International Journal of Leading Research Publication (IJLRP)

E-ISSN: 2582-8010 ● Website: www.ijlrp.com ● Email: editor@ijlrp.com

An Essential Understanding of Water Pipe Assets Repair, Replacement, and Rehabilitation

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Abstract

Water distribution networks (WDNs) are vital infrastructures that ensure reliable access to safe drinking water, supporting urban, rural, and industrial needs. However, aging pipelines, increasing populations, resource constraints, and climate variability have heightened the challenges of maintaining these systems. Issues such as frequent pipe failures, rising operational costs, and escalating non-revenue water (NRW) underscore the urgent need for strategic interventions. This paper addresses the ambiguities surrounding repair, replacement, and rehabilitation by providing explicit definitions and evaluating their distinct benefits and constraints. A conceptual framework is proposed to guide decision-makers in selecting cost-effective, sustainable pipeline management strategies, balancing technical, economic, regulatory, and environmental considerations. By offering a structured approach to managing WDNs, this research aims to improve operational efficiency, extend infrastructure longevity, and reduce NRW. The findings are applicable across diverse contexts, benefiting developed nations with aging systems and emerging economies expanding their water networks. The study's insights empower policymakers, utility managers, and planners in optimizing resource allocation and enhancing the resilience of water distribution systems.

Keywords: Water Distribution Network, Repair, Replacement, Rehabilitation, Sustainability, Asset Management

1. INTRODUCTION

1.1 Background

Water distribution networks (WDNs) form the backbone of modern communities, delivering reliable and safe drinking water to urban centers, rural towns, and industrial regions worldwide. They ensure that residents have uninterrupted access to cooking, cleaning, and sanitation water while meeting the demands of agriculture, manufacturing, and emergency services. Over the last few decades, however, managing these networks has become increasingly challenging. Aging pipes, many installed several decades ago, have begun to deteriorate. As a result, WDNs now face an expanding range of issues, including frequent pipe failures, escalating repair costs, and rising non-revenue water (NRW) - the portion of water produced that does not generate income due to leakage, meter inaccuracies, or unbilled consumption.This set of challenges, compounded by growing populations, resource limitations, and climate variability, underscores the importance of ensuring that WDNs remain efficient and resilient.

The cumulative impact of small leaks can translate into substantial financial losses, while larger pipeline breaks threaten public health, disrupt daily life, and severely damage infrastructure and the environment. Consequently, maintaining WDNs is not merely a matter of patching leaks; it involves strategic interventions that target long-term serviceability and sustainability. Repair, replacement, and rehabilitation of pipes—methods encompassing localized fixes, systematic upgrades, and wholesale renewals—emerge as critical strategies in extending service life and improving operational performance. These interventions promise to stabilize or reduce NRW and operational costs and foster trust and reliability in essential water services.

1.2 Problem Statement

Despite the widespread necessity of these strategies, water utilities often struggle with determining when and how to employ them. The terminologies and methodologies—repair, replacement, and rehabilitation—are frequently used interchangeably or without a firm grasp of their distinct scopes, benefits, and constraints. Without clear guidelines and decision-making frameworks, utilities risk investing in suboptimal interventions that fail to deliver the greatest possible returns on limited budgets. Financial resources, skilled labor, and time are finite, compelling decision-makers to balance multiple factors such as pipe age, material, hydraulic performance, environmental concerns, and community expectations.This confusion hampers the adoption of comprehensive asset management strategies, leaving water managers to navigate a complex landscape of rising operation and maintenance costs. Given these pressures, it is imperative to develop well-structured approaches that help utilities rationalize their investments and set clear priorities, all while managing risks and adhering to regulatory mandates.

1.3 Research Objectives

This study aims to clarify these complexities by first offering precise definitions and delineations of repair, replacement, and rehabilitation. It will then identify the core factors—technical, financial, regulatory, and environmental—that influence the selection of intervention strategies. The goal is to propose a conceptual framework for cost-effective, sustainable pipeline management. Such a framework will enable informed decision-making and consistent application across different scales of WDNs.

