

A Simplified Rockfall Hazard Rating System for Highways in the Higher Himalaya: Case Study of NH-03, Nepal

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ABSTRACT: Nepal's mountainous highways traverse steep slopes and geologically complex terrain, making them highly susceptible to rockfall hazards. The risk is amplified by active tectonics, intense rainfall, and limited roadway width, with constrained maintenance budgets making it impractical to address all hazard sites simultaneously. This study develops a Simplified Rockfall Hazard Rating System (SRHRS) tailored to the Himalayan context, providing rapid method to prioritize slopes for mitigation. The SRHRS retains the 9 core parameters of the original Rockfall Hazard Rating System (RHRS), but introduces key modifications suited to local conditions: the slope-height scoring; ditch effectiveness and roadway-width scoring being re-calibrated. The method was applied to a 16.73 km section of the Mid-Hill Highway (NH-03) in western Nepal, where 49 slope sections were inventoried and 14 high-hazard sites were evaluated in detail. SRHRS scores ranged from 246 to 572 (mean 410), closely matching RHRS rankings (Spearman $\rho = 0.98$). Using a threshold of 396, seven slopes were identified as priority sites for intervention. The SRHRS offers a practical tool for highway authorities in Nepal and other Hindu Kush Himalayan countries to efficiently allocate resources and enhance slope hazard management.

KEYWORDS: Rockfall hazard, Hindu Kush Himalaya, Hazard rating system, Slope stability, SRHRS.

1 INTRODUCTION

The Himalayas, born of ongoing convergence between the Indian and Eurasian plates, are among the youngest and most dynamic mountain chains on Earth, marked by extreme relief, active deformation, and rapid geomorphic change (Shroder and Bishop, 1998; Yin, 2006). Nepal lies at the core of this orogen, with roughly 83% of its terrain classified as mountainous or hilly (Land Use Statistics of Nepal, 2020). National highways frequently cling to steep valley flanks cut into fractured bedrock, where intense monsoon rainfall, seasonal freeze-thaw, seismic shaking, and anthropogenic slope excavations combine to produce persistent rockfall hazard. The consequences are recurrent: road closures, infrastructure damage, and heightened accident risk, as documented widely in rockfall mechanics, modelling, and risk literature (Agliardi and Crosta, 2003; Dorren, 2003; Budetta, 2004). The 2015 Mw 7.8 Gorkha earthquake further exposed this vulnerability by triggering widespread slope failures, including numerous rockfalls along critical corridors (Roback et al., 2018).

Globally, rating frameworks such as the Oregon Rockfall Hazard Rating System (RHRS) provide a structured, parameter-based approach to prioritize mitigation along highways (Pierson, Lawrence A. Pierson and Robert Van Vickle, 1993). Variants including the Colorado system and regional adaptations like the Rockfall Hazard Rating System for India (RHRSI) score roadway/traffic conditions, slope geometry, geology, and triggering factors on an exponential (3-9-27-81) scale to rank sites for action (Ansari et al., 2016; Vishal et al., 2017; Tanoli et al., 2022). However, direct application in the Himalaya is problematic. Himalayan highways often operate as single, intermediate lanes or Narrow Two Lanes (7.5m) with negligible shoulder, sharp curvature, and limited sight distance; roadside "ditches" are typically shallow and narrow (field measurements along the study corridor commonly ~0.6 m deep and ~0.7 m wide), providing little functional rockfall catchment. Under these conditions, standard ditch-effectiveness and roadway-width scoring may understate risk, while the original slope-height scoring offers limited separation across the moderate-height yet geotechnically adverse cuts common in Nepal. Prior Himalayan studies—ranging from rating plus trajectory assessments on India's NH-58 to modified

RHRS applications in Pakistan's Karakoram corridor and multiple Nepali sites—converge on the need for locally calibrated scoring that reflects this operational reality (Gnyawali et al., 2015; Regmi et al., 2016). In response, this paper develops and field tests a Simplified Rockfall Hazard Rating System (SRHRS) tailored to Himalayan highways. The SRHRS preserves the nine core RHRS parameters but adjusts specific scoring functions to reflect Nepal's context: ditch effectiveness is treated as functionally absent for prioritization purposes; roadway-width scores are re-scaled for single/intermediate/two-lane (≈ 7.5 m) carriageways with minimal evasive maneuvering space; and the slope-height curve is recalibrated to improve discrimination within the height ranges typical of Himalayan cuts. This research applies the framework to a 16.73 km section of the Mid-Hill Highway (NH-03) between Musikot and Chaurjahari, a corridor adjacent to the Main Central Thrust and dominated by steep, faulted dolomitic limestone slopes. Forty-nine slope sections were inventoried; fourteen high-hazard (A-rated) sites underwent detailed scoring using both RHRS and SRHRS. Results show SRHRS scores spanning 246 to 572 (mean 410), closely tracking RHRS rankings (Spearman $\rho = 0.98$; Kendall $\tau = 0.93$) while better capturing Himalayan constraints; using a pragmatic threshold of 396, seven sites emerge as priority candidates for mitigation. These findings indicate that SRHRS can provide a standard, rapid, and context-appropriate prioritization tool for Nepal's Department of Roads and, more broadly, for highway authorities across the Hindu Kush Himalaya.

