



## **RISK ANALYSIS AND ECONOMIC FEASIBILITY EVALUATION OF FLOOD MITIGATION IN THE SIAK RIVER BASIN**

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**ABSTRACT:** The Siak River Basin is experiencing rapid socio-economic growth while facing significant flood hazards, creating the need for a comprehensive and integrated assessment. This study evaluates flood risk based on BNPB guidelines by analyzing hazard, vulnerability, and capacity conditions. Hazard levels are examined through two-dimensional hydraulic modelling in HEC-RAS to identify the spatial extent and depth of inundation. Vulnerability is assessed across social, physical, economic, and environmental dimensions, while capacity is measured using the regional resilience index and community preparedness index. The study also incorporates an economic feasibility evaluation of several mitigation alternatives using Benefit–Cost Analysis (BCA). Benefits include improved transportation accessibility, protection of household assets and income, and the sustained functioning of agricultural, fisheries, plantation sectors, and public facilities. Costs consist of both structural and non-structural flood control measures. The results indicate that most areas in the Siak River Basin fall within the medium-risk category, highlighting the need for continued mitigation efforts. Pekanbaru City has the largest share of high-risk zones, whereas Siak and Kampar Regencies are predominantly classified as medium risk. Among the evaluated alternatives, Alternative 4 is identified as the most effective, reducing the inundation area from 9,465.74 hectares under existing conditions to 3,177.00 hectares. This option also provides the highest total benefits, reaching IDR 490,657,826,002, and is the only alternative with a BCR value  $\geq 1$ , indicating economic feasibility. In conclusion, integrating flood risk analysis with economic evaluation supports more informed and strategic decision-making for flood management in the Siak River Basin.

*Keywords: Benefit–cost analysis, Economic feasibility evaluation, Flood, Risk analysis, Siak river basin*

### **1. INTRODUCTION**

A river basin can be regarded as a natural system characterized by complex hydrological and biophysical processes interacting with socio-economic activities. The hydrological and biophysical processes of a river basin are natural processes that form part of the hydrological cycle. Meanwhile, socio-economic activities represent human interventions in the natural river basin system, such as urban development, construction of hydraulic structures, and the development of protected and cultivated land areas. Therefore, a river basin is a natural system whose hydrological and sediment dynamics vary considerably in response to climatic fluctuations and human activities, such as land use changes and water diversion, as reflected in measurable changes in peak discharge, sediment load, and flood frequency [1]. Communities play an important role in managing natural resources within a river basin, both as actors, beneficiaries, and

affected parties. As actors, communities can support river basin sustainability through efforts such as maintaining vegetation cover and constructing water infiltration facilities. As beneficiaries, communities gain advantages in the form of surface water and groundwater availability, soil fertility, and increased agricultural productivity. Through these functions, river basins provide vital services for human life, including drinking water, irrigation, energy, and ecological habitats [1].

However, when river basin conditions deteriorate, communities may also experience negative impacts such as flooding during the rainy season, drought during the dry season, and various other environmental disturbances. These disaster threats may arise from natural processes, human activities, or a combination of both. In some cases, natural hazards can escalate into disasters due to human-induced errors, such as improper land use changes [2]. Flooding is a hydrometeorological disaster that frequently occurs in rapidly developing

urban areas. This phenomenon also occurs in the Siak River Basin, which administratively covers six regencies/cities in Riau Province, namely Kampar Regency, Pekanbaru City, Bengkalis Regency, Siak Regency, Rokan Hulu Regency, and Pelalawan Regency. These areas are experiencing high pressure due to land use changes and population growth, particularly in urban centers such as Pekanbaru. This situation leads to a decline in the land's capacity to control surface runoff, thereby increasing the potential hazards and flood risks along the Siak River Basin. Land use transformation in peri-urban areas or the upstream parts of the river basin, such as the reduction of vegetation cover and the expansion of impervious surfaces, can increase surface runoff which eventually triggers a rise in flood discharge in downstream urban areas [3]. Changes in land use and land cover influence how rainfall is partitioned into the components of the water balance, such as interception, infiltration, evapotranspiration, surface runoff, and groundwater recharge [4]. Patterns of flood-induced losses not only occur in the Siak River Basin but also in other major river basin such as Citarum, causing economic disruption and risks to communities [5].

Disaster risk assessment is an approach used to identify potential negative impacts that may arise from a disaster hazard. Flood risk assessment in Indonesia is regulated through BNPB Regulation No. 02 of 2012, which emphasizes the importance of hazard, vulnerability, and capacity analyses in determining the level of risk. The assessment of potential negative impacts is carried out by integrating flood hazard levels, the vulnerability of exposed elements, and the capacity of an area to reduce disaster consequences. Effective flood mitigation does not solely rely on structural engineering approaches but also requires integrating physical analysis with economic benefit evaluation to obtain a more comprehensive overview of the effectiveness of each mitigation option. This approach enables the assessment not only of the infrastructure's capability to reduce flood hazards, but also of the socio-economic benefits gained by communities as a result of reduced risks. Since flood mitigation projects are long-term investments with cost and benefit streams that vary throughout their service life, a discounted analysis method is required to estimate the present economic value of future benefits. Therefore, feasibility indicators such as the Net Benefit–Cost Ratio are used to ensure that the selected intervention can deliver greater benefits compared to the costs incurred. Benefit–Cost Analysis is a widely applied method for economic evaluation in flood risk management [6]. The integration of flood risk analysis with economic

evaluation provides a holistic perspective in determining the best mitigation alternatives [6]. Thus, the integration of physical and economic analyses becomes crucial in supporting a more accurate, effective, and efficient decision-making process, especially considering the limited funding resources at the local government level.

