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Integrating DEM-Derived Parameters for Composite Vulnerability Assessment: A GIS-Based Study of a Sub-tropical River Basin of Eastern India

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This study presents a GIS-based method for evaluating terrain vulnerability by creating a Composite Vulnerability Index (CVI) for the lower Ajay River Basin in eastern India. It combines seven DEM-derived parameters, Slope, LS-Factor, Stream Power Index (SPI), Topographic Wetness Index (TWI), Convergence Index (CI), Valley Depth (VD) and Plan Curvature (PC), to reflect geomorphic and hydrological features that influence erosion and surface stability. Each parameter was reclassified, normalized and given equal weight to calculate the CVI, using raster analysis in ArcGIS (Evaluated copy). The CVI values ranged from 1.28 to 4.43 and were divided into five vulnerability categories. The spatial analysis revealed that the medium vulnerability zone is the largest, covering about 42.54% of the basin, followed by low (23.74%) and high (20.22%) zones. Very high and very low vulnerability areas make up 8.56% and 4.94%, respectively. The western uplands and dissected lateritic regions are the most vulnerable, while the eastern floodplains are relatively stable. The results highlight that slope, flow convergence and relief energy are key factors driving geomorphic instability in the basin. The CVI framework provides a reliable and reproducible method for identifying priority zones for soil and water conservation, supporting sustainable watershed management in eastern India's sub-tropical regions.

Keywords: Composite Vulnerability Index (CVI); Geomorphic and Hydrological Parameters; DEM-Based Modelling; Terrain Susceptibility; GIS and Remote Sensing; Lower Ajay River Basin

1. Introduction

In recent years, assessing terrain vulnerability has become crucial for watershed research and environmental management, especially in areas undergoing rapid geomorphic and hydrological changes (Fuchs et al. 2019). River basins in eastern India are experiencing increasing impacts from irregular rainfall, deforestation, unplanned land use, and surface modifications (Chakraborty 2021), all of which increase erosion and runoff. Using quantitative geospatial modelling to understand the spatial variation of terrain vulnerability offers important insights for sustainable land and water resource management.

The Composite Vulnerability Index (CVI) provides a comprehensive framework for assessing spatial susceptibility by combining terrain and hydrological parameters derived from Digital Elevation Models (DEMs). These DEM-derived indices, such as slope, topographic wetness index (TWI), stream power index (SPI), convergence index (CI), LS-factor, valley depth and curvature, effectively represent the morphological and hydrological features that influence erosion, infiltration and flow concentration. Using these indicators within a GIS environment enables the identification of areas at risk of physical instability, erosion and surface runoff stress (Sarkar and Mondal 2020; Das and Paul 2021).

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The lower Ajay River Basin, located in the semi-arid-subtropical transition zone of eastern India, features a distinctive landscape characterized by rolling terrain, dissected uplands and a history of soil degradation (Dey and Sahoo 2023). The basin exhibits significant topographic variability, from lateritic uplands to floodplains, which affects hydrological processes and surface vulnerability (Mukherjee et al. 2022; Nautiyal, Bhaskar and Khan 2015). While various studies have examined groundwater or soil erosion in parts of the Ajay Basin, a comprehensive assessment of geomorphic and hydrological vulnerability using a combined index approach is still limited.

Several researchers have explored combining morphometric and hydrological parameters to assess terrain vulnerability across various regions. Singh and Panda (2019) utilized morphometric indices to identify erosion-prone areas in the Subarnarekha Basin, while Bera and Bhattacharya (2020) applied a multi-criteria GIS method for landform susceptibility mapping in West Bengal's western lateritic tract. Similarly, Pradhan and Sahoo (2021) created a composite erosion vulnerability model based on slope, SPI and TWI in the upper Mahanadi Basin. These studies highlight the effectiveness of DEM-based analysis in revealing spatial patterns of terrain sensitivity. Nevertheless, most existing research tends to focus on either morphometric or hydrological aspects, with few efforts to integrate both into a unified framework.

