A SYSTEMATIC LITERATURE REVIEW ON ASSET MAINTENANCE PRIORITISATION APPROACHES RELEVANT TO WATER INFRASTRUCTURE

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ABSTRACT

While various maintenance prioritisation approaches exist, there is a need for a comprehensive understanding of their effectiveness, applicability, and implications for resource allocation and risk mitigation in water infrastructure maintenance. The study aims to identify, examine gaps and best practices in existing knowledge regarding maintenance prioritisation as applied to water infrastructure assets. A systematic literature review methodology was utilised, adhering to the PRISMA reporting protocol, to explore the Scopus database for literature addressing maintenance prioritisation approaches. The findings reveal that organisations commonly use risk-based approaches to prioritise maintenance tasks. The literature emphasises the importance of considering the frequency and consequences of failure when setting priorities for maintenance tasks. Additionally, popular methods for priority-setting include risk assessment and failure mode effect analysis. The study findings could enhance industrial engineers' contributions to maintenance optimisation and inform the development of a prioritisation framework for water infrastructure maintenance for a small South African municipality.

Keywords: maintenance prioritisation, water infrastructure, systematic literature review

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1 INTRODUCTION

Municipal water infrastructure plays a crucial role in sustaining communities, industries, and ecosystems by providing reliable access to clean drinking water and ensuring the adequate disposal of wastewater, both of which are fundamental for public health and economic development [1].

The effective functioning of municipal infrastructure depends heavily on the maintenance practices implemented to address challenges ranging from ageing components to unexpected failures [2]. Velmurugan & Dhingra [3] and Chong et al. [4] emphasise that effective planning for asset maintenance encompasses various maintenance techniques and requires making wise choices among maintenance options.

Mobley [5] highlighted that effective maintenance is crucial for operational reliability and efficiency. Despite widespread awareness, inadequate maintenance procedures in the water industry persist, underscoring the need to optimise operations while minimising risks and costs [6, 7].

Municipalities face multiple water infrastructure challenges, such as managing aging assets, budget constraints, and increasing maintenance demands [4, 8]. These challenges are compounded by the need for effective resource allocation. Consequently, municipalities often defer maintenance to reduce expenses and direct resources toward more critical areas, leading to the accumulation of maintenance backlogs [4].

Balzer and Schorn [9] acknowledged the compounding challenges facing the water industry due to rising demand. Furthermore, the interplay between limited resources and the need for robust and sustainable water infrastructure underscores the necessity of a comprehensive understanding of the latest best practices and context-specific approaches for prioritising maintenance [10].

This study aims to investigate the maintenance prioritisation approaches commonly applied to water infrastructure assets. By conducting a systematic literature review (SLR), the study seeks to identify and examine gaps and best practices in the current knowledge of maintenance prioritisation for water infrastructure assets. The findings will inform the development of a prioritisation framework for water infrastructure maintenance, focusing on reducing service delivery interruptions and enhance infrastructure reliability.

2 BACKGROUND OF THE STUDY

According to Mutamba [11], water infrastructure encompasses essential physical components and mechanisms that play a crucial role in delivering safe and reliable water services to communities. However, these assets inevitably degrade overtime, impacting their reliability and functionality [12]. Thus, strategic maintenance is vital to ensure safety and stability while minimising repair costs.

Maintenance activities encompass regular inspections, condition assessments, identifying of critical components, repairs, and the developing of maintenance plans [3, 4, 9]. Despite these efforts, resource limitations often result in maintenance backlogs, necessitating the prioritisation of maintenance tasks to ensure operational continuity.

Maintenance prioritisation, as explained by Chong et al. [4], is a technique utilised to ease the immediate burden of maintenance requests, enabling the immediate handling of pressing issues. However, postponed tasks require attention eventually, underscoring the need for judicious decision-making by maintenance practitioners.

Effective asset management decision-making is pivotal for developing cost-effective maintenance programs and enhancing infrastructure performance [13, 14]. This systematic approach allows utility companies and municipalities to make well-informed decisions regarding intervention strategies [2, 13, 14].

Given financial constraints and dynamic regulatory landscapes, prioritising maintenance based on risk exposure and critical criteria is crucial. Chirito [14] and Petersdorff and Vlok [13], emphasised developing targeted maintenance strategies to address the challenges posed by aging infrastructure and evolving needs .

The complexity of creating a comprehensive maintenance prioritisation system for municipal water infrastructure is acknowledged by the Development Bank of Southern Africa [15], Mutamba [11], and Mnguni [16], emphasising the need to consider the unique characteristics and interdependencies of water infrastructure assets.

To address the aforementioned complexity, it is imperative to analyse the selection and implementation of context-based maintenance prioritisation strategies, as articulated by Teixeira et al [17]. This study acknowledges the research conducted by Chong et al. [4] and Wing et al. [18], which explored factors and methods for prioritising maintenance. However, while comprehensive, these studies did not specifically target water infrastructure assets.

The SLR conducted in this study could enhance understanding of maintenance decision-making processes in water infrastructure management by evaluating various maintenance prioritisation approaches. The study is driven by the recognition that current approaches may not yield optimal outcomes, potentially resulting in costly and ineffective maintenance practices or a narrow focus on high-consequence assets. The goal is to provide recommendations for improving maintenance prioritisation strategies and asset management practices in the water sector, ensuring efficient management and safeguarding of critical water infrastructure assets to continuously provide vital services to communities.

3 METHOD

The study follows an SLR methodology to assess and interpret relevant research on asset maintenance prioritisation strategies relevant to water infrastructure in line with Kitchenham [19] and Siddaway et al.'s [20] approach. The systematic literature review (SLR) study consolidated existing information on asset maintenance prioritisation strategies relevant to water infrastructure. Through meticulous documentation of the methodology, the study ensured a comprehensive overview of current strategies, facilitating the identification of best practices and prevailing trends in the field. The approach not only aided the understanding of asset maintenance but also underscores the importance of replicability and transparency in research, as emphasised by Grant and Botha [21]. The SLR is guided by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [22].

3.1 Research protocol

Table 1 provides a detailed account of the research protocol, which includes information on the purpose of the study, research questions, inclusion criteria, exclusion criteria, databases searched, keywords used and quality assessment criteria employed.

