Asian Journal of Engineering Geology, 2025, Vol. 2 Special Issue, ARC-15 of IAEG, Abstract No.: 153

Extended Abstract **DOI: https://doi.org/10.64862/ajeg.2025.2sp.46.153** **Open Access**

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

Subash Duwadi[1*], Danda Pani Adhikari[1], Krishna KC Katuwal[2], and Ramesh Kathariya[3]

[1]Department of Environmental Science, TU, Tri-Chandra Multiple Campus, Kathmandu, Nepal
[2]Department of Engineering Geology, TU, Tri-Chandra Multiple Campus, Kathmandu, Nepal
[3]Central Department of Environmental Science, Tribhuvan University, Nepal

(*[*]Corresponding E-mail: subash.duwadi@trc.tu.edu.np, duwadi.subash@gmail.com*)

Received: September 25, 2025, Accepted: October 19, 2025

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., 2015). 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 an elevation range of approximately 800–5,875 m, traversing subtropical to alpine climatic zones and exhibiting strong orographic gradients (Sharma et al., 2019; Dahal and Hasegawa, 2008). This complex topography strongly influences hydrological processes, soil distribution, and vegetation patterns within the basin. All spatial datasets were projected to WGS 84 / UTM Zone 45°N and harmonized at a 30 m spatial resolution to ensure compatibility for subsequent analyses. Ten environmental and anthropogenic 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 its derivatives were obtained from the Shuttle Radar Topography Mission (SRTM, 30 m) dataset (Farr et al., 2007). Precipitation fields represent the 2012–2022 average annual precipitation recorded by the Department of Hydrology and Meteorology, which were reclassified for basin-wide mapping (Fick and Hijmans, 2017). LULC information was derived from the regional ICIMOD database, while NDVI values were calculated from cloud-free (≤10%) Landsat 8 imagery covering January–December 2021 using Google Earth Engine (GEE) (FRTC, 2022; Mustafa et al., 2005). Soil data were compiled from FAO digital resources and classified based on infiltration and storage behavior to reflect hydrological response variability (FAO, 2003; FAO, 2007). Spatial layers representing road networks and river systems were also extracted from ICIMOD's regional datasets (ICIMOD, 2009), providing essential information on accessibility and drainage patterns. Collectively, these harmonized datasets form the basis for advanced hydrological modeling, land-use planning, and disaster risk assessment in this complex mountainous basin.

Methods

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

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

Where r_i is the class rating (1-5) and w_i is the AHP-derived weight (Saaty and Vargas, 2012).

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 reflect the dominant hydrometeorological and geomorphic controls operating in a monsoon–steep-terrain environment. As expected, precipitation receives the highest weight (19.04%), underscoring its role as the primary driver of flood generation during intense monsoonal storm periods. This is followed by TWI (15.38%), distance to rivers (15.12%), and distance to roads (13.97%), all of which strongly regulate runoff concentration, drainage connectivity, and exposure to channelized flows. Slope (9.83%) and elevation (8.26%) function as critical secondary predictors, influencing flow acceleration, storage potential, and the vertical distribution of rainfall and temperature. Meanwhile, NDVI (5.99%), LULC (5.89%), soil type (3.91%), and curvature (2.61%) contribute localized refinement by capturing surface roughness, infiltration pathways, material properties, and micro-topographic convergence (Lee et al., 2017; Tehrany et al., 2014).

The overall weighting structure coherently aligns with orographic modulation of monsoon rainfall—a well-documented control on storm magnitude and spatial distribution in the Nepal Himalaya (Sharma et al., 2019)—as well as the role of terrain-driven saturation and storage dynamics conceptualized in physically based runoff models (Beven and Kirkby, 1979). Additionally, the prominence of proximity metrics reflects not only direct flood exposure near channels but also the infrastructure-mediated drainage disruptions increasingly recognized in Himalayan watersheds, where expanding road networks alter flow paths, concentrate runoff, and intensify localized hazard potential. This relationship further emphasizes the integrated influence of topography, hydrology, and anthropogenic interventions in shaping flood susceptibility patterns, particularly in rapidly developing mountain environments where land use changes, drainage modification, and increasing climatic variability collectively contribute to heightened flood risks and more complex hazard dynamics.

Composite results and spatial pattern

The FHI map delineates five susceptibility classes, with Very High (14%), High (24%), Moderate (26%), Low (22%), and Very Low (14%) zones distributed across the basin. Collectively, approximately 38% of the total area falls within the High to Very High hazard categories, forming a continuous band along the central-to-southeastern corridors where the density of settlements, agricultural land, and transportation networks is greatest. This spatial concentration aligns with previous findings that urban expansion and linear infrastructure amplify hydrological response and flood sensitivity in physiographically dynamic basins (Lee et al., 2017; Tehrany et al., 2014). The underlying spatial logic is driven by the co-occurrence of intense orographic precipitation, convergent terrain with elevated Topographic Wetness Index (TWI), and anthropogenic alterations to natural drainage pathways, all of which enhance surface runoff and reduce infiltration capacity. These interacting factors reflect broader regional patterns in Himalayan flood dynamics, where steep relief, concentrated monsoon inputs, and infrastructure growth combine to elevate hazard levels (Shrestha et al., 2020).

Validation with June 2021 event

The overlay of mapped susceptibility with documented 2021 impacts shows strong agreement: heavily affected settlements including Syaule, Jethal, and Haibung occur predominantly in High/Very High classes, supporting the model's event-scale credibility (MoWS, 2022). This alignment indicates that the chosen criteria and weights capture dominant flood-generating mechanisms in the basin (Shrestha et al., 2021).