1.4 Significance of Study

The outcomes of this research have far-reaching implications for water utility planners, asset managers, and policymakers tasked with ensuring safe and reliable water delivery.Providing a structured reference point can enhance operational planning, reduce NRW, and extend the life expectancy of critical infrastructure assets. Both developed and developing countries stand to benefit: While many wealthier nations grapple with aging systems and skyrocketing rehabilitation costs, emerging economies face the dual challenge of expanding their network coverage while maintaining quality and efficiency.

2.LITERATURE REVIEW

2.1 Overview of Water Distribution Network Challenges

Global WDNs face numerous challenges as infrastructure ages, causing an increase in pipeline failures. Aging pipelines are particularly prevalent in both developed and developing countries. Studies show that water loss due to leakages can reach up to 50% in some regions, with pipe materials such as cast iron and asbestos cement being especially vulnerable to degradation over time (Bhagat et al., 2019). Environmental stressors, such as soil corrosion and seismic activities, further exacerbate the deterioration of pipe infrastructure, often resulting in increased maintenance demands and water quality risks (Ancaș et al., 2019). Hydraulic conditions, including pressure surges and flow variability, also contribute to the accelerated wear of pipelines, underscoring the need for effective maintenance strategies (Oberascher et al., 2020).

2.2 Definitions and Key Differences

The management of water pipelines requires understanding the distinct roles of repair, rehabilitation, and replacement.

Repair involves localized interventions to address immediate failures, such as leaks or bursts. Methods include clamps and patching materials to restore basic functionality, often as a temporary measure (Gómez-Martínez et al., 2017).Rehabilitation, by contrast, entails systematic upgrades aimed at restoring both structural integrity and hydraulic performance. Techniques such as cured-in-place pipe (CIPP) lining and epoxy coatings are widely used to extend pipelines' service life while minimizing excavation (Viccione et al., 2019).Replacement represents the complete renewal of a pipeline using modern materials like high-density polyethylene (HDPE) or ductile iron. Although expensive, replacement ensures long-term reliability and resilience against future stressors (Zangenehmadar et al., 2020).

2.3 Factors Influencing Decision-Making

Decision-making in pipeline management is multifaceted, incorporating technical, economic, risk, and regulatory considerations (Table 1).

Table 1: Factors Influencing Decision-making

Category	Factor	Description	Paper
Technical Factors	Pipe Age and Material	Older pipes made of materials like cast iron or asbestos cement are more prone to failure.	Gómez-Martínez et al. (2017)
	Hydraulic Performance	Pressure and flow characteristics influence whether localized repairs or larger interventions are needed.	Bosco et al. (2020)
	Failure History	Pipes with frequent failures are prioritized for replacement or rehabilitation.	Gorenstein et al. (2020)
	Environmental Stressors	Soil corrosivity, seismic activity, and traffic loads accelerate pipe deterioration.	Ancaș et al. (2019
Economic Factors	Life-Cycle Cost Analysis (LCCA)	Evaluates long-term costs to ensure economic efficiency.	Zangenehmadar et al. (2020)
	Budget Limitations	Budget constraints require prioritizing cost-effective interventions.	Oberascher et al. (2020)

	Energy and Operational Costs	Energy savings from improved efficiency can offset intervention costs.	Meirelles et al. (2018)
Risk Management	Service Disruptions	Failures cause water supply loss and economic disruption.	Giraldo-González & Rodríguez (2020)
	Health and Environmental Risks	Failures may lead to water contamination or wastage.	Bhagat et al. (2019)
	System Resilience	Resilient systems are better equipped to handle extreme events like earthquakes.	Dercole et al. (2018)
Regulatory & Policy Requirements	Leakage and Efficiency Standards	Regulations prioritize reducing NRW and improving efficiency.	Oberascher et al. (2020)
	Water Quality Standards	Rehabilitation methods must ensure water quality is not compromised.	Bosco et al. (2020)
	Environmental Policies	Interventions must minimize waste and consider sustainability.	Viccione et al. (2019)
Integration of Advanced Tools	Predictive Models	Statistical and ML models predict failures and prioritize interventions.	Gómez-Martínez et al. (2017), Giraldo-González & Rodríguez (2020)
	Optimization Algorithms	Genetic algorithms allocate budgets and plan effectively.	Zangenehmadar et al. (2020)
	GIS and Real-Time Monitoring	GIS and SCADA systems provide real-time data to enhance decision-making.	Bosco et al. (2020)

