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Urban Flood Risk Management Based on Asset Life Cycle Method for Drainage System: Case Study Gedebage Area, Bandung, Indonesia

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ABSTRACT

Flooding is a natural phenomenon influenced by various factors and occurs frequently across many regions in Indonesia, including Gedebage in Bandung City, West Java. Gedebage is one of the city's lowest-lying areas, with an elevation of 666–669 meters above sea level, making it particularly prone to recurrent flooding. The main issue is the absence of an integrated disaster management system. This research aims to identify the drainage system's asset life cycle (planning, implementation, and operation & maintenance) and assess flood risk in Gedebage. The risk assessment was conducted using questionnaires to evaluate the likelihood and potential impact of risks. In response to major risks, appropriate mitigation strategies were developed. Mitigation efforts included both structural and non-structural measures. The structural mitigation design involved selecting technological alternatives using the Analytical Hierarchy Process (AHP), a decision-making tool that helps compare multiple criteria and alternatives in a structured way. The results indicate that 27% of the assessed risks were unacceptable, 42% undesirable, and 31% acceptable. Flood risk in Gedebage can be managed through structural actions, such as drainage revitalization using a closed system, and non-structural strategies, including human-centric, administrative, and cultural approaches. Based on AHP analysis,

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the most effective technology was a closed drainage system and porous paving blocks.

Keywords: Urban Floods; Risk Management; Mitigation

1. Introduction

Flooding is a natural phenomenon influenced by multiple factors, such as heavy rainfall, rapid urbanization, inadequate drainage systems, poor waste management, watershed degradation, and poor urban planning [1,2]. This risk is further intensified by global climate change. The Intergovernmental Panel on Climate Change (IPCC, 2022) highlights with high confidence that the future risk of urban flooding is expected to increase in line with continued rises in global surface temperatures [3]. In Indonesia, flooding remains a persistent challenge, particularly in urban areas with poor drainage systems. Gedebage, located in the eastern part of Bandung, West Java, is one of the most flood-prone areas [4–9]. Topographically, Gedebage lies at an elevation of just 666–669 meters above sea level, making it one of the lowest-lying areas in the city [10,11].

Urban flooding in Gedebage frequently occurs in residential areas due to a combination of inadequate drainage capacity and rapid urbanization, which increases impermeable surfaces and runoff [12]. Intense rainfall over a short period often causes flooding in several parts of Gedebage, with water depths reaching 16–40 cm. The flooding lasts between 2 to 8 hours, covering 3 to 12 hectares, and occurs 5 to 8 times per year. Additionally, the accumulation of domestic waste in drainage channels further obstructs water flow, exacerbating the flooding problem [11,13,14]. Previous studies have attempted to map flood-prone locations in Gedebage. For example, Triningsih and Juwana identified key flood-prone areas in Gedebage District, including the Adipura Residential Complex, SOR GBLA Road, and South Gedebage Road [15]. However, a specific urban flood risk management study focused on Gedebage remains limited.

A critical aspect of flood risk management is understanding how flood risks manifest across different stages of infrastructure development. This aligns with Priority 1 of the Sendai Framework for Disaster Risk Reduction 2015–2030, which emphasizes that disaster risk management must be grounded in a comprehensive understanding of disaster risks in all their dimensions [16]. In the case of drainage systems, risks emerge throughout their asset life cycle, from initial planning and design to implementation and long-term maintenance [17]. These risks are not clearly identified, particularly major risks that could serve as the basis for effective mitigation strategies. By systematically identifying these risks, flood mitigation strategies can be tailored according to each phase of the drainage system's development and operational lifespan. Through risk identification, risks can be categorized based on asset life cycle stages [18], allowing mitigation efforts to be implemented according to risk levels.

Currently, Gedebage's drainage system primarily employs conventional methods, which lack adaptability to changing environmental conditions and increasing urbanization. This rigidity results in system inefficiencies and excessive runoff during heavy rainfall. Moreover, the lack of an asset life cycle-based approach in drainage planning has resulted in infrastructure deterioration, higher maintenance costs, and reduced system reliability over time. In light of the increasing severity and frequency of floods, a shift is needed from reactive flood management, which focuses on post-event responses, to a proactive and integrated risk-based approach that enhances urban flood resilience [19,20]. A literature review and regulatory analysis can help identify the most effective mitigation strategies, integrating both structural and non-structural approaches to flood risk management.

Flood mitigation strategies can be categorized into structural and non-structural approaches [21]. Structural mitigation focuses on technical interventions and engineering solutions [22], including the selection of appropriate construction technologies. To support decision-making, the Analytical Hierarchy Process (AHP) can be applied to evaluate alternative technologies based on factors such as cost, execution process, land and material availability, time, and functionality [23,24]. AHP is suitable due to its ability to compare multi-criteria alternatives in a systematic and structured manner. Meanwhile, non-structural mitigation emphasizes human resources, regulations, and policies, as well as societal and cultural measures [25,26]. The AHP method can also measure the consistency of decision maker's judgments since the government stakeholders become the main sources during the interview process of field observation in this research. Government institutions and organizations also play a critical role in flood mitigation. A study by Soeharno et al. found that improving organizational behavior dynamics significantly enhances flood mitigation capacity [27].

Recognizing the crucial role of institutional and governmental bodies, this study involves experts and personnel from the Department of Water Resources and Highways (DWRH)/Dinas Sumber Daya Air dan Bina Marga (DSDABM) of Bandung City, who are directly responsible for managing the drainage network. Their insights are essential for identifying key risks within the drainage infrastructure and evaluating sustainable strategies for risk reduction.

Furthermore, in supporting structural mitigation efforts, a proactive drainage conceptual design is essential. It must be effective, sustainable, efficient, and technology driven. However, conventional drainage planning often prioritizes short-term reactive measures rather than long-term resilience. Drainage planning and management are often reactive, responding to flood events and leading to emergency situations due to unexpected asset failures. Instead, a proactive approach that includes comprehensive planning can minimize the total cost of ownership and operation while continuously delivering the expected level of service at an acceptable risk level [28].

The adoption of closed drainage systems should be seriously considered. A closed drainage system is an urban drainage system that consists of a network of closed conduits designed to collect runoff and transport it through enclosed channels to terminal points where the water is either treated or discharged into a channel or lake [29]. These systems can help prevent solid waste from entering the drainage network, which is a major issue in Gedebage due to domestic waste accumulation from residential areas and traditional markets. By implementing a closed drainage system, water flow efficiency can be significantly improved while minimizing blockages caused by improper waste disposal.

Additionally, selecting appropriate construction technologies is crucial for improving Gedebage's drainage system. The application of innovative material-based technologies offers sustainable solutions, with one proven approach being the use of permeable paving blocks [30]. These blocks facilitate water infiltration into the ground [31], reducing surface runoff [32], alleviating pressure on the drainage system, and increasing water absorption capacity in urban environments [33]. Future developments of permeable paving blocks can be focused on enhancing material durability, cost-effectiveness, and environmental sustainability.

