

Risk Analysis of Water-Related Hazards in the Batang Merao Watershed, Jambi

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ABSTRACT

Sungai Penuh City, located in the Batang Merao Watershed, Jambi Province, faces increasingly severe flooding, exemplified by the January 2024 event that inundated over 2,945 ha with depths of 0.5–1.5 m. This study assesses water-related hazard risk by integrating HEC-HMS/HEC-RAS hydrological-hydraulic modeling, multi-variable GIS spatial analysis, and the BNPB Risk Triangle framework. Design rainfall was derived using the GEV distribution from nine stations (2001–2023), yielding Q25 peak discharges of ~220 m³/s upstream and 2,300 m³/s downstream. Two-dimensional HEC-RAS simulation and BNPB-based indices (Peraturan Kepala BNPB No. 02/2012) show seven of eight districts classified as HIGH hazard (18,569 ha), with vulnerability and capacity both LOW. Combining these components yields an overall MODERATE risk level, with 3,271 ha classified as high risk and estimated economic losses of IDR 26.906 billion. Structural mitigation through Batang Merao River normalization could reduce hazard from HIGH to MODERATE, cutting population exposure by 72% (8,640 to 2,419 persons/km²) and property losses from IDR 24.657 billion to IDR 6.904 billion. Policy recommendations span three horizons: short-term (early warning systems, sediment dredging, Destana), medium-term (river normalization, retention ponds, Danau Kerinci revitalization), and long-term (a Flood-Resilient City based on Smart Water Management).

INTRODUCTION

Flooding is one of the most destructive natural hazards worldwide, affecting millions of people and causing substantial economic losses each year (Farid et al., 2017; Gunawan et al., 2025; Kardhana et al., 2022). According to the Organisation for Economic Co-operation and Development (OECD), flood-related losses have exhibited a consistent upward trend since 1970 (Awah et al., 2024). In Indonesia, floods account for nearly 32% of all recorded disaster events, making them a national priority for disaster risk management (Rahayu et al., 2023). This situation

has been further exacerbated by watershed degradation resulting from land-use change and the intensification of anthropogenic activities.

Sungai Penuh City, located within the Batang Merao Sub-watershed of the Batanghari River Basin, Jambi Province, is one of the most flood-prone regions in Sumatra. The Batang Merao River flows through Kerinci Regency and Sungai Penuh City over a total length of approximately 66 km, originating in Taman Nasional Kerinci Seblat (TNKS) and discharging into Danau Kerinci (Ningsih et al., 2020). In January 2024, a major flood inundated approximately 2,945 ha of Sungai Penuh City – an increase from 650 ha in 2016 – and forced 2,942 people from 1,138 households to evacuate (Firmana et al., 2026; Putra et al., 2022).

The Batang Merao Watershed experiences a tropical humid climate, with the rainy season generally extending from October to March and average annual rainfall ranging from 2,200 to 3,500 mm. An extreme rainfall event reaching 141 mm/day was recorded between 26 and 31 December 2023, triggering the catastrophic flood that inundated Sungai Penuh City throughout January 2024. Historical records reported by Firmana et al. (2026) indicate that the inundated area increased from 85 ha in 2016 to 96 ha in 2017, 82 ha in 2018, 93 ha in 2022, 113 ha in 2023, and 2,945 ha in 2024, highlighting a dramatic escalation in flood severity over the past decade.

The flood-generating factors within the Batang Merao Watershed can be classified into two categories. Natural factors include: (1) extreme rainfall during the wet season (October–March), reaching up to 141 mm/day; (2) mountainous terrain with elevations ranging from 500 to 3,805 m above sea level, resulting in rapid flow concentration; and (3) the watershed's soil and geological characteristics. Anthropogenic factors include: (1) the conversion of forests into agricultural land and residential areas, leading to increased surface runoff; (2) the expansion of residential areas, which reduces infiltration capacity; (3) vegetation loss, resulting in decreased rainfall interception; and (4) upstream sand mining activities that accelerate sedimentation and reduce the river's conveyance capacity (Mandasari, 2020; Isma et al., 2024).

Table 1. Spatial Planning Zones within the Floodplain Area of Sungai Penuh City

No	Spatial Planning Zone	Hampanan Rawang	Koto Baru	Kumun Debai	Pesisir Bukit	Pondok Tinggi	Sungai Bungkal	Sungai Penuh	Tanah Kampung	Total	Percentage
1	Road	7.73	0.00	0.23	0	2.16	0	1.92	4.77	16.8	0.90%
2	River	12.99	0.00	8.28	0	1.69	0	3.07	14.35	40.39	2.16%
3	Healthcare Zone	0.27	0.00	0	0	0	0	0	0	0.27	0.01%
4	Educational Zone	1.91	0.00	0	0	0	0	0	0.46	2.37	0.13%
5	Commercial and Service Zone	2.11	0.00	0	0	0.53	0	0.01	1.15	3.79	0.20%
6	Government Office Zone	0.00	0.00	0	0	0.01	0	0	0	0.01	0.00%

7	Wet Agricultural Land Zone Low-Density	748.14	2.57	26.74	0	193.01	3.23	157.41	329.87	1460.97	78.15%
8	Residential Zone Medium- Density	40.67	0.00	0.00	0.02	0	0	0	15.38	56.07	3.00%
9	Residential Zone Zona Perumahan Kepadatan	37.46	0.00	0.00	0	2.1	0	9.81	17.61	66.98	3.58%
10	High-Density Residential Zone Green Open Space (GOS)	96.09	0.00	0.50	0	0	0	0	6.91	103.49	5.54%
11	Zone Zona	27.10	0.00	10.57	0	21.33	0	10.18	34.15	103.33	5.53%
12	Transportation Zone	0.00	0.00	0.00	0	0	0	0.71	0	0.71	0.04%
13	Tourism Zone	0.00	0.00	0.00	0	14.34	0	0	0	14.34	0.77%
14	Total	974.45	2.57	46.32	0.02	235.16	3.23	183.11	424.66	1869.52	100.00%
15	Percentage	52.12%	0.14%	2.48%	0.00%	12.58%	17.00%	9.79%	22.71%	100%	

Source: Putra R. et al.. Delineation and Evaluation of Land Use and Spatial Planning in the Floodplain of Sungai Penuh City. 2022

Flood disaster risk assessment provides a fundamental basis for formulating comprehensive disaster risk management policies. The disaster risk assessment framework adopted by Badan Nasional Penanggulangan Bencana (BNPB) through Peraturan Kepala BNPB Nomor 02 Tahun 2012 defines disaster risk using the Risk Triangle approach:

$$\text{Risk} = f(\text{Hazard, Vulnerability, Capacity}) \quad (1)$$

According to the World Risk Report 2024, Indonesia ranks second among 193 countries with the highest disaster risk worldwide (BNPB, 2025).

Hydrological and hydraulic modeling using HEC-HMS and HEC-RAS has proven to be an effective foundation for flood risk assessment across various regions of Indonesia (Ansori, 2023; Mustamin et al., 2024; Supratman et al., 2024; El-Bagoury et al., 2024). However, existing studies specific to the Batang Merao Watershed remain limited in scope. Firmana et al. (2026) examined flood inundation patterns in Hamparan Rawang District, but their analysis was confined to a single sub-district and did not extend to hydraulic-based hazard mapping, vulnerability assessment, or risk quantification across the entire watershed. Putra et al. (2022) analyzed land-

use and spatial planning conditions within the Sungai Penuh floodplain, providing valuable insight into exposure patterns, but did not incorporate hydrological-hydraulic simulation or a formal disaster risk assessment framework. More broadly, Mustamin et al. (2024) demonstrated the effectiveness of integrating HEC-RAS and GIS for flood forecasting and early warning system design in the Gilireng Watershed; however, this and other comparable studies typically address only isolated components of flood risk—either hydraulic simulation, hazard mapping, or land-use analysis—without combining them with vulnerability, capacity, and economic loss assessment, let alone evaluating structural mitigation options within a unified decision-support framework.