2 MATERIAL AND METHODS

2.1 Study area

The study corridor covers a 16.73 km section of the Mid-Hill Highway (NH-03) between Musikot and Chaurjahari in Rukum District, western Nepal. The alignment occupies the Midland physiographic zone at elevations of roughly 1,000–2,500 m, a.s.l., trending sub-parallel to the Main Central Thrust (MCT) and traversing the Higher Himalayan belt dominated by faulted dolomitic limestone (Dhital, 2015). As shown in Figure 1, the highway closely follows the left bank of the Bheri River, with constrained valley geometry and frequent sharp curves. Carriageway width is predominantly two-lane (7.5m), roadside

ditches are typically shallow and narrow, offering minimal debris retention. Field reconnaissance recorded low decision sight distances on tight bends, recurrent rock fragments on the carriageway, localized pavement distress, and impact damage to W-beam barriers, indicating active rockfall processes along multiple cut slopes. The corridor limits used in this study extend approximately from 28°38'30" N to 28°41'34" N and 82°11'36" E to 82°16'18" E, encompassing reference points such as Bheri River, Rukum west and Jajarkot district borders for spatial context as shown in Figure 1.

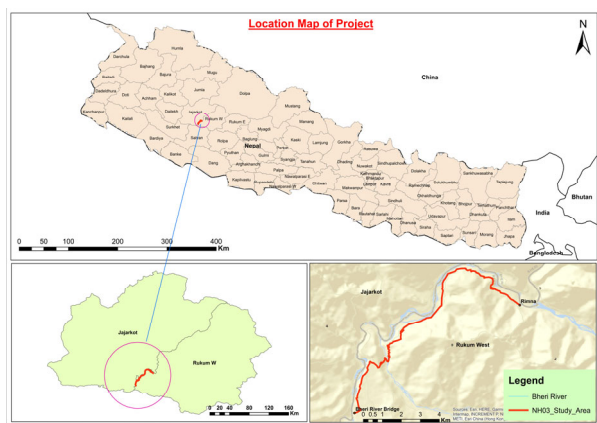


Figure 1. NH-03 study area map (Rukum West, Nepal).

The 16.73 km segment assessed in this study is highlighted in red along the left bank of the Bheri River, between Bheri Bridge (southwest) and Rimna (northeast). Approximate coordinate bounds are 28°38'30" N, 28°41'34" N and 82°11'36" E, 82°16'18" E.

2.2 Data collection

Fieldwork covered the 16.73 km NH-03 corridor shown in Figure 1. A reconnaissance first inventoried visible indicators of active or recent rockfall fresh fragments on the carriageway, small talus cones and detachment scars on cut faces, localized pavement distress, and impact damage to W-beam barriers yielding 49 slope sections. A preliminary RHRS screen then assigned A/B/C classes by rockfall potential and history, and 14 A-rated sites were advanced to detailed rating for prioritization (Pierson, Lawrence A. Pierson and Robert Van Vickle, 1993).

At detailed sites, slope height was measured to the highest credible initiation point (crest or dominant bench), and exposed roadway length was logged for the Average Vehicle Risk (AVR) calculation per RHRS (Pierson, Lawrence A. Pierson and Robert Van Vickle, 1993). Roadway width was measured perpendicular to the centerline (including paved shoulders where present) and classified operationally as single/intermediate or standard two-lane, consistent with Himalayan highway geometry reported in regional studies (Verma et al., 2019; Ali et al., 2021). Decision sight distance (DSD) was determined on curves using intervisible targets and odometer readings; measured values were compared with AASHTO design sight-distance guidance at the posted/design speed to compute %DSD for rating. Ditch characteristics—depth, width, geometry, and infill—were recorded at representative cross-sections; ditches were typically ~0.6 m deep and ~0.7 m wide and frequently infilled, consistent with limited catchment effectiveness in Himalayan corridors (Vishal et al., 2017; Pokhrel, Adhikari and Dahal, 2022)

Where fresh scars or talus were present, representative block sizes (a-, b-, c-axes) were measured and event volume inferred from deposit footprint and fragment counts. Geologic character was described using ISRM discontinuity terms (orientation, spacing, persistence, surface roughness/infilling)

and evidence of differential erosion to ensure consistency across sites ('International society for rock mechanics commission on standardization of laboratory and field tests', 1978). Rockfall history combined Department of Roads maintenance logs and staff interviews with field evidence of cleaned or fresh debris, as recommended by RHRS guidance (Turner and Schuster, no date; Pierson, Lawrence A. Pierson and Robert Van Vickle, 1993).

