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Rainfall–Road Synergy and Landslide Risk Mapping in the Nepal Himalayas: A GIS–MCDA Framework with Level-4 Citizen Science Validation

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Abstract

Himalayan catchments face increasing landslide risk from the synergy of monsoon rainfall and unplanned road construction. Traditional top-down mapping often fails to capture localized hazards and socio-economic last mile vulnerabilities. This study developed hybrid framework integrating Geographic Information System (GIS) and Multi-criteria Decision Analysis (MCDA) in Melamchi Nepal. Moving beyond passive crowdsourcing, we implemented a level 4 extreme citizen science approach engaging 28 diverse stakeholders including farmers and individuals with disabilities as active co-analysts for hazard validation and risk interpretation. Primary spatial data were collected using KoboToolbox and validated through a multi-model protocol to mitigate GPS imprecision in high-relief terrain. A weighted linear combination model synthesized seven parameters, utilizing Euclidean distance as a standardized metric for adaptive capacity. Findings reveal that the synergy of rainfall and road construction triggered 58% of landslides, dominating regional geomorphic control. Furthermore, 42 vulnerability individuals reside in high-hazard zones with structurally fragile crude housing, highlighting critical risk accumulation areas. By bridging local temporal memory with scientific GIS-MCDA, the human centered approach transforms static record into dynamic tools for evacuation logic. This research provides a scalable blueprint for institutionalizing bottom-up inventories within Nepal's DRRM act 2017 transitioning from reactive rescue to proactive, evidence-based resilience.

1. Introduction

The Hindu Kush Himalayan (HKH) is a region particularly affected by cascading, compounding and amplifying geohazards, including India, Pakistan, and Nepal, which are among the most affected by climate-induced slope instability (Singh 2011). Traditionally, landslides were treated as single-trigger events mainly associated with rainfall. However, recent evidence highlights multi-driver interactions, including earthquake induced landslides (Polykretis et al. 2019), forest fire amplified slope failure and infrastructure driven instability (Rengers et al. 2020). During the monsoon season, the combination of intense precipitation, fragile lithology and steep topography produces frequent slope failure that exceeds historical thresholds of rainfall induced landslide activity.

Landslides in the region not only threaten human safety but also disrupt infrastructure systems, particularly road networks, leading to loss of connectivity and isolation of rural communities (McAdoo et al. 2018). They also influence long-term geomorphic evolution by transporting large volumes of debris into river systems, reshaping channel morphology and sediment dynamics. These cascading impacts directly and indirectly affect livelihoods in the Himalayan foothill settlement.

Nepal located between China and India, is characterized by deeply incised river valleys where settlements are concentrated, including the Melamchi valley, positioned at the interface between the high Himalaya and middle hills (Graf et al. 2024). The region is highly sensitive to both climate variability and anthropogenic disturbance. Although the high Himalaya is often considered relatively pristine, increasing climate stress combined with rapid infrastructure expansion in intensifying localized hazard

in the middle mountain regions. A key characteristic of Nepal is the high exposure of mountain populations to slope instability driven by unplanned infrastructure development and steep-slope agriculture (Smith-Hall et al. 2025).

Among anthropogenic drivers, rural road construction through traditional excavation methods has become a major factor influencing slope stability. Road cutting, slope undercutting and drainage modifications significantly reduce hillslope resistance, increasing landslide susceptibility (Pradhan et al. 2022). Recent spatial inventories indicate that infrastructure induced disturbance is primary trigger of small-to medium scale landslides, which cumulatively represent a substantial portion of total landslide occurrence in high relief terrain.

Landslide frequency in Nepal exhibits strong seasonality ranging from near-zero conditions in winters to peak activity during the monsoon season, often exceeding historical baselines of rainfall trigger failure thresholds (Neupane and Bhandari 2025). The government of Nepal has recognized this risk through the Disaster Risk Reduction Management Act 2017 which is aligned with international frameworks such as the Sendai Framework for Disaster Risk Reduction (United Nation 2015). However, operationalization of local risk assessment remains limited practice, particularly in remote mountainous areas.

In western Nepal and similar Himalayan regions, continuous road expansion during pre-monsoon periods further destabilizes slopes, while climate change intensifies rainfall extreme, creating conditions for cascading landslide outbreaks (Kumar Dahal 2012). Recent studies emphasize the importance of volunteered Geographic Information (VGI) and citizen science approach for supporting decision making in data-scarce environments (Shrestha et al. 2023). However, existing frameworks often remain limited to passive crowdsourcing or low-level participation with insufficient integration into formal geospatial modeling systems (Rinne et al. 2025). There is still a need for more robust and scalable modeling framework that integrates participatory data with spatial decision support tools to improve both hazard representation and policy relevance.

At the methodological level, application of machine learning and deep learning in mountainous terrain have significantly improved in mapping inventories(Mohan et al. 2021), however adding vulnerability data still needs field data collection. Most GIS-based landslide susceptibility models operate at coarse spatial resolution 30 meters to 1 kilometer (Gautam et al. 2021; Zhao et al. 2024), which limits the ability to capture micro scale failure and localized vulnerability patterns. Recent European Studies demonstrate that high resolution modeling improves understanding of social inequalities in risk exposure, suggesting that similar granular approaches are necessary in South Asian Mountain systems (Hussainzad and Gou 2024; Scognamiglio et al. 2025).

