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# What Can Spatial Assessment Reveal About Flash Flood Risk and Ecosystem Carrying Capacity in Tropical Highland Environments?

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**Abstract:** Flash floods are among the most destructive hydrometeorological hazards in tropical highland regions, yet their spatial risks remain poorly quantified in data-scarce environments. This study assessed flash flood risk in Solok Selatan Regency, West Sumatra (Indonesia), by integrating landform and slope classification with the Topographic Wetness Index (TWI) derived from a 30 m DEM. Historical records of 11 flood events between 2010 and 2020 were used for model validation. The analysis revealed that most of the regency is characterized by moderate flash flood risk, while high-risk zones are concentrated in steep fluvial landscapes. Validation against observed flood locations demonstrated a spatial match of 95.2%, confirming the reliability of the model. In addition, the evaluation of hydrological ecosystem service capacity indicated that over 80% of the landscape has only moderate regulatory function, limiting its ability to buffer runoff. These findings highlight the importance of integrating DEM-based hydrological indices with ecosystem assessments to support more effective disaster risk reduction and spatial planning in tropical highland environments.

**Keywords:** DEM; Ecosystem Carrying; Flash floods; Landform classification; Tropical Highland.

## Introduction

Flash floods have emerged as increasingly frequent hydrometeorological disasters in tropical regions, with a global frequency increase of 23% over the past two decades (Jayawardena, 2015; Quesada-Román et al., 2020). Southeast Asia, including Indonesia, bears 43% of the global economic impact of these disasters (Kim, 2013; Tan et al., 2020). In Indonesia, Solok Selatan Regency (West Sumatra) has been one of the most disaster-prone areas, recording seven significant flash flood events between 2010 and 2020. These events caused severe damage to upstream watershed ecosystems and posed substantial risks to downstream development sustainability (Supangat et al., 2023). Such recurrent disasters indicate the degradation of environmental carrying capacity, particularly the declining ability of upstream watersheds to provide water regulation ecosystem services (Gordon et al., 2012; Uchijima, 2015; Zeng et al., 2023).

Previous studies on flash floods remain fragmented. First, spatial analyses using the Topographic Wetness Index (TWI) have been widely applied, but often without integrating ecological

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carrying capacity (Berhanu & Bisrat, 2018), Second, ecosystem service assessments typically emphasize provisioning or cultural services and rarely validate regulating services against actual disaster events (Villa et al., 2014), third, administrative-boundary approaches to disaster risk assessment often neglect hydrological functional units, namely watersheds, which are essential for reliable flood modeling (Flotemersch et al., 2016). These gaps reduce the accuracy and policy relevance of risk assessments, particularly in mountainous tropical regions where watershed integrity strongly controls runoff dynamics.

The case of Solok Selatan is particularly urgent. More than half of its landscape is dominated by steep slopes (>45°) in fluvial and denudational landforms (Purwanto & Paiman, 2023), creating a geomorphological predisposition to rapid runoff. In addition, extensive land-use changes, including forest conversion into monoculture plantations, have substantially reduced infiltration capacity and disrupted natural hydrological regulation (Sari & Hermon, 2025). This ecological degradation has pushed local watersheds closer to a tipping point, thereby amplifying the frequency and magnitude of flash floods.

This study addressed these critical gaps by developing an integrated, watershed-oriented framework that combined DEM-derived hydrological indices (Topographic Wetness Index), geomorphological classification (landform and slope), and an ecosystem-based carrying-capacity assessment of water-regulating services. We linked spatially explicit hazard mapping with an operational carrying-capacity index, informed model thresholds with documented flood occurrences and field verification, and examined the spatial correspondence between hydrological vulnerability and declines in regulatory ecosystem function. By delivering reproducible, watershed-scale hazard and management maps and by providing an evidence-based procedure to incorporate ecosystem regulation into flood-risk zoning, the study supplies a practical pathway for integrating ecological capacity into upstream management and disaster risk-reduction planning.

## Method

*Area of Interest and Scope*

The study was carried out in Solok Selatan Regency, West Sumatra Province, Indonesia (1°15′–1°45′ S; 101°15′–101°45′ E). The study area covered approximately 3,346 km² and included the upland portions of the Batang Suliti and Batang Hari catchments. The locality was selected because of its complex topography and recurrent flash flood events recorded between 2010 and 2020.

