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Failure Mode and Its Effects on Enhancing Operational Reliability in Water-Treatment Facilities: A Case Study of Regional Public Water Company †

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Abstract

Access to safe and reliable drinking water is essential for public health. However, regional public water companies often face challenges that compromise service quality, such as equipment failure, water contamination, and inconsistent treatment processes. This study applies the failure mode and effects analysis (FMEA) method to systematically identify, evaluate, and prioritize operational risks in a water treatment facility. By analyzing 17 potential failure modes across the treatment process, five modes were classified as critical, prompting targeted mitigation strategies. The results demonstrate FMEA's effectiveness in enhancing reliability and supporting continuous improvement efforts in water treatment operations.

Keywords: failure mode and effects analysis (FMEA); operational risk; public water company; reliability improvement; water treatment

1. Introduction

The global water and sanitation crisis remains a pressing concern, with many people lacking access to safely managed drinking water and without safely managed sanitation services [1]. Despite global efforts and international commitments, stark disparities in water access and quality persist across urban and rural populations, particularly in low- and middle-income regions [2]. These gaps pose substantial public health risks and hinder the potential for building resilient and productive communities.

Regional drinking water companies play a crucial role in ensuring water accessibility; however, many continue to face significant operational challenges such as pipeline leakage, equipment malfunction, and untreated water source contamination [3,4]. As a result, the number of customer complaints is increasing, particularly those related to water quality and chemical imbalances [5]. In this study, we assess a regional public water company operating in a low- and middle-income region. These issues indicate critical operational risks within the water-treatment system. While past evaluations primarily focused on ensuring supply continuity and quantity, comprehensive risk assessment of operational processes remains limited [6,7]. Addressing this gap is vital, as unmitigated operational risks can compromise service reliability, increase maintenance costs, and jeopardize consumer health [8].

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Failure mode and effects analysis (FMEA) is a structured risk assessment method widely used in industrial settings, including water-treatment systems, for its ability to identify potential failure modes and prioritize them based on severity, frequency of occurrence, and detectability [9]. Compared with methods such as Hazard Analysis and Critical Control Points (HACCP) or risk matrices, FMEA offers a more detailed and quantifiable approach to operational failure diagnosis [10]. It enables organizations to proactively identify high-risk components and apply mitigation strategies that enhance service reliability and quality. We applied the FMEA method to evaluate operational risks to identify critical failure modes within the treatment process and propose targeted mitigation strategies based on risk priority number (RPN) scores. The findings contribute to improved decision-making and risk-management frameworks for regional water companies.

The remainder of this paper is structured as follows. Section 2 demonstrates the technical FMEA methodology. Section 3 presents the results and discussion of this study. We also summarize the main contributions and propose future research recommendations.

2. Materials and Methods

We applied a semi-quantitative descriptive research design to analyze operational risks in the water treatment process. This approach enables structured risk evaluation based on numerical scoring while preserving the interpretative value of field observations and expert opinions [9,11]. It is particularly useful in complex systems like water utilities, where direct measurement of risks is often constrained by uncertainty and variability in operational conditions [12].

FMEA is a structured and widely adopted technique for identifying and prioritizing potential failure points in operational systems. It assesses failure risks based on three factors: the severity of the impact (S), the likelihood of occurrence (O), and the ability to detect the failure before it causes harm (D) [13]. This approach is applicable in water treatment operations, where failures often arise from complex interactions among chemical processes, mechanical equipment, and human factors [14].

We collected data through field observations, interviews with operational personnel, and questionnaires distributed to experts within the company. The interviews helped identify past and current process failures, while questionnaires measured risk levels across three FMEA parameters: severity, occurrence, and detection [8]. The scores were collected on a 1–10 Likert scale to compute RPN using the standard formula formulation as follows [15,16].

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection}, \quad (1)$$

Risks were prioritized based on their RPN scores, with those exceeding the average RPN classified as critical. We conducted a root cause analysis with the 5 Whys method to propose corrective measures. Ultimately, the structured analysis supported the development of targeted mitigation strategies to improve water quality and customer satisfaction in the study area.