All measurements were geo-referenced and paired with site photographs documenting ditch functionality, operational width/shoulder condition, limited sight distance, and fragment size/bounce marks.

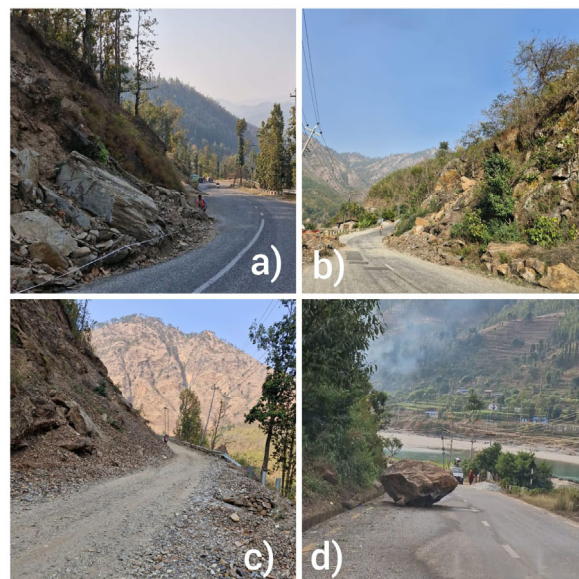


Figure 2. Representative field photographs from the NH-03 study corridor (Musikot–Chaurjahari); (a) Fresh rock fragments on the carriageway adjacent to a shallow, narrow ditch, illustrating ineffective catchment; (b) Prominent rockfall site showing cleared debris and patch-repaired pavement, indicating recurrent events; (c) Tight curve operating as single/intermediate lane with limited decision sight distance and loose debris on the shoulder; (d) Recent large-block fall partially blocking one lane near the river; measured block ~3.45 × 1.90 × 2.25 m.

2.3 Analytical framework

2.3.1 Baseline RHRS

As the benchmark, the Oregon Rockfall Hazard Rating System (RHRS) was applied in its original two-stage form to the 16.73 km NH-03 corridor. A preliminary screen classified 49 inventoried slopes into A/B/C based on visible rockfall potential and history; the A-rated subset (n = 14) then underwent detailed scoring. In detailed rating, nine parameters—slope height, ditch effectiveness, average vehicle risk (AVR), percent decision sight distance (DSD), roadway width, geologic character (joint- or erosion-controlled, recording the higher case), block size/event volume, climate/water, and rockfall history are mapped to exponential scores (3, 9, 27, 81) and summed, so as poor conditions dominate the total and hence the priority.

For traffic exposure, AVR represents the fraction of time one or more vehicles occupy the rockfall-exposed section. Let ADT be two-way average daily traffic (veh/day), L the exposed length (m), and V the posted/design speed (m/s). Then

$$AVR(\%) = 100 \times \frac{ADT}{86,400} \times \frac{L}{V} \quad (1)$$

Values exceeding 100% indicate that, on average, more than one vehicle is present simultaneously within the section; per RHRS, AVR is then binned to the exponential scores using the published thresholds (25,50,75,100%) (Pierson, Lawrence A. Pierson and Robert Van Vickle, 1993).

For sight-distance limitation, measured centerline sight distance on curves is compared against the AASHTO decision sight-distance requirement for the posted/design speed Nepal Road Standard, 2070 . The dimensionless percentage used for scoring is

$$\%DSD = 100 \times \frac{\text{Measured Sight Distance}}{\text{AASHTO DSD Requirements (V)}} \quad (2)$$

This ratio is then categorized from “adequate” ($\approx 100\%$) to “very limited” ($\approx 40\%$) and mapped to the exponential scores as per RHRS.