In the context of the Ajay River Basin, previous studies have addressed land degradation, morphometric characterization and sediment yield analysis (Chakraborty et al. 2020; Mukherjee et al. 2022), yet no comprehensive research has examined the combined influence of geomorphic and hydrological indices on spatial vulnerability. This gap highlights the need for a systematic composite assessment capable of quantifying the relative instability of various terrain units. The present study addresses this gap by developing a GIS-based Composite Vulnerability Index (CVI) model using seven DEM-derived parameters to identify and map vulnerability zones within the lower Ajay River Basin. The approach not only improves scientific understanding of terrain behaviour but also helps formulate effective watershed management strategies for sustainable development.

2. Study Area:

This study focuses on the lower Ajay River Basin in eastern India, spanning the states of Jharkhand and West Bengal. The basin roughly extends from 23°30′N to 24°05′N and from 86°45′E to 87°30′E, covering approximately 2,600 square kilometres. The Ajay River begins in the Jamui Hills of Jharkhand and flows eastward through lateritic uplands before joining the Bhagirathi River near Katwa in Purba Bardhaman District. The lower basin, which is the primary focus of this research, includes parts of the districts of Bankura, Birbhum, Paschim Bardhaman, and Purba Bardhaman (Dey and Sahoo 2023).

The region features a mix of gently rolling lateritic uplands, large pediplains and floodplains, illustrating its transitional landscape between the Chota Nagpur Plateau and the Bengal alluvial plains. Elevations vary from about 40 meters in the eastern floodplains to over 280 meters in the western highlands, creating diverse slopes and drainage systems (Nautiyal, Bhaskar, and Khan 2015). The river network mainly follows a dendritic pattern, with temporary tributaries such as Kunur and Tumuni, which cause rapid surface runoff during heavy monsoon rains.

The climate features a subtropical monsoonal pattern with hot, dry summers, a humid monsoon season and mild winters. Annual rainfall varies from 1,100 to 1,400 mm, with about 80% falling between June and September. The soils are primarily lateritic and sandy loam, exhibiting low water retention in upland areas and higher moisture levels in floodplains (Dey and Sahoo 2023). Land use mainly includes rainfed agriculture, fallow lands and forest patches. However, surface instability is increasing due to agricultural intensification and deforestation (Nautiyal, Bhaskar, and Khan 2015).

The lower Ajay Basin's varied geomorphic and hydrological features make it suitable for analyzing the Composite Vulnerability Index (CVI). Its landscape includes both erosional and depositional characteristics shaped by topography and rainfall. The area's physiographic diversity, human influences and climate variations provide a solid basis for evaluating spatial vulnerability and creating sustainable watershed management plans (Sarkar and Mondal 2020; Mukherjee et al. 2022).

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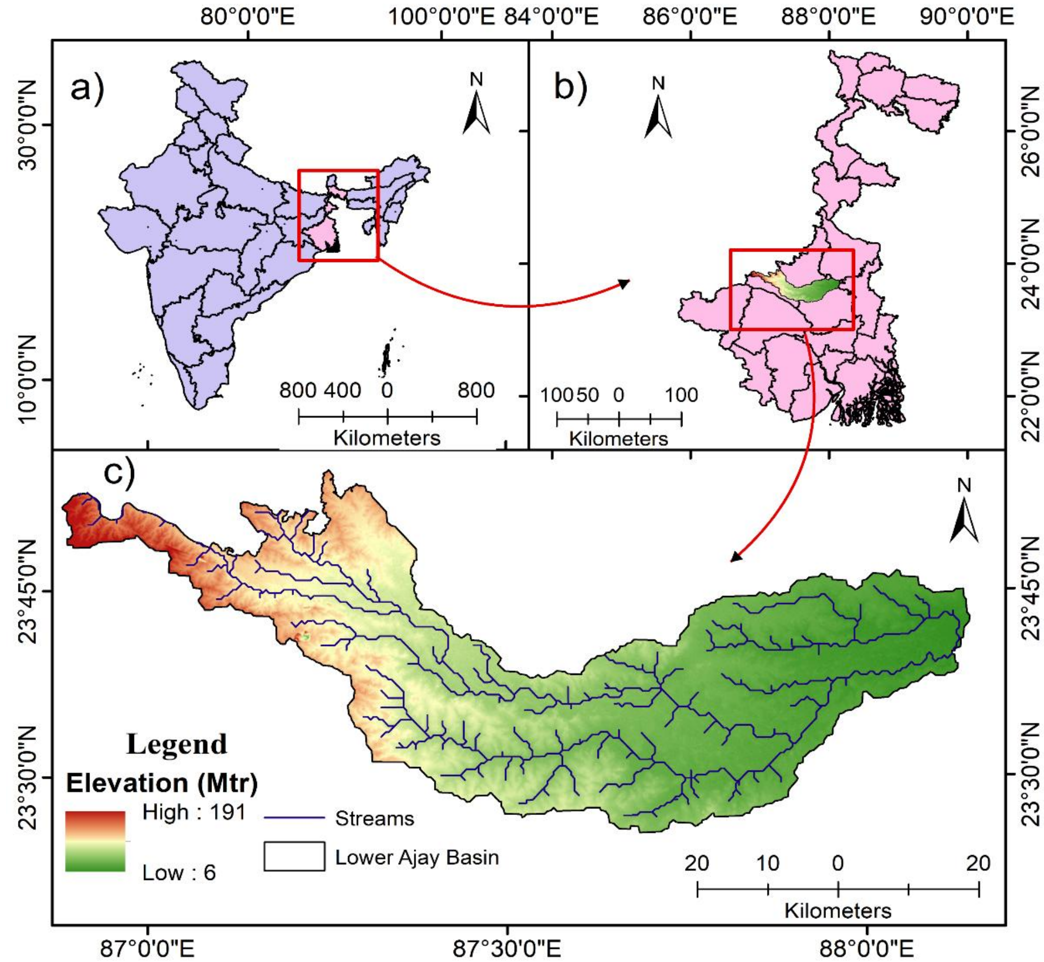