**Figure 1**. Research location

*Research Design and Approach*

A spatial-quantitative design was adopted. The analytical workflow combined Digital Elevation Model (DEM)-derived hydrological indices (Topographic Wetness Index, TWI), geomorphological classification (landform), slope analysis, and an ecosystem-based carrying-capacity assessment for water-regulating services (Rahimi et al., 2017). Spatial layers were produced independently and subsequently integrated using a reproducible Multi-Criteria Evaluation (MCE, weighted linear combination) to generate a flash-flood risk map. Model outputs were validated against documented flash-flood occurrences (2010–2020) and by field verification (Abdelkareem & Mansour, 2023; Alam et al., 2021; Kwarteng et al., 2005).

*Data Sources and Types*

The research used a combination of primary and secondary data sources:

The research relied on a combination of primary and secondary data sources. Topographic data were obtained from the national DEMNAS digital elevation model, which provides a resolution of 0.27 arc-seconds (~8.1 m) and was accessed through the Geospatial Information Agency (BIG). Land use and land cover information was extracted from 2020 Landsat 8 imagery, classified through a supervised approach, and validated using field observations as well as high-resolution imagery from Google Earth. Records of flash-flood events between 2010 and 2020 were compiled from the Indonesian National Board for Disaster Management (BNPB) and the Regional Disaster Management Agency (BPBD) of Solok Selatan, and subsequently georeferenced for spatial analysis. Hydrological data, including daily measurements of river discharge (m³/s) and water level (m), were obtained from gauging stations along the Batang Suliti and Batang Hari rivers, operated by the Ministry of Public Works and Housing (PUPR).

*Analytical Techniques and Procedures*

*Landform and Slope Analysis*

Landforms were classified into five categories: denudational, fluvial, karst, structural, and volcanic (Utama & Mulyasari, 2024). Classification was conducted through DEM image digitization and interpretation, corroborated with geological and physiographic maps (Juita et al., 2020). Slope gradients were derived from DEM using the slope raster function and categorized as follows: Flat (0–8%), Gentle (8–15%), Moderately steep (15–25%), Steep (25–45%), and very steep (>45%).

*Topographic Wetness Index (TWI) Calculation*

TWI values were calculated to identify potential flow accumulation and waterlogging zones using the classical formula (Sørensen et al., 2006):

Where: $TWI = \ln(a / \tan(\beta)$
a = flow accumulation,
$\beta$ = slope gradient (in radians).

Where *a* denotes the upslope contributing area per unit contour length (flow accumulation; m²) and *β* denotes the local slope in radians. Note: slope values were converted from percent to radians prior to computation ($\beta = \arctan(slope/100)$). Flow direction and accumulation were computed using standard D8 algorithms (after sink filling). TWI rasters were produced with SAGA GIS and exported to ArcGIS for further processing (Meles et al., 2019).

TWI classification thresholds (High / Medium / Low) were derived by combining (i) histogram analysis of the study-area TWI distribution, (ii) visual inspection against known drainage features, and (iii) iterative calibration with observed flood locations. Final thresholds were documented in the supplementary material (Kopecký et al., 2021). Spatial zoning was conducted through raster-vector overlay using ArcGIS 10.8. Risk areas were delineated as topologically simplified polygon vectors (Sørensen et al., 2006). Validation was performed through spatial overlay with flash flood event maps from 2010 to 2020.

*Environmental Carrying Capacity Analysis of Water Regulation Services*

The carrying capacity assessment Firmansyah et al. (2020); Mulawarman et al. (2019), was conducted by integrating land use and land facet components consisting of: Slope (40%), Soil material (30%), Relief (20%), and Soil depth (10%) (Brost & Beier, 2012). Each component was scored based on its water retention potential (Liu et al., 2015). Total scores were then classified into three levels: High carrying capacity, Moderate carrying capacity, and Low carrying capacity (Kastanya & Matulessy, 2023). All data processing and analysis were conducted using: ArcGIS 10.8 for spatial analysis, raster classification, TWI computation, and DEM preprocessing. Microsoft Excel for numerical processing and tabulation of results.