3. Results and Discussion

3.1. Risk Identification

Risk identification was performed through field observations, interviews, and document analysis, which operates under a regional public water company. This facility has been reported to produce substandard water quality based on testing conducted during a recent monitoring period, particularly failing to meet pH and chlorine residual standards. Through observation of each treatment stage, from raw water intake to final storage in the reservoir, 17 failure modes were identified Table 1.

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Table 1. Identified potential failure modes across water treatment stages.

No.	Treatment Stage	Activity/Component	Identified Failure Mode
1	Raw water intake	Intake pump	Pump malfunction or damage
2	Raw water intake	Intake screen	Screen damage or ineffective filtration
3	Raw water intake	River water quality	Contamination of water source
4	Coagulation	Chemical stock management	Coagulant chemical out of stock
5	Coagulation	Dosing pump	Coagulant dosing pump malfunction
6	Coagulation	Chemical calculation	Inaccurate dosage of coagulant
7	Coagulation	Safety procedures	Operator exposure to coagulant chemicals
8	Coagulation	Handling mixed solution	Operator contact with mixed chemical water
9	Sedimentation	Sedimentation system	Mechanical failure of sedimentation unit
10	Filtration	Filter media performance	Suboptimal filtration (e.g., clogging, reduced efficiency)
11	Disinfection	Chemical stock management	Disinfectant chemical out of stock
12	Disinfection	Chemical calculation	Inaccurate dosage of disinfectant
13	Disinfection	Safety procedures	Operator exposure to disinfectant chemicals
14	Disinfection	Handling mixed solution	Operator contact with mixed chemical water
15	Disinfection	Dosing pump	Disinfectant dosing pump malfunction
16	Reservoir storage	Reservoir sanitation	Entry of external contaminants into reservoir
17	Reservoir storage	Reservoir maintenance	Sediment accumulation at bottom of reservoir tank

The failure modes range from technical malfunctions such as pump failure and chemical dosing errors to process inefficiencies like sediment accumulation and filter underperformance. Additionally, environmental factors such as water contamination and external debris entering the reservoir were considered. These risks were corroborated by frequent customer complaints, where service quality concerns were most reported.

The complete list of identified potential failures was validated through expert judgment, involving a panel of nine personnel, including production managers, laboratory staff, and field operators, each with relevant educational and professional experience in water treatment operations.

3.2. FMEA

Following the identification of 17 potential failure modes across the water treatment process, each risk was further analyzed using the FMEA method. In this study, a panel of nine respondents—including process operators, laboratory staff, and the assistant manager—was asked to assign scores from 1 to 5 for each of the three FMEA parameters. The scoring used a Likert scale, with 1 indicating the least critical or least likely and 5 indicating the most severe, most likely, or most difficult to detect.

The RPN results ranged from 6 to 100 as shown in Table 2. Based on the recorded values and RPN calculations for each identified risk, a criticality threshold was determined. Critical risks are those that require further analysis and improvement recommendations to enhance the effectiveness of the water treatment operations at the company. The critical threshold was calculated using the following formula [17].

$$\text{Critical RPN Threshold} = \frac{\text{Total RPN}}{\text{Number of Risks}} = \frac{501}{17} = 29.47 = 29 \quad (2)$$

Following this calculation and with approval from the company, an RPN value of 29 was adopted as the benchmark. Any failure mode with an RPN value exceeding 29 was categorized as critical. The five highest RPN scores are listed in Table 3.

Table 2. Complete FMEA results for operational failure modes at Facility Z.

No.	Failure Mode	S	O	D	RPN
1	Inaccurate dosage of coagulant chemicals	5	4	5	100
2	Inaccurate dosage of disinfectant chemicals	5	4	5	100
3	Sediment accumulation at bottom of reservoir tank	5	4	3	60
4	Entry of external contaminants into reservoir	5	3	3	45
5	Contamination of raw water source	3	2	5	30
6	Damage to screen filter (intake)	3	3	3	27
7	Disinfectant chemical stock depletion	3	2	3	18
8	Coagulant chemical stock depletion	3	2	3	18
9	Intake pump malfunction	3	2	3	18
10	Disinfectant dosing pump malfunction	3	2	2	12
11	Coagulant dosing pump malfunction	3	2	2	12
12	Sedimentation system equipment failure	3	2	2	12
13	Suboptimal filtration performance	3	2	2	12
14	Operator exposure to coagulant chemicals	1	3	2	6
15	Operator contact with coagulant-treated water	1	3	2	6
16	Operator exposure to disinfectant chemicals	1	3	2	6
17	Operator contact with disinfectant-treated water	1	3	2	6

Table 3. Top five critical risks (RPN > 29).

