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1 Introduction

Large cities worldwide face serious challenges in stormwater management due to rapid urbanization, climate change, and the increasing use of impervious surfaces. The expansion of areas covered by concrete and asphalt reduces natural infiltration, increasing surface runoff, leading to flooding, erosion, and stress on drainage systems. This also leads to social and economic consequences such as disruption of activities, infrastructure damage, and increased maintenance costs (Eckart et al., 2017; Meerow and Newell, 2019). Furthermore, climate change is increasing the frequency and intensity of extreme rainfall events, making conventional drainage systems based on historical data less adaptable (Ashley et al., 2020; IPCC, 2022), Therefore, successful stormwater management depends not only on technical aspects but also on organizational readiness and human resource capacity.

Previous studies have shown that improvements in organizational capacity do not automatically translate into better organizational performance unless they are supported by enabling institutional mechanisms and effective implementation processes (Pranitasari et al., 2026). This indicates that sustainable stormwater management requires not only appropriate technical solutions but also organizational capabilities that can effectively implement strategic decisions.

Jakarta's rapid urbanization has created various challenges in urban infrastructure management, particularly related to stormwater management. The increase in impervious surface area, changes in land use, and limitations of conventional drainage systems have increased the risk of flooding and reduced the quality of the urban environment (Demirguc-Kunt et al., 2022; Habitat, 2020). Therefore, a stormwater management approach is needed that is not only technically effective but also economically, socially, and environmentally sustainable (Fletcher et al., 2015).

Various approaches have been developed to address this issue, such as Conventional Drainage Systems, GI, LID, NbS, and Integrated Stormwater Management Systems. Conventional approaches tend to focus on accelerating water flow, while GI, LID, and NbS emphasize rainwater retention, infiltration, and reuse as part of an ecological system (Ahiablame and Engel, 2012; Eckart et al., 2018; Fletcher et al., 2013; Joksimovic and Alam, 2014). Each approach has distinct characteristics, advantages, and limitations, making selecting the best alternative a complex, multi-criteria decision-making process. Furthermore, integrating green infrastructure into urban planning also provides long-term economic and social benefits, including reduced flood control costs and improved quality of life for urban residents (Locatelli et al., 2020).

In this context, the Multi-Criteria Decision Making (MCDM) approach becomes relevant for supporting decision-making involving multiple conflicting criteria (Hwang and Yoon, 1981; Saaty, 2008). Methods such as the Analytical Hierarchy Process (AHP) allow for systematic weighting of criteria through pairwise comparisons, while the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is used to rank alternatives based on their proximity to the ideal solution (Behzadian et al., 2012). The AHP-TOPSIS combination has been widely used in decision-making studies due to its ability to integrate subjective and objective assessments.

Various studies have addressed stormwater management using both technical and ecosystem-based approaches, but most studies still focus solely on evaluating hydrological performance or cost efficiency, without comprehensively integrating strategic management and long-term planning perspectives (Eckart et al., 2017; Kuller et al., 2019; Nazari et al., 2023). Limitations of previous research include the tendency to use only quantitative approaches without integrating qualitative perspectives from stakeholders, and the lack of comprehensive comparisons of various stormwater management methods in the context of a developing city like Jakarta. Furthermore, the use of sensitivity analysis to test the stability of decision outcomes is still relatively limited in MCDM studies (Triantaphyllou and Sslnchez, 1997).

Therefore, the novelty of this research lies in the integration of a strategic management framework with the MCDM method (AHP-TOPSIS) in evaluating stormwater management alternatives. The development of an evaluation model that comprehensively integrates technical, economic, environmental, and social dimensions in accordance with the Triple Bottom Line (TBL) principle (Elkington, 1997), The application of the model to the context of a developing metropolitan city like Jakarta also identifies strategic implications, including the importance of organizational capacity and human resources in supporting the implementation of sustainable stormwater strategies.

Based on these gaps, this study aims to develop a comprehensive decision-making framework using the AHP–TOPSIS method to evaluate sustainable stormwater management alternatives in Jakarta. This study integrates technical, economic, environmental, and social dimensions, while also incorporating qualitative insights from expert interviews. In addition, a sensitivity analysis is conducted to test the robustness of the decision results. This research is expected to contribute by providing a more holistic, robust, and practical framework for strategic urban stormwater management.

2 Literature review

2.1 Urban stormwater concept

Urban stormwater is rainwater runoff that occurs due to the increase in impermeable surfaces such as roads, buildings, and urban infrastructure. Urbanization causes significant changes to the natural hydrological cycle, resulting in increased runoff volume, flood frequency, and decreased water quality (Fletcher et al., 2015; Teo et al., 2022). Furthermore, climate change increases the intensity and frequency of extreme rainfall events, making conventional drainage systems less effective in managing stormwater runoff (Alves et al., 2020; Teo et al., 2022).