Several previous studies have applied economic evaluation methods in flood risk management. Study [6] employed a life-cycle Cost–Benefit Analysis (CBA) framework to assess flood mitigation measures by incorporating both cost and benefit components over time, using indicators such as Net Present Value (NPV) and Benefit–Cost Ratio (BCR). The study also highlighted that conventional economic assessments often focus primarily on flood damage reduction (e.g., expected annual damage) while overlooking additional co-benefits, leading to a less comprehensive evaluation of mitigation strategies. Furthermore, it emphasized the importance of integrating broader benefit components into economic analysis to support more effective decision-making in flood risk management. However, such approaches remain limited in integrating hydraulic modelling, flood risk assessment, and economic evaluation within a unified framework. Although previous studies have examined flood hazard modelling, vulnerability assessment, and economic evaluation of mitigation measures separately, limited research has integrated spatial flood risk analysis based on national regulatory frameworks with a comprehensive economic feasibility assessment within a single decision-support framework. Many flood studies focus primarily on hydraulic modelling to estimate inundation extent, while others emphasize socio-economic vulnerability or cost–benefit evaluation independently. However, the integration of hazard, vulnerability, and capacity indices in accordance with BNPB guidelines, combined with a quantitative Benefit–Cost Analysis of structural mitigation alternatives, remains relatively limited, particularly at the river basin scale in Indonesia. Therefore, this study aims to address this gap by developing an integrated framework that links two-dimensional hydraulic modelling, risk index mapping, and economic feasibility evaluation to support more strategic and evidence-based flood management planning in the Siak River Basin. The novelty of this research lies in the systematic integration of regulatory-based risk assessment and engineering economic analysis to prioritize mitigation alternatives under limited regional financial resources.

This study offers several original contributions to flood risk management research. First, it integrates

two-dimensional hydraulic modelling with a BNPB-based risk assessment framework that combines hazard, vulnerability, and capacity indices into a spatially explicit risk map at the river basin scale. Second, the study links the quantified flood risk results directly with a structured Benefit–Cost Analysis of multiple structural mitigation alternatives. Unlike previous studies that evaluate technical performance and economic feasibility separately, this research establishes a unified decision-support framework that connects risk assessment outputs with economic prioritization. Third, the application of this integrated approach to the Siak River Basin provides empirical evidence for strategic flood mitigation planning in developing regions with limited financial resources. These contributions distinguish the present study from existing literature and enhance its practical and methodological relevance.

This paper is organized as follows: Section 2 explains the significance of the study and highlights the importance of integrating flood risk analysis with economic feasibility evaluation to support strategic decision-making in the Siak River Basin. Section 3 presents the data and methodology used in the research, as well as the analytical procedures applied for assessing hazard, vulnerability, capacity, and economic aspects. Section 4 presents the results and discussion related to the risk analysis and economic feasibility evaluation of flood mitigation in the Siak River Basin, Riau Province, supported by spatial mapping outputs and comparative assessments of the mitigation alternatives. Finally, Section 5 presents the conclusions of the study along with recommendations aimed at strengthening future flood risk management.

## 2. RESEARCH SIGNIFICANCE

This study contributes to flood risk management practice by integrating two-dimensional hydraulic modelling, BNPB-based multi-index risk assessment, and economic feasibility evaluation within a unified decision-support framework. Unlike approaches that assess risk and economic performance separately, this research links spatial risk outputs with investment prioritization at the river basin scale. The framework provides practical guidance for allocating limited public resources. Its application to the Siak River Basin demonstrates how risk-informed economic evaluation can support strategic flood mitigation planning in developing regions.

## 3. MATERIALS AND METHOD

### 3.1 Data

The types and sources of data required in this study are presented in Table 1, Table 2, and Table 3. The data sets used in this study were collected from various institutions with temporal coverage ranging from 2001 to 2023. Hydrological data cover the period 2001–2021, while socio-economic and land-use datasets primarily represent the most recent available conditions (2020–2023). This temporal range was selected to ensure consistency between hydrological modelling and current exposure and vulnerability assessment.

Table 1. Data Requirements for the Research Analysis (Spatial and Physical Data)

No	Type of Data	Source
1	Village Administrative Boundary Map (1:25,000) (2002)	Geospatial Information Agency (BIG)
2	Land Use Data (2023)	Ministry of Environment and Forestry (KLHK)
3	Land Value Zone Map (2022)	ATR/BPN – Riau Province
4	Road Network Distribution Map (2023)	PUPR; BAPPEDA; Transportation Office
5	Distribution of Public and Social Facilities (2022-2023)	Education Office; PUPR; Health Office
6	Distribution of Commercial Activity Locations (2022)	Trade Office

Table 2. Data Requirements for the Research Analysis (Socio-Economic Data)

No	Type of Data	Source
1	Village-Level Population Data (2010–2022)	Statistics Indonesia (BPS) – Riau Province
2	Data on Persons with Disabilities and Poor Households (2021-2022)	BPS; Social Affairs Office
3	Employment, Income, and Household Expenditure Data (2023)	Community surveys and interviews
4	Agricultural Productivity Levels (2010-2022)	Riau Provincial Agriculture Office
5	Agricultural Product Prices (2022)	Riau Provincial Agriculture Office

Table 3. Data Requirements for the Research Analysis (Institutional and Capacity Data)

No	Type of Data	Source
1	District-Level Regional Resilience Index (2022)	BAPPEDA; BPBD; Education Office; PUPR; ATR/BPN
2	Community Resilience Index (30 respondents per village) (2023)	Community questionnaire

Although datasets originate from different years, the analysis assumes that socio-economic and infrastructure conditions during 2022–2023 represent the baseline exposure condition for the flood hazard scenario derived from historical rainfall analysis (2001–2021). This approach ensures consistency between long-term hydrological variability and current risk conditions. The datasets used in this study consist of spatial, hydrological, socio-economic, and institutional data obtained from official government agencies and field surveys. Spatial datasets, including administrative boundaries and land-use maps, are available at a scale of 1:25,000.

