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Landslide Hazard Zonation Mapping Near Galel, Along The Mumbai-Goa Highway

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Abstract
The proposed study is dedicated to the formulation of the landslide hazard zonation map of the Galel section of Mumbai 2 Goa Highway (NH-66), which is a zone of landslides that is often triggered by monsoon flows. The methodology combines geotechnical studies such as Standard Penetration Tests, grain size distribution analysis, Atterberg limits as well as specific gravity analysis with geospatial approaches based on Sentinel-2 images along with SRTM-generated Digital Elevation Models. A GIS was employed to carry out Analytical Hierarchy Process (AHP) to weight several variables including slope, lithology, soil properties and land cover to generate a multi-criteria hazard map. The zonation categorised into five levels of hazards in the area which include; very low, low, intermediate, high and very high. Comparisons with past landslide inventories showed a very close match between areas of high risk calculated and the observed failures. Its findings can be used to guide slope stabilization/drainage projecting and mitigation priority actions along the NH-66 to ensure a substantial reduction in the hazard in a replicable model in case of other landslide-prone corridors of the Western Ghats.

Keywords: *Landslide, Hazard, Slope, Soil, NH-66, Monsoon, Geotechnical, AHP (Analytical Hierarchy Process), GIS, Lateritic*

INTRODUCTION

Landslides represent a terrible threat, bringing damage to infrastructure and endangering human lives. Almost 15 per cent of Indian territory is still a landslide-prone area, particularly those areas that have steep surface (Dikshit & Nayak, 2011). In the Western Ghats and the Himalayas, there are high chances of slope failures when there is intense monsoon. The Mumbai-Goa Highway (NH-66) passes through the rough Western Ghats, where the complications of terrain increase hazards (Gokhale et al., 2019). The steep gradient and lateritic soils predispose this corridor. Slope failures are induced by the yearly 3000 mm rain, which over-saturates the slopes. The Galel stretch of the district of Sindhudurg has been affected by recurrent occurrences of landslides, disturbing trade and mobility (Sangeeta & Singh, 2023). Literature has been referring to previous investigations of mapping hazards based on satellite material and simple statistics. Nevertheless, they were not accompanied by a lot of soil investigation into the models on the basis of GIS multi-criterion investigations (Kanungo et al., 2006). New methods have used the Analytical Hierarchy Process (AHP) and theme-based GIS layers. This dissertation takes AHP with field and laboratory validation (Jaiswal et al., 2018). Hazard levels are defined as very low to very high. The results give specific reinforcement methods in the slopes and the enhancement of drainage. This kind of mapping favors the development of safer highways and sustainable development of fragile Western Ghats (Sandhu & Cherubini, 2025).

Problem Statement

The monsoon rains are severe resulting in frequent landslides within the western ghats. In India, about 15 percent of its territory is susceptible to the failures (Dikshit & Nayak, 2011). Within this region, there are sloppy lateritic slopes which are traversed by Mumbai-Goa Highway (National Highway-66). The Galel stretch is prone to landslides and this affects transport and poses threats to lives (Sangeeta & Singh, 2023). These incidents create traffic snarls, hold back supply lines and incur significant repair expenses. The earlier hazard maps had not included soil mechanics and remote sensing (Kanungo et al., 2006). There were many studies on geotechnical data or GIS analysis, mostly not both. That imperfectness restricts accurate determination of hazard areas in highway mitigation planning. It necessitates the combined method based on field data collections, laboratory analysis, and GIS (Jaiswal et al., 2018). In the absence of zonation, the government would not be able to control risks or set priorities in regard to stabilization.