Stormwater also carries various pollutants such as heavy metals, sediment, and surface waste that can contaminate water bodies and disrupt urban ecosystems (Gajewska et al., 2020). Therefore, stormwater management is a crucial component in supporting environmental sustainability and urban resilience to climate change and urbanization (Meerow and Newell, 2019). Traditional approaches to stormwater management utilize gray infrastructure such as drainage channels, canals, and pipes. However, this approach has limitations in supporting long-term sustainability

(Eckart et al., 2017). Therefore, green infrastructure and LID-based approaches have been developed to increase water infiltration and reduce surface runoff (Celebrini et al., 2020; Kabisch et al., 2017b).

Green infrastructure such as permeable pavements, rain gardens, and green roofs have proven effective in reducing runoff volume and improving water quality (Allison et al., 2023). Furthermore, the integration of green and gray infrastructure can increase the resilience of urban drainage systems and support sustainable urban development (Gajewska et al., 2020; Yang and Zhang, 2021). NbS also provide additional benefits such as improved environmental quality, reduced urban temperatures, and increased resilience to climate change (Celebrini et al., 2020; Kabisch et al., 2017b).

2.2 Strategic management in stormwater

Strategic management is a long-term planning and decision-making process aimed at improving the effectiveness and sustainability of management systems. In the context of stormwater, strategic management helps integrate various technical, economic, environmental, and social aspects in the management of urban drainage systems (Kuller et al., 2019). A strategic management approach enables decision-makers to design adaptive and sustainable strategies to address the challenges of urbanization and climate change (Meerow and Newell, 2019). Furthermore, the use of decision support systems and data-driven models can improve the effectiveness of stormwater management and support the development of more resilient cities (Ka et al., 2022; Teo et al., 2022).

2.3 MCDM in stormwater management

Stormwater management involves various complex criteria, such as cost, technical effectiveness, environmental impact, and sustainability. Therefore, MCDM methods are used to assist decision-makers in systematically evaluating various alternatives (Alhumaid et al., 2018).

MCDM methods such as AHP, TOPSIS, and VIKOR have been widely used in stormwater management to determine the most optimal strategy (Nazari et al., 2023). The use of MCDM allows the evaluation of various green infrastructure alternatives and helps select the most effective and sustainable solution (Allison et al., 2023; Yang and Zhang, 2021).

The integration of MCDM with hydrological models such as the Storm Water Management Model (SWMM) also improves decision-making accuracy and supports the development of more efficient and sustainable stormwater systems (Nazari et al., 2023).

The use of MCDM provides a systematic framework to support sustainable and resilient urban development. This method allows the evaluation of various alternatives based on various criteria and assists decision-makers in selecting the most optimal strategy (Teo et al., 2022). This approach also supports the integration of strategic planning, technology, and environmental sustainability in urban stormwater management (Ka et al., 2022). Thus, the integration of strategic management and MCDM is an effective approach to increasing urban resilience to flooding and climate change and supporting sustainable urban development (Celebrini et al., 2020; Meerow and Newell, 2019).

Recent developments in Multi-Criteria Decision Making (MCDM) methods demonstrate the increasing use of fuzzy approaches to accommodate uncertainty and subjectivity in expert judgment. Methods such as Fuzzy AHP and Fuzzy TOPSIS have been widely used in various complex decision-making contexts, including water resource management and the selection of sustainable strategies (Kahraman, 2008; Kannadasan and Polisetty, 2025).

Several studies have shown that fuzzy approaches can improve model accuracy and flexibility compared to classical methods, particularly in conditions of ambiguous or uncertain data (Kannadasan and Polisetty, 2025; Konstadinos et al., 2025). Therefore, the integration of fuzzy methods in future research could provide an opportunity to develop more adaptive and comprehensive models.

Various MCDM methods such as ELECTRE, PROMETHEE, and VIKOR have been widely applied in environmental decision-making. ELECTRE is effective in handling outranking relations but tends to be complex in interpretation. PROMETHEE provides clear ranking but requires careful parameter selection. VIKOR focuses on compromise solutions but is sensitive to weight changes.

Compared to these methods, the integration of AHP and TOPSIS offers several advantages. AHP is effective in determining criteria weights through structured pairwise comparisons, while TOPSIS provides a clear ranking based on distance from the ideal solution. This combination is relatively simple, transparent, and suitable for integrating both qualitative and quantitative data. However, this method also has limitations, particularly in handling uncertainty, which can be addressed in future studies using fuzzy approaches.

2.4 Alternative stormwater strategies

The alternative strategies evaluated in this study were selected based on a Scopus-indexed literature review and international best practices in urban stormwater management. These alternatives represent key approaches used globally and are relevant to support strategic decision-making in sustainable urban infrastructure management (Eckart et al., 2017; Fletcher et al., 2015; Kabisch et al., 2017a).

