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Hydrological and Flood Analysis of the Cipager River

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Keywords

Cipager River, flood risk, hydrological modeling, hydraulic capacity, rainfall distribution, sedimentation, return period

ABSTRACT

This study investigates the flood vulnerability of the Cipager River Basin through integrated hydrological and hydraulic analysis. Maximum daily rainfall data from UPTD Mandirancan, UPTD Cilimus, and Cipager Weir were analyzed using four statistical models—Gumbel, Log-Normal, Normal, and Log-Pearson Type III—to estimate design rainfall for return periods of 2 to 100 years. The Log-Normal model produced the most conservative rainfall values, while the Log-Pearson Type III showed anomalous behavior at higher return periods, raising concerns regarding its reliability for modeling extreme hydrological events. Using Manning's equation, design discharges were derived and compared against the hydraulic capacities of 12 river segments. Results indicate that many segments, particularly Megu Gede, Astana, and Jatimerta, have discharge capacities below 1 m^3/s, far below the design discharges associated with longer return periods. This mismatch was further validated during the January 2025 flood, which caused severe inundation in subdistricts such as Weru, Tengahtani, and Gunung Jati. Compounding these risks are physical constraints including channel narrowing, sediment accumulation, and encroachment into riparian zones—conditions exacerbated by weak enforcement of spatial planning regulations. The study recommends structural measures such as river normalization, sediment control, and retention basins, alongside policy enforcement and real-time hydrological monitoring. By aligning statistical discharge modeling with actual river capacity, this research offers a strategic framework for flood risk reduction and supports evidence-based decision-making for climate-resilient watershed management in the Cipager River Basin.

INTRODUCTION

Flooding remains one of the most frequent and destructive hydrometeorological disasters in Indonesia, particularly in river basins undergoing rapid land-use transformation and lacking adequate drainage infrastructure (Ramadhan et al., 2022). The Cipager River, located in Cirebon Regency, West Java, exemplifies such vulnerability (Copernicus EMS, 2025). The flood event of January 2025, which inundated the subdistricts of Weru, Tengahtani, and Gunung Jati, underscores the urgent need to address both hydrometeorological extremes and anthropogenic stressors in flood-prone regions (ANTARA News, 2025; Radar Cirebon, 2025; OECD, 2024; Shah et al., 2023; Yosua et al., 2024).

Previous research by Asdak (2010) has shown that tropical catchments in regions such as West Java are significantly influenced by orographic effects and seasonal monsoons, which intensify rainfall variability during the wet season. Unlike Hidayat (2022), who focused solely on sedimentation impacts, this study integrates field-based morphological assessments with probabilistic rainfall modeling to offer a more comprehensive view. Although rainfall frequency analysis using statistical distribution models is widely practiced, most existing studies concentrate on upstream hydrology or rely solely on statistical estimation, often neglecting the hydraulic capacity of river channels and associated geomorphological constraints. Furthermore, while the role of land-use change in driving flood risk is well documented, localized hydrological modeling that incorporates spatial rainfall variability, hydraulic responses, and on-site channel conditions remains limited (Gori et al., 2019).

This study addresses these gaps by combining four statistical rainfall distribution models (Gumbel, Log-Normal, Normal, and Log-Pearson Type III) with hydraulic capacity analysis using Manning's equation across multiple segments of the Cipager River. The novelty of this research lies in its spatially explicit integration of rainfall probability modeling with field-validated channel geometry and discharge capacity. This dual-perspective approach provides a realistic evaluation of design discharge exceedance under current morphological and hydrological conditions (Tariq et al., 2021; Soemarto, 2024; Vangelis et al., 2022; Chaibandit & Konyai, 2012; Mundra, 2021; Wijaya, 2024; Wikipedia-Manning formula, 2025).

Unlike previous studies that generalize flood risk across broader watersheds, this research identifies segment-specific vulnerabilities and translates them into actionable recommendations for infrastructure planning, spatial policy enforcement, and adaptive flood risk management. The methodology developed offers a transferable framework for tropical catchments affected by climate variability, morphological degradation, and unregulated development.