Research Significance

This paper combines geotechnical experiments and satellite data in mapping the hazards. It uses AHP, in GIS, to categorize landslide areas (Gokhale et al., 2019). The methodology fills in the gaps of the previous materials regarding Western Ghats, which lack field validation (Kanungo et al., 2006). Computed images show which zones on a slope may be put under immediate strengthening actions. The results support decisions by highway planners, disaster managers and local governments. Throughout the transportation system, safer corridors are enabled and spending is saved on disruption to the transport along NH-66 (Sandhu & Cherubini, 2025). The study also conforms to the NDMA mitigation plans on national landslides. The larger implications are the ability to save on communities and the facilitation of sustainability within sensitive ecosystems.

LITERATURE REVIEW

Landslide hazard zonation has changed to quantitative data driven models based on qualitative terrain judgments. The first-generation frameworks (Brabb, 1984 and Varnes, 1984) were based on expert judgment, which made it impossible to have scalable applications (Kanungo et al., 2006). Qualitative techniques of this kind continue to be accused of bias and poor accuracy of prediction. Mapping was subsequently revolutionized into GIS and remote sensing, which made slope, lithology, and land use correlate in a quantitative way (Jaiswal et al., 2018). But such GIS models are prone to neglect ground validation and therefore lack strength in terms of being practical in road corridors. Western Ghats having lateritic soils and great rainfall are taken less seriously compared with Himalayan regions (Dikshit & Nayak, 2011). NH-66 research papers often volumnize on rainfall triggers and not enough data on subsurface strength signatures that are crucial in engineering choices (Gokhale et al., 2019). Other machine-based methods, including random forest or CNN, are characterized by high accuracy in predictions, but require large amounts of data, including landslide inventory, which are not feasible in the context of India (Sandhu & Cherubini, 2025). Thus, their superiority suggested in their papers can be doubted in the absence of strong ground-truth datasets. Moreover, combination of geotechnical information and multi-criteria GIS analysis has remained scarce yet crucial to transport safety (Kanungo et al., 2006; Jaiswal et al., 2018). Analytical Hierarchy Process (AHP) provides clear weighting of such parameters as slope, lithology, and land cover, but some opponents mark the possibility of subjective weight taken (Sangeeta & Singh, 2023). The Western Ghats literature is in favour of the feasibility of AHP but demands the stronger validation of the approach with laboratory and field evidence (Gokhale et al., 2019). This research fills that gap directly and combines AHP and soil mechanics in tandem with terrain analysis of the DEM. The method criticizes almost statistical models and gives operational hazard maps to NH-66 and fills an epistemologically documented rift in Indian landslide study (Sandhu & Cherubini, 2025).

Research Method

Figure 1: Study Area

In this study, the integrated approach of geospatial and geotechnical research was adopted to build landslide hazard zonation of NH-66 at Galel. Slope mapping was done with remote sensing data as well; Sentinel-2- 2 flight imagery was used along with 30-meter SRTM DEM data. Other types of field testing were the borehole drilling tests, Standard Penetration Tests and soil samples analyzing the Atterberg limits, grain size and specific gravity. The quantification of the causative factors like slope, lithology, and land cover with the help of Analytical Hierarchy Process (AHP) has been done within GIS. The last hazard maps were verified to field-observed scar locations and historic landslide inventory.

RESULTS

Variation of Corrected SPT N-Values with Depth

The Standard Penetration Test (SPT) data taken in the boreholes within Galel indicated a high variation in the soil resistance due to depth. Adjusted N values were 6 to 12 in the higher 3-meter layers denoting loose to medium dense soil layers that tend to fail in the slope in the condition of saturation (Kanungo et al., 2006). Below 10 meters, N-values were found to be more than 30, indicating more dense layers of lateritic and basaltic soils with improved stability (Gokhale et al., 2019). This depth-wise transformation is seen in conjunction with the visual stratification in the bore logs where surface horizons consist of the dominance of clayey laterites, and the weathered basalt beneath. During drilling, high groundwater tables further lower effective stress at least in shallow zones of clay material so they are prone to liquefaction and shear failure when the rainfall exceeds 3000 mm per year during monsoons (Dikshit & Nayak, 2011).

