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Evaluating Operational Risk in Circular Water Systems in Indonesian Wastewater Treatment Plants

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ABSTRACT

This study examines the implementation of operational risk management in Tirta Selaras, a pseudonym for a regional water utility company. A qualitative case study was conducted through interviews, field observations and document analysis. ISO 31000:2018, PESTLE, and Failure Mode and Effects Analysis (FMEA) were integrated to provide a comprehensive assessment of risk management. FMEA identifies political, social and economic risks as the most critical failure modes affecting operational performance. The findings indicate that operational risks arise from standard operating procedures that do not fully align with policy changes; limited operator competence; and rising maintenance costs during operational disruptions. The study recommends strengthening Standard Operating Procedure (SOP) governance; providing regular employee training and refreshment; enhancing preventive maintenance; and reinforcing compliance to support the resilience of circular water operations.

SARI PATI

Penelitian ini mengkaji penerapan manajemen risiko operasional pada Tirta Selaras, sebuah nama samaran. Studi kualitatif dilakukan melalui wawancara, observasi lapangan, dan analisis dokumen. Penelitian ini mengintegrasikan ISO 31000:2018, analisis PESTLE, serta Failure Mode and Effects Analysis (FMEA) untuk memberikan penilaian komprehensif terhadap evaluasi manajemen risiko. Hasil FMEA menunjukkan bahwa risiko politik, sosial, dan ekonomi merupakan mode kegagalan paling kritis yang memengaruhi kinerja operasional. Temuan menunjukkan bahwa risiko operasional muncul karena SOP yang belum sepenuhnya selaras dengan perubahan kebijakan, kompetensi operator yang terbatas, serta meningkatnya biaya perbaikan saat terjadi gangguan operasional. Penelitian ini merekomendasikan penguatan tata kelola SOP, pelatihan dan penyegaran kompetensi karyawan secara berkala, peningkatan pemeliharaan preventif, serta penguatan kepatuhan untuk meningkatkan ketahanan operasi air sirkular.

INTRODUCTION

Water is essential for human life, economic activity and environmental health, yet its availability and quality are increasingly threatened by climate change, urbanization and pollution. The Global Risks Report 2025 identifies water crises as one of the most critical global risks, with a projected 40 percent gap between supply and demand by 2030 due to droughts, floods and other extreme events (World Economic Forum, 2025). The Yale Center for Environmental Law and Policy (2024) also highlights that access to sanitation and safe drinking water remains a major global and regional challenge. Among 25 evaluated nations in the Asia-Pacific region—covering East Asia, Southeast Asia, and Oceania—Indonesia ranks 128th out of 180 countries worldwide and 20th regionally, well below the global average. In Indonesia, due to infrastructure gaps, emissions from the waste sector have risen significantly, largely from industrial and domestic wastewater, with 203 districts lacking suitable treatment facilities (Kementerian PPN/Bappenas, 2025). Recently, water quality has been measured through the Indeks Kualitas Air (IKA), increasing from 53.1 percent in 2015 to 53.88 percent in 2023, still below the target of 54.59 percent (KLKH, 2023).

In response to these challenges, Tirta Selaras was established as an Indonesian enterprise specializing in integrated water and wastewater management, with a focus on resource efficiency. The company adopts circular practices by reusing treated water for non-potable uses such as toilet flushing and landscape irrigation. Due to the technical and environmental complexity of wastewater management, its operations require effective risk management to address system failures, regulatory compliance, and changes in external policies and technologies.

Research on risk management and circular economy applications has grown significantly, spanning environmental, social, operational and risk management perspectives. Rodrigues et al. (2024) assessed circular performance models in four Portuguese Water Treatment Plants (WTPs) between 2021 and 2023. They recommended more practical and integrated models that explicitly account for technical, environmental, economic and social dimensions. Although their study advanced conceptual modeling, it did not address real-world implementation. In contrast, Alizadeh et al. (2022) applied both traditional and fuzzy FMEA to the Sahand Wastewater Treatment Plant (WWTP) in Iran, identifying 53 failure modes in screening and grit removal units. Their findings demonstrated that incorporating uncertainty and expert subjectivity, fuzzy FMEA produced more realistic risk prioritization. However, their study concentrated exclusively on unit-level operational risks, leaving broader environmental, social and regulatory dimensions of circular economy implementation largely unaddressed. This gap highlights the need for approaches that integrate multidimensional risks. Tušer and Oulehlová (2021) assessed a Slovak WWTP serving 1,250 population equivalents, using ISO 31000 and Bowtie analysis. They identified operational, health and environmental risks, concluding that integrated risk management can enhance both safety and sustainability. However, their case was limited in scale and complexity, meaning their findings cannot be easily generalized to urban-industrial systems.

Compared with previous research, this study offers new insights by integrating risk management and circular economy frameworks to address political, economic, social, technological, legal, and environmental risks in Indonesian wastewater systems. Earlier studies largely emphasized conceptual models, unit-level risks, or small-scale applications, providing limited guidance on system-wide risk governance. Our study addresses these gaps by developing a comprehensive and scalable framework that situates circular economy implementation within Indonesian urban–industrial wastewater operations. The framework broadens integrated risk management beyond individual process risks, including institutional, regulatory and socio-environmental dimensions. ISO 31000:2018

provides overall guidance for enterprise risk management, but lacks mechanisms for identifying and prioritizing technical failure modes. On the other hand, PESTLE analysis captures external macro-environmental influences, but does not quantify internal vulnerabilities. Finally, FMEA supports systematic prioritization of operational risks, but is rarely integrated into governance-oriented risk frameworks.

By combining these three approaches, this study delivers a novel integration model that enhances adaptive risk governance and promotes sustainable circular water operations in developing country contexts. This integrative model bridges governance principles, macro-environmental risk drivers and technical failure prioritization, thereby addressing the fragmentation observed in previous studies. However, a clear research gap remains, as limited work has been conducted on an integrated risk management framework that simultaneously embeds ISO 31000:2018, PESTLE and FMEA to address the full spectrum of operational, institutional, regulatory and macro-environmental risks in urban-industrial wastewater systems using circular economy models.