Table 1: Research protocol

Purpose of the study	To investigate the maintenance prioritisation approaches commonly applied to water infrastructure assets
Research questions	**RQ1**: What are the prevalent water infrastructure asset maintenance prioritisation strategies in literature? **RQ2**: What are the key factors influencing the selection of maintenance prioritisation strategies in managing water infrastructure?
Inclusion criteria	• The paper discusses maintenance prioritisation being applied to water infrastructure management. • The research paper focuses on asset management in water infrastructure.
Exclusion criteria	• The paper is a duplicate publication. • The full text of the paper is not in English except for the title. • There is no access to the full text of the paper. • The research paper loosely uses terms and synonyms related to maintenance and prioritisation. • The research paper focuses solely on maintenance prioritisation outside the context of water infrastructure. • The research papers that are unrelated to the primary focus of the study.
Search Database	Scopus
Keywords	"water infrastructure" and "asset management" and "maintenance prioritisation"
Quality assessment criteria	• All duplicate literature must be removed. • Correct scientific methods must be used throughout the research study. • The overall methodology should be described in a manner that allows the study to be replicated. • Recovered literature should be checked for relevance and credibility. • Proper grammar, syntax, and terminology should be used to ensure the reader fully understands the research's intentions and outcomes.

3.2 Search strategy

The primary approach used to gather data involved searching the Scopus databases for articles using specific keywords related to "maintenance prioritisation", "asset management", and "water infrastructure". Search terms were carefully selected to reflect the main themes presented in the research questions while considering spelling variation, synonyms and usage differences. The approach followed increases the chances of identifying relevant studies [20].

Table 2 presents alternative terms used to encompass any potential differences in spellings or usage of synonyms.

Table 2: Search terms (alternative terms included)

Search terms	Alternative search words
Water infrastructure	
Asset management	Infrastructure management
Maintenance prioritisation	Maintenance prioritization, maintenance priority, maintenance management, maintenance priority setting, maintenance planning, maintenance scheduling, reliability-centred maintenance (RCM), priority setting methods, maintenance strategy selection

3.3 Search scope

The SLR review was conducted on the Scopus database, and only papers published in the last ten years, i.e. from January 2014 to December 2023, were reviewed to advance the existing research. The Scopus database was chosen for its extensive repository of peer-reviewed literature, providing a significant range of research contributions relevant to our research questions. The search returned a total of 442 studies which underwent scrutiny and evaluation following the PRISMA guidelines.

3.4 Study selection

Guidelines for selecting papers in this study adhered to the exclusion and inclusion criteria outlined in Table 1. The screening process involved a thorough examination of each paper's title, abstract, and full text. This comprehensive evaluation aimed to determine the potential relevance of each paper to the research objectives and adherence to the specified criteria. Papers that did not meet these criteria (described in Table 1) were excluded from the study. Despite retrieving many articles, many were not directly related to water infrastructure due to their abstract nature. Each article's abstract was carefully examined, and those considered relevant were further explored.

Ambiguous abstracts led to a review of the conclusion section or a rapid assessment starting from the introduction to determine relevance. Articles that remained unclear were ultimately disregarded.

Figure 1 summarises the selection stages followed in this study which included the removal of articles that were duplicated (DP), non-English studies (LC), studies that did not allow full access (NF), unrelated to the study's primary focus (NR) and studies that casually related to this study. This led to the remaining 14 eligible articles which were further analysed.

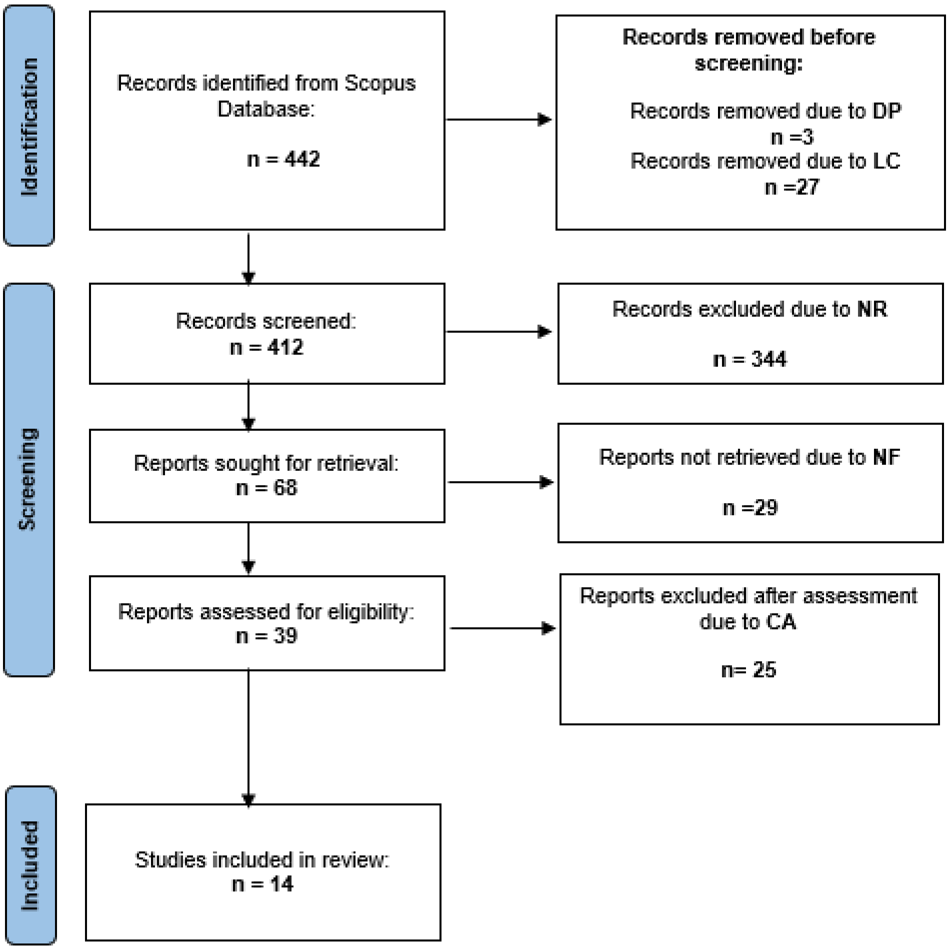

Figure 1: PRISMA flow diagram for systematic reviews [22]

3.5 Quality assessment for relevant studies

The quality of relevant literature was evaluated by thoroughly reading the articles. The retrieved studies were examined to determine their relevance to maintenance prioritisation in water infrastructure asset management and the factors they addressed. Evaluation criteria included language use, writing credibility, and reputable scientific research methods used in the literature.

3.6 Data analysis

To address the research questions outlined in Table 1, a total of 14 articles were selected for in-depth study. The data collection and review process were intentionally open-ended, permitting exploration of various aspects related to maintenance prioritisation without imposing predefined categories or biases. This approach facilitated a comprehensive examination of the topic.