Gray infrastructure (GI) is a conventional approach that uses concrete channels, canals, and pipelines to rapidly channel stormwater runoff. This approach is effective for short-term flood control but has limitations in supporting sustainability and climate change adaptation because it does not increase infiltration and long-term system resilience (Eckart et al., 2017; Fletcher et al., 2015). GI and Low Impact Development (LID) are sustainable approaches that mimic natural hydrological processes by increasing infiltration, retention, and management of stormwater at the source, such as permeable pavement, green roofs, and bioretention. This approach has proven effective in reducing runoff, improving water quality, and providing environmental, social, and economic benefits (Berland et al., 2017; Dietz, 2007; Locatelli et al., 2020). NbS use ecosystem-based processes, such as green space and wetland restoration, to increase urban resilience to flooding and

climate change, while providing ecological benefits and improving the quality of life for residents (Cohen-Shacham et al., 2016; Kabisch et al., 2017b). An Integrated Stormwater Management System is a strategic approach that integrates various management methods, including gray infrastructure, green infrastructure, and ecosystem-based solutions, to holistically improve the effectiveness, efficiency, and sustainability of the system (Fletcher et al., 2015; Kuller et al., 2019).

From a strategic management perspective, each alternative has different implications for resource allocation, organizational capacity, and human resource competency requirements in the planning, implementation, and management of sustainable infrastructure. Therefore, evaluating alternative strategies is not only crucial for determining optimal technical solutions, but also for supporting strategic decision-making and organizational capacity development in sustainable stormwater management.

Therefore, these five alternatives are suitable for evaluation using MCDM methods, specifically AHP and TOPSIS, to support a structured, objective, and sustainable strategic decision-making framework (Velasquez and Hester, 2013; Zavadskas et al., 2016). The characteristics, advantages, and limitations of the five stormwater management approaches evaluated in this study are summarized in Table 1.

Although GI, LID, and NbS share similarities in promoting infiltration and sustainability, their main differences lie in scale, approach, and implementation focus. LID operates at a micro-scale and emphasizes source control, GI focuses on integrating green elements into urban infrastructure, while NbS adopts a broader ecosystem-based perspective. Integrated systems combine these approaches to achieve optimal performance.

The main differences between the approaches lie in the level of integration of ecological aspects, the scale of implementation, and the orientation toward long-term sustainability.

In the context of modern sustainability, the NbS approach also aligns with the principles of the circular economy, which emphasizes efficient resource use and rainwater reuse as part of a closed-loop system. Stormwater management functions not only as a drainage system but also as an alternative resource through rainwater harvesting, groundwater recharge, and enhancing the value of urban ecosystems.

The integration of circular economy principles into NbS allows for the simultaneous optimization of environmental, economic, and social benefits, thus supporting more resilient and sustainable urban development.

3 Research methods

3.1 Research design

This study uses a quantitative approach with the MCDM method to determine the most sustainable urban stormwater management strategy and increase city resilience. This method was chosen because stormwater management involves various multidimensional criteria, such as environmental, economic, technical, and social aspects. Therefore, a systematic approach is needed to objectively evaluate and prioritize alternative strategies (Celebrini et al., 2020; Kuller et al., 2019). The MCDM approach has been widely used in urban water resources management because it integrates various indicators and supports complex decision-making (Allison et al., 2023; Nazari et al., 2023).

3.2 Research location and object

The research was conducted in Jakarta, an Indonesian city, which faces stormwater runoff issues, such as increased impervious surfaces, flood risk, and limitations of conventional drainage systems. The unit of analysis in this study is alternative urban stormwater management strategies, which can include conventional drainage infrastructure, green infrastructure, LID, NbS, and integrated management systems. These alternatives were selected based on literature reviews and best practices in sustainable stormwater management.

3.3 Data collection techniques

This research used primary and secondary data. Primary data was obtained through an expert judgment approach to conduct pairwise comparisons between criteria and alternatives within the MCDM framework, specifically the AHP. This approach is commonly used in complex decision-making because it systematically integrates professional knowledge and experience (Ishizaka and Labib, 2011; Saaty, 2008). Expert selection was conducted using a purposive sampling technique with the following criteria: a minimum of a master's degree in a relevant field (environmental engineering, civil engineering, urban and regional planning, or infrastructure management), ≥5 years of professional experience in urban water management or drainage, direct involvement in stormwater planning, implementation, research, or policy, and willingness to participate voluntarily. These criteria were intended to ensure the competence and credibility of the respondents. A total of 15 experts participated in this study. This number falls within the recommended range in AHP and expert-based decision-making studies (5–20 respondents), which is considered sufficient to achieve stability and consistency in assessments (Ishizaka and Labib, 2011; Saaty, 2008). Previous studies have also shown that 10–20 experts is common practice in MCDM research to maintain a balance between decision quality and result reliability (Rezaei, 2015).