This study aims to fill this gap by: (1) evaluating how ISO 31000:2018 is implemented in Tirta Selaras's operational risk management; (2) integrating PESTLE and FMEA within the ISO 31000:2018 framework to comprehensively identify and prioritize operational failure modes in context; and (3) proposing actionable mitigation strategies to strengthen organizational resilience for circular water operations.

THEORETICAL FOUNDATION

Circular Water Economy

The circular water economy (CWE) is a transformative approach to water management that aims to move beyond the traditional linear "extraction–use–disposal" model toward circular systems that promote conservation, reuse and recovery (Farfán Chilicaus et al., 2025). These principles align with the broader concept of the circular economy, which seeks to retain materials and products in the loop for as long as possible, transforming waste into resources, and improving process efficiency (Hernández-Chover et al., 2023). This transition is increasingly recognized as a strategic response to the global water crisis, which is marked by scarcity, pollution and unequal distribution, while highlighting the interconnectedness of water systems, feedback loops, and the dual role of water as both an input and a recoverable resource (Farfán Chilicaus et al., 2025; Piubello Orsini et al., 2023).

In this context, CWE promotes efficient use, recycling and resource regeneration, and is increasingly acknowledged as a viable framework for sustainable water governance (Morseletto et al., 2022). As an economic framework, it aims to minimize waste, conserve resources and optimize water utilization through avoidance strategies, efficient management and quality maintenance, while simultaneously ensuring environmental protection and advancing circularity in water systems (Delgado et al., 2024). This approach entails the viewing of wastewater as a valuable resource and a carrier of materials, rather than as a burden in the water sector (Marques et al., 2023).

Risk Management

Risk management systematically identifies, assesses and mitigates potential risks to enable goal achievement and value creation, while simultaneously enhancing management systems, thus fostering innovation and improving operational efficiency (ISO 31000:2018). The risk management framework comprises five key phases: risk identification; risk measurement and assessment; risk evaluation; mitigation and contingency planning; and risk control and monitoring (Kähkönen et al., 2023).

Within this context, risk management has emerged as a critical and continuously evolving discipline to safeguard the long-term sustainability and resilience

of water resources and related operations (Gramlich & Walker, 2023). The risk management process must be integrated into managerial functions and decision-making, and embedded within the organization's structure, operations and processes. It can be applied at strategic, operational, program and project levels, adapting to organizational objectives and external and internal contexts (ISO 31000:2018).

Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) is a widely used reliability management technique applied across various industrial sectors to ensure the safety and dependability of systems, services and projects (Huang et al., 2020). It is designed to identify and evaluate potential failure modes within a system, process or product, along with their possible effects and likelihood of occurrence (Salah et al., 2023). FMEA influences organizational processes, including internal regulations and operational procedures, in addition to identifying and assessing risks (Kardos et al., 2021).

PESTLE Framework

The PESTLE (Political, Economic, Social, Technological, Legal and Environmental) framework is widely used to identify and categorize external factors influencing an organization's risk environment. Originally developed as an environmental scanning tool (Saudi et al., 2021), PESTLE supports a structured assessment of macro-environmental risks that lie beyond managerial control. In risk management studies, it is frequently applied to identify external risk events before conducting deeper analyses, such as FMEA (Muntoha & Sudiarno, 2019). By systematically mapping political, economic, social, technological, legal and environmental drivers, PESTLE ensures that external uncertainties are recognized early, enabling more comprehensive risk identification and supporting integrated models that combine qualitative scanning with quantitative prioritization (Christodoulou & Cullinane, 2019).

In sustainability and urban development studies, PESTLE indicators have also been operationalized and quantified to support risk prioritization during evaluation stages, demonstrating the framework's adaptability across sectors (Vardopoulos et al., 2021).

Risk Management in the Circular Water Economy

Risks in the industrial water sector are multifaceted, encompassing human errors, management weaknesses, technological failures, irrational exploitation of natural resources, and non-disposable waste generation, all of which can lead to accidents, disruption and financial instability (Trubetskaya et al., 2021). At the same time, the transition toward a circular economy introduces unique risks that require tailored approaches. This often demands stronger collaboration, strategic partnerships, technological adoption and long-term perspectives across supply chains (Schultz et al., 2021).

In parallel, implementing circular water management can also mitigate risks such as water shortages for production, compromised product quality, and regulatory non-compliance related to wastewater disposal (Meiryani et al., 2022). In the context of the CWE, risk management has become a critical and evolving field aimed at ensuring the long-term sustainability of water resources and operational resilience. Within this framework, risk management plays a pivotal role in identifying the causes and consequences of system failures, as well as anticipating wastewater-related risks, which remain underexplored but hold significant potential to disrupt industrial activities (Trubetskaya et al., 2021).

Integrating ISO 31000:2018, PESTLE and FMEA

While ISO 31000:2018, PESTLE and FMEA draw on different theoretical roots, they complement rather than duplicate one another, mapping onto successive stages of the risk management process. ISO 31000:2018 supplies the overarching governance architecture, establishing the scope, context and

criteria against which risk is identified, analyzed and evaluated (ISO 31000:2018). PESTLE operates at the context-establishment and risk-identification stages, functioning as a structured environmental-scanning lens that brings to the surface the political, economic, social, technological, legal and environmental drivers of risk outside managerial control (Christodoulou & Cullinane, 2019; Saudi et al., 2021).

FMEA, by contrast, operates at the risk-analysis and risk-evaluation stages, translating qualitatively identified failure modes into quantified severity, occurrence and detection ratings from which a Risk Priority Number can be derived (Huang et al., 2020; Salah et al., 2023).