The extracted data encompass diverse elements of maintenance prioritisation, including various methods, models, factors, algorithms, frameworks, tools, and decision-making processes. These elements form the basis for further analysis and synthesis aimed at effectively addressing the research questions and objectives of the study.

A qualitative analysis was employed to interpret the collected data, specifically through the application of descriptive coding. This method was chosen to identify the maintenance prioritisation strategies utilised in addressing water infrastructure maintenance issues and to determine the factors influencing these prioritisation decisions. Table 4 provides a summary of the literature included in the study, listing relevant references and offering a brief overview of each article's content.

4 SYSTEMATIC LITERATURE REVIEW FINDINGS

4.1 Literature overview

Figure 2 below illustrates the distribution of studies on water infrastructure maintenance by country, revealing a notable lack of contribution from developing countries. The majority of studies were conducted in the Netherlands and the USA, constituting 30% of the reviewed journal articles and conference papers.

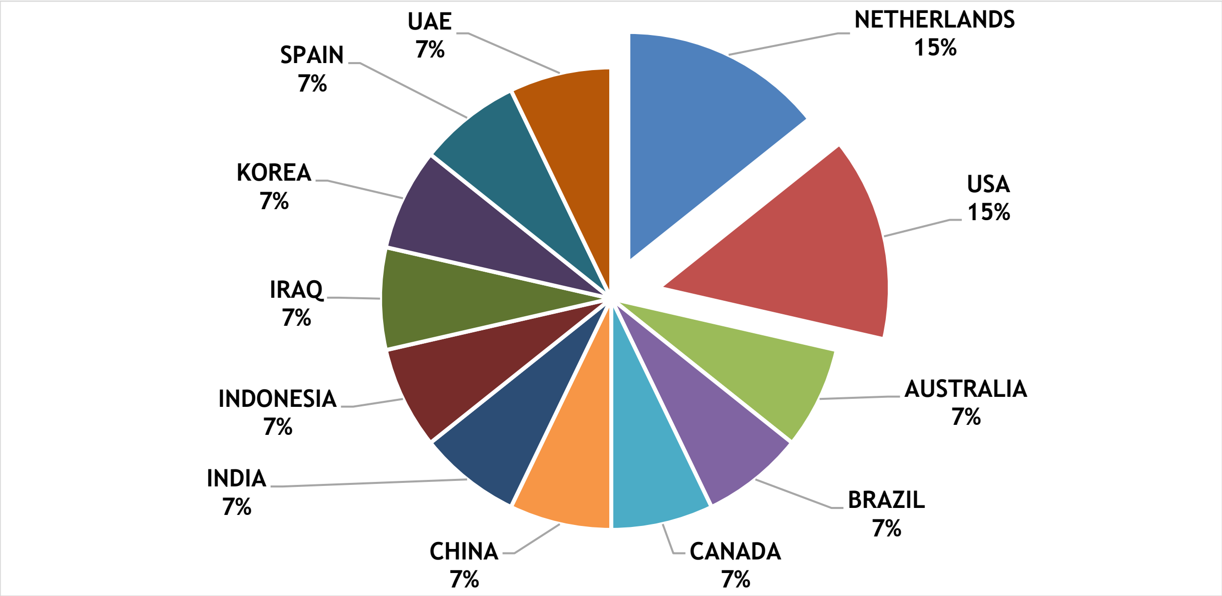

Figure 2: Countries in the reviewed studies

The water distribution and wastewater infrastructure are essential elements of urban systems, ensuring access to clean water and proper wastewater management. However, research exhibit a notable maintenance priorities discrepancy between these two infrastructural types, as depicted in Figure 3. Literature predominantly emphasises maintenance of water distribution infrastructure pipeline networks.

The emphasis on pipeline networks in both water distribution and wastewater infrastructure is justified by their essential role as the backbone of these systems, facilitating water transportation. Their critical function, susceptibility to deterioration, and significant economic implications underscore the focus on pipeline maintenance. Any disruptions in these pipelines can lead to severe consequences, highlighting the need for prioritised maintenance efforts.

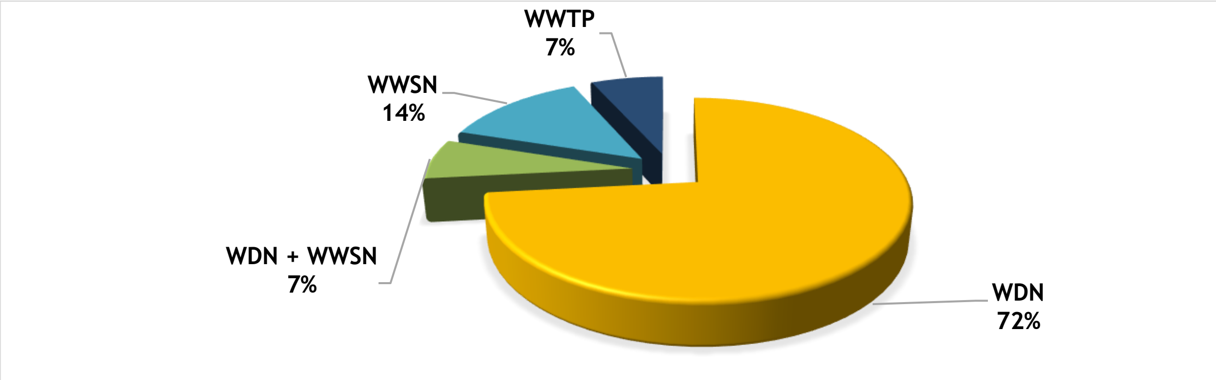

Figure 3: Application context of the reviewed studies (wastewater sewage network (WWSN), wastewater treatment plant (WWTP), water distribution network(WDN))

4.2 Prevalent maintenance prioritisation strategies

Table 3 provides a summary of common maintenance prioritisation strategies used in the water infrastructure sector, identified through a systematic literature review. The summary categorises the strategies, techniques, or methods employed, along with corresponding references from eligible articles meeting the inclusion criteria.