Given these challenges, this study seeks to address a critical research gap in flood risk management in Gedebage. Previous studies have highlighted flood-prone locations and general risk factors, but a comprehensive risk-based drainage planning approach remains limited. This study specifically aims to identify key factors influencing urban flood risk in Gedebage, with a focus on major risk categories and the maintenance of drainage systems in affected areas. Moving beyond short-term solutions is essential, and this study also examines the asset life cycle of Gedebage's drainage network to support the long-term resilience of existing infrastructure. In addition to risk assessment, flood mitigation strategies must be developed to address major risks (unacceptable risks) at both the governmental policy level and the community level in Gedebage.

2. Methods

A conceptual framework (**Figure 1**) was developed around three key components: flood risk in Gedebage [5–9,11–13,15,27], the asset life cycle of drainage systems [18,19,23,24], and risk management [34,35]. Building on these components, this study aims to address a key research gap by exploring how risk management can be applied throughout the asset life cycle of drainage systems in Gedebage.

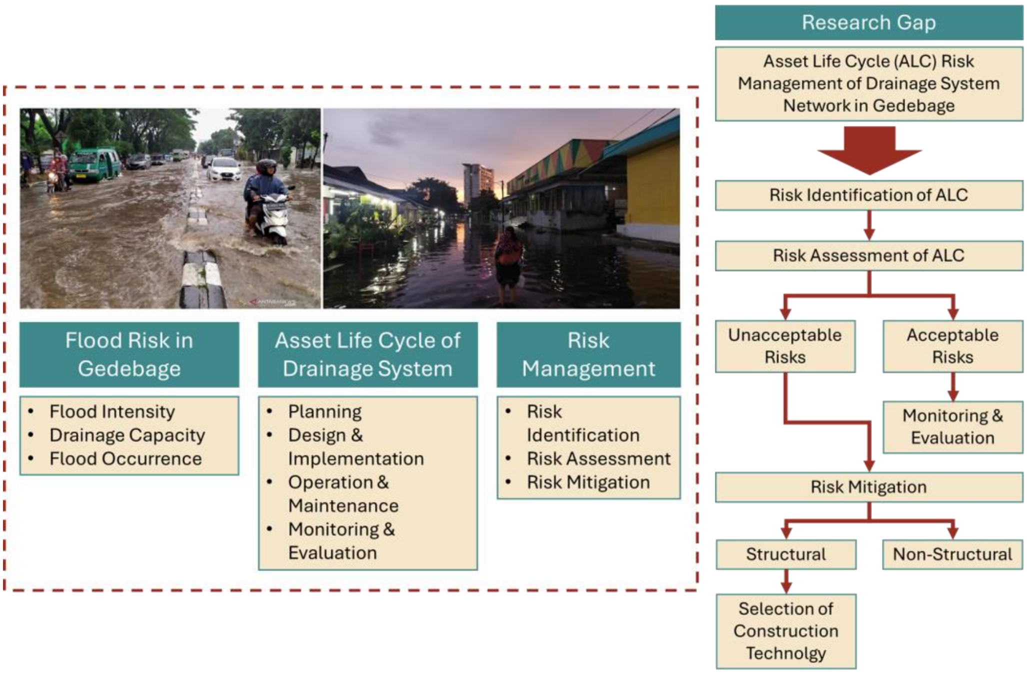

Figure 1. Conceptual framework.

The data in this study are classified into primary and secondary sources. Primary data were obtained directly through field observations, interviews, and questionnaires to understand the existing drainage system and gather stakeholder insights. Secondary data were sourced from pre-existing materials compiled and analyzed by other parties, including literature and official documents on urban flood risk management and flood risk analysis in Gedebage.

Data collection was carried out in two stages. The first stage involved passive field observations and interviews with the local community, alongside secondary data collection. Observations were conducted by visually assessing the existing drainage system, while interviews provided insights into past and ongoing waste-related issues affecting the system. This was followed by a literature review to identify relevant risks, which were cross-checked with the observed field conditions. The literature review covered peer-reviewed journal articles, conference proceedings, academic theses, and official publications published between 2012 and 2024. Sources were selected based on their relevance to urban flood risk, drainage system asset management, and risk assessment frameworks. Key publications included studies from Sinayangsih and Purbawijaya [11,36].

In the second stage, data were collected through structured interviews based on a questionnaire format. Although the instrument used was a questionnaire, the questions were delivered directly by the researcher during the interviews to ensure clarity and consistency in responses. Respondents were selected through purposive sampling based on their expertise and relevance to the research topic. The research methodology is further illustrated in **Figure 2**.

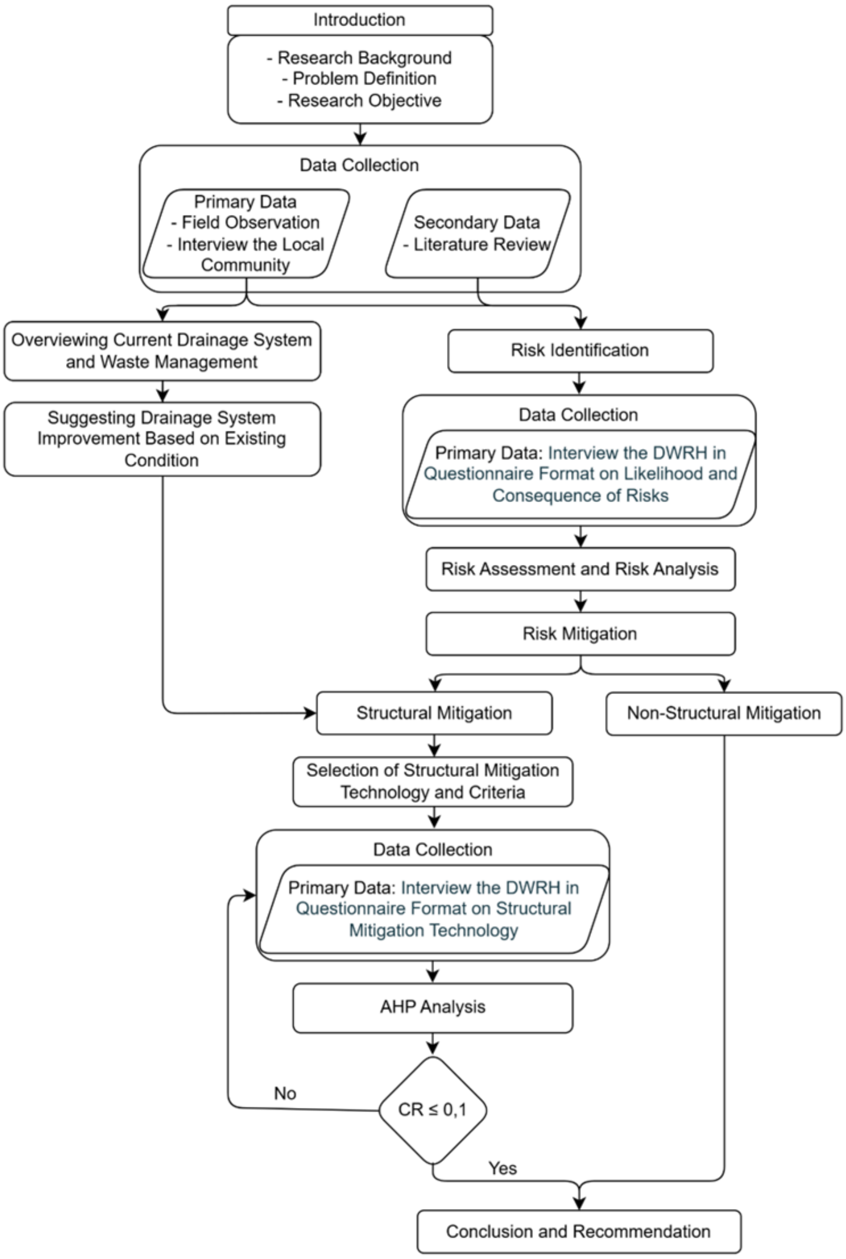

Figure 2. Research methodology.