All other parameters follow the original RHRS binning without alteration: slope height is evaluated to the highest credible initiation point above the carriageway against the 25/50/75/100 ft thresholds; ditch effectiveness is classified from “good catchment” to “no catchment”; roadway width is measured perpendicular to the centerline (including paved shoulders) and compared with 44/36/28/20 ft thresholds; geologic character is scored under the joint-controlled (structural condition and rock-friction condition) or erosion-controlled (structural condition and difference in erosion rates) cases, with the higher of the two cases recorded for a site; block size/event volume uses characteristic block dimension (1–4 ft) or equivalent event volume (3–12 yd³); climate/water ranges from dry, low-precipitation settings to high-precipitation with long freezing periods and continual water on slope; and rockfall history ranges from few to constant events. The total RHRS score for a site is the simple sum of the nine parameter scores,

$$R_{RHRS} = \sum_{k=1}^9 r_k \quad (3)$$

with the geologic character term taken as

$$r_{geo} = \max(r_{case 1}, r_{case 2}) \quad (4)$$

All field measurements were made in SI units and converted as needed to the RHRS bin thresholds originally expressed in imperial units. The resulting totals were used to rank sites in descending order of hazard. Because RHRS does not prescribe a universal intervention threshold, a pragmatic, corridor-specific cut-off is introduced in the results to identify priority candidates; this RHRS ranking then serves as the reference for evaluating the Himalayan adaptations introduced subsequently in the SRHRS, including formal rank-stability checks (Spearman’s ρ , Kendall’s τ) to verify that simplification preserves the essential prioritization.

2.3.2 SRHRS Adaptations for Himalayan Roads

To reflect operational realities observed along NH-03 narrow carriageways, shallow and frequently infilled ditches, and moderate-height but structurally adverse cuts, the Simplified Rockfall Hazard Rating System (SRHRS) retains the RHRS workflow yet recalibrates the scoring functions for a small subset of parameters while leaving the remainder unchanged. The goal is not to alter the relative importance of parameters arbitrarily, but to improve score resolution where RHRS bins tend to collapse distinct Himalayan conditions into the same class, and to encode the fact that, along this corridor, roadside “ditches” seldom function as meaningful rockfall catchments.

For slope height, RHRS uses four discrete thresholds corresponding to 25/50/75/100 ft ($\approx 7.6/15.2/22.8/30.4$ m). Field data on NH-03 showed many cuts falling below 25 ft yet still hazardous because of jointing, weathering, and adverse fabric. Accordingly, SRHRS replaces the four-bin step function

with a monotonic exponential curve that maps height $H(m)$ to a continuous score $r_{geo}(H)$ on a 0–100 scale, fitted to Nepal-specific calibration points derived from the workbook (3, 10, 20, 30 m mapped to the nominal RHRS scores 3, 9, 27, 81). The mapping is expressed as

$$r_{ht}(H) = \text{clip}_{[0,100]}(\alpha_{ht}e^{\beta_{ht}H}) \quad (5)$$

Where α_{ht}, β_{ht} are obtained by least-squares fit to the four calibration pairs $\{(3,3), (10,9), (20,27), (30,81)\}$ from the Slope Ht. Mod. sheet, and clip $[0,100]$ limits scores to the 0–100 range. This change preserves RHRS ordering at larger heights but adds separation among common Himalayan cut heights (≈ 3 –20 m), reducing ties that otherwise mask meaningful differences in exposure.

For roadway width, RHRS bins are anchored at 44/36/28/20 ft ($\approx 13.4/10.9/8.5/6.1$ m), reflecting multilane highways uncommon on Himalayan corridors. Along NH-03, operational width often falls in the two lane (7.5m) range, with virtually no shoulder and cliffs or river gorges precluding evasive maneuvers. SRHRS therefore uses a decreasing exponential that penalizes narrowing much more strongly below ≈ 8 m, fitted to Himalayan calibration pairs visible in the workbook (20, 13, 7.5, 3.5 m mapped to target scores 3, 10, 55, 100):

$$r_{wd}(W) = \text{clip}_{[0,100]}(\alpha_{wd}e^{\beta_{wd}W}), \quad \beta_{wd} < 0, \quad (6)$$

With α_{wd}, β_{wd} fitted by least squares to $\{(20,3), (13,10), (7.5,55), (3.5,100)\}$ from the Slope Ht. Mod. sheet. This mapping compresses the influence of wide, two-lane segments and amplifies the hazard contribution of narrow segments observed in the study corridor.

For ditch effectiveness, site reconnaissance and maintenance evidence indicate typical dimensions of ~ 0.6 m depth and ~ 0.7 m width with frequent infill, providing negligible catchment for rockfall fragments. To avoid spurious discrimination between similarly ineffective ditches, SRHRS treats ditch capacity as functionally absent for prioritization purposes, assigning a constant high penalty

$$r_{ditch} = 81 \quad (7)$$

This is consistent with the RHRS category “no catchment” while making the assumption explicit and uniform for the corridor studied.