Table 3: Maintenance prioritisation strategies

Strategy/Approach	Method/ Technique	Reference
Risk-based	• Risk analysis + Complex network theory analysis • Fuzzy-FMEA • Risk analysis/assessment) + Risk map • Risk assessment • AHP-fuzzy model • FMECA + Life cycle cost analysis • Risk assessment	[23-28]
Asset criticality analysis	• Segment Criticality Measure/assessment/analysis • Graph theory method • Element-based simulation approach + Critical index • Graph theory	[29-32]
Optimisation	• Non-dominated Sorting Genetic Algorithm • Multi-Objective Genetic Algorithm	[33, 34]
Multi-Criteria Decision Analysis (MCDA)	• FFM-EA + FMRPI-FMTI Risk diagram • Strategic Options Development and Analysis + ELECTRE TRI-nC method	[35, 36]

Table 44: Summary of the studies included in the review

Author	Factors considered	Prioritisation approaches	Results
[29]	Asset criticality, impact on service delivery	Segment Criticality Measure/assessment/analysis	Framework for scheduling maintenance routine
[23]	Risk, asset criticality	Risk analysis + Complex network theory analysis.	Risk-informed decision support framework for integrated water and road infrastructure asset management.
[33]	Condition - economic cost, network reliability, and network health	Non-dominated Sorting Genetic Algorithm	A Life Cycle Oriented Multi-objective Optimal Maintenance model for Water Distribution
[35]	Asset condition, risk, budget constraints	Fuzzy-Failure mode effect analysis(FFM-EA) - Risk Priority Index and the Total Intensity (TI)-AHP, FMRPI-FMTI Risk diagram	Fuzzy-based Multi-Criteria Decision Support System for maintenance of wastewater treatment plants
[30]	Asset criticality, impact on service delivery	Graph theory method	A method of Identifying critical elements in drinking water distribution networks
[34]	Risk , asset criticality, proximity, budget constraints, asset condition	Multi-objective genetic algorithm (MOGA)	A decision support system to design water supply and sewer pipe replacement intervention programs
[32]	Asset criticality	Element-based simulation approach Criticality index	A methodology to Identify Critical Pipes Using a Criticality index
[25]	Risk, asset condition	Fuzzy-FMEA	A risk-based method of identifying and prioritising causes of failure for maintenance planning
[24]	Risk	Risk analysis/assessment) Risk map	Framework for risk assessment of pipes in a WDN for maintenance prioritisation
[26]	Asset condition, risk, budget constraint	Risk assessment - risk rating matrix; Life Cycle Costs analysis	Risk-based approach to develop a maintenance strategy
[36]	Asset criticality, asset condition	Strategic Options Development and Analysis (SODA), Elimination and Choice Translating Reality (ELECTRE TRI-nC) method,	A methodological framework for sorting the water distribution network areas for the maintenance plan.
[31]	Asset criticality	Graph theory method	A method of identifying the most critical elements in a network with respect to malfunctioning of the whole system.
[27]	Environmental impact, risk	AHP-fuzzy model	An AHP-fuzzy model to determine maintenance priority based on environmental factors
[28]	Asset condition, asset criticality, risk	Failure mode effect analysis Asset Criticality analysis Life cycle cost analysis	Water asset replacement maintenance prioritisation procedure

Figure 4 shows that 43% of the analysed studies employed a risk-based strategy to prioritise maintenance activities based on the likelihood and consequences of asset failure. Given the substantial impacts of water infrastructure malfunctions on public health and environmental safety, this approach is crucial. The widespread use of risk-based methods underscores their effectiveness in providing proactive maintenance for vital assets and in mitigating long-term expenses by preventing significant failures.

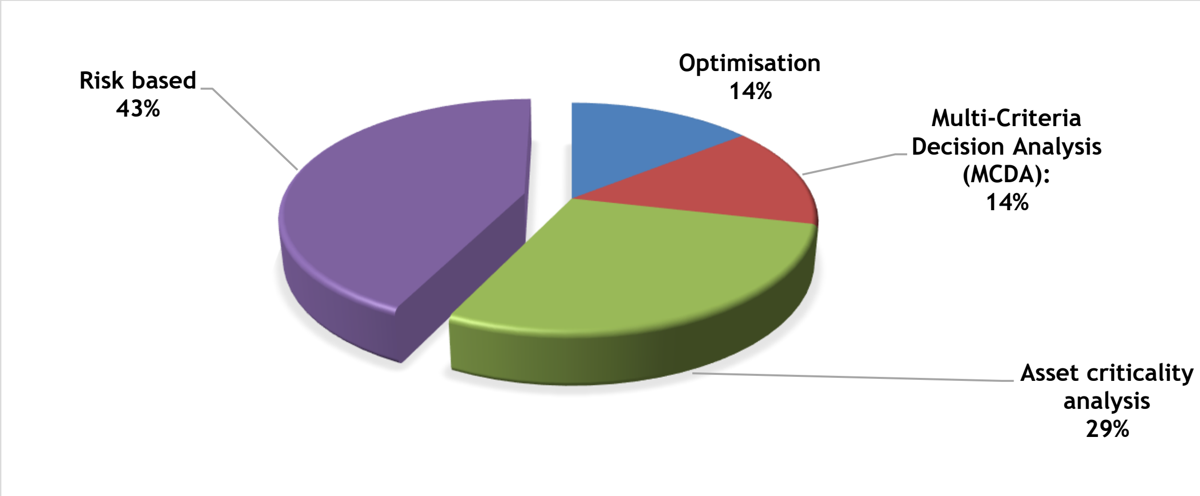

Figure 4: Application of maintenance prioritisation approaches

The importance of risk management techniques in maintenance prioritisation extends beyond identifying high-risk areas within water infrastructure networks. Maintenance practitioners not only address these high-risk areas to prevent potential failures that could endanger public health, safety, and the environment, but also utilise risk assessments to inform resource allocation decisions [23-25].

In addition, risk assessment is essential for ensuring regulatory compliance in water infrastructure management. Non-compliance with regulatory standards, such as pipeline leakages or deteriorating wastewater treatment plants, can lead to contamination or poor water quality, violating water utilities' obligations to provide safe and continuous clean water [26].

Asset criticality analysis, comprising 29% of reviewed articles, ranks as the second most dominant approach, as shown in Figure 4. This analysis evaluates each asset in the water infrastructure network to determine its significance. Assets deemed crucial, either due to their key role in the system or their potentially severe impact if disrupted, are given top priority in maintenance operations. A study by Tornyeviadzi et al [29], employed segment criticality analysis to identify specific segments within the water distribution network (WDN) that can undergo maintenance without causing operational disruptions or hindering service delivery.

Incorporating asset criticality analysis emphasises the importance of maintaining high-priority components within water infrastructure and enables effective resource allocation by establishing priorities necessary for optimal functionality and uninterrupted service delivery across all networks involved.