3. Database and Methodology:

The methodology adopted in this study integrates multiple DEM-derived geomorphic and hydrological parameters to generate a Composite Vulnerability Index (CVI) that reflects spatial variations in terrain instability and hydrological stress within the lower Ajay River Basin. The analysis was entirely conducted within a Geographic Information System (GIS) environment using *ArcGIS 10.8* (Evaluated copy), *Q-GIS* and *SAGA GIS*, ensuring consistency in spatial resolution, coordinate system and cell alignment.

3.1 Database:

The main database for this study consists of the Shuttle Radar Topography Mission (SRTM) DEM at 30-meter resolution, sourced from the United States Geological Survey (USGS) EarthExplorer platform. This DEM served as the basis for deriving topographic and hydrological parameters. Additional layers, including drainage networks and administrative boundaries, were also used for contextual analysis. All datasets were standardized to the WGS 84 projection system (UTM Zone 45N) and clipped to the boundary of the lower Ajay Basin for analysis.

The analysis involved creating seven DEM-based parameters that represent both geomorphic and hydrological features: Slope, LS-Factor, Stream Power Index (SPI), Topographic Wetness Index (TWI), Convergence Index (CI), Valley Depth (VD) and Plan Curvature (PC). These indices were chosen for their complementary ability to depict how the terrain responds mechanically and hydrologically during rainfall-runoff processes.

3.2 Methodological Framework

3.2.1 Derivation of Parameters

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Slope - Derived directly from the DEM, slope expresses the steepness of the terrain and controls runoff velocity, infiltration rate, and soil detachment. Higher slopes generally indicate greater erosion susceptibility. Thus, slope was considered a beneficial parameter (i.e., higher values indicate greater vulnerability).
LS-Factor - This factor combines slope length (L) and steepness (S), representing the erosive power of flowing water. The LS-Factor was computed using the formula of Moore and Burch (1986) within the SAGA GIS environment. Since longer, steeper slopes accelerate soil loss, they were classified as a beneficial parameter.
Stream Power Index (SPI) - SPI quantifies the erosive power of surface flow as a function of slope and catchment area. It highlights zones with high flow accumulation and energy, often corresponding to channel initiation or gullying. SPI was treated as a beneficial parameter because higher values indicate greater erosional potential.
Topographic Wetness Index (TWI) - TWI measures the spatial distribution of soil moisture and potential water accumulation. It is inversely related to erosional risk, as higher TWI areas indicate moisture concentration and lower flow velocity. Therefore, TWI was considered a non-beneficial parameter (i.e., higher values indicate lower vulnerability).
Convergence Index (CI) - CI defines the degree to which surface flow converges or diverges at a point. Highly convergent areas tend to accumulate water and experience concentrated flow erosion. Consequently, CI was considered a beneficial parameter, with higher values indicating more vulnerability.
Valley Depth (VD) - Valley depth represents the relative incision of the landscape, showing the difference between ridge tops and valley bottoms. Deeply incised valleys reflect intense erosional processes and strong hydrological energy. Therefore, VD was classified as a beneficial parameter.
Plan Curvature (PC) - This curvature parameter reflects the shape of the surface in a horizontal plane and influences flow acceleration or deceleration. Convex curvature areas promote runoff acceleration, while concave ones encourage deposition. Since convex slopes enhance erosion, positive curvature values were assigned higher vulnerability ranks, making PC a beneficial parameter.