All other parameters like Average Vehicle Risk (AVR), Percent Decision Sight Distance (DSD), block size or event volume, geologic character (Case 1 or Case 2, taking the higher), climate/water, and rockfall history are retained from RHRS without change in definition or binning. The total SRHRS score is then the sum of parameter scores, mixing the two continuous 0-100 mappings with the unchanged RHRS-style bins (Pierson, Lawrence A. Pierson and Robert Van Vickle, 1993; Budetta, 2004) :

$$R_{SRHRS} = r_{ht}(H) + r_{ditch} + r_{wd}(W) + r_{AVR} + r_{DSD} + r_{geo} + \max(r_{blk}, r_{vol}) + r_{clim} + r_{hist} \quad (8)$$

Absolute totals increase modestly; the adapted mappings preserved ranking while better capturing Himalayan constraints and providing clearer separation among the highest-priority sites.

As summarized in Table 1 , three parameters were adapted while the remaining six follow the baseline formulation.

2.3.3 Scoring, Ranking, and Thresholding

For each detailed site, nine parameter scores are computed and summed to obtain a total hazard score under the baseline i.e. original RHRS and simplified formulations by SRHRS.

Sites are ranked by descending total score. Let S_i , S_j denote the total for site i (RHRS or SRHRS). The rank assigned to site i is

$$\text{rank}(i) = 1 + \#\{j: S_j > S_i\} \quad (9)$$

with ties broken (only when needed) by comparing, in order, larger AVR, smaller %DSD, narrower roadway width, and larger characteristic block size; if still tied, the longer exposed section length receives the higher rank. This rule preserves prioritization toward sections with greater traffic exposure and poorer operational visibility.

Table 1. Summary of RHRS vs SRHRS parameterization used in this study

Parameter	RHRS treatment (baseline)	SRHRS treatment used here	Remarks
Slope height	Step thresholds at 25/50/75/100 ft	Continuous exponential mapping rht(H) on 0–100 scale (Eq. 5)	Adds resolution for 3–20 m cuts common on NH-03
Ditch effectiveness	Good → No catchment (3–81)	Fixed as “No catchment,” rditch = 81 (Eq. 7)	Reflects shallow, infilled ditches observed in corridor
Roadway width (incl. shoulders)	44/36/28/20 ft thresholds	Decreasing exponential rwd(W) on 0–100 scale (Eq. 6)	Penalizes single/intermediate widths appropriately
Average Vehicle Risk (AVR)	As per baseline	Unchanged	Uses ADT, section length, posted speed
Percent Decision Sight Distance (DSD)	As per baseline	Unchanged	Measured sight distance vs design requirement
Geologic character (Case 1/2)	Higher of the two cases recorded	Unchanged	Same descriptors and scoring logic
Block size / Event volume	Characteristic size or equivalent volume	Unchanged	Same bins and field estimation approach
Climate / Water	Precipitation, freezing, water on slope	Unchanged	Same categorical scoring
Rockfall history	Few → Constant	Unchanged	Same categorical scoring

A programmatic threshold T is used to separate “priority” from “routine-monitoring” sites within a given corridor. To avoid arbitrary cut-offs while keeping the method corridor-specific, T is defined as the mean of the baseline totals across the detailed (A-rated) set:

$$T = \frac{1}{n} \sum_{i=1}^n R_{RHRS,i} \quad (10)$$

Classification is then

$$\text{Priority (P1): } S_i \geq T \text{ and Routine (P2): } S_i < T \quad (11)$$

applied consistently to both RHRS and SRHRS so that any changes in membership reflect only the adapted scoring. In this study, the resulting TTT is reported in the Results, together with the counts #P1 and #P2.

To demonstrate that simplification preserves the baseline ordering, rank-stability is evaluated by comparing RHRS and SRHRS ranks across the detailed set. With d_i the difference between RHRS and SRHRS ranks for site i , the Spearman statistic is

$$\rho = 1 - \frac{6 \sum_{i=1}^n d_i^2}{n(n^2-1)} \quad (12)$$

Kendall’s τ , is also computed with standard tie corrections. Both metrics and their interpretation are presented in the Results. Finally, a threshold sensitivity check perturbs T by $\pm\delta$ (here $\delta=10$ points) and recomputes P1/P2 membership to confirm that conclusions are not artefacts of a single cut-off choice; outcomes are summarized alongside the main results.

3 RESULTS

3.1 Hazard Scores and Ranking

Across the fourteen detailed sites, baseline RHRS totals span approximately 236 to 556 (mean 396; SD 96.0), while SRHRS totals span approximately 247 to 572.0 (mean 410; SD 99.2). The modest increase in the SRHRS mean (about +14 points) is expected because slope height and roadway width now are modified to suit Locally.