The objectives of this study are to (1) assess the flood risk along the *Cipager River* by integrating probabilistic rainfall modeling with field-based hydraulic and morphological analysis, and (2) identify segment-specific vulnerabilities to inform effective flood mitigation, infrastructure planning, and spatial management strategies. By employing four statistical rainfall distribution models (Gumbel, Log-Normal, Normal, and Log-Pearson Type III) alongside Manning's equation for hydraulic capacity assessment, this research aims to provide a comprehensive understanding of flood dynamics under both natural and anthropogenic influences. The anticipated benefits of the study include enhanced accuracy in estimating design discharge exceedance, improved identification of high-risk river segments, and the development of actionable recommendations for local authorities to optimize flood management, spatial planning, and climate-adaptive infrastructure. Additionally, the methodology offers a transferable framework for similar tropical catchments, contributing to sustainable watershed management and reducing the socioeconomic and environmental impacts of recurrent flooding events.

METHOD

This research adopts a quantitative-descriptive approach within the field of civil and water resources engineering. It analyzes hydrologic behavior and identifies flood hazards in the Cipager River Basin (DAS Cipager) through a synthesis of field observations and secondary data analysis. The study offers a holistic perspective on the cause-and-effect relationships among climatological, morphological, and anthropogenic factors contributing to flood events.

The research was conducted in Cirebon Regency, with the Cipager River as the primary study object. According to data from BBWS, the Cipager watershed covers an area of 67.86 km^2, and the river extends approximately 34.71 km in length. The river's width ranges between 25 and 41 meters, while its depth varies across different segments. This study specifically focused on river sections affected by the flood event that occurred on January 17, 2025.

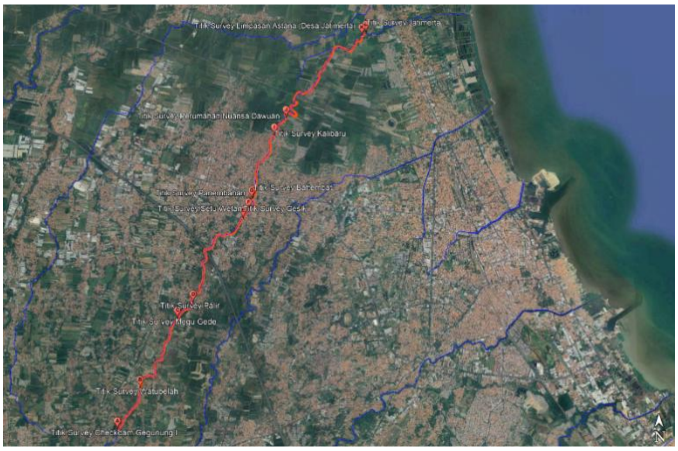

Figure 1. Map of the Cipager River Basin

The research made use of primary and secondary data sources:

a. The rainfall and discharge records were obtained from three hydrological stations: Mandirancan, Cilimus, and Cipager Weir, comprising the annual maximum river discharge and rainfall data.
b. River cross-sectional and land use data were gathered through field surveys to evaluate river morphology, narrowing, sedimentation, and encroachment.
c. Historical flood information was collected, in this instance, for January 2025 flood, such as inundation area, impacted villages, and approximated socio-economic effect. Google Earth and satellite image software were utilized for visual examination of land cover and riverbank change.

The study utilized the procedures outlined below:

a. Document analysis to collect historical and institutional rainfall/discharge data.
b. Field surveys for measurement of river cross-sections manually with measuring rods and tapes at chosen segments.
c. Visual observation to determine sedimentation, riverbank erosion, and existence of informal settlements.
d. Remote sensing for verification of field results through the latest satellite imagery and establishment of river alignment and buffer zone change.

The analysis involved three main steps:

1. Design Rainfall Estimation:

   The four probability distributions were employed to analyze annual maximum rainfall data for the three stations: Gumbel, Log-Pearson Type III, Normal, and Log-Normal

   Return periods (T) of 2, 5, 10, 25, 50, and 100 years were used. Goodness-of-fit was tested to determine model fit for each data set.
2. Design Flood Discharge Estimation:

   Equivalent design flood discharges (Q) were computed from the rainfall analysis using suitable hydrological transformation methods. These were compared with the historical peak discharges to determine capacity exceedance.
3. River Capacity Evaluation:

   Cross-sectional river dimensions were utilized in calculating the flow capacity using the Manning equation:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}$$

where:
Q = discharge (m³/s)
A = flow area (m²)
R = hydraulic radius (A/P)
S = slope
n = Manning roughness coefficient

These capacities were further compared against the corresponding design discharges to identify the segments at risk of overtopping.