While deep learning approaches have been increasingly used for landslide detection, there remain limited research integrating high resolution participatory data with Multi-Criteria Decision Analysis (MCDA) frameworks for combined hazard vulnerability capacity assessment. MCDA remains valuable in data scarce environment due to its interpretability and ability to integrate heterogeneous indicators

(Saha et al. 2023); however, it requires stronger validation mechanisms to reduce subjectivity in weighting and classification.

In this context, this study develops a hybrid geospatial participatory framework that integrates Geographic Information System (GIS), MCDA and Level 4 extreme citizen science to quantify localized landslide risk. Unlike conventional participatory approaches, level 4 citizen science in this study involves active co-analysis of hazard validation and interpretation with 28 diverse stakeholders including farmers, and individuals with disabilities, ensuring inclusion of lived experience in spatial validation. Thus, the objective of this study was to evaluate a hybrid geospatial participatory framework that integrates citizen science with GIS-based MCDA to quantify localized landslide risk by synthesizing hazard triggers, socio-economic vulnerability and spatial adaptation capacity.

2. Study Area

Nepal, nestled in the heart of the Himalayas, makes up a third of this majestic mountain range. With 83% of its terrain being mountainous and 17% comprising of fertile plains in the south, it presents a diverse landscape. The combination of rugged topography, intricate geology, soft soil, heavy monsoon rains, and frequent earthquakes makes the mountains particularly prone to landslides, debris flows, and erosion (Gerrard 1990). The Melamchi municipality, located in the Sindhupalchowk district of Bagmati Province, Nepal, sits at an elevation ranging from 2600ft to 2800ft. Several studies have shown a strong correlation between landslides and precipitation (Dahal et al. 2012). The municipality receives annual rainfall varying from 1500 to 3000 millimeters, with an average annual temperature of 16.3°C (Data 2020). Earthquakes are also a significant factor in triggering landslides. The 7.8 Mw earthquake that hit Nepal on April 25th, 2015, resulted in over 21,000 landslides across the country (Rosser et al. 2021). The link between earthquakes and landslides depends on several factors, including the velocity and frequency of seismic activities, spatial distribution, and terrain characteristics such as topography, geology, morphology, and land use Observations indicate that landslides are often associated with earthquakes of magnitude 4 or more (Parkash 2013). Between 2000 and 2020, Sindhupalchowk District recorded approximately 90 seismic events ranging from MW 4.1 to 6.7 indicating persistent tectonic activity. Importantly, Melamchi is also a rapidly transforming socio-technical landscape where road expansion and slope modification are actively reshaping hillslope stability. The combination of monsoonal rainfall, earthquake recurrence and unplanned rural road construction make this catchment an ideal natural laboratory for analyzing rainfall-road interactions effect on landslide occurrence and associated socio-economic vulnerability Fig. 1.

3. Methodology

This study adopts a hybrid socio-technical framework that integrates volunteered Geographic Information (VGI), Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) to assess localized landslide risk. The workflow is structured into three sequential stages:

3.1 Survey Design and Data Acquisition:

A structured survey framework was developed using the KoboToolbox platform to collect spatial and socio-economic data. Landslide locations were first mapped through field-based inventory surveys, ensuring independent and primary hazard data collection. Each landslide was recorded with field-based including trigger type (rainfall, road construction or combined influence). A broad set of community resources was initially mapped to characterize spatial exposure and adaptative capacity. These included agricultural areas, governance institutions, education facilities, financial services, cultural sites, hospital services, and open evacuation spaces. For the MCDA model, only functionally relevant indicators directly linked to emergency response and evacuation capacity were selected. Specifically, distance to health facilities and distance to open evacuation space were used as quantitative proxies of accessibility and adaptive capacity. Euclidean distance was calculated in a GIS environment using (Sekarrini et al. 2022):

$$d\left(h,r\right)=\sqrt{\left(x_r-x_h\right)^2+\left(y_r-y_h\right)^2}$$

Where:

$d\left(h,r\right)$ is the straight-line distance between the hazard point to the resources

$\left(x_h,\ y_h\right)$ are the coordinates of the landslide hazard centroid.

$\left(x_r,\ y_r\right)$ are the coordinates of the resources.

The socio-economic vulnerability was defined using government recognized sensitive population groups including elderly individuals, persons with disabilities and pregnant women. Physical vulnerability was further represented using housing typology (crude, semi-concrete and reinforced structures) use as a proxy for structural fragility and exposure sensitivity.

3.2 Data validation:

To reduce spatial uncertainty associated with handheld GPS measurement in the steep Himalayan terrain, a multi-stage validation protocol was implemented. All geospatial datasets were initially reviewed in Google Earth pro and cross-checked with municipal records.

A participatory validation workshop was conducted where geo-tagged features were visualized on high resolution satellite imagery. Participants used local knowledge and temporal memory to confirm or correct spatial location.