Using the corridor mean of the baseline RHRS totals as a pragmatic cut-off ($T \approx 396$), seven of the fourteen sites, exactly fifty percent fall into the program-priority band under both frameworks. Under SRHRS, the most hazardous locations occur at chainages 1216+530 (572), 1217+230 (567), 1221+960 (492), 1223+660 (481), and 1219+030 (464). Under RHRS, the top end is led by 1216+530 (556), 1217+230 (552), 1221+960 (479), 1223+660 (468), and 1220+960 (436). Table 2 shows that the SRHRS adaptation raises absolute scores slightly while preserving which slopes are most critical, and it improves separation at the upper end where narrow operational width, very limited sight distance, and ineffective ditches combine to elevate exposure.

Table 2. Site-level hazard scores and ranks (RHRS vs SRHRS)

Chain age	Total R HRS	Total S RHRS	Rank R HRS	Rank S RHRS	Rank Delta
1216+530	556	572	1	1	0
1217+230	552	567	2	2	0
1221+960	479	492	3	3	0
1223+660	468	481	4	4	0
1220+960	436	439	5	6	1
1215+630	418	431	6	7	1
1219+030	396	464	7	5	-2
1217+530	368	370	8	9	1
1226+160	360	371	9	8	-1
1222+960	359	364	10	10	0
1215+230	322	331	11	11	0
1221+630	319	330	12	12	0
1219+430	275	284	13	13	0
1226+060	236	247	14	14	0

3.2 Rank Stability Analysis

Ranking consistency between the baseline RHRS and the adapted SRHRS is very high. Across the fourteen detailed sites, the Spearman rank correlation is approximately 0.98 and Kendall's τ is approximately 0.93, both computed with standard tie adjustments. These values indicate that the SRHRS preserves the monotonic ordering of hazard nearly perfectly, with only minor local shifts. The top four sites remain identical under both frameworks, and the program-priority set defined at the corridor cut-off $T \approx 396$ is unchanged: 7 of 14 sites are flagged in both cases. Rank differences are small in magnitude, with a maximum $|\Delta|$ of 2, a median Δ of 0, and a mean absolute change of about 0.43 positions. The only non-adjacent movement is the intuitive upgrade of 1219+030 from rank 7 (RHRS) to rank 5 (SRHRS), reflecting how the continuous slope-height mapping and the steeper width penalty better capture its operational exposure. All other changes are single-position swaps among mid-table neighbors for example, 1220+960 shifts from rank 5 to 6 and 1215+630 from 6 to 7 leaving the identity of the highest-priority group intact. Taken together with the totals in Table 2, these statistics show that SRHRS delivers finer separation where Himalayan constraints are most influential while preserving the baseline prioritization required for consistent, defensible decision-making.

3.3 Field Observations

Field evidence closely mirrors the score patterns and explains the few rank shifts between frameworks. Three indicators recur along the highest-scoring reaches: fresh fragments on the carriageway and shoulders, impact or deformation of valley-side W-beam barriers, and very limited decision sight distance on tight bends. As shown in Figure 2, these conditions appear most persistently where the carriageway operates as single/intermediate or constrained two-lane (~ 7.5 m) and roadside ditches are shallow and frequently infilled, providing negligible catchment.

At chainage 1216+530—the corridor's top-ranked site—the approach is through a sharp curve with constrained width and low sight distance. The barrier shows impact damage consistent with past block strikes, and small to medium fragments accumulate after rainfall, indicating active sources upslope; the shallow ditch is quickly overwhelmed. The second-ranked site, 1217+230, illustrates large-block hazard: a recently fallen boulder ($\sim 3.45 \times 1.90 \times 2.25$ m) occupied one lane near the river, forcing opposing-flow maneuvers. With mixed traffic at rural hill-road speeds, even short blockages create substantial operational risk.

At 1221+960 and 1223+660, tall cuts with adverse fabric exhibit recurrent small-fragment detachments; repeated patch repairs and talus lenses at the toe corroborate the “many to constant” rockfall history. Seepage and wet streaks recorded after rainfall align with elevated climate/water scores and help explain their stable placement near the top. Chainage 1219+030 demonstrates SRHRS's added resolution: a tight bend with very low sight distance and an infilled ditch raises its rank from 7 (RHRS) to 5 (SRHRS). By contrast, 1226+060 and 1219+430 show shorter slopes, better sight distance, fewer fragments, and limited barrier impacts, consistent with their low rankings.

