higher runoff potential. On steeper gradients, this contrast becomes more pronounced, as clay-rich soils are more easily dispersed and transported. Vegetation cover and conservation practices can also alter the slope–erosion relationship by reducing runoff velocity and increasing infiltration, thereby flattening the curve. Scientifically, the figure underscores that slope gradient is not only a geometric determinant but also a critical amplifier of erosion risk when combined with erodible soils and intense storm events. The steep rise in soil loss at higher gradients signals the need for targeted soil conservation interventions, including terracing, contour bunding, and vegetative barriers, particularly in hill agriculture systems.

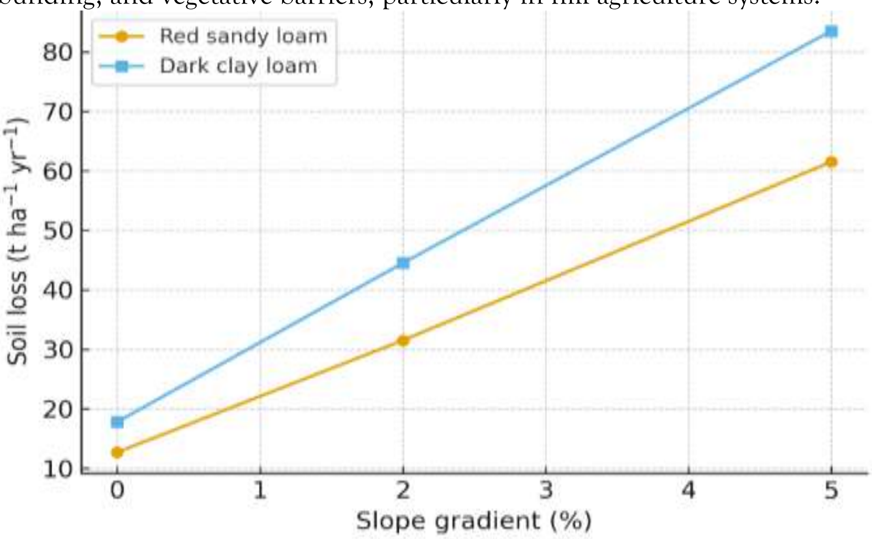

Figure 2: Relationship between soil loss and slope gradient

DISCUSSION

The results of this study reaffirm the multi-factorial nature of soil erosion, where rainfall characteristics, slope topography, and soil properties interact to determine the magnitude and variability of soil loss. Consistent with the findings of Renard et al. (1997) and Kinnell (2010), the erosive storms recorded during 2015-2016 in Chandel District demonstrated that high-intensity, short-duration rainfall events exert a disproportionate influence on annual soil erosion. The rainfall erosivity values, averaging 645 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$, align with Lal's (2019) observations that erosivity serves as the dominant force in accelerating soil degradation in tropical and subtropical agricultural systems. The high variability in erosivity further supports the view of Naish (2014) and Das et al. (2016) that extreme rainfall events are central to understanding erosion risk in monsoon-dominated environments. Topographic controls on soil loss also showed strong agreement with previous literature. Zhang et al. (2003) and Nearing et al. (2017) emphasized that slope length and steepness intensify runoff and sediment yield, findings echoed in the present study where both runoff and soil loss increased markedly with slope extension and gradient. The nonlinear escalation of soil loss at 5% slope reflects Morgan's (2005) and Ghosh et al.'s (2015) assertion that relatively small increases in slope steepness can trigger threshold responses in runoff velocity and sediment detachment, accelerating land degradation in fragile hill systems.

Soil type further modulated the magnitude of erosion, in agreement with Singh et al. (2009) and Mandal et al. (2016). Dark clay loam soils consistently produced higher runoff and soil loss compared to red sandy loam soils, underscoring their weaker structural stability, reduced infiltration capacity, and greater susceptibility to dispersion. This aligns with Liu et al. (2014), who highlighted that soil texture, aggregation, and organic matter critically influence erosion responses to rainfall energy. The greater losses observed in clay loam soils under steep gradients also corroborate Pimentel and Burgess's (2013) warning that erosion-induced fertility decline poses serious threats to agricultural productivity. The utility of the EI_{30} index in capturing rainfall erosivity was further confirmed, consistent with Renard et al. (1997), Sharda et al. (2016), and Kannan et al. (2014), who validated its robustness in diverse agro-ecological contexts. The integration of rainfall erosivity estimates with field-based runoff plot data, as also advocated by Nearing et al. (1999), strengthened the predictive reliability of this study. However, as Sharma and Singh (2010) stressed, the seasonal concentration of rainfall in Northeast India magnifies erosion risks, particularly in fragile hill ecosystems like Chandel District, necessitating localized studies to refine erosion models. The present findings extend previous research by combining rainfall erosivity, slope gradient, and slope length across contrasting soil types in Northeast India, an approach rarely applied at field scales in this region. The findings emphasize that the interaction between climatic and topographic drivers, moderated by soil properties, shapes erosion dynamics in a nonlinear and context-specific manner.

SUMMARY AND CONCLUSION

This research investigated the influence of rainfall erosivity, slope length, and slope steepness on runoff and soil loss in red sandy loam and dark clay loam soils of Chandel District, Manipur. Findings revealed that rainfall erosivity, with a mean value of 645 $MJ \bullet mm \bullet ha^{-1} \bullet h^{-1}$, was a dominant factor driving erosion. High-intensity, short-duration storms were the main contributors to soil loss, showing that extreme rainfall events play a disproportionate role in accelerating erosion in monsoon-dominated hill ecosystems. Topographic factors exerted significant control, as longer slopes and steeper gradients consistently amplified runoff and sediment yield. The nonlinear increase in soil loss under 5% slope conditions reflected threshold dynamics, where small increments in steepness generated disproportionately large erosion responses, highlighting the sensitivity of hill slopes to slight topographic changes. Soil properties further shaped erosion outcomes, with dark clay loam soils consistently producing greater soil loss than red sandy loam soils across all slope treatments. This variation is attributed to the lower infiltration capacity, weaker structural stability, and higher runoff generation in clay-dominated soils compared to sandy loams. The greater vulnerability of clay loam soils under steep slopes emphasizes the risk of accelerated fertility decline and degradation in these fragile agricultural landscapes. The use of the EI_{30} index proved effective in quantifying rainfall erosivity, and its integration with field-based runoff plot measurements enhanced the reliability of erosion assessments. Collectively, the study demonstrates that soil erosion in Chandel District is governed by the interplay of climatic forces, slope geometry, and soil characteristics, which reinforce one another in driving land degradation. The results provide a scientific basis for implementing slope-specific and soil-specific conservation practices. Measures such as contour bunding, terracing, vegetative barriers, and improved land cover management are essential to mitigate erosion. Tailoring erosion models to reflect local soil and rainfall conditions will be vital for sustaining hill agriculture and reducing the risks of land degradation. In the face of increasing climatic variability and more frequent extreme rainfall events, adopting integrated soil and water conservation strategies will be crucial to protect agricultural productivity and ensure long-term sustainability in Northeast India's fragile hill ecosystems.

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