## Result and Discussion

*Landform Classification*

The morphological analysis revealed that Solok Selatan Regency comprises five major landform types: denudational, fluvial, karst, structural, and volcanic. Denudational landforms—formed through weathering, erosion, mass movement, and sedimentation—are the most widespread, occurring in nearly all districts. In contrast, fluvial landforms, shaped by surface runoff and river activity, play a crucial role in influencing surface flow dynamics and water accumulation during flash flood events. The spatial distribution of landforms shows that denudational types dominate the region, covering an area of approximately 280,698.7 hectares or more than 85% of the regency. Meanwhile, fluvial landforms occupy around 30,908.8 hectares, equivalent to roughly 11% of the total area (Table 1).

**Table 1.** Distribution of Landform Types in Solok Selatan Regency

| Subdistrict | Denudasional (Ha) | Fluvial (Ha) | Karst (Ha) | Structural (Ha) | Volcanic (Ha) |
|---|---|---|---|---|---|
| Sangir | 31.387,50 | 11.226,50 | 488,3 | - | 20.111,40 |
| Koto Parik Gadang Diateh | 59.254,10 | 2.429,00 | 5.582,60 | - | - |
| Pauh Duo | 18.554,10 | 1.187,00 | 486,7 | - | 6.303,60 |
| Sangir Balai Janggo | 51.119,70 | 8.547,60 | - | 777,4 | 2.690,00 |
| Sangir Batang Hari | 63.793,10 | 1.768,30 | 7.443,90 | 1.501,70 | 659,1 |
| Sangir Jujuan | 24.577,90 | 3.284,70 | - | - | - |
| Sungai Pagu | 32.012,30 | 2.465,70 | 1.362,50 | - | - |
| Total | 280.698,70 | 30.908,80 | 15.364,10 | 2.279,10 | 29.764,10 |

The distribution of fluvial landforms generally follows river networks and alluvial plains, especially in areas located along riverbanks. The largest extent of denudational landforms is found in the Sangir Batang Hari subdistrict (63,793.1 ha), while the widest fluvial landform area is located in Sangir Balai Janggo (8,547.6

ha). Both landforms are prevalent in areas with a high frequency of flash flood events.

*Slope Gradient Classification*

Slope classification results indicate that Solok Selatan Regency is predominantly characterized by steep (25–45%) and very steep (>45%) slope classes. The total area with moderately steep to very steep slopes reaches 226,187 hectares, accounting for approximately 60% of the regency's territory. The subdistrict with the largest area of very steep slopes is Koto Parik Gadang Diateh, covering 34,383 hectares or 52.8% of its total area. Conversely, Sangir Balai Janggo is dominated by flat to gentle slopes (52,219 ha), which significantly contribute to surface water pooling and flow deceleration (Table 2).

**Table 2**. Distribution of Slope Gradients in Solok Selatan Regency by Subdistrict

| Subdistrict | Flat (Ha) | Gentle (Ha) | Moderately Steep (Ha) | Steep (Ha) | Very Steep (Ha) |
|---|---|---|---|---|---|
| Sangir | 5.856 | 4.300 | 12.256 | 30.740 | 10.061 |
| Koto Parik Gadang Diateh | 1.623 | 992 | 3.679 | 26.589 | 34.383 |
| Pauh Duo | 578 | 906 | 5.577 | 8.556 | 10.915 |
| Sangir Balai Janggo | 36.285 | 15.934 | 2.916 | 5.261 | 2.739 |
| Sangir Batang Hari | 24.249 | 21.865 | 21.933 | 5.168 | 1.952 |
| Sangir Jujuan | 7.755 | 7.954 | 8.897 | 3.257 | - |
| Sungai Pagu | 2.666 | 1.866 | 6.904 | 19.372 | 5.033 |
| Total | 79.011 | 53.815 | 62.162 | 98.943 | 65.082 |

The spatial distribution of slopes reflects a complex topographic pattern. The western region of the regency is dominated by flat to gently sloping terrain, while the southern and eastern regions are characterized by predominantly steep and very steep slopes. These topographic patterns serve as critical indicators in flash flood risk modeling, as extreme slopes are closely associated with high runoff velocity and erosion potential.