Technical Factors such as the condition of pipes, material type, and hydraulic performance are critical in determining the appropriate intervention strategy. Historical failure data and pressure testing are commonly used to assess pipe reliability (Gómez-Martínez et al., 2017).Economic Factors include life-cycle cost analysis (LCCA), which balances initial capital investments with long-term operational expenses. Rehabilitation is often the most cost-effective strategy under constrained budgets (Zangenehmadar et al., 2020).Risk Management evaluates potential service disruptions, public health risks, and environmental impacts. For instance, pipe bursts in densely populated areas can have significant social and economic consequences (Ngamalieu-Nengoue et al., 2019).Regulatory and Policy Requirements further shape decision-making, mandating compliance with water quality standards and leakage reduction targets, particularly in regions with water scarcity (Oberascher et al., 2020).

2.4 Existing Models and Approaches for Pipe Asset Management

Advancements in predictive modeling and optimization techniques have improved asset management in WDNs.Statistical and machine learning models, such as gradient-boosted trees (GBT), predict pipe failures based on age, material, and hydraulic stress (Giraldo-González & Rodríguez, 2020). Pressure management strategies, including district metered areas (DMAs) and real-time control systems, reduce leakages and improve network efficiency (Bosco et al., 2020). Optimization models that integrate rehabilitation planning under budget constraints have shown promise in prioritizing interventions (Zangenehmadar et al., 2020).

3. METHODOLOGY

3.1 Research Design

This section reviews the literature to identify frameworks, models, and strategies for repair, replacement, and rehabilitation in WDNs. Table 4, at the end of this paper, provides a detailed summary.

Frameworks for Decision-Making

*Multi-Criteria Decision-Making (MCDM) Approaches:*MCDM frameworks integrate technical, economic, and environmental factors to prioritize interventions. Tscheikner-Gratl et al. (2017) evaluated MCDM methods such as ELECTRE, PROMETHEE, and AHP for rehabilitation planning. These methods enable utility managers to balance competing objectives, such as minimizing costs and maximizing system reliability. PROMETHEE and TOPSIS are advantageous for their capacity to handle uncertainty and provide clear prioritization criteria.

Risk-Based Approaches: Risk assessment frameworks are widely used to identify critical segments of WDNs. Dercole et al. (2018) emphasized the importance of reliability-based risk assessments that incorporate failure probabilities, unsupplied demand, and pressure deficits. Such frameworks prioritize interventions based on the likelihood of failure and its impact on network performance.

Lifecycle Analysis and Cost-Benefit Frameworks: Lifecycle cost analysis (LCCA) is critical for evaluating long-term costs associated with different interventions. Zangenehmadar et al. (2020) proposed genetic algorithm-based optimization models incorporating LCCA to allocate budgets effectively while minimizing failure risks. This approach aligns economic feasibility with operational reliability.

Models for Decision-Making

Statistical and Machine Learning Models: Statistical models, such as Poisson and Bayesian regression, predict pipe failures by analyzing variables like age, material, and environmental stressors (Gómez-Martínez et al., 2017; Giraldo-González & Rodríguez, 2020). These models help utilities forecast failure trends and allocate resources accordingly. Machine learning models, including gradient-boosted trees and artificial neural networks, outperform traditional statistical methods in scenarios with complex interactions between variables.

Optimization Models: Optimization techniques, such as genetic algorithms and particle swarm optimization, are increasingly employed for rehabilitation planning. Zangenehmadar et al. (2020) demonstrated the use of genetic algorithms to schedule repairs and replacements, optimizing cost and reliability over a 20-year planning horizon. These models are particularly effective in networks with budgetary constraints.

