

Upstream Watershed Degradation and Increased Risk of Flash Floods Amid Climate Change

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ARTICLE INFO

Keywords: Jeneberang Watershed, Upstream Degradation, Flash Flood, Climate Change, Spatial Analysis, Disaster Risk.

Received : 27, January

Revised : 29, February

Accepted: 31, March

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ABSTRACT

Land cover change in the upstream area of the Jeneberang Watershed, South Sulawesi, has altered river hydrological dynamics and amplified the impacts of increasingly intense extreme rainfall associated with climate change, thereby elevating the risk of flash floods in downstream regions. This study aims to examine the relationship between upstream watershed degradation, trends in extreme rainfall, and the escalation of flash flood risk through an integrated spatial-temporal analysis. A quantitative approach was employed using secondary data, including multitemporal satellite imagery from 2003–2023, 20 years of daily rainfall records, documented flood events, and population data. The analysis involved land cover classification and change detection using GIS, trend testing of extreme rainfall with the Mann-Kendall method, estimation of runoff coefficients and peak discharge, and risk modeling based on the Hazard-Vulnerability-Exposure framework. The results indicate a 17.8% decline in forest cover in the upstream area, associated with a 19% increase in the runoff coefficient and a 24% rise in estimated peak discharge during high-intensity rainfall events. Maximum daily rainfall intensity also shows a statistically significant upward trend ($p < 0.05$). Risk mapping reveals a 29% expansion of high-risk zones, particularly in densely populated downstream areas. These findings demonstrate that the interaction between land use change and intensifying extreme rainfall exacerbates watershed hydrological vulnerability, providing a scientific basis for upstream restoration policies and ecosystem-based climate change adaptation strategies in the Jeneberang Watershed

INTRODUCTION

Land use change in upstream watershed areas constitutes a critical factor influencing hydrological balance, particularly in tropical regions characterized by high rainfall intensity and steep topography. The intensification of extreme rainfall driven by global climate change has increased the frequency of flash flood events worldwide (Pörtner et al., 2022). This condition is further exacerbated by anthropogenic pressures, including deforestation, agricultural expansion, and urban growth, which reduce soil infiltration capacity. In the Asia-Pacific region, increases in surface runoff and peak river discharge have become more pronounced in watersheds experiencing large-scale forest conversion (Darmawan et al., 2021). In Indonesia, these dynamics are reflected in the rising occurrence of floods and landslides in regions with significant land cover change pressures, including South Sulawesi.

At the national level, numerous studies indicate that forest cover loss in upstream areas directly contributes to higher runoff coefficients and increased river sedimentation. Austin et al. (2020) emphasized that tropical forest loss has significant implications for regional water cycles and heightened flood risk. Similarly, Tan-Soo et al. (2021) found that forest conversion to agricultural land increases hydrological vulnerability by reducing soil water retention capacity. In South Sulawesi, pressure on the upstream area of the Jeneberang Watershed has intensified due to agricultural activities and population growth. These changes raise concerns regarding the natural capacity of the watershed to dissipate runoff energy during high-intensity rainfall events. Therefore, an integrated analysis combining land use dynamics and climate variability is essential.

Although research on climate change and flooding has expanded considerably, most studies focus primarily on rainfall as the dominant variable without quantitatively integrating land use change into risk models (Alfieri et al., 2020). Meanwhile, hydrological simulations often emphasize river discharge modeling without incorporating social vulnerability dimensions into risk assessment (Ward et al., 2020). In Indonesia, disaster risk approaches remain largely sectoral and have not fully integrated spatial land use change, extreme rainfall trends, and population distribution within a comprehensive analytical framework (Rahman et al., 2023). This gap highlights the need for an integrative approach capable of explaining the simultaneous interaction between upstream watershed degradation and increasing flash flood risk. Consequently, research that combines spatial-temporal analysis with the Hazard-Vulnerability-Exposure framework is relevant to address this scientific gap.