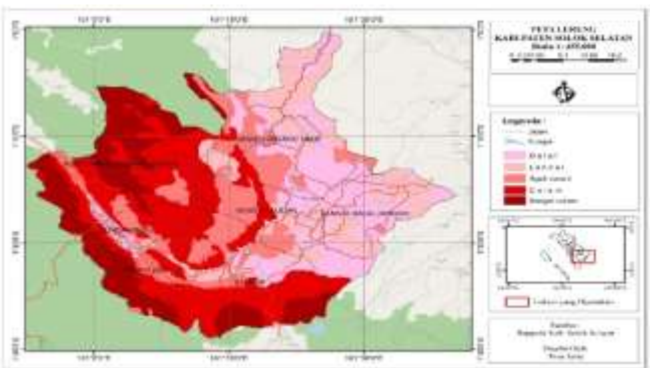

**Figure 2**. Map of the slopes of Solok Selatan Regency

*Topographic Wetness Index (TWI) Analysis*

Spatial mapping based on the Topographic Wetness Index (TWI) revealed that areas with low TWI values (<6.7) are extensively distributed across the southern and southeastern parts of the regency. These zones are primarily found within fluvial areas and along steep riverbanks—conditions that significantly increase vulnerability to flash flooding due to the convergence of two critical factors: high slope gradient and flow accumulation zones. In contrast, areas with high TWI values (>6.7) are concentrated in the central and northwestern parts of Solok Selatan Regency, where the topography tends to favor surface water retention and is more prone to inundation-type flooding rather than rapid-onset flash floods.

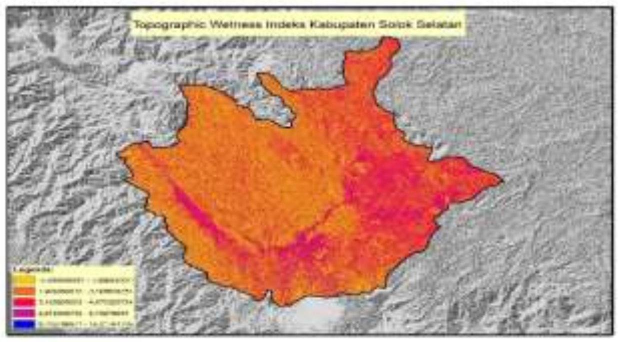


**Figure 3**. TWI Map of Solok Selatan Regency

A cross-analysis of TWI values with landform and slope characteristics identified three classes of flash flood risk across the regency. The areal distribution of each risk category is summarized in the following table:

**Table 3.** Flash Flood Risk Classification Based on TWI in Solok Selatan Regency

| Risk Class | Area (ha) | Percentage (%) |
|---|---|---|
| High | 1.260,14 | 9.2 |
| Medium | 12.053,95 | 87.99 |
| Low | 384,54 | 2.81 |
| Total | 13.698,63 | 100 |

The majority of the study area (±88%) falls under the medium risk classification, reflecting a complex morphological character with considerable flash flood potential. High-risk zones cover more than 1,200 hectares, mainly concentrated in fluvial zones with steep slopes in the southwestern and southeastern regions of the regency. Low-risk areas cover only 384.54 hectares (2.81%) and are randomly distributed in flat and gently sloping lowland areas. The TWI mapping results were then overlaid with administrative maps to identify the most affected subdistricts. Subdistricts with the largest high-risk zone areas include: Sungai Pagu, Koto Parik Gadang Diateh, Pauh Duo, Sangir Batang Hari, and Sangir Jujuan. These areas are dominated by a combination of fluvial landforms, steep slope gradients, and are located along the main flow catchments of the Batang Suliti and Batang Hari watersheds. The spatial model developed using TWI showed high accuracy. Validation was conducted by comparing the risk classification results with actual flash flood event data (2010–2020) and field observation points. The model's accuracy reached 95.2%, indicating that TWI is a reliable quantitative approach for identifying flash flood-prone zones in areas with extreme topography and high geomorphic variability.