Given the necessity to balance multiple objectives and navigate conflicting constraints during decision-making, multi-criteria decision analysis (MCDA) methods offer a comprehensive approach to assessing maintenance priorities aligned with organisational goals and stakeholder preferences [28, 35, 36]. Figure 4 shows that MCDA approaches account for 14% of the studies. Multi-criteria decision analysis involves the use of multiple criteria to evaluate and prioritise maintenance activities. These criteria can include risk, cost, asset criticality, and other relevant factors [28]. This approach provides a structured framework to balance various competing factors. The adoption of MCDA indicates the recognition of complexity involved in asset management decision-making and multifaceted nature of maintenance prioritisation in water infrastructure.

Although potentially powerful, multi-criteria optimisation is the least common approach in the reviewed literature (Figure 4). It employs mathematical and computational techniques to determine efficient resource allocation and maintenance schedules with specific objectives like cost minimisation or asset reliability maximisation. For instance, in a study conducted by Chu et al. [33], the genetic algorithm was utilised to optimise maintenance schedules by exploring trade-offs between conflicting objectives, such as minimising risks and maintenance costs while maximising system reliability, all within the constraints of available resources or system limitations. Chu et al. [33] asserted that genetic algorithms help decision-makers identify maintenance strategies that effectively balance multiple goals by generating a varied set of pareto-optimal solutions to enhance operational efficiency, reduce costs, and prolong asset lifespan.

4.3 Key factors influencing maintenance prioritisation

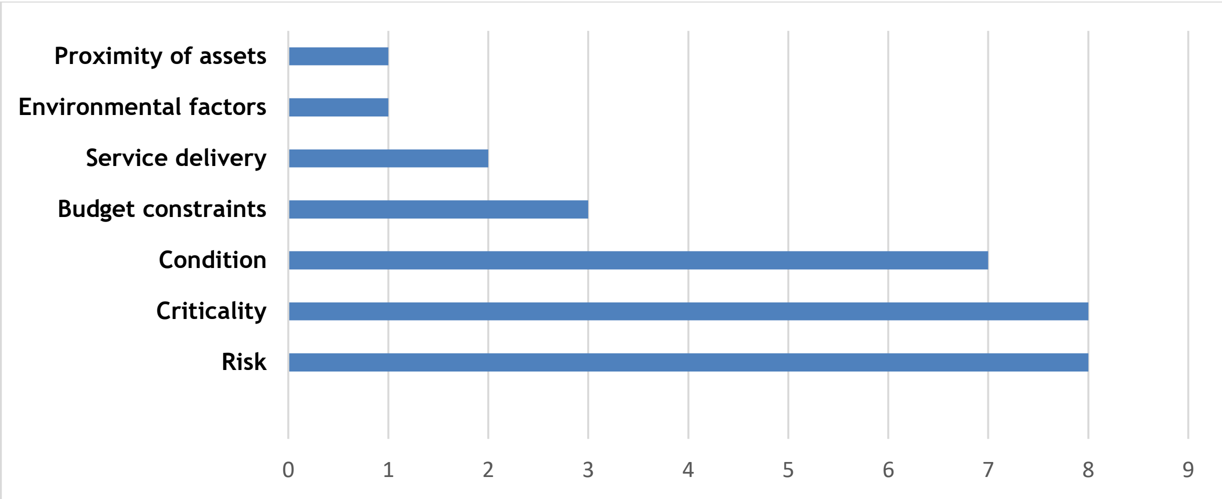

Figure 5: Factors on maintenance prioritisation

Figure 5 shows the key maintenance prioritisation factors that emerged from the study: criticality, asset condition, risk, budget constraints, service delivery, and proximity. The analysis of these factors reveals a multifaceted decision-making process influencing maintenance prioritisation in water infrastructure. The interaction between these factors in determining maintenance priorities for water infrastructure is complex and dynamic, with each factor uniquely shaping the decision-making process. Equipment risk, criticality and condition had top frequency of discussion in the papers considered.

The study findings reveal consistent theme of risk consideration across various aspects when prioritising maintenance for water infrastructure assets (Figure 5). Evaluating risk involves analysing both the probability and potential consequences of asset breakdowns [26]. This process helps identify assets that may pose significant risks to public safety or system functionality.

By prioritising risk assessment, water infrastructure managers can prevent serious accidents and protect high-risk assets through strict adherence to safety protocols. This emphasises the importance of avoiding hazards to mitigate potential risks proactively. Mazumder et al. [23], emphasised the importance of considering the potential impact of failure, particularly in the context of buried pipelines that could affect nearby infrastructure. This underscored the necessity of integrating risk assessment into maintenance planning to proactively address risks and enhance the resilience of water infrastructure systems.

The condition of water infrastructure assets is also a critical factor. Maintenance decisions are heavily influenced by the physical state of the infrastructure, with deteriorating assets requiring immediate attention. By monitoring and conducting inspections, water utilities can identify assets in poor condition or at risk of failure, a sentiment echoed by Al-Attar et al. [35]. Notably, the age and condition of assets are intertwined with their lifecycle, with assets deteriorating towards the end of their life and requiring increased maintenance, as observed by Chong et al [4]. The knowledge of the asset age and asset condition helps prioritise maintenance tasks, addressing immediate risks and preventing service disruptions or safety hazards over assets in better condition.

Water infrastructure assets in poor condition can lead to service disruptions, impacting consumer satisfaction and regulatory compliance [34]. Identifying critical assets, particularly those in poor condition or at higher risk of failure, is crucial as they can significantly impact water quality, service reliability, and public health if they fail. Condition assessment is a fundamental aspect of many models, such as life cycle-oriented maintenance and criticality index methodologies, which prioritise maintenance based on the current state of the assets.

Criticality is a key factor in the decision-making process, especially when it comes to prioritising, budgeting, and planning for repairs and replacements as articulated by Katheeri et al. [28] and Marlim et al. [32]. Asset criticality becomes even more imperative in scenarios involving aging infrastructure, limited budgets, asset interdependencies, and potential impacts on network performance or operations. These insights echo findings from studies by Al-ttar et al. [35] and Marlim et al. [32], highlighting the central role of asset criticality in guiding maintenance prioritisation efforts to enhance the resilience and reliability of water infrastructure systems.

In summary, SLR findings indicate that a balanced approach, considering both technical and practical factors, is essential for effective maintenance prioritisation in water infrastructure. By integrating these diverse factors and strategies, maintenance practitioners can develop comprehensive maintenance strategies that improve water infrastructure resilience, optimise resource use, and ensure continuous service delivery.

5 DISCUSSION

5.1 Discussion of the SLR

The systematic literature review (SLR) identified a consistent theme of risk consideration and the implementation of risk-based strategies, demonstrating the effectiveness of risk management techniques in the maintenance prioritisation of water infrastructure systems.