This study aims to analyze the relationship between upstream land cover change in the Jeneberang Watershed, trends in extreme rainfall, and the escalation of flash flood risk in a comprehensive manner. The analysis employs a quantitative approach based on secondary data, including multitemporal satellite imagery, daily rainfall records, documented flood events, and population data. Methods include land cover change detection using geographic information systems, statistical trend analysis of extreme rainfall, estimation of hydrological parameters, and spatial risk modeling. This approach aligns with recent recommendations emphasizing the integration of climate and land use

data to better understand hydrometeorological risk dynamics (Zscheischler et al., 2020). Focusing on the Jeneberang Watershed provides a specific empirical context within the broader framework of global environmental change.

Theoretically, this study reinforces the socio-hydrology framework, which explains the reciprocal interactions between natural systems and human activities in shaping disaster risk (Di Baldassarre et al., 2020). Integrating land cover change variables and climate trends within a unified risk model offers a more comprehensive understanding of mechanisms driving hydrological vulnerability. The study also enriches the literature on the importance of spatial approaches in ecosystem-based risk evaluation. Thus, its theoretical contribution lies in strengthening analytical models that explain causal relationships between upstream degradation and the escalation of flash flood risk.

From a practical perspective, the findings are expected to provide a scientific basis for adaptive watershed management policies in response to climate change. Forest restoration and spatial planning based on environmental carrying capacity have proven effective in reducing flood risk through improved infiltration capacity and slope stabilization (Griscom et al., 2020). By providing empirical evidence of the relationship between upstream degradation and increasing flash flood risk in the Jeneberang Watershed, this study supports the integration of disaster mitigation and climate change adaptation into sustainable regional development planning.

THEORETICAL REVIEW

Upstream Watershed Degradation and Hydrological Response Changes

Land cover change in upstream watershed areas directly influences hydrological characteristics, particularly infiltration capacity, groundwater storage, and runoff response to extreme rainfall events. Bradshaw et al. (2021) demonstrated that deforestation in upstream regions increases peak river discharge due to reduced evapotranspiration and diminished soil water retention capacity. Global assessments further indicate that vegetation loss accelerates flow concentration time and elevates the probability of flash floods, especially in steep-sloped watersheds (Zhang et al., 2022). In the Indonesian context, Nugroho and Paimin (2021) found that land use change in tropical watersheds significantly increases runoff coefficients and river sedimentation rates. These findings suggest that upstream degradation acts as an amplifying factor in hydrological disturbances, particularly when combined with high-intensity rainfall events.

H1: Upstream land cover degradation positively influences increases in runoff coefficients and peak river discharge.

Intensification of Extreme Rainfall under Climate Change

Global climate change has intensified short-duration, high-intensity rainfall events, contributing to a growing risk of flash floods. Donat et al. (2021) reported significant increases in extreme rainfall intensity in tropical regions due to atmospheric warming that enhances moisture-holding capacity. Fowler et al. (2022) further confirmed that rising global temperatures intensify extreme precipitation through thermodynamic mechanisms consistent with the Clausius-

Clapeyron relationship. In Southeast Asia, increasing trends in extreme rainfall have been associated with a higher frequency of flood events over the past decade (Supari et al., 2020). These studies collectively indicate that climatic variability plays a critical role in amplifying hydrometeorological hazards, particularly in watersheds already subjected to land use pressures.

H2: Increasing extreme rainfall intensity due to climate change significantly contributes to higher peak discharge and greater flash flood frequency.

Integrating Land Degradation and Extreme Rainfall in Risk Modeling

Contemporary disaster risk frameworks emphasize the integration of hazard, vulnerability, and exposure within a unified analytical structure. Koks et al. (2021) argued that flood risk escalates exponentially when environmental degradation coincides with rapid population growth. Winsemius et al. (2022) demonstrated that uncontrolled land use change magnifies the socioeconomic impacts of floods, even when rainfall intensity remains relatively constant. In Indonesia, Hidayati et al. (2023) showed that downstream watershed areas with high population density exhibit substantially greater risk levels compared to less populated areas, despite experiencing similar hydrological hazard intensity. These findings highlight that the interaction between upstream degradation and socioeconomic factors intensifies disaster risk escalation.

H3: The combined interaction of upstream watershed degradation and intensified extreme rainfall significantly increases flash flood risk in densely populated downstream areas.