The questionnaire was designed to assess stakeholders' perspectives on key flood risk management factors in Gedebage's drainage system. It consisted of two sections. The first section required respondents to assess the probability and impact of each risk identified in Gedebage's drainage system using a 1–5 scale for both likelihood/frequency and consequences, referring to Regulation No. 4 of 2008 by the National Disaster Management Agency (NDMA). The second section focused on the selection of structural mitigation technologies, using a pairwise comparison approach with a 1–9 scale to indicate the intensity of respondents' preferences. This section evaluated six different criteria to determine the criteria weights and three construction/material technologies for closed drainage systems, assessing each technology against the specified criteria.

According to the IPCC (2022), a wide range of decision-analytic methods can support climate risk management, including Bayesian methods, interval methods, decision-making under deep uncertainty, cost-benefit analyses, multi-criteria decision analysis (MCDA), and general decision support tools. Among MCDA techniques, methods such as AHP have been widely applied due to their use of multi-attribute value functions and structured weighting of conflicting objectives. Although AHP has limitations in scaling for a large number of alternatives, it remains suitable for the relatively limited scope and scale of policy alternatives in this study, thus justifying its application [3].

A total of 16 professionals from the Department of Water Resources and Highways (DWRH) of Bandung City participated in the study. These respondents had expertise in hydrology, drainage planning, construction, and operations & maintenance. Their profiles are summarized in **Table 1**.

Table 1. Respondent profile.

Number of Respondents	Division in the DWRH of Bandung City	Percentage
5	Drainage and Sidewalks	31.25%
4	Water-Related Damage Control	25.00%
4	Regional Technical Implementation Unit for Operations and Maintenance of the Gedebage Area	25.00%
3	Personnel Administration Secretariat	18.75%

The urban flood risk management analysis for Gedebage's drainage system asset life cycle began with risk identification. This stage utilized insights obtained from earlier field observations, interviews, and literature reviews. Based on the identified risks, a risk assessment was conducted by evaluating the likelihood and consequences of each risk using the severity index from Regulation No. 4 of 2008 by the National Disaster Management Agency (NDMA) [34].

The next step involved risk analysis and assessment, using data collected through structured interviews based on a questionnaire format conducted. This process aimed to identify and evaluate risks associated with the asset life cycle of the drainage network system. The assessment was based on respondents' perceptions, with the median value of their responses used to represent the likelihood and impact of each identified risk.

The subsequent step focused on developing structural and non-structural mitigation strategies to address the identified risks, with particular emphasis on unacceptable risks. The assessment of disaster risk values was carried out using the following approach, as shown in Equation (1) [35]:

$$R = \mathrm{L} \times \mathrm{C} \tag{1}$$

The disaster risk value (R) quantifies risk based on two key factors: likelihood (L) and consequence (C). Likelihood represents the probability of an adverse event occurring, while consequence measures the resulting impact or loss.

According to NDMA Regulation No. 4 of 2008, the risk value is determined by combining these two factors, where likelihood reflects the frequency or tendency of occurrence, and consequence quantifies the associated losses [34]. Additionally, risk acceptability is analyzed based on the calculated risk value. As noted by Godfrey, the assessment of risk acceptability involves evaluating the exten t to which a given risk value can be deemed acceptable [35]. The risk acceptability matrix is shown in **Figure 3**.

The risk acceptability scale, shown in **Table 2**, categorizes risks based on their value derived from likelihood and consequence. Unacceptable risks (≥15) must be eliminated or transferred. Undesirable risks (8–15) should be minimized but can be tolerated with mitigation.
Acceptable risks (3–8) pose no significant threat and need no further reduction. Negligible risks (<3) are insignificant and require no action. This scale helps prioritize risk management based on severity.

Assessment of Risk Acceptability					
Consequence / Likelihood	Catastrophic (5)	Critical (4)	Serious (3)	Marginal (2)	Negligible (1)
Frequent (5)	Unacceptable (25)	Unacceptable (20)	Unacceptable (15)	Undesirable (10)	Acceptable (5)
Probable (4)	Unacceptable (20)	Unacceptable (16)	Undesirable (12)	Undesirable (8)	Acceptable (4)
Occasional (3)	Undesirable (15)	Undesirable (12)	Undesirable (9)	Acceptable (6)	Acceptable (3)
Remote (2)	Undesirable (10)	Undesirable (8)	Acceptable (6)	Acceptable (4)	Negligible (2)
Improbable (1)	Acceptable (5)	Acceptable (4)	Acceptable (3)	Negligible (2)	Negligible (1)

Description
Unacceptable: Must be eliminated or transferred
Undesirable: Should be avoided if possible
Acceptable: Risk does not need to be reduced further
Negligible: Insignificant and does not need to be considered

Figure 3. Risk acceptability matrix [35].

Table 2. Risk acceptance scale.

Risk Acceptance Indicators	Acceptance Scale
Unacceptable	$X \geq 15$
Undesirable	$8 \leq X < 15$
Acceptable	$3 \leq X < 8$
Negligible	$X < 3$

Risk mitigation recommendations include preventive, reduction, and risk transfer measures, which can be categorized into structural and non-structural approaches. The selection of structural mitigation strategies is based on evaluating available construction technology alternatives using the AHP.

By applying AHP, decision-makers can systematically and objectively assess various alternatives. The Consistency Ratio (CR) is used to measure deviations in the comparison matrix, where the CR value must be ≤ 0.1. Based on experimental studies and previous applications, a comparison matrix is considered acceptable if its maximum CR value does not exceed 10%, representing a tolerable level of inconsistency. If the CR exceeds this threshold, revisions are required to ensure accuracy and prevent errors in the decision-making process.

The AHP analysis begins with an assessment of decision-making criteria using pairwise comparisons. According to Saaty, a 1-to-9 scale is the most effective method for expressing relative judgments in decision-making scenarios [37]. Each criterion is assigned to weight based on its importance and priority. To ensure objectivity in weight determination, the assessment relied on input from respondents at the DWRH of Bandung City, as detailed earlier.

The criteria used in the AHP calculation include: the efficiency of implementation costs, the size of the area covered by the drainage network subsystem, the duration of the implementation process, the feasibility of execution in the field, the accessibility of materials in the market, and the drainage system's capability to reduce runoff effectively. By incorporating these criteria, the AHP approach ensures a structured and comprehensive evaluation for decision-making.