4. Validation and Calibration:
   Validations were made with empirical data in the January 2025 flood. Calibration was made with respect to large rainfall anomalies and local observations so that model outputs are consistent with actual events.

RESULTS AND DISCUSSION

Hydrological Characteristics and Physical Constraints of the Cipager River Basin

This study of the Cipager River Basin includes analysis of annual maximum rainfall, return period estimation, discharge modeling, and cross-sectional flow capacity. Rainfall data were collected from three representative stations: UPTD Mandirancan, UPTD Cilimus, and Cipager Weir. Design rainfall values were estimated for return periods ranging from 2 to 100 years using four probability distribution models: Gumbel, Log-Pearson Type III, Normal, and Log-Normal.

Table 1. Comparison of Rainfall Data from Three Stations

Return Period (Years)	**UPTD Mandirancan Station**				**PCH UPTD Cilimus Station**				**Cipager Weir Station**			
	Normal	Gumbel	Log-Normal	Log Pearson III	Normal	Gumbel	Log-Normal	Log Pearson III	Normal	Gumbel	Log-Normal	Log Pearson III
2	57.51	51.10	42.33	70.62	50.17	45.30	38.60	60.16	61.73	56.10	50.69	70.08
5	90.37	85.60	94.75	110.01	75.12	71.50	80.74	91.90	90.59	86.40	93.09	102.32
10	107.54	108.44	144.38	103.92	88.17	88.85	118.74	89.29	105.68	106.47	127.91	103.89
25	125.86	137.30	226.23	78.62	102.08	110.77	179.16	71.66	121.76	131.82	179.51	91.96
50	137.69	158.72	302.38	58.24	111.07	127.03	233.70	56.03	132.16	150.62	223.43	78.79
100	148.33	179.97	392.55	41.04	119.15	143.18	296.80	41.89	141.50	169.29	272.05	65.17

At UPTD Mandirancan, rainfall estimates varied moderately, ranging from 42.33 mm (Log-Normal) to 70.62 mm (Log-Pearson III). The Log-Normal model yielded the lowest value, indicating a conservative bias, while Log-Pearson III produced the highest, reflecting higher sensitivity to short-term events. Gumbel (51.10 mm) and Normal (57.51 mm) offered intermediate and consistent estimates, suggesting their relative stability in representing moderate rainfall conditions. The divergence between models at this site highlights the need for caution, particularly when applying Log-Pearson III for long-term design.

In contrast, UPTD Cilimus exhibited relatively uniform results among the Gumbel (88.85 mm), Log-Pearson III (89.29 mm), and Normal (88.17 mm) models, indicating stable and coherent data behavior. However, the Log-Normal model yielded a significantly higher estimate (118.74 mm), showing greater sensitivity to skewed data distributions. This makes Log-Normal more suitable for conservative design approaches, especially in flood-prone areas, whereas the other models remain appropriate for general-purpose planning.

The Cipager Weir station presents a unique case where Log-Normal, Normal, and Log-Pearson III produced identical estimates (127.91 mm), potentially due to symmetrical rainfall distribution or model convergence under certain statistical conditions. The Gumbel model offered a lower estimate (106.47 mm), suggesting a more tempered approach. Despite this discrepancy, the overall consistency among the three models supports their reliability, while Gumbel remains suitable for infrastructure designs that balance performance with moderate risk.

In summary, the analysis confirms that rainfall estimates are highly dependent on the chosen distribution model, even at shorter return periods. The Log-Normal model consistently produces conservative projections, making it ideal for high-risk infrastructure. Gumbel and Normal models demonstrate stability and moderate outputs, supporting their application in standard hydrological planning. Log-Pearson Type III, however, exhibits location-dependent reliability and should be applied cautiously, particularly where accurate extreme-event modeling is critical.