Hydraulic and Network Simulation Models: Hydraulic models simulate network performance under varying conditions to identify weak points and evaluate intervention impacts. Bosco et al. (2020) utilized EPANET for simulating leakage reduction scenarios, combining rehabilitation and pressure management strategies. Simulation models also support real-time monitoring, enabling dynamic adjustments to maintenance schedules.

Strategies for Repair, Replacement, and Rehabilitation

Repair Strategies: Repair involves localized interventions aimed at addressing immediate failures. Techniques such as clamp installation and epoxy patching are commonly employed for minor leaks. Bhagat et al. (2019) noted that repair strategies are cost-effective for temporary fixes but may not address underlying issues in aging infrastructure.

Rehabilitation Strategies: Rehabilitation focuses on restoring structural integrity and hydraulic performance. Trenchless technologies, including cured-in-place pipe (CIPP) lining and slip-lining, are widely used to minimize excavation and reduce disruption (Viccione et al., 2019). Rehabilitation also includes pressure management strategies, such as installing pressure control valves to reduce leakages and extend pipe lifespan (Bosco et al., 2020).

Replacement Strategies: Replacement involves the complete renewal of pipelines, often using modern materials like high-density polyethylene (HDPE). While costly, replacement ensures long-term reliability and is essential for pipes with frequent failures or significant material degradation (Meirelles et al., 2018). Prioritizing replacement requires robust predictive models and detailed condition assessments to maximize cost-effectiveness.

3.2 Quantitative and qualitative synthesis of factors influencing asset interventions

Table 2 and Table 3summarize the quantitative and qualitative reviews of factors influencing asset interventions.

Table 2: Quantitative synthesis of factors influencing asset interventions

Paper	Factor	Purpose	Remarks
Gómez-Martínez et al. (2017)	Asset Age and Material	To predict failure likelihood based on material and aging characteristics.	Older pipes (e.g., cast iron, asbestos cement) are more failure-prone. Regular condition assessment recommended.
Bosco et al. (2020)	Hydraulic Performance	To assess pressure and flow metrics for optimal network operation.	EPANET simulation highlights rehabilitation areas where hydraulic performance is suboptimal.
Zangenehmadar et al. (2020)	Life-Cycle Cost Analysis	To balance initial costs with long-term operational savings in	Replacement preferred for critical segments despite higher initial costs; LCCA crucial for planning.

		intervention.	
Giraldo-González & Rodríguez (2020)	Failure History	To forecast future vulnerabilities and prioritize interventions.	Historical data integrated into ML models for high accuracy. Recommended proactive use of predictive tools.
Ancaş et al. (2019)	Environmental Stressors	To assess impacts of soil corrosion, seismic events, and climate.	Dynamic stresses necessitate seismic-resistant designs and materials to enhance durability.
Dercole et al. (2018)	Risk and Resilience Metrics	To prioritize segments based on risk of failure and resilience needs.	Probabilistic reliability metrics used for long-term resilience planning; recommended for high-risk segments.
Wagner et al. (1986)	Probabilistic Reliability	To calculate probabilities of system failure under varied scenarios.	Stochastic models useful for moderately large systems; early implementation of risk management recommended.
Meirelles et al. (2018)	Energy Efficiency	To optimize rehabilitation costs using energy recovery (e.g., PAT systems).	Energy recovery offsets initial investment, making it feasible for trunk network upgrades.
Bhagat et al. (2019)	Leakage Rates	To quantify water loss for targeting repairs.	Leakage hotspots identified as priority areas for localized repair interventions.
Viccione et al. (2019)	Asset Performance	To evaluate the condition and utility of decommissioned assets for reuse.	GIS-integrated models enable cost-efficient reuse of assets like water tanks for system rehabilitation.