Building on the established criteria, the next step in the AHP process involves quantifying these criteria through a pairwise comparison matrix. The weighting of the criteria comparison matrix is derived from the geometric mean of responses collected through questionnaires completed by 16 respondents. Reciprocal values for comparisons are calculated as 1 divided by the geometric mean of the responses. The sum of each criterion is used to calculate its weight, followed by normalization, where each value in the criteria table is divided by the total sum of the criteria values.

The calculated weights for both criteria and alternatives are synthesized to produce final results. At the criteria level, pairwise comparisons determine the relative importance of each criterion, providing a consistent and objective basis for decision-making. This process ensures that alternative evaluations align with stakeholder priorities, supporting the selection of the most suitable option.

After determining the normalized weights for each criterion, the AHP method prioritizes alternatives by calculating eigenvectors and eigenvalues through matrix operations, where the eigenvector determines the ranking of the selected alternatives, while the eigenvalue measures the consistency of the comparison process [38]. This ranking is represented by the priority vector, obtained by normalizing the principal eigenvector. The priority vector (V_j) is calculated by multiplying the comparison matrix with the weight vector, as presented in Equation (2):

$$V_j = K_{ij} \times w_i \tag{2}$$

where K_{ij} is a matrix structured as shown in Matrix (3):

$$\begin{bmatrix} w_{11} & w_{12} & \dots & w_{1p} \\ w_{21} & w_{22} & \dots & w_{2p} \\ \dots & \dots & \dots & \dots \\ w_{n_1} & w_{n_2} & \dots & w_{n_p} \end{bmatrix} \tag{3}$$

After determining the priority rankings using eigenvectors and eigenvalues, the next step is to evaluate the consistency of the comparison matrix. The consistency of the matrix is measured based on the maximum eigenvalue used to assess consistency (λ_{max}). The closer λ_{max} is to the number of elements in the matrix (n), the more consistent the results are. This consistency is measured using the Consistency Index (CI), as shown in Equation (4):

$$CI = \frac{(\lambda_{max}) - n}{n - 1} \tag{4}$$

where CI is the Consistency Index, λmax is the maximum eigenvalue, and n is the number of elements in the matrix. Additionally, the Random Index (RI) is used to provide an average consistency index based on random experiments for matrices of orders 1 to 15. The Consistency Ratio (CR) is then determined using the formula shown in Equation (5):

$$CR = \frac{CI}{RI} \tag{5}$$

According to Saaty (1987), the comparison matrix is considered acceptable if the consistency ratio (CR) is less than 0.1. This indicates that the comparison matrix has a sufficient level of consistency to be used in decision-making [37].

3. Results and Discussion

3.1. Gedebage Area Profile

The Gedebage area has a drainage system composed of both closed and open types. Observations indicate that approximately 80% of the drainage system in Gedebage is closed. However, waste management issues significantly affect its functionality. Observations and interviews with residents reveal that many households in Gedebage lack permanent waste storage facilities due to limited land availability. This problem is further aggravated by infrequent waste collection, which occurs only once a week and is managed by local neighborhood associations.

In contrast, Summarecon Bandung—a privately owned township in Gedebage, developed by PT Summarecon Agung Tbk., consisting of residential and commercial areas—has a more structured waste management system. The area features daily waste collection and permanent waste storage facilities for each household. Meanwhile, in other areas, the lack of proper waste storage and irregular collection schedules contribute to garbage accumulation and dispersal, which in turn clogs the drainage system and exacerbates flooding issues. An example of the drainage condition in Gedebage is shown in **Figure 4**. The layout of Gedebage is also crucial in understanding the drainage challenges faced by the area. **Figure 5** provides an overview of the Gedebage area, highlighting key features such as the roads and waterways.

Figure 4. Condition of the drainage system in Gedebage.

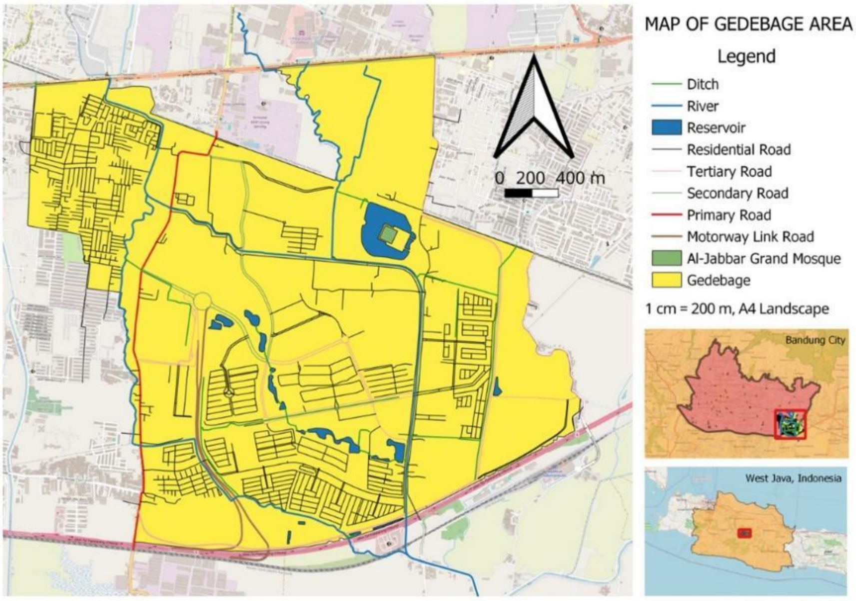

Figure 5. Map of Gedebage area.

3.2. Risk Identification

Risk identification was conducted by compiling a list of risks observed from field observations and identified in the literature review of previous studies on flood risk management in drainage system networks [11,36]. The identified risks are categorized according to the asset life cycle of the urban drainage system in Gedebage, which includes the Planning, Implementation, and Operation & Maintenance phases. The risks identified during the planning phase are presented in **Table 3**, those in the implementation phase in **Tables 4**, and those in the operation and maintenance phase in **Table 5**.

Table 3. Identified risks in the planning phase.

Risk Code	Risk Variable
1	Drainage planning is focused on local issues and lacks system integration
2	Obstacles in providing compensation for land use by the community for the planned construction of drainage diversion channels/secondary drains
3	Obstacles in socializing the community regarding the planned development of the drainage network
4	The limited number of waste filters installed in the secondary drainage channels
5	Lack of clarity from the relevant authorities regarding the disappearance of drainage networks in land consolidation development areas
6	Public complaints and rejection of the planning results due to insufficient socialization
7	Unclear flow pattern of the drainage system in tertiary channels
8	Unresolved waterlogging in basin areas due to the lack of drainage facilities
9	Many secondary drainage networks that have not been normalized
10	Many tertiary drainage networks that have not been normalized.
11	Obstacles in socializing with the community to prevent waste from being disposed of in drainage channels
12	Difficulties in changing the dimensions of tertiary channels due to permanent blockage
13	Difficulties in changing the dimensions of secondary channels due to permanent blockage
14	Decreased infiltration areas due to rapid land conversion into residential areas
15	Challenges in land acquisition for drainage channel development
16	Lack of continuity in the preparation of Detailed Engineering Design (DED) for the improvement of the drainage network system
17	Implementation of socialization to encourage community participation in the construction of infiltration wells for each household in the Gedebage area

Table 4. Identified risks in the implementation phase.