This study used a structured questionnaire based on the AHP pairwise comparison scale to obtain expert assessments of the relative importance of criteria and alternative stormwater strategies (Supplementary File 1). The questionnaire consisted of three sections: respondent profiles, pairwise comparisons between criteria, and pairwise comparisons between alternatives using the Saaty 1–9 scale (Saaty, 2008). In addition to the questionnaire, semi-structured interviews were also conducted to gain a deeper understanding of expert considerations in stormwater strategy selection and strategic implications, including organizational readiness and human resource capacity to support sustainable strategy implementation. Interview data was used to strengthen the interpretation of the quantitative analysis results and increase the validity of the study.

The semi-structured interview data was analyzed using a thematic analysis approach. This process included the following stages:

TABLE 1 Comparison of rainwater management approaches.

Approach	Main focus	Key characteristics	Advantages	Limitations
Conventional drainage	Rapid water conveyance	Concrete channels, pipes, centralized system	Effective for short-term flood control	Low sustainability, no infiltration
Green infrastructure (GI)	Ecological integration	Green roofs, bioswales, permeable surfaces	Improves water quality, reduces runoff, multi-benefit	Requires land and maintenance
Low impact development (LID)	Source control	Small-scale, decentralized infiltration	Flexible, reduces runoff at source	Limited impact at large scale
Nature-based Solutions (NbS)	Ecosystem-based approach	Wetlands, urban forests, natural systems	High environmental and social benefits	Complex implementation
Integrated System	Hybrid approach	Combines gray + green + NbS	Holistic and adaptive	High complexity and coordination needs

1. Transcription of interview results
2. Open coding to identify initial themes
3. Categorization based on criterion dimensions (environmental, economic, technical, social)
4. Interpretation to support the quantitative AHP results

This approach was used to ensure that the subjective perspectives of experts could be systematically integrated into the decision-making framework.

Secondary data was obtained from journal articles, government reports, urban planning documents, and literature related to stormwater management. Secondary data was used to identify relevant criteria and strategic alternatives (Meerow and Newell, 2019). The criteria used in this study were adapted from previous studies and cover four main dimensions: Environmental Criteria (Runoff Reduction, Water Quality Improvement, Ecosystem Conservation), Economic Criteria (Implementation Cost, Maintenance Cost, Long-Term Efficiency), Technical Criteria (System Effectiveness, Ease of Implementation, System Reliability), and Social Criteria (Community Acceptance, Social Impact, Contribution to Quality of Life). These criteria have been widely used in the evaluation of sustainable urban water management (Alhumaid et al., 2018; Yang and Zhang, 2021).

The AHP hierarchy developed in this study consists of four levels to better represent the complexity of sustainable stormwater management decision-making. The first level defines the overall objective, which is to select the most sustainable stormwater management strategy. The second level consists of four primary decision criteria: Environmental, Economic, Technical, and Social. The third level consists of 12 sub-criteria derived from an extensive literature review and expert consultation. Specifically, the Environmental criteria include Runoff Reduction, Water Quality Improvement, and Ecosystem Conservation; the Economic criteria include Initial Investment Cost, Maintenance Cost, and Long-Term Cost Efficiency; the Technical criteria include System Effectiveness, Ease of Implementation, and System Reliability; and the Social criteria include Community Acceptance, Social Impact, and Quality of Life Improvement. The fourth level consists of five alternative stormwater management strategies: Conventional Drainage, Green Infrastructure, Low-Impact Development (LID), Nature-Based Solutions (NbS), and Integrated Stormwater Management Systems.

This hierarchical structure allows for a more comprehensive evaluation by capturing the multidimensional nature of sustainable stormwater management while enhancing the transparency and robustness of the AHP-based decision-making framework (Figure 1).

3.4 Research criteria and indicators

The main criteria, sub-criteria, and their operational descriptions used in the AHP model are presented in Table 2. Based on the literature review and interview results, the criteria used in this study encompass technical, economic, environmental, and social aspects. The selection of these criteria is based on previous research stating that stormwater management must consider various dimensions of sustainability in an integrated manner (Eckart et al., 2017; Fletcher et al., 2015; Gajewska et al., 2020; Kabisch et al., 2017a; Meerow and Newell, 2019).

Indicators for each criterion were selected to represent key aspects of stormwater management: technical effectiveness, cost efficiency, environmental impact, and social acceptability. This approach aligns with the concept of sustainable development, which emphasizes a balance between economic, environmental, and social aspects in decision-making.

Each alternative was evaluated based on specific indicators under each criterion. For example, technical indicators include runoff reduction effectiveness and system reliability; economic indicators include investment and maintenance costs; environmental indicators include water quality improvement and ecosystem impact; and social indicators include public acceptance and aesthetic value. These indicators were applied consistently across all alternatives to ensure comparability and depth of analysis. This structured indicator-based evaluation ensures that each stormwater management approach is assessed not only conceptually but also based on measurable technical and sustainability parameters.

