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Analyzing Failure Risks in Clean Water Distribution Networks Using the Failure Mode and Effect Analysis (FMEA)

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ABSTRACT

Reliable provision of clean water is is a major challenge in managing public infrastructure, particularly in areas with rapid population growth and complex geography. One of the clean water service unit in Padang Sidempuan City faces obstacles in water transmission and distribution, including pipe damage due to aging infrastructure, non-standard materials, ineffective gravity-based systems, and limited raw water sources. This study aims to identify and analyze these inhibiting factors using the Failure Mode and Effects Analysis (FMEA) method. Data were collected through field observations, interviews with technical personnel, and review of operational documents, then analyzed by calculating the Risk Priority Number (RPN) to determine repair priorities. The findings reveal the highest RPN of 720, in areas with elevation issues, where gravity flow fails to maintain sufficient pressure posing the greatest operational risk. The second most critical issue involves failure of water flow due to elevation and inadequate pressurization, with an RPN of 630, highlighting the gravity system's limitations. Pipe damage, mainly from high internal pressure and poor maintenance, scored an RPN of 560, marking it as another high-priority issue. Based on these findings, this study recommends upgrading the system by installing mechanical pressure devices (booster pumps), replacing pipes with standard-compliant materials, and exploring alternative water sources These improvements are essential for reducing system vulnerability and improving service reliability. The results underscore that applying FMEA systematically is a practical approach for prioritizing technical interventions and enhancing the overall performance of regional clean water supply systems.

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Introduction

The availability of clean water ensures the quality of life and supports sustainable development (Muhaimin et al. 2023). In Indonesia, the challenges in providing clean drinking water are still high, especially in areas with rapid population growth and limited infrastructure. The Central Statistics Agency (BPS Indonesia 2023) noted that only 80.11% of households in Padang Sidempuan City have access to clean drinking water sources, indicating that around one in five households have not received clean water services according to health standards. This condition is exacerbated by the high risk of failure of the water distribution system caused by aging infrastructure, the use of substandard pipe materials, and minimal routine maintenance. The risk of failure can result in service disruptions and potential health and economic losses for the community. (Gheibi et al. 2023; Hadidi et al. 2021; Pratama, Wardhana, and Nugroho 2020)

Pressure stability, pipe network design, and compliance with technical standards greatly influence an effective clean water distribution system. In the context of water pressure, research by (Star et al. 2025) Shows that transient pressures caused by water hammer phenomena can increase drastically as temperatures in the distribution system increase. Pressures that exceed the limit can cause cavitation and structural damage to pipes, especially if the system is not designed to respond to thermal and hydraulic changes simultaneously. While international standards recommend an operating pressure of between 20–80 psi, many distribution systems in small and medium-sized cities in Indonesia, especially those based on gravity, cannot meet this minimum threshold. This causes uneven water distribution, especially to areas that are topographically higher.

The gravity-based water distribution system itself has advantages in terms of energy efficiency because it does not require additional pumps. However, this system is very susceptible to elevation variations, pressure changes and lacks flexibility in flow regulation. A study by (Wang et al. 2025) Piping systems in permafrost areas showed that systems passing through areas with unstable geotechnical conditions experienced higher damage due to water accumulation, erosion, and ground movement. These findings indicate the importance of implementing technical mitigation principles in gravity water distribution systems, such as the use of pressure valves and backflow control systems that are still rarely used in clean water networks in developing areas.

In addition to design challenges, piping materials also play a critical role in the resilience of distribution systems. (Nie et al. 2025) Found that exposure to vibration and cyclic loading due to water flow caused significant degradation of the mechanical properties of pipe materials, including decreased toughness and yield strength. This is exacerbated by using low-quality pipes or substandard connection techniques. (Zhang et al. 2023) Added that in collapsible soils such as loess, pipe leakage can trigger large foundation deformations, with direct implications for the stability of the piping system. They recommend the use of stabilized soil pads to reduce the risk of deformation due to water infiltration.