Interpretation of risk management

The relief setting fundamentally differentiates the dominant hazard pathways across the basin. Settlements located along ridge-tops and steep slopes—including Helambhu, Tarke Ghyang, Nakote, Melamchigaon, and Sermanthang—are comparatively less exposed to classic overbank inundation because they lie outside the natural floodplain envelope. However, their topographic position places them at heightened risk of debris flows, shallow landslides, and short-lead-time flash floods generated within small, steep headwater catchments, where intense convective rainfall can rapidly mobilize colluvium and channel sediments (Dahal and Hasegawa, 2008). In contrast, valley-floor communities situated near active channels—such as Timbu, Syaule, Jethal, Haibung, Angbu Danda, Ichok, Helmu, Dongdhing, Chhimi, Kharchung, and Kiwool—experience direct exposure to riverine flooding, bank overtopping, and high-magnitude sediment pulses, particularly within the 0–500 m river-buffer zones identified as critical inundation corridors (Tehrany et al., 2014; ICIMOD, 2021).

Across both terrain contexts, road density emerges as a major local-scale determinant of flood behavior, as road cuts, embankments, and undersized drainage structures can obstruct or divert surface flow, concentrate runoff, and trigger localized overtopping. This emphasizes the need for hydrologically informed corridor design, integrating appropriate cross-drainage, slope stabilization, and alignment planning to mitigate the compounded hazards associated with expanding mountain infrastructure.

Conclusion

Approximately 38% of the basin area falls within High to Very High hazard zones, while 26% is classified as Moderate hazard. These findings highlight the substantial flood risk faced by communities and infrastructure within the basin. The AHP-based MCDA approach effectively integrates multiple environmental and anthropogenic factors, such as topography, precipitation, land cover, and proximity to rivers and roads, to produce accurate and spatially explicit flood hazard maps. This methodology provides a robust and replicable framework that can be applied to other mountainous watersheds for risk assessment, planning, and disaster management.

References

Beven, K. J., and Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin, 24(1), 43–69. https://doi.org/10.1080/02626667909491834

Correia, F. N., Saraiva, M. D., Silva, F. N., and Ramos, I. (1999). Floodplain management in urban developing areas. Part II: GIS-based flood analysis and urban growth modelling. Water Resources Management, 13(1), 23–37. https://doi.org/10.1023/A:1008045419517

Duncan, C. C., Masek, J. G., and Fielding, E. J. (2003). How steep are the Himalaya? Characteristics and implications of along-strike topographic variations. *Geology*, 31(1), 75–78. https://doi.org/10.1130/0091-7613(2003)031

Dahal, R. K., and Hasegawa, S. (2008). Representative rainfall thresholds for landslides in the Nepal Himalaya. Geomorphology, 100(3–4), 429–443. https://doi.org/10.1016/j.geomorph.2008.01.014

Dhital, Megh Raj. (2015). Geology of the Nepal Himalaya: Regional perspective of the classic collided orogen. Springer. https://doi.org/10.1007/978-3-319-02496-7

Department of Hydrology and Meteorology. (2015). Climatological and hydrological records of Nepal. Government of Nepal.

Food and Agriculture Organization. (2003). Soil resources and land use database. FAO.

Food and Agriculture Organization. (2007). Digital soil map of the world. FAO.

Farr, T. G., et al. (2007). The Shuttle Radar Topography Mission. Reviews of Geophysics, 45, 1–33. https://doi.org/10.1029/2005RG000183

Fick, S. E., and Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology, 37(12), 4302–4315. https://doi.org/10.1002/joc.5086

Forest Research and Training Centre. (2022). Land cover of Nepal. ICIMOD. https://doi.org/10.26066/RDS.1972729

Gigović, L., Pamučar, D., Bajić, Z., and Drobnjak, S. (2017). Application of GIS-interval rough AHP methodology for flood hazard mapping in urban areas. Water, 9(6), 360. https://doi.org/10.3390/w9060360

International Centre for Integrated Mountain Development. (2009). Roads of Nepal. ICIMOD Regional Database System.

Malczewski, Jacek. (1999). GIS and multicriteria decision analysis. John Wiley and Sons. Available at: https://doi.org/10.1111/j.1538-4632.2002.tb01077.x

Mustafa, Y. T., et al. (2005). Land cover classification using remote sensing for flood risk assessment. Remote Sensing of Environment, 98(4), 463–475.

Ministry of Water Supply. (2022). Melamchi Flood Disaster Report. Government of Nepal. https://books.google.com.np/books/about/GIS_and_Multicriteria_Decision_Analysis.html?id=2Zd54x4_2Z8C&redir_esc=y

Sharma, S., et al. (2019). Climatic variability and water resources in Nepal Himalaya. Climate, 7(9), 109.

Saaty, T.L. and Vargas, L.G. (2012). Models, Methods, Concepts & Applications of the Analytic Hierarchy Process. 2nd ed. New York: Springer Science & Business Media. https://doi.org/10.1007/978-1-4614-3597-6

Shrestha, U. B., Karmacharya, S., and Adhikari, R. (2020). Increasing climate-induced flood risk in the Himalayan region. Climatic Change, 162(2), 587–604.

Shrestha, R., Thapa, M., and K. C., M. (2021). GIS-based flood hazard mapping in Nepalese river basins. Hydrology Research, 52(3), 640–654.

Tehrany, M. S., Pradhan, B., and Jebur, M. N. (2014). Flood susceptibility mapping using a novel ensemble approach of evidential belief function and support vector machine. Journal of Hydrology, 512, 332–343. https://doi.org/10.1016/j.jhydrol.2014.03.008

United Nations Office for Disaster Risk Reduction. (2019). Global Assessment Report on Disaster Risk Reduction 2019. https://doi.org/10.18356/f4ae4888-en

World Bank. (2020). World Bank disaster risk profile: Global flood impacts. World Bank.