Upstream Restoration and Ecosystem-Based Adaptation

Ecosystem-based adaptation strategies are increasingly recognized as effective approaches for reducing flood risk through the restoration of natural hydrological functions. Chausson et al. (2020) demonstrated that forest restoration and rehabilitation of degraded lands significantly enhance infiltration capacity and reduce surface runoff. Ferreira et al. (2023) emphasized that vegetation-based watershed management provides long-term stabilization of river discharge during extreme rainfall events. In Indonesia, Sari and Prasetyo (2022) found that upstream forest rehabilitation reduces flood risk by improving soil water retention and regulating hydrological flow. These findings underscore the strategic importance of upstream ecosystem management in supporting sustainable climate change adaptation.

H4: Upstream ecosystem restoration significantly reduces flash flood risk through improved hydrological retention capacity.

METHODOLOGY

Research Approach and Design

This study employs a quantitative explanatory approach with an integrated spatial-temporal analytical design to examine the relationship between upstream watershed degradation, extreme rainfall trends, and the escalation of flash flood risk. This design was selected because it enables the analysis of causal relationships among variables using numerical and spatial data across a defined time period. Quantitative spatial approaches are widely recognized in contemporary hydrological studies as they allow the integration of remote sensing data, climatic variables, and socio-environmental parameters

within a unified analytical framework (Bui et al., 2020). Furthermore, spatially based risk modeling is increasingly recommended in disaster studies to improve the accuracy of hazard zone identification (Merz et al., 2021). Accordingly, this research integrates land cover change analysis, statistical trend analysis of extreme rainfall, hydrological parameter estimation, and risk modeling based on the Hazard–Vulnerability–Exposure framework.

Population and Sampling

The study population encompasses the entire Jeneberang Watershed, including upstream, middle, and downstream zones. The spatial unit of analysis consists of 30-meter resolution satellite image grid pixels and administrative village units in the downstream area for risk assessment. Spatial sampling was conducted using systematic grid-based probability sampling to ensure representative coverage of the entire watershed in land cover change analysis. For social vulnerability analysis, aggregated secondary demographic data, including population density statistics from the national statistical agency, were used for all affected areas, eliminating the need for individual respondent sampling. This approach aligns with established practices in population-based flood risk assessment studies (Jongman et al., 2021).

Data Collection Techniques

The study utilizes secondary data comprising: (1) Landsat satellite imagery from 2003–2023 for land cover change analysis; (2) 20 years of daily rainfall data from the nearest meteorological stations; (3) historical flood event records; and (4) downstream demographic data. Land cover classification was performed using supervised classification based on the Random Forest algorithm due to its high accuracy in tropical land mapping (Belgiu & Drăguț, 2020). Classification accuracy was assessed using a confusion matrix, overall accuracy calculation, and kappa coefficient. Extreme rainfall trends were analyzed using the Mann–Kendall test and Sen’s slope estimator to detect long-term statistical tendencies (Hamed, 2021). Spatial validation was strengthened through overlay analysis with a 30-meter resolution Digital Elevation Model.

Research Procedure

The research was conducted in sequential stages. The first stage involved data collection and pre-processing of satellite imagery, including atmospheric correction and mosaicking. The second stage consisted of land cover classification and multitemporal change detection to quantify forest loss and built-up land expansion. The third stage involved statistical analysis of extreme rainfall trends and the calculation of hydrological parameters such as runoff coefficients and peak discharge estimation using the rational method. The fourth stage comprised risk modeling by integrating hazard components (rainfall intensity and discharge), vulnerability (population density), and exposure (affected area extent). The final stage included result interpretation and spatial validation. This procedure follows the principle of multi-source data integration in hydrometeorological risk modeling (Shrestha et al., 2022).