Each raster layer was normalised and reclassified into five ranks (1-5) using the natural breaks method (Jenks), where 1 represents the lowest vulnerability and 5, the highest. For the non-beneficial parameter (TWI), ranking was reversed to maintain consistency of interpretation.

3.2.2 Composite Vulnerability Index (CVI) Model

The Composite Vulnerability Index (CVI) was computed by integrating all seven ranked layers using an equal-weight linear combination model, assuming that each parameter contributes equally to the overall terrain vulnerability (Liyew and Essén 2017). The computation was performed in the *Raster Calculator* tool in ArcGIS (Evaluated copy) using the following mathematical expression:

$$CVI = \frac{1}{7} \times (\mathrm{Re\_Slope} + \mathrm{Re\_LS} + \mathrm{Re\_SPI} + \mathrm{Re\_TWI} + \mathrm{Re\_CI} + \mathrm{Re\_VD} + \mathrm{Re\_PC})$$

Where, CVI= Composite Vulnerability Index, Re= Reclassified raster layers. To avoid integer division errors, weights were applied as floating-point constants (0.142857). The output raster was saved in 32-bit float format to preserve decimal precision.

Subsequently, the CVI raster was reclassified into five vulnerability classes, Very Low, Low, Moderate, High and Very High, using the Natural Breaks (Jenks) method to preserve the natural clustering of data. This classification provided a clear spatial representation of vulnerability zones across the basin.

3.2.3 Model Validation and Interpretation

Although direct field validation of terrain vulnerability is complex, the CVI pattern was compared with observed slope-drainage relationships, known erosion-prone locations and geomorphic features visible on high-resolution satellite imagery. Areas with higher CVI values corresponded well with deeply incised valleys, steep slopes, and lateritic uplands, confirming the model's reliability. The consistency between computed vulnerability zones and geomorphic reality suggests that the model effectively captures the combined impact of topography and hydrological flow concentration (Bera and Bhattacharya 2020; Pradhan and Sahoo 2021).

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4. Results

The DEM-derived parameters used in the present study collectively reveal the geomorphic and hydrological characteristics that control terrain instability in the lower Ajay River Basin. Each parameter expresses a specific aspect of the terrain, influencing runoff, erosion, and water-accumulation patterns. The spatial patterns of these indices in figure 2 provide a comprehensive picture of how the landscape responds to rainfall and surface-flow processes.

4.1. Slope

The slope map of the basin shows values ranging from 0° to 30.70°, indicating a gradual transition from the steep lateritic uplands in the west to nearly level floodplains in the east (Figure 2). The western part of the basin, particularly around the elevated dissected plateau remnants, exhibits slopes exceeding 20°, indicating higher erosional susceptibility and greater runoff generation. In contrast, the central and eastern sectors are dominated by gentle slopes below 5°, associated with depositional landforms and lower mechanical instability. The spatial trend demonstrates that slope-induced erosion risk is concentrated in the western and northwestern highlands, where relief energy and drainage incision are prominent (Bera and Bhattacharya 2020).

4.2. LS-Factor

The LS-Factor, representing slope length and steepness, ranges from 0 to 76.64 within the study area (Figure 2). High LS values occur along elongated hill slopes and stream corridors in the western upland section, implying stronger erosive power of overland flow. The central pediplain zone shows moderate LS values due to longer slope lengths and reduced steepness, while the eastern plains record minimal LS values, reflecting stable, less erosive surfaces. The spatial configuration suggests that the western ridges and their flanks contribute significantly to sediment detachment during monsoon runoff events (Pradhan and Sahoo 2021).