Although various studies have identified systemic risks in piped networks, no study has comprehensively examined the failure risk of gravity-based water distribution systems in tropical and urban environments using the Failure Mode and Effects Analysis (FMEA) method. FMEA allows for systematic and quantitative analysis of potential failures, including assessing severity, frequency, and detectability. This gap is the main urgency of this study to fill the gap in technical risk assessments and provide a basis for mitigation recommendations that can be implemented in real terms by local water service units. Previous studies have evaluated various aspects of the clean water distribution network, but the application of the Failure Mode and Effect Analysis (FMEA) method in depth at the operational level of local service units, especially in cities such as Padang Sidempuan, is still rare. (Odjegba et al. 2023; Smaranda, C-tin, and

Daroczi 2010). Most existing studies emphasize technical or administrative aspects without systematically identifying potential failures and their mitigation priorities. Thus, there is a gap in the literature that needs to be filled, namely, studies that use a systematic approach to evaluate and mitigate the risk of failure in clean water distribution systems in local areas.

This study aims to identify and analyze the risk of major failures in the clean water transmission and distribution system in Padang Sidempuan City using the FMEA approach. The selection of this method is based on several main reasons. First, the clean water distribution system has complex characteristics with various components that are susceptible to technical and operational failures, and FMEA allows for systematic and comprehensive failure identification. (Smaranda, C-tin, and Daroczi 2010). Second, this method offers a quantitative approach to assess the severity, frequency of occurrence, and detection capability of a failure, thus facilitating the determination of repair priorities. (Weeraddana et al. 2021). Third, potential failures in pipe networks can often be observed visually, making FMEA a practical and effective analysis tool for use in the field. (Nikoloudi et al. 2021). Therefore, this study is expected to provide scientific and practical contributions in efforts to improve the reliability and efficiency of the clean water supply system at the regional level.

Literature Review

Clean Water Distribution Networks

Clean water distribution systems are composed of several key components: water sources, pumping stations, treatment units, storage reservoirs, transmission mains, and distribution pipelines. These components work collectively to ensure the reliable delivery of potable water from the source to consumers. (Hadidi et al. 2021; Smaranda, C-tin, and Daroczi 2010). The design of these systems must account for factors such as topography, water demand, and pipe material. Factors influencing the efficiency and reliability of distribution networks include water pressure stability, pipe material durability, maintenance scheduling, and demand variability. According to (Aghapoor Khameneh et al. 2020)The use of aged or substandard materials significantly reduces the operational lifespan of pipelines. Similarly, (Pietrucha-Urbanik and Tchórzewska-Cieślak 2018) Emphasize the role of proactive maintenance in minimizing service interruptions.

Common problems in water distribution systems include leakage, pressure loss, contamination, and system downtime. Studies by (Pietrucha-Urbanik and Tchórzewska-Cieślak 2018; Tchórzewska-Cieślak, Pietrucha-Urbanik, and Piegdoń 2023) Highlight that leakage is a leading cause of non-revenue water, while inadequate pressure often results in poor service in elevated regions. Furthermore, failure to maintain hygienic standards during distribution can lead to public health issues.

Failure Risks In Water Infrastructure

Failures in water infrastructure can be categorized into structural failures (e.g., pipe bursts), operational failures (e.g., pump malfunction), and systemic failures (e.g., network overload). (Tang, Parsons, and Jude 2019) Identified pipe joint failure and sediment accumulation as recurring causes of structural failure. Meanwhile, (Nikoloudi et al. 2021) Categorized systemic risks that disrupt service continuity due to inadequate redundancy. The impacts of such failures are multifaceted, ranging from public health crises to economic losses. (Sharma et al. 2024) The report states that infrastructure failure can compromise the safety of urban water reuse systems. (Park et al. 2023) Quantified economic losses due to pipe bursts in aging networks, linking failure frequency to network age and condition. Common causes of infrastructure failure include corrosion, improper installation, aging materials, and inadequate monitoring. According to (Gheibi et al. 2023)Corrosion is exacerbated by poor water quality and fluctuating pressure. (Star et al. 2025) Point out that thermal effects can intensify pressure surges (water hammer), degrade pipe integrity later.