Additionally, landslide points were refined through collaborative delineation of head scrap and deposits extents enabling conversion of point-based observations into improved spatial representation of hazard zone.

3.3 Risk zonation using weighted linear combination (WLC):

Landlide risk was estimated using weighted linear combination approach integrating hazard, exposure and vulnerability components (Malczewski 2000) :

$$Risk = \sum_{i=1}^{n} w(i) * r(i)$$

Where, $w(i)$ represent normalized weights derived through participatory consensus, and $r(i)$ represent a semi-quantitative rank (1–3) assigned to each criterion.

The selection of these parameters moves beyond traditional geomorphic mapping by hazard by incorporating hazard triggers, social sensitivity and adaptive capacity as shown in Table 1.

Table 1
Multi-Criteria Decision Analysis (MCDA) Scoring Matrix for Landslide Risk Assessment

Parameter	Specific indicator	Rank (1) Low risk	Rank (2) Medium risk	Rank 3 (high risk)
Hazard trigger	Cause of event	Rainfall alone	Road construction	Rain falls and road synergy
Frequency	Event recurrence	1 time	2 times	3 times
Medical access	Distance to hospital	<650 meters	650–980 meters	> 980 meters
Adaptive capacity	Distance to open space	< 850 meters	850–1000 meter	1000 meters
Impact	Physical exposure	cropland	Road and cropland	settlements
Vulnerability	Social sensitivity			Disabled/ Elderly/ Pregnant
Landslide zone	Probable Area digitized (m^2)	< 500	500–1000	1000

3.4 Final map Generation and validation:

The aggregated risk scores were classified into three categories:

- Low risk zone: Total Score < = 10
- Medium risk zone: <=14
- High risk zone: >=15

The resulting risk zonation maps were generated in a GIS environment. A participatory validation session was conducted to assess the spatial plausibility of results. Stakeholders reviewed whether mapped high-risk zones aligned with observed landslide occurrences and local experience, particularly in areas affected by rainfall and road construction. Feedback was incorporated to refine interpretation of the final outputs.

4. Result

The integration of GIS and citizen science enabled detail mapping of community resources in Ward 2 of Melamchi Muncipality. The study area contains a diverse range of assets contributing to local disaster response capacity as shown in Fig. 2.

Agricultural resources include 10 agriculture farm, 6 livestock (cow and buffalo) farms, 2 poultry farms and individual goat and pig farms. Cultural infrastructure consists of 2 Buddhist stupas and 8 temples, reflecting strong community presence and potential social cohesion during disaster response.

Institutional resources are limited to only 2 education institutions, one financial institution and 2 governance bodies. Health infrastructure is particularly constrained with only one health post serving entire area. A total of 15 open spaces were identified, which are critical for evacuation and emergency shelter. The spatial distribution of these resources, in relation to settlements, roads, and agricultural lands provide an important basis for evaluating adaptive capacity within the study area as shown in Fig. 3.

Participatory and ground collected data identified vulnerable population groups including elderly individuals' person with disabilities, pregnant women and socio-economically disadvantage individuals. Housing topology was used as proxy for physical vulnerability. The result indicates a heterogeneous distribution of living conditions:

- 19 individuals reside in concrete houses (relatively low structural vulnerability)
- 53 individuals live in semi-concrete houses (moderate vulnerability)
- 42 individuals live in crude houses (high vulnerability)

The concentration of vulnerable populations in structurally weak housing highlights significant exposure to landslide risk, particularly in areas with limited access to resources and infrastructure.

The MCDA-based assessment of 12 landslide locations reveals a clear spatial differentiation of risk classes driven by variations in exposure, triggering mechanisms, accessibility conditions and aggregated scoring outcomes. The total risk scores ranging from 8 to 18, reflecting moderate variability across the study area, with higher values concentrated in zones where multiple conditioning and triggering factors overlap. Overall, the classification producer five high risk zones, four medium risk zones and three low risk zones, indicating a structured but uneven spatial distribution of landslide risk zones as shown in Fig. 4.

High-risk zones are primarily characterized by the combined influence of rainfall and road construction particularly in areas where infrastructure intersects with cropland and settlements. These zones also exhibit higher exposure intensity and greater cumulative risk scores ranging from 15 to 18. Notably, this zone demonstrates the strongest convergence of multiple risk drivers, including larger affected areas, higher frequency values and relatively complex land-use configurations (road, settlement and cropland combinations). The presence of vulnerable population groups in at least one high risk zone's location further increases the potential consequences severity, although vulnerability data is not consistently represented across all sites.

Medium risk zones are mainly associated with either single dominant triggers (rainfall or road construction) or transitional conditions where land-use exposure is moderate. These zones show intermediate total scores (12–14) reflecting partial influence of anthropogenic disturbance and hydro-metrological forcing, but without the full interaction effect observed in high-risk zones. In this area, risk is primarily driven by infrastructure proximity and moderate frequency values, suggesting localized instability rather than system-wide slope failure conditions.