Data analysis was conducted using the AHP and TOPSIS methods. AHP was used to determine the importance weight of each criterion. This process included constructing a decision hierarchy structure, creating a pairwise comparison matrix, calculating criterion weights, and testing the consistency of assessments. The AHP method is effective in prioritizing criteria in complex decision-making systems (Kuller et al., 2019; Saaty, 2008). TOPSIS was used to rank alternative strategies based on their proximity to the ideal solution. The TOPSIS method is widely used in evaluating environmental management strategies because

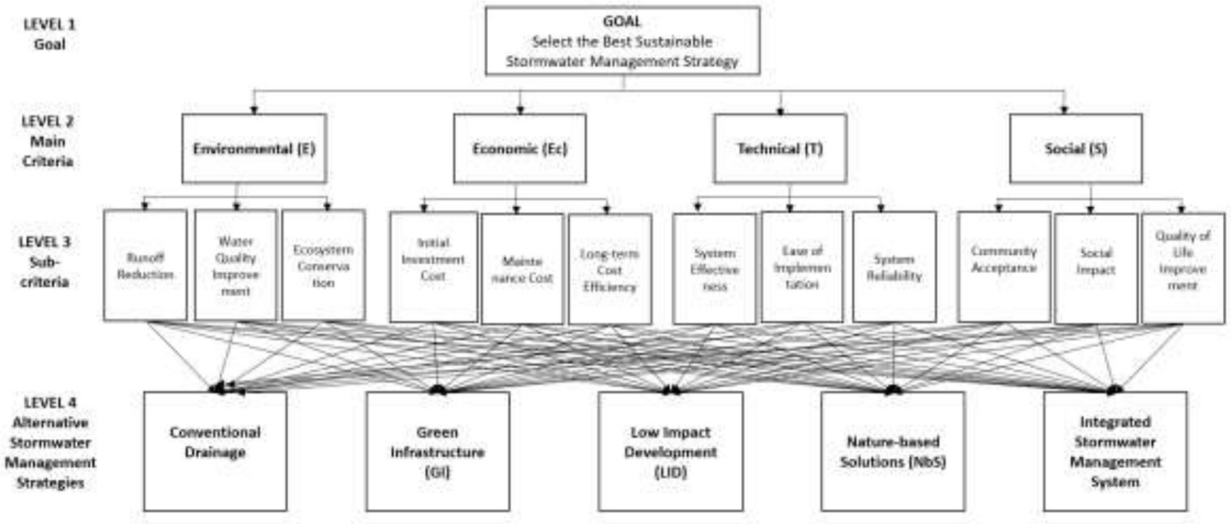

FIGURE 1
A four-level AHP hierarchy for sustainable stormwater management strategy selection.

it produces objective and easily interpretable results (Allison et al., 2023; Nazari et al., 2023). Research validity was ensured through the use of criteria from Scopus-indexed literature, consultation with experts, and the use of scientifically tested MCDM methods. Reliability is tested through the Consistency Ratio (CR) in the AHP method, with a CR value ≤ 0.1 indicating that the assessment is consistent and acceptable.

4 Research results

4.1 Respondent characteristics within a multi-criteria decision-making (MCDM) framework

This study involved 15 expert respondents selected using purposive sampling based on a minimum of 5 years of professional experience in urban drainage management, water resources, and urban infrastructure planning. Data collection was conducted from January to February 2026 through structured questionnaires and in-person interviews (Supplementary File 1). Respondents came from various institutions directly involved in stormwater management in Jakarta, enabling them to provide a comprehensive assessment within the MCDM framework.

The characteristics of the expert respondents are presented in Table 3. Based on work experience, 11 respondents (73.3%) had more than 8 years of experience, while 4 respondents (26.7%) had between 5 and 8 years of experience. This indicates that respondents possess an adequate level of competence to provide assessments in multi-criteria decision-making processes.

4.2 Determining criteria weights using AHP

Within the MCDM framework, the AHP method is used to determine the relative weights of four main criteria: environmental, economic, technical, and social.

A pairwise comparison matrix is compiled based on the average of respondents' ratings. The pairwise comparison matrix is presented in Table 4.

Next, normalization and eigenvector calculations were performed to obtain the weights for each criterion. The resulting criteria weights are presented in Table 5.

These results indicate that environmental criteria have the highest weighting. This reflects that, in the context of urban stormwater management in Jakarta, the system's ability to reduce runoff, increase infiltration, and support environmental sustainability is a top priority.

4.3 AHP matrix consistency test

A consistency test was conducted to ensure that respondents' assessments in the pairwise comparison matrix had an acceptable level of consistency.

The test results showed:

Consistency Index (CI) = 0.048

Consistency Ratio (CR) = 0.054

Because the CR value is less than 0.10, the comparison matrix is considered consistent and can be used in further analysis.

4.4 Alternative evaluation matrix

Within the MCDM framework, the AHP method is used to determine the relative weights of four main criteria:

A1 = Conventional drainage

A2 = Green infrastructure

A3 = Low Impact Development (LID)

A4 = Nature-based solutions

A5 = Integrated management system

The assessment is carried out using a scale of 1–9 based on four criteria. The evaluation scores for each alternative under the four decision criteria are presented in Table 6.