Taken together, the three frameworks operate as a funnel. ISO 31000:2018 sets the governance boundaries within which risk management takes place; PESTLE then broadens the view so that macro-environmental risk sources are not missed during identification; and FMEA brings the analysis back to a narrower, prioritized set of failure modes that feed directly into treatment planning. This sequence echoes earlier work that combined PESTLE-based scanning with structured prioritization tools ahead of more detailed analysis (Muntoha & Sudiarno, 2019), as well as sustainability-focused extensions of FMEA, which call for incorporating broader environmental and social considerations into what is otherwise a technical scoring exercise (von Ahsen et al., 2022).

METHODS

The study adopted a qualitative case study approach designed to explore and analyze the implementation of risk management in the circular water economy context, focusing on a company engaged in wastewater recycling, Tirta Selaras. The case study method was chosen to allow an in-depth and contextual exploration of risks, their probability, and their impact on operational and strategic processes (Ellet, 2018).

All research procedures involving human participants followed institutional ethical standards and the principles of informed consent. Before participation, each respondent received a written explanation describing the study purpose, confidentiality measures, and voluntary participation rights. Written consent was obtained from all participants, and anonymity was maintained throughout the data collection, transcription and reporting.

A purposive sample of seven key experts was selected to provide rich, context-specific insights into the implementation of risk management practices within the circular water economy. The interviewees included the Managing Director (D.2), Operations Manager (M.1), General and Finance Manager (M.2), QHSE Officer (Q1), Operations Supervisor, and two Operations Staff (O.2), with interview durations ranging from 50 to 65 minutes. Among the participants, six were male and one was female, reflecting the company's operational composition. While this small sample limited statistical generalization, it enabled an in-depth exploration of managerial and technical perspectives relevant to wastewater treatment operations. To strengthen the credibility and validity of the findings, methodological triangulation was applied by combining semi-structured interviews, document analysis and field observations, allowing cross-verification from multiple data sources.

Given the small, purposively selected sample of seven key informants, saturation was approached using an information-power logic rather than a strict sample-size threshold (Saunders et al., 2018). Interviews continued until successive transcripts stopped producing substantively new themes, failure modes or risk perspectives. The interviewees' near-complete organizational coverage, spanning ownership, operations, finance, quality and field-level roles, was treated as a proxy for informational completeness rather than statistical representativeness. Consensus among the key informants was reinforced further through the calibration step described below, in

which individually assessed FMEA scores were reconciled across raters. The convergence of severity, occurrence and detection ratings following calibration served as an additional, practice-based indicator that the qualitative scoring had stabilized, rather than being driven by a single dominant perspective.

To ensure a comprehensive and systematic analysis, internationally recognized frameworks were incorporated, specifically ISO 31000:2018 for structured risk management, PESTLE analysis for assessing external macro-environmental factors, and FMEA for quantifying and prioritizing operational risks. These frameworks collectively provided a holistic basis for evaluating the effectiveness and resilience of risk management systems in circular water operations. Three complementary data collection techniques were employed:

1. Document Analysis

Document analysis involved reviewing internal company records relevant to operational risk and wastewater management, including Customer Quality Feedback (CQF) reports, Standard Operating Procedures (SOPs), Key Performance Indicators (KPI), and laboratory test outcomes. These documents were analyzed to validate field findings and to cross-check consistency with ISO 31000:2018 standards. The documentation also supported the verification of risk identification and mitigation processes across departments.

2. Semi-Structured Interviews

Semi-structured interviews were conducted with the seven key informants, namely the company's Managing Director, Operations Manager, Finance and HR Manager, QHSE officer, and two Operations staff members. The interview protocol was designed in accordance with ISO 31000:2018, covering the stages of communication and consultation, risk identification, assessment, treatment and monitoring. Each interview lasted 50 to 65 minutes and was conducted at the company's operational sites to ensure contextual accuracy.

To complement the qualitative findings, PESTLE and FMEA were employed to quantify the operational risks identified during the preliminary ISO 31000 and PESTLE assessments. This analytical stage aimed to determine the relative priority of each risk based on expert judgment and consensus validation, translating qualitative insights into quantitative prioritization metrics. Each expert independently assessed the failure modes using the FMEA framework. After the individual assessments, calibration was conducted to reconcile variations and achieve consensus, ensuring inter-rater reliability and minimizing subjective bias.

3. Direct Observation

Systematic field observations were conducted at Tirta Selaras's wastewater recycling facility over three consecutive working days, with sessions lasting 2–3 hours per day. The researcher acted as a non-participatory observer, recording operational practices, adherence to safety and environmental procedures, and the application of circular water principles such as separation, reuse and recycling of treated water. Observations were documented through field notes and checklist formats to ensure data reliability and traceability. Both primary and secondary data sources were integrated to ensure validity and reduce bias. Triangulation was applied by cross-verifying the results from the observations, interviews and document analysis (Bougie & Sekaran, 2020). This approach enhanced the reliability and comprehensiveness of the findings regarding risk management practices in circular water operations.

RESULTS AND DISCUSSION

Communication and Consultation

According to ISO 31000:2018, the initial stage that should be planned before the risk management process concerns communication and consultation. Through these, decisions can be made appropriately because stakeholders will be able to understand risks involved and the reasons why actions must be taken. Such risks are closely linked to both operational and managerial aspects of Tirta Selaras,

particularly in maintaining service quality and client trust. In addition to routine meetings, risk communication also takes place through a tiered mechanism.