Low risk zones are predominantly cropland dominated areas with relatively lower exposure complexity and lower cumulative scores (8–10). These locations are mainly influenced by rainfall-induced processes or isolated road effects but lack significant interaction between triggering mechanisms and anthropogenic slope modification. As a result, their overall risk contribution remains limited compared to zones where multiple drivers converge. However, the relatively low differentiation between some low and medium risk scores suggests that the current ranking structure may not fully capture nonlinear interactions between variables, particularly in relation to road-rainfall synergy.

5. Discussion

This study applied level extreme citizen science framework in Melamchi represents a fundamental shift in analyzing the data over complex mountainous terrain. While previous studies have primarily utilized citizen science as a complex effective data collection tool (level 1 or level 2), this research transitions towards a collaborative co-analysis model (Den Broeder et al. 2018). By engaging diverse stakeholders including farmers, teachers, and individuals with disabilities as active co-analysts, the study moves beyond passive crowdsourcing to a deliberative process of hazard validation and risk interpretation.

This human-centered GIS approach challenges the top-down hegemony of remote sensing (Skarlatidou et al. 2022), which often suffers from observation bias in the Himalayas due to forest canopy or cloud cover (Rai and Mukherjee 2021). By integrating the temporal memory of residents, we produced a scientific map that identifies micro-scale high-impact landslides invisible to satellite sensors. This process shifts spatial authority from the often-unreliable mobile GPS chip to the local observer, providing that in high-relief topography, the human eye acts as superior sensor for delineating the physical transition from head scrap to deposit area.

Furthermore, the participatory framework democratizes the GIS environment (Dunn 2007). By involving marginalized groups in the Weighted Linear combination (WLC) ranking process, the resulting maps are no longer just geomorphic records; they are social instruments that allow the community to prioritize infrastructure projects and disaster interventions. This confirms that the integration of local knowledge is not merely a social exercise (Karki and Adhikari 2015) but a technical necessity for capturing the last-mile vulnerabilities that automated, non-linear models frequently overlook.

A critical geospatial decision in this study was the transition from subjective, resident perceived travel times to the calculated Euclidean distance as a standardized metric for adaptive capacity. In the past community-based practices, rough estimates of time were often used (Bhangdia et al. 2022), but these are highly subjective, a distance perceived as a short walk by young farmer may be an insurmountable barrier for the elderly or disabled individuals identified in our vulnerability mapping. Furthermore, in the high-relief, dynamic geography of Himalayas, road networks are often ephemeral and prone to total collapse during monsoon events, rendering traditional network analysis unreliable (Dahal et al. 2006). By using a precise geometric formula, we provide a standardized baseline that identifies isolation pockets zones where residents are geographically trapped regardless of fluctuating road conditions. This transforms the map from collection of feelings into a scientifically defensible tool for municipal planners to justify placement of emergency supplies and safe open spaces in the most isolated high-risk zones.

From the citizen science it was found that synergy between monsoon precipitation and unplanned road construction has surpassed natural geomorphic characteristics as the primary driver of slope failure in Ward 2. While traditional models treat rainfall and topography as independent variables (Du et al. 2025; Quintero et al. 2025), our findings confirm that hill-cutting without adequate drainage oversight creates a primed environment for catastrophic failure during extreme weather events. This interaction is not merely coincidental but causal; the removal of the slope toe for rural roads dictates the scale and frequency of landslides in the Melamchi Corridor. This confirms that unplanned development has become a dominant geomorphological control, necessitating that local authorities mandate nature-based bioengineering as the technical necessity for stabilizing the region’s socio-technical risk profile.

Integrating housing typology into vulnerability assessment is critical because it identifies the structural fragility that serves as the most direct link between a physical hazard and a disaster (Balasbaneh et al. 2020). While many international organizations and researchers prioritize demographic parameters such as gender, age, and ability to align with standardized global reporting frameworks like Sendai Framework (Beccari 2016), they often overlook the built environment as primary drivers of socio-economic risk. In Melamchi, where our study found that more than 83% of vulnerable individuals reside in crude or semi-concrete structures, housing is not merely a shelter but the fundamental determinant of livelihood stability and physical security. Structural mapping is often missed because it requires technical field level inspections compared to simple demographic survey; however, ignoring this parameter creates an invisibility gap for the rural poor who lack the financial capital to upgrade their dwellings. Prioritizing responses based on housing status is a technical necessity, as residents in crude structure face the highest probability of total asset loss and secondary displacement during landslide events.

Consequently, adaptation funds should be redirected towards target structural retrofitting grants and the training of local masons in building back better technologies. By moving beyond demographic counts to map structural fragility, local governments can transform disaster strategy from reactive rescue to proactive, evidence-based resilience model that protects both lives and long-term economic dignity of the community.

The transition from reactive to proactive landslide management int this study provides a scalable blueprint for evidence-based decision making within the framework of Nepal DRRM act 2017 (Government of Nepal Ministry of Home Affairs 2018). For municipal decision makers, these co-created risk maps move beyond simple hazard identification to provide a defensible foundation for targeted resource allocation. This allows the local government to justify specific investments such as structural retrofitting for crude housing in high-risk areas or the implementation of automated Early Warning System based on quantified risk rather than political convenience.