The Digital Elevation Model (DEM) applied in the hydraulic modelling is based on DEMNAS with a spatial resolution of approximately 8 m and is complemented by field topographic measurements to enhance vertical accuracy in critical river and floodplain areas. Rainfall data for hydrological analysis cover the period 2001–2021, providing adequate temporal coverage for frequency analysis in accordance with the Indonesian national standard (SNI 2415:2016). Population data span 2010–2022, while socio-economic indicators are derived from official statistics and supplemented by structured community surveys involving 30 respondents per village. The HEC-RAS 2D hydraulic model was developed using a computational grid size of 20 × 20 m, providing a balance between computational efficiency and spatial accuracy for watershed-scale flood simulation. Although the datasets are derived from official and validated sources, several limitations should be acknowledged.

The DEMNAS resolution (approximately 8 m) may not fully capture micro-topographic variations in densely built urban areas. The use of 30 respondents per village provides indicative preparedness results but may not represent all demographic variations. Additionally, socio-economic datasets originate from different reporting years; however, they are assumed to represent relatively stable baseline conditions during the analysis period. These limitations do not significantly alter the overall spatial risk patterns but should be considered when

interpreting detailed local results.

The two-dimensional hydraulic modelling was performed using HEC-RAS 2D to simulate flood inundation under design discharge conditions. The upstream boundary condition was defined using design flood hydrographs derived from rainfall frequency analysis for selected return periods. The design flood hydrographs used as upstream boundary conditions were derived from rainfall frequency analysis. A 25-year return period (Q25) was selected as the representative design event for flood hazard assessment. The selection of the 25-year return period is consistent with common hydrological planning practices in Indonesia for urban flood control and regional drainage systems, where return periods in the range of 10–25 years are typically applied depending on the level of risk and infrastructure classification. The downstream boundary condition was specified using normal depth conditions based on the average channel slope of the lower Siak River reach.

The computational domain was discretized using a uniform mesh grid with a cell size of 20 × 20 m, which provides an appropriate balance between computational efficiency and spatial accuracy for basin-scale modelling. Smaller cell refinement was applied along the main river channel and critical floodplain areas to better capture flow dynamics. Manning’s roughness coefficients were assigned based on land-use classifications, following standard hydraulic references and adjusted according to local conditions. Model performance was evaluated qualitatively by comparing simulated inundation extents with historical flood occurrence records and reported flood-prone areas from the Regional Disaster Management Agency (BPBD). Due to limited availability of observed water level time-series data, quantitative calibration using gauge records was not feasible. However, spatial consistency between simulated flood maps and historical flood reports indicates that the model provides a reasonable representation of flood behavior in the Siak River Basin.

### 3.2 Risk Analysis

The risk analysis in this study was conducted by identifying the flood risk levels based on the BNPB Guideline No. 02 of 2012. The assessment includes the analysis of hazard, vulnerability, and capacity analyses, which serve as the basis for determining the overall magnitude of risk. Hazard is defined as a physical phenomenon or human activity that has the potential to cause damage and lead to loss of life. In this study, flood hazard analysis was carried out through hydraulic modelling using HEC-RAS 2D by

considering hydrological conditions and the physical characteristics of the area, including design rainfall, river topography, land use within the river basin, as well as the presence of hydraulic structures that influence inundation depth. The modelling results provide information regarding the spatial extent and depth of flooding, which are then classified into flood hazard level categories based on the BNPB hazard index. Flood hazard classification is primarily based on inundation depth, following the criteria defined in BNPB Regulation No. 02 of 2012.

The use of water depth as the principal hazard indicator reflects the national standard applied in Indonesian flood risk assessments and ensures consistency with regional disaster management planning frameworks. Although additional hydraulic parameters such as flow velocity and flood duration may influence damage mechanisms, inundation depth is considered the most practical and widely applied indicator for settlement-scale flood hazard classification in Indonesia. The hazard weights were assigned using a simple ordinal scaling approach, where low, medium, and high hazard classes were proportionally represented as 0.33, 0.67, and 1.00, respectively.

These values represent normalized scores derived from a three-level classification (1/3, 2/3, 3/3) rather than statistically estimated parameters. The purpose of this normalization is to maintain proportional differentiation among hazard levels while ensuring transparency and interpretability of the composite index. The weighting approach follows common practice in composite risk index construction where ordinal categories are converted into standardized numerical scores.

Table 4. Flood Hazard Classification

No	Inundation Depth (m)	Hazard Index	Weighting
1	0.00 – 0.75	Low	0.33
2	0.75 – 1.50	Medium	0.67
3	> 1.50	High	1.00

Vulnerability refers to the degree of potential loss experienced by elements or community groups exposed to hazards due to a certain level of severity of an event. The higher the level of vulnerability of a group, the greater the potential impacts and losses that may occur. Thus, vulnerability can be understood as social, economic, physical, and environmental conditions that reduce a community's capacity to cope with and recover from disaster threats. Socio-economic factors have a significant influence on the level of vulnerability and the adaptive capacity of communities facing

disasters [7]. The United Nations Office for Disaster Risk Reduction defines vulnerability as a condition determined by physical, social, economic, and environmental factors that increase the susceptibility of a community to the impacts of hazards [8]. The scoring of vulnerability indices and the classification of vulnerability levels are determined based on the method formulated by BNPB. The parameters and value ranges used in the assessment are presented in Tables 5 and 6.