The operator or supervisor reports findings to the operations manager, which are then forwarded to QHSE for compilation, passed to the operations manager, and then returned to the operator for corrective action. With this pattern, each party remains connected, and follow-ups can be ensured. One of the informants explained:

> *"Every month, we hold a management meeting to discuss the progress of the wastewater treatment projects. All matters related to operational risk, chemical stock and HSE procedures are reported here. Problems are usually discussed directly. If a solution is not found, the issue will be escalated to management or up to the board for a decision. So, no one forces their will; we find solutions during meetings."* (M2)

In addition, the interviews with the company leaders highlighted the further challenges in implementing risk management practices. One respondent noted:

> *"Regarding risk management, communication to each division has not been optimal. The standards are there, and we know the process, but implementation is still weak. Toolbox Meetings were held, but not consistently. Going forward, we plan to emphasize the importance of risk management in every meeting."* (D2)

Tirta Selaras management uses a communication process that involves various areas of expertise in monthly management meetings. Participants include the project manager, head of operations, head technician, field staff, and local contract workers. Meetings review issues that have arisen during the past month and the mitigation steps to be taken. The primary aim is to ensure smooth coordination, avoid misunderstandings, and minimize operational risk. This aligns with research by De Oliveira et al. (2021), which demonstrated that risk management planning ensures that stakeholders understand the rationale for actions and the basis for decisions, covering all process phases, with communication and consultation taking place simply through meetings involving all relevant parties.

Moreover, to date documentation of communication process records has been conducted mainly for administrative and operational project matters, such as chemical stock reports, training records and laboratory test results. However, the application of communication and consultation at Tirta Selaras remains focused on operational coordination and administration, with documentation limited to chemical stock reports, customer complaint reports, training records, and laboratory test results, without comprehensive integration across the overall risk management process. Therefore, the communication that takes place is more responsive to issues, rather than anticipatory of risks, and therefore does not yet fully support the management of uncertainty related to achieving organizational objectives (ISO 31000:2018).

Scope, Context and Criteria

The scope of risk management at Tirta Selaras encompasses all operational activities related to the provision of water treatment services, including wastewater treatment plants (WWTP). The company's strategic choice of this sector is informed not only by business opportunity, but also by sustainability considerations. As one director explained:

> *"Initially, this was not a strategic plan; it was more of an opportunity that came along. But we saw water as an essential need, more sustainable than other industries. In addition, this aligns with the SDGs, particularly on access to clean water and waste recycling."* (M1)

The external context includes stakeholder expectations and regulatory obligations. Key external

influences are client performance specifications, environmental discharge permits (including hazardous waste disposal requirements where applicable), third-party laboratory verification, contractor capability, and evolving governmental regulations and certification requirements. To assure compliance and comparability, management reports laboratory results to clients and regulators:

> *". .usually there are daily reports and monthly reports. Then we also submit lab results so they can be compared with government standards."* (Q1)

In practice, the company combines experiential judgement, field inspection, external laboratory reports, and stakeholder feedback to assess risk. Nevertheless, when judged against ISO 31000:2018, the articulation of scope and the formal definition of measurable risk criteria remain incomplete. While management employs accepted risk-assessment inputs and routine communications, there is no systematic documentation that for each project type specifies the boundaries of risk assessment, the chosen risk-analysis techniques, or quantitative thresholds for consequence and likelihood.

Evaluation Risk

According to ISO 31000:2018, the risk identification stage aims to detect, recognize and describe risks that may hinder the achievement of an organization's objectives. Organizations can employ a range of methods to identify future uncertainties arising from events that could impede strategic or operational goals. As stated by De Oliveira et al. (2021), companies should involve individuals with adequate knowledge in the risk identification process, use relevant and up-to-date information, and apply appropriate identification techniques and tools suited to the organization's objectives, capacity and risk types.

In the case of Tirta Selaras, the risk identification process was conducted through an analysis of CQF documents, interviews with service users, and a review of root-cause findings derived from customer complaints. Actual client feedback serves as a primary input for understanding risks directly associated with service quality and customer satisfaction. CQF data analysis revealed several operational risks that could impede organizational objectives, such as delays in monthly reporting, incomplete work uniforms, the absence of standardized operating procedures (SOPs), and inadequately documented maintenance procedures.

The FMEA approach assesses three key parameters: Severity, Occurrence and Detection (SOD), as presented in Tables 1, 2 and 3. Severity reflects the internal impact of failure; Occurrence represents the likelihood that the external factor will activate the failure mode; and Detection indicates the ability of current controls to identify the issue before it results in adverse outcomes. The Risk Priority Number (RPN) is calculated by multiplying these parameters and is used to prioritize the underlying causes of potential failures. This structure aligns with established FMEA methodology, in which risks are systematically scored to determine the urgency of mitigation actions. The RPN framework supports organizations in identifying and prioritizing critical risks by quantifying failure likelihood, detectability and potential impact (Tangestani et al., 2025). Conventional FMEA universally adopts the S–O–D scoring system, with the RPN serving as a central indicator for ranking failure modes across industries (Aleksić et al., 2025).

External factors identified through the PESTLE framework can also be incorporated into this assessment, as PESTLE highlights external triggers that may lead to internal process failures (Muntoha & Sudiarno, 2019). These triggers are then translated into specific failure modes that can be evaluated using FMEA (von Ahsen et al., 2022). Based on the information obtained, a PESTLE analysis was developed in accordance with the company's organizational structure and business process flow, as presented in Table 4.

Table 1. Severity Scale Parameter

Category	Score	Impact Description
Hazardous without warning	10	Causes serious risk without warning
Hazardous with warning	9	Causes severe losses but is preceded by warning signs
Very Critical	8	Causes major service disruption, directly affecting users
Critical	7	Causes moderate service disruption directly affecting users
Significant	6	Causes major service disruption but without affecting users
Moderate	5	Causes minor service disruption that does not affect users
Low	4	Causes slight disruption involving users but without need for reworking
Minor	3	Causes slight disruption not involving users
Very Slight	2	No significant disruption
None	1	Causes no impact whatsoever

Source: Tangestani et al. (2025)

Table 2. Occurrence Scale Parameter

Category	Score	Impact Description
Very Frequent	10	More than once a day
Frequent	9	Once every three to four days
High	8	Once a week
Fairly High	7	Once a month
Moderate	6	Once every three months
Medium	5	Once every six months
Low	4	Once a year
Rare	3	Once one to three years
Very Rare	2	Once three to six years
Seldom	1	Once in more than seven years

Source: Tangestani et al. (2025)