This approach fundamentally shifts the cultural practices of landslide management in Nepal. By engaging local stakeholders as co-analysts, the community transitions from passive victims of unpredictable disasters to active co-creators of knowledge. The democratizes the scientific process, fostering local ownership of the data which is a prerequisite for the success of long-term resilience strategies. For the most vulnerable residents, this shifted management culture provides a life-saving benefit; it increases risk literacy, enabling them to identify isolation pockets and prioritize their own safety through community lead bioengineering.

To operate these findings, disaster managers can utilize a tiered intervention strategy based on three identified risk categories:

- High risk zone: Requires institutional responsibility. The municipality must prioritize these for grey structure engineering, reinforcement drainage and potential resettlement programs for high-risk settlement.
- Medium risk zones: Driven by nature-based solutions. Local cooperatives and farmers should lead bio-engineering projects and participate in rescue mock drills and emergency training to prevent these zones from escalating.
- Low risk zone: Focus on continuous monitoring. Citizen scientists should be empowered with simple hydro-metrological tools, for instance rain gauges to track triggers, ensuring that development remains in equilibrium with geomorphic stability.

Ultimately, by integrating these local insights into formal governance, the Melamchi municipality ensures that the last-mile vulnerabilities to the marginalized are no longer invisible to the scientific or political record.

Despite the high resolution achieved, several limitations must be acknowledged. First the sample size (n = 12) limits the statistical robustness required for broader geomorphological generalization beyond Ward 2. Second the model remains static while it captures the current structural and environmental risk, it

does not account for temporal variability of climate change or increasing monsoon intensity. The reliance on Volunteered Geographical Information (VGI) introduces potential participation bias, where hazard near settlement may be over-reported compared to remote areas. Additionally, while the 1–3 ranking system ensures interpretability for local governance, it simplifies complex, non-linear landslide process into discreate categories. Finally, GPS imprecision in deep valleys can propagate through the Euclidean Distance analysis, through our human in the loop validation on high resolution imagery significantly mitigate these spatial errors. Future research should explore AI-augmented validation to transition this static framework into a real time, dynamic monitoring system.

6. Conclusion

This research integrates GIS technology with extreme citizen science framework provides a high-resolution risk assessment that traditional top-down models frequently overlook. By using the local knowledge of diverse stakeholders with multi-criteria decision analysis, this study proves that landslide risk in the Himalayas is a socio-technical phenomenon rather than geomorphic hazard. The finding highlights the synergy between monsoon precipitation and unplanned infrastructure development is now a dominant control of slope stability, necessitating a shift in how mountainous regions approach rural expansion. From the analysis of this hybrid framework, we draw the following additional conclusions:

- Increased Spatial resolution via participatory digitizing improves the identification of small size landslide through improvements in the spatialization of localized drainage failures are still needed.
- Euclidean distance establishes a standardized metric for isolation pocket, transforming static geomorphic records into dynamic tools for evacuation logic that account for total infrastructure collapse
- Structural housing typology acts as the primary determinant oof livelihood stability where the physical fragility of crude structures creates an invisibility gap in standard demographic-only vulnerability assessment
- Unplanned road construction must be regulated through mandatory bioengineering as it represents a primary anthropogenic trigger for large-scale failure during monsoon events.
- Extreme citizen science democratizes the GIS environment, shifting epistemic authority to local observers whose human-in-the-loop validation correct for GPS inaccuracies in high relief topography.

Declarations

Author Contribution

NT conceptualized the study, led the field investigation, conducted the validation workshop, designed and modified the survey instruments, analyzed the data, and prepared the initial manuscript draft. SS provided overall supervision, contributed detailed contextual and project-related inputs, and critically

revised the manuscript. RS contributed to manuscript editing, improved the technical writing, and refined the structure of the manuscript. MT and all co-authors contributed to the final review, discussion, and approval of the manuscript.All authors read and approved the final manuscript.

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Data Availability

All the data used in this study are available to download through https://zenodo.org/records/15096313 and questionaries through https://zenodo.org/records/19438940