Failure Mode and Effect Analysis (FMEA)

FMEA is a structured method for identifying and prioritizing potential failure modes based on their severity, frequency, and detectability (Abdelgawad and Fayek 2010). It was originally developed in the aerospace and automotive sectors, but has since been widely adopted in healthcare, manufacturing, and infrastructure. (Mafruchati, Othman, and Wardhana 2023) The standard FMEA process involves the following steps: identifying potential failure modes, assessing their effects, evaluating the causes, and assigning risk scores (S, O, D), which are multiplied to obtain the Risk Priority Number (RPN). (Fauzi, Ulfah, and Wijayanti 2024; Ribas et al. 2021) Implemented this framework to evaluate the failure risks in hydroelectric dams, providing a model for similar infrastructure applications. In the water sector, FMEA has been applied to analyze pipeline risks, valve failures, and treatment system vulnerabilities. Studies by (Sharma et al. 2024) Show its effectiveness in mapping risks and supporting decision-making in utility management.

The advantages of FMEA include its simplicity, systematic nature, and adaptability to various operational contexts. However, its limitations lie in its reliance on subjective scoring and lack of dynamic modeling. (Park et al. 2023) Suggest integrating FMEA with probabilistic models such as Bayesian Networks to enhance reliability. Prior research using FMEA in water systems includes Rak and (Tchórzewska-Cieślak, Pietrucha-Urbanik, and Piegdoń 2023), who explored health-related risks in municipal water, and (Smaranda, C-tin, and Daroczi 2010), who applied the method for criticality analysis in Eastern European distribution networks.

Methodology

This study is a quantitative study that aims to identify and analyze risk factors for failure in clean water transmission and distribution systems. The approach used is *Failure Mode and Effect Analysis* (FMEA), Each risk factor was scored using a scale from 1 (lowest) to 10 (highest) based on three dimensions: Severity (impact on service and user safety), Occurrence (frequency of incidents in the past 12 months), and Detection (likelihood of early identification). This scoring method follows the standardized FMEA assessment framework. (Gheibi et al. 2023; Ribas et al. 2021). The FMEA method was chosen because it has been proven effective in various previous studies in analyzing the vulnerability of clean water distribution systems. (Gheibi et al. 2023; Hadidi et al. 2021; Smaranda, C-tin, and Daroczi 2010). The study was conducted at one of the regional clean water service provider units, which serves the Padang Sidempuan City area and its surroundings.

Data collection was carried out from March to April 2024. Although data were collected over two months (March–April 2024), this time frame coincided with the peak operational phase and enabled comprehensive access to daily reports, maintenance logs, and incident records. Thus ensuring representativeness in the data. The object of this study is the clean water transmission and distribution system, including the main transmission pipe network. Water distribution system to customers, and the raw water resources used. Respondents consisted of network supervisory technical personnel, field technicians, operational managers, and some customers affected by service disruptions.

Data were obtained through a combination of primary data sources, namely, semi-structured interviews with operational staff, direct observation of the physical condition of the transmission and distribution pipelines, and risk assessment questionnaires based on severity, occurrence, and detection parameters. Secondary data, namely, annual operational reports, documentation of distribution disruption incidents, and literature studies related to risk analysis and FMEA implementation in clean water networks (Nikoloudi et al. 2021; Sirsant and Hamouda 2023).

FMEA analysis steps are carried out through the following stages:

1. Identify Failure Modes by identifying all potential failures that occur in the transmission, distribution, and water source systems.
2. Risk Score Assessment, by assigning scores on three main parameters:
   - 2.1 Severity (the severity of the impact of failure).
   - 2.2 Occurrence (frequency of possible failure).
   - 2.3 Detection (the ability to detect failures before they have an impact).
3. Calculation of Risk Priority Number (RPN) by calculating the RPN value for each failure mode using the formula:

   $RPN = S \times O \times D$
   Where:
   S = Severity
   O = Occurrence
   D = Detection
4. Repair Priority, by looking at the failure mode with the highest RPN, will be the top priority for corrective action.

The following is a table of operationalization of variables used in risk analysis with the FMEA method on a gravity-based clean water distribution system. Table 1 explains the definition, indicators, and data sources for each main variable.