Data Analysis Techniques

Spatial analysis was conducted using ArcGIS and QGIS software, while statistical analyses were performed using R Studio and SPSS. Land cover changes were quantified through raster-based change detection analysis. Runoff coefficients were calculated based on land use classification and slope characteristics. Peak discharge estimation employed the rational formula incorporating maximum daily rainfall intensity. The risk model was constructed using a composite index approach with standardized weighting for each Hazard-Vulnerability-Exposure component. Multiple linear regression analysis was applied to test the influence of land degradation and extreme rainfall on peak discharge increases. This methodological approach is consistent with contemporary quantitative flood risk studies that integrate biophysical and socio-environmental variables (Tellman et al., 2021). Through these stages, the collected data were systematically processed into land cover change maps, extreme rainfall trend graphs, peak discharge increase estimations, and flash flood risk zoning maps, which were subsequently analyzed to empirically test the research hypotheses.

RESEARCH RESULTS

Upstream Land Cover Change and Forest Decline (2003–2023)

Multitemporal classification of Landsat imagery shows a clear decline in forest cover in the upstream zone of the Jeneberang watershed between 2003 and 2023. Forest area fell from an estimated 31,250 ha in 2003 to 25,688 ha in 2023, which means a net loss of 5,562 ha (17.8%). In the same period, mixed farmland and shrub/grass increased, signaling a transition to a surface that is more susceptible to runoff. Built-up areas are increasing moderately, but the pattern tends to be concentrated around access corridors and residential clusters. Overall, the trajectory of land cover change confirms upstream degradation that has the potential to decrease infiltration and increase the sensitivity of watershed hydrological responses.

Table 1. Land Cover Composition in the Upstream Jeneberang Watershed (2003–2023)

Land Cover Class	2003 Area (ha)	2023 Area (ha)	Absolute Change (ha)	Change (%)
Forest	31,250	25,688	-5,562	-17.8
Mixed Agriculture	12,480	15,964	+3,484	+27.9
Shrub/Grassland	8,120	9,734	+1,614	+19.9
Built-up	1,150	1,614	+464	+40.3
Water/Other	620	620	0	0.0

Source: Processed from Landsat imagery 2003–2023 using Random Forest classification and raster change analysis (ArcGIS/QGIS).

Methodologically, these findings were obtained through atmospheric correction and mosaicking, then supervised classification using the Random Forest algorithm and accuracy evaluation with confusion matrix metrics. Change detection is carried out through raster-based cross-tabulation to quantitatively calculate class shifts between time. The spatial analysis unit uses 30 m pixels so that results between years can be compared consistently. The systematic grid approach ensures full coverage of the upstream region and minimizes spatial bias. The results of this land cover pattern are an empirical basis for evaluating the hydrological impact on the next analysis. The observed forest decline supports the upstream degradation component in H1, namely land cover degradation contributes to an increase in runoff coefficient and peak discharge.

These findings confirm that the transformation of upstream land cover is not small, but significant in structure and direction. Conversion from forest to mixed farming and shrub/grass indicates a decrease in surface roughness and water retention ability during heavy rains. The growth of localized built-up areas also increases imperviousness and accelerates local runoff. These changes are consistent with watersheds that are increasingly responsive to rainfall pulses. Thus, forest loss is understood as a major trigger that forms upstream degradation signals in hydrological and risk models.

Extreme Rainfall Trends and Statistically Significant Increases

Analysis of daily rainfall over 20 years shows an increasing trend in the maximum daily rainfall intensity in the Jeneberang watershed. The Mann-Kendall test produced a statistically significant uptrend in annual 1-day maximum rainfall ($p < 0.05$), signaling a strengthening of extreme rainfall conditions. Estimates of Sen's slope indicate an average increase of about 1.8 mm/year in the annual maximum daily rainfall. The frequency of days with rainfall exceeding the threshold of "very dense" (≥ 100 mm/day) has also increased, especially after 2013. This pattern shows climate signals that are in line with the potential for greater flash flood triggers, especially when combined with reduced retention capacity in upstream regions.

Table 2. Trend Statistics for Extreme Rainfall Indicators (20-Year Daily Rainfall Series)

Indicator	Mann-Kendall Z	p-value	Sen's Slope	Interpretation
Annual Maximum 1-Day Rainfall (Rx1day)	2.21	0.027	+1.8 mm/year	Significant increase
Days ≥ 100 mm/day	1.98	0.048	+0.22 days/year	Significant increase
Annual Total Rainfall	1.12	0.262	+9.5 mm/year	Not significant

Source: Calculated from 20 years of daily station rainfall data using the Mann-Kendall trend test and Sen's slope estimation (R Studio/SPSS).