This study aims to: (1) analyze flood hazards through HEC-HMS and HEC-RAS modeling using GEV-based design rainfall as input; (2) develop GIS-based, multi-variable flood hazard, vulnerability, and capacity maps; (3) produce comprehensive water-related hazard risk maps and risk matrices for Sungai Penuh City; (4) estimate the associated economic and physical losses; and (5) formulate structural mitigation scenarios and integrated flood disaster management policy recommendations for the short, medium, and long term.

Unlike previous studies that focused only on flood inundation modelling or land-use analysis, this study integrates hydrological modelling, hydraulic simulation, GIS-based multi-index vulnerability assessment, BNPB Risk Triangle analysis, economic loss estimation, and structural mitigation evaluation into a unified flood risk assessment framework. This integrated approach represents the principal novelty of the present study relative to Firmana et al. (2026), Putra et al. (2022), and Mustamin et al. (2024), offering a more comprehensive and decision-relevant basis for flood risk management in the Batang Merao Watershed.

METHODS

Study Area

The Batang Merao Watershed is located within Kerinci Regency and Sungai Penuh City, Jambi Province, Indonesia, as part of the Batanghari River Basin (Wilayah Sungai). The watershed covers approximately 680 km², with elevations ranging from 500 to 3,805 m above sea level. The upstream area is characterized by steep mountainous terrain that is highly susceptible to erosion, whereas the downstream area consists of relatively flat topography that functions as a flood accumulation zone, particularly within Sungai Penuh City, which is directly adjacent to Danau Kerinci. The Batang Merao River extends for approximately 66 km, while the upstream watershed is dominated by slopes exceeding 30°. The study area is presented in Figure 1.

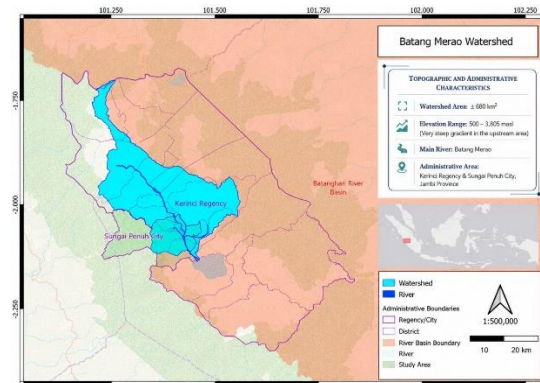


Figure 1. Study Area of the Batang Merao Watershed, Sungai Penuh City, Jambi Province, Indonesia.

The Batang Merao Watershed experiences a tropical humid climate, with the rainy season generally occurring from October to March. Annual rainfall ranges from approximately 2,200 to 3,500 mm. Extreme rainfall reaching 141 mm/day was recorded between 26 and 31 December 2023, triggering the severe flood event that inundated Sungai Penuh City throughout January 2024. Historical records reported by Firmana et al. (2026) indicate that the inundated area increased from 85 ha in 2016 to 96 ha in 2017, 82 ha in 2018, 93 ha in 2022, 113 ha in 2023, and 2,945 ha in 2024, demonstrating a substantial escalation in flood hazard over the past decade.

Data and Data Sources

This study integrates remote sensing, hydrological, topographic, and socio-economic datasets to support hydrological modeling, hydraulic simulation, and flood risk assessment. The datasets employed are summarized in Table 2.

Table 2. Data Sources

Data	Source
2025 Land Cover	Sentinel-2 satellite imagery (10 m spatial resolution)
Digital Elevation Model (DEM)	Badan Informasi Geospasial (BIG)
Rupa Bumi Indonesia (RBI) Map	Badan Informasi Geospasial (BIG)
Rainfall Data (2001–2023)	Balai Wilayah Sungai (BWS) Sumatra VI and BMKG Kerinci Meteorological Station
GPM IMERG Satellite Rainfall	NASA and JAXA
Soil Type	FAO
Population Density	WorldPop

Spatial datasets used for flood vulnerability assessment included the productive crop index, building physical index, population density index, and environmental index. These datasets were processed and integrated using a Geographic Information System (GIS) to develop hazard, vulnerability, and risk maps.

To provide an overview of the overall research workflow, Figure 2 illustrates the integrated methodological framework adopted in this study.

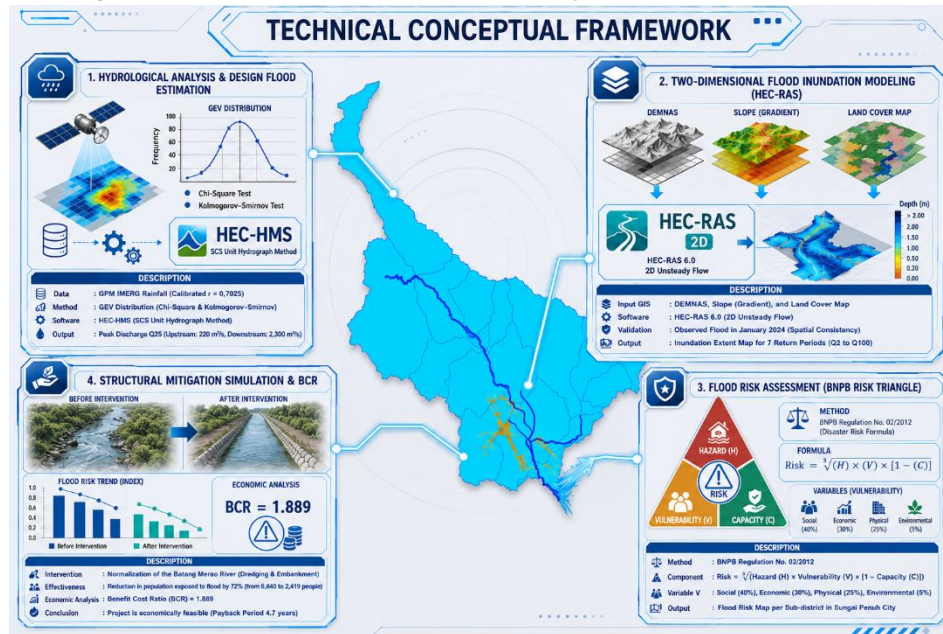


Figure 2. Overall Research Framework.

Rainfall Frequency Analysis and Design Flood Estimation

Rainfall frequency analysis was conducted using annual maximum daily rainfall records from nine rainfall stations. GPM IMERG satellite rainfall data were calibrated against observed rainfall using the Pearson correlation coefficient ($r = 0.7025$ at the Siulak Deras station). The statistical suitability of the probability distributions was evaluated using the Chi-square and Kolmogorov–Smirnov goodness-of-fit tests. The General Extreme Value (GEV) distribution was selected because it provided the best statistical performance compared with the Gumbel, Log-Normal, and Log-Pearson Type III distributions (Hosking & Wallis, 1997).