Table 3: Qualitative synthesis of factors influencing asset interventions

Paper	Factor	Purpose	Remarks
Bhagat et al. (2019)	Community Expectations	To maintain public trust by ensuring reliable service delivery.	Failures affecting service reliability necessitate urgent repairs to prevent public dissatisfaction.
Oberascher et al. (2020)	Regulatory Compliance	To align interventions with leakage reduction and environmental standards.	Leakage detection and repair prioritized to meet regulatory targets in resource-constrained small systems.
Meirelles et al. (2018)	Budget Constraints	To balance immediate needs with long-term	Resource constraints often lead to favoring low-cost repair strategies

		planning under funding limits.	over comprehensive replacements.
Liu et al. (2020)	Technological Feasibility	To leverage advanced methods for precise problem identification.	Acoustic methods enable targeted repairs, reducing unnecessary disruptions and costs.
Viccione et al. (2019)	Environmental Impact	To minimize ecological disruption during interventions.	Trenchless rehabilitation and asset reuse reduce excavation-related environmental impact.
Balut et al. (2019)	Emergency Response Needs	To restore critical services rapidly following disasters.	PROMETHEE-based prioritization ensures that critical nodes (e.g., hospitals) are addressed first during post-disaster recovery.
Ancaş et al. (2019)	Design Resilience	To ensure infrastructure withstands environmental and seismic stresses.	Seismic-resistant materials and adaptive designs recommended for high-risk regions.
Bosco et al. (2020)	Social Acceptance	To gain public support for interventions causing temporary disruptions.	Emphasis on minimizing disruption during pressure management or rehabilitation activities.
Tscheikner-Gratl et al. (2017)	Stakeholder Prioritization	To align interventions with diverse stakeholder goals.	Multi-criteria decision-making (MCDM) balances economic, technical, and societal considerations in intervention planning.

4. DISCUSSION

4.1 Comparative Analysis of Repair, Rehabilitation, and Replacement

A complex interplay of factors, including cost, longevity, environmental considerations, and operational constraints, influences the decision to repair, rehabilitate, or replace water distribution pipelines. This section examines the implications of these strategies, drawing from insights across diverse studies.

Short-Term Versus Long-Term Benefits

Repair strategies often offer short-term solutions for localized failures such as leaks or bursts. Bhagat et al. (2019) highlighted that repairs can swiftly restore functionality at minimal cost; however, they fail to address underlying issues like material degradation, which can lead to recurring failures. In contrast, **rehabilitation** techniques such as cured-in-place pipe (CIPP) lining restore structural and hydraulic performance, extending the pipe's service life by decades (Bosco et al., 2020). **Replacement** strategies provide the most enduring benefits, ensuring reliability for up to a century with modern materials like HDPE or ductile iron. While initial costs are high, the long-term reliability often justifies the investment (Zangenehmadar et al., 2020).

Cost Implications for Different Approaches

Repair is the least expensive option in the short term, requiring only localized interventions. However, frequent repairs can accumulate costs, as seen in Jakarta's network, where high leakage rates demand continuous maintenance (Bhagat et al., 2019). Rehabilitation involves moderate costs, depending on the technique used. Trenchless technologies like CIPP are cost-effective alternatives to full replacement, particularly in urban areas with dense infrastructure (Viccione et al., 2019). Replacement incurs the highest upfront cost but minimizes recurring expenditures, especially in pipelines with frequent or severe failures.

Environmental and Operational Trade-Offs

Rehabilitation techniques like CIPP minimize excavation, reducing disruption to surrounding ecosystems and communities (Viccione et al., 2019). Replacement, while environmentally intensive due to excavation and waste, ensures improved hydraulic efficiency, reducing energy consumption over the pipe's lifetime (Meirelles et al., 2018). Although quick and localized, repair strategies often fail to address systemic issues, leading to operational inefficiencies and elevated leakage rates over time.

4.2 Influencing Factors for Strategy Selection

The choice between repair, rehabilitation, and replacement is driven by several factors, as outlined below.