No	Failure Mode	S	O	D	RPN
1	Inaccurate dosage of coagulant chemicals	5	4	5	100
2	Inaccurate dosage of disinfectant chemicals	5	4	5	100
3	Sediment accumulation at bottom of reservoir tank	5	4	3	60
4	Entry of external contaminants into reservoir	5	3	3	45
5	Contamination of raw water source	3	2	5	30

These five failure modes represent the most urgent risks to operational reliability and water quality safety. The two most significant risks—both with RPN scores of 100—involve chemical dosing inaccuracies, which might result in water that is unsafe for consumption. The other three critical risks, though with lower RPNs, relate to post-treatment storage and source quality, which have indirect but compounding effects on customer satisfaction and health.

3.3. Root Cause Analysis and Improvement Recommendations

After identifying the five most critical failure modes using the FMEA method, a detailed root cause analysis was performed to understand the underlying factors contributing to each risk. The 5 Whys technique was employed to trace each failure mode back to its core cause, allowing targeted and effective recommendations to be formulated. These risks not only reflect operational inefficiencies but also reveal broader systemic issues such as training gaps, lack of monitoring mechanisms, and environmental management weaknesses [18,19].

The first two critical risks—inaccurate dosage of disinfectant and coagulant chemicals—were both assigned the highest RPN score of 100. These risks stem primarily from operators' limited understanding of proper chemical dosing and the frequent depletion of chemical supplies, which encourages underdosing to extend inventory lifespan. The third critical risk, sediment accumulation in the reservoir, was caused by unoptimized filtration and the absence of structured cleaning protocols. The fourth risk, entry of external contaminants into the reservoir, was linked to the lack of a daily inspection SOP, leaving the facility vulnerable to contamination through open access points. The final critical risk, contamination of

the raw water source, was driven by unmanaged household and industrial waste entering the river due to low environmental awareness and limited outreach from authorities and the water company.

Based on these findings, a set of tailored improvement actions is proposed to mitigate these risks and strengthen operational reliability as summarized in Table 4. These include structured operator training by external institutions, implementation of digital stock monitoring tools, creation of inspection checklists, and environmental education programs targeting local communities.

Table 4. Root causes and improvement actions for critical failure modes.

No	Critical Failure Mode	Root Cause (5 Whys Summary)	Improvement Action
1	Inaccurate dosage of disinfectant chemicals	No structured training for dosing	Provide training from external certified institutions
		Manual, inaccurate stock records	Implement chemical stock logbook
2	Inaccurate dosage of coagulant chemicals	No structured training for dosing	Provide training from external certified institutions
		Manual, inaccurate stock records	Implement chemical stock logbook
3	Sediment accumulation in reservoir tank	No routine cleaning schedule	Create reservoir cleaning SOP and checklist
		No cleaning checklist or supervision	Set digital reminders (e.g., Google Calendar)
4	Entry of external contaminants into reservoir	No daily maintenance SOP	Develop daily SOP for inspection
		No documentation of previous failures	Implement checklist-based inspection
5	Contamination of raw water source	Poor environmental awareness in community	Launch joint outreach and education campaigns on sanitation and waste disposal
		No outreach to nearby households/industries	

4. Conclusions

We identify, analyze, and prioritize operational risks in the water treatment process, which is managed by a regional public water company. Regarding the results, the coagulation-flocculation and disinfection stages posed the highest number of risks, each with five potential failures, including chemical stock issues, dosing inaccuracies, operator exposure, and pump malfunctions. Seven other risks were identified in other stages. The FMEA results showed five critical risks (RPN > 29): incorrect dosing of disinfectants and coagulants, sediment buildup in the reservoir, external contamination of the tank, and raw water pollution. Each was further assessed using root cause analysis.

Operator training and a digital stock system are recommended for chemical dosing, scheduled cleaning and checklist development for sediment control, SOPs for reservoir inspection, and environmental outreach to reduce water source pollution.

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