Table 1. Operationalization of Research Variables

No	Main Variable	Operational Definition	Indicators	Data Sources
1	Severity (S)	The degree of impact caused by system failure on water supply services and community well-being	- Impact scale (1–10) based on: Service disruption, Economic loss, public health risk	- Interviews with utility technicians - Indonesian State Water Company technical documentation - (Sharma et al. 2024)
2	Occurrence (O)	The relative frequency of potential failures occurring within a defined period	- Number of incidents per year, Pipe leakage • Low pressure, Valve or joint failure	- Monthly incident reports from the Indonesian State Water Company - Field

				surveys - (Ribas et al. 2021)
3	Detection (D)	The system’s capability to detect a failure before it impacts users	- Average response time (in days) - Presence of manual or automatic detection systems - Maintenance log analysis	- Indonesian State Water Company SOP documents - Field observations - (Park et al. 2023)
4	Operating Pressure	The actual water pressure in the pipes relative to the minimum standard (20 psi or 140 kPa)	- Measured pressure readings - Deviation from standard	- On-site pressure measurements - Instrumental data logs
5	Pipe Material Condition	The physical quality and durability of the piping materials against pressure and corrosion	- Pipe age - Material type (PVC, HDPE, cast iron) - Laboratory test results	- Asset registry - Material integrity test reports -(Odjegba et al. 2023; Safitri and Khairi 2022)
6	Topographic Characteristics	The slope and elevation profile of the pipeline route from the source to the endpoints	- Elevation profile - Gradient mapping - Pressure variation risk	- GIS data - Field mapping - (Bakhtawar et al. 2025)
7	Failure Modes	Specific types of failures identified in the system	- Leakage, water hammer, sedimentation, air intrusion	- Focus group discussions with field experts - (Hu et al. 2025; Wang et al. 2025)

Source: (Bakhtawar et al. 2025; Hu et al. 2025; Odjegba et al. 2023; Park et al. 2023; Ribas et al. 2021; Sharma et al. 2024; Wang et al. 2025)

The appropriateness of the FMEA approach is supported by Sharma et al. (2024), who emphasized that integrating operational field data with literature-based modeling enhances the accuracy of risk assessments. The operational variables utilized in this study include actual operating pressure (measured in kPa), frequency of pipeline failures (cases per year), degree of pipe corrosion (based on visual inspections and material testing), and the speed of failure detection (measured in days from occurrence to initial response). (Park et al. 2023) Further note that FMEA becomes more precise when paired with advanced modeling techniques such as Bayesian Networks; however, in this study, conventional FMEA is employed as the core analytical framework.

By combining empirical data gathered from field inspections and technician interviews with documented records of maintenance and disruptions from the local water authority (INDONESIAN STATE WATER COMPANY), the failure mode identification process becomes more comprehensive. Concurrently, literature references such as (Park et al. 2023; Ribas et al. 2021; Sharma et al. 2024) Provide normative and technical foundations for categorizing common failure types within water distribution systems, ranging from water hammer effects and pipe joint failures to early leak detection. With this integrated framework, the research methodology systematically maps risks, evaluates their root causes, and formulates mitigation strategies based on quantifiable risk priorities.

Results and Discussion

Results.

The identification of risk factors and potential failure modes in clean water distribution systems is not solely based on field observations but is also reinforced by a comprehensive literature review. Failure Mode and Effects Analysis (FMEA), as employed in this study, relies on three primary parameters: severity, occurrence, and detection. The combination of these parameters yields the Risk Priority Number (RPN), which serves as a quantitative basis for prioritizing risk mitigation actions (Adirestuty et al. 2025; Ribas et al. 2021). In this context, the initial identification of potential failure modes involves a systematic assessment of the pipeline system from source, through pumping mechanisms, to the end-user distribution network. Each component is analyzed for susceptibility to failures such as unstable pressure, corrosion, leakage, and environmental factors including topographic contour and soil type (Mafruchati, Musta'ina, and Wardhana 2024; Susanto et al. 2025).

This investigation identifies numerous failure modes in clean water transmission and distribution systems, as well as constraints in water sources. These are subsequently examined using the Failure Mode and Effects Analysis (FMEA) method. The Risk Priority Number (RPN) is calculated for each failure to ascertain the priority of repair. Table 2 illustrates the primary factors that impede water transmission, as determined by the FMEA analysis of the transmission system.