Table 3. Detection Scale Parameter

Category	Score	Impact Description
Most Impossible	10	No available method for detecting failure
Very Rare	9	Probability of failure detection extremely low
Rare	8	Failure detection possible under certain conditions
Very Low	7	Very low probability of detecting failure
Low	6	Detection capability remains limited
Medium	5	Detection capability limited
Fairly High	4	The system can identify failures
High	3	Most failures can be detected
Very High	2	Nearly all failures can be recognized
Almost Certain	1	Failures are certainly and effectively detected

Source: Tangestani et al. (2025)

Table 4. PESTLE Risk Analysis

PESTLE	Failure Risk Mode
Political	Changes in stakeholder policies, particularly those related to quality standards, create operational non-compliance risks.
Economic	Strict B3 waste rules raise treatment costs, while demand shifts, inflation, and limited financing cut margins, a situation further strained by higher maintenance costs during disruptions.
Social	A shortage of skilled labor and an organizational culture resistant to change lead to low operational effectiveness, and increased safety and compliance risks, while hindering the implementation of innovation and process improvement.
Technological	Inadequate treatment technology, incomplete implementation of automated monitoring across all sites, and dependency on several key vendors heighten the risk of operational process disruptions.
Legal	Weak monitoring and documentation increase the risk of violating effluent and hazardous waste regulations, leading to penalties or legal action.
Environmental	Inadequate treatment performance and ineffective process control result in effluent non-compliance, environmental contamination, customer and community complaints, and reputational harm.

At this stage, the list of identified risk events was further assessed using the Failure Mode and Effects Analysis (FMEA) method by calculating the Risk Priority Number (RPN). The values for severity, occurrence and detection were determined based on managerial experience, gathered through interviews and discussions. Using expert judgment in this way is widely accepted, especially when quantitative failure data are limited (von Ahsen et al., 2022). The results of this are presented in Table 5.

Based on the FMEA results, the total RPN across Tirta Selaras's operational processes is 1,877, representing the overall level of operational risk. This aggregate RPN reflects both the cumulative risk exposure and the urgency of implementing corrective and preventive measures (Kardos et al., 2021).

As shown in Table 6, several high-priority RPN values indicate the need for focused corrective actions to ensure operational compliance and effective risk mitigation. According to the classification, RPN scores of 1–250 are categorized as low risk, 250–500 as moderate risk, and 500–1000 as high risk, requiring immediate action and continuous monitoring (Jafari et al., 2025).

The findings indicate that Tirta Selaras's risk management framework is primarily oriented toward risk mitigation and capacity-building strategies designed to reduce the potential impact of operational and compliance risks. The FMEA results demonstrate that the highest RPNs are associated with political, social and economic factors, reflecting a concentration of vulnerabilities in regulatory adaptation, workforce competency and financial resilience. From a political perspective, the highest RPN of 448 results from the uncontrolled and inconsistently applied SOP in following policy changes. This issue is classified as Moderate. Consequently, the CQF results show that customer complaints mainly stem from inconsistent procedures, especially when the wastewater treatment process fails to meet required quality standards. This situation highlights the need to develop a structured SOP control mechanism, supported by routine evaluations and integrated documentation systems, to ensure consistent adherence to regulatory and operational standards (Raya Shinta et al., 2019).

Social risks, reflected by an RPN of 392, arise from a shortage of certified operators and an organizational culture resistant to change, reducing

Table 5. FMEA Analysis

Risk Source	Failure Mode	Potential Cause of Failure	Potential Effect of Failure	S	O	D	RPN SxOxD
Political (R1)	SOP implementation is not fully optimized with policy changes	Policy updates not promptly integrated into SOP	Potential non-compliance findings and risk of administrative sanctions	8	8	7	448
Economic (R2)	Rising wastewater treatment costs amid financial pressure	Fluctuating demand, inflation, and limited financing capacity	Increased operating costs and reduced profit margins	7	6	8	336
Social (R3)	Lack of certified and skilled operators	Shortage of skilled workers and organizational culture resistant to change	Low operational effectiveness, increased safety and compliance risks, and delayed innovation	8	7	7	392
Technology (R4)	High-complexity treatment technology and the absence of automated monitoring	Outdated processing systems, and absence of real-time monitoring sensors	Increased risk of operational disruptions, and potential non-compliance with effluent quality	7	5	7	245
Legal (R5)	Failure to comply with stricter effluent standards and hazardous waste (B3) disposal regulations	Weak monitoring or documentation, and regulatory compliance	Legal sanctions, penalties, and operational suspension due to regulatory violations	8	5	6	240
Environmental (R6)	Treated effluent does not comply with required environmental parameters and contaminates water	Inadequate treatment performance, poor maintenance, high grease load, or ineffective process control	Environmental contamination, customer dissatisfaction, community complaints, and reputational damage	9	4	6	216

Table 6. RPN Priority

Failure Mode	RPN	Priority
Standard Operating Procedures (SOP) implementation is not fully optimized to follow policy changes (R1)	448	1 (Moderate)
Lack of certified and skilled operators (R3)	392	2 (Moderate)
Rising wastewater treatment costs amid financial pressure (R2)	336	3 (Moderate)
High-complexity treatment technology and the absence of automated monitoring (R4)	245	4 (Low)
Failure to comply with stricter effluent standards and hazardous waste (B3) disposal regulations (R5)	240	5 (Low)
Treated effluent does not comply with the required environmental parameters and contaminates the water (R6)	216	6 (Low)

operational effectiveness and increasing safety risks. This is reinforced by the fact that only a small percentage of employees currently hold the required certifications, thus indicating limited technical readiness. Addressing this requires targeted certification and training programs to enhance employee competence and compliance (Mathiang & Djakman, 2023). Furthermore, promoting continuous learning and safety awareness through regular staff training and incentive systems is essential to the strengthening of operational discipline and sustainability (Tangestani et al., 2025).