Risk Code	Risk Variable
18	Incompatibility between the dimensions of the drainage facility profile and the channel dimensions
19	Construction of the channel profile does not follow the profile recommended in the planning
20	The discrepancy between the project implementation results and the planning outcomes
21	Lack of control over the channel base slope in the implementation results
22	Non-compliance of the implementation results with the specified requirements
23	Flood management implementation remains patchwork and reactive
24	The contractor's proposed execution method is not suitable.
25	Material procurement does not comply with technical specifications
26	Obstacles in execution due to utility networks embedded in the base of the tertiary channels
27	Many street inlets are covered by road pavement due to overlay
28	Irregular placement of street inlets along the tertiary channel
29	Unclear flow pattern due to the construction of tertiary channels following road terrace elevation
30	Field measurements to determine the position of points, lines, elevation, and the accuracy of elevation measurements are inconsistent with the planning drawings
31	Health and safety conditions are not well assured, especially in drainage channels contaminated with waste
32	Obstacles in land acquisition
33	Obstacles in field execution related to the role of the community
34	Obstruction in water flow due to the base elevation of the tertiary channel being higher than the secondary channel's base elevation

Table 5. Identified risks in the operation and maintenance phase.

Risk Code	Risk Variable
35	Obstacles in monitoring residential development by relevant authorities along the primary channel
36	Obstacles in monitoring residential development by relevant authorities along the secondary channel
37	Limited availability of supporting equipment for operation and maintenance (O&M)
39	Obstacles in routine monitoring and security of the drainage network due to water and human damage
40	Lack of field personnel on relevant authorities in monitoring the functionality of the channels and its facilities
41	Limited availability of sluice gates and waste filters in secondary drainage channels
42	Inspection roads along primary channels are decreasing due to residential development
43	Lack of monitoring and evaluation of the physical condition of the entire drainage network
44	Effectiveness of the channels decreases due to high sedimentation levels in the tertiary drainage channels
45	Effectiveness of the channels decreases due to high sedimentation levels in the secondary drainage channels
46	Operational maintenance costs not in line with estimates
47	Limited availability of funds for O&M implementation
48	The public perception that drainage channels are private property
49	Public habit of littering and dumping waste into drainage channels
50	Obstacles in efforts to improve staff capabilities in drainage O&M
51	Slow rehabilitation of the drainage network to restore its function and service due to limited operational funds
52	Slow waste management in drainage channels due to insufficient operational vehicles
53	Obstacles in waste cleaning due to the widespread distribution of waste in the tertiary network
54	Obstacles in waste cleaning due to the widespread distribution of waste in the secondary network
55	Obstacles in waste cleaning due to the widespread distribution of waste in the primary network

3.3. Risk Assessment

An analysis of risk acceptability is conducted, which depends on the risk value determined by the product of likelihood (frequency) and consequences of the risk. The purpose of the risk assessment is to identify potential risks, rank them from highest to lowest value, and address the majority of relevant risks that can be controlled. The summary of risk assessments conducted by the respondents is presented in **Table 6** for the planning phase, **Table 7** for the implementation phase, and **Table 8** for the operation and maintenance phase.

Table 6. Risk assessment in the planning phase.

Risk Code	L	C	Risk Assessment	Acceptance Level
Technical Risk				
1	4	4	16	Unacceptable
4	3	3	9	Undesirable
7	4	4	16	Unacceptable
8	4	4	16	Unacceptable
9	4	3	12	Undesirable
10	4	3	12	Undesirable
16	2	3	6	Acceptable
Economy Risk				
2	3	4	12	Undesirable
15	3	3	9	Undesirable
Human Risk				
3	2	3	6	Acceptable
6	3	3	9	Undesirable
11	4	4	16	Unacceptable
12	4	4	16	Unacceptable
13	3	4	12	Undesirable
17	2	3	6	Acceptable
Political Risk				
5	1	3	3	Acceptable
14	3	4	12	Undesirable

Table 7. Risk assessment in the implementation phase.

Risk Code	L	C	Risk Assessment	Acceptance Level
Project Risk				
18	3	4	12	Undesirable
19	3	4	12	Undesirable
20	2	4	8	Undesirable
21	2	4	8	Undesirable
22	1	3	3	Acceptable
24	3	3	9	Undesirable
25	1	3	3	Acceptable
30	2	3	6	Acceptable
23	4	4	16	Unacceptable
26	4	4	16	Unacceptable
27	2	3	6	Acceptable
28	2	3	6	Acceptable
29	4	4	16	Unacceptable
34	3	4	12	Undesirable
Safety Risk				
31	31	31	31	31
Economy Risk				
32	4	3	12	Undesirable
Human Risk				
33	3	3	9	Undesirable

Table 8. Risk assessment in the operation and maintenance phase.

Risk Code	L	C	Risk Assessment	Acceptance Level
Technical Risk				
35	1	4	4	Acceptable
36	2	4	8	Undesirable
41	4	4	16	Unacceptable
43	3	4	12	Undesirable
Economy Risk				
37	2	3	6	Acceptable
38	2	3	6	Acceptable
40	2	4	8	Undesirable
51	2	3	6	Acceptable
Environmental Risk				
39	3	4	12	Undesirable
44	4	4	16	Unacceptable
45	4	4	16	Unacceptable
46	1	3	3	Acceptable
47	1	3	3	Acceptable
49	4	4	16	Unacceptable
53	4	4	16	Unacceptable
54	4	4	16	Unacceptable
55	3	4	12	Undesirable
Political Risk				
42	2	2	4	Acceptable
Human Risk				
48	4	4	16	Unacceptable
50	2	2	4	Acceptable

The risks contributing to urban flooding in the Gedebage area are analyzed through the asset life cycle of the urban drainage system, encompassing the planning, implementation, and operation & maintenance (O&M) phases. This suggests that undesirable risks are most dominant during the planning and implementation phases, indicating gaps in early strategic formulation and field execution. Meanwhile, the highest proportion of unacceptable risks occurs in the operation and maintenance phase, suggesting that existing systems are not yet robust enough to ensure the effectiveness and sustainability of the drainage infrastructure. Overall, across all phases, there are 15 unacceptable risks (27%), 23 undesirable risks (42%), and 17 acceptable risks (31%), with no risks categorized as negligible. The summary of risk assessments for the different phases is shown in **Figure 6**.