TABLE 2 Hierarchical criteria, sub-criteria, and descriptions used in the AHP model.

Main criteria	Sub-criteria	Operational description
Environmental	Runoff reduction	Ability to reduce surface runoff volume
	Water quality improvement	Improvement of receiving water quality
	Ecosystem conservation	Protection and enhancement of ecosystem functions
Economic	Initial investment cost	Capital expenditure for infrastructure implementation
	Maintenance cost	Operation and maintenance expenditure
	Long-term cost efficiency	Life-cycle economic efficiency and cost savings
Technical	System effectiveness	Effectiveness in stormwater management
	Ease of implementation	Technical feasibility and constructability
	System reliability	Reliability and operational performance
Social	Community acceptance	Public acceptance and stakeholder support
	Social impact	Positive impacts on communities
	Quality of life improvement	Contribution to urban livability and well-being

TABLE 3 Respondent characteristics.

No	Respondent category	Number	Percentage
1	Academics in environmental engineering and regional planning	5	33.3%
2	Environmental engineering practitioners and drainage consultants	4	26.7%
3	Urban planners	3	20.0%
4	Local government (Water Resources Agency and Bappeda)	3	20.0%
	Total	15	100%

The highest score for the environmental criteria was given to green infrastructure, indicating that this strategy is considered the most effective in supporting sustainable rainwater management.

4.5 Normalization matrix and weighted normalization

Normalization was performed using the vector normalization method, then multiplied by the criterion weights obtained from the AHP.

These results indicate that green infrastructure has the highest total value. The normalized and weighted normalized decision matrix is presented in Table 7.

4.6 Ideal solution and preference value calculation using TOPSIS

Positive and negative ideal solutions are determined based on the maximum and minimum values of the weighted normalization matrix.

Positive ideal solution (A^+): (0.230; 0.105; 0.145; 0.076)

Negative ideal solution (A^-): (0.118; 0.094; 0.127; 0.042)

Based on the distance calculation to the ideal solution, the following preference values are obtained: The TOPSIS preference values and ranking of the alternative strategies are presented in Table 8.

4.7 Sensitivity analysis

To test the robustness of the alternative ranking results, a sensitivity analysis was conducted by varying the weights of the main criteria, particularly the economic and technical criteria, which significantly contribute to decision-making.

Simulations were conducted by increasing the weight of the economic criteria from 21.4 to 30% and the weight of the technical criteria from 27.9 to 35%, with proportional adjustments to the other criteria.

The analysis results show that:

1. GI remains in first place with insignificant changes in preference scores.

2. LID and NbS experienced slight changes in scores, but did not change their ranking positions.

3. Conventional drainage remains the alternative with the lowest score.

These findings indicate that the decision results are relatively stable against changes in criterion weights, thus demonstrating a good level of robustness in the AHP–TOPSIS model.

Therefore, the resulting decisions can be considered reliable in supporting strategic planning for sustainable stormwater management.

5 Discussion

5.1 Priority criteria in stormwater management

The AHP results indicate that environmental criteria have the highest weighting (38.2%), followed by technical (27.9%),

TABLE 4 Pairwise comparison matrix of criteria.

Criteria	Environmental	Economic	Technical	Social
Environmental	1.000	2.125	1.643	3.214
Economic	0.471	1.000	0.782	2.184
Technical	0.608	1.279	1.000	2.531
Social	0.311	0.458	0.395	1.000

TABLE 5 Criteria weights.

Criteria	Weight	Percentage	Rank
Environmental	0.382	38.2%	1
Economic	0.279	27.9%	2
Technical	0.214	21.4%	3
Social	0.125	12.5%	4

economic (21.4%), and social (12.5%). This finding is consistent with the principles of sustainable urban water management, which emphasize ecosystem protection and sustainable runoff management (Hurlimann and Wilson, 2018; Rydningen et al., 2025). According to the TBL theory, urban management must consider environmental, social, and economic aspects in a balanced manner (Elkington, 1997). This research data shows that although economic and social criteria are important, experts consider environmental protection to be the top priority for reducing flood risk and the impacts of climate change in Jakarta.

Consequently, urban planners and policymakers need to prioritize environmental aspects as a primary factor in selecting stormwater management strategies. Infrastructure investments should prioritize green infrastructure solutions, such as infiltration wells, bioswales, and urban vegetation, which can reduce runoff, improve environmental quality, and support city resilience to climate change.

Furthermore, the successful implementation of this strategy also depends on organizational readiness and human resource capacity. Planners, engineers, and infrastructure managers need to be competent in green infrastructure planning and management. Therefore, developing human resource capacity through training and competency enhancement is a crucial factor in supporting sustainable stormwater management.

5.2 Evaluation of alternative strategies: superior green infrastructure

Based on the TOPSIS calculation, GI had the highest preference score (0.918), surpassing LID (0.841) and NbS (0.712). This indicates that GI is closer to the ideal solution based on all criteria.

