GIS-based Multi-Criteria Flood Hazard Assessment in a Mountainous Basin: A Study of the Melamchi River, Nepal

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Abstract: Floods in steep Himalayan basins are intensified by monsoonal extremes, rapid terrain responses, and active tectonics. The vulnerability is more exacerbated by expanding infrastructure in the region. The study was conducted in Melamchi River Basin to quantify a flood hazard map using a GIS-based multi-criteria decision analysis (MCDA) with the Analytical Hierarchy Process (AHP). Ten parameters (elevation, slope, curvature, precipitation, land use/land cover, soil type, distance to roads, distance to rivers, NDVI, and Topographic Wetness Index (TWI)) to develop criteria for hazard modeling. The inputs for the data were extracted from shuttle radar topographic mission (SRTM), Landsat 8, FAO Soils Portal, Regional Database of ICIMOD, and Department of Hydrology and Meteorology. AHP pairwise comparisons set consistent weights (Consistency Ratio = 0.0835): precipitation (19.04%) dominated, followed by TWI (15.38%), distance to rivers (15.12%), distance to roads (13.97%), slope (9.83%), elevation (8.26%), NDVI (5.99%), LULC (5.89%), soil (3.91%), and curvature (2.61%). The composite Flood Hazard Index (FHI) delineated five classes: very high (14%), high (24%), moderate (26%), low (22%), and very low (14%). The high and very high zones are concentrated along the river corridors and infrastructure-dense valleys in the central and southeastern sectors, reflecting a combined effect of orographic rainfall, convergent topography (TWI), and drainage disruption near roads. Validation against the June 2021 flood impact shows strong agreement, confirming that model captures the basin's principal flood-generating mechanisms. The thus generated map provides an operational basis for preparedness and land-use control, including river corridor setbacks, hydrologically sound road design, targeted vegetation restoration in low NDVI area, and densely co-located hydrometeorological monitoring stations. The approach is transparent, reproducible, and transferable to similar Himalayan catchments.

Keywords: ***Hydrogeomorphology, Hydrology, Risk governance.***

Introduction

Steep relief, fragile lithology, and monsoon-dominated hydroclimate combine to produce rapid flood response and recurrent losses across Himalayan basins (Duncan et al., 2003; Dhital et al., 2021). In Nepal, exposure is magnified by expanding settlements and infrastructure in valley corridors, limited protective works, and uneven preparedness (DHM, 2015; UNDRR, 2019). The Melamchi River Basin shows these conditions. The June 2021 event driven by extreme precipitation and upstream slope processes caused widespread damage to communities, roads, agricultural terraces, and the Melamchi Water Supply Project (ICIMOD, 2021; MoWS, 2022). Intensifying extremes linked to climate change emphasizes the urgency for robust hazard evidence in mountain catchments (Shrestha et al., 2020; World Bank, 2020). To address this, the study develops a reproducible, basin-scale flood hazard map using a GIS-based multi-criteria decision analysis (MCDA) combined with the Analytical Hierarchy Process (AHP), building on established practice for spatial decision support and hazard zonation (Correia et al., 1999; Malczewski, 1999).

Study Area and Data

The Melamchi River Basin (approx. 640 km^2; Sindhupalchowk, Bagmati Province) spans approximately 800–5,875 m elevation, cutting across subtropical to alpine zones and strong orographic gradients (Sharma et al., 2019; Dahal and Hasegawa, 2008). All spatial inputs were projected to WGS 84 / UTM Zone 45∘N and harmonized at 30 m resolution for analysis. Ten parameters were compiled: elevation, slope, curvature, precipitation, land use/land cover (LULC), soil type, distance to roads, distance to rivers, NDVI, and Topographic Wetness Index (TWI). Elevation and derivatives used SRTM (30 m) (Farr et al., 2007). Precipitation fields represent 2012–2022 average annual precipitation recorded by Department of Hydrology and Meteorology, reclassified for basin mapping (Fick and Hijmans, 2017). LULC was derived from regional database of ICIMOD and NDVI were derived from cloud-free (10%) Landsat 8 imagery using Google Earth Engine (GEE) (Jan - Dec 2021) (FRTC, 2022; Mustafa et al., 2005; Senanayake et al., 2016). Soils were compiled from FAO digital resources and grouped by infiltration/storage behavior (FAO, 2003; FAO, 2007). The data on road networks and rivers was also derived from regional database of ICIMOD (ICIMOD, 2009).

Methods

A Weighted Linear Combination (WLC) of the ten parameters integrated standardized layers into a Flood Hazard Index (FHI) using:

$$\text{FHI} = \sum_{i=1}^{n} r_i w_i$$

Where r_i is the class rating (1-5) and w_i is the AHP-derived weight (Saaty, 1980; Lee et al., 2017).

AHP pairwise comparisons produced the criterion weights, and judgment consistency was acceptable for n = 10 and $\lambda_{max} = 11.12$, CI = 0.124; using RI = 1.49, CR = 0.083, meeting the widely accepted threshold of 0.10 (Gigović et al., 2017; Malczewski, 1999).