Beyond hydrological modeling, the Cipager River faces substantial physical and operational constraints that hinder its function, especially during peak rainfall events. These include channel narrowing, excessive sedimentation, and delays in land acquisition along riparian zones—all of which critically impair the river's capacity and increase flood risk.

a. Channel Narrowing

Progressive narrowing of the river channel, primarily due to uncontrolled development and inadequate spatial planning, has significantly reduced the effective cross-sectional area. Encroachment by residential housing, agriculture, and informal structures along the riverbanks restricts flow, elevates flood risk during high-discharge events, and induces backwater effects, particularly in downstream reaches. The constriction also accelerates flow velocity in confined sections, aggravating bank erosion and compromising infrastructure stability.

b. Sedimentation

Sediment deposition—driven by upstream deforestation, poorly managed agriculture, and construction activities—has led to significant aggradation in the Cipager River. Sediment is carried during storm events and accumulates in low-velocity areas such as meanders and near hydraulic structures. This reduces effective channel depth, alters riverbed morphology, and disrupts hydraulic continuity. The sediment build-up not only limits flow conveyance but also obstructs drainage outflows, increasing the vulnerability of surrounding areas to flooding and reducing the efficiency of irrigation and urban stormwater systems.

c. Land Acquisition Constraints

Efforts to acquire land along the riverbanks for normalization and flood control infrastructure are impeded by legal, social, and administrative challenges. Riparian zones that are essential for widening channels, constructing levees, or establishing buffer strips are often occupied or contested, delaying critical interventions. Without secured river corridors, improvement projects face implementation delays or cost escalations due to redesign requirements. Moreover, the absence of continuous green buffers diminishes opportunities for natural infiltration, exacerbating surface runoff and decreasing river resilience.

Hydrologic and Hydraulic Assessment of the Cipager River Using Statistical Models

A comprehensive rainfall analysis was conducted in the Cipager River Basin using maximum daily rainfall data from three key observation stations: UPTD Mandirancan, UPTD Cilimus, and Cipager Weir. To estimate design rainfall depths for return periods of 2, 5, 10, 25, 50, and 100 years, four statistical distribution models—Gumbel, Log-Normal, Normal, and Log-Pearson Type III—were employed. Results show that rainfall depth increases proportionally with return period, in line with probabilistic hydrology principles. The Log-Normal model consistently produced the highest rainfall estimates across all return periods, highlighting its conservative nature, ideal for high-risk infrastructure planning. Conversely, Log-Pearson Type III demonstrated irregular behavior, especially at higher return periods, with a paradoxical decline in estimated values—indicating unreliability for extreme event modeling in the region. Gumbel and Normal models provided more moderate and stable projections, aligning well with general planning needs.These rainfall estimates were then used to calculate design discharges using Manning's equation, which incorporates channel slope, cross-sectional geometry, and roughness coefficients to reflect actual hydraulic capacity.

Table 2. Estimated Design Flood Discharge for the Cipager River

Return Period (years)	Q Gumbel (m^3/s)	Q Normal (m^3/s)	Q Log Normal (m^3/s)	Q Log Pearson III (m^3/s)
2	3,19	2,16	1,33	1,19
5	6,37	4,52	1,69	3,10
10	8,47	5,75	1,92	5,53
25	11,13	7,07	2,20	11,08
50	13,11	7,92	2,40	18,31
100	15,06	8,69	2,59	30,01

Discharges corresponding to each statistical rainfall model were computed for comparative evaluation. At short return periods (2–10 years), discharges from all models remained within the existing infrastructure's operational capacity. However, for 25-year return periods and beyond, sharp divergence emerged—especially under the Log-Pearson III and Log-Normal models. The Log-Pearson III model produced the highest discharge at 100 years (30.01 m^3/s), reflecting extreme sensitivity to skewed data, while Log-Normal provided lower but consistently rising values. The Gumbel method showed a steady increase in discharge (from 3.19 m^3/s at 2 years to 15.06 m^3/s at 100 years), and the Normal model followed a similar pattern with slightly lower values (2.16–8.69 m^3/s). These differences underscore the importance of aligning the model choice with both the statistical nature of local rainfall data and the objectives of infrastructure design.