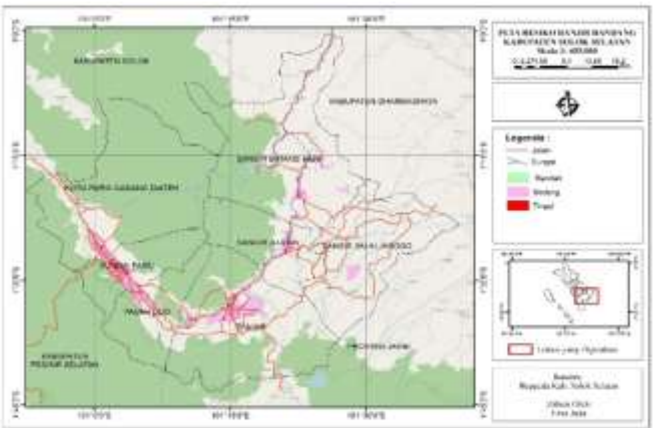

**Figure 4**. Flash Flood Risk Map of Solok Selatan Regency

Data from the Regional Disaster Management Agency (BPBD) of Solok Selatan Regency recorded that flash flood events were fluctuating and experienced a significant increase in the second half of the last decade. Between 2013 and 2023, seven flash flood events were recorded, with the highest frequency occurring in 2019, with three events in one year (Table 4).

The increase in event frequency began to be observed since 2020, with the most drastic spike in 2022. This trend indicates a pattern of flash flood intensification, potentially related to land use changes, upstream vegetation degradation, and extreme hydrological conditions. The overlay results between the risk classification map (based on TWI) and the historical flood event points show a very high spatial correspondence. All flash flood events recorded between 2012–2020 occurred within areas classified as high or medium risk, as produced by the TWI model. Subdistricts that historically recorded flash flood events—namely Koto Parik Gadang Diateh (KPGD), Pauh Duo, Sungai Pagu, and Sangir Batang Hari—are also areas categorized by the model as high-risk zones, with fluvial morphological characteristics, steep slope gradients, and low TWI values (<6.7). These findings confirm that the TWI model is not only theoretically accurate but also empirically valid. The spatial distribution of historical events shows a concentration in two main watershed systems: the Batang Suliti watershed, which includes KPGD, Pauh Duo, and Sungai Pagu; and the Batang Hari watershed, particularly in the Sangir Batang Hari area.

**Table 4**. Historical Flash Flood Events in Solok Selatan Regency (2010–2020)

| Year | Number of incidents | Location |
|---|---|---|
| 2013 | 0 | - |
| 2014 | 0 | - |
| 2015 | 1 | Koto Parik Gadang Diateh (KPGD) |
| 2016 | 0 | - |
| 2017 | 0 | - |
| 2018 | 0 | - |
| 2019 | 0 | - |
| 2020 | 1 | Pakan Rabaa, KPGD |
| 2021 | 1 | KPGD |
| 2022 | 3 | Sungai Pagu, KPGD, Pauh Duo, Sangir Batang Hari |
| 2023 | 1 | Sungai Pagu, KPGD, Pauh Duo, Sangir Batang Hari |

The distribution of flash flood events forms a spatial pattern that aligns with the main flow paths and runoff slopes. This further reinforces the notion that flash flood events are a direct reflection of the weakened water regulation capacity of upstream areas, as indicated by landform, slope, and TWI parameters. Flash flood events do not always coincide with peak discharge values but often occur during sudden increases in discharge and water level over a short time. River water level tends to increase more consistently on the day of the event compared to discharge variation, thus making it a potential early indicator of flash flood occurrence. The hydrological response in the Batang Suliti watershed is faster (reactive) to local rainfall, while the Batang Hari watershed exhibits a slower and delayed response pattern. Both watersheds show different characteristics but are equally at high risk of flash floods, depending on flow dynamics, river morphology, and upstream land retention capacity. This highlights the importance of integrating spatial parameters (landform, slope, TWI) with temporal data (discharge and water level) in building a science-based early warning system.

*Carrying Capacity Values by Land Use Type*

The assessment of the carrying capacity of water regulation ecosystem services in Solok Selatan Regency was conducted using two primary parameters: land use and land facets. Land use represents the vegetative ability of the landscape to absorb and retain water, while land facets encompass biophysical characteristics, including slope gradient, relief, rock material, and soil depth. Each parameter was assigned a weight to reflect its relative contribution to the landscape's water regulatory capacity, with land use weighted more heavily (0.67) compared to land facets (0.33). By calculating the weighted combination of scores from these parameters, the region was classified into three categories of environmental carrying capacity for water regulation services. The high carrying capacity zone covers an area of 59,767.80 hectares or 18.22% of the total region. The medium category dominates the landscape, encompassing 267,520.45 hectares (81.57%), while areas with low carrying capacity are relatively limited, totaling only 651.09 hectares or 0.19%.

**Table 5.** Carrying Capacity Values by Land Use Type

| Land Use | Score | Value |
|---|---|---|
| Forest | 0.2 | 0.133 |
| Water Bodies | 0.18 | 0.119 |
| Mixed Plantations | 0.16 | 0.104 |
| Plantations | 0.16 | 0.089 |
| Rice Fields | 0.11 | 0.074 |
| Savanna/Grassland | 0.09 | 0.059 |
| Dry Land/Farmland | 0.07 | 0.044 |
| Open land | 0.04 | 0.03 |
| Settlements/Built-up Area | 0.02 | 0.015 |

Areas dominated by forest cover are concentrated in the southern part of Solok Selatan Regency, which also overlaps with steep slope zones, making this region the most effective in terms of water regulation capacity. In contrast, areas with low carrying capacity are generally dominated by open land, rice fields, and scattered settlements, particularly in the western region and central lowlands.

Spatially, high carrying capacity zones are primarily distributed across denudational, volcanic, and karst landforms with moderate to steep slopes, yet are covered by dense vegetation. Meanwhile, medium carrying capacity areas are largely found in fluvial and karst landscapes, where land cover has become increasingly fragmented due to the expansion of agriculture, plantations, and residential development.

**Figure 5.** Map of Environmental Carrying Capacity of Ecosystem Services for Water Management in Solok Selatan Regency

Although limited in extent, low carrying capacity zones present critical flash flood hotspots, as they are located within fluvial areas characterized by low TWI values and minimal protective vegetation. Identifying these areas is crucial for guiding ecologically based interventions in priority zones for disaster risk mitigation.

The combination of flash flood risk classification and ecosystem service carrying capacity reveals a significant spatial correlation. Most areas classified as high-risk for flash floods are located within zones of medium to low ecological carrying capacity, indicating that ecosystem degradation directly undermines the natural capacity for water regulation.

*Discussion*

The results of this study demonstrate that the geomorphological characteristics of Solok Selatan Regency inherently shape an environmental condition that is highly vulnerable to flash floods. The combination of fluvial landforms with steep slopes along the Batang Suliti and Batang Hari watersheds creates a landscape configuration that facilitates surface runoff accumulation and acceleration, especially during episodes of extreme rainfall intensity. Similar studies by Azizah (2024); Mirus & Loague (2013); Westra et al. (2014); Yang et al. (2024), have also emphasized that the interaction between fluvial landforms and sharp slope gradients is a key determinant of the intensity and frequency of flash flood events in mountainous tropical regions.

In addition, the dominance of denudational landforms—formed through natural erosion and weathering processes—further decreases soil stability and increases sediment volume during flood events. This finding aligns with Blanckenburg (2005); Hirmas & LaGarry (2011); Mandych (2020), who stated that geologically unstable areas with poor vegetation cover significantly elevate the risk of concurrent landslides and flash floods, exacerbating both ecological and socio-economic impacts.

The application of the Topographic Wetness Index (TWI) in this study proved effective in identifying flash flood risk zones with high accuracy (95.2%). These results indicate that TWI, originally developed to detect wet areas and waterlogging potential (Chipatiso, 2022; Thannoun & Ismaeel, 2024), can also be adapted to measure extreme runoff tendencies in complex topographic regions (Fitra et al., 2024). The advantage of TWI lies in its ability to simultaneously capture the spatial effects of flow accumulation and slope gradient, making it more sensitive than administrative-based classifications or historical flood mapping alone.

The overlay with flood occurrence data confirmed that all recorded flash flood events between 2013–2023 were located within the high and medium-risk zones identified by the TWI analysis. This validation supports the findings of Fitra et al. (2024), who also used TWI in a similar study and recommended it as an efficient data-driven approach for early warning systems in hydrometeorological disaster risk management (Brigandì et al., 2017). Hydrological findings revealed that peak flash flood events in Solok Selatan did not always correlate with absolute peak discharge levels, but were often triggered by sudden spikes in discharge and river stage over short timeframes. This suggests the presence of a hydro-geomorphic lag, wherein the river system is unable to absorb sudden inflows due to degraded upstream landscape retention capacity. This phenomenon is consistent with the study of Meles et al. (2019); Nagamani et al. (2024), which highlighted that sudden discharge spikes pose greater hazards than sustained high flows, especially in small watersheds with extreme topography. The failure of vegetative and soil retention systems accelerates overland flow processes, triggering destructive surges within the main river channels.

One of the most critical findings of this study is that the majority of Solok Selatan Regency—particularly the upstream zones of its watersheds—falls under the medium carrying capacity class (81.5%), with only a small portion classified as high (18.2%). This indicates that although much of the landscape is still functioning as a conservation area, its water regulation capacity has significantly declined. The degradation in carrying capacity is directly linked to changes in land cover, particularly the conversion of forest areas into plantations, fields, and settlements. As highlighted by Jaarsveld et al. (2005) and the Millennium Ecosystem Assessment (MEA) (Finlayson et al., 2005), the decline in water regulation ecosystem services is an early indicator of the collapse of life-supporting systems, particularly in humid tropical climates. These findings also reinforce the argument that spatial and watershed planning should no longer be oriented solely by administrative boundaries, but rather based on actual evaluations of ecosystem capacity.

This study provides empirical evidence that flash flood risk mitigation must be grounded in a spatial-ecological approach that accounts for actual biophysical conditions and ecosystem services. The resulting risk zoning and carrying capacity classification systems can serve as a foundation for disaster-risk-informed spatial planning. In practical terms, areas classified as high risk with low carrying capacity should be designated as priority zones for ecosystem restoration and excluded from land conversion activities. Ignoring these ecological indicators will only accelerate the mutually reinforcing cycle of degradation and disaster—a positive feedback loop—as warned by Yu et al. (2010) in their study of social-ecological systems (Oudenhoven et al., 2011).

The main contribution of this study lies in its integration of spatial indices (TWI), ecosystem service indicators, and hydrological variables into flash flood risk modeling. This approach goes beyond conventional risk mapping by incorporating ecological dimensions and environmental system capacity. Nevertheless, certain limitations remain, particularly regarding the resolution of rainfall data and the validation of discharge and water level, which were only available at selected observation points. To strengthen the results, future studies are recommended to integrate satellite-based precipitation data and dynamic hydrological simulations using tools such as HEC-HMS or SWAT.

## Conclusion

This study demonstrates that flash flood risk in Solok Selatan is shaped by the interaction of steep geomorphology, rapid hydrological responses, and declining ecosystem regulatory capacity. By integrating the Topographic Wetness Index with landform, slope, and ecosystem carrying-capacity analysis, we provide a spatially explicit framework that captures both physical susceptibility and ecological resilience. The findings confirm that areas of elevated flood risk frequently coincide with landscapes of reduced regulatory capacity, highlighting how land-use change weakens natural buffering functions. Beyond advancing technical accuracy, the study's key contribution lies in linking hydrological modeling with ecosystem service assessment in a data-limited tropical watershed. This integrated approach offers a transferable framework for shifting disaster mitigation from reactive, administrative measures toward proactive, spatial-ecological planning that strengthens the resilience of upstream watersheds.

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**Author Contribution**
Erna Juita and Dasrizal contributed to the conceptualization of the problem and analysis of research gaps as well as writing the outline of the article, Mohd Hairy Ibrahim to determine the methodology and verification, Elsa Yuniarti and Arie Zella Putra Ulni contributed to the processing of field data and satellite imagery data, Soni contributed to the collection of field data

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The authors declare no conflict of interest.

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