In economic terms, the risk associated with rising wastewater treatment costs, reflected by its score of 336, arises from fluctuating demand, inflationary pressures, and limited financing capacity, all of which erode profit margins. These conditions are further intensified by market uncertainty and variable loan interest rates, which increase financial exposure for water-related service projects (Ma et al., 2021). The high-complexity of treatment technology and the absence of automated monitoring contributed to a score of 245, indicating potential non-compliance with environmental and ESG standards, accompanied by outdated treatment technologies and a lack of automated monitoring systems. Reliance on periodic manual measurements by operators further increases the likelihood of delayed detection and corrective action.

Legal risk, with an RPN of 240, presents considerable challenges because non-compliance with effluent quality standards directly leads to water contamination and ecological degradation (Hernández-Chover et al., 2023). The environmental risk associated with stricter effluent standards and hazardous waste (B3) disposal regulations, with an RPN of 216, heightens the risk of operational disruptions and effluent quality deviation. This assessment is based on the interview findings and recent laboratory tests, which show that most effluent parameters already meet the required thresholds, indicating generally effective controls.

In line with the above, integrating circular economy principles into organizational strategies enhances resilience and resource efficiency, facilitating the transition toward a sustainable and competitive economic framework that simultaneously advances industrial performance and environmental well-being (Prendi & Murrja, 2025).

After determining the RPN values, the next step was to assess the organization's risk detection capability. The results were then mapped into a risk matrix to classify risks as high, medium or low, helping to prioritize mitigation efforts effectively. The matrix represents the Severity–Probability (Detection × Occurrence) Risk Assessment, offering a qualitative overview of potential failures by considering both impact severity and the likelihood of occurrence. Based on the classification, risks with a score of 1–250 were considered low, those with 251–500 moderate, and those with 501–1000 high, thus requiring immediate action and monitoring (Jafari et al., 2025). The results of this assessment are shown in Figures 1, 2 and 3.

Based on the Severity–Occurrence Matrix shown in Figure 1, more risks fall within the red and yellow zones compared with the green zone, indicating that these two factors strongly influence the RPN values. The mapping shows that weaknesses in SOP implementation and the lack of operator certification contribute to higher clustering of risks in the upper zones. The other yellow matrix shows similar tendencies, where many risks combine high severity with limited detection capacity, emphasizing the need for stronger controls and more consistent monitoring across operational processes.

Based on the Severity–Detection Matrix shown in Figure 2, several risks, such as misalignment of SOPs with policy changes or insufficient operator competence, appear difficult to detect at the early stages. This finding highlights the need for more reliable monitoring systems and better skills development for operational personnel. Risks

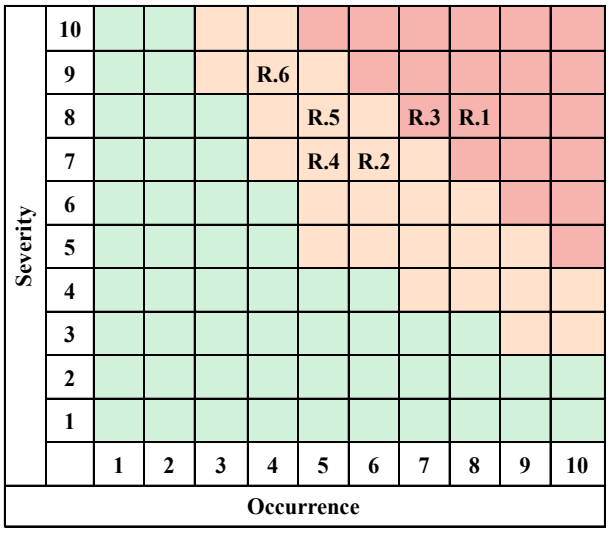


Figure 1. Severity x Occurrence Risk Matrix

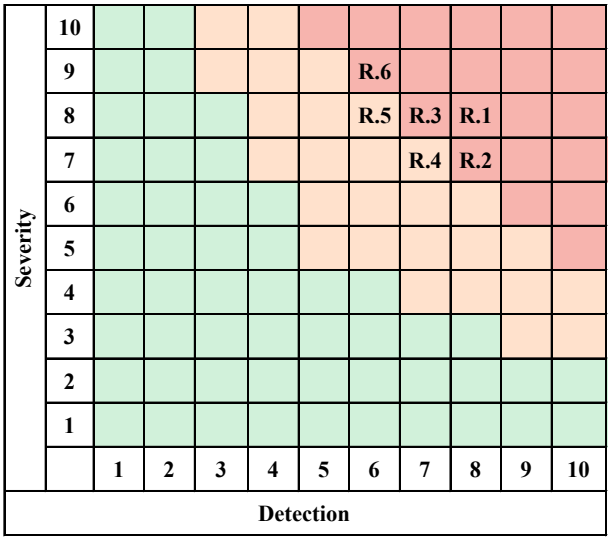


Figure 2. Severity x Detection Risk Matrix

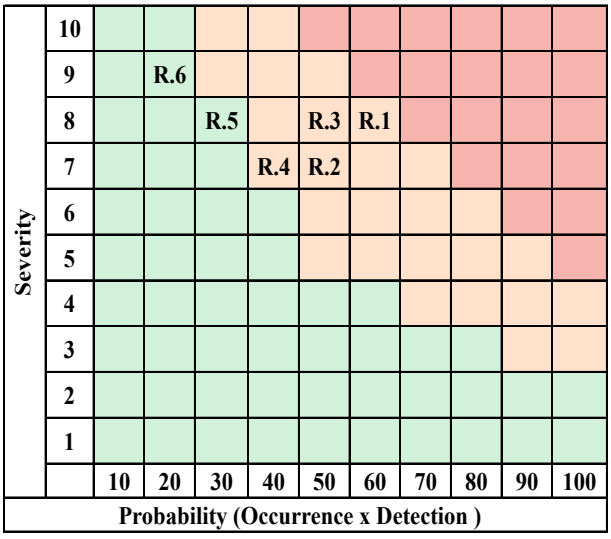


Figure 3. Severity x Probability (Occurrence x Detection) Risk Matrix

related to effluent quality fall within the low to moderate categories across the three matrices, suggesting that they remain manageable, but still require regular oversight to prevent environmental non-compliance.