4 DISCUSSION

4.1 Practicality and Benefits of SRHRS

SRHRS keeps the RHRS workflow and nine inputs intact, altering only what Himalayan field conditions demand—slope-height scoring, roadway-width scoring, and treating ditches as effectively absent—so crews can adopt it with virtually no

retraining and still produce results comparable to past RHRS campaigns. Rank agreement with the baseline remains high and the priority set is unchanged, meaning SRHRS sharpens separation at the top end without disrupting decision history. The continuous height curve adds resolution across the common 3–20 m cuts, the width mapping penalizes single/intermediate/two lanes where maneuvering is unrealistic, and standardizing ditch effectiveness removes low-value subjectivity. Implementation is straightforward: equations are explicit, calibration is documented, totals sum directly, and a corridor-mean cut-off provides a defensible split between priority works and routine monitoring. Outputs drop cleanly into existing Department of Roads asset and GIS systems for year-to-year tracking. Field evidence matches the sites that rise slightly in rank—narrow carriageways, very low sight distance, ineffective ditches, fresh debris—building practitioner confidence. The approach is also scalable, as height and width curves can be re-fitted as more corridors are surveyed, preserving a common framework while tuning to local geometry and traffic.

4.2 Implications for Hazard Management

Using the corridor mean as a practical cut-off (≈ 396) cleanly separates an actionable priority set from routine monitoring; here, 7 of 14 sites qualify and the group is stable across RHRS and SRHRS, so funding and works can be committed with confidence. For the highest-ranked locations, immediate measures should focus on traffic control and rock scaling, followed by targeted anchoring/bolting; where recurrent small fragments dominate, drapery/mesh and toe containment are appropriate, while large-block exposure on valley edges warrants energy-rated catch fences or barrier upgrades. At wet faces, simple drainage (crest diversion, shallow trench drains) and spot shotcrete reduce weathering; at very low sight-distance bends, pair structural works with delineation and speed management. Programmatically, enter scores and chainages into the road-asset/GIS system, schedule post-monsoon rapid checks and re-rating after threshold events (heavy rain, floods, felt earthquakes), and track year-to-year changes to demonstrate benefit.

5 CONCLUSION AND RECOMMENDATIONS

This study developed and field-tested a Simplified Rockfall Hazard Rating System (SRHRS) that preserves the RHRS workflow and nine inputs while adapting slope-height and roadway-width scoring (continuous 0–100 curves) and treating ditches as functionally absent. Applied to a 16.73 km section of NH-03, SRHRS produced totals that remained comparable to RHRS yet offered clearer separation among the most hazardous sites. Across the 14 detailed locations, RHRS totals ranged 236–556 (mean 396) and SRHRS totals 247–572 (mean 410); using a corridor cut-off near 396, seven sites were consistently flagged as priority in both frameworks. Rank agreement was very high, with only small, intuitive shifts (e.g., 1219+030 moving from rank 7 to 5), and field evidence—narrow width, very low sight distance, ineffective ditches, recurrent fragments, barrier impacts, and a recent large-block fall—aligned with the highest scores. Together, these results show that SRHRS sharpens prioritization for Himalayan roads without disrupting RHRS compatibility or field practice.

Based on these findings, we recommend the following actions for immediate adoption and program rollout:

- Adopt SRHRS as the rapid screening method for Himalayan corridors, retaining the RHRS workflow with adapted height/width/ditch treatments.

- Use the corridor mean score as the prioritization threshold (≈ 396 here), revisiting the cut-off as additional sections and seasons are added.
- Match mitigation to dominant conditions at priority sites: scaling and selective bolting; drapery/mesh and toe containment for recurrent small fragments; energy-rated catch fences or barrier upgrades for large-block exposure; local drainage (crest diversion, trench drains) and sight-distance/speed management on tight bends.
- Improve data capture to reduce subjectivity and accelerate surveys (UAV photogrammetry/LiDAR for heights and discontinuities; vehicle-mounted video for width/DSD; periodic ADT updates).
- Re-fit the height and width curves and re-validate the threshold as more corridors are surveyed; track outcomes against incident and maintenance logs to demonstrate benefit.

6 ACKNOWLEDGEMENTS

We acknowledge Nepal's Department of Roads for providing corridor data, maintenance logs, and Road Register access, and for facilitating field access and logistics along NH-03 during reconnaissance and detailed rating.