Table 5. Vulnerability Index Scoring

No	Vulnerability Index	Weighting
1	Social Vulnerability	0.40
2	Physical Vulnerability	0.25
3	Economic Vulnerability	0.25
4	Environmental Vulnerability	0.10
Total		1

Table 6. Vulnerability Index Classification

No	Score	Vulnerability Index
1	0.00 – 0.33	Low
2	0.33 – 0.67	Medium
3	0.67 – 1.00	High

Capacity refers to the ability of an entity whether a state, institution, or organization to perform specific functions and achieve predetermined objectives [9]. Factors commonly associated with the capacity of states, institutions, and organizations in disaster risk management include human and financial resources, technical training, community participation, collaboration, data management, administrative capabilities, as well as the political characteristics of the area [9]. In the context of risk analysis, capacity represents the ability of systems, communities, and populations that are potentially affected by hazards to adapt and maintain their existing levels of function and structure. In other words, capacity reflects the ability of regions and communities to undertake structured, planned, and integrated efforts to reduce threats and minimize potential losses from disasters.

The determination of capacity level in this study is based on two main parameters: the Regional Resilience Index and the Community Preparedness Index, as recommended in the BNPB guidelines. The assessment of the Regional Resilience Index refers to seven priority indicators, namely strengthening policies and institutional frameworks; risk assessment and integrated planning; development of information systems, training, and logistics; thematic management of disaster-prone areas;

improvement of disaster prevention and mitigation effectiveness; strengthening preparedness and emergency response; and development of disaster recovery systems.

The regional capacity index was developed through the design of a questionnaire instrument aimed at assessing institutional capacity in disaster management. The assessment of institutional capacity was carried out through structured interviews with several agencies at the provincial level, namely the Regional Development Planning Agency (BAPPEDA), the Regional Disaster Management Agency (BPBD), the Department of Education and Culture, the Public Works and Spatial Planning Office (PUPR), and the Agrarian Affairs and Spatial Planning/National Land Agency (ATR/BPN). Meanwhile, the assessment of community preparedness refers to the Community Preparedness Assessment for Flood Risk developed by LIPI, which has been widely used since 2013 in disaster risk assessments at the regency/city level in Indonesia.

The Community Preparedness Index (IKM), as one of the components of regional capacity, was measured using a combination of survey methods and in-depth interviews with government officials and community leaders. The respondents were selected using a stratified random sampling technique in disaster-prone villages or urban communities, with a standardized questionnaire serving as the main instrument for data collection. The institutional capacity assessment was conducted using a purposive sampling approach targeting key informants from relevant governmental agencies directly involved in flood risk management and spatial planning.

Table 7. Regional Resilience Index

No	Parameter	Information
1	Strengthening of policies and institutional frameworks	(30%)
2	Risk assessment and integrated planning	
3	Development of information systems, training, and logistics	
4	Thematic management of disaster-prone areas	
5	Enhancement of disaster prevention and mitigation effectiveness	(70%)
6	Strengthening disaster preparedness and emergency response	
7	Development of disaster recovery systems	

Representatives from BAPPEDA, BPBD, the Department of Education and Culture, the Public

Works and Spatial Planning Office (PUPR), and ATR/BPN were included in the assessment. For each institution, one or more senior officials or technical staff responsible for disaster-related programs were interviewed. The selection of respondents was based on their formal roles, decision-making authority, and direct involvement in flood risk management policies and implementation. This key-informant approach is commonly applied in institutional capacity assessments, where strategic knowledge and program oversight are concentrated within specific officials. To improve clarity and readability, the Community Preparedness Index indicators are grouped into thematic dimensions and presented in separate tables.

Table 8. Preparedness Knowledge Indicators

Resilience Parameter	Resilience Indicators	Indicator Weight
Preparedness Knowledge	Knowledge of Types of Threats	0.10
	Knowledge of Disaster Warning Information	0.15
	Disaster Early Warning System	0.25
	Prediction of Disaster Losses	0.20
	Self-Rescue Methods	0.30

Table 9. Emergency Response Management Indicators

Resilience Parameter	Resilience Indicators	Indicator Weight
Emergency Response Management	Evacuation Sites and Routes	0.35
	Sheltering Facilities	0.30
	Water and Sanitation	0.20
	Health Services	0.15

The Community Preparedness Index (IKM) was measured using structured questionnaires distributed to 30 respondents per village. This sample size follows the common practice in community-based disaster risk assessments in Indonesia and aligns with the LIPI preparedness assessment framework, which emphasizes representative perception-based sampling at the village scale rather than full statistical population inference. The respondents were selected using stratified random sampling to ensure representation across gender, age groups, and socio-economic backgrounds within each village. The purpose of the

survey was to capture general preparedness patterns and institutional awareness rather than to perform large-scale statistical generalization. While a larger sample size could further improve statistical robustness, the selected number of respondents is considered adequate for village-level composite index construction and comparative analysis across sub-districts. Future studies may expand sample sizes or apply advanced statistical validation methods to strengthen the robustness of preparedness assessments. The parameters and value ranges used in the capacity index assessment are presented in Tables (7)–(13).