Figure 3 represents the Probability Matrix, which combines occurrence and detection. The results show that failures continue to appear frequently, while the system's ability to detect deviations remains limited. The high clustering of risks in the upper zones indicates that existing monitoring practices require improvement to prevent disruptions in wastewater treatment performance.

In our study, FMEA identified six primary failure modes, with RPN values ranging from 216 to 448, indicating several high-priority operational concerns. The consistent alignment between high RPN values and the red-coded zones across all matrices demonstrates the reliability of this integrated assessment.

The study findings underscore the importance of adaptive risk management that integrates technical, managerial and environmental considerations. By highlighting key vulnerabilities related to workforce competence, financial capacity and technological limitations, the analysis emphasizes the need for coordinated strategies that support operational continuity and long-term sustainability within the circular water economy model.

According to Tušer and Oulehlová (2021), similar operational and technological vulnerabilities are common in WWTPs, especially those with aging infrastructure, limited safety protocols and fragmented documentation systems. Their findings confirm that weak procedural control significantly heightens risk activation, particularly when preventive and reactive measures are poorly established. Additionally, the sustainability and efficiency of WWTPs are also strongly influenced by operator expertise, technological readiness and the adequacy of operational protocols (Rodrigues et al., 2024). The findings are also consistent with the broader literature, which notes that regulatory barriers, outdated technologies and insufficient monitoring systems continue to hinder effective wastewater treatment and circular economy transitions (Mannina et al., 2022).

Other risks, such as ineffective waste management and non-compliance with effluent and hazardous waste regulations, are categorized as lower priorities, but remain significant for ensuring environmental compliance. As emphasized by Smol (2023), the shift toward CE in WWTPs will continue to grow, encouraging not only new technologies, but also new organizational practices, financing models and business strategies. This transformation supports the evolution of WWTPs into future "resource facilities" capable of ensuring secure access to water, energy and nutrients under increasing climate and resource pressures. Furthermore, circular economy frameworks for wastewater treatment emphasize that improved waste management and compliance practices enhance resource recovery, strengthen environmental performance and support overall sustainability (Soo & Shon, 2024).

Risk Treatment

According to ISO 31000:2018, risk treatment is an iterative process involving the selection and implementation of options to mitigate, transfer or avoid risks. Furthermore, risk classification based on the Risk Priority Number (RPN) is applied to determine the level of urgency in handling potential failures of specific components. At Tirta Selaras, the risk treatment process is performed based on technical experience and expert input in the field of water treatment, particularly concerning effluent quality, regulatory compliance and occupational safety. Coordination among the operational, human resources and supply chain divisions plays a crucial role in determining mitigation priorities, both before and after risks occur. In practice, risk-handling decisions are made by the operations manager by considering the severity, occurrence frequency and detectability of potential failures. As one key

informant emphasized:

"Risks in water treatment cannot be completely avoided, but they can be controlled through supervision and improving operator competence" (M2).

This statement underlines that the risk management approach of Tirta Selaras primarily emphasizes mitigation efforts and human resource capacity building to minimize the impact of risks as much as possible. Based on the FMEA results, the highest RPN values were identified in the human resources and regulatory compliance aspects. These findings indicate the need for enhanced operator certification, improvements in treatment system performance and strengthened adherence to environmental quality standards. Table 7 presents the detailed risk sources and their corresponding treatments.

The mitigation strategies presented in Table 7 illustrate significant cross-functional synergy across the political, social, technological, economic and legal risk domains. Consistent with this, suitably trained operators also play a critical role in monitoring operational parameters and preventing deviations that may lead to contamination risks within the circular water systems (Rodrigues et al., 2024). Furthermore, improved staff competency supports the reliable functioning of energy-efficient technologies and reduces the likelihood of operational failures that disrupt effluent quality stability (Longo et al., 2023) These interdependencies demonstrate that the effectiveness of individual mitigation measures is significantly enhanced when implemented in an integrated manner, thereby strengthening organizational resilience

Table 7. Risk Treatment

Risk Source	Failure Mode	Current Situation	Risk Treatment
Political (R1)	SOP implementation is not fully optimized to follow policy changes	Potential non-compliance findings during inspections, and risk of administrative sanctions	Regular SOP review and alignment with new government regulations
Economic (R2)	Rising wastewater treatment costs amid financial pressure	Increased operating costs and reduced profit margins	Implement cost-efficiency programs, strengthen preventive maintenance, and explore alternative financing
Social (R3)	Lack of certified and skilled operators	Low operational effectiveness, increased safety and compliance risks, and delayed innovation	Conduct refresher training, certification programs, and develop incentive systems to enhance skills and retention
Technology (R4)	Highly complex treatment technology and the absence of automated monitoring	Water quality monitoring is performed manually at set intervals, limiting real-time visibility and delaying deviation detection	Upgrade treatment technology and install real-time automated monitoring systems to ensure continuous tracking of critical parameters
Legal (R5)	Failure to comply with stricter effluent standards and hazardous waste (B3) disposal regulations	Legal sanctions, financial penalties, and potential operational suspension due to violations	Strengthen compliance documentation, conduct regular internal audits, and implement updated SOPs for hazardous waste handling
Environment (R6)	Treated effluent does not comply with the required environmental parameters and contaminates the water	Effluent quality does not meet environmental standards, with potential contamination risk	Periodic lab testing, manual sampling, ad-hoc corrective actions, basic SOPs, and some operator training.

and supporting more stable, compliant and cost-efficient circular water operations (Roccaro, 2018). Integrated risk–technology–operations approaches are also recognized as essential for achieving long-term circular economy outcomes in the water sector, particularly under regulatory and financial pressures (Piubello Orsini et al., 2023).