From the perspective of LID and NbS theory, this strategy effectively manages runoff, increases infiltration, and maintains water quality (Dietz, 2007; Huang, 2020). GI, such as infiltration gardens, permeable pavements, and green roofs, not only manages stormwater but also provides additional ecosystem benefits, including carbon sequestration, reduction of the urban heat island effect, and enhancement of the city's aesthetic quality.

The practical implications of these findings suggest that local governments need to prioritize the implementation of GI in urban drainage system planning, particularly in areas at high risk of flooding. Integrating GI into drainage master plans can improve the effectiveness of sustainable runoff management and reduce reliance on conventional systems. Furthermore, the MCDM approach used in this study can support more objective decision-making and assist city planners in determining optimal infrastructure investment priorities. GI implementation also provides additional benefits in the form of improved environmental quality and green open spaces. However, successful implementation of this strategy requires adequate human resource capacity, making the competency development of planners, engineers, and infrastructure managers a crucial factor in supporting sustainable stormwater management.

Interview results indicate that experts consistently emphasized the importance of environmental sustainability and system flexibility in the face of climate uncertainty. Key themes that emerged included the need for green infrastructure integration, the limitations of conventional drainage systems, and the importance of human resource capacity in implementation. These findings reinforce the quantitative results of the AHP, which prioritized environmental criteria.

To test the stability of the decision-making results, a sensitivity analysis was conducted by increasing the weighting of economic and technical criteria by 10%–20% each. The results showed that the ranking of alternatives was relatively stable, with Green Infrastructure remaining the best alternative. This indicates that the AHP–TOPSIS model used is robust enough to accommodate changes in criteria weightings, thus increasing the reliability of the results in supporting strategic decision-making.

5.3 Low-impact development and nature-based solutions: approaching the ideal alternative

LID and NbS ranked second and third, respectively, indicating that both strategies are effective alternatives in supporting sustainable stormwater management. This approach emphasizes managing rainwater at its source by increasing infiltration and utilizing natural processes, thereby reducing pressure on conventional drainage systems (Berland et al., 2017). This finding aligns with the concept of urban resilience, which emphasizes the importance of adaptive and multifunctional infrastructure in addressing flood risks and climate change (Meerow and Newell, 2019).

TABLE 6 Decision matrix.

Alternatives	Environmental	Economic	Technical	Social
A1	4.35	6.42	6.75	4.68
A2	8.47	7.18	7.82	8.05
A3	8.16	7.03	7.54	7.76
A4	7.74	6.85	7.12	7.43
A5	6.95	6.58	7.26	6.89

TABLE 7 Weighted normalization matrix.

Environmental	Alternatives	Economic	Technical	Social	Total
A1	0.118	0.094	0.127	0.042	0.381
A2	0.230	0.105	0.145	0.076	0.556
A3	0.222	0.103	0.140	0.073	0.538
A4	0.211	0.100	0.132	0.070	0.513
A5	0.189	0.096	0.134	0.064	0.483

TABLE 8 Preference values and rankings.

Alternative	Values Preference	Rankings
Green infrastructure	0.918	1
Low-impact development	0.841	2
Nature-based solutions	0.712	3
Integrated systems	0.528	4
Conventional drainage	0.084	5

Policy-wise, LID can be integrated into new residential area planning through the implementation of rain gardens and infiltration trenches, while NbS can be applied to public spaces and city parks to increase infiltration capacity and ecological function. However, implementing these strategies requires human resource readiness, particularly in terms of ecosystem-based planning competency, green infrastructure design, and cross-sector coordination. Therefore, strengthening technical and managerial capacity is crucial for successful implementation.

5.4 Limitations of conventional drainage and integrated systems

Conventional drainage had the lowest preference score (0.084), indicating that while this system is relatively stable technically and cost-wise, its contribution to environmental and social aspects is very limited. This finding confirms that a solely concrete channel-based approach is no longer adequate to address the challenges of climate change and the increasing risk of urban flooding. In line with the principles of Integrated Water Resource Management (IWRM), which emphasize the integration of technical, environmental, and social aspects in water resource management [Global Water Partnership (GWP), 2000], the integrated system actually offers a more holistic management framework. However, its fourth-place ranking indicates that its implementation in Jakarta still faces obstacles, such as budget constraints, weak inter-agency coordination, and limited land.

Consequently, strengthening the integrated system requires improved strategic coordination between the Water Resources Agency, the Regional Development Planning Agency (Bappeda), and the private sector to ensure that planning and implementation are aligned. Furthermore, investment in an integrated monitoring and maintenance system is crucial to ensure optimal infrastructure performance. Without integrated governance support and adequate organizational capacity, an integrated system may not deliver maximum benefits compared to a green infrastructure-based approach.