Table 10. Socio-Structural and Institutional Dependence Indicators Dimension

Resilience Parameter	Resilience Indicators	Indicator Weight
Community Vulnerability Impact Toward Disaster Risk Reduction Efforts	Livelihood/Income Level	0.40
	Community Education Level	0.35
	Community Settlement Area	0.25
Community Dependence on Government Support	Life Assistance After Disaster	0.25
	Compensation for Loss and Damage	0.25
	Research and Development	0.20
	Emergency Response Handling	0.15
Forms of Community Participation	Community-Level Disaster Risk Reduction Activities	0.65
	Village Volunteers	0.35

Table 11. Classification of the Regional Resilience Index and the Community Preparedness Index

No	Value Range	Score Range	Index Category
1	0.00 – 0.40	0.00 – 0.33	Low
2	0.40 – 0.80	0.33 – 0.67	Medium
3	0.80 – 1.00	0.67 – 1.00	High

The weighting scheme for the vulnerability and capacity indices was not arbitrarily assigned but follows the framework established in BNPB Regulation No. 02 of 2012, which serves as the national standard for disaster risk assessment in Indonesia. The relative weights of social (0.40),

physical (0.25), economic (0.25), and environmental (0.10) vulnerability reflect the national policy emphasis on social exposure as the dominant determinant of disaster impact. Social vulnerability was assigned a weight of 0.40 to reflect its direct influence on human exposure, population sensitivity, and livelihood disruption.

Table 12. Weighting of the Regional Capacity Index

No	Hazard Index	Weighting
1	Regional Resilience Index (City/District Level)	0.40
2	Community Preparedness Index (Sub-district/Village Level)	0.60
Total		1.00

Table 13. Classification of the Regional Capacity Index

No	Score Range	Index Category
1	0.00 – 0.33	Low
2	0.33 – 0.67	Medium
3	0.67 – 1.00	High

Economic vulnerability was weighted at 0.25 due to its role in determining recovery capacity, while physical vulnerability was assigned 0.25 based on infrastructure exposure. Environmental vulnerability was weighted at 0.10, reflecting its indirect contribution to flood impact compared to human-centered components. Similarly, the weighting of the Regional Resilience Index (0.40) and Community Preparedness Index (0.60) in the capacity assessment is based on the BNPB guideline, which prioritizes community-level preparedness as a critical component of adaptive capacity. In this study, the term “capacity” refers to the adaptive ability of a region to anticipate, respond to, and recover from flood events.

This adaptive capacity is operationalized through a Regional Resilience Index that integrates institutional performance, infrastructure readiness, social preparedness, and economic coping capacity. In this context, “regional resilience” represents the measurable expression of adaptive capacity rather than a separate conceptual construct. Institutional ability constitutes one of the key components within this resilience-based capacity framework.

Table 13 presents the classification of the Regional Capacity Index, which reflects the adaptive capacity of a region in responding to flood hazards. The index is categorized into three levels: low, medium, and high, based on normalized score ranges. A low capacity level (0.00–0.33) indicates

limited institutional readiness, weak community preparedness, and insufficient resources to effectively respond to flood events, resulting in higher potential impacts. A medium capacity level (0.33–0.67) represents moderate preparedness, where basic institutional systems and community awareness are in place but may not be fully effective under extreme flood conditions. A high capacity level (0.67–1.00) indicates strong institutional coordination, well-established disaster management systems, and a high level of community preparedness, enabling effective mitigation, response, and recovery efforts. This classification plays a critical role in the overall risk analysis, as capacity functions as a risk-reducing factor in the risk formulation. Higher capacity values contribute to lowering the overall flood risk, even in areas with relatively high hazard and vulnerability levels.

Disaster risk refers to the potential losses that may be caused by a disaster event within a specific area and time period. These losses may include fatalities, injuries, threatened lives, loss of security, physical damage, and property loss. As previously described, the flood risk analysis in this study is based on three main parameters, namely hazard index, vulnerability index, and capacity index. This approach aligns with the concept that risk increases when both hazard and vulnerability levels are high, while the capacity of a region to cope with disasters is low.

This concept is a development of Crichton’s risk triangle, which consists of hazard, exposure, and vulnerability as key elements that determine disaster risk levels [10]. In this analysis, capacity is treated as a risk-reducing factor, meaning that the lower the capacity of an area, the greater the potential impacts that may occur even if the hazard or vulnerability level is similar. These three parameters are then combined to produce a risk value, which is subsequently classified into three categories: low, medium, and high. The risk analysis formulation used in this study is presented in Equation (1), which is conceptually derived from the disaster risk framework that defines risk as the interaction between hazard, vulnerability, and capacity, as outlined in BNPB Regulation No. 02 of 2012 and supported by previous studies [10].

$$R = H \times \frac{V}{C} \quad (1)$$

Where  $R$  is flood risk,  $H$  is hazard threat,  $V$  is vulnerability, and  $C$  is adaptive capacity.

This multiplicative formulation reflects the non-linear interaction among the components, where risk increases when hazard and vulnerability are high,

and decreases with greater adaptive capacity. For example, even moderate hazard levels can result in high risk under conditions of high vulnerability and low capacity. Therefore, this formulation is consistent with established disaster risk theory and national risk assessment principles.

### 3.3 Economic Feasibility Evaluation

The economic feasibility evaluation in this study was carried out by considering benefit components, which include the improvement of traffic flow efficiency, protection of household assets and income, as well as the sustainability of economic activities in the agriculture, fisheries, plantation sectors, and public facilities. Meanwhile, the cost components consist of the construction costs for both structural and non-structural flood mitigation measures. Project feasibility was using discounted analysis through the Net Benefit–Cost Ratio parameter to evaluate the balance between long-term benefits and costs. The Benefit–Cost Ratio is the comparison between benefits and costs that have been adjusted to their present value.