4.3. Stream Power Index (SPI)

The SPI values range widely from -15,123.3 to 30,036.7, reflecting substantial variability in erosive energy across the basin (Figure 2). Positive high SPI zones, mainly along the middle and lower reaches of tributaries, denote areas where flow accumulation and gradient combine to produce high stream power. The central basin displays moderate SPI values, indicating transitional areas where slope-driven energy begins to decline. Negative SPI values in the upper divides correspond to flat or divergent surfaces, where flow initiation is minimal. The high SPI regions along entrenched valleys clearly correspond with areas of active fluvial incision and high sediment mobility.

4.4. Topographic Wetness Index (TWI)

The TWI map shows values between 4.35 and 20.86, depicting the relative distribution of soil moisture and runoff convergence (Figure 2). Higher TWI values, concentrated in the lower and eastern parts of the basin, represent areas with greater water accumulation and lower erosion susceptibility. Conversely, low TWI zones in the upper and western uplands correspond to steep, convex surfaces with poor moisture retention and high runoff potential. This pattern indicates that the basin's hydrological response is spatially controlled by topography: western ridges promote surface flow, while the eastern plains facilitate water storage and infiltration. TWI thus acts as a balancing index, moderating the influence of slope and SPI on overall vulnerability (Das and Paul 2021).

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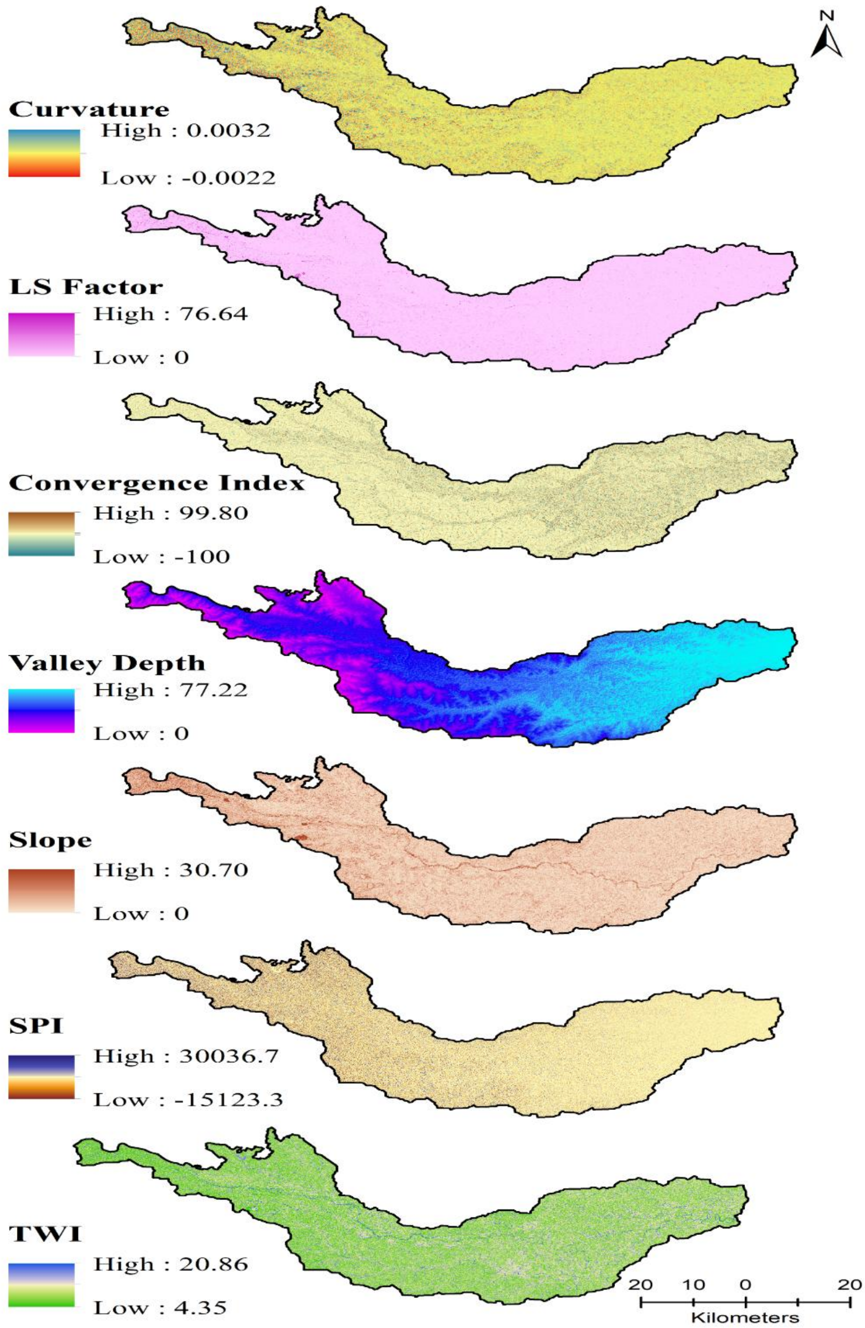