5.5 MCDM integration for strategic decision-making

This research demonstrates that the MCDM approach (AHP-TOPSIS) can be used as a systematic, transparent, and evidence-based strategic decision-making framework for evaluating stormwater management alternatives. In line with Decision Support System (DSS) theory, this method assists policymakers in addressing complex decisions by simultaneously considering multiple criteria (Saaty, 2008).

Practically, MCDM results can be used by local governments to prioritize infrastructure investments more objectively and accountably, and assist planners in balancing cost, technical effectiveness, environmental sustainability, and social acceptability. Furthermore, this model can be replicated in other cities with similar characteristics, potentially serving as a reference framework for sustainable stormwater planning. However, the effectiveness of this approach also depends on organizational capacity and human resource competencies, particularly in analytical skills, strategic planning, and data-driven decision-making. Therefore, human

resource capacity development is a crucial factor in supporting its implementation.

This finding is in line with previous research showing that organizational capability and technology readiness are important determinants of successful strategy implementation and organizational performance (Harini et al., 2023). Accordingly, decision-support tools such as AHP–TOPSIS should be accompanied by investments in organizational capability, analytical competencies, and strategic leadership to maximize their effectiveness.

5.6 Human resource and organizational implications

Research results indicate that green infrastructure is the best alternative for urban stormwater management. However, the successful implementation of this strategy depends not only on technical and financial aspects, but also on human resource capacity and organizational readiness.

This finding is consistent with previous studies showing that sustainable outcomes require not only technical interventions but also a structured process of capacity building, competency development, institutional support, and continuous stakeholder engagement (Pranitasari et al., 2026). Therefore, selecting the most appropriate stormwater management strategy should be accompanied by organizational efforts to strengthen human resource capabilities and institutional readiness to ensure successful implementation.

GI implementation requires multidisciplinary competencies, including environmental planning, infrastructure management, and cross-sector coordination. Therefore, public organizations need to develop supportive human resource strategies, such as enhancing technical competencies, sustainability training, and strengthening institutional capacity. The concept of GHRM suggests that integrating green values into HR practices, including green recruitment, environmental training, and environmentally-based performance management, can increase ecological awareness, strengthen employee pro-environmental behavior, and support the achievement of organizational sustainability performance (Khan et al., 2022; Liu et al., 2026; Li et al., 2023). From the Resource-Based View (RBV) perspective, human resources are valuable, rare, and difficult-to-imitate strategic assets, making them a crucial factor in creating competitive advantage and enhancing organizational capacity to effectively manage sustainable infrastructure (Li et al., 2023). Therefore, integrating infrastructure strategy and human resource development strategy is a key factor in supporting the success of long-term stormwater management and strengthening institutional capacity toward sustainable urban development.

6 Conclusion

Based on the research results using Multi-Criteria Decision-Making (MCDM) with AHP and TOPSIS, it can be concluded that urban stormwater management must emphasize environmental sustainability. Environmental criteria were the top priority (38.2%), emphasizing the importance of strategies that reduce runoff, prevent flooding, and maintain the quality of urban ecosystems. Green Infrastructure (GI) emerged as the best strategy with the highest preference score (0.918), as it was effective across all criteria and provided additional benefits, including green open space, urban aesthetics, and increased climate resilience. Conventional drainage systems proved to have limitations, as they did not support sustainability and climate change adaptation, even though they were technically functional. The MCDM approach proved effective as a systematic, evidence-based strategic decision-making tool. Successful strategy implementation also depends on organizational capacity and human resources, so integrating GHRM and improving technical competency are key to supporting sustainable stormwater management.

7 Recommendation

Based on the research results, practical recommendations for stormwater management in Jakarta:

1. Prioritize GI.

Focus investments on infrastructure, such as infiltration parks, green roofs, and permeable pavements, as they effectively manage water runoff and improve environmental quality and urban aesthetics.

2. Strengthen organizational and human resource capacity

Improve technical competency, environmental planning, and cross-sector coordination through training and the implementation of GHRM.

3. Use MCDM for strategic decision-making

Apply AHP-TOPSIS to systematically, transparently, and evidence-basedly assess alternative strategies.

4. Combine green and ecosystem approaches

Integrate GI with LID and NbS to enhance urban resilience to flooding and climate change.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Ethics statement

The studies involving humans were approved by Sekolah Tinggi Ilmu Ekonomi Indonesia Jakarta. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

DP: Data curation, Visualization, Investigation, Validation, Methodology, Project administration, Conceptualization, Supervision, Funding acquisition, Software, Resources, Writing – review & editing, Writing – original draft, Formal analysis. SN: Formal analysis, Validation, Data curation, Writing – review & editing, Conceptualization, Software, Methodology. SHari: Investigation, Resources, Writing – review & editing, Formal analysis, Supervision, Conceptualization. SHara: Methodology, Writing – review & editing, Formal analysis, Data curation, Investigation. AS: Writing – review & editing, Conceptualization, Methodology, Formal analysis, Software, Data curation.

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Supplementary material

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