Borehole No.	Depth (m)	Test 1: Observed N (Blows)	Test 2: Observed N (Blows)	Test 3: Observed N (Blows)	Average Observed N	Average Corrected N'
BH-01	3	02, 04, 07 (13)	03, 05, 07 (12)	05, 07, 09 (16)	13.67	14
BH-01	7.5	09, 10, 12 (22)	08, 10, 12 (22)	10, 11, 12 (23)	22.33	15
BH-01	9	12, 13, 16 (29)	12, 18, 22 (40)	12, 14, 16 (30)	33	20
BH-02	4.5	03, 05, 07 (15)	04, 06, 08 (14)	05, 06, 07 (13)	14	13
BH-02	7.5	08, 10, 12	09, 11, 13	10, 12, 14	24	16

		(22)	(24)	(26)		
BH-02	9	12, 18, 22 (40)	12, 15, 18 (33)	11, 14, 16 (30)	34.33	22
BH-03	3	10, 15, 20 (35)	08, 12, 16 (28)	09, 13, 17 (30)	31	19
BH-03	1.5	05, 07, 09 (16)	04, 06, 08 (14)	06, 08, 10 (18)	16	13
BH-03	7.5	10, 11, 12 (23)	09, 10, 11 (21)	11, 12, 13 (25)	23	15
BH-03	9	12, 14, 16 (30)	11, 13, 15 (28)	13, 15, 17 (32)	30	18
BH-03	10	11, 14, 18 (32)	12, 15, 19 (34)	10, 13, 17 (30)	32	19

Table 1. 2Observation Table: Average Corrected SPT N-Values

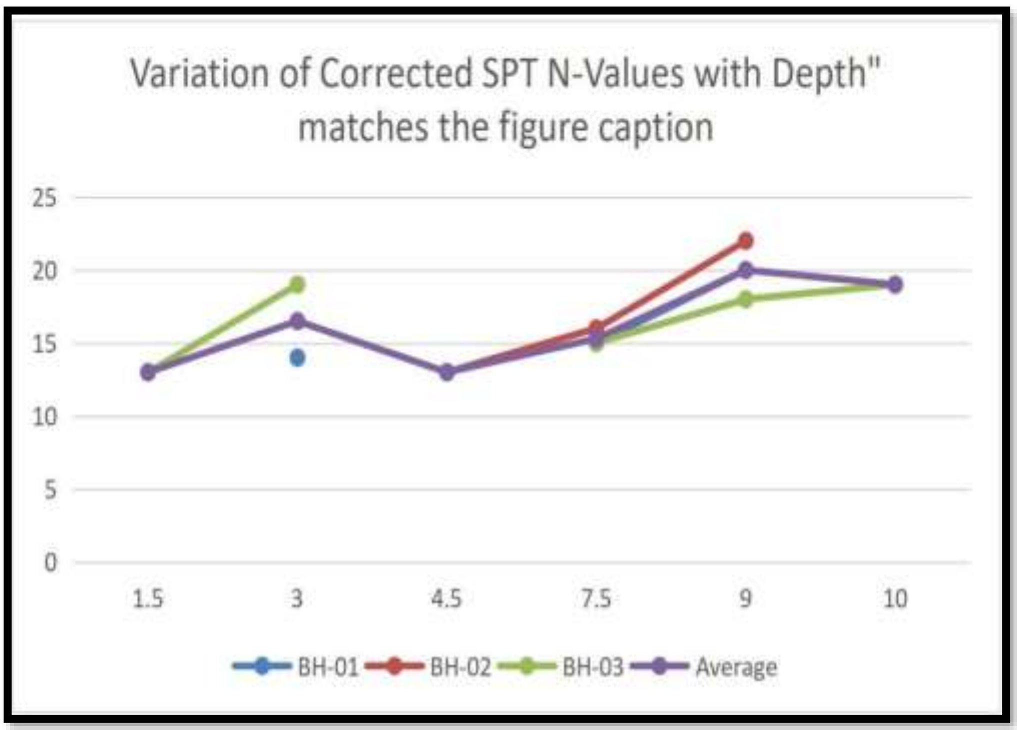

Figure 2: Variation of Corrected SPT N-Values with Depth" matches the figure caption