7 REFERENCES

- Agliardi, F. and Crosta, G.B. (2003) 'High resolution three-dimensional numerical modelling of rockfalls', *International Journal of Rock Mechanics and Mining Sciences*, 40(4), pp. 455–471. Available at: [https://doi.org/10.1016/S1365-1609\(03\)00021-2](https://doi.org/10.1016/S1365-1609(03)00021-2).
- Ali, S. et al. (2021) 'Empirical assessment of rockfall and debris flow risk along the Karakoram Highway, Pakistan', *Natural Hazards*, 106(3), pp. 2437–2460. Available at: <https://doi.org/10.1007/S11069-021-04549-4/TABLES/4>.
- Ansari, M.K. et al. (2016) 'Rockfall Hazard Rating System along SH-72: a case study of Poladpur–Mahabaleshwar road (Western India), Maharashtra, India', *Geomatics, Natural Hazards and Risk*, 7(2), pp. 649–666. Available at: <https://doi.org/10.1080/19475705.2014.1003416;JOURNAL:JOURNAL:TGNH20;WGROU:STRING:PUBLICATION>.
- Budetta, P. (2004) 'Assessment of rockfall risk along roads', *Natural Hazards and Earth System Science*, 4(1), pp. 71–81. Available at: <https://doi.org/10.5194/NHESS-4-71-2004>.
- Dhital, M.R. (2015) 'Geology of the Nepal Himalaya: Regional perspective of the classic collided orogen', *Geology of the Nepal Himalaya: Regional Perspective of the Classic Collided Orogen*, pp. 1–498. Available at: <https://doi.org/10.1007/978-3-319-02496-7/COVER>.
- Dorren, L.K.A. (2003) 'A review of rockfall mechanics and modelling approaches', *Progress in Physical Geography*, 27(1), pp. 69–87. Available at: <https://doi.org/10.1191/0309133303PP359RA;PAGE:STRING:ARTICLE/CHAPTER>.
- Gnyawali, K.R. et al. (2015) 'Rockfall Characterization and Structural Protection in the Siddhababa Section of Siddhartha Highway H10, Nepal', *Journal of the Institute of Engineering*, 11(1), pp. 1–11. Available at: <https://doi.org/10.3126/JIE.V11I1.14689>.
- Government of Nepal Ministry of Physical Infrastructure & Transport Department of Roads Planning and Design Branch Road and Traffic Unit Babarmahal, Kathmandu (2013).
- 'International society for rock mechanics commission on standardization of laboratory and field tests' (1978) *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 15(6), pp. 319–368. Available at: [https://doi.org/10.1016/0148-9062\(78\)91472-9](https://doi.org/10.1016/0148-9062(78)91472-9).
- Land Use Statistics of Nepal (2020).
- Pierson, L.A., & Lawrence A. Pierson and Robert Van Vickle (1993) *Rockfall Hazard Rating System- Participant's Manual*.
- Pokhrel, C., Adhikari, I. and Dahal, R.K. (2022) 'Qualitative rock-fall hazard mapping around the Siddhababa area along the Siddhartha Highway in western Nepal', *Journal of Nepal Geological Society*,

- pp. 71–82. Available at: <https://doi.org/10.3126/JNGS.V63I01.50843>.
- Regmi, A.D. et al. (2016) 'Rock fall hazard and risk assessment along Araniko Highway, Central Nepal Himalaya', *Environmental Earth Sciences*, 75(14), pp. 1–20. Available at: <https://doi.org/10.1007/S12665-016-5905-X/METRICS>.
- Roback, K. et al. (2018) 'The size, distribution, and mobility of landslides caused by the 2015 Mw7.8 Gorkha earthquake, Nepal', *Geomorphology*, 301, pp. 121–138. Available at: <https://doi.org/10.1016/J.GEOMORPH.2017.01.030>.
- Shroder, J.F. and Bishop, M.P. (1998) 'Mass movement in the Himalaya: new insights and research directions', *Geomorphology*, 26(1–3), pp. 13–35. Available at: [https://doi.org/10.1016/S0169-555X\(98\)00049-X](https://doi.org/10.1016/S0169-555X(98)00049-X).
- Tanoli, J.I. et al. (2022) 'Modified "Rockfall Hazard Rating System for Pakistan (RHRSP)": An Application for Hazard and Risk Assessment along the Karakoram Highway, Northwest Pakistan', *Applied Sciences* 2022, Vol. 12, Page 3778, 12(8), p. 3778. Available at: <https://doi.org/10.3390/AP12083778>.
- Turner, A.K. and Schuster, R.L. (no date) 'ROCKFALL CHARACTERIZATION AND CONTROL'.
- Verma, A.K. et al. (2019) 'Investigation of rockfall-prone road cut slope near Lengpui Airport, Mizoram, India', *Journal of Rock Mechanics and Geotechnical Engineering*, 11(1), pp. 146–158. Available at: <https://doi.org/10.1016/J.JRMGE.2018.07.007>.
- Vishal, V. et al. (2017) 'Hazard assessment in rockfall-prone Himalayan slopes along National Highway-58, India: rating and simulation', *Natural Hazards*, 85(1), pp. 487–503. Available at: <https://doi.org/10.1007/S11069-016-2563-Y/METRICS>.
- Yin, A. (2006) 'Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation', *Earth-Science Reviews*, 76(1–2), pp. 1–131. Available at: <https://doi.org/10.1016/J.EARSCIREV.2005.05.004>.