This result was obtained through the application of a non-parametric Mann–Kendall test to the daily rainfall derivative index and the estimation of the magnitude of change using Sen's slope. Rainfall data were checked for quality, then processed into an annual extreme index and tested for monotonic tendencies. This approach is appropriate for hydroclimatic data that often do not meet the assumption of normality. Statistical processing is done in R Studio and double-checked at SPSS to maintain consistency. The trend results are then integrated into the peak discharge calculation through the daily maximum rainfall intensity input. A significant increase in the intensity of extreme rainfall supports H2, i.e. strengthening extreme rainfall contributes to an increase in peak discharge and frequency of flash floods.

The findings of the trend show that climate coercion is not only present, but can be measured statistically. The increase in Rx1day and the frequency of very heavy rainy days mean that events that exceed the threshold of triggering rapid runoff are becoming more frequent. The insignificance of the trend of annual total rainfall suggests that the change is more concentrated on the extreme, rather than the annual volume, which is in line with the character of flash floods. This reinforces the argument that the danger of flooding is increasingly driven by short-duration but very intense rains. Thus, the strengthening of extreme rainfall is understood as a hazard amplifier that interacts with upstream land degradation.

Hydrological Response: Increase in Peak Runoff and Discharge Coefficients

Estimation of hydrological parameters shows that the degradation of upstream areas is associated with increased runoff response during high-intensity rainfall. The composite runoff coefficient increased from 0.42 (baseline condition) to 0.50 (current condition), which means it is up 19% and consistent with land cover changes. With rational methods and daily maximum rainfall intensity input, the peak discharge is estimated to increase from 312 m³/s to 387 m³/s or an increase of 24%. The greatest discharge sensitivity occurred in steeply sloped sub-areas with forest to agricultural transitions, demonstrating the combined effect of slope and land cover. In general, these results indicate that watersheds become more "flashy", i.e. faster and larger to produce peak flows due to decreased buffer capacity.

Table 3. Changes in Runoff Coefficient and Estimated Peak Discharge Under Extreme Rainfall

Parameter	Baseline Condition	Current Condition	Change	Change (%)
Composite Runoff Coefficient (C)	0.42	0.50	+0.08	+19.0
Estimated Peak Discharge (Q _{peak} , m ³ /s)	312	387	+75	+24.0

Source: Estimated from land cover-based runoff coefficients, 30 m DEM slope correction, and rational method peak discharge under extreme rainfall (ArcGIS/QGIS; R Studio).

The runoff coefficient is calculated by determining the value of the coefficient per land cover class, then adjusted using the slope class of DEM results. The peak discharge estimate follows a rational method procedure using a consistent watershed area, daily maximum rainfall intensity, and calculated runoff coefficient. This stage relates the results of remote sensing (land cover) and the results of extreme rainfall trends in the exponential quantitative design. The calculations are done through spatial weighting in GIS and numerical processing in R Studio so that they can be replicated. Furthermore, multiple linear regression was used to test the effect of land degradation indicators and extreme rainfall indices on peak discharge variations. The increase in runoff coefficients and peak discharge provides direct empirical support for H1 and at the same time strengthens H2 through the role of increased extreme rainfall inputs.

These findings confirm that land degradation is not just a change in landscape, but a hydrological mechanism that changes the efficiency of runoff formation. A higher runoff coefficient means that the proportion of rain that turns into surface flow increases, resulting in larger flood waves. The increase in peak discharge also indicates reduced watershed storage and decreased infiltration. Since discharge is calculated using extreme rainfall intensity inputs, these results also reflect the contribution of climate coercion. Thus, the hydrological results become a mechanistic bridge that explains how land change and rainfall intensification escalate the danger of flash floods.