Design flood hydrographs were simulated using HEC-HMS based on the SCS Unit Hydrograph method (USACE, 2016). Curve Number (CN) values were derived from the overlay of land-cover data, Hydrologic Soil Group (HSG) maps, and sub-watershed boundaries in QGIS. Design hydrographs were generated for seven return periods (Q2–Q100), producing peak discharges of approximately 220 m³/s in the upstream reach and 2,300 m³/s at the downstream watershed outlet for the 25-year return period (Q25). Similar methodologies have been successfully applied in several Indonesian watersheds (Mustamin et al., 2024; Ridwan & Baskoro, 2025).

Two-Dimensional Flood Inundation Modeling

Flood inundation was simulated using HEC-RAS 6.0 with DEMNAS as the primary terrain dataset. Four spatial datasets were prepared before hydraulic modeling: (1) the BMKG

Flood Hazard Zonation Map; (2) the Q25 flood hazard map generated using HEC-RAS; (3) the DEMNAS elevation map; and (4) the slope map. These datasets were processed within a GIS environment prior to model implementation.

The upstream boundary condition was defined using the Q25 design flood hydrograph, whereas the downstream boundary adopted a normal-depth flow condition. Model performance was evaluated using the observed inundation extent from the January 2024 flood event, demonstrating good spatial agreement between simulated and observed flood extents (Sari et al., 2025; Gunawan et al., 2025).

GIS-Based Flood Risk Assessment

Flood risk assessment followed the Risk Triangle framework adopted by Badan Nasional Penanggulangan Bencana (BNPB) through Peraturan Kepala BNPB Nomor 02 Tahun 2012. Disaster risk was evaluated using the following formulation:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Exposure} \quad (2)$$

Following the BNPB framework, disaster risk was also expressed as:

$$\text{Risk} = \sqrt[3]{[\text{Hazard} \times \text{Vulnerability} \times (1 - \text{Capacity})]} \quad (3)$$

The hazard index was derived from two components: (1) the BMKG/PUPR Flood Hazard Zonation Map and (2) flood depth obtained from the HEC-RAS Q25 simulation. Flood depths were classified according to the BNPB guideline into low (<0.76 m; score = 0.333), moderate (0.76–1.50 m; score = 0.667), and high (>1.50 m; score = 1.000).

The vulnerability index was calculated as a weighted combination of four dimensions: social (40%), economic (30%), physical (25%), and environmental (5%). Each dimension consisted of specific indicators and classification criteria. The capacity index was assessed through multi-stakeholder Focus Group Discussions (FGDs) covering five dimensions: institutional and regulatory capacity, early warning systems and risk assessment, disaster education, infrastructure-based risk reduction, and government preparedness (BNPB, 2012).

Economic Loss Estimation

Economic losses were estimated based on the economic value of inundated land and affected buildings. Unit values were assumed as IDR 5,000/m² for paddy fields, IDR 3,000/m² for dry agricultural land, and IDR 2,000/m² for vegetation to estimate productive land losses. Physical losses were estimated using a replacement value of IDR 2,000,000/m² for residential buildings. Loss categories (low, moderate, and high) were determined according to the BNPB loss assessment matrix, which relates hazard intensity to the corresponding loss index.

RESULT AND DISCUSSION

Design Rainfall and Design Flood

Rainfall frequency analysis identified the General Extreme Value (GEV) distribution as the most appropriate probability model for estimating design rainfall in the Batang Merao Watershed. The distribution was selected based on its superior performance in the Chi-square and Kolmogorov-Smirnov goodness-of-fit tests compared with the Gumbel, Log-Normal, and Log-Pearson Type III distributions. Furthermore, calibration of GPM IMERG satellite rainfall against observations at the Siulak Deras rainfall station produced a Pearson correlation coefficient of $r = 0.7025$, indicating that the satellite-derived rainfall data provide reliable supplementary information for hydrological modelling.

The estimated design rainfall for different return periods is presented in Table 3. As expected, the design rainfall increased progressively with increasing return period, ranging from 81.15 mm for the 2-year return period to 156.52 mm for the 100-year return period. This trend reflects the increasing probability of more extreme rainfall events associated with lower occurrence frequencies.

Table 3. Design Rainfall Analysis of the Batang Merao Watershed Using the General Extreme Value (GEV) Distribution

Return Period (Years)	Design Rainfall (mm)	Annual Exceedance Probability
2	81.15	0.500
5	98.39	0.200
10	110.63	0.100
20	123.25	0.050
25	127.48	0.040
50	141.32	0.020
100	156.52	0.010

Among these rainfall scenarios, the 25-year return period (Q25), corresponding to a design rainfall of 127.48 mm and an annual exceedance probability of 4%, was selected as the design event for subsequent hydraulic modelling. The Q25 event was adopted because it represents the design standard commonly applied for flood-control infrastructure in Indonesia and provides an appropriate balance between engineering safety and economic feasibility.

The selected design rainfall was subsequently used as input for hydrological simulation using HEC-HMS with the SCS Unit Hydrograph method. The simulated design hydrograph is presented in Figure 3.

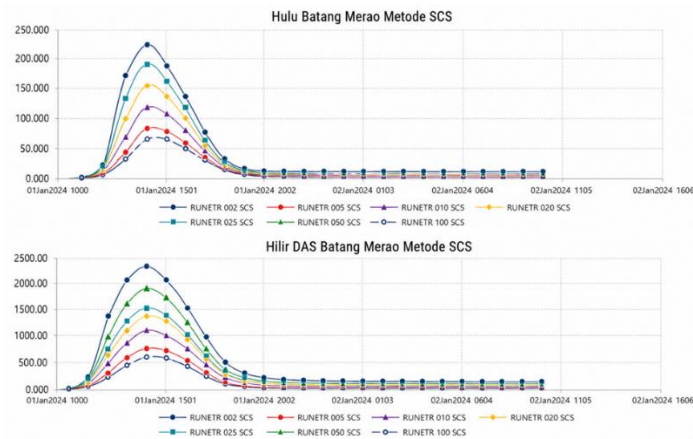


Figure 3. Design Flood Hydrograph Generated by HEC-HMS

The HEC-HMS simulation produced a peak discharge of approximately 220 m³/s in the upstream Batang Merao Sub-watershed and approximately 2,300 m³/s at the downstream watershed outlet. These simulated peak discharges substantially exceed the estimated conveyance capacity of the existing river channel, which is approximately 250–300 m³/s based on the current channel geometry. Consequently, the existing river system is unable to accommodate a Q25 flood event without overtopping, thereby increasing the likelihood of widespread inundation within Sungai Penuh City.

The simulated hydrograph also exhibits a steep rising limb with a time to peak of less than 6 h, indicating a rapid hydrological response to intense rainfall. This response is primarily attributed to the steep topographic gradients in the upstream watershed, which accelerate runoff concentration and significantly shorten flood travel time. From a flood management perspective, this hydrological behaviour considerably limits the available lead time for emergency response, emphasizing the importance of implementing an effective real-time flood forecasting and early warning system throughout the Batang Merao Watershed.

Overall, the hydrological analysis confirms that extreme rainfall events can rapidly generate large flood discharges that exceed the conveyance capacity of the existing river channel. These results provide the hydrological basis for the subsequent two-dimensional hydraulic simulation and spatial flood hazard assessment presented in the following section.

Flood Hazard Assessment

Flood hazard assessment was conducted by integrating the BMKG flood-prone zoning map with the two-dimensional HEC-RAS flood inundation simulation generated for the Q25 design flood. In addition to the simulated inundation depth, supporting spatial variables, including elevation and land slope, were incorporated to improve the representation of flood propagation and inundation characteristics across Sungai Penuh City. Elevation within the study

area ranges from 178 to 2,405 m above sea level, while land slopes vary between 0° and 66°, both of which strongly influence the direction, velocity, and accumulation of overland flow.