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Figures

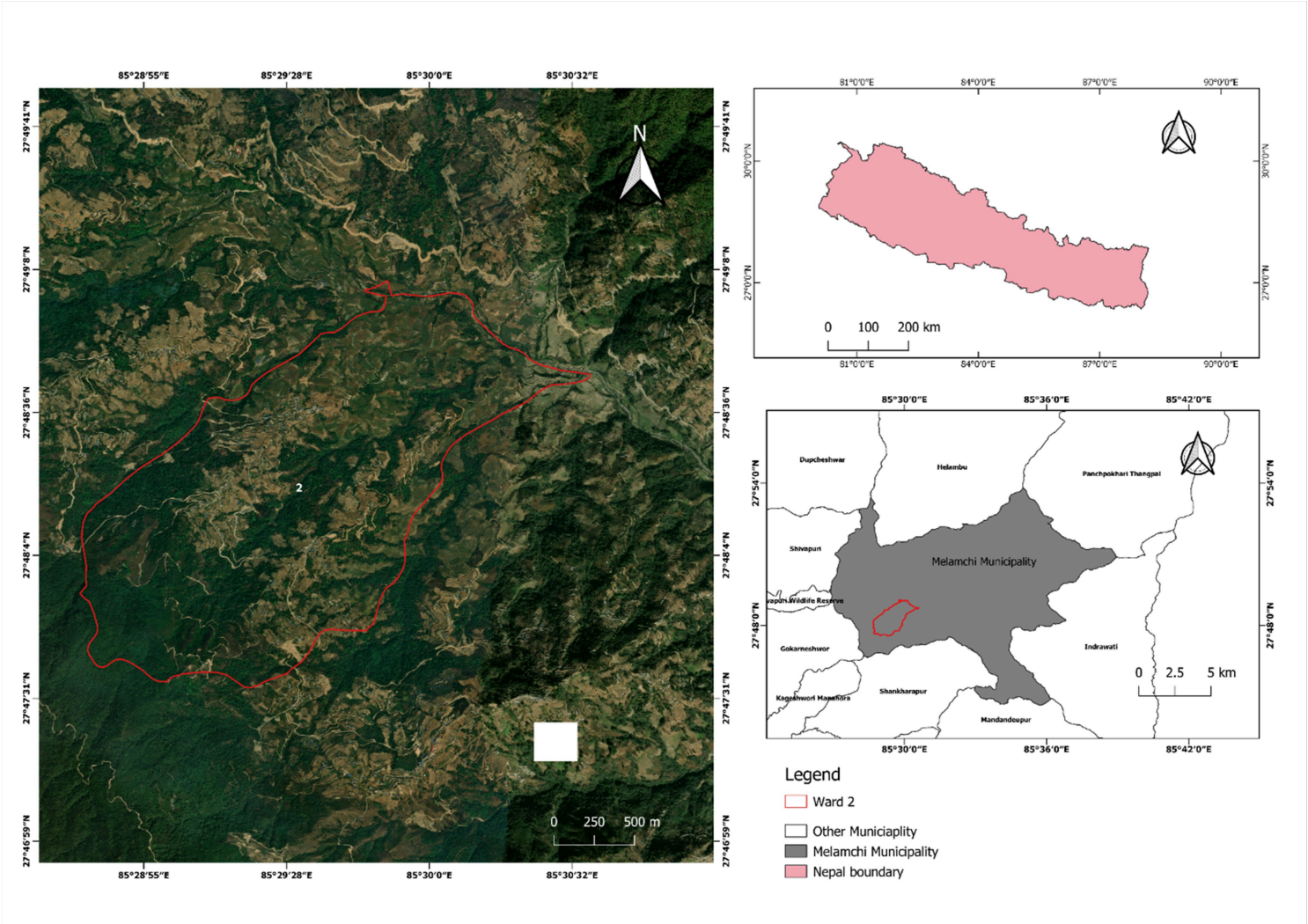


Figure 1

A detailed map showing Ward 2 of Melamchi Municipality, the primary study area for evaluating rainfall-road interactions and landslide risk