Table 2. Risk Priority Number (RPN) Value Factors Causing Transmission Process Delays

Factor	Potential Failure	Severity	Occurrence	Detection	RPN
Method	The transmission pipe is damaged or leaking	5	8	10	640
	The age of the pipe is old	5	8	8	320
Equipment	Poor pipe material	5	9	7	315
Natural factors	The transmission pipe was swept away by the flood	8	6	8	384
	The transmission pipe is damaged. Due to a landslide	8	6	8	384

Source: data processing by the author (2025)

The analysis results indicate that an RPN value of ≥ 500 is classified as a high-criticality risk based on global FMEA practice standards. (Royden et al. 2021). Thus, the 640 (pipe damage) and 720 (ineffective gravity system) values indicate an urgent need for remedial action. The transmission system is obstructed by three primary factors. The first factor was the method factor, where the absence of routine inspections results in failure to detect early damage to pipes. The RPN score for the method factor is recorded at 640, indicating the highest priority for corrective action. 2) Equipment Factor: The pipes used are more than 80 years old and are made of non-standard materials, making them susceptible to leakage. 3) Natural Factor: Pipe damage is also often caused by natural disasters such as floods and landslides. The RPN value for natural factors is recorded at 384. Based on the FMEA analysis of the distribution system, the main factors obstructing the water distribution process are listed in Table 3.

Table 3. Risk Priority Number (RPN) Value Factors Causing Obstruction of the Distribution Process

Factor	Potential Failure	Severity	Occurrence	Detection	RPN
Method	Water cannot be distributed to customers.	8	9	10	720
	The pipe is damaged	7	8	10	560
	The pipe is leaking	5	6	8	240
	The pipe size does not meet the standard.	6	8	10	480
	Poor pipe material	8	6	10	480
Natural factors	Water cannot flow through the pipe distribution	7	9	10	630

Source: data processing by the author (2025)

The analysis results show five main failure modes: 1) Inadequate Distribution Method, with a distribution system that still uses gravity, causing water to have difficulty reaching areas with high elevations. This failure mode has the highest RPN of 720. 2) Leakage due to Project Excavation, where uncontrolled construction activities cause leaks in distribution pipes. 3) Inadequate Pipe Material, with low-quality distribution pipe materials contributing to leaks and pressure failures. 4) Pipe Damage, which occurs due to excessive pressure and a lack of routine maintenance programs. 5) Uneven Distribution, because customers in high areas experience a limited water supply. Based on the FMEA analysis of water sources, the main factor causing the lack of water sources is shown in Table 4.

Table 4. Risk Priority Number (RPN) Value of Factors Causing Lack of Water Resources

Factor	Potential Failure	Severity	Occurrence	Detection	RPN
Method	Failure to find additional water sources	5	8	10	400
Man	The number of customers is increasing.	9	8	6	432
Natural factors	Water quality does not meet standards.	10	5	8	400
	Geographical conditions where water sources are difficult to reach	7	8	7	392

Source: data processing by the author (2025)

The results of the analysis show that the water resource shortage factor identified three main causes, with human factors, especially the increase in the number of customers, being the factor with the highest RPN of 432. Furthermore, the method factor and natural factors with an RPN value of 400, and the natural factor with the potential for failure. Geographical conditions where water sources are difficult to reach have an RPN value of 392.

Discussion

This study analyzes the inhibiting factors in the clean water transmission and distribution system using the Failure Mode and Effects Analysis (FMEA) method. The results of the study indicate that several failure modes have high Risk Priority Number (RPN) values, thus requiring immediate priority handling. This study establishes the primary hypothesis, compares it to the previous research, and determines the practical implications for the urban transportation system.

One of the most significant factors in human health development is the application of advanced methods, especially the quality of medical transmission and monitoring systems. A RPN of 640 indicates a high risk of accidents during the investigation. This is consistent with the hypothesis of Hadidi et al. (2021), which posits that infrastructure that is more than 30 years old and has not been modernized has a 1.8% higher risk of failure than healthy networks.