Flood hazard classes were determined according to inundation depth following the classification adopted by BNPB, BMKG, and the Ministry of Public Works. The corresponding hazard scores are presented in Table 4.

Table 4. Flood Hazard Classification Based on Inundation Depth

Inundation Depth (m)	Hazard Class	Score
< 0.76	Low	0.333
0.76–1.50	Moderate	0.667
> 1.50	High	1.000

The resulting flood hazard map is presented in Figure 4.

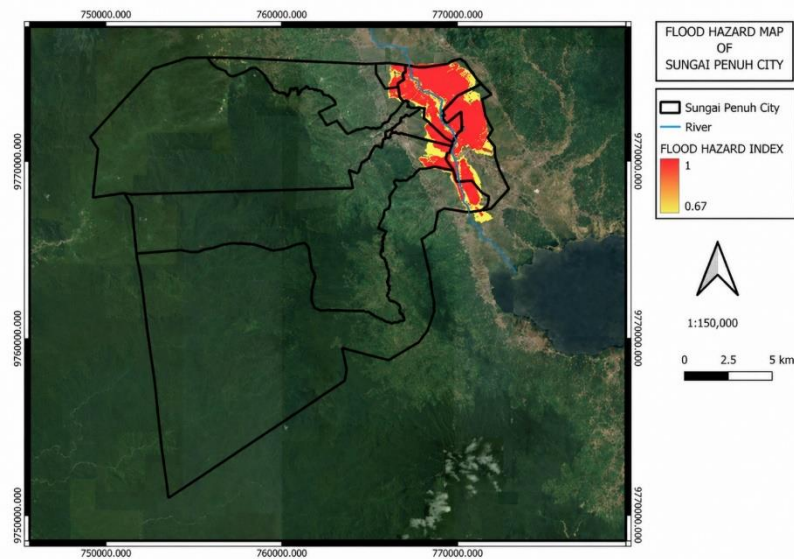


Figure 4. Flood Hazard Map of Sungai Penuh City

The spatial analysis indicates that seven of the eight sub-districts within Sungai Penuh City fall into the HIGH flood hazard category, with a cumulative high-hazard area of approximately 18,569 ha. Only Sungai Bungkal Sub-district is classified as MODERATE, primarily because of its relatively higher elevation and considerably lower population density compared with the remaining sub-districts.

The distribution of flood hazard by sub-district is summarized in Table 5.

Table 5. Flood Hazard Distribution by Sub-district in Sungai Penuh City

Sub-district	Moderate (ha)	High (ha)	Hazard Class
Sungai Penuh	267.40	782.50	HIGH
Pesisir Bukit	143.40	239.70	HIGH
Hamparan Rawang	1,836.80	8,332.40	HIGH

Tanah Kampung	1,818.00	6,046.40	HIGH
Kumun Debai	809.40	1,356.00	HIGH
Pondok Tinggi	800.80	1,219.50	HIGH
Koto Baru	272.50	592.50	HIGH
Sungai Bungkal	35.90	0.10	MODERATE
TOTAL	5,984.00	18,569.00	HIGH

Among all administrative areas, Hamparan Rawang exhibits the highest flood hazard, with approximately 8,332.40 ha classified as high hazard and an exposed population density of 4,643 persons/km². Similarly, Tanah Kampung contains approximately 6,046.40 ha of high-hazard area with an exposed population density of 1,682 persons/km². These areas are located within the downstream floodplain where low topographic gradients promote prolonged water accumulation during extreme flood events. In contrast, the relatively elevated terrain in Sungai Bungkal limits flood depth and inundation extent despite experiencing similar regional rainfall conditions.

The predominance of high-hazard zones throughout Sungai Penuh City reflects the combined effects of intense design rainfall, rapid runoff concentration from the steep upstream catchment, limited river conveyance capacity, and extensive low-lying floodplain areas downstream. Similar spatial patterns have been reported in previous flood modelling studies employing integrated HEC-HMS, HEC-RAS, and GIS approaches in Indonesian watersheds, where watershed morphology and land-use characteristics strongly controlled the spatial distribution of flood hazards (Mustamin et al., 2024; Gunawan et al., 2025; Supratman et al., 2024). Consequently, structural interventions alone may not be sufficient to eliminate flood hazards, highlighting the need for integrated watershed management that combines river improvement, land-use planning, and non-structural flood mitigation measures.

Flood Vulnerability Assessment

Flood vulnerability was assessed by integrating four principal components, namely the social, economic, physical, and environmental vulnerability indices, following the weighting scheme prescribed in the BNPB disaster risk assessment framework. The composite vulnerability index was generated through GIS-based spatial overlay, enabling the identification of areas where flood impacts are likely to be amplified by socioeconomic and environmental conditions.

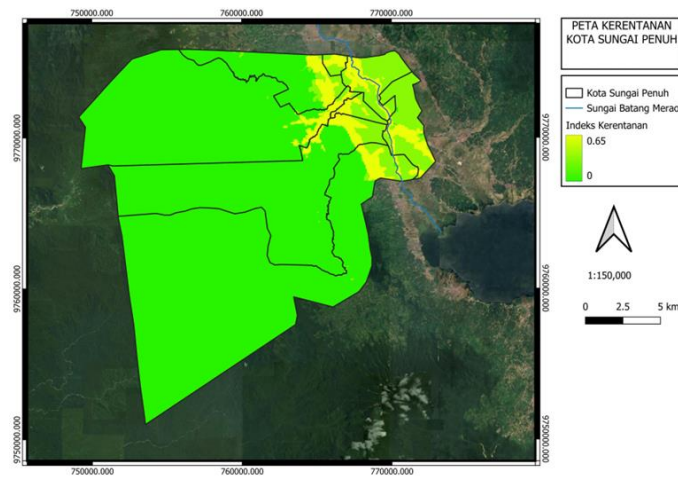


Figure 5. Flood Vulnerability Map of Sungai Penuh City

The spatial analysis indicates that the overall flood vulnerability of Sungai Penuh City is generally LOW, with approximately 38,297 ha classified within the low-vulnerability category. This finding suggests that although the study area is exposed to substantial flood hazards, its intrinsic vulnerability remains relatively moderate because of the distribution of land use, population characteristics, and environmental conditions. Nevertheless, localized areas with higher concentrations of settlements and productive land exhibit relatively greater vulnerability owing to their higher potential for physical damage and economic disruption.

The social vulnerability component was primarily influenced by population density and the spatial distribution of residents within flood-prone areas. Sub-districts with densely populated residential zones, particularly Hamparan Rawang, Sungai Penuh, and Tanah Kampung, exhibited relatively higher social vulnerability because a larger number of people are directly exposed during flood events. Conversely, areas with lower population densities demonstrated reduced social vulnerability despite experiencing similar flood depths.

Economic vulnerability was dominated by the extensive distribution of productive agricultural land across the floodplain. As indicated in the land-use analysis presented earlier, irrigated rice fields constitute the largest proportion of land use within the inundation area. Consequently, flooding not only disrupts residential activities but also threatens agricultural productivity and local livelihoods. This finding highlights the importance of incorporating agricultural resilience into flood management strategies, particularly in downstream floodplain areas where agricultural activities remain the primary source of household income.