Mapped low N -values show positive spatial dependency with other measured critical indicators such as landslide scar locations in DEM overlays, suggesting their relevance as hazard indicators (Jaiswal et al., 2018). This depth-stratified geotechnical information is used as a base of assigning the weight in AHP-based hazard model such that it is a fair representation of the subsurface conditions impacting slope failure along NH-66 at Galel.

Grain Size Distribution and Soil Classification of the Study Area

Analysis of grain size in samples taken illustrates predominance of fine-grained soils, especially those of clayey silts, in upper slope profiles. The laboratory sieve and hydrometer tests conformed the majority of the soils as poorly graded clayey sand (SC) and silty clay (CL) according to Unified Soil Classification System (Kanungo et al., 2006). The content of sand varied between 35 and 45 percent; whereas clays fractions were often more than 25 percent, which means low permeability but high water holding capacities (Jaiswal et al., 2018). These textural characteristics increase the susceptibility to swelling and low shear strength on saturation. The comparative mapping with slope zones revealed finer soils concentrated on mid-slopes where highway development using a cut-and-fill aspect has interfered with natural grading (Gokhale et al., 2019). The coarser materials such as weathered lateritic gravels were located and generally distributed in ridge and lower-hazard areas. The results are consistent with those of other studies (related to the Western Ghats) that find clay predominance in failure areas (Dikshit & Nayak, 2011). Incorporating the grain size data into GIS thematic layers made it possible to weight the soil parameters with other causative factors such as slope and drainage density. It is this grouping that forms the basis of subsequent hazard zonation, on the LHZ map where finer zones of soils overlapped with high-risk regions which in turn justified their contribution to the failure of the road seen along NH66 during peak monsoons.

Atterberg Limits and Plasticity Index Evaluation

Results of Atterberg limits showed high plasticity soils in Galel slope slopes and such results are important in establishing shrink-swell behavior when exposed to diverse moisture conditions. The average liquid limit (LL) was 48% and plastic limit (PL) was close to 22% with Plasticity Index (PI) 0f approximately 26% (Jaiswal et al., 2018). These values categorize the soils to be high plasticity clays according to the IS:2720 specifications and being sensitive to develop a high degree of strength loss when subjected to saturation (Kanungo et al., 2006). This insecurity is enhanced by rainfall of more than 3000 mm received seasonally, and results in slopes failure even when stress is not heavy (Dikshit & Nayak, 2011). Pi values were correlated with observed failure locations to reveal a good spatial overlap especially at the highway cut positions where natural excavation caused exposure of highly plastic layers (Sangeeta & Singh, 2023). High PI areas were associated with low SPT N -values confirming multi- parameter susceptibility knowledge. The soils with high PI are also characterized by low permeability that further complicates pore work overload in case of extended rainfalls (Gokhale et al., 2019). This feature goes directly into AHP weighting that would place more hazard influence over high plasticity classes during GIS modeling. Said combined assessment can fairly cover the description of the soil behavior, a gap between laboratory measurements and field hazard expression along the Mumbai-Goa Highway.