MANAGERIAL IMPLICATIONS

The study offers several practical insights for managers in the circular water and wastewater treatment sectors. First, operational risk management should be aligned with ISO 31000:2018 to ensure that risk scope, context and criteria are clearly defined. Strengthening adaptive SOP review mechanisms is essential, not only to improve internal efficiency, but also to enhance resilience against political and legal uncertainties, such as regulatory shifts and evolving environmental compliance requirements. As highlighted by Delgado et al. (2024), wastewater treatment facilities must be robust and flexible to withstand climate uncertainty, demographic change and technological evolution within circular economy transitions.

Second, the findings underscore the critical importance of workforce competence. A shortage of certified operators elevates operational, safety and technological risks. Management should therefore invest in targeted training, certification programs and performance-based incentives to ensure operational reliability while advancing long-term sustainability.

Third, rising operational costs and financial pressures require efficient resource management. According to Kumar et al. (2025), financial innovation serves as a pivotal enabler in driving sustainable and resource-efficient transitions within circular economy frameworks. Hernández-Chover et al. (2023) also show that many WWTPs already generate value beyond regulatory pollutant-removal requirements, suggesting untapped opportunities to expand by-product recovery and achieve economies of scale.

Fourth, managers should adopt an integrated risk governance framework that combines ISO 31000:2018, FMEA and PESTLE analyses. This approach enables proactive identification of political, economic, social, technological, legal and environmental risks, improving resilience and supporting long-term sustainability in the circular water economy. This recommendation is strongly supported by the sustainability-oriented FMEA literature, which emphasizes the growing need to integrate environmental and social criteria into technical risk assessments to ensure holistic decision-making (von Ahsen et al., 2022). In line with Carrard et al. (2024), the adoption of circular economy frameworks in water and sanitation systems promotes inclusive, climate-resilient and safely managed operations, ultimately strengthening both operational efficiency and social equity across the circular water management sector. By operationalizing this integration, managers can reinforce both the internal robustness of wastewater operations and the broader social-ecological resilience of water systems amid external uncertainties.

Fifth, to close the gap identified under Scope, Context and Criteria, where measurable risk criteria remain informally defined, management should adopt a standardized risk-criteria template aligned with ISO 31000:2018. For each project type or process line, this template should specify the following: (a) likelihood scales anchored to defined frequency bands, consistent with the occurrence ratings already used in the FMEA scoring used in this study; (b) consequence scales covering safety, environmental, financial and regulatory-compliance impacts, each with explicit thresholds (for example, cost bands or discharge-permit deviation limits); (c) a defined risk-acceptance threshold that determines when a finding requires escalation rather than routine monitoring; and (d) designated owner and review frequency for each criterion. Formalizing these criteria would convert Tirta Selaras's currently

experience-based judgments into an auditable, comparable format, and would make the qualitative FMEA scoring easier to benchmark across future assessment cycles.

Sixth, to address the documentation gap identified, in which communication and consultation records remain responsive to issues rather than anticipatory of risks, management should move toward an integrated, proactive risk-documentation system. In practice, this could take the form of a centralized risk register that consolidates chemical stock reports, customer complaint reports, training records, and laboratory results into a single repository, cross-referenced against the risk identification, assessment and treatment stages of ISO 31000:2018. Populating the register prospectively, by logging anticipated risk triggers and early-warning indicators rather than only recording incidents after they occur, would allow Tirta Selaras to shift from reactive issue tracking toward anticipatory risk communication, supporting more timely consultation with stakeholders and regulators.

CONCLUSION

The main contribution of the study is the integration of the FMEA model, the PESTLE framework and ISO 31000:2018, which together produce a more detailed and adaptive risk-prioritization approach for Tirta Selaras. This aligns with the purpose stated in the abstract, to provide a comprehensive assessment of operational risk management within the context of Indonesia's circular water economy. Through this integrated analysis, the study has identified political, social and economic risks as the most critical failure modes that significantly influence operational performance.

The findings confirm that current operational risk management practices have not fully met the scope, context and criteria required by ISO 31000:2018. Key sources of risk include SOPs that are not consistently aligned with evolving policies, limited operator competence due to insufficient certification and refresher training, and increasing maintenance costs during operational disruptions. These issues indicate that Tirta Selaras's existing risk governance system requires adaptive improvements to ensure long-term operational sustainability. Through the combined application of PESTLE and FMEA, the study highlights the strategic importance of strengthening operational planning, especially in anticipating external regulatory, technological and socioeconomic changes.

In addition, continuous training and certification programs are needed to improve workforce capability, while the adoption of digital monitoring for predictive analytics can enhance real-time detection and response to operational failures. To support system resilience and ensure continuity in circular water operations, mitigation measures should include preventive maintenance, upgrading of wastewater treatment technologies, and development of risk-based financing plans to reduce exposure to cost volatility. Establishing a cross-functional risk coordination team will also help ensure effective communication and integrated decision-making across departments. Collectively, these strategies will strengthen Tirta Selaras's ability to manage complex operational risks and contribute to Indonesia's broader transition toward climate-resilient and resource-efficient circular water management.

Although the case study design limits statistical generalization, several elements of Tirta Selaras's risk profile are structural rather than firm-specific and could be transferred to other urban-industrial wastewater operators in Indonesia. Facilities that similarly combine SOP-based compliance with ISO 31000:2018; rely on experiential judgment in the absence of formalized risk criteria; and face evolving environmental-discharge regulation are likely to show a comparable pattern of political-social-economic risk, particularly where operator certification and workforce competence are similarly constrained (Trubetskaya et al., 2021). Adapting the integrated ISO 31000-PESTLE-FMEA

approach to another site would require recalibrating the PESTLE risk categories and the FMEA severity, occurrence and detection scales to that site's own regulatory, technological and organizational context. The underlying sequencing logic, context-setting through ISO 31000:2018, external scanning through PESTLE, and quantified prioritization through FMEA, is not specific to Tirta Selaras's operations and offers a transferable template for risk assessment across Indonesia's broader circular-water and urban-industrial wastewater sector (Kementerian PPN/Bappenas, 2025).

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