Fig. 2: Spatial distribution of geomorphic and hydrological parameters: a) Curvature, b) LS-Factor, c) Convergence Index, d) Valley Depth, e) Slope, f) Stream Power Index (SPI) and g) Topographic Wetness Index (TWI)

4.5. Convergence Index (CI)

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The Convergence Index ranges from -100 to +99.8, indicating whether surface flow converges or diverges at specific points (Figure 2). High positive CI values are observed in the central and southern regions, corresponding to concave valley networks where water flow converges, leading to concentrated erosion. Negative CI values dominate the upland divides, indicating divergent slopes where flow disperses. The CI pattern effectively outlines the basin's internal drainage structure and closely aligns with the natural channel network. Areas of high convergence coincide with zones of high SPI, confirming their joint influence on flow accumulation and gully formation.

4.6. Valley Depth

Valley depth varies from 0 to 77.22 metres, highlighting the degree of fluvial incision and relief contrast within the basin (Figure 2). The deepest valleys occur in the western highlands, where long-term erosion has produced narrow V-shaped channels and strong vertical dissection. Moderate valley depth in the central portion represents transition zones between erosional uplands and depositional lowlands. The eastern sector displays shallow valleys due to reduced slope energy and finer alluvial deposits. The strong correlation between valley depth and slope emphasises that relief energy and incision potential are primary controls of vulnerability in this region (Sarkar and Mondal 2020).

4.7. Plan Curvature

Plan curvature values range from -0.0022 to +0.0032, indicating both concave and convex surface characteristics (Figure 2). Positive curvature (convex) areas, mainly in the western and central highlands, accelerate surface runoff and enhance erosional force. In contrast, negative curvature (concave) areas correspond to depositional zones or local depressions where sediment and moisture accumulate. The near-zero curvature in the eastern plains signifies gently undulating or flat terrain with minimal flow acceleration. Overall, the curvature distribution provides a refined understanding of micro-topographic influences on flow direction and surface stability.

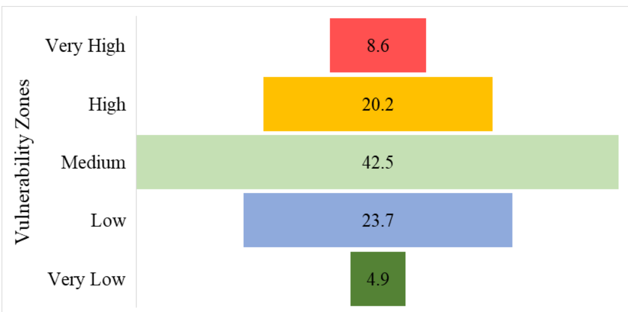
4.8. Composite Vulnerability Index (CVI)

The seven DEM-derived parameters were combined to create a Composite Vulnerability Index (CVI), which clearly shows the terrain susceptibility across the lower Ajay River Basin. The CVI scores were divided into five vulnerability levels, very low, low, medium, high and very high, using the natural break classification. The area proportions of each category reflect the basin's geomorphic and hydrological diversity (Figure 3).