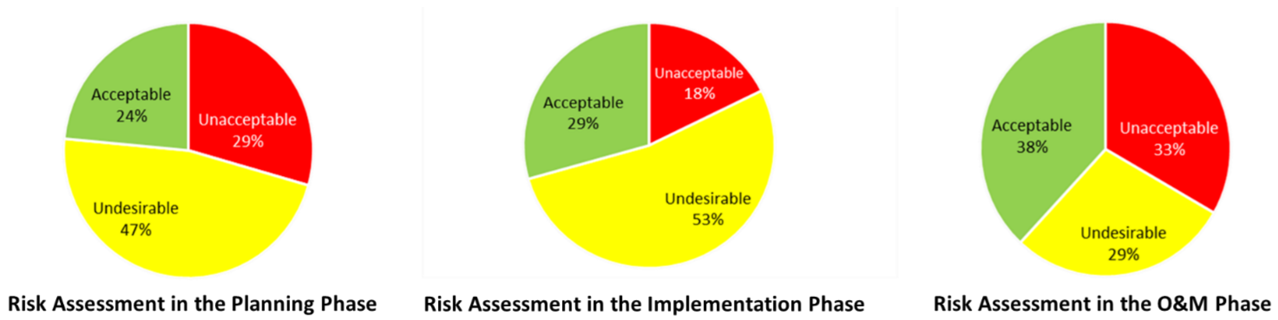

Figure 6. Summary of risk assessments for the different phases.

At the planning phase, major risks were identified in both the technical and human risk variables. The technical risk stems from the lack of an integrated drainage system plan, which points to policy gaps in long-term infrastructure planning and coordination across various sectors (e.g., urban development, water management). The human risk arises from challenges in community engagement, particularly in discouraging behaviors such as obstructing drainage and disposing of waste in drainage channels. This reflects a gap in public policy and education, where insufficient outreach and enforcement measures fail to promote community responsibility and awareness regarding proper waste disposal.

During the implementation phase, the project risk variable poses a major risk, primarily due to reactive and patchwork repair approaches. The lack of integration between drainage maintenance, road development, and utility management further exacerbates this issue. This suggests a policy gap in the coordination between urban planning and infrastructure maintenance, where fragmented and siloed approaches to urban development and infrastructure management fail to create resilient and sustainable systems.

At the O&M phase, major risks were observed in the technical, environmental, and human risk variables. The technical risk is attributed to the limited number of water gates and trash filters in drainage channels, highlighting a policy gap in investing in modern and adequate infrastructure for flood management. The environmental risk is driven by reduced drainage effectiveness due to high sedimentation levels and the difficulty of waste removal caused by widespread waste accumulation. This points to policy gaps in environmental management and waste management infrastructure, where inadequate policies to address pollution and sedimentation in urban drainage systems lead to diminished system performance. The human risk is influenced by the community's perception that drainage channels are part of their private property, leading to improper use and maintenance challenges. This indicates a policy gap in public awareness and ownership, as well as insufficient community engagement strategies to ensure proper maintenance and protection of public infrastructure.

3.4. Risk Response

If these risks are deemed unacceptable, stakeholders must develop strategies to mitigate them and reduce risk levels to the minimum possible extent. Based on the risk assessment results, the following mitigation approaches can be implemented.

3.4.1. Technical Approach

The failure of drainage systems to effectively channel runoff due to sedimentation and garbage accumulation can be mitigated through the revitalization of a closed drainage system. According to Abda, closed drainage systems are particularly well-suited for urban areas, as they efficiently manage wastewater while requiring less surface area [39]. Unlike open channels, closed systems prevent sediment and waste buildup, ensuring smoother and more effective water flow. This is particularly important in regions where sedimentation poses a significant challenge. For instance, a study conducted on the Cisokan River analyzed the risks associated with debris and non-debris flows caused by sedimentation and changes in the river's cross-section. The results revealed that the flood inundation area for debris flow was 12.5% larger than that for non-debris flow, highlighting the heightened flood risks linked to debris flow [40].

Given that closed drainage systems offer various construction technologies, it is crucial to conduct a thorough comparative analysis to determine the most appropriate option for the Gedebage area. This selection process should consider key factors such as implementation cost, construction timeline, land availability, technical feasibility, material accessibility, and long-term functionality. To support this multi-criteria decision-making, the Analytic Hierarchy Process (AHP) is applied and is further discussed in Section 3.5 of this paper.

3.4.2. Social Approach

A study by Kastolani et al. highlights that in Bandung, the increasing population and activities have led to greater waste production, but the community's participation in waste management remains low, as evidenced by the exceeding capacity of Temporary Disposal Sites (TDS) and the lack of institutionalized efforts to encourage environmental cleanliness [41]. They are more inclined to follow existing government programs rather than initiate or encourage community involvement. Based on these findings, mitigation efforts should include community outreach and awareness campaigns focused on flood risks and environmental responsibility. This can be achieved by educating residents on flood hazards and promoting compliance with Regional Regulation of Bandung City Number 9 of 2018 on Waste Management [42].

3.4.3. Administrative Approach

In addition to the technical and social measures, the government has established a comprehensive regulatory framework for water resources through Law Number 17 of 2019 and for waste management through Regional Regulation of Bandung City Number 9 of 2018 [42,43]. These regulations provide a solid foundation for the Bandung City Government to implement administrative mitigation measures. Specifically, they can be used to enhance the management of water resources by adding technical details to water resources responsibilities, creating topographic maps, and developing a drainage master plan for the Gedebage area. Furthermore, these regulations allow the enforcement of compliance with spatial planning, building permits, and other policies aimed at disaster prevention.

In a related context, a study conducted in Pekalongan City examined the impact of climate crises, floods, and tidal waves, highlighting the critical need for accurate flood hazard classification. The study's findings revealed that land subsidence significantly contributes to elevated hazard levels, particularly increasing flood depth. In response, the study proposed a more balanced flood depth and velocity classification system that would address both the underestimation and overestimation present in existing flood hazard assessments [44]. This approach could further inform the administrative and technical strategies for flood mitigation in Gedebage, ensuring a more precise and comprehensive hazard management framework.

3.4.4 Cultural Approach

A cultural approach can also be integrated by leveraging the traditional value of *gotong royong* (mutual cooperation) [45]. The government can initiate programs that encourage community participation in routine drainage maintenance and revitalization of tertiary drainage channels in residential areas, fostering a collective sense of responsibility for flood prevention. Two practical actions that can be implemented include organizing regular community-based drainage clean-up days through collaboration with *Rukun Tetangga (RT/Local Community Group)/Rukun Warga (RW/Village Council)* and *kelurahan (uban village)*, and forming volunteer groups trained in basic flood preparedness and waste management.

Gotong royong is an institutionalized practice rooted in mutual help, where community members carry out shared tasks for collective benefit [46,47]. For instance, in Tenggilis Mejoyo, Surabaya, a community-led flood prevention initiative called KERBAMAS was conducted in January 2024 [48]. That program mobilized residents of all ages to clean clogged drains, plant trees, and build small canals using the Asset-Based Community Development (ABCD) approach. As a result, the neighborhood remained flood-free even after heavy rainfall. Another example is in Bojongloa, Rancaekek, where flood-prone residents engage in gotong royong to build embankments, clean mud, and raise house floors [49]. They also voice their concerns to the local government and independently plan river normalization efforts. These examples demonstrate how cultural values can strengthen flood resilience through community-driven actions.

3.5. AHP Analysis

In this AHP analysis, an assessment of alternative technologies was conducted for the revitalization of the closed drainage system, with the following options: Revitalization using in-situ cast concrete (A1), precast concrete (A2), and porous paving blocks (A3). The selection of these alternative construction technologies is based on both conventional and renewable construction methods.