Spatial Risk Mapping and Expansion of High-Risk Zones in the Downstream

Risk mapping based on the Hazard-Vulnerability-Exposure framework shows a substantial expansion in the high risk zone of flash floods in the downstream area of the Jeneberang watershed. The high-risk class increased from 4,860 ha to 6,269 ha or an increase of 29% in the assessment period. The most prominent expansion occurred in densely populated village/sub-district units, where exposure and vulnerability scores were high, even when the intensity of the hazard was at a moderate level. Moderate risk zones are also changing, indicating a wider spread of risk, rather than just isolated hotspots. These results suggest that the interaction between upstream hazard reinforcement and downstream social exposure forms an ever-evolving risk landscape.

Table 4. Change in Flash Flood Risk Zone Extent (Downstream Area)

Risk Class	Baseline Extent (ha)	Current Extent (ha)	Change (ha)	Change (%)
Low Risk	8,420	7,160	-1,260	-15.0
Medium Risk	6,210	6,061	-149	-2.4
High Risk	4,860	6,269	+1,409	+29.0

Source: GIS-based composite index modeling integrating hazard (extreme rainfall, peak discharge), vulnerability (population density), and exposure (affected area) using ArcGIS/QGIS.

These results were produced through the preparation of composite indices with standardized weighting on hazard, vulnerability, and exposure components. The hazard layer includes the extreme rainfall index and peak discharge modeled results, vulnerability is represented by population density at the village level, and exposure is represented by the area of potentially affected area based on inundation paths. All layers are normalized to a consistent scale and then combined to classify the risks into low, medium, and high. Spatial validation is carried out through overlays with records of flood occurrences and proximity to the river/drainage network. This procedure reflects an integrated spatial-temporal design in the methodology and operationalizes the risk framework in a replicative manner. The expansion of the high-risk zone strongly supports H3, that the combination of upstream degradation and increased extreme rainfall increases the risk of flash floods, especially in densely populated downstream areas.

Risk outcomes show that the escalation of risk is not only determined by hazard, but by the spatial linkage between hazards and vulnerable and exposed populations. The increase in the breadth of high risk means that downstream communities face an increasing threat even if the protection infrastructure remains unchanged. High risk concentrations in dense residential clusters show a multiplier effect of exposure according to the logic of the risk framework. Reduced area of low risk indicates a structural shift to a higher risk distribution overall. Thus, these findings confirm that the risk of flash floods in the Jeneberang watershed is increasingly shaped by the dynamics of interconnected natural-human systems.

Implications of Upstream Restoration and Ecosystem-Based Adaptation

To assess the relevance of restoration, scenario-based sensitivity analysis was used to estimate how increased upstream retention affects hydrological responses and downstream risks. In the restoration scenario that increases forest cover in upstream priority sub-areas by 10% through degraded slope rehabilitation, the composite runoff coefficient is projected to decrease from 0.50 to 0.46 (down 8%). With the same extreme rainfall input, the peak discharge was estimated to drop from 387 m³/s to 356 m³/s (down 8%), indicating a meaningful moderation of hazards. Risk reclassification shows that the area of the high-risk zone can be reduced by approximately 6–10% depending on the spatial distribution of the restoration patch, particularly when rehabilitation is directed at strongly-connected, steep-sloped runoff pathways. These findings suggest that upstream ecosystem restoration has the potential to reduce the risk of flash floods through increased hydrological retention capacity.

Table 5. Restoration Sensitivity Scenario: Projected Hydrological and Risk Changes

Variable	Current Condition	Restoration Scenario	Change	Change (%)
Composite Runoff Coefficient (C)	0.50	0.46	-0.04	-8.0

Variable	Current Condition	Restoration Scenario	Change	Change (%)
Estimated Peak Discharge (Q _{peak} , m ³ /s)	387	356	-31	-8.0
High-Risk Zone Extent (ha)	6,269	5,770	-499	-8.0

Source: Scenario-based recalculation using adjusted land cover runoff coefficients, constant extreme rainfall, rational method discharge estimates, and recomputed H-V-E risk index (ArcGIS/QGIS; R Studio).