Tools such as risk assessment, risk matrices, FMEA, FMECA, and risk maps augment the decision-making process aimed at mitigating the associated risks. By identifying critical failure modes and assessing risks, decision-makers can optimise maintenance planning, allocate resources efficiently, and enhance the overall reliability of water infrastructure systems. Risk assessments prioritise maintenance efforts on critical assets to prevent potential issues and improve practices. However, the study revealed that due to resource constraints, maintenance practitioners tend to focus primarily on addressing maintenance risks that pose the greatest threat to their business objectives.

The success of a decision-making system relies heavily on amassing sufficient and relevant data [35]. Limited access to asset data poses significant challenges, hindering effective infrastructure monitoring and problem resolution. Reliable data is fundamental to understanding the current condition of assets, predicting future performance, and formulating appropriate maintenance and management strategies. The SLR revealed the difficulty of conducting thorough risk assessments with inadequate data, underscoring the necessity of robust data collection strategies to enhance asset condition monitoring and evaluation. Chu et al [33], further proposed that dependable data collection and model validation are crucial for scientifically managing water distribution networks.

Multi-criteria decision analysis (MCDA) approaches effectively incorporate qualitative factors into decision-making processes, particularly when information or analytic resources are scarce. MCDA supports maintenance decisions involving multiple factors, constraints and adapts as more data becomes available. However, selecting the appropriate MCDA technique for resource allocation remains challenging. Techniques such as the analytic hierarchy process (AHP), failure mode effect analysis (FMEA) and others have inherent strengths and weaknesses that must be evaluated to determine their suitability in specific context, as demonstrated by Pereira et al. [36] and Maryati & Romdoni [27]. These techniques can be complex and require specialised knowledge, which may not be available in some municipalities.

Life cycle-oriented, multi-objective optimisation and multicriteria decision models are important for balancing objectives such as cost, reliability, and service level in comprehensive maintenance management. Optimisation techniques can significantly reduce operational costs and enhance service delivery, which is increasingly important as water utilities aim to improve financial sustainability and operational efficiency. While promising, these approaches are less widely adopted due to complexity and resource demands.

Advanced analytical techniques, fuzzy logic, and decision support models are prevalent, yet there a need for customised models to handle uncertainty and complexity in maintenance decision-making. Life cycle cost (LCC) analysis for budget allocation and asset replacement/renewal decisions as noted by Katheeri et al. [28]. However, there is a lack of comprehensive discussion on the practical implementation of LCC analysis in the reviewed studies.

In summary, the literature indicates the need for adaptable maintenance prioritisation strategies that incorporate structured decision-making methods, consider resource constraints, and employ advanced analytical techniques.

5.2 Gaps in literature and recommendations for research

A notable research gap exists regarding the economic consequences of maintenance decisions, particularly in water infrastructure management. This gap hinders effective collaboration between technical and financial teams, potential leading to misalignment between technical decisions and financial constraints, resulting in suboptimal resource allocation and inefficiencies.

There is an identifiable gap in the literature regarding the development of tailored solutions and strategies for managing water infrastructure, particularly in the developing countries of Southern Africa.

Currently, most research studies tend to narrow their focus to specific situations, concentrating on prioritising maintenance for individual assets. However, this approach often results in a fragmented understanding, lacking a comprehensive strategy that considers the interconnectedness of all assets within a portfolio. This fragmented approach poses challenges for practitioners, who may struggle to implement these findings across different contexts. Therefore, future research efforts should aim to refine existing solutions and assess their effectiveness across a range of settings. By doing so, we can bolster the resilience of water infrastructure worldwide, ensuring that strategies are adaptable and beneficial in diverse environments.

The synthesis of the research outcomes highlights several critical implications for academic research in water infrastructure maintenance. Researchers can undertake several strategic studies to enhance water infrastructure asset management practices and understand their implications across various dimensions:

- Studies can assess the effectiveness and outcomes of different asset management approaches. By employing longitudinal research, scholars can track how asset distribution changes over time and its consequent effects on maintenance performance, resilience, and sustainability.
- Future research in water infrastructure asset management should prioritise the integration of emerging trends such as advanced analytics, machine learning, IoT technologies, and digital twins. Digital twins allow for predictive maintenance, where potential issues can be identified and resolved before they lead to costly failures. Incorporating these advanced technologies enhances the effectiveness and efficiency of maintenance operations and contributes to the overall reliability and sustainability of water infrastructure systems. With improved prediction and optimisation mechanisms, the lifespan of assets can be extended, and the risks of catastrophic failures can be significantly reduced. Therefore, future research must continue to explore and refine these technologies. Ongoing innovation will ensure that asset management practices evolve in line with the demands of modern infrastructure systems. By staying ahead of technological advancements, asset managers can better safeguard water infrastructure, ensuring its resilience and reliability for future generations
- Examining asset management across different industries can uncover transferable strategies and best practices. Comparative analysis can identify common challenges and opportunities for cross-sector collaboration and knowledge sharing, providing a broader understanding of effective water infrastructure asset management.
- Conducting cost-benefit analyses of various maintenance strategies will help water utilities and policymakers understand the economic impacts of investing in advanced maintenance technologies and practices. These evaluations can provide a solid economic rationale for adopting innovative asset management approaches.

By synthesising insights from these areas, researchers can contribute to the development of robust, efficient, and sustainable asset management practices for water infrastructure assets.

5.3 Contribution of the study

The study consolidates and analyses existing research on maintenance prioritisation for water infrastructure assets, providing a holistic view and comprehensive understanding that is often missing in individual studies. The study identifies and compiles commonly used maintenance practices and effective strategies from various sources, offering a clear guide for maintenance practitioners to adopt proven approaches in the water industry. By effectively prioritising maintenance, water infrastructure managers can optimise resource allocation, reduce downtime, and extend the lifespan of critical assets.

By examining the breadth of existing literature, the study identified areas needing further exploration, thus acting as a guide for future research by pinpointing unexplored areas, emerging trends, and technologies (as highlighted in section 5.2) in the maintenance of water infrastructure assets. The review allows for a comparative analysis of different maintenance prioritisation strategies, highlighting their applicability to various contexts within water infrastructure. This study is valuable as it provides a comprehensive synthesis of current knowledge and sets the stage for future advancements in the field, ultimately contributing to more efficient, reliable, and sustainable water infrastructure management. The study offers a clear and reproducible methodology, that will enable other researchers to build upon these findings, ultimately contributing to more efficient and sustainable maintenance practices for water infrastructure assets.