The incorporation of renewable construction technologies, such as porous paving blocks, enhances rainwater infiltration into the ground, thereby increasing groundwater volume and reducing the burden on the drainage system. This approach helps mitigate flood risks and prevent waterlogging [30]. Nano-modified paving blocks can effectively fill the pores between aggregates, reducing the overall permeability of the mixture while still maintaining the necessary porosity for effective drainage [50].

At the criteria level, a pairwise comparison is conducted to assess the relative importance of each criterion. This comparison is presented in the form of a comparison matrix, which quantifies the weight of each criterion based on stakeholder input. **Table 9** summarizes the relative importance of each criterion, derived from the geometric mean of the questionnaire responses, while **Tables 10** and **11** presents the results of the importance level at the criteria level. The weighting calculation is then performed for each alternative variation based on all the criteria. The following are the results of the alternative level against various criteria. **Table 12** for execution cost criteria, **Table 13** for land availability criteria, **Table 14** for implementation process criteria, **Table 15** for time criteria, **Table 16** for material availability criteria, and **Table 17** for function criteria.

Table 9. Criteria-level comparison matrix.

Comparison Matrix						
	EC	**LA**	**EP**	**ET**	**MA**	**F**
Execution Cost	1.00	0.27	0.63	0.22	0.23	0.21
Land Availability	3.74	1.00	1.01	0.48	0.62	0.60
Execution Process	1.60	0.99	1.00	0.29	0.26	0.22
Execution Time	4.58	2.06	3.45	1.00	0.61	0,33
Material Availability	4.36	1.61	3.89	1.64	1.00	0.21
Function	4.70	1.68	4.63	3.08	4.86	1.00
Sum	19.99	7.61	14.60	6.70	7.58	2.56

Table 10. Results of the importance level at the criteria level.

Criteria Value		
Execution Cost	0.046	4.57%
Land Availability	0.129	12.93%
Execution Process	0.073	7.35%
Execution Time	0.182	18.24%
Material Availability	0.192	19.20%
Function	0.377	37.72%
Sum	1	100%

Table 11. Results of alternative level against execution cost criteria.

Alternative Value Based on Execution Cost		
A1	0.122	12.23%
A2	0.511	51.08%
A3	0.367	36.69%
Sum	1	100%

Table 12. Results of alternative level against land availability criteria.

Alternative Value Based on Land Availability		
A1	0.173	17.32%
A2	0.251	25.06%
A3	0.576	57.62%
Sum	1	100%

Table 13. Results of alternative level against implementation process criteria.

Alternative Value Based on Execution Process		
A1	0.286	28.56%
A2	0.184	18.43%
A3	0.530	53.01%
Total	1	100%

Table 14. Results of alternative level against time criteria.

Alternative Value Based on Execution Time		
A1	0.1584	15.84%
A2	0.2184	21.84%
A3	0.6232	62.32%
Sum	1	100%

Table 15. Results of alternative level against material availability.

Alternative Value Based on Material Availability		
A1	0.1448	14.48%
A2	0.2564	25.64%
A3	0.5988	59.88%
Sum	1	100%

Table 16. Results of alternative level against function criteria.

Alternative Value Based on Function		
A1	0.2560	25.60%
A2	0.3341	33.41%
A3	0.4099	40.99%
Sum	1	100%

The criteria values, as shown in **Table 10**, reflect the relative importance of each factor in the decision-making process for revitalizing the drainage system. Function holds the highest weight at 37.72%, indicating its critical role in determining the success of the project. Following that, Material Availability and Execution Time are also significant, with values of 19.20% and 18.24%, respectively, highlighting the importance of ensuring that materials are readily available and the project is completed in a timely manner. Land Availability (12.93%) and Execution Process (7.35%) are also important but have relatively lower weights, suggesting that while these factors are necessary, they are not as critical as functionality and efficiency in execution. Finally, Execution Cost (4.57%) is the least influential factor, emphasizing that while cost is a consideration, it is less impactful compared to the project's functionality and material requirements.

The data presented in **Tables 11–16** show the alternative values for three methods, A1 (In-situ Cast Concrete), A2 (Precast Concrete), and A3 (Porous Paving Blocks), based on various criteria for the revitalization of a closed drainage system. When considering Execution Cost, A2 leads significantly with 51.08%, followed by A3 at 36.69%, and A1 at 12.23%. In terms of Land Availability, A3 is the most favorable with 57.62%, far surpassing A1 and A2, which are at 17.32% and 25.06%, respectively. Execution Process shows A3 as the most efficient with 53.01%, while A1 takes the lead over A2 with 28.56%. Execution Time is also dominated by A3 with 62.32%, leaving A1 and A2 at much lower values. For Material Availability, A3 again excels at 59.88%, while A2 and A1 stand at 25.64% and 14.48%, respectively. Lastly, when assessing Function, A3 scores the highest at 40.99%, with A2 and A1 following at 33.41% and 25.60%.

The results of the alternative weighting calculations for each criterion indicate consistent evaluations, as all CR values remain below the required threshold of 0.1. Specifically, the CR values are as follows: construction cost (0.056), land availability (0.061), implementation process (0.090), implementation time (0.004), material availability (0.095), and functionality (0.037). These results confirm that the weighting at the criteria level is consistent.

Uncertainty in AHP weighting is an inherent aspect to be considered when analyzing the results. The AHP process relies on subjective pairwise comparisons, which can introduce inconsistencies or biases based on respondent perceptions and expertise. Although all CR values are below the threshold, slight variations in stakeholder input could lead to different weightings, potentially affecting the final alternative selection. This uncertainty could be mitigated through techniques such as sensitivity analysis or additional rounds of expert validation to refine the pairwise comparisons and strengthen the results.

However, sensitivity analysis and additional expert validation were not conducted in this study, which is a limitation. These techniques could help reduce uncertainty, as sensitivity analysis would show how small changes in criteria weights or expert preferences impact the results, and additional validation could address biases. Despite this, the results are considered acceptable, as the CR values for each AHP level meet the required threshold. These techniques are suggested for future research to further enhance accuracy and reliability.

The final analysis for selecting the most suitable drainage revitalization technology in the Gedebage area using the AHP method is determined by multiplying the alternative scores with their respective criterion weights. The final result of alternative drainage technology selection and its ranking is shown in **Table 17** and **Figure 7**.

Table 17. Results of drainage revitalization.