This scenario analysis follows the same methodological pipeline as the main model, only differing in the land cover input layer where forest cover is increased on a specific upstream cell. The runoff coefficient layer is recalculated based on the proportion of new land cover and slope weighting, and then the peak discharge is reestimated by a rational method while holding the intensity of rain still to isolate the effect of land cover. The risk mapping is then re-run with the same normalization and weighting in the composite index. This approach maintains methodological consistency and makes the restoration a controlled sensitivity experiment in explanatory quantitative design. The resulting outputs provide a proven basis for linking ecosystem-based interventions with measurable changes in hazard and risk metrics. The restoration scenario supports H4, that increased retention through upstream ecosystem restoration can lower the risk of flash floods.

These results emphasize that restoration is worth considering because a relatively moderate increase in forest cover results in a measurable decrease in runoff and peak discharge. Projected high-risk area reductions suggest that upstream rehabilitation can provide real benefits to downstream areas, especially when their location is optimized. Containment of extreme rainfall inputs remains evidence that restoration can provide risk reduction even as climate intensification continues. This strengthens ecosystem-based adaptation as a complementary strategy for structural and governance efforts. Thus, this study not only identifies risk drivers, but also shows actionable mitigation pathways through upstream landscape management.

DISCUSSION

The main findings of this study indicate that upstream degradation of the Jeneberang Watershed plays a significant role in increasing hydrological vulnerability, particularly through a 17.8% decline in forest cover accompanied by increases in the runoff coefficient and peak discharge. Theoretically, these results align with the concept of watershed resilience, which positions vegetation as a regulator of energy and water balance within hydrological systems (Creed et al., 2021). Global studies have shown that forest loss in tropical regions accelerates surface runoff and reduces groundwater storage capacity, thereby heightening the likelihood of flash flooding (Filoso et al., 2022). This study confirms that framework within the context of a tropical Indonesian watershed using a

quantitative spatial–temporal approach. Its distinction lies in the direct integration of land cover change analysis with peak discharge estimation within a consistent analytical pipeline. Thus, its scientific contribution extends beyond descriptive assessment to elucidating the causal mechanism linking land degradation and hydrological response.

The statistically significant increase in maximum daily rainfall intensity reinforces the role of climate change in escalating flash flood risk. Recent climatological literature emphasizes that climate change tends to alter the distribution of extreme events rather than total annual precipitation (Sun et al., 2021). Similarly, Pendergrass and Knutti (2023) demonstrate that rising global temperatures increase the probability of high-intensity rainfall through enhanced atmospheric moisture-holding capacity. The findings of this study are consistent with these patterns, as Rx1day increased significantly while annual total rainfall showed no meaningful trend. This implies that flood risk is driven not merely by water volume, but by short-duration, high-intensity rainfall that triggers rapid runoff. Unlike many regional studies, this research directly links extreme rainfall trends to changes in peak discharge, enabling a quantitative examination of the relationship between climatic signals and hydrological response.

The interaction between upstream degradation and intensified extreme rainfall resulted in a 24% amplification of peak discharge, indicating a synergistic effect. Within the framework of nonlinear hydrology, even a small increase in the runoff coefficient can generate a disproportionately larger rise in discharge in steep watersheds (Blöschl et al., 2021). Studies conducted in Latin America and Southeast Asia similarly report that the combination of deforestation and extreme rainfall increases flood risk exponentially (Barlow et al., 2020). These results support Hypotheses H1 and H2, demonstrating that land use change and climate variability operate interactively rather than independently. The study's contribution lies in its empirical validation through multiple linear regression, which tests the simultaneous influence of land degradation indicators and extreme rainfall indices on peak discharge. In doing so, it advances socio-hydrological scholarship that conceptualizes flood risk as an outcome of coupled human–natural system dynamics (Di Baldassarre et al., 2021).

The 29% expansion of high-risk zones in downstream areas illustrates that risk emerges from the interaction between physical hazards and social exposure. Risk layering theory posits that risk intensifies when strengthening hazards intersect with concentrated populations and assets in vulnerable spaces (Tellman et al., 2021). Recent global research indicates that uncontrolled urbanization accelerates flood risk escalation even when hazard changes are moderate (Jongman, 2022). The present findings are consistent with this perspective, as high-risk zones are concentrated in densely populated downstream villages. However, this study differs in its integrated application of the Hazard–Vulnerability–Exposure framework combined with hydrological modeling based on local empirical data, rather than relying solely on descriptive composite indices. This integration enhances both conceptual robustness and operational validity in understanding flash flood dynamics in tropical developing regions.

The upstream restoration scenario demonstrates that a 10% increase in forest cover could reduce peak discharge and high-risk zone extent by approximately 8%. Theoretically, this aligns with the concept of ecosystem-based adaptation, which frames landscape restoration as a nature-based strategy for disaster risk reduction (Locatelli et al., 2022). Griscom et al. (2020) further argue that nature-based solutions hold substantial potential for climate mitigation and adaptation when spatially targeted. The findings of this study support that argument by providing quantitative evidence that moderate upstream interventions yield measurable downstream benefits. Its distinct methodological strength lies in the use of controlled simulations with constant rainfall inputs, thereby isolating the effect of land cover change from climatic variability. These results offer a scientific basis for upstream rehabilitation policies as complementary structural and non-structural adaptation strategies.

Nevertheless, several limitations warrant critical consideration. First, the use of the rational method for peak discharge estimation assumes uniform rainfall intensity, which may oversimplify the spatial complexity of precipitation patterns. Second, while a 20-year rainfall dataset is adequate for trend analysis, longer time series would enhance the robustness of long-term climate signal detection (Kundzewicz et al., 2020). Third, the risk model does not incorporate adaptive capacity variables such as early warning systems or flood control infrastructure. Future research should employ process-based hydrological models such as SWAT or HEC-HMS and integrate long-term climate projection scenarios. Overall, this study contributes to applied hydrology and disaster risk management by demonstrating that upstream degradation and climate change are two principal drivers that must be addressed in an integrated watershed governance framework.

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that upstream land degradation and intensifying extreme rainfall jointly amplify flash flood risk in the Jeneberang Watershed. The 17.8% decline in forest cover has significantly altered hydrological dynamics, as reflected in the 19% increase in the runoff coefficient and the 24% rise in estimated peak discharge under high-intensity rainfall. The statistically significant upward trend in maximum daily rainfall further strengthens the hazard component, while the 29% expansion of high-risk zones confirms that downstream communities are increasingly exposed to compounded environmental pressures. These findings demonstrate that watershed vulnerability is shaped by the interaction between land use change and climate-driven extreme events rather than by single factors operating independently. Therefore, it is recommended that watershed governance prioritize upstream forest restoration, stricter land-use regulation in erosion-prone slopes, and the integration of ecosystem-based adaptation into regional spatial planning. In parallel, downstream risk reduction should incorporate improved land-use control, floodplain management, and community-based early warning systems to reduce exposure and vulnerability in densely populated areas.

FURTHER STUDY

Despite providing robust empirical evidence, this research has several limitations that open avenues for further investigation. The use of the rational method for peak discharge estimation simplifies rainfall spatial variability and watershed storage dynamics, which may underestimate or overestimate actual flood magnitudes under complex storm patterns. Additionally, the 20-year rainfall dataset, while adequate for detecting short- to medium-term trends, may not fully capture long-term climate variability or multi-decadal oscillations. Future studies are encouraged to apply process-based hydrological models such as SWAT or HEC-HMS to simulate runoff dynamics more comprehensively and to integrate regional climate model projections for scenario-based risk forecasting. Incorporating socio-economic adaptive capacity indicators – such as infrastructure resilience, governance quality, and community preparedness – would also enrich the Hazard–Vulnerability–Exposure framework and produce a more holistic flood risk assessment. Longitudinal field validation of restoration impacts is further recommended to verify modeled reductions in runoff and risk under real-world conditions.

ACKNOWLEDGMENT

The author expresses sincere appreciation to colleagues and academic peers at Universitas Indonesia Timur for their constructive feedback and scholarly discussions that strengthened the analytical framework of this study. Gratitude is also extended to the relevant local government agencies and meteorological institutions for providing access to rainfall data, spatial datasets, and documented flood event records that were essential to this research.

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