Technical Considerations

Pipe age, failure frequency, hydraulic performance, and material type are critical determinants. Older materials like asbestos cement and cast iron are more prone to failure, necessitating frequent repairs or replacements (Gómez-Martínez et al., 2017). Hydraulic performance, including flow and pressure metrics, influences whether a pipe requires rehabilitation or replacement to restore efficiency (Bosco et al., 2020).

Economic Constraints

Budget limitations often force utilities to prioritize lower-cost interventions, such as repairs, over comprehensive replacements (Meirelles et al., 2018). Life-cycle cost analysis (LCCA) is crucial in weighing immediate expenses against long-term savings, particularly for high-risk segments requiring replacement (Zangenehmadar et al., 2020).

Risk and Resilience

Risk-based frameworks prioritize interventions that mitigate service disruptions, public health risks, and environmental impacts. In seismic-prone regions, rehabilitation with resilient materials is essential to prevent catastrophic failures (Ancaș et al., 2019). Ensuring water supply reliability often justifies higher expenditures for replacements in critical network segments.

4.3 Case Studies

Case 1: Rehabilitation Strategies Using Trenchless Technologies in Italy

In Italy, trenchless technologies like CIPP and slip-lining have been implemented to minimize disruption in densely populated urban areas. Viccione et al. (2019) reported that these methods reduced project timelines and significantly lowered environmental impact compared to traditional excavation-based approaches.

Case 2: Machine Learning Models for Failure Prediction in Bogotá, Colombia
Machine learning models, including gradient-boosted trees (GBT), have been deployed in Bogotá to predict pipe failures based on historical and environmental data. Giraldo-González and Rodríguez (2020) demonstrated that ML approaches outperformed statistical models, enabling proactive maintenance planning that reduced failures and associated costs.

Case 3: Reactive Maintenance Challenges in Jakarta with High Leakage Rates
Jakarta's water distribution network has high leakage rates, and reactive maintenance is the dominant strategy. Bhagat et al. (2019) noted that this approach escalated operational costs and inefficiencies, emphasizing the need to shift towards proactive strategies like predictive maintenance and systematic rehabilitation.

4.4 Decision-Making Framework

A robust decision-making framework integrating technical, economic, and risk-based factors is essential to optimizing repair, rehabilitation, and replacement strategies.

Conceptual Model

The proposed framework involves:

- *Data Integration:* Combining historical failure records, hydraulic performance metrics, and environmental conditions into predictive models.
- *Risk Assessment:* Employing probabilistic tools to evaluate the likelihood and impact of failures (Dercole et al., 2018).
- *Economic Analysis*: LCCA compares costs across different intervention strategies (Zangenehmadar et al., 2020).

4.5 Optimization Techniques

Optimization models, such as genetic algorithms and particle swarm optimization, can prioritize interventions under budget constraints. For example, Zangenehmadar et al. (2020) demonstrated the efficacy of genetic algorithms in reducing network failures while minimizing costs.

Comparative analysis of repair, rehabilitation, and replacement strategies highlights the necessity of context-specific decision-making frameworks. While repair offers short-term cost benefits, rehabilitation, and replacement provide superior long-term reliability and efficiency. Influencing factors like pipe age, material, and hydraulic performance must be balanced against economic constraints and risk considerations. Case studies from Italy, Colombia, and Indonesia underscore the importance of adopting advanced technologies and predictive models to optimize asset interventions. A conceptual decision-making framework, augmented by optimization techniques, can enable utilities to maximize operational efficiency and sustainability in water distribution networks.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Findings

This study highlights the critical importance of repair, rehabilitation, and replacement (3R) strategies for managing water distribution network (WDN) assets. Each strategy has distinct applications, strengths, and limitations:

- **Repair**: A cost-effective and localized solution suitable for addressing minor leaks or bursts. However, it often serves as a short-term measure and may fail to address underlying issues such as material degradation (Bhagat et al., 2019).
- **Rehabilitation**: Focused on restoring structural integrity and hydraulic performance through techniques like cured-in-place pipe (CIPP) lining or slip-lining. Rehabilitation balances cost and long-term reliability, particularly in urban settings where excavation is impractical (Viccione et al., 2019).
- **Replacement**: This is the most expensive option but offers the longest lifespan and improved resilience. It is ideal for pipelines nearing the end of their service life or experiencing frequent failures (Zangenehmadar et al., 2020).