The economic feasibility analysis was conducted over a 20-year evaluation period, as reflected in the projected annual cash flows from Year 1 to Year 20. This time horizon was selected to represent a long-term assessment period for flood mitigation infrastructure and to capture the recurring costs and benefits over the project lifecycle. A discounted cash flow approach was applied using Net Present Value (NPV) and Benefit–Cost Ratio (BCR) indicators. A discount rate of 10% was adopted as the base case to represent the time value of money in public investment evaluation. In addition, higher discount rates were tested to assess the sensitivity of the feasibility results.

The annual economic benefit was estimated as a constant value throughout the analysis period, representing the quantified economic gains from flood mitigation under the proposed alternative. These benefits were incorporated into the cash flow structure and compared against the investment and operational costs to determine overall project feasibility. The Benefit–Cost Ratio (BCR) is calculated as shown in Equation (2), based on discounted cash flow analysis within cost–benefit evaluation, following standard engineering economic principles commonly applied in infrastructure feasibility studies.

$$BCR = \frac{\sum_{t=0}^n \frac{B_t}{(1+r)^t}}{\sum_{t=0}^n \frac{C_t}{(1+r)^t}} \quad (2)$$

Where  $t$  is the year,  $r$  is the discount rate,  $B_t$  is the benefit in year  $t$ ,  $C_t$  is the cost in year  $t$  and  $n$  is the project lifespan (years). If the  $BCR$  value is greater than 1, the project is considered feasible. If the  $BCR$  value is less than 1, the project is considered not feasible to be implemented.

#### 4. RESULTS AND DISCUSSIONS

##### 4.1 Risk Analysis

Flood risk assessment in Indonesia has been regulated under the Head of BNPB Regulation No. 02 of 2012, which emphasizes the importance of hazard, vulnerability, and capacity analyses as the primary basis for determining the level of risk. Disaster risk will increase if an area has high levels of hazard and vulnerability while possessing low capacity, as such conditions indicate limited ability to prevent, respond to, and minimize the impacts caused by flood threats. In this study, the hazard, vulnerability, and capacity indices were spatially integrated using GIS at the urban village/rural village level to generate a risk map.

The GIS spatial overlay analysis was conducted using a vector-based approach. Hazard, vulnerability, and capacity indices were prepared as polygon layers. The overlay process involved spatial union operations to combine these thematic layers and generate composite risk units. Since all datasets were maintained in vector format, no raster resampling, spatial resolution adjustment, or interpolation technique was applied. The resulting overlay polygons represent spatial units where hazard, vulnerability, and capacity attributes coexist and were subsequently used for risk index calculation. The results of the flood risk analysis at the sub-district level in the Siak River Basin indicate that most areas fall into the medium-risk category. These findings indicate that the region, in general, still faces a significant potential impact of flooding and requires anticipatory efforts through continuous interventions.

Based on the results of the risk mapping as shown in Figure 1 and Table 14, Pekanbaru City is identified as the area with the highest number of sub-districts categorized as high risk, particularly in Payung Sekaki, Rumbai, Rumbai Pesisir, Senapelan, and Tenayan Raya Districts. Sub-districts included in the high-risk category consist of Labuh Baru Barat, Tirtasiak, Sri Meranti, Tebing Tinggi Okura, Padang Terubuk, Bencah Lesung, and Industri Tenayan. These areas exhibit high intensity of socio-economic activities and rapid land-use development, which increase vulnerability while limiting disaster response capacity, making them the dominant factors driving

the high flood risk.

Meanwhile, most of the other sub-districts in Pekanbaru City remain in the medium-risk category, particularly in Bukit Raya, Lima Puluh, Sukajadi, and Tampan Districts. This condition indicates that risk reduction efforts have been implemented, but they have not yet fully kept pace with the increasing flood threats. In addition, no sub-districts with a low-risk level were identified in Pekanbaru City, implying that the entire urban area must remain a top priority in flood risk management.

In the Siak Regency area, all urban villages and predominantly classified as medium-risk, including Bunga Raya, Koto Gasib, Mempura, Pusako, Siak, Sungai Mandau, and Tualang Districts. This condition indicates that although the levels of hazard and vulnerability in several locations are quite significant, the capacity of the community and local government to cope with floods is still relatively sufficient to prevent the risk level from escalating into the high-risk category. Only one area is recorded as being in the low-risk category, namely Merempan Hulu/Sri Gemilang Village in Siak District, which suggests that the capacity and resilience of this area are better compared to other regions.

In contrast to Pekanbaru City and Siak Regency, all affected areas in Kampar Regency fall under the medium-risk category, such as in Siak Hulu, Tapung, and Tapung Hilir Districts. The absence of urban villages categorized as low or high risk indicates that the risk level in this region is relatively homogeneous and can still be managed through strengthened mitigation capacity at the local level.

Overall, the analysis highlights that the downstream area of the Siak River Basin, particularly the urban area of Pekanbaru, represents the highest flood-risk zone and should be prioritized for intervention. This aligns with the fact that floods occur more frequently in urban areas due to the intense pressure of urbanization [11], which ultimately increases flood hazard threats in these regions. Enhancing community capacity and controlling land use become key strategies for reducing flood risk in the future.

Table 14. Recapitulation of the Risk Analysis for the Siak River Basin

City/District	Sub-districts	Villages	Risk Level per Village		
			Low	Medium	High
Pekanbaru City	11	48	0	41	7
Siak	8	40	1	39	0
Kampar	3	5	0	5	0

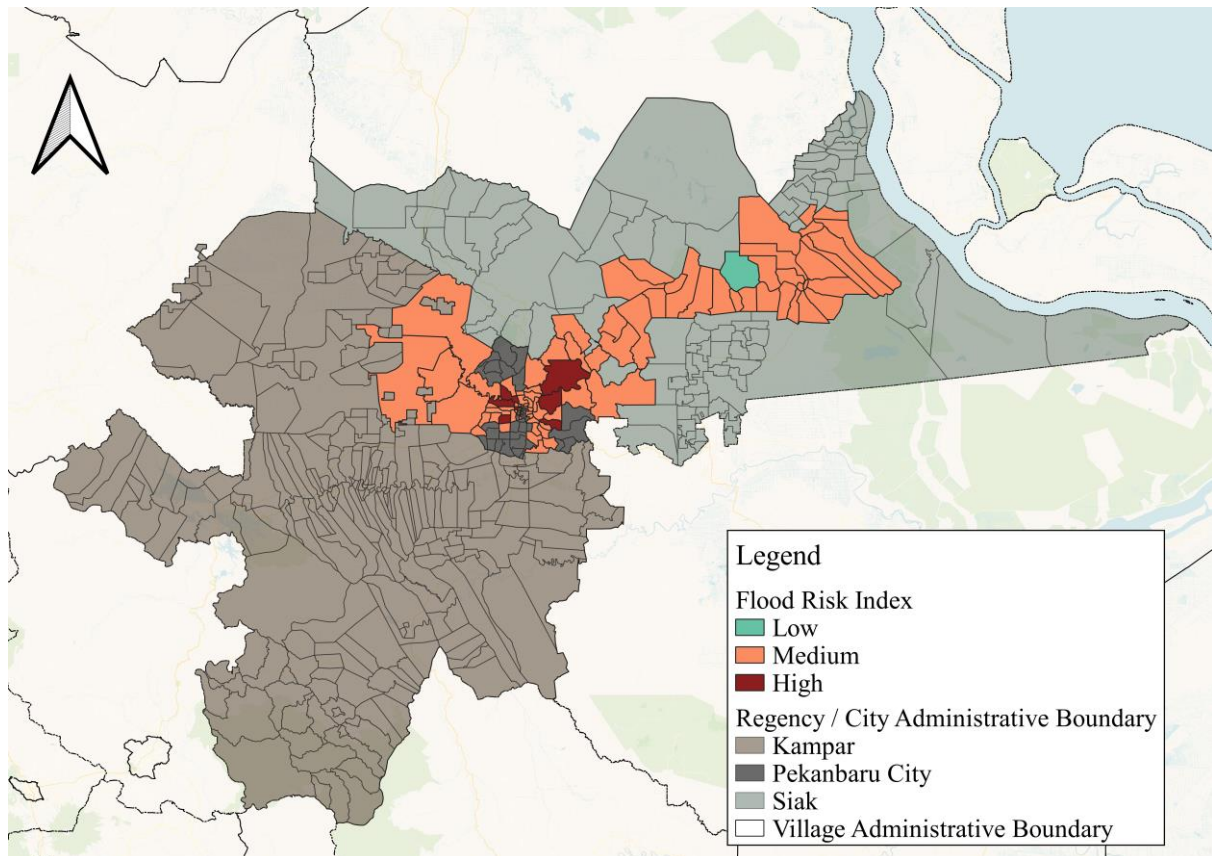


Fig.1 Flood Risk Map of the Siak River Basin

Therefore, flood risk management must regard the river basin as an integrated system that reflects the interconnection between natural conditions and human activities [12]. The current flood risk levels in the Siak River Basin are also influenced by the presence of existing flood-control infrastructure and land-use policies.

Several structural measures, such as embankments and pump stations, have already been implemented in urban areas, particularly in Pekanbaru City. These measures contribute to reducing flood duration in certain locations; however, their effectiveness is limited by increasing peak discharges resulting from upstream land-use changes and rapid urban expansion. The conversion of vegetated areas into built-up land, especially in peri-urban and upstream zones, has increased surface runoff and reduced natural retention capacity.

Although spatial planning policies (RTRW) aim to regulate land use within the river basin, enforcement challenges and development pressures may reduce their effectiveness in controlling flood risk. Therefore, the current medium-to-high risk levels observed in the downstream urban areas reflect not only hydrological conditions but also the cumulative

interaction between structural infrastructure capacity and ongoing land-use dynamics. These findings highlight the importance of integrating infrastructure-based mitigation with stricter land-use control and watershed-scale management strategies.

#### 4.2 Economic Feasibility Evaluation

The flood mitigation alternatives in the Siak River Basin consist of four physical intervention options, as presented in Table 15, which are designed to reduce the extent and depth of inundation in affected areas. To assess the economic effectiveness of each option, an engineering economic analysis was conducted as the basis for evaluating investment feasibility. This analysis aims to compare the total implementation costs of the flood mitigation measures with the economic benefits generated after the interventions are applied.

Previous studies indicate that the benefits of flood mitigation generally focus on the reduction of asset damage, decreased transportation disruptions, and increased agricultural productivity as direct outcomes of risk mitigation [13–14]. Therefore, in this study, the benefit components considered include the reduction of transportation activity

disruptions, decreased household asset damage, increased productivity in the agricultural sector as well as fisheries and plantation commodities, and improved community accessibility to public facilities. Meanwhile, the cost components consist of construction and non-construction expenses required for implementing each mitigation alternative. Accordingly, the economic analysis was carried out to identify the flood control alternative that provides the highest benefit relative to its cost, thereby enabling it to be recommended in the decision-making process.

Table 15. Alternatives for Flood Mitigation in the Siak River Basin

Scenario	Handling on the Main River	Handling on Tributaries
1	Construction of retention ponds at several locations within the Siak River Basin. Existing flood embankment with active pumps.	Normalization of Sail, Tenayan, Palas, Lukud, Parit Belanda, Sembilang, Pengambang, Takuana, Senepelan, Siban, and Teleju tributaries.
2	Normalization of Tapung Kiri River along 15 km. Existing flood embankment with active pumps.	Normalization of Sail, Tenayan, Palas, Lukud, Parit Belanda, Sembilang, Pengambang, Takuana, Senepelan, Siban, and Teleju tributaries.
3	Construction of Tapung Kanan and Tapung Kiri dams. Existing flood embankment with active pumps.	Normalization of Sail, Tenayan, Palas, Lukud, Parit Belanda, Sembilang, Pengambang, Takuana, Senepelan, Siban, and Teleju tributaries.
4	Construction of levees in the upstream, midstream, and downstream segments, equipped with flood pumps, gates, and flood detention/retention storage. Existing flood embankment with active pumps.	Normalization of Sail, Tenayan, Palas, Lukud, Parit Belanda, Sembilang, Pengambang, Takuana, Senepelan, Siban, and Teleju tributaries, and construction of tributary embankments supported by flood pump facilities at 8 locations.

Based on the cost–benefit calculations for each flood mitigation alternative, the resulting economic values vary considerably, as shown in Tables 16 and 17. Alternative 4 yields the highest total benefits, amounting to IDR 490,657,826,002, which is attributed to the largest reduction in inundation extent and more optimal protection of community assets compared with the other alternatives.

Conversely, Alternative 2 provides the lowest benefit, at IDR 19,935,785,525, due to its relatively small reduction in inundation.

In terms of investment costs, the differences between alternatives are also quite pronounced. Alternative 1 has the highest total cost, reaching IDR 3,039,522,834,055, due to the requirement for large-scale construction works. In contrast, Alternative 3 is the option with the lowest cost, amounting to IDR 330,706,020,747. This variation indicates that in a cost–benefit analysis, higher investment values do not necessarily yield proportional economic benefits, as evidenced by the differences in NPV values across alternatives in previous studies [15].

The evaluation based on the benefit–cost ratio (BCR) shows that Alternatives 1, 2, and 3 have BCR values < 1, indicating that they are not economically feasible. Meanwhile, Alternative 4 has a BCR ≥ 1, suggesting that the benefits generated are sufficient to cover all investment costs and provide a positive economic return. Therefore, Alternative 4 is the most viable option to be recommended as the priority for flood control infrastructure development in the Siak River Basin.

Table 16. Results of the Benefit–Cost Analysis (BCA)

Alternative	Total Benefits (IDR)	Total Costs (IDR)	BCR
Alt 1	53,677,997,560	3,039,522,834,055	< 1
Alt 2	19,935,785,525	1,728,396,219,202	< 1
Alt 3	93,927,930,054	330,706,020,747	< 1
Alt 4	490,657,826,002	754,304,901,668	≥ 1

Table 17. Effects of Flood Mitigation Alternatives on Inundation Area

Treatment / Scenario	Flood Inundation Area (Ha)
Existing Condition	9,465.74
Alternative 1	8,816.10
Alternative 2	9,239.32
Alternative 3	6,982.85
Alternative 4	3,177.00

## 5. CONCLUSIONS

The flood risk analysis at the sub-district level in the Siak River Basin indicates that most areas fall into the medium-risk category, with Pekanbaru City exhibiting the highest number of high-risk sub-districts due to high socio-economic exposure and limited adaptive capacity. No low-risk zones were identified in Pekanbaru, highlighting the urgency of

strengthened mitigation efforts in downstream urban areas. The hydraulic simulation results demonstrate that Alternative 4 provides the most significant reduction in inundation area, decreasing flood extent from 9,465.74 ha under existing conditions to 3,177.00 ha. The economic evaluation further confirms that Alternative 4 is the only scenario with a Benefit–Cost Ratio (BCR)  $\geq 1$ , generating total benefits of IDR 490,657,826,002, thereby making it economically feasible. In contrast, the other alternatives do not achieve economic viability despite lower investment costs. From a policy perspective, the findings emphasize that flood mitigation in the Siak River Basin should prioritize integrated structural measures combined with pump systems and tributary embankments, as represented by Alternative 4. However, structural interventions alone are insufficient. Strengthened land-use control, enforcement of spatial planning policies, and enhancement of community preparedness are equally critical to sustainably reduce flood risk. The integration of spatial risk assessment and economic feasibility analysis demonstrated in this study provides a practical decision-support framework for local governments in allocating limited public resources more effectively. Future research should incorporate climate change scenarios and uncertainty analysis to improve the reliability of flood risk and economic evaluations. In addition, the integration of nature-based solutions and the inclusion of indirect economic benefits are recommended to enhance the sustainability of flood mitigation strategies. Furthermore, the development of real-time, data-driven flood risk assessment systems is also suggested to support adaptive flood management in rapidly urbanizing areas.

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## 7. ABBREVIATIONS

Table 18. Journal Abbreviations

Journal Abbreviations	
BNPB	National Disaster Management Agency
BPBD	Regional Disaster Management Agency
PUPR	Ministry of Public Works and Housing
ATR/BPN	Ministry of Agrarian Affairs and Spatial Planning / National Land Agency
GIS	Geographic Information System
HEC-RAS	Hydrologic Engineering Center – River Analysis System

HEC-RAS 2D	Two-Dimensional Hydrologic Engineering Center – River Analysis System
BCA	Benefit Cost Analysis
BCR	Benefit Cost Ratio
Net B/C	Net Benefit Cost Ratio
IDR	Indonesian Rupiah
IKM	Community Preparedness Index
LIPI	Indonesian Institute of Sciences

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