Specific Gravity and Free Swell Index of Lateritic Soils

Values of specific gravity measurements in all the samples ranged between 2.65 and 2.72, which is characteristic of lateritic and basaltic soils in the Western Ghats (Gokhale et al., 2019). These readings are owing to mineral compositions that mainly are iron-aluminium oxides and secondary clays (Kanungo et al., 2006). Free swell index (FSI) tests suggested medium expansivity with 45 to 55 expansivity percentage, which supports that the material is vulnerable to volumetric instability about wettingdrying cycles (Sangeeta & Singh, 2023). This kind of expansion causes fissuring and eventual softening of slope materials with the recharge of the monsoons. Together with having low SPT N-values in shallow layers they indicate high vulnerability of surficial lateritic caps. The FSI outcomes also augur well with those of Atterberg Limit results, where soils with high values of PI showed swelling properties. Spatial plots, DEM linked emphasised the concentration of expansive soils along the mid slopes cutting through NH 66 alignment. This geotechnical observation supports the empirical findings sustained by frequent road shoulder collapses and minor slips when there is a heavy down pour (Dikshit & Nayak, 2011). The addition of length and specific gravity and FSI in the AHP model gave an additional weighting to the hazards and depicted the tension between density-related stability and swell-forced weakness. Such bi-parameterization is crucial to predictive zonation as is the case in engineered slopes that traversed through lateritic profiles of varying weathering, which are present in the study corridor.

DEM-Derived Slope and Contour Analysis

The analysis of Digital Elevation Model (DEM) based on 30-meter SRTM inferred that the terrain has steep conditions with the slope gradient of the critical areas in excess of 35 o (Jaiswal et al., 2018).