The medium vulnerability zone is the largest, covering approximately 1,117.73 sq. km (42.54%) of the basin. It represents transitional terrain with moderate slopes, mixed soil moisture and balanced runoff processes. The low vulnerability zone spans 623.91 sq. km (23.74%), mainly in the eastern floodplains and gentle pediplains, where gentler slopes and higher TWI values reduce erosion risk. The high-vulnerability zone, covering 531.22 sq. km (20.22%), is mainly found in the western uplands and dissected plateau edges, where steeper slopes, higher LS-Factor values, and elevated SPI values increase runoff speed and soil erosion.

The very high vulnerability zone covers over 225.00 sq. km (8.56%), primarily along steep lateritic ridges and incised valleys, representing geomorphologically unstable landscapes with high erosion risk that need urgent soil and water conservation measures. In contrast, the very low vulnerability zone spans just 129.70 sq. km (4.94%) and is located on nearly flat alluvial and depositional surfaces characterized by low relief energy and high moisture accumulation.

Overall, the CVI results reveal that about two-thirds of the lower Ajay Basin exhibits medium to high vulnerability, highlighting notable geomorphic sensitivity to hydrological disturbances. The results emphasize that the slope gradient, flow convergence, and relief depth together influence the spatial variation in terrain vulnerability.



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4. Discussion

The results of the Composite Vulnerability Index (CVI) analysis reveal a complex interplay between geomorphic form and hydrological behaviour within the lower Ajay River Basin. The spatial variation of vulnerability categories reflects the combined influence of slope gradient, drainage convergence and surface moisture conditions. The predominance of medium and high-vulnerability zones (nearly 63% of the basin) suggests that the terrain is moderately to highly sensitive to rainfall-driven erosion and surface instability.

The western and northwestern upland sectors of the basin exhibit the highest vulnerability. These areas are characterised by steep slopes, elongated hill fronts and narrow valleys that promote rapid runoff and concentrated flow energy. The dominance of high LS-Factor and Stream Power Index (SPI) values further confirms the erosive nature of these landscapes. The presence of lateritic soils with limited water-retention capacity aggravates the vulnerability by enhancing infiltration deficits and increasing surface wash. Similar patterns have been reported by Sarkar and Mondal (2020) and Bera and Bhattacharya (2020) in other lateritic terrains of West Bengal, where high relief and coarse-textured soils contribute significantly to geomorphic instability.

In contrast, the eastern and southeastern portions of the basin exhibit low to very low vulnerability. These regions are predominantly alluvial plains with gentle slopes, shallow valleys and high TWI values, indicating greater moisture accumulation and reduced runoff velocity. The hydrological setting favours deposition rather than erosion, stabilising the terrain surface. The moderate category, which accounts for the largest share, serves as a transition between upland erosion zones and stable floodplains. This middle band represents mixed hydrological conditions, where moderate slopes and variable soil textures balance erosional and depositional forces.

The spatial organisation of the vulnerability classes mirrors the basin's geomorphic evolution, from dissected plateau remnants in the west to sedimentary plains in the east. The gradual decline in slope, valley depth and SPI from west to east highlights a west-east gradient of decreasing erosional energy, consistent with the region's morphotectonic framework (Mukherjee et al. 2022). This transition also underscores the sensitivity of upland catchments, which serve as the primary sources of sediment and runoff that affect downstream floodplain stability.

From a management perspective, the CVI findings emphasise that high and very high vulnerability areas require priority intervention through soil and water conservation measures such as contour bunding, gully plugging and vegetative stabilisation. In moderately vulnerable areas, integrated land-use management, including agroforestry and controlled cultivation, can help balance productivity with sustainability. Low-vulnerability zones, which are relatively stable, can be developed for groundwater recharge and small-scale water-harvesting structures.

The present approach demonstrates that a DEM-based composite index can effectively delineate terrain vulnerability even in data-scarce regions. By combining geomorphic and hydrological dimensions, the model captures the true spatial variation in environmental stress zones. These findings contribute to a broader understanding of terrain-process relationships and support regional-level planning for sustainable watershed management in eastern India.

5. Recommendations

The CVI analysis shows that the lower Ajay River Basin faces substantial geomorphic and hydrological stress, especially in the western and northwestern uplands. These fragile ecological zones are highly vulnerable to rainfall-driven erosion, soil degradation and surface runoff. To promote sustainable management and ensure long-term landscape stability, the following recommendations are offered, taking into account the vulnerability zones and terrain conditions.