5.4 Limitations

This SLR was based on publications from 2014 to 2023. The SLR exclusively considered English-language publications, potentially excluding significant studies published in other languages. The SLR solely reviewed research indexed in the Scopus database, thereby leaving out pertinent studies published elsewhere. Additionally, the SLR did not include grey literature, even though these sources can sometimes offer valuable insights and data. This exclusion was because grey literature is often not peer-reviewed and may lack the rigorous quality control and academic validation that peer-reviewed journal articles and conference papers provide. This decision was made to ensure the reliability and credibility of the data included in our systematic review. The wide variety of research goals and methodologies among the reviewed studies created substantial heterogeneity, precluding the possibility of conducting a meta-analysis.

6 CONCLUSION

This study presented a systematic literature review of maintenance prioritisation strategies in the water infrastructure sector. It enhanced the understanding of maintenance prioritisation practices applied to water infrastructure assets, highlighting prevailing strategies (section 4.2) and the dominant factors considered (section 4.3). The review underscores the necessity for data-informed, holistic maintenance prioritisation strategies in the water infrastructure sector.

Current efforts emphasise risk-based and criticality analyses, which constitutes 72% of the maintenance prioritisation strategies employed. However, there is considerable room for advancement. Future research should aim to develop comprehensive, data-driven strategies that leverage advanced analytics, machine learning, and predictive modelling. These strategies should evaluate entire asset portfolios rather than individual components, allowing for the identification of trends and failure modes across various water infrastructure assets. This approach would enhance long-term performance and sustainability. Addressing the identified gaps requires creating adaptable, universally applicable maintenance strategies capable of addressing diverse contextual challenges, especially in underrepresented regions such as developing countries in Southern Africa.

7 REFERENCES

[1] P. Bikam and J. Chakwizira, "Municipal asset operations and maintenance performance in metropolitan and rural municipalities in Gauteng Province and Vhembe District Local Municipalities, South Africa," Cogent Engineering, vol. 8, no. 1, pp. 1-24, January 2021, Art no. 1935409, doi: 10.1080/23311916.2021.1935409.

[2] S. Carpitella, F. Carpitella, J. Benitez, A. Certa, and J. Izquierdo, "Prioritization of maintenance actions in water distribution systems," in Congress on Numerical Methods in Engineering, CMN 2017, Valencia, Spain, I. Arias, J. M. Blanco, S. Clain, P. L. Paulo Flores, J. J. Ródenas, and M. Tur, Eds., July 3 - 5 2017: International Center for Numerical Methods in Engineering (CIMNE), pp. 1656-1664.

[3] R. S. Velmurugan and T. Dhingra, "Maintenance strategy selection and its impact in maintenance function: A conceptual framework," International Journal of Operations & Production Management, vol. 35, no. 12, pp. 1622-1661, 2015, doi: 10.1108/IJOPM-01-2014-0028.

[4] A. K. W. Chong, A. H. Mohammed, M. N. Abdullah, and M. S. A. Rahman, "Maintenance prioritization – a review on factors and methods," Journal of Facilities Management, vol. 17, no. 1, pp. 18-39, 2019, doi: 10.1108/JFM-11-2017-0058.

[5] R. K. Mobley, An Introduction to Predictive Maintenance. Butterworth-Heinemann, 2002.

[6] U. Kumar, D. Galar, P. Aditya, C. Stenström, and L. Berges-Muro, "Maintenance performance metrics: A state-of-the-art review," Journal of Quality in Maintenance Engineering, vol. 19, pp. 233-277, 2013, doi: 10.1108/JQME-05-2013-0029.

[7] A. Garg and S. G. Deshmukh, "Maintenance management: literature review and directions," Journal of Quality in Maintenance Engineering, vol. 12, no. 3, pp. 205-238, 2006, doi: 10.1108/13552510610685075.

[8] South African Institution of Civil Engineering, "SAICE 2022 Infrastructure Report Card for South Africa," Midrand, 2022. Accessed: 5 April 2023. [Online]. Available: https://saice.org.za/irc/

[9] G. Balzer and C. Schorn, Asset Management for Infrastructure Systems, 2 ed. (Energy and Water). Switzerland: Springer Cham, 2022.

[10] M. Dubillard, G. Martin, M. Lauras, X. Lorca, and J. Cantet, "Toward Resilient and Efficient Maintenance Planning for Water Supply Networks," in Smart and Sustainable Collaborative Networks 4.0, Cham, L. M. Camarinha-Matos, X. Boucher, and H. Afsarmanesh, Eds., 2021: Springer International Publishing, pp. 591-600, doi: https://doi.org/10.1007/978-3-030-85969-5_55.

[11] J. Mutamba, "Infrastructure maintenance, upgrade & repair," in "Infrastructure Maintenance for Water Supply System: A Chapeu," Rand Water: Water Services Forum, Presentation 17 May 2023. Accessed: 15 January 2024. [Online]. Available: https://www.randwater.co.za/media/forums/presentations/INFRASTRUCTURE%20MAINTENANCE,%20UPGRADE%20&%20REPAIR.pdf

[12] A. Delnaz, F. Nasiri, and S. S. Li, "Asset management analytics for urban water mains: a literature review," Environmental Systems Research, vol. 12, no. 1, pp. 1-17, 2023, doi: 10.1186/s40068-023-00287-7.

[13] H. A. V. Petersdorff and P. J. Vlok, "Prioritising maintenance improvement opportunities in physical asset management," South African Journal of Industrial Engineering, vol. 25, pp. 154-168, 2014.

[14] L. F. M. Chirito, "Decision framework for maintenance activities in water pipelines: repair or replace?: A literature review and a decision framework proposal," Degree project, Civil and Architectural Engineering KTH Royal Institute of Technology,

Stockholm, Sweden, 2023. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:1766410/FULLTEXT01.pdf

[15] Development Bank of Southern Africa, "National Water Services Infrastructure Asset Management Strategy," DBSA, 2021. Accessed: 5 June 2023. [Online]. Available: https://www.dbsa.org/sites/default/files/media/documents/2021-03/DWA_WS_IAM_Strategy-for-Stakeholder_Inputs090910.pdf

[16] E. S. Mnguni, "Water infrastructure asset management: A comparative analysis of three urban water utilities in South Africa," Sustainable Development and Planning X, vol. 217, pp. 927-938, Feb 2017, doi: 10.2495/SDP180781.