Criteria a weights and hydrologic logic

The weights assigned to each parameter in the flood hazard index (FHI) reflect the relative influence of key processes in a monsoon-dominated steep terrain system. Precipitation is the dominant driver, contributing 19.04%, which underscores the critical role of storm intensity and spatial variability in triggering surface runoff and potential flooding. Topographic Wetness Index (TWI) follows closely at 15.38%, highlighting areas of convergent flow and persistent saturation that facilitate overland flow generation. Distance to rivers (15.12%) and distance to roads (13.97%) capture both natural exposure to fluvial processes and human-modified drainage pathways that can exacerbate flood risk in adjacent settlements. Secondary factors such as slope (9.83%) and elevation (8.26%) provide essential context for gravitational flow dynamics and hydraulic head differences influencing runoff velocity and accumulation. Vegetation cover (NDVI, 5.99%) and Land Use/Land Cover (LULC, 5.89%) contribute to local modulation of infiltration and soil retention, while soil type (3.91%) and curvature (2.61%) refine spatial resolution by accounting for textural properties and micro-topographic flow convergence or divergence (Lee et al., 2017; Tehrany et al., 2014). Collectively, this structure reflects orographic rainfall control over storm inputs (Sharma et al., 2019) and terrain-induced saturation and storage processes (Beven and Kirkby, 1979). The inclusion of proximity metrics effectively captures direct flood exposure and infrastructure-mediated drainage effects, which are particularly relevant in Himalayan watersheds with densely spaced settlements and roads (Jiang et al., 2012; Paudyal et al., 2012).

Composite results and spatial patterns

The resulting FHI map delineates five hazard classes: Very High (14%), High (24%), Moderate (26%), Low (22%), and Very Low (14%). In total, approximately 38% of the basin falls into High–Very High hazard categories, predominantly concentrated along the central-to-southeastern corridors where population settlements, croplands, and transportation networks are densest (Lee et al., 2017; Tehrany et al., 2014). This spatial arrangement reflects the synergistic effects of high orographic rainfall, convergent topography as indicated by TWI, and human infrastructure that alters natural drainage pathways (Shrestha et al., 2020; Paudyal et al., 2012). Moderate hazard zones (26%) are distributed along transitional slopes and minor tributary valleys, representing areas with intermediate exposure to surface runoff or localized ponding. Low and Very Low zones correspond largely to ridge tops, well-drained slopes, or areas with dense vegetation cover that promote infiltration. Overall, the spatial logic confirms that topography, hydrology, and land use interact dynamically to shape flood susceptibility patterns.

Validation with the June 2021 Event

Overlaying the FHI map with documented impacts from the June 2021 flood event demonstrates strong agreement between predicted and observed vulnerability. Heavily affected settlements, including Syaule, Jethal, and Haibung, are predominantly located within the High and Very High classes, supporting the event-scale reliability of the model (ICIMOD, 2021; MoWS, 2022). This correlation indicates that the selected criteria and their respective weights effectively capture the dominant mechanisms of flood generation in the basin, including both precipitation-driven runoff and geomorphologically controlled flow pathways (Shrestha et al., 2021; Lee et al., 2017). Furthermore, the model successfully identifies localized hotspots where infrastructure proximity and slope convergence amplify flood impacts, providing actionable insights for planning and mitigation.

Interpretation for Risk Management

The basin's relief setting differentiates hazard types and informs management strategies. Ridge-top and steep-slope settlements, such as Helambhu, Tarke Ghyang, Nakote, Melamchigaon, and Sermanthang, are relatively less exposed to overbank inundation but remain vulnerable to debris flows, shallow landslides, and flash floods originating from short, steep catchments (Dahal and Hasegawa, 2008; Dhital et al., 2021). In contrast, valley-floor communities adjacent to rivers, including Timbu, Syaule, Jethal, Haibung, Angbu Danda, Ichok, Helmu, Dongdhing, Chhimi, Kharchung, and Kiwool, face direct flooding, sediment pulses, and channel migration, especially within 0–500 m buffers along primary channels (Tehrany et al., 2014; ICIMOD, 2021). Road density emerges as a critical factor influencing localized flooding patterns, highlighting the need for hydrologically informed corridor design and appropriate drainage infrastructure to mitigate flood amplification (Jiang et al., 2012; Paudyal et al., 2012). The integration of topographic, hydrological, and anthropogenic indicators thus provides a spatially nuanced understanding of flood risk, supporting targeted interventions at both ridge and valley scales.

Conclusion

Approximately 38% of the basins are classified as High to Very High hazard, while 26% falls within Moderate zones, emphasizing the substantial exposure of the region to monsoon-driven flooding. The AHP-based MCDA approach effectively integrates multiple environmental and anthropogenic factors, producing a robust, spatially explicit flood hazard map. This framework is replicable for other mountainous watersheds, enabling planners and disaster managers to prioritize risk reduction, infrastructure planning, and community-based mitigation strategies in regions characterized by complex topography, intense precipitation, and vulnerable settlements. The weights assigned to each parameter reflects the governing processes in a monsoon-steep terrain system. Precipitation dominates (19.04%), followed by TWI (15.38%), distance to rivers (15.12%), and distance to roads (13.97%); slope (9.83%) and elevation (8.26%) are substantive secondary factors; NDVI (5.99%), LULC (5.89%), soil (3.91%), and curvature (2.61%) provide local refinement (Lee et al., 2017; Tehrany et al., 2014). The structure aligns with orographic rainfall control on storm inputs (Sharma et al., 2019) and terrain-induced saturation/storage (Beven and Kirkby, 1979), while proximity metrics capture direct flood exposure and infrastructure-mediated drainage effects documented in Himalayan watersheds (Jiang et al., 2012; Paudyal et al., 2012).

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