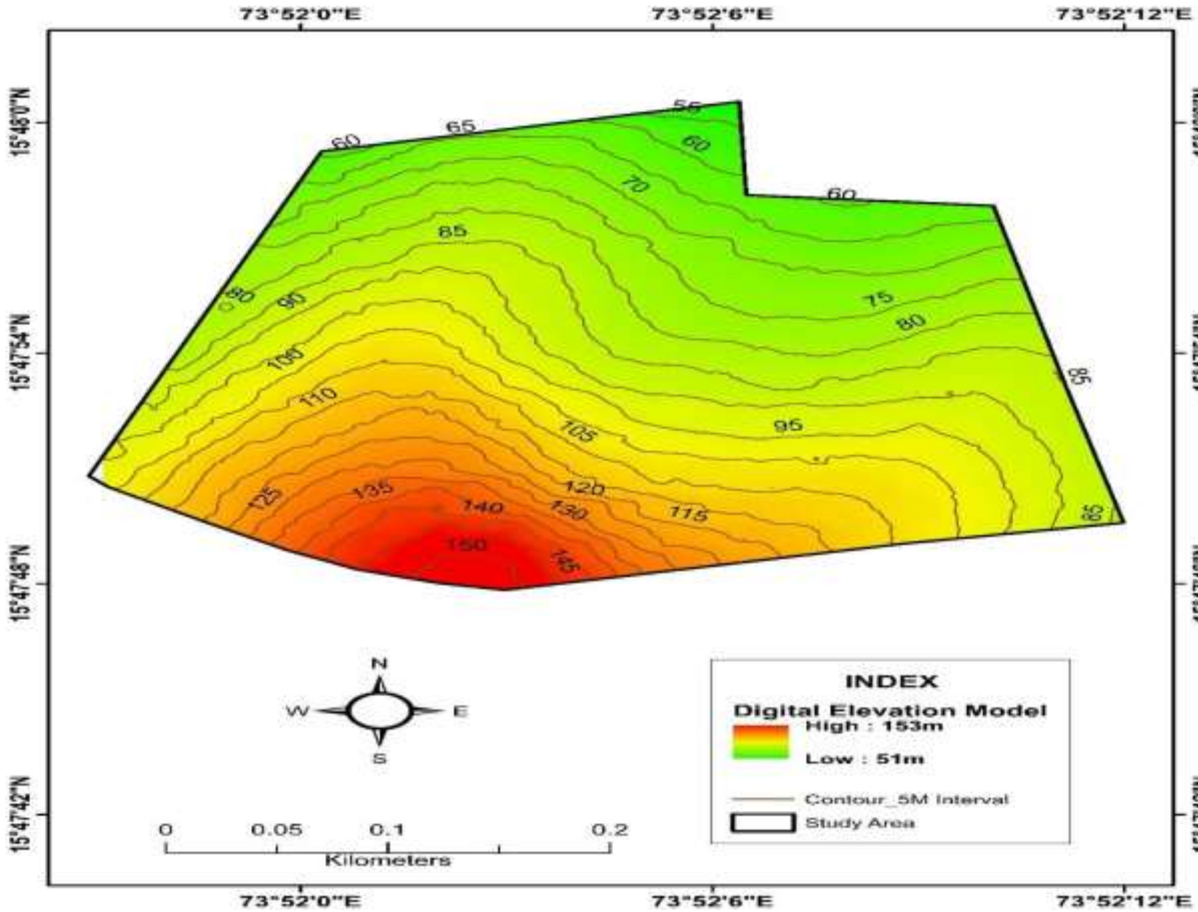

Figure 3: Digital Elevation Model

The steep slopes parallel to the highway pieces were most likely to fail and can be proved by the field-scars. In the case of contour mapping, steep relief transitions were observed, and the proximity of contours in the areas of cut slopes marked areas of zones of active instability (Gokhale et al., 2019). Such geomorphology was coupled with high rainfall catchments to a great extent, increasing chances of saturation (Dikshit & Nayak, 2011). Slope aspect analysis showed the south west facing slopes to be most prone to failures as it is the direction that is exposed directly to monsoonal rainshower (Kanungo et al., 2006). Combination of slope and contour data with soil layers proved that high hazard exists in mid-slope convexities where the runoff is focused which promotes rapid erosion. Derivatives of DEM such as curve also indicated depressions that were likely to trap rubbles and lead to their movement. This terrain assessment overlaid all-hazard placement of strategic boreholes, which ensured the geotechnical data were of the worst case conditions. Factors had the largest score of hazard assigned to slope by directly using DEM-based maps in calculating AHP weights. Such prioritization is in line with findings of global landslides studies which focus on slope gradient as the prevailing landslide triggering parameter especially in lateritic tropical regions of Western Ghats corridor.

Final Landslide Hazard Zonation (LHZ) Map and Risk Categorization

Under the integrated hazard map, the Galel landmass was divided into five categories, such as very low, low, moderate, high, and very high hazards (Sangeeta & Singh, 2023). The most dangerous zones are located along highway cut slopes that pass through weak lateritic soils and slopes with a gradient of more than 30 (Gokhale et al., 2019).