Table 3. Discharge Estimation Using Manning's Equation Across River Segments

Location	Water Depth (m)	Channel Bottom Width (m)	Side Slope (z)	Channel Slope (m/m)	Elevation Difference (m)	Channel Length (km)	Channel Length (m)	Cross-Sectional Area (A) (m^2)	Wetted Perimeter (P) (m)	Hydraulic Radius (R) (m)	Manning's Roughness Coefficient (n)	Discharge (Q) (m^3/s)
Checkdam Gegunung I	0,5	18	6,92	0,001671	58	34,71	34.710	10,73	31,98985262	0,34	0,035	6,05
Watubelah	0,8	25	7,14	0,001239	43	34,71	34.710	24,57	53,85006985	0,46	0,037	13,85
Megu Gede	0,2	18	6,92	0,001037	36	34,71	34.710	3,88	59,96955786	0,06	0,036	0,56
Palir	0,7	22	5,50	0,000922	32	34,71	34.710	18,10	66,72135955	0,27	0,036	6,39
Gesik	1,3	21	6,00	0,000490	17	34,71	34.710	37,44	81,8276253	0,46	0,040	12,30
Setu Wetan	1,3	21	6,00	0,000432	15	34,71	34.710	37,44	93,99315036	0,40	0,045	9,36
Panembahan	1,3	20	10,00	0,000461	16	34,71	34.710	42,90	160,6982587	0,27	0,038	10,05
Battembat	1,5	20	10,00	0,000461	16	34,71	34.710	52,50	180,7980099	0,29	0,036	13,73

Location	Water Depth (m)	Channel Bottom Width (m)	Side Slope (z)	Channel Slope (m/m)	Elevation Difference (m)	Channel Length (km)	Channel Length (m)	Cross-Sectional Area (A) (m²)	Wetted Perimeter (P) (m)	Hydraulic Radius (R) (m)	Manning's Roughness Coefficient (n)	Discharge (Q) (m³/s)
Kalibaru	1,4	15	3,19	0,000288	10	34,71	34.710	27,26	75,20079574	0,36	0,037	6,36
Nuansa Dawuan	1,5	9	1,91	0,000173	6	34,71	34.710	17,81	52,20563651	0,34	0,040	2,86
Astana	0,6	15	6,52	0,000144	5	34,71	34.710	11,35	160,1551285	0,07	0,045	0,52
Jatimerta	0,6	15	6,52	0,000202	7	34,71	34.710	11,35	173,3510493	0,07	0,040	0,65

Hydraulic analysis using Manning's equation across multiple river segments revealed significant variation in channel flow capacity. Segments such as Watubelah (13.85 m³/s) and Battembat (13.73 m³/s) demonstrated relatively high discharge capacities due to favorable geometry and slope, while Megu Gede, Astana, and Jatimerta exhibited critically low capacities, below 1 m³/s, due to shallow flow depths and high wetted perimeters. Several other locations, including Nuansa Dawuan and Kalibaru, showed moderate capacity but remained inadequate when compared to discharges derived from high-return-period rainfall events. These disparities point to the structural limitations of the river in its current state.

Crucially, the comparison between design discharge projections and actual channel capacity confirms that many river segments—especially in the downstream reaches—are incapable of safely conveying flood flows associated with return periods beyond 10 years. Factors such as sedimentation, channel narrowing, and unregulated development further diminish effective flow area, exacerbating flood risks. This mismatch between expected hydrologic loads and physical capacity was evidenced during the flood events of January 2025, which severely impacted subdistricts such as Weru, Tengahtani, and Gunung Jati.

In conclusion, the integration of rainfall frequency analysis and hydraulic modeling reveals a critical vulnerability in the Cipager River system. The Log-Normal model, due to its conservative estimates, should be prioritized for flood-control infrastructure. Gumbel and Normal remain reliable for standard planning. The erratic performance of Log-Pearson Type III renders it unsuitable for high-return-period design. To address current and future flood risks, urgent river normalization, sediment control, and structural improvement efforts are necessary to restore alignment between projected discharge loads and actual channel capacity.