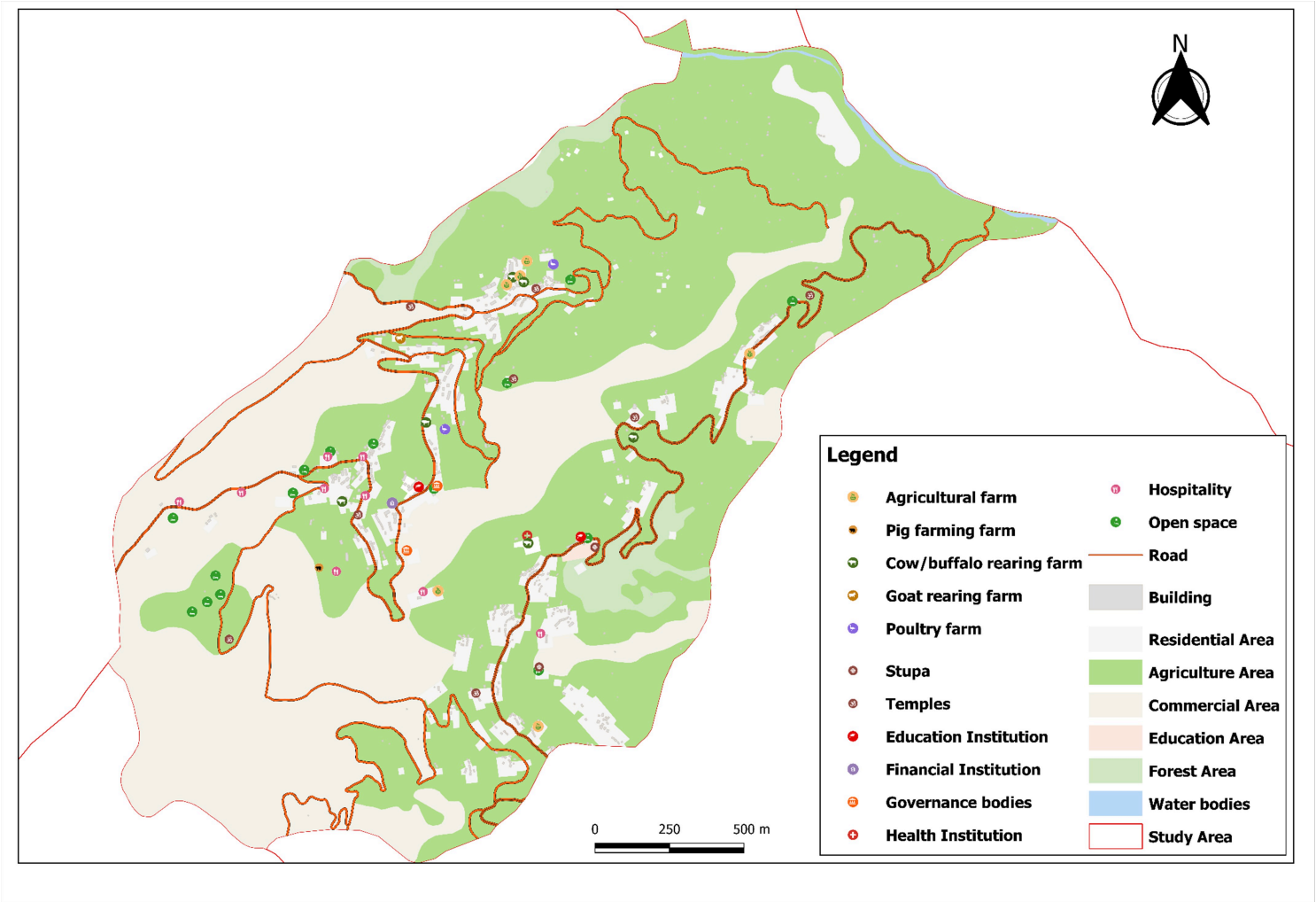


Figure 2

Visualization of community resources in Ward 2, Melamchi Municipality, mapped through integrated GIS and citizen science to assess local disaster response capacity

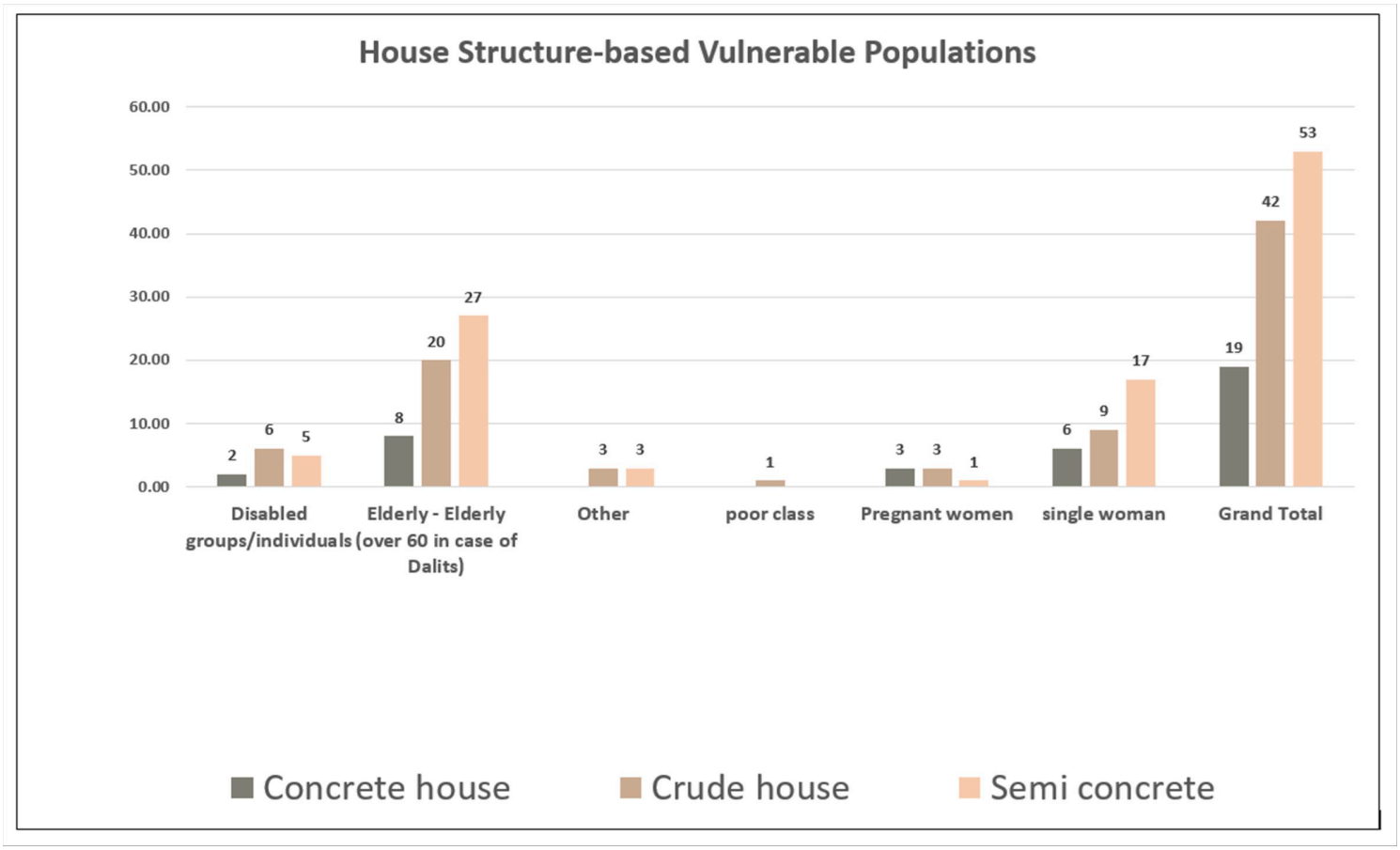


Figure 3

Comparative analysis of housing structures in Melamchi Ward 2, using housing typology as a proxy for physical vulnerability and exposure sensitivity

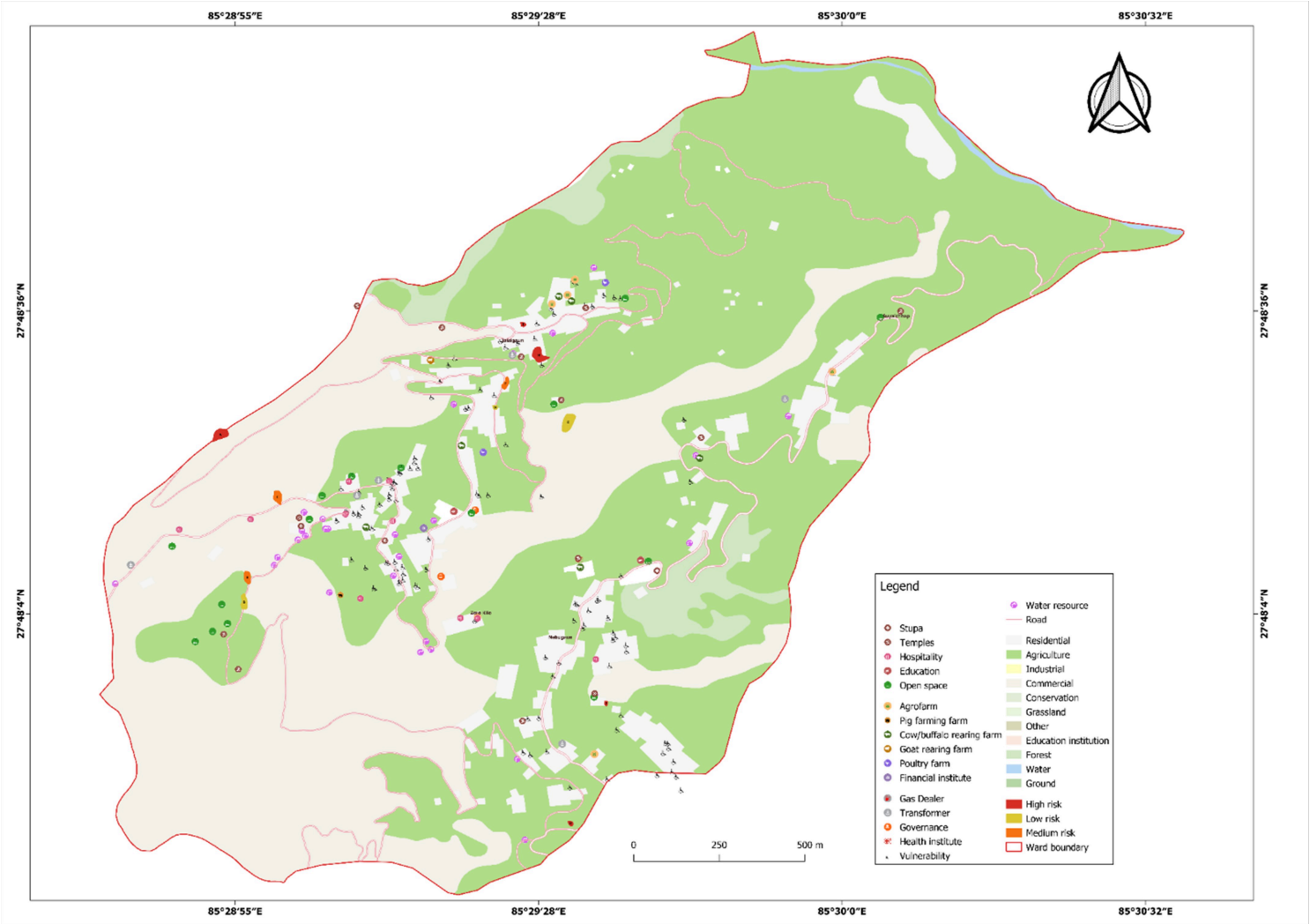


Figure 4

Spatial zonation of landslide risk based on a Multi-Criteria Decision Analysis (MCDA) framework, integrating hazard triggers, socio-economic vulnerability, and adaptive capacity