Alternatif Selection			Rank
A1	0.202	20%	3
A2	0.284	28%	2
A3	0.513	51%	1
Total	1	100%	

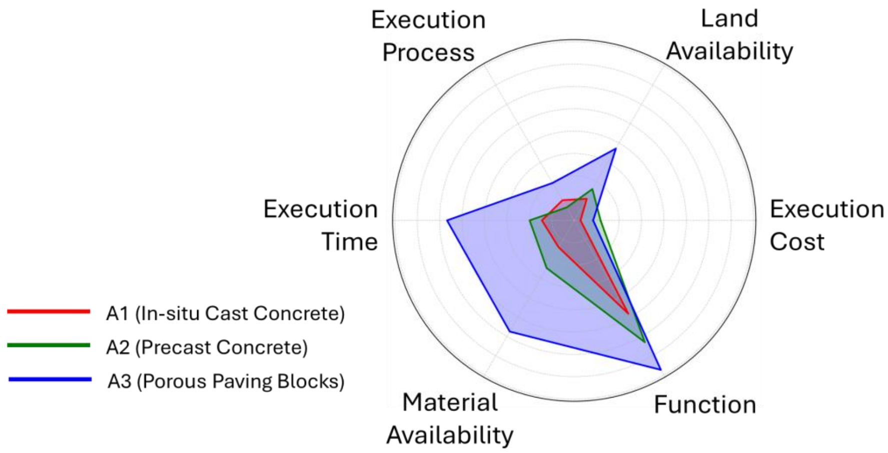

Figure 7. AHP results for drainage revitalization alternatives.

Based on the radar chart analysis, A3 (Porous Paving Blocks) outperforms A1 (In-situ Cast Concrete) and A2 (Precast Concrete) in most categories, including Execution Time, Material Availability, and Function. A3 is the most efficient in terms of speed and material sourcing, making it a strong choice for projects where these factors are critical. Implementing porous paving can contribute to sustainable urban drainage systems (SUDs), aligning with environmental regulations and promoting green infrastructure [51]. A2 (Precast Concrete) performs well in Land Availability and Function, making it suitable for projects with land constraints or specific functional requirements. While A1 (In-situ Cast Concrete) shows strengths in Execution Process, it lags behind in Material Availability and Execution Time, limiting its overall efficiency. A3 excels in the most important criteria, particularly Execution Time and Material Availability, which are crucial for effective drainage system revitalization. Although A3 might incur higher initial costs, it offers long-term efficiency and sustainability. A1 and A2 may still be viable choices depending on specific project constraints, such as budget or land availability. In conclusion, A3 is the best choice for projects prioritizing efficiency and sustainability, while A1 and A2 are better suited for projects with budget constraints or specific land requirements.

3.6. Limitations and Recommendations for Future Research

The limitations of this study arise from the scope of data collection, which relied on field observations, interviews, and questionnaires. While these methods provided valuable insights, they were limited in geographical scope and community involvement. Future research could benefit from a broader and more diverse sample, capturing a wider range of perspectives and providing more comprehensive results. Another limitation is the absence of sensitivity analysis or further expert validation, especially in the application of the Analytic Hierarchy Process (AHP). Although the consistency ratio (CR) met the acceptable threshold, the lack of sensitivity analysis introduces the potential for inconsistencies that may affect the findings. Future studies should include sensitivity analysis to assess how variations in data or expert input could influence the outcomes, ensuring a more robust and reliable decision-making process.

Additionally, this research did not focus on the long-term effectiveness of the proposed drainage improvements, such as the closed drainage systems with porous paving blocks. Long-term monitoring of the system's performance would provide a clearer picture of its sustainability and resilience. Future research could also expand the study area to other flood-prone regions in Bandung or different urban areas, offering valuable insights. A comparative analysis across various urban settings would help identify the most effective flood mitigation strategies and drainage system technologies adaptable to diverse conditions.

Future studies should also place greater emphasis on community engagement. While this research identified gaps in public participation, further studies could develop strategies to improve community involvement in flood risk management. Educational programs, community workshops, and collaborative initiatives could enhance public understanding of flood risks and encourage responsible waste management practices. By addressing these limitations and exploring these recommendations, future research can contribute to more robust and sustainable flood management solutions.

4. Conclusions

The risk assessment results, derived from risk identification and grouped according to the urban drainage asset life cycle in the Gedebage area (Planning, Implementation, and O&M), indicate that 27% are classified as unacceptable, 42% as undesirable, and 31% as acceptable. Based on respondents' assessments of 55 identified risks, several are classified as major risks, including the lack of an integrated drainage system plan, challenges in community engagement regarding drainage obstruction and waste disposal, patchy and reactive repair implementations, lack of integration with road development and utility infrastructure, and decreased channel effectiveness due to high sedimentation and difficulty in cleaning caused by waste dispersion.

Among these, the most urgent risks are the absence of a long-term, integrated drainage master plan and the persistent human-related issues, especially improper waste disposal. These two factors have a particularly high impact on flood vulnerability in the area and are difficult to resolve without systemic coordination and deep community involvement.

Flood mitigation efforts in the Gedebage area are proposed through both structural and non-structural approaches. Structural mitigation includes the revitalization of the drainage system using closed channels. Based on the Analytic Hierarchy Process (AHP) evaluation, the most suitable technology is the closed drainage system with porous paving blocks.

Non-structural mitigation is categorized into administrative, human, and cultural approaches. The administrative approach includes developing a comprehensive drainage system master plan and topographic maps to serve as a foundation for planning and implementation. The human approach focuses on public outreach programs involving neighborhood associations, community leaders, and the general public to promote awareness of the Regional Regulation of Bandung City Number 9 of 2018 on Waste Management and ensure enforcement of its sanctions.

The cultural approach encourages community participation in *gotong royong* (mutual cooperation) for the revitalization of drainage systems near their residences, as supported by Law Number 17 of 2019 on Water Resources, Article 40, Paragraph 2, which allows for community involvement in construction implementation. Two practical actions include organizing regular community-based drainage clean-up days through collaboration with *RT/RW* and *kelurahan*, and forming volunteer groups trained in basic flood preparedness and waste management.

To ensure the effectiveness and sustainability of these efforts, periodic evaluations are recommended. These can include biannual assessments of drainage conditions, community participation levels, and compliance with relevant policies. A clear monitoring framework will help track progress, identify areas for improvement, and support adaptive flood risk management in Gedebage.

Author Contributions

Conceptualization, R.G.K.P., E.O.N., and F.N.; methodology, R.G.K.P. and E.O.N.; validation, E.O.N. and C.T.E.; formal analysis, A.B.W.; investigation, A.B.W.; resources, H.S. and A.T.Y.; data curation, A.B.W.; writing—original draft preparation, H.S. and A.B.W.; writing—review and editing, R.G.K.P., E.O.N., C.T.E., R.D.O., and D.P.W.; visualization, H.S. and R.D.O.; supervision, R.G.K.P., E.O.N., and A.T.Y.; project administration, R.G.K.P., E.O.N., and A.T.Y.; funding acquisition, R.G.K.P. and E.O.N. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study did not require formal ethical approval in accordance with institutional guidelines and due to the anonymous and non-invasive nature of the questionnaire, no sensitive personal data was collected. However, research permission was obtained through an official letter from the Head of the Civil Engineering Program of Institut Teknologi Bandung (Letter No. 1180/ITI.C06.4.10/KM.00/2023, dated 1 November 2023).

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study. Participation was voluntary and anonymous, and the purpose of the research was explained at the beginning of the questionnaire.

Data Availability Statement

The data presented in this study are available on request from the corresponding author at nugrohoeka@itb.ac.id. The data are not publicly available due to privacy or institutional restrictions.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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