5.1 Soil and Water Conservation Measures

In zones with high and very high vulnerability, it is essential to prioritize mechanical and vegetative soil conservation methods. Techniques such as contour bunding, terracing, check dams and gully plugging effectively reduce runoff speed and prevent soil erosion. Planting vetiver grass and other

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deep-rooted species along slope edges can help stabilize the soil and enhance water infiltration (Bera and Bhattacharya 2020).

5.2 Afforestation and Land Rehabilitation

The western lateritic uplands, which are highly vulnerable, require widespread afforestation with native, drought-resistant species. Reforestation of degraded slopes supports vegetation restoration, minimizes splash erosion and enhances soil quality. Implementing controlled grazing and community-driven planting initiatives can further strengthen slope stability and ecological resilience.

5.3 Agroforestry and Sustainable Land Use

In areas with moderate vulnerability, promoting an agroforestry land-use system can help balance farming outputs and environmental conservation. Techniques such as mixed cropping, interplanting legumes and establishing vegetative barriers along contour lines can lessen surface runoff and enhance soil health. Land-use zoning should also aim to limit intensive farming on steep slopes to avoid further land degradation (Sarkar and Mondal 2020).

5.4 Water Harvesting and Groundwater Recharge

The zones with low and very low vulnerability, mainly on gentle slopes and alluvial plains, are ideal for small water-harvesting projects such as farm ponds, percolation tanks and recharge pits. These solutions will boost groundwater reserves, reduce reliance on monsoon rainfall, and support dry-season irrigation.

5.5 Community Awareness and Participatory Management

Local participation is vital for the success of conservation programs (Nguyen 2015). Awareness campaigns about soil erosion, land degradation and water management should be organized through Panchayat-level institutions and self-help groups. Engaging local stakeholders in planning and monitoring will help ensure the long-term sustainability of these initiatives (Mukherjee et al. 2022).

5.6 Policy Integration and Periodic Monitoring

The results of this study can be incorporated into district-level watershed management programs. Regular monitoring using remote sensing and GIS should be formalized to observe changes in vulnerability and assess the success of measures taken. Updating the CVI model periodically with high-resolution DEM and multi-temporal data can enhance the precision of future evaluations.

Overall, these recommendations highlight that addressing vulnerability requires a comprehensive watershed management approach that integrates engineering, vegetative and community strategies rather than relying on individual interventions. Applying these methods can notably decrease geomorphic instability and promote sustainable resource use in the lower Ajay River Basin.

Conclusion

This study used GIS to combine various DEM-derived geomorphic and hydrological parameters to evaluate terrain vulnerability in the lower Ajay River Basin in eastern India. A Composite Vulnerability Index (CVI) was developed to illustrate spatial differences in geomorphic susceptibility clearly. Results show that the western and northwestern uplands are most vulnerable due to steep slopes, high LS-Factor values, and elevated Stream Power Index (SPI) values. Conversely, the eastern and southeastern areas, characterized by gentle slopes and high Topographic Wetness Index (TWI) values, exhibit lower vulnerability. The presence of predominantly medium- and high-vulnerability zones underscores the basin's moderate sensitivity to geomorphic and hydrological issues.

The CVI method has been successful in identifying vulnerable zones in regions with limited data. Incorporating basic terrain parameters within a GIS framework provides a practical, repeatable way to prioritize areas for soil and water conservation efforts. These results enhance understanding of the spatial distribution of landscape stability and can support targeted watershed planning and management in specific regions.

However, some limitations should be recognized. The study used only a single-resolution DEM, which may have affected the accuracy of derived indices such as slope and curvature. Limited field data restricted comprehensive ground validation. Additionally, the equal-weighting method used for parameter integration might not accurately reflect the differing importance of each factor.

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Future research should use higher-resolution DEMs, apply multi-criteria weighting methods and include field-based erosion and rainfall data to improve validation. Adding land-use and lithological variables could further improve the model's accuracy.

Overall, this study finds that the main factors influencing terrain vulnerability in the lower Ajay Basin are topographic steepness, flow convergence and relief energy. These findings provide a scientific foundation for sustainable watershed management and land-use planning in comparable sub-tropical river basins in eastern India.

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