[17] H. N. Teixeira, I. S. Lopes, and R. N. Pires, "Maintenance Strategy Selection: An Approach Based on Equipment Criticality and Focused on Components," in Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems, FAIM 2023, Cham, F. J. G. Silva, L. P. Ferreira, J. C. Sá, M. T. Pereira, and C. M. A. Pinto, Eds., June 18 - 22 2024, vol. 2: Springer Nature Switzerland, pp. 3-11.

[18] A. Wing, M. A. H. Mohammed, and M. Abdullah, "A literature review on maintenance priority - conceptual framework and directions," MATEC Web of Conferences, vol. 66, no. 4, pp. 1-7, 2016, doi: 10.1051/matecconf/20166600004.

[19] B. Kitchenham, "Procedures for Performing Systematic Reviews," Keele University, Technical Report 0400011T.1, August 1 2004.

[20] A. P. Siddaway, A. M. Wood, and L. V. Hedges, "How to Do a Systematic Review: A Best Practice Guide for Conducting and Reporting Narrative Reviews, Meta-Analyses, and Meta-Syntheses," Annual Review of Psychology, vol. 70, no. 1, pp. 747-770, 2019, doi: 10.1146/annurev-psych-010418-102803.

[21] M. Grant and A. Booth, "A typology of reviews: An analysis of 14 review types and associated methologies," Health Information and Libraries Journal, vol. 26, no. 2, pp. 91-108, 07/01 2009, doi: 10.1111/j.1471-1842.2009.00848.x.

[22] M. J. Page et al., "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," BMJ, vol. 372, n71, pp. 1-7, 2021, doi: 10.1136/bmj.n71.

[23] R. K. Mazumder, A. M. Salman, Y. Li, and X. Yu, "Asset Management Decision Support Model for Water Distribution Systems: Impact of Water Pipe Failure on Road and Water Networks," Journal of Water Resources Planning and Management, Article vol. 147, no. 5, 2021, Art no. 04021022, doi: 10.1061/(ASCE)WR.1943-5452.0001365.

[24] H. C. Phan, A. S. Dhar, G. Hu, and R. Sadiq, "Managing water main breaks in distribution networks--A risk-based decision making," Reliability Engineering and System Safety, Article vol. 191, 2019, Art no. 106581, doi: 10.1016/j.ress.2019.106581.

[25] P. Srivastava, M. Agrawal, G. Aditya Narayanan, M. Tandon, M. N. Tulsian, and D. Khanduja, "Risk Analysis of Water Treatment Plant Using Fuzzy-Integrated Approach," in Harmony Search and Nature Inspired Optimization Algorithms. Advances in Intelligent Systems and Computing, Singapore, N. Yadav, A. Yadav, J. C. Bansal, K. Deep, and J. H. Kim, Eds., 24 August 2019, vol. 741: Springer Singapore, pp. 761-770, doi: https://doi.org/10.1007/978-981-13-0761-4_73.

[26] M. F. Masud, G. Chattopadhyay, and I. Gunawan, "Development of a Risk-Based Maintenance (RBM) Strategy for Sewerage Pumping Station Network," in 2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Macao, China, 15-18 December 2019: IEEE Computer Society, pp. 455-458, doi: 10.1109/IEEM44572.2019.8978633.

[27] S. Maryati and Y. Romdoni, "Priority maintenance of drinking water network and environmental factors," in Proceeding of 2017 International Conference on Smart Cities, Automation and Intelligent Computing Systems, ICON-SONICS 2017, Yogyakarta, Indonesia, November 08-10 2017: Institute of Electrical and Electronics Engineers Inc., pp. 76-80, doi: 10.1109/ICON-SONICS.2017.8267825.

[28] M. A. Katheeri, A. R. A. Dhaheri, and T. Almasaleha, "Water asset replacement maintenance prioritization procedure based on criticality and optimisation of energy consumption," in 2015 IEEE Global Humanitarian Technology Conference, (GHTC), Seattle, WA, USA, 08-11 October 2015: Institute of Electrical and Electronics Engineers Inc., pp. 326-333, doi: 10.1109/GHTC.2015.7343992.

[29] H. M. Tornyeviadzi, H. Mohammed, and R. Seidu, "Dynamic segment criticality analysis: A precursor to scheduling of maintenance routines in water distribution networks," Alexandria Engineering Journal, Article vol. 61, no. 12, pp. 9261-9272, 2022, doi: 10.1016/j.aej.2022.03.012.

[30] D. Meijer, J. Post, J. P. van der Hoek, H. Korving, J. Langeveld, and F. Clemens, "Identifying critical elements in drinking water distribution networks using graph theory," Structure and Infrastructure Engineering, vol. 17, no. 3, pp. 347-360, 2021, doi: https://doi.org/10.1080/15732479.2020.1751664.

[31] D. Meijer, M. Bijnen, J. Langeveld, H. Korving, J. Post, and F. Clemens, "Identifying critical elements in sewer networks using graph-theory," Water (Switzerland), vol. 10, no. 2, 2018, Art no. 136, doi: 10.3390/w10020136.

[32] M. S. Marlim, G. Jeong, and D. Kang, "Identification of critical pipes using a criticality index in water distribution networks," Applied Sciences (Switzerland), vol. 9, no. 19, pp. 1-14, 2019, Art no. 4052, doi: 10.3390/app9194052.

[33] J. Chu, Z. Zhou, X. Ding, and Z. Tian, "A Life Cycle Oriented Multi-objective Optimal Maintenance of Water Distribution: Model and Application," Water Resources Management, Article vol. 36, no. 11, pp. 4161-4182, 2022, doi: https://doi.org/10.1007/s11269-022-03246-6.

[34] C. Ramos-Salgado, J. Muñuzuri, P. Aparicio-Ruiz, and L. Onieva, "A decision support system to design water supply and sewer pipes replacement intervention programs," Reliability Engineering and System Safety, vol. 216, 2021, Art no. 107967, doi: 10.1016/j.ress.2021.107967.

[35] R. T. Al-Attar, M. S. Al-Khafaji, and F. H. Al-Ani, "Fuzzy - Based Multi - Criteria Decision Support System for Maintenance Management of Wastewater Treatment Plants," Civil and Environmental Engineering, vol. 17, no. 2, pp. 654-672, 2021, doi: https://doi.org/10.2478/cee-2021-0065.

[36] L. D. S. Pereira, D. C. Morais, and J. R. Figueira, "Using criticality categories to evaluate water distribution networks and improve maintenance management," Sustainable Cities and Society, vol. 61, no. 3, pp. 1-11, 2020, Art no. 102308, doi: 10.1016/j.scs.2020.102308.