Physical vulnerability reflects the distribution of residential buildings, public facilities, transportation infrastructure, and other built assets. Areas with dense residential development experience substantially greater potential losses because flood damage directly affects housing, roads, educational facilities, and public services. Environmental vulnerability, although assigned the lowest weighting in the BNPB framework, remains an important component because

vegetation cover and natural ecosystems contribute to runoff regulation, sediment retention, and flood attenuation.

Overall, the vulnerability assessment demonstrates that the severity of flood impacts within Sungai Penuh City is controlled not only by flood depth but also by the spatial distribution of exposed populations, productive land, and infrastructure. Therefore, reducing flood losses requires integrated measures addressing both flood hazards and the underlying socioeconomic vulnerability.

Disaster Management Capacity Assessment

Disaster management capacity was evaluated through a multi-stakeholder Focus Group Discussion (FGD) following the BNPB capacity assessment framework. Five dimensions were assessed, namely (1) institutional and regulatory capacity, (2) disaster risk assessment and early warning systems, (3) disaster education and public awareness, (4) infrastructure-based risk reduction, and (5) emergency preparedness and response capacity.

Table 6. Flood Disaster Management Capacity Index Assessment in Sungai Penuh City

No.	Capacity Dimension	Capacity Level	Brief Description
1	Institutional and Regulatory Capacity	MODERATE / Adequate	A national regulatory framework is available; however, institutional responsibilities remain fragmented between BWS Sumatra VI and the Sungai Penuh City Government. The 2017 Detailed Engineering Design (DED) prepared by the Ministry of Public Works has not yet been followed by a comprehensive Flood Management Master Plan.
2	Early Warning System and Risk Assessment	LOW	BMKG flood forecasts are primarily passive; no real-time Automatic Water Level Recorder (AWLR) system is available, resulting in insufficient lead time for effective early warning during the January 2024 flood event.
3	Disaster Education	LOW	No active community-based disaster preparedness programme (TSBD) has been implemented. Illegal sand mining remains uncontrolled, community participation is limited, and residents' reports from Siulak Deras received no formal institutional response.
4	Risk Reduction (Infrastructure)	VERY LOW	Proposed structural mitigation measures—including river normalization, retention ponds, revitalization of Lake Kerinci, and construction of 4,353 m of drainage channels—remain at the planning stage and have not yet been implemented.
5	Government Preparedness	MODERATE	BPBD Jambi issued flood early warning notifications, while BWS Sumatra VI operated flood pumps during the emergency response.

Nevertheless, disaster management remains predominantly reactive, and no official evacuation shelters have been established.

The assessment results indicate that the overall disaster management capacity of Sungai Penuh City remains within the LOW category. Although disaster management institutions have been formally established, several critical deficiencies continue to limit the effectiveness of flood risk reduction. These include the limited implementation of community-based disaster preparedness programmes, insufficient coverage of flood early warning systems, inadequate hydrological monitoring infrastructure, and constrained institutional coordination among relevant stakeholders.

Infrastructure-related capacity also remains relatively limited. Existing flood-control structures are unable to accommodate extreme flood discharges, while river sedimentation and channel degradation further reduce hydraulic conveyance. Consequently, structural interventions alone are insufficient unless accompanied by improvements in institutional preparedness, emergency planning, and community participation.

The limited capacity identified in this assessment has important implications for disaster risk. According to the Risk Triangle concept, insufficient institutional capacity reduces the ability of communities and governments to anticipate, respond to, and recover from flood events. Consequently, even areas with moderate vulnerability may experience considerable flood losses if preparedness and emergency response remain inadequate.

These findings highlight the necessity of strengthening disaster governance through improved early warning systems, enhanced hydrological monitoring, regular emergency drills, community-based disaster risk reduction (Destana), and stronger inter-agency coordination. Enhancing institutional capacity is expected to significantly improve overall flood resilience while complementing structural flood mitigation measures.

Flood Risk Assessment

Flood risk was assessed by integrating the hazard, vulnerability, and capacity indices using the BNPB Risk Triangle framework. This approach recognizes that disaster risk is not determined solely by flood intensity but also by the susceptibility of exposed elements and the capability of institutions and communities to manage disaster impacts.

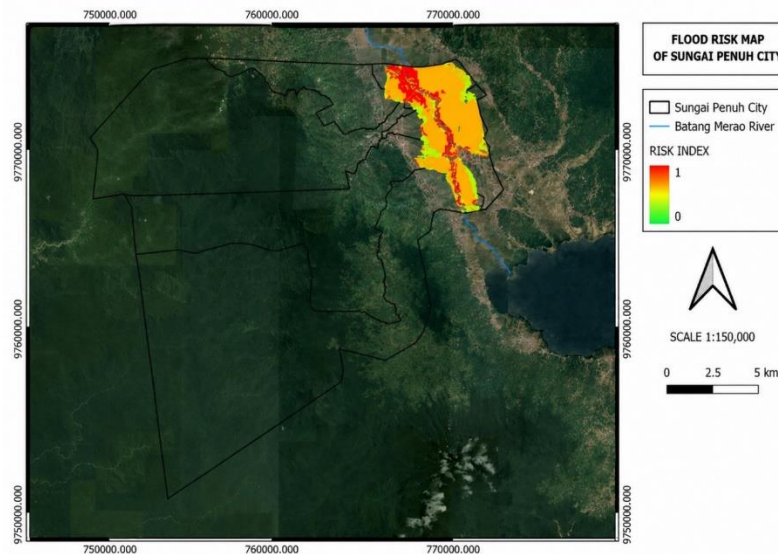


Figure 6. Flood Risk Map of Sungai Penuh City

The resulting flood risk map indicates that MEDIUM flood risk predominates across Sungai Penuh City, despite the widespread occurrence of high flood hazard. This outcome reflects the relatively low overall vulnerability of the study area, which partially offsets the severe flood hazard identified in the hydraulic simulations. Nevertheless, several areas remain classified as HIGH flood risk, particularly where high flood hazard coincides with concentrated settlements, productive agricultural land, and limited institutional capacity.

Table 7. Flood Risk Assessment by Sub-district in Sungai Penuh City

District	Hazard Level	Low (ha)	Moderate (ha)	High (ha)	Total (ha)	Risk Class
Sungai Penuh	High	231	767	53	1,051	Moderate
Pesisir Bukit	High	125	250	9	384	Moderate
Hamparan	High	1,110	6,855	2,193	10,158	Moderate
Rawang	High	1,328	6,011	486	7,825	Moderate
Tanah	High	644	1,298	185	2,127	Moderate
Kampung	High	757	1,196	68	2,021	Moderate
Kumun	High	81	507	277	865	Moderate
Debai	Moderate	32	4	0	36	Low
Pondok	Moderate	4,307	16,887	3,271	24,465	Moderate
Tinggi						
Koto Baru						
Sungai						
Bungkal						
Total						

The total area classified as HIGH flood risk reaches approximately 3,271 ha, whereas the remaining flood-prone areas fall predominantly within the MEDIUM risk category. Hamparan Rawang represents the most critical sub-district because it combines extensive inundation, high population exposure, and substantial concentrations of productive land. Similar conditions are also observed in Tanah Kampung and portions of Sungai Penuh Sub-district, where flood hazards overlap with densely developed areas.

Table 8. Supplementary Flood Risk Matrix for Sungai Penuh City

No.	District	Risk Level	Hazard Level	Exposed Population (Persons/km ²)	Assets (Million IDR)	Environment (ha)	Capacity	Priority
1	Sungai Penuh	High	High	363	1,169	—	Regulatory and Institutional Strengthening; Preparedness	
2	Pesisir Bukit	Moderate	High	96	428	—	Early Warning Systems; Disaster Risk Reduction (Infrastructure)	
3	Hamparan Rawang	Moderate	High	4,643	11,245	49	Disaster Risk Reduction; Early Warning Systems; Disaster Education	
4	Tanah Kampung	Moderate	High	1,682	8,535	122	Disaster Risk Reduction; Early Warning Systems; Disaster Education	
5	Kumun Debai	Moderate	High	769	2,282	54	Disaster Risk Reduction; Early Warning Systems; Disaster Education	
6	Pondok Tinggi	Moderate	High	510	957	—	Disaster Risk Reduction; Early Warning Systems; Disaster Education	
7	Koto Baru	Moderate	Moderate	565	41	—	Regulatory and Institutional Strengthening; Preparedness	
8	Sungai Bungkal	Low	Moderate	12	0	—	Regulatory and Institutional Strengthening; Preparedness	
Total		Moderate	High	8,640	24,657	225	—	

The comparison between hazard and risk maps demonstrates the importance of adopting a comprehensive risk-based assessment rather than relying solely on flood hazard mapping. While hydraulic modelling identifies areas likely to be inundated, the incorporation of vulnerability and capacity provides a more realistic representation of potential disaster consequences. Consequently, risk maps offer stronger support for prioritizing mitigation investments, emergency planning, and land-use management.

The results further demonstrate that flood risk within the Batang Merao Watershed is governed by the interaction between natural watershed characteristics and human-induced factors, including land-use change, increasing urbanization, and limited institutional preparedness. Similar conclusions have been reported in previous studies employing integrated HEC-HMS, HEC-RAS, and GIS approaches for flood risk assessment in Indonesian watersheds, confirming the effectiveness of combining hydrological modelling with spatial risk analysis to support disaster risk reduction planning.

Flood Loss Estimation

Flood losses were estimated based on the economic value of productive land and the replacement cost of physical assets affected by the Q25 flood inundation scenario. Economic losses represent the reduction in the value of agricultural production resulting from flood damage, whereas physical losses primarily reflect damage to residential buildings and associated infrastructure. This approach provides a quantitative assessment of the potential economic consequences of flooding and supports the prioritization of structural mitigation investments. The estimated flood losses for each sub-district are summarized in Table 9.

Table 9. Estimated Flood Losses by Sub-district in Sungai Penuh City

District	Economic Losses (Million IDR)	Economic Loss Level	Physical Losses (Million IDR)	Physical Loss Level	Total Losses (Million IDR)
Sungai Penuh	0	Low	1,169	High	1,169
Pesisir Bukit	0	Low	428	Moderate	428
Hampanan	1,189	High	10,056	High	11,245
Rawang					
Tanah	177	Moderate	8,358	High	8,535
Kampung					
Kumun Debai	47	Low	2,235	High	2,282
Pondok Tinggi	0	Low	2,249	High	2,249
Koto Baru	242	High	715	Moderate	957
Sungai	0	Low	41	Low	41
Bungkal					
Total	1,655	—	25,251	—	26,906

The total estimated flood loss reached IDR 26.906 billion, consisting of IDR 1.655 billion in economic losses and IDR 25.251 billion in physical losses. The predominance of physical losses

indicates that flood impacts are concentrated within residential areas and built infrastructure rather than agricultural production alone. Consequently, the protection of residential settlements represents the highest priority for flood mitigation planning in Sungai Penuh City.

Among all administrative units, Hamparan Rawang experienced the largest estimated loss, totaling IDR 11.245 billion, equivalent to approximately 41.8% of the total flood loss. Tanah Kampung ranked second, with estimated losses of IDR 8.535 billion (31.7% of the total). The substantial losses recorded in these two sub-districts are primarily attributable to the concentration of residential buildings located within low-lying floodplain areas that are repeatedly affected by inundation.

The estimated physical asset exposure of IDR 24.657 billion was subsequently adopted as the baseline condition for evaluating the effectiveness of the structural mitigation scenario presented in the following section. This baseline enables direct comparison of flood losses before and after river normalization, thereby providing quantitative evidence of the economic benefits associated with structural flood mitigation.

Overall, the flood loss assessment demonstrates that although agricultural damage contributes to overall economic losses, residential buildings remain the dominant component of flood-related damage in the Batang Merao Watershed. These findings emphasize the importance of integrating structural flood control measures with improved spatial planning to reduce future economic losses.

Structural Mitigation Scenario

To evaluate the effectiveness of engineering-based flood mitigation, a structural intervention scenario was simulated through river normalization along the Batang Merao River as it passes through Sungai Penuh City. The proposed intervention follows the recommendations of the 2017 Detailed Engineering Design (SID) prepared by the Ministry of Public Works and Housing (PUPR). River normalization was designed to increase channel conveyance capacity through sediment dredging, channel widening, and embankment improvements at critical locations where flood overtopping frequently occurs.

Post-normalization cross-sectional profiles indicate a riverbed elevation ranging from approximately 785 to 790 m above sea level, accompanied by a substantially wider channel compared with existing conditions. The enlarged channel geometry increases hydraulic capacity and reduces floodwater overtopping during high-flow events.

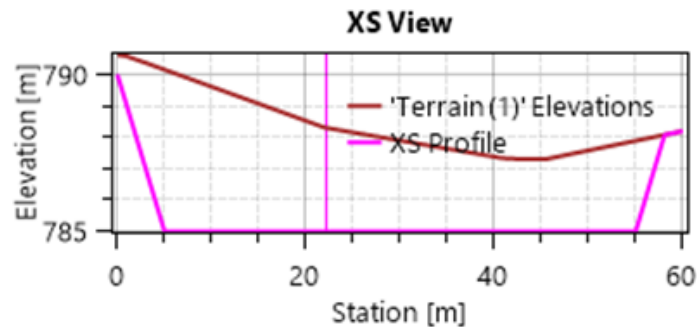


Figure 7. River Cross-section after Channel Normalization

The effectiveness of the proposed river normalization was evaluated by comparing flood inundation characteristics, hazard levels, exposure, and estimated economic losses before and after implementation.

1. Reduction in Flood Hazard Following River Normalization

The post-normalization HEC-RAS simulation demonstrates a substantial reduction in flood hazard throughout Sungai Penuh City. The comparison between existing and post-normalization conditions indicates that the overall flood hazard decreases from HIGH to MODERATE, reflecting the increased hydraulic capacity of the normalized river channel.

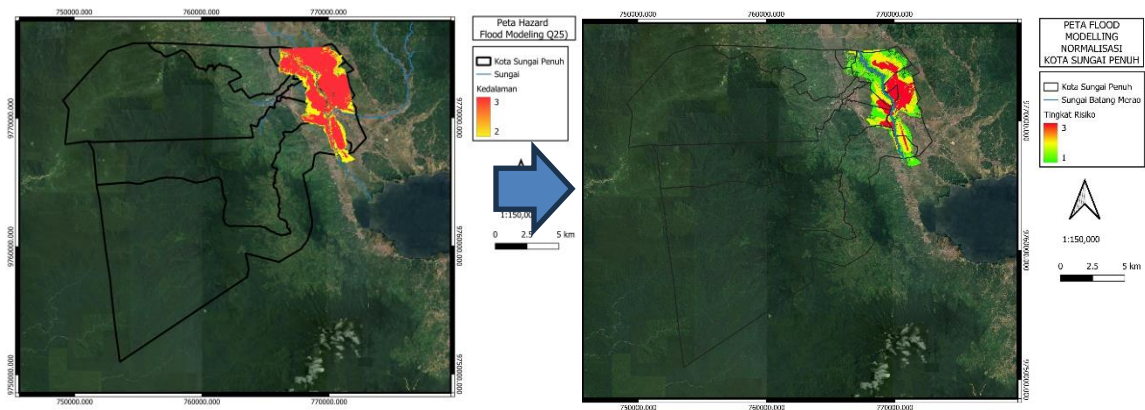


Figure 8. Flood Hazard Reduction after River Normalization

The spatial distribution of flood hazard before and after river normalization is summarized in Table 10.

Table 10. Comparison of Flood Hazard before and after River Normalization

District	Existing Moderate Hazard (ha)	Existing High Hazard (ha)	Post-Normalization Low Hazard (ha)	Post-Normalization Moderate Hazard (ha)	Post-Normalization High Hazard (ha)	Post-Normalization Hazard Class
Sungai Penuh	267.40	782.50	224	339	534	High

Pesisir Bukit	143.40	239.70	175	12	0	Low
Hamparan Rawang	1,836.80	8,332.40	4,095	3,568	1,851	Low
Tanah Kampung	1,818.00	6,046.40	1,887	2,811	3,849	High
Kumun Debai	809.40	1,356.00	892	1,224	293	Moderate
Pondok Tinggi	800.80	1,219.50	870	816	563	Low
Koto Baru	272.50	592.50	355	161	0	Low
Sungai Bungkal	35.90	0.10	2	0	0	Low
Total	5,984	18,569	8,500	8,931	7,090	Moderate

Overall, the area classified as HIGH flood hazard decreased by approximately 72% following river normalization. The most significant improvements were observed in Pesisir Bukit, Hamparan Rawang, Pondok Tinggi, and Koto Baru, where flood hazard classes decreased from HIGH to LOW. These improvements indicate that increasing channel conveyance effectively reduces flood inundation in areas where river capacity was previously the principal limiting factor.

In contrast, Sungai Penuh and Tanah Kampung remained within the HIGH hazard category despite measurable reductions in inundation extent. The persistence of high hazard in these areas is primarily attributed to their low-lying topography and the continued accumulation of floodwater, even after channel capacity has been increased. These findings demonstrate that structural interventions alone cannot completely eliminate flood hazards in downstream floodplain environments where topographic controls remain dominant.

2. Reduction in Exposure and Flood Losses

River normalization substantially reduced both population exposure and the potential economic consequences of flooding. The post-normalization vulnerability matrix is presented in Table 11.

Table 11. Post-normalization Vulnerability Matrix

District	Post-Normalization Risk Level	Post-Normalization Hazard Level	Post-Normalization Exposed Population (Persons/km ²)	Post-Normalization Assets (Million IDR)	Post-Normalization Environmental Exposure (ha)
Sungai Penuh	Moderate	Moderate	102	327.32	—
Pesisir Bukit	Moderate	Moderate	27	119.84	—
Hamparan Rawang	Low	Low	1,300	3,148.60	13
Tanah Kampung	Moderate	High	471	2,389.80	34

Kumun Debai	Moderate	Moderate	215	638.96	15
Pondok Tinggi	Moderate	Moderate	143	267.96	—
Koto Baru	Low	Low	158	11.48	—
Sungai Bungkal	Low	Low	3	0.00	—
Total	Moderate	Moderate	2,419	6,903.96	62

The total exposed population decreased from 8,640 persons/km² under existing conditions to 2,419 persons/km² following river normalization, representing an overall reduction of approximately 72%. Similarly, estimated physical asset exposure declined from IDR 24.657 billion to IDR 6.904 billion, corresponding to a reduction of approximately 72%.

Among all sub-districts, Hamparan Rawang experienced the greatest improvement. Flood risk was reduced from HIGH/HIGH to LOW/LOW, while population exposure declined from 4,643 persons/km² to 1,300 persons/km². Estimated flood losses were also reduced substantially, decreasing from IDR 11.245 billion to IDR 3.149 billion.

Overall, the implementation of river normalization resulted in an estimated reduction of approximately IDR 17.753 billion in flood losses for a single Q25 flood event. This substantial reduction provides strong economic justification for implementing channel improvement works as part of the long-term flood mitigation strategy. Similar reductions in flood risk following structural river improvements have been reported by Supratman et al. (2024) and Ridwan and Baskoro (2025), supporting the effectiveness of river normalization as a structural flood mitigation measure in Indonesian watersheds.

3. Benefit–Cost Ratio Analysis

The economic feasibility of the proposed river normalization project was evaluated using a Benefit–Cost Ratio (BCR) approach based on the Expected Annual Damage (EAD) method. The calculated ratio between the existing EAD and the estimated Q25 flood loss was approximately 1.51, which falls within the typical range reported for medium-sized watersheds. This result indicates that the estimated flood losses are consistent with values reported in previous flood damage studies (Merz et al., 2010).

Table 12. Present Value of Project Benefits

Benefit Component	Annual Benefit (Million IDR/year)	Present Value (Million IDR)
Direct Benefits (Reduction in Physical and Economic Losses)	17.896	191.032
Indirect Benefits ($\times 0.8$)	14.316	152.820
Total	32.212	343.857

The analysis considered both direct benefits, representing reductions in physical and economic flood losses, and indirect benefits, estimated using a multiplier of 0.8 to account for

broader socioeconomic impacts. Consequently, the total present value of project benefits reached approximately IDR 343.857 billion.

A sensitivity analysis was subsequently performed using three construction cost scenarios (IDR 30, 20, and 15 billion/km) combined with two alternative project lengths (10 km and 15 km). The resulting BCR values for six investment scenarios are presented in Figure 9.

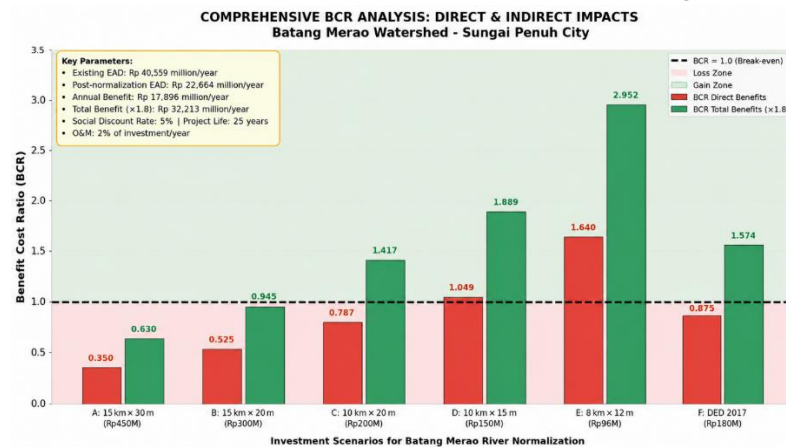


Figure 9. Benefit–Cost Ratio (BCR) Analysis under Alternative Investment Scenarios

The conservative investment scenarios produced BCR values below unity, indicating that direct economic benefits alone may not fully offset construction costs. Nevertheless, this outcome remains consistent with previous studies demonstrating that structural flood-control projects in developing countries frequently exhibit $BCR < 1$ when only direct monetary benefits are considered (Mechler, 2016). Many important social, environmental, and institutional benefits cannot be fully monetized using conventional economic evaluation methods.

These findings therefore reinforce the importance of combining structural interventions with relatively low-cost non-structural measures, including real-time hydrological early warning systems, community-based disaster preparedness (Destana), improved land-use management, and watershed conservation. Such integrated approaches are expected to provide substantially higher overall economic efficiency while simultaneously enhancing long-term flood resilience within the Batang Merao Watershed.

Policy Implications

The integrated flood risk assessment developed in this study provides a scientific basis for formulating comprehensive flood disaster management policies in Sungai Penuh City. By combining hydrological and hydraulic modelling, GIS-based spatial analysis, disaster risk assessment, economic loss estimation, and structural mitigation evaluation, the proposed framework enables decision-makers to prioritize mitigation measures according to both technical effectiveness and socioeconomic impact. Consequently, flood management should not rely solely

on structural engineering interventions but should also incorporate institutional strengthening, watershed conservation, and community-based disaster risk reduction.

1. Institutional and Administrative Implications

The disaster risk assessment indicates that improving institutional capacity is essential for reducing future flood risk within the Batang Merao Watershed. Strengthening local regulations through the preparation of flood management bylaws and the integration of flood risk considerations into regional spatial planning (RTRW/RDTR) would provide a stronger legal foundation for sustainable watershed management. Equally important is the establishment of an integrated Batang Merao Watershed Management Forum involving the River Basin Organization (BWS Sumatra VI), the Regional Disaster Management Agency (BPBD), regional development agencies, and the municipal government to improve coordination among responsible institutions.

Flood risk management should also be supported by systematic disaster risk assessment and periodic updating of flood hazard and risk maps. The implementation of an integrated hydrological early warning system based on Automatic Water Level Recorders (AWLR) and Automatic Weather Stations (AWS), combined with operational HEC-HMS and HEC-RAS forecasting, would substantially improve flood forecasting capability and emergency preparedness. Furthermore, multi-channel warning dissemination through SMS, sirens, mobile applications, and web-based dashboards would enhance the effectiveness of emergency communication during extreme flood events.

Capacity building at the community level remains equally important. The expansion of Destana (Disaster-Resilient Villages) throughout flood-prone sub-districts, regular evacuation drills, disaster education programmes, and the integration of disaster risk reduction into school curricula would significantly strengthen local preparedness. At the same time, institutional preparedness should be reinforced through contingency planning, emergency response standard operating procedures, logistics management, and the establishment of an integrated flood emergency command centre.

2. Engineering and Planning Implications

The structural mitigation scenario demonstrates that river normalization substantially reduces flood hazard, exposure, and economic losses. Nevertheless, long-term flood resilience requires a combination of structural and non-structural measures implemented within an integrated watershed management framework.

a. Short-term Strategies (0–2 Years)

Immediate priorities should focus on reducing the impacts of existing flood hazards through the installation of AWS and AWLR monitoring stations at critical locations, sediment dredging within severely silted river reaches, localized river normalization, emergency embankment reinforcement, and routine maintenance of drainage channels. Simultaneously,

annual evacuation exercises and the establishment of Destana programmes should be prioritized within high-risk communities. Updating flood hazard maps, validating inundation areas, and improving the inventory of exposed assets would further strengthen disaster preparedness.

b. Medium-term Strategies (3–5 Years)

Medium-term interventions should prioritize comprehensive river normalization along the Batang Merao, Batang Sangkir, and Batang Bungkal rivers. Additional structural measures, including urban retention ponds, check dams, sabo dams, and runoff detention reservoirs, would further reduce downstream flood peaks. Watershed conservation through reforestation, agroforestry, erosion control, and rehabilitation of degraded catchments should accompany these engineering measures. Urban drainage improvements and flood-sensitive spatial planning, including the designation of floodplain management areas and development restrictions within high-risk zones, are equally essential for reducing future flood exposure.

c. Long-term Strategies (5–20 Years)

Long-term flood resilience requires a transition toward integrated and adaptive water management. Restoration of natural floodplains and wetlands would increase flood storage capacity while simultaneously improving ecosystem services. Where technically feasible, strategic flood-control reservoirs or flood diversion channels may further enhance regional flood protection. In parallel, gradual relocation of settlements located within extremely high-risk areas, construction of flood-resilient housing, and implementation of adaptive urban development policies should be considered.

Digital technologies are expected to play an increasingly important role in future flood management. The development of a Digital Twin of the Batang Merao Watershed, supported by real-time hydrological monitoring, GIS-based flood risk dashboards, and integrated decision-support systems, would enable dynamic flood forecasting and adaptive flood management. Long-term governance should also promote sustainable watershed financing mechanisms, including Payment for Ecosystem Services (PES), periodic flood risk audits, and continuous multi-stakeholder collaboration to ensure the long-term effectiveness of flood risk reduction strategies.

Overall, these policy implications demonstrate that sustainable flood risk reduction in Sungai Penuh City requires an integrated approach combining structural engineering, ecosystem-based watershed management, institutional strengthening, technological innovation, and community participation.

CONCLUSION AND SUGGESTIONS

Conclusion

This study developed an integrated framework for assessing flood risk in the Batang Merao Watershed, Sungai Penuh City, by combining hydrological modelling (HEC-HMS), two-dimensional hydraulic simulation (HEC-RAS), GIS-based multi-variable spatial analysis, the BNPB Risk Triangle framework, economic loss estimation, and structural mitigation evaluation. The proposed framework provides a comprehensive assessment of flood hazard, vulnerability, capacity, and disaster risk while supporting evidence-based decision-making for flood management.

Rainfall frequency analysis identified the General Extreme Value (GEV) distribution as the most suitable statistical model for estimating design rainfall. The resulting HEC-HMS simulation generated a Q25 peak discharge of approximately 220 m³/s in the upstream watershed and 2,300 m³/s at the downstream outlet, substantially exceeding the existing river conveyance capacity. Subsequent HEC-RAS simulation indicated that seven of the eight sub-districts within Sungai Penuh City are classified as HIGH flood hazard, with a total high-hazard area of approximately 18,569 ha. Although overall flood vulnerability remained relatively low, limited institutional capacity contributed to a predominantly MEDIUM flood risk, with approximately 3,271 ha classified as high risk and total estimated flood losses reaching IDR 26.906 billion.

The structural mitigation scenario demonstrated that river normalization substantially improves flood conditions. Hydraulic simulation indicated an overall reduction in flood hazard from HIGH to MODERATE, accompanied by approximately 72% reductions in both exposed population and estimated physical asset losses. Total flood losses decreased by approximately IDR 17.753 billion for a single Q25 flood event, confirming the technical effectiveness of channel improvement as a flood mitigation measure. Nevertheless, the Benefit–Cost Ratio analysis indicates that structural measures alone may not always provide sufficient economic returns when only direct monetary benefits are considered, highlighting the importance of integrating engineering interventions with non-structural measures such as early warning systems, community-based disaster preparedness, land-use management, and watershed conservation.

The principal contribution of this study lies in the development of an integrated flood risk assessment and mitigation framework that links hydrological and hydraulic modelling with spatial risk analysis, economic evaluation, and policy formulation. This integrated approach provides a practical decision-support framework for prioritizing flood mitigation investments and may be adapted for flood-prone watersheds with similar hydrological and geomorphological characteristics throughout Indonesia.

Suggestions

Future research should incorporate climate change projections, real-time hydrometeorological observations, and nature-based flood mitigation measures to further

improve the reliability and long-term sustainability of flood risk management in the Batang Merao Watershed. In addition, local authorities are encouraged to adopt the proposed risk assessment framework as a basis for prioritizing investment in both structural measures (e.g., river normalization, retention ponds) and non-structural measures (e.g., early warning systems, community-based disaster preparedness) in accordance with the short-, medium-, and long-term strategies outlined in this study.

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