Design Discharge vs. River Capacity: A Case Study of the Cipager River

In the Cipager River Basin, the interaction between rainfall intensity, river discharge, flood discharge, design discharge, and river storage capacity forms a critical framework for understanding and managing flood risk. Rainfall serves as the primary hydrological input, and its magnitude directly influences river discharge. When intense rainfall occurs—particularly during short durations—it leads to rapid surface runoff, significantly increasing river discharge. Design discharge, which represents the peak flow expected for a given return period, is estimated using statistical rainfall models such as Gumbel, Log-Normal, Normal, and Log-Pearson Type III. These models provide different projections based on their sensitivity to extreme values. The Log-Normal model consistently delivers conservative, higher estimates suitable for high-risk infrastructure, while the Gumbel and Normal models produce more moderate and stable values. Conversely, Log-Pearson Type III exhibits erratic behavior, particularly at higher return periods, and is thus unreliable in some contexts.

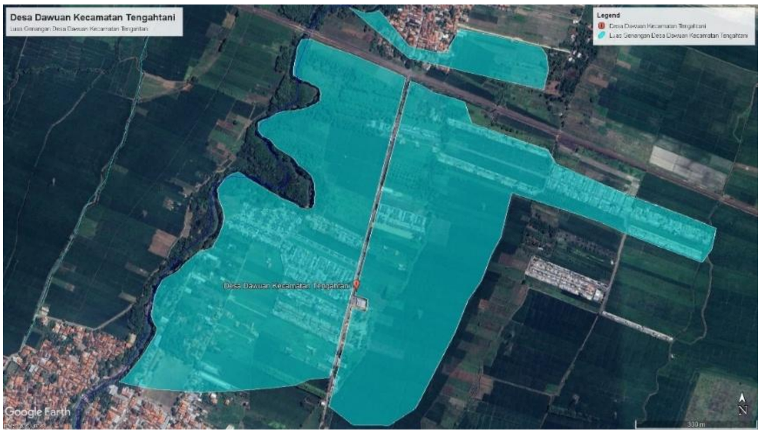

Figure 2. Flood Inundation Area in Dawuan Village, January 17th 2025

When design discharge exceeds the river's storage and conveyance capacity, flooding becomes inevitable. The hydraulic analysis of the Cipager River using Manning's equation shows that many segments—particularly those with shallow depths and high wetted perimeters—are unable to handle discharges associated with 25-year or greater return periods. Physical constraints such as channel narrowing, sedimentation, and delayed land acquisition for riverbank development further reduce the river's capacity to safely transport peak flows. The January 2025 flood events clearly exemplify this mismatch between design discharge and actual channel capacity that severely impacted several subdistricts, including Weru, Tengahtani, and Gunung Jati.

To mitigate rising discharge and flood risks, several strategies must be implemented. These include river normalization through channel widening and dredging, sediment control via upstream watershed rehabilitation, and enforcement of river corridor zoning to allow for structural improvements such as levees and retention basins. Where land constraints exist, flood detention ponds and improved drainage infrastructure should be considered. Additionally, adopting conservative rainfall models (e.g., Log-Normal) for infrastructure design ensures resilience under future climate variability. Early warning systems based on real-time rainfall and flow monitoring can also enhance community preparedness. Ultimately, aligning hydrological estimates with the river's physical capacity is essential to building a flood-resilient watershed system.

DISCUSSION

This study presents a detailed hydrological and hydraulic assessment of the Cipager River Basin, emphasizing the interaction between extreme rainfall events, statistical discharge modeling, and physical constraints along the river channel. Using rainfall data from UPTD Mandirancan, UPTD Cilimus, and Cipager Weir, design rainfall intensities were estimated for return periods of 2 to 100 years using four statistical distributions: Gumbel, Log-Normal, Normal, and Log-Pearson Type III.

The results show that rainfall depth generally increases with return period. Among the models, the Log-Normal distribution consistently yielded the highest rainfall estimates, supporting its use in conservative flood infrastructure design. In contrast, the Log-Pearson III model demonstrated anomalous behavior—such as decreasing values at higher return periods—raising concerns over its reliability for extreme event estimation. Gumbel and Normal models provided stable, intermediate results, aligning with general hydrological design standards.

When translated into design discharge using Manning's equation, these rainfall estimates revealed critical discrepancies between projected flood flows and actual river capacity. While segments such as Watubelah (13.85 m^3/s) and Battembat (13.73 m^3/s) exhibited higher conveyance capacity, most others—including Megu Gede, Astana, and Jatimerta—were critically undersized (below 1 m³/s). Discharges associated with return periods beyond 10 years, particularly from Log-Normal and Log-Pearson III, exceeded the hydraulic capacity of most river segments. This misalignment significantly increases the risk of overtopping and flooding, particularly during high-intensity storms.

This mismatch is further compounded by anthropogenic factors. Field observations revealed widespread physical constraints: channel narrowing due to informal settlements and agricultural encroachment, sedimentation from upstream erosion, and delays in land acquisition for flood infrastructure. These constraints not only reduce effective flow area but also disrupt hydraulic continuity, aggravating backwater effects and erosion.

The January 2025 flood event provides empirical validation, wherein high-intensity rainfall led to extensive inundation in Weru, Tengahtani, and Gunung Jati. GIS-based flood mapping of Dawuan Village, for instance, confirmed widespread overflow caused by peak discharges that surpassed the designed conveyance capacity of the river.

This aligns with Handayani et al. (2022), who demonstrated that a 30% increase in urban land cover—paired with vegetation loss—amplified peak discharge and runoff in West Java. Other studies support these findings: Hidayat (2022) identified sediment accumulation as a major factor limiting flow capacity, Tarigan et al. (2018) emphasized the role of land-use change in altering hydrological responses, and Sulistiyowati (2020) noted that the absence of green buffers weakens natural flood attenuation. Ardiansyah et al. (2023) further highlighted the combined effects of climate change and land-use transformation in expanding flood-prone zones.

Although Government Regulation No. 38/2011 mandates a 10-meter riparian buffer and Ministerial Regulation No. 28/PRT/M/2015 defines legal river boundaries, enforcement remains weak. Settlements continue to encroach upon floodplains, undermining river normalization efforts and increasing the exposure of built environments to flood hazards.

To mitigate these risks, a multi-pronged approach is essential. Structural measures such as river normalization (e.g., widening and dredging), sediment control through upstream reforestation, and construction of retention basins must be prioritized. These should be complemented by non-structural interventions, including enforcement of spatial planning laws, integrated watershed management, and implementation of real-time hydrological monitoring and early warning systems.

This study advances existing literature by quantitatively linking rainfall frequency analysis with physical river capacity, demonstrating the urgency of aligning design discharges with actual conveyance capabilities. Future work should integrate climate projections to enhance infrastructure resilience and support evidence-based policy development.

In conclusion, the Cipager River Basin's flood vulnerability is a consequence of both natural extremes and compounded anthropogenic pressures. Addressing these requires harmonizing hydrological modeling, spatial planning, and structural interventions to build a climate-resilient and flood-safe watershed.

CONCLUSION

This study demonstrates that flood vulnerability in the *Cipager River* Basin results from the combined effects of hydrometeorological extremes and anthropogenic pressures. Rainfall frequency analysis across Gumbel, Log-Normal, Normal, and Log-Pearson Type III models reveals substantial variability, with the Log-Normal model offering conservative estimates ideal for high-risk infrastructure planning. Discrepancies between projected peak flows and actual river conveyance capacities highlight critical structural inadequacies worsened by sedimentation, channel narrowing, and land-use constraints. The January 2025 flood event validates these findings, emphasizing the insufficiency of existing infrastructure and the urgent need for integrated flood management strategies that combine structural measures—such as river normalization and flood retention facilities—with non-structural approaches including riparian buffer protection, watershed governance, and early warning systems. By assessing segment-specific flood risk and translating statistical rainfall analysis into actionable hydraulic evaluation, this study provides a transferable framework for managing tropical watersheds adaptively and data-driven. Future research should integrate climate projections, real-time monitoring, and socio-environmental indicators to further enhance resilience against evolving hydrological threats.

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