The selection among these strategies is influenced by several factors:

1. Technical considerations, including pipe material, age, failure frequency, and hydraulic performance (Gómez-Martínez et al., 2017).
2. Economic constraints include budget limitations and the results of life-cycle cost analysis (LCCA) (Meirelles et al., 2018).
3. Risk and resilience, encompassing failure risks, water supply reliability, and environmental impacts (Ancaș et al., 2019).

5.2 Recommendations for Water Utilities

Water utilities face the dual challenge of managing aging infrastructure and meeting increasing service demands. To optimize their interventions, the following recommendations are proposed:

1. Adoption of Predictive Failure Models and LCCA
    - Predictive models leveraging statistical and machine learning techniques can enhance the accuracy of failure predictions. Giraldo-González and Rodríguez (2020) demonstrated that gradient-boosted trees (GBT) outperform traditional models in predicting failure likelihood.
    - Incorporating LCCA enables utilities to compare different strategies' long-term costs and benefits, ensuring cost-effective decision-making (Zangenehmadar et al., 2020).
2. Integration of Real-Time Monitoring Technologies
    - Real-time monitoring systems, such as acoustic leak detection and pressure sensors, can improve the detection of leaks and assess pipeline conditions dynamically (Liu et al., 2020).
    - Advanced SCADA systems combined with GIS platforms allow utilities to pinpoint problem areas precisely, enabling timely interventions (Bosco et al., 2020).

5.3 Future Research Directions

To address current knowledge gaps and emerging challenges, future research should focus on:

1. Development of Advanced Hybrid Models

  - Combining machine learning with hydraulic simulations can create hybrid models capable of capturing systemic and localized pipeline vulnerabilities. This integration will enhance the predictive accuracy and scalability of failure models, particularly for complex networks (Giraldo-González & Rodríguez, 2020; Bosco et al., 2020).

2. Assessment of Emerging Materials and Techniques
    - Novel materials, such as polymer composites and bio-resistant coatings, should be rigorously tested for their durability and environmental performance in WDN applications (Ancaș et al., 2019).
    - Innovative techniques, including robotic trenchless rehabilitation and modular pipeline replacement, offer promising avenues for minimizing disruption while ensuring structural reliability (Viccione et al., 2019).

5.4 Conclusion

This research study emphasizes the pivotal role of repair, rehabilitation, and replacement strategies in ensuring the sustainability and reliability of WDNs. Each of these strategies is uniquely suited to specific scenarios, balancing short-term and long-term needs for infrastructure maintenance. Utilities should invest in advanced tools such as GIS-integrated systems, machine learning models, and pressure control technologies to optimize interventions.Policymakers should encourage rehabilitation and replacement efforts through targeted funding, particularly in aging systems where repair is no longer sustainable.By systematically addressing the challenges in WDN maintenance, this study underscores the importance of adopting comprehensive strategies that enhance infrastructure reliability and operational efficiency. A structured, data-driven approach to repair, replacement, and rehabilitation strategies will enable utilities worldwide to meet growing water demands while managing aging infrastructure effectively.By integrating predictive tools, advanced monitoring technologies, and innovative materials, water utilities can significantly enhance the sustainability and resilience of WDNs. Future research efforts should align with these priorities, ensuring that future solutions are economically viable and technically robust. Through targeted investments and strategic planning, utilities can effectively manage the challenges of aging infrastructure while meeting the growing demands of modern water distribution systems.

Table 4: Summary of literature review on frameworks, models, and strategies for repair, replacement, and rehabilitation in WDNs

Paper	Decision-Making Frameworks	Models	Strategies
Bhagat et al. (2019)	Not explicitly discussed	Not applicable	Repair-focused; localized interventions (e.g., clamp installation, patching) to address minor leaks.
Bosco et al. (2020)	Integrated framework combining rehabilitation and pressure management	Hydraulic simulation model (EPANET) to assess leakage reduction under different scenarios.	Rehabilitation using trenchless techniques and active pressure control strategies, including remote real-time control (RTC).

Dercole et al. (2018)	Reliability-based risk assessment	Reliability models evaluating unsupplied demand and pressure deficits under failure scenarios.	Risk-driven rehabilitation prioritization targeting high-risk pipe segments.
Gómez-Martínez et al. (2017)	Not explicitly discussed	Statistical models (Bayesian regression) analyzing pipe failures based on explanatory variables like age, material, and environmental factors.	Data-driven planning for targeted repairs and renewals based on failure likelihood.
Giraldo-González & Rodríguez (2020)	Not explicitly discussed	Comparison of statistical models (Poisson regression) and machine learning (ML) models (e.g., gradient-boosted trees) for failure prediction.	Proactive planning for repair and replacement based on predictive failure insights.
Meirelles et al. (2018)	Resilience-based planning	Optimization model using particle swarm optimization (PSO) to improve trunk network performance and incorporate energy recovery.	Replacement strategies focusing on trunk network upgrades and energy recovery systems for cost-efficiency and enhanced resilience.
Oberascher et al. (2020)	Small WDN-specific frameworks for resource-constrained systems	Not applicable	Leakage detection campaigns and flow monitoring for early repairs in small systems with limited resources.
Tscheikner-Gratl et al. (2017)	Multi-criteria decision-making (MCDM): ELECTRE, PROMETHEE, AHP	Not applicable	Integrated rehabilitation strategies balancing economic, technical, and societal priorities using MCDM.
Viccione et al. (2019)	Not explicitly discussed	Simplified hydraulic models integrated with GIS for optimizing network performance and planning rehabilitation.	Rehabilitation using decommissioned assets like water tanks to enhance system performance while minimizing costs.

Zangenehmadar et al. (2020)	Genetic algorithm-based optimization framework	Optimization models combining budget constraints, life-cycle costs, and failure probabilities to prioritize interventions.	Comprehensive repair and replacement scheduling to minimize failures and optimize long-term costs.
Ancaș et al. (2019)	Seismic resilience framework	Not applicable	Rehabilitation strategies incorporating seismic-resistant materials and designs to improve pipeline resilience under dynamic stresses.
Balut et al. (2019)	Post-disaster restoration frameworks using PROMETHEE	Hydraulic and GIS models for ranking and scheduling repairs after disasters.	Emergency repair prioritization based on resilience and criticality to restore essential services after major disruptions.
Ngamalieu-Nengoue et al. (2019)	Multi-objective optimization framework	Stormwater management models incorporating search-space reduction and genetic algorithms to minimize flood risks and optimize infrastructure rehab.	Combining pipe rehabilitation with storm tank installation to address flooding issues while optimizing costs and system performance.
Garcia et al. (2020)	Asset management framework for sanitation systems	Hydrogen sulfide (H2S) modeling to prioritize pipeline rehabilitation based on corrosion and wear severity.	Rehabilitation prioritization using chemical data and predictive modeling to identify critical segments for renewal.
Liu et al. (2020)	Trenchless detection technology framework	Acoustic models for locating and assessing buried pipelines, particularly for non-metallic materials.	Detection of leaks and weak points using advanced acoustic methods, facilitating targeted repairs and maintenance planning.
Morosini et al. (2020)	Pressure-driven analysis (PDA) framework	Binary classification models using PDA and neural networks for simulating pipe performance under variable conditions.	Proactive maintenance strategies using PDA to ensure hydraulic reliability and minimize service disruptions.

Wagner et al. (1986)	Probabilistic reliability frameworks	Stochastic simulation models for calculating probabilistic reliability measures in water distribution systems.	Long-term planning to enhance system reliability by addressing probabilistic link failures and integrating resilience in design.

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