INTEGRATED RISK MANAGEMENT MODELS FOR ENHANCING RESILIENCE AND SUSTAINABILITY OF WASTEWATER INFRASTRUCTURE IN URBAN ENVIRONMENTS

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Abstract:
Urbanization, population growth and climate change are intensifying pressures on municipal wastewater treatment systems, while billions of people worldwide still lack access to safely managed sanitation and safe drinking water. This study develops an integrated risk governance model to support the planning and design of municipal wastewater treatment plants (WWTPs) within the framework of the United Nations 2030 Agenda for Sustainable Development. Building on a Delphi-based identification of thirty-seven discrete risks, classified into legal, financial, logistical, environmental, managerial and design-related categories, the research expands traditional risk assessment through two key innovations: (i) systematic mapping of risk categories to Sustainable Development Goals (SDGs 6, 11 and 13), and (ii) inclusion of institutional and policy contextualisation reflecting national and European Union regulatory frameworks. The analysis reveals that legal, managerial, financial and design-related risks exert the strongest influence on achieving targets for pollution reduction, integrated water resource management and urban infrastructure resilience. These findings highlight three strategic imperatives for policy makers and municipal authorities: aligning local planning with evolving EU and international standards, strengthening institutional capacity and inter-agency coordination, and embedding comprehensive risk assessment at the conceptual stage of WWTP projects.

Key words: *wastewater infrastructure, integrated risk management, SDGs, urban resilience*

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1. Introduction

Urbanization, population growth, and climate change are intensifying pressures on municipal wastewater treatment systems. Despite progress, ~3.5 billion people worldwide still lack access to safely managed sanitation services, and around 2.2 billion do not have reliably safe drinking water. Meanwhile, only about 11% of treated wastewater is reused globally, and a substantial fraction of wastewater remains untreated posing serious environmental and public health risks, especially in rapidly urbanizing, climate-vulnerable regions [1-2].

Against this backdrop, risk management frameworks are becoming indispensable in the early planning and design phases of wastewater treatment plants (WWTPs). In addition to classical identification and prioritization of risks (for which Delphi-based approaches remain useful), recent studies have expanded methodological toolkits to include Fault Tree Analysis, Bow-Tie diagrams, Bayesian Networks, and multi-criteria decision methods, allowing for more robust modeling across technical, operational, financial, regulatory, and climate-linked hazards [3-4].

Policy and regulatory landscapes are also evolving. For example, the EU's revised Urban Waste Water Treatment Directive (2024) [5] introduces stricter requirements for micro-pollutants, expanded urban coverage (agglomerations), and targets toward energy neutrality. Concurrently, standardization efforts like ISO 14091[6] and newly published Water Resilience Assessment Frameworks (2024) are helping utilities and planners systematically evaluate vulnerabilities and resilience in light of multiple stressors including climate change [5,7].

Furthermore, sustainable development goals (SDGs), especially SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), are being tied more closely with measurable indicators such as 6.3.1 / 6.3.2 (wastewater treatment and water quality). This alignment offers both normative and operational anchors for integrating risk governance with sustainability outcomes [8].

This paper introduces a comprehensive risk assessment model designed for the planning and design stages of municipal WWTPs. Building on prior research that used a Delphi-type framework to classify and evaluate 37 specific risks associated with WWTP planning and construction, the proposed approach emphasizes not only the categorization and prioritization of risks, but also risk mapping across domains (technical, operational, environmental, financial, regulatory) and explicit linkage to SDGs 6, 11, and 13 including their measurable indicators. Recommendations are provided for local governments, policy makers, and infrastructure practitioners to adopt holistic, cross-sector mitigation strategies that enhance resilience, align with international development agendas, promote circularity (reuse, energy, nutrients), and improve environmental and social outcomes over the long term.

2. Methodology

The initial development of this model was undertaken as part of a doctoral thesis [9] and serves as the foundation for the present study. The original model identified and classified 37 specific risks, divided into six main categories: legal, financial and economic, logistical, environmental, managerial, and design-related. The classification was derived through expert consensus using the Delphi method, enabling structured risk prioritization at early stages of the project.

In the present research, the model is conceptually expanded to support a more holistic, **integrated risk management framework** that accounts for risk interdependence, cross-sectoral planning requirements, and alignment with global sustainability priorities.

2.1 Risk Identification and Classification

The foundational stage of the model involved systematic identification and categorization of risks through literature review and expert evaluation. The Delphi method, known for its iterative and anonymous consensus-building process among subject-matter experts, was used to evaluate the significance of each risk and assign weighted scores [9]. The full set of risks is grouped into six categories:

- **Legal risks**, such as regulatory inconsistencies and contract disputes.
- **Financial risks**, including budget shortfalls and cash flow instability.
- **Logistical risks**, like poor inter-agency coordination or a lack of skilled designers.
- **Environmental risks**, such as inappropriate plant location.
- **Managerial risks**, including weak project governance.
- **Design-related risks**, such as incomplete technical data or inappropriate technology selection.

2.2 SDG Mapping Procedure

To evaluate the strategic relevance of these risks within a sustainability context, a qualitative mapping procedure was applied to identify linkages with the United Nations Sustainable Development Goals (SDGs), drawing on established SDG-alignment methodologies [10], with specific focus on:

- **SDG 6**: Clean Water and Sanitation (Targets 6.3, 6.4, 6.5),
- **SDG 11**: Sustainable Cities and Communities (Targets 11.5, 11.6),
- **SDG 13**: Climate Action (infrastructure resilience).

Each risk was assessed for its potential to either **hinder** or **advance** progress toward these targets using a three-level scale, strong, moderate, or no contribution, adapted from recognised sustainability-mapping frameworks [11].

2.3 Methodological framework for integrated risk management

To evolve the original diagnostic tool into a strategic planning and governance framework, one complementary analytical dimension was introduced:

- Institutional and policy contextualization considers governance structures, public-sector capacity, and institutional fragmentation as key factors influencing risk exposure and mitigation capability [12]. As part of this study, the risk-assessment model was complemented by an institutional and policy contextualization focused on the national governance framework of the Republic of Serbia. The analysis examined how legislative arrangements, administrative capacities and inter-institutional relationships shape both risk exposure and the effectiveness of mitigation strategies for municipal WWTPs.

3. **Results and Discussion**

3.1 SDG Mapping

The expanded risk–SDG mapping confirms the continued relevance of the original Delphi-based model for sustainability-oriented infrastructure planning. Table 1 presents the updated matrix showing the alignment of the six risk categories with SDGs 6, 11 and 13.

Table 1. Risk–SDG Mapping Matrix

Risk Category	SDG 6 (6.3, 6.4, 6.5)	SDG 11 (11.5, 11.6)	SDG 13 (Climate Action)
Legal	Strong	Moderate	Moderate
Financial and Economic	Strong	Strong	Moderate
Logistical	Moderate	Moderate	None
Environmental	Strong	Moderate	Strong
Managerial	Strong	Strong	Moderate
Design-related	Strong	Strong	Strong

The strongest overall alignment was observed with **SDG 6**, particularly Targets 6.3 and 6.5, which emphasize pollution reduction and integrated water resource management. Legal, environmental, and design-related risks directly affect these targets through mechanisms such as project delays, inadequate site selection, and fragmented technical data [13][10].

Substantial contributions were also identified with **SDG 11**, particularly through the managerial and financial categories. Risks such as under-budgeting, delayed decision-making, and inadequate stakeholder coordination were shown to endanger the development of inclusive and resilient wastewater infrastructure in urban contexts [11].

Although SDG 13 is less directly tied to wastewater infrastructure, environmental, financial and design-related risks affect the resilience of treatment systems under climate variability. For example, poorly located plants or outdated technologies can reduce adaptive capacity to increased precipitation or prolonged droughts [14].

3.2 Institutional and policy contextualization

The regulatory environment was reviewed with particular attention to Serbia's ongoing harmonisation with the EU Urban Waste Water Treatment Directive (UWWTD) and related EU water directives. The assessment highlighted that the dynamic process of EU approximation creates both opportunities and uncertainties: while it drives higher treatment standards and stimulates investment, it also introduces transitional compliance risks and potential delays in project permitting. Second, administrative capacity was evaluated at three levels: local, provincial, and the national. Findings indicate that while some municipality units possesses strong technical expertise, staffing and financial constraints at the provincial and national levels can slow approval procedures and complicate multi-year budgeting. Third, the analysis of inter-institutional coordination revealed areas of overlapping mandates and fragmented responsibilities between municipal utilities, provincial agencies and national regulators. Such fragmentation increases the likelihood of legal and managerial risks, including delayed procurement and ambiguous accountability in large WWTP projects.

Conclusion

This study demonstrates the importance of embedding a sