Review Article

Hydrometeorological and Watershed Drivers of the November 2025 Floods in Aceh, North Sumatra, and West Sumatra under Tropical Cyclones Senyar and Koto

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Abstract

The November 2025 floods in Aceh, North Sumatra, and West Sumatra were triggered by extreme rainfall associated with Tropical Cyclones Senyar and Koto. Still, their severity was strongly amplified by watershed and land-use conditions across 32 affected river basins. Using event-based data on watershed area, estimated runoff coefficient, daily rainfall, runoff volume, and peak discharge, this study quantifies hydrological response at the basin scale and compares patterns among the three provinces. Descriptive statistics show that daily rainfall frequently exceeded 200–300 mm, with province-level mean discharges of roughly 765–859 m³/s and maxima above 1,300–1,400 m³/s, values consistent with independently reported flood impacts. Runoff coefficients of about 0.16–0.28 indicate that a substantial share of event rainfall was converted into quick surface runoff, reflecting mixed land uses and upper-watershed degradation documented in recent environmental assessments. Correlation analysis confirms that peak discharge is primarily controlled by adequate runoff volume and basin area. At the same time, the roles of land use and rainfall become clearer when interpreted alongside geomorphology and multi-hazard studies for Sumatra. The findings demonstrate that the disaster resulted from a compound interaction between extreme meteorological forcing, reduced hydrological buffering capacity, and high exposure in floodplains and steep uplands, underscoring the need for watershed-based land-use regulation, ecological restoration, and integrated multi-hazard risk governance in northern and western Sumatra.

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Shrine Journal of Research and Sciences (SJRS)

ISSN: 3069-2032

Volume 3 Issue 2, 2026

Article Information
Received date: February 23, 2026
Published date: March 10, 2026

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DOI: 10.65070/SJRS.2026.824

Keywords
Tropical cyclone Senyar; Flood disaster; Watershed hydrology; Runoff coefficient; Land-use change; Multi-hazard risk; Aceh; North Sumatra; West Sumatra; Indonesia

Introduction

Tropical Cyclones Senyar and Koto triggered one of the most destructive flood episodes in recent decades in northern and western Sumatra, with extreme rainfall causing widespread flooding and landslides across Aceh, North Sumatra, and West Sumatra in late November 2025. Satellite and situational analyses describe Senyar as a rare cyclone that formed in the Strait of Malacca, delivering torrential rains to the rugged Barisan Mountains belt, where steep slopes, short river response times, and populated floodplains combine to generate high-impact flash floods. Reports from international and national agencies indicate hundreds of deaths, hundreds of thousands of displaced people, and extensive damage to housing and infrastructure, with Mandailing Natal, Sibolga, Pesisir Selatan, and several districts in Aceh and Langkat among the hardest hit [1].

At the hydro-meteorological level, the 2025 Sumatra floods fit a broader pattern of increasing exposure to extreme rainfall in Indonesia, where intense events are projected to become more frequent as the climate warms. Northern and western Sumatra are particularly vulnerable because moist air masses from the Indian Ocean and the equatorial Pacific can interact with regional circulation anomalies, topography, and tropical disturbances to concentrate rainfall over relatively small areas. In the November 2025 event, BMKG (Indonesian Meteorology, Climatology and Geophysics Agency) reported daily rainfall totals exceeding 300 mm at several stations in North Sumatra and Aceh, values that far exceed standard flood-generation thresholds in Indonesian basins. Observational accounts emphasize that the physical trigger—extreme rainfall from Senyar and associated systems—interacted with pre-existing watershed and land-use conditions, amplifying downstream flood impacts [2].

Recent scientific literature on Indonesian basins underscores that extreme rainfall alone is rarely sufficient to explain severe flood disasters, and that land-use change, watershed degradation, and geomorphological setting play critical roles. Studies in the Cirasea and Upper Citanduy basins show that conversion of forest and shrubland into agriculture and urban land has increased runoff coefficients and peak discharges, effectively shifting design floods associated with particular return periods toward more frequent occurrence. Similar patterns are reported in other Indonesian watersheds, where reductions in vegetation cover and increases in impervious surfaces raise surface runoff and diminish natural flood attenuation capacity. In Aceh and parts of North Sumatra, experts have explicitly linked recent flash flood severity to upper-watershed forest degradation and weak land-use governance, suggesting that the November 2025 disaster was the outcome of a compound hazard involving both weather extremes and anthropogenic watershed changes [3].

Despite expanding literature on flood hazard and land-use impacts in specific Indonesian basins, multi-watershed, event-based analyses that combine cyclone-induced rainfall with watershed-scale hydrological response remain limited for Sumatra. Existing studies often focus either on single-watershed hydrodynamic modeling or on regional hazard mapping using composite indices, without systematically comparing runoff and discharge responses across multiple rivers subjected to the same extreme rainfall event. For the November 2025 floods, data on rainfall, land use, and hydrological response are available for a set of key watersheds in Aceh, North Sumatra, and West Sumatra, but have not yet been analyzed together to quantify how differences in watershed area, runoff coefficient, and rainfall depth translated into varying flood magnitudes. A multi-basin perspective is critical in ungauged or sparsely gauged regions, where design and planning often rely on derived or estimated parameters rather than long instrumental records [4].

This study addresses these gaps by conducting a comparative hydrological analysis of 32 watersheds (Daerah Aliran Sungai, DAS) affected by Tropical Cyclones Senyar and Koto in Aceh, North Sumatra, and West Sumatra, using a dataset that includes watershed area, estimated runoff coefficient, event rainfall, runoff volume, and estimated river discharge. The dataset has been prepared, processed, and managed by Dimas Haryo Pamungkas, a senior researcher of IPOSS Jakarta. The research aims to: (1) quantify the hydrometeorological forcing and hydrological response of key DAS during the November 2025 event; (2) examine how watershed area and runoff coefficient interact with extreme rainfall to produce differences in runoff volumes and peak discharges across provinces; and (3) discuss the relative importance of cyclone-induced rainfall, watershed condition, and land-use patterns in driving the severity of the observed floods and landslides. By integrating event-based estimates with insights from recent Indonesian and international hydrology literature, the study seeks to inform multi-hazard flood risk management and watershed planning in Sumatra under current and future climate conditions [5].

Methods

Overall methodological approach

The methodological framework combines event-based hydrological estimation, fundamental statistical analysis, and literature-based interpretation to investigate the causes of the November 2025 floods across multiple watersheds. The approach starts with a compiled Table of 32 DAS affected by the event, containing, for each watershed, province, and regency, watershed area, runoff coefficient, daily rainfall depth during the peak of the event, estimated runoff volume, and estimated river discharge. This dataset, derived from BMKG rainfall records, national topographic and watershed maps, and conservative runoff-coefficient assumptions informed by hydrological studies, provides a consistent basis for cross-basin comparison. Analytically, the study proceeds in three main stages: (1) hydrometeorological characterization of the event and watersheds, (2) estimation review and simple statistical analysis of runoff and discharge, and (3) interpretation of spatial patterns and correlations in light of existing hydrological research for Indonesia and comparable regions [6].

Data sources

Rainfall and event characterization

Daily rainfall totals (mm/day) for the late November 2025 event were obtained from BMKG stations and gridded products, aggregated to produce representative event rainfall depths for each watershed during the peak flood day. The rainfall values in the dataset range approximately from 112 mm/day to over 320 mm/day, reflecting the intense precipitation associated with Tropical Cyclones Senyar and Koto over northern and western Sumatra. Meteorological and satellite analyses describing the track, intensity, and rarity of Senyar and related disturbances were used to contextualize the rainfall data, including reports that emphasize the unusual formation of a cyclone in the Strait of Malacca and the concentration of extreme precipitation over Aceh, North Sumatra, and West Sumatra [7].

Watershed boundaries and areas

Watershed boundaries (DAS limits) and areas (hectares) for the studied rivers (e.g., Krueng Aceh, Manyak Payed/Tamiang, Jambo Aye, Peusangan, Singkil, Batang Gadis, Wampu, Indrapura, Pasaman, Sikilang, Kampar, Masang Kiri) were delineated using national topographic maps and official river-basin datasets. These sources align with earlier hydrological studies in Indonesia that rely on topographic and river network data to define sub-basins for runoff and flood modeling, including work in the Kuranji, Jemelak, and Lhoksukon watersheds. Watershed areas in the dataset span from about 57,000 ha to more than 320,000 ha, capturing small to large basins that respond differently to the same rainfall forcing [8].

Land use, land cover, and runoff coefficients

Runoff coefficients (C) in the dataset were assigned for each DAS (watershed area) based on land-use and land-cover information extracted from national land-use maps, supported by literature-derived ranges of C for different land-cover types and soil conditions. Studies employing the curve number method or equivalent runoff-coefficient approaches in Indonesian basins - such as Cirasea, Upper Citanduy, Cisangkuy, Jemelak, and Krueng Baro—were used to guide C selection and ensure that values remain conservative yet realistic. These studies consistently report that conversion of forest to agriculture, plantations, or settlements increases composite runoff coefficients and runoff depths for design storms, often by several percentage points over one or two decades. The C values in the present dataset range roughly from 0.16 to 0.28, consistent with mixed land-use conditions, including substantial vegetative cover, as well as agricultural and built-up areas [9].

Hydrological estimates of runoff volume and discharge

The table used in this study reports, for each watershed, an estimated runoff volume (m^3) and corresponding peak river discharge (m^3/s) during the event. These hydrological quantities were calculated using standard event-based runoff equations and hydrograph assumptions widely applied in ungauged or data-scarce basins. The estimation procedure is consistent with approaches in Indonesian and international literature where rainfall–runoff transformation is modeled using lumped parameters and unit-hydrograph methods (e.g., SCS-CN, Nakayasu, or synthetic unit hydrographs), and peak discharge is obtained by dividing adequate runoff volume by an estimated characteristic time (such as time to peak or hydrograph duration) [10].

Runoff volume and discharge estimation

For a given watershed, event-based runoff volume V was estimated from rainfall depth P, watershed area A, and runoff coefficient C using a standard proportional relationship of the form $V=C\times P\times A$, with appropriate unit conversions. In this formulation, C represents the fraction of rainfall that becomes direct runoff during the event after accounting for infiltration, interception, storage, and other losses, and is typically derived from land-use and soil-type information. The rainfall depth P was taken as the daily total on the peak flood day, a common simplification for event-based analyses in contexts where sub-daily data are unavailable but daily totals exceed threshold values for flood generation [11].

Peak discharge Q for each watershed was then derived from the estimated runoff volume using a conceptual relationship between V and the shape and duration of the flood hydrograph. In many practical applications, including Indonesian studies of small- to medium-sized basins, the peak flow can be approximated as $Q\approx k\times V/TQ$ and $TQ\approx k\times V/T$, where T is a characteristic time parameter (such as the time to peak or the effective event duration), and k is a shape factor reflecting the concentration and recession properties of the watershed. The estimation procedure for the November 2025 event assumed conservative values for these parameters, informed by previous modeling efforts in morphologically similar basins (steep headwaters draining rapidly to lowland floodplains), to avoid overestimating peak discharges while capturing the order of magnitude of observed flood impacts. The resulting discharge estimates in the dataset thus reflect event-scale peaks for each DAS and reach values above 1,300–1,400 m^3/s in several large basins, consistent with magnitudes reported in independent flood modeling studies in Aceh and West Sumatra [12].

Statistical analysis

The compiled dataset was subjected to descriptive and correlation analyses to reveal patterns in hydrological response across provinces and watersheds. First, basic descriptive statistics—mean, minimum, and maximum—were computed for watershed area, daily rainfall, runoff volume, and peak discharge for each province (Aceh, North Sumatra, West Sumatra). These statistics provide a concise summary of the range of hydrometeorological conditions and hydrological outcomes, and allow direct comparison of typical and extreme values among provinces during the same event. Second, a correlation matrix was calculated for key variables (runoff coefficient, rainfall, runoff volume, and discharge) across all 32 watersheds to examine bivariate linear relationships [3].

The correlation analysis revealed, as expected from the calculation procedure, an almost perfect positive correlation between runoff volume and discharge, confirming that discharge differences essentially mirror differences in the amount of adequate runoff for this event. Simple linear correlations between runoff coefficient and discharge, and between rainfall and discharge, appeared relatively weak at the cross-basin level, reflecting the dominant effect of watershed area and the limited range of C values in the sample. These findings are interpreted in light of the hydrological literature, which shows that cross-basin comparisons can obscure strong within-basin sensitivities because multiple controls (area, slope, channel network structure, land use) interact nonlinearly to shape flood peaks. Consistent with event-based modeling in other Indonesian basins, this study therefore uses the statistical results primarily as a support for a qualitative, process-based interpretation rather than as evidence for simple linear controls [13].

Spatial and comparative analysis

To interpret spatial differences in flood severity, the hydrological estimates and statistics were analyzed by grouping watersheds by province and physiographic setting (e.g., coastal lowland rivers with short, steep upstream catchments, large trans-provincial basins, and mountainous headwater-dominated basins). This grouping reflects approaches used in previous multi-basin flood and multi-hazard assessments in Indonesia, where spatial patterns of hazard are linked to topography, land use, and exposure indicators. For each group, patterns in rainfall, runoff coefficient, runoff volume, and discharge were examined to identify combinations associated with particularly severe floods or combined flood–landslide events, such as those reported in Mandailing Natal, Sibolga, Pesisir Selatan, and East Aceh during the November 2025 disaster [14].

The cross-basin comparisons were complemented with qualitative insights from published case studies and hazard mapping in Aceh, North Sumatra, and West Sumatra, which document how deforestation, agricultural expansion, road construction, and settlement growth in upper watersheds increase flood and landslide susceptibility. By framing the numerical results from the 32 DAS within this broader body of evidence, the analysis aims to clarify how extreme cyclone-induced rainfall interacted with watershed conditions and land-use patterns to produce the observed disaster outcomes in late 2025 [15].

Results

Daily rainfall during the peak of the November 2025 event over the studied watersheds ranged from about 112 mm/day to more than 320 mm/day, confirming that all 32 DAS experienced intense to extreme precipitation within a short time window. BMKG and satellite-based assessments reported that several stations in North Sumatra and Aceh exceeded 300 mm/day, consistent with the highest values in the dataset and with independent descriptions of the Senyar-induced rainfall "swamping" northern Sumatra. These magnitudes exceed typical rainfall thresholds for flooding in Indonesian river basins. They are comparable to daily extremes that have caused severe flooding in West and South Sumatra in recent years [2].

When aggregated by province, the dataset shows that West Sumatra had the highest mean event rainfall, at roughly 257 mm/day, followed by North Sumatra at about 224 mm/day and Aceh at about 208 mm/day. Despite differences in mean rainfall, all three provinces registered very high estimated discharges, with mean peak flows during the event of approximately 765 m^3/s in Aceh, 822 m^3/s in North Sumatra, and 859 m^3/s in West Sumatra, and maximum values exceeding 1,300–1,400 m^3/s in at least one watershed in each province. These discharge magnitudes are consistent with, or exceed, peak flows reported in hydrodynamic and flood-hazard studies for Aceh and West Sumatra, which document that steep, short-response basins can easily reach several hundred cubic metres per second during intense rainfall [16].

Watershed-scale runoff and discharge characteristics

The 32 watersheds in the dataset cover a broad range of areas, from about 57,340 ha (Lepan, North Sumatra) to 323,017 ha (Singkil, Aceh Tenggara), and this variation strongly influences the estimated runoff volumes and peak discharges. Large basins such as Singkil (323,017 ha) and Batang Gadis in Mandailing Natal (314,407 ha) show relatively moderate event rainfall (about 178–218 mm/day) but generate huge runoff volumes and estimated discharges, often above 1,250–1,400 m^3/s, illustrating how basin size amplifies hydrological response even without the highest rainfall totals. Similar behavior has been documented in other Indonesian catchments, where large or highly connected upstream contributing areas yield substantial flood peaks under intense but not necessarily record-breaking rainfall [5].

Smaller basins with high rainfall and moderate-to-high runoff coefficients also display significant hydrological response. Watersheds such as Lepan (57,340 ha) and Sikilang (73,951 ha) experienced rainfall near or above 300 mm/day and runoff coefficients of 0.24–0.26, producing estimated peak discharges of 500–700 m^3/s. These results align with case studies in West Sumatra and other steep tropical basins where relatively small catchments generate damaging flash floods under concentrated extreme rainfall, especially when upstream slopes are degraded, and channel conveyance is limited. In the dataset, no watershed remains hydrologically "benign" once daily rainfall exceeds roughly 200–250 mm, regardless of size, underscoring the systemic risk posed by cyclone-induced precipitation across the region [13].

Runoff coefficients and link to land-use conditions

Runoff coefficients in the compiled table range from approximately 0.16 to 0.28, indicating that 16–28% of event rainfall was transformed into direct runoff at the scale of each watershed after accounting for losses. These values are consistent with composite runoff coefficients reported for Indonesian basins dominated by mixed forest, agricultural land, and scattered settlements. They are notably lower than values found in highly urbanized or heavily degraded catchments. For example, studies in the Upper Citanduy and Batang Merao basins show that land-use change from forest to agriculture and built-up areas has increased runoff coefficients by several tens of percent over recent decades, with corresponding increases in peak discharge for the same design rainfall [17].

Although the November 2025 dataset was constructed using conservative C values, the observed range still suggests substantial variations in hydrological regulation capacity among watersheds. Watersheds with higher C values (around 0.25–0.28), such as Bayeun, Peusangan, and Sikilang, typically correspond to land-use mosaics with more agriculture, plantations, and settlements and less intact forest, reflecting patterns noted in land-use and hydrology studies in Sumatra. The combination of moderate-to-high runoff coefficients and very high rainfall implies that a significant fraction of the rainfall was rapidly converted to surface runoff, a mechanism explicitly highlighted by regional analyses linking forest degradation and reduced infiltration capacity to worsening flash flood severity in Sumatra [18].

Correlation structure among hydrological variables

Correlation analysis across all 32 watersheds confirms a near-perfect positive linear relationship between runoff volume and peak discharge, reflecting the direct dependence of discharge estimates on event runoff volume in the calculation procedure. This strong association is consistent with event-based modeling studies in ungauged Indonesian basins, where peak flows are largely controlled by effective rainfall and contributing area, given a fixed set of hydrograph parameters. In contrast, the simple linear correlations between runoff coefficient and discharge, and between rainfall and discharge, are relatively weak in the cross-basin sample, primarily because watershed areas vary widely and the range of C values is modest [12].

These results illustrate a well-known challenge in comparative hydrology: cross-sectional correlations between individual controls and peak discharge can obscure strong sensitivities within individual watersheds. For instance, modeling in the Upper Citanduy basin shows that a roughly 17% increase in composite runoff coefficient can shift design floods associated with a 5-year return period toward magnitudes previously associated with much rarer events. Similarly, multi-hazard assessments for Kalimantan and Sumatra indicate that interactions among rainfall, land use, and slope are the most critical determinants of flood and landslide hazard, rather than any single factor alone. The weak cross-basin correlations in this study, therefore, do not imply that C or rainfall are unimportant; instead, they indicate that the combined effects of rainfall, watershed area, land use, and topography must be considered jointly to explain local flood severity [13].

Provincial contrasts in watershed response

At the provincial level, the results reveal distinct but overlapping hydrological signatures for Aceh, North Sumatra, and West Sumatra during the event. In Aceh, watersheds such as Krueng Aceh, Manyak Payed/Tamiang, Jambo Aye, Peusangan, and Singkil recorded rainfall mostly between about 178 and 307 mm/day, with estimated peak discharges ranging from roughly 529 to 1,339 m^3/s. These values are consistent with documented flooding across multiple districts, including Aceh Besar, Aceh Tamiang, Aceh Utara, and Aceh Tenggara, where reports highlight rapid river rises and inundation of lowlands. In several Aceh basins, large watershed areas combined with moderate rainfall and C values produced flood peaks comparable to or exceeding those in smaller, more intensively rainfed basins in other provinces, emphasizing the role of drainage area in modulating hydrological response [19].

West Sumatra shows the highest mean rainfall and mean discharge in the sample, with watersheds such as Indrapura, Pasaman, Sikilang, Kampar, and Masang Kiri experiencing rainfall of 279–304 mm/day and estimated discharges of about 633-1,447 m^3/s. This pattern matches independent accounts of highly destructive floods and landslides in Pesisir Selatan and other regencies, where steep coastal catchments rapidly funnel runoff from the Barisan Mountains toward densely settled floodplains. In North Sumatra, large basins in Mandailing Natal (Batang Gadis, Batahan, Natal) and Langkat (Batang Serangan, Wampu, Besitang, Lepan) display moderate to high rainfall and substantial contributing areas, leading to high estimated discharges (roughly 501–1,409 m^3/s) that align with reports of widespread damage, riverbank failures, and landslides. Overall, the provincial comparison demonstrates that while West Sumatra received the highest average rainfall, the combination of basin size, land use, and rainfall in Aceh and North Sumatra produced flood peaks that were comparably destructive in many watersheds [20].

Multi-hazard manifestations: floods and landslides

The hydrological results coincide with a clear multi-hazard pattern on the ground: many watersheds with high runoff volumes and peak discharges also experienced landslides, debris flows, and riverbank failures during the event. Multi-hazard assessments for the broader Sumatra region have shown that areas combining steep slopes, high rainfall, and degraded land cover are especially susceptible to compound flood–landslide events, with rainfall, land use, and slope aspect identified as critical interacting controls. The November 2025 event follows this pattern: steep upstream terrain in Mandailing Natal, Pesisir Selatan, and several districts in Aceh and Langkat, where forest cover has been reduced, generating both high runoff and slope instability, leading to simultaneous channel floods and mass movements [13].

Expert commentary and case analyses further indicate that upper-watershed forest degradation and river narrowing intensified the impact of the cyclone-driven rainfall by reducing interception, infiltration, and channel capacity, effectively increasing the practical runoff coefficient beyond what would be expected under intact forest conditions. This interpretation is consistent with quantitative studies in other Indonesian basins, where land-cover changes toward more impervious or degraded states have been associated with increased surface runoff, higher peak discharges, and greater flood frequency under similar rainfall forcing. In the context of the 32 watersheds analyzed here, the combination of extreme event rainfall, moderate-to-high runoff coefficients, large contributing areas, and exposed populations produced the observed disaster, illustrating how hydrometeorological and land-use drivers jointly shape flood and landslide risk in Aceh, North Sumatra, and West Sumatra [21].

Discussion and Analysis

Cyclone forcing versus watershed condition

The results confirm that the November 2025 floods cannot be explained by meteorology alone; instead, they resulted from an interaction between extreme cyclone-induced rainfall and already-stressed watershed systems in Aceh, North Sumatra, and West Sumatra. Event rainfall frequently exceeded 200–300 mm/day, which is sufficient to trigger flooding even in relatively healthy catchments. Still, the scale of runoff volumes and peak discharges suggests that watershed storage and buffering capacity had been substantially reduced in many basins. Hydrology experts analyzing the same flood crisis highlight extensive upper-watershed forest degradation, river narrowing, and encroachment on floodplains as key factors that transformed a rare extreme storm into a catastrophic hydrometeorological disaster [2].

of flood risk rather than independent causal factors. Multi-hazard modeling for Kalimantan and Sumatra has shown that rainfall, land use, and slope aspect jointly determine flood and landslide hazard, with areas combining high rainfall, steep terrain, and degraded land cover exhibiting the highest probabilities of compound events. Resulted from an interaction between extreme cyclone-induced rainfall and already-stressed the November 2025 event, large runoff coefficients (0.16–0.28), large contributing areas, and intense rainfall all pointed in the same direction, indicating that the watersheds had crossed a functional threshold where much of the rainfall was converted into rapid runoff rather than being absorbed and slowly released [2].

Runoff coefficient as a proxy for ecological degradation

The moderate-to-high runoff coefficients estimated for the 32 watersheds can be interpreted as proxies for the cumulative effects of land-use change, soil degradation, and river corridor modification. Studies in the Upper Citanduy, lower Cimanuk, Ciliwung, and other Indonesian basins show that conversions from forest to plantations or urban land typically increase composite runoff coefficients and reduce infiltration, leading to higher flood peaks for a given storm. For example, rainfall–runoff modeling in Ciliwung indicates that projected land-cover change by 2030 could increase peak discharge and flood area by 25–100%, even without substantial changes in rainfall intensity. Similar modeling for the lower Cimanuk shows that combined land-use and climate change markedly expand flood-inundation areas, confirming that hydrological response is highly sensitive to land-cover trajectories [22].

Against this backdrop, runoff coefficients of 0.20–0.28 in many of the Aceh, North Sumatra, and West Sumatra basins are unlikely to represent pristine conditions; instead, they are consistent with catchments where forest has partially given way to agriculture, plantations, and settlements. Independent analyses of the 2025 Sumatra floods report severe forest-cover degradation in key watersheds such as Peusangan, Singkil, and Batang Toru, with some sub-basins experiencing damage levels above 70%, which drastically reduces interception and infiltration capacity. From a process perspective, this degradation means that root networks, organic matter, and soil structure that once stored water and stabilized slopes have been reduced or removed, causing a larger fraction of rainfall to appear as quick surface runoff and increasing susceptibility to both flooding and landslides [23].

Why cross-basin correlations underestimate land-use effects

The correlation analysis shows weak simple linear relationships between the runoff coefficient and rainfall, and between the runoff coefficient and peak discharge across the 32 basins.

In contrast, watershed area and adequate runoff volume dominate the variability in estimated flood peaks. At first glance, this could be misinterpreted as indicating that land use or rainfall intensity plays a minor role in controlling flood magnitude. Still, comparative hydrology literature cautions that such cross-sectional correlations can be misleading when key variables co-vary and interact nonlinearly. In this dataset, the range of runoff coefficients is relatively narrow. At the same time, watershed areas vary by almost an order of magnitude, so area naturally appears as the strongest statistical control on discharge when all catchments are pooled [13].

Evidence from single-basin studies, however, makes clear that within individual catchments, changes in land use and the runoff coefficient can significantly magnify flood peaks under the same or slightly increased rainfall. For instance, hydrological simulations in the Upper Citanduy show that a moderate increase in composite runoff coefficient associated with deforestation and agricultural expansion can shift what used to be a 25-year flood toward a much shorter return period. Multi-hazard assessments in Kalimantan and Sumatra similarly find that land-use and slope conditions modulate the translation of rainfall into hazard probability, with high-risk areas often coinciding with degraded land on steep slopes. Thus, the weak cross-basin correlations in this study reflect the statistical structure of the sample, not the underlying physical importance of land use; they reinforce the need to interpret coefficients and rainfall in combination with basin area, topography, and channel characteristics rather than in isolation [13].

Provincial contrasts and their structural drivers

The provincial comparison shows that West Sumatra had the highest mean rainfall and mean peak discharge. Still, Aceh and North Sumatra also produced very high discharges, with large basins and degraded upper watersheds overlapping during heavy rain. In West Sumatra, steep Barisan Mountain catchments draining to narrow coastal plains, as in Pesisir Selatan, are intrinsically prone to rapid runoff concentration, so extreme rainfall readily translates into high flood peaks and debris-laden flows, a pattern documented in previous analyses of West Sumatra flood disasters. In Aceh, basins such as Krueng Aceh, Peusangan, and Singkil combine large contributing areas, steep headwaters, and evidence of forest-cover decline, explaining why event discharges in these watersheds were comparable to those in West Sumatra despite somewhat lower mean rainfall [24].

North Sumatra presents yet another structural configuration: major rivers such as Batang Gadis, Batang Toru, and the Langkat system (Batang Serangan, Wampu, Besitang, Lepan) drain large, partly degraded hill and mountain regions into heavily inhabited valleys and coastal zones. Recent assessments emphasize that deforestation in the Batang Toru ecosystem and other North Sumatra uplands has weakened natural buffers against extreme rainfall, leading to more rapid, erosive runoff. The high estimated discharges for Mandailing, Natal, and Langkat in this study, therefore, align with geotechnical and hazard analyses documenting pervasive slope instability, riverbank failures, and sediment-laden floods in these regions during the 2025 event. Taken together, the provincial contrasts point toward a common message: differences in geomorphology and land-use histories shape how cyclone rainfall is translated into local hazard, but the underlying trend is a regional loss of hydrological resilience [25].

Multi-hazard cascades: floods, landslides, and debris flows

The floods in November 2025 unfolded as classic multi-hazard cascades, with high river runoff coinciding with landslides, debris flows, and sediment pulses from steep, degraded hillslopes. Multi-hazard studies for Kalimantan and Sumatra demonstrate that the joint probability of floods and landslides peaks where heavy rainfall intersects with steep slopes and disturbed land cover, and they estimate that more than 15% of some regions may face overlapping hazards. Similar patterns are observed in Mandailing Natal, Pesisir Selatan, and parts of Aceh, where reports describe simultaneous river overtopping, road washouts, and slope failures along valley walls, confirming that the November 2025 event was not a pure riverine flood but a compound crisis [13].

The runoff and discharge estimates for the studied watersheds are consistent with conditions known to trigger such multi-hazard cascades. Large runoff volumes increase river stage and shear stress, promoting channel erosion and bank collapse. At the same time, intense rainfall on deforested or poorly managed slopes drives shallow landslides and debris flows that can temporarily dam rivers and then fail catastrophically. Case-based analyses of recent Indonesian disasters highlight that where upstream sediment sources are abundant, and channel conveyance is constrained by encroachment or infrastructure, flood waves can become heavily laden with sediment and woody debris, greatly increasing their destructive power. In this light, the November 2025 floods in Aceh, North Sumatra, and West Sumatra should be interpreted as the expression of an evolving multi-hazard landscape in which hydrological extremes, geomorphic instability, and human exposure converge [26].

Implications for flood-risk governance and mitigation

The findings have several implications for flood-risk governance and mitigation strategy in northern and western Sumatra. First, they reinforce calls from hydrology and disaster-governance studies to move beyond reactive crisis management toward proactive, watershed-based risk reduction that targets the structural drivers of flooding. Analyses of flood and landslide governance in Mandailing Natal and Solok point to the need for integrating structural measures (e.g., channel improvements, retention basins) with non-structural actions such as land-use regulation, reforestation, and rainwater-harvesting programs that demonstrably reduce runoff. The runoff coefficients and discharge levels observed in this study suggest that even modest increases in forest cover, soil conservation, and floodplain protection could significantly attenuate peak flows during extreme events [27].

Second, the results argue for embedding multi-hazard thinking into local and provincial planning systems. Multi-hazard risk assessments in Kalimantan and Sumatra show that when flood and landslide hazards are considered jointly, priority intervention zones shift toward steep, degraded uplands and rapidly urbanizing lowlands, which closely correspond to the most impacted areas in the 2025 event. Incorporating such assessments into spatial plans, building codes, and infrastructure siting could help reduce exposure and promote more resilient development trajectories in Aceh, North Sumatra, and West Sumatra. Third, the study underscores the importance of linking local land-use decisions - such as plantation expansion, road construction, and floodplain reclamation - to regional hydrological consequences, as demonstrated by research on plantation-driven flooding in Indonesian lowlands. Without tighter regulation of watershed-scale land-use change and more consistent enforcement of environmental safeguards, similar cyclone events are likely to produce disasters comparable to or worse than those in the past, even if rainfall intensities do not increase substantially [28].

Research needs and methodological extensions

Finally, the analysis highlights several research needs to refine the understanding of cyclone-driven flood disasters in Sumatra. Event-based estimates using daily rainfall and conservative runoff coefficients provide robust first-order insights. Still, they should be complemented by high-resolution hydrological and hydraulic modeling that incorporates sub-daily rainfall, channel routing, and floodplain dynamics for priority basins such as Krueng Aceh, Manyak Payed/Tamiang, Batang Gadis, and Indrapura. Coupling such models with land-use scenarios, as done in the Ciliwung and lower Cimanuk studies, would allow quantification of how different forest-protection, plantation-expansion, or urbanization trajectories translate into changes in peak discharge and inundation extent under future extreme rainfall [29].

In addition, integrating social vulnerability metrics, governance indicators, and infrastructure resilience data with hydrological outputs would enable truly multi-dimensional risk assessments, similar to recent work on disaster-risk indices in Palu and multi-hazard zonation in other Indonesian regions. Such integrated approaches are particularly relevant in Aceh, North Sumatra, and West Sumatra, where marginalized communities often occupy the most exposed floodplains and unstable slopes and where institutional capacity to enforce land-use and environmental regulations remains uneven. Advancing this research agenda would help transform insights from the November 2025 disaster—namely, that extreme rainfall interacting with degraded watersheds produced cascading floods and landslides—into actionable strategies for a more resilient Sumatra under a changing climate [30].

Conclusion

The November 2025 floods in Aceh, North Sumatra, and West Sumatra were the product of a compound hazard in which extreme rainfall from Tropical Cyclones Senyar and Koto interacted with degraded watershed conditions and exposed communities across at least 32 major and minor river basins. Event rainfall frequently exceeded 200–300 mm/day, placing it among the most intense daily precipitation episodes recorded in the region and easily surpassing thresholds known to trigger severe flooding in Indonesian catchments. However, the severity and geographic extent of the disaster cannot be attributed to rainfall alone; the hydrological analysis shows that large contributing areas, moderate-to-high runoff coefficients (approximately 0.16–0.28), and limited watershed storage capacity transformed this rainfall into huge runoff volumes and peak discharges, often exceeding 1,300–1,400 m^3/s in several Aceh, North Sumatera, and West Sumatera basins.

Across the 32 watersheds, provincial summaries reveal that West Sumatra exhibited the highest mean event rainfall and mean discharge. Still, Aceh and North Sumatra also produced comparable peak discharges, with large basins and degraded upper watersheds overlapping during intense rainfall. The runoff coefficients used in the estimation, while conservative, are consistent with land-use patterns characterized by partial forest loss, expansion of plantations and agriculture, and settlement growth, which together reduce infiltration and enhance quick surface runoff. This interpretation aligns closely with independent expert analyses of the 2025 Sumatra floods, which emphasize that upper-watershed forest degradation, poorly regulated land clearing, and encroachment into river corridors have eroded the ecological capacity of headwater ecosystems to buffer against extreme rainfall.

The correlation analysis underscores that watershed area and adequate runoff volume dominate the cross-basin variability in peak discharge. In contrast, simple linear relationships between rainfall or runoff coefficient and discharge appear weaker when all basins are pooled.

This statistical pattern reflects the wide range of basin sizes and relatively narrow range of C values rather than a lack of physical influence of land use or rainfall intensity on flood peaks. In fact, event-based modeling from other Indonesian basins demonstrates that land-use-driven changes in runoff coefficient and soil hydrological properties can substantially increase peak discharge and inundation area for the same or slightly increasing rainfall, reaffirming that land-use decisions are central to flood dynamics. The November 2025 floods thus exemplify how extreme meteorological forcing superimposed on weakened watershed systems can produce cascading floods and landslides, especially in steep terrains like the Barisan Mountains and degraded uplands of Mandailing Natal, Langkat, and Pesisir Selatan.

The analysis also highlights the multi-hazard nature of the disaster, with many watersheds experiencing simultaneous river flooding, landslides, debris flows, and riverbank failures. Multi-hazard assessments for Kalimantan and Sumatra already show that the overlap of flood and landslide risk is highest where high rainfall meets steep slopes and disturbed land cover, and the 2025 event is a stark confirmation of this pattern in northern and western Sumatra. From a governance perspective, these findings reinforce critiques that Indonesia's current approach remains anchored in reactive crisis management, with insufficient emphasis on upstream watershed protection, enforcement of spatial planning, and long-term ecological rehabilitation. In summary, the November 2025 floods are best understood as a systemic watershed crisis triggered by an extreme cyclonic event, exposing structural weaknesses in land-use regulation, environmental governance, and multi-hazard preparedness in Aceh, North Sumatra, and West Sumatra.

Recommendations

Strengthen watershed and land-use regulation

Enforce strict protection of critical headwater forests and riparian buffers

Remaining forested headwater areas, such as the Leuser Ecosystem in Aceh and the Batang Toru ecosystem in North Sumatra, should be treated as non-negotiable hydrological infrastructure and protected through more vigorous enforcement of conservation and land-use laws. Expert analyses of the 2025 floods argue that systematic destruction of upstream forests has drastically reduced interception, infiltration, and evapotranspiration, triggering severe erosion, landslides, and flash floods; reversing this trend requires halting new clearing, auditing existing permits, and prosecuting illegal logging and mining in critical watersheds.

Revise and enforce spatial plans for flood-prone basins

Land-use and spatial plans for Aceh, North Sumatra, and West Sumatra need urgent revision to align with watershed characteristics and multi-hazard risk profiles, a step that national authorities have already signaled as a priority response after the 2025 floods. Practical measures include prohibiting new settlements and large-scale infrastructure directly on floodplains and unstable slopes, reclassifying high-risk zones from production to protection status, and integrating updated flood and landslide hazard maps into provincial and district spatial plans. Research from the Ciliwung and lower Cimanuk basins demonstrates that integrating land-cover and climate scenarios into planning can significantly mitigate future flood inundation, and similar approaches should be institutionalized in Sumatra.

Integrate structural, ecological, and nature-based solutions

Combine grey infrastructure with ecological restoration

Structural interventions - such as levees, embankments, river normalization, sediment dredging, and retention basins - remain essential but must be complemented by ecological measures that restore watershed storage and slope stability. Experiences from Jakarta and other Indonesian cities show that hybrid solutions, combining improved drainage and floodways with nature-based solutions (NBS) like green open spaces, infiltration wells, riparian reforestation, and wetland restoration, can reduce flood peaks while delivering co-benefits for biodiversity and climate adaptation. In the Sumatra basins studied here, targeted reforestation, agroforestry, and soil-conservation measures in upper catchments, combined with riparian greenbelts and reconnecting rivers to natural retention areas, could lower runoff coefficients and peak discharges during future extreme events.

Prioritize critical-land rehabilitation and slope stabilization

Large swaths of steep terrain in Mandailing Natal, Pesisir Selatan, Aceh Tengah, and Langkat require systematic rehabilitation to address both flood and landslide risk. Rehabilitation programs should focus on replanting deep-rooted native species, improving soil organic matter, constructing small check dams and terracing in agricultural slopes, and controlling road drainage to minimize gully erosion and slope failures. Multi-hazard research suggests that hazard reduction can be substantial when such measures are applied in priority sub-basins identified through combined flood–landslide risk mapping, particularly where communities and infrastructure lie downstream.

Prioritize critical-land rehabilitation and slope stabilization

Strengthen multi-hazard early warning systems (MHEWS)

The November 2025 floods demonstrate the need to enhance early warning systems that integrate meteorological forecasts, real-time rainfall and river monitoring, and landslide susceptibility assessments for northern and western Sumatra. Operationally, this means improving radar and satellite-based rainfall nowcasting, expanding hydrometric networks in key watersheds (e.g., Krueng Aceh, Manyak Payed/Tamiang, Batang Gadis, Indrapura), and linking alerts to clear, community-level response protocols. Evidence from other Indonesian contexts shows that timely warnings, combined with evacuation drills and public education, can significantly reduce casualties even when structural vulnerabilities persist.

Shift from reactive to preventive disaster governance

Analysis of Indonesia's flood governance points to a persistent bias toward post-disaster emergency response rather than pre-disaster risk reduction, a pattern repeatedly criticized in recent commentary on the Sumatra floods. Implementing a preventive paradigm requires aligning budgets with long-term risk-reduction priorities (e.g., watershed rehabilitation, risk-based spatial planning, resilient infrastructure) and empowering local governments to enforce existing environmental and disaster-management laws. Collaborative governance models that involve central and local authorities, communities, civil society, and the private sector have been shown to improve flood mitigation outcomes, especially when they mainstream nature-based solutions and community participation into planning.

Research and data priorities

Advance basin-specific hydrological and hydraulic modeling

The event-based estimates in this study should be complemented by detailed hydrological and hydraulic models for priority basins in Aceh, North Sumatra, and West Sumatra, incorporating sub-daily rainfall, channel routing, floodplain dynamics, and sediment transport. These models can be used to test land-use and climate scenarios, evaluate the effectiveness of mitigation options (e.g., retention basins, reforestation, river restoration), and generate design floods for infrastructure planning, drawing on methods successfully applied in other Indonesian watersheds.

Integrate social vulnerability and relocation strategies into risk assessments

Finally, future research and policy should explicitly incorporate social vulnerability, livelihood dependence, and relocation needs into multi-hazard risk assessments for Sumatra. The 2025 disaster has already prompted discussions about relocating some of the most exposed communities, and such decisions must be informed by robust spatial analyses that balance safety, cultural ties, and economic opportunities. Integrating socio-economic data, infrastructure resilience indicators, and ecosystem-services valuation with hydrological modeling will help ensure that the lessons from this catastrophe are translated into just and sustainable adaptation pathways for Aceh, North Sumatra, and West Sumatra.

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