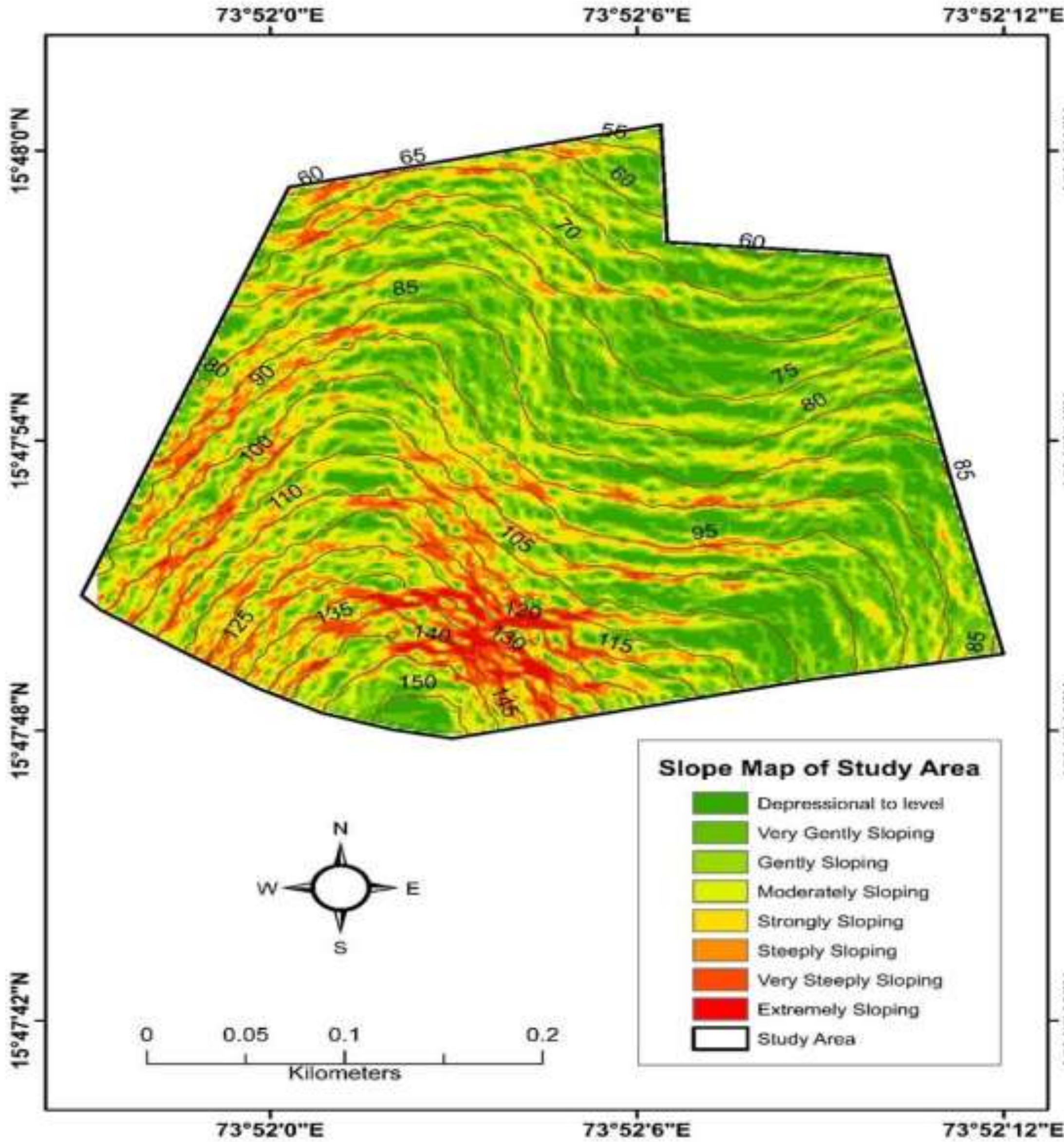

Figure 4: Slope Map of Study Area

The use of historical landslide inventory also indicated good correlation between the predicted high-risk areas and the areas where slips were reported (Jaiswal et al., 2018). The study reveals that about 28 percent of the study area was characterized as being subject to high to very high hazard classes with majority of it occurring in the mid-slope regions subject to heavy monsoon rainfall (Dikshit & Nayak, 2011). Low hazard areas identified with mild topography with rougher soil and heavy tree cover providing natural protection to terrain. Such zonation will facilitate in the prioritisation of slope stabilisation work, drainage measures and realignment factors on NH-66 in a direct manner. AHP-GIS model provided transparency in the weighting of causative factors where the geotechnical, hydrological and topographic factors were balanced (Kanungo et al., 2006). In comparison to the previous regional studies that did not offer field verification, this map proves to be more accurate and functionally applicable by the highway management authorities. It will establish a scientific rationale on early warning systems and sustainable corridor planning in the landslide-affected lands in the Western Ghats.

CONCLUSION

This paper showed a detailed landslide hazard zonation map of Galel stretch of NH-66 using a mixture of geotechnical studies and GIS, as well as the AHP analysis. The findings revealed steep slopes and clay lateritic soils as well as rainfall intensity (during monsoon rain) being the main causes of frequent landslides in the area. Very low to very high risk areas in the final hazard map were correct and coincided with field observations of failures. The results can serve as guiding force in making slope stabilization and better drainage planning, as well as setting the focus of areas with a high risk on intervention. The methodology can also provide a framework of assessment and mitigation of landslides hazards in other transport corridors over similar terrains that can be replicative.

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