In addition, the risk of failure can also result in a significant RPN. The research conducted by (Gheibi et al. 2023) Indicates that the distribution network must be adapted to the global risk, including the reorganization of the distribution network in the Banjir region. The practical application of this concept is the development of predictive maintenance software that employs technology, such as sensor-based water monitoring and leak detection, to mitigate risk. The primary concern is the gravitational system, which is characterized by a maximum RPN value of 720. This implies that the existing transportation system is unable to satisfy the needs of the population in the area efficiently. This is following the research conducted by (Sirsant and Hamouda 2023), which asserts that regions with high rainfall require an active drainage system, such as a pumping station, to maintain the quality of the soil. Factors such as the complexity of the construction project and the use of plastic materials that do not meet the standards for determining the construction conditions. (Aghapoor Khameneh et al. 2020) Said that reduced quality pipes increase the frequency of damage by up to 25% in various materials that do not have technical specifications. This implies that the implementation of an air distribution system based on pump stations and an air network modernization program is an infeasible solution.

Urbanization is a systemic issue that is associated with population growth without the necessity of increasing the number of urban areas. (Pratiwi, Wardhana, and Rusgianto 2022; Riduwan and Wardhana 2022). The human factor is the most significant in the decision-making process, with an RPN of 432. (Weeraddana et al. 2021) Involved in recognizing water resource planning strategies based on population projects to maintain clean water systems. Extreme geographical conditions are also a significant challenge. The study by (Tchórzewska-Cieślak, Pietrucha-Urbanik, and Piegdoń 2023) Showed that in difficult geographical areas, integration of water storage systems (reservoirs) and optimization of the search for new sources are essential (Mafruchati, Wardhana, and Ismail 2022). Therefore, it is necessary to design a long-term strategy that includes exploration of alternative water sources, sustainable use of groundwater, and construction of new reservoirs to overcome fluctuations in water discharge. (Wijayanti, Herianingrum, and Ryandono 2020).

This study strengthens the evidence that the FMEA method can be used effectively to identify major failure modes in clean water distribution systems at the operational level of regional units. These results also enrich the national literature, which has so far focused more on the study of the reliability of large-scale distribution systems. (Nikoloudi et al. 2021; Smaranda, C-tin, and Daroczi 2010). Practically, the results of the study provide a basis for priority-based risk improvements in water service provider units, including modernization of the transmission network inspection system, changing the gravity distribution system to a pressure-based system, and preparing a master plan for water source exploration and conservation.

However, this study has limitations in the limited scope of the study area and has not integrated software-based hydraulic network simulation (hydraulic modeling software), which can be an agenda for further research.

Conclusion

This study successfully applied the Failure Mode and Effects Analysis (FMEA) methodology to evaluate and prioritize failure risks within the clean water transmission and distribution network in Padang Sidempuan City. The findings revealed that the highest risk factor originated from the inadequacy of routine inspections, as evidenced by an RPN score of 640. This was followed by the inefficiency of the gravity-based distribution system, which recorded the highest RPN across all systems at 720, highlighting critical performance issues in supplying water to elevated areas. Additionally, the old and substandard pipeline materials and increased service demands were shown to further exacerbate service failures.

These findings have direct implications for water utilities and policymakers. First, it is essential to transition from gravity-based to pressure-assisted systems, especially in areas with complex elevation. Second, replacing aging and non-standard pipelines with certified materials should be prioritized to reduce leakage and enhance system resilience. Third, implementing early detection technologies such as leak sensors and pressure monitors will allow proactive maintenance. Finally, water authorities must adopt a structured risk management framework to routinely evaluate and mitigate systemic vulnerabilities. Future research should build upon this study by incorporating hydraulic modeling tools to simulate different distribution scenarios under variable demand and pressure conditions. Additionally, expanding the scope to include comparative analysis across different regions would provide a broader understanding of infrastructure vulnerabilities and adaptability. Such advancements would not only strengthen the operational resilience of local water networks but also contribute to the strategic planning of sustainable urban water infrastructure.

Author’s Contribution

All authors have contributed to the final manuscript. The contributions of each author are as follows: AS was responsible for collecting data, compiling the manuscript, compiling figures, and compiling the main conceptual ideas. DKS processed the data calculations as the second author, and HN provided excellent guidance and critical revisions of the article. All authors discussed the results and contributed to the final manuscript.

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Declaration of Competing Interest

The author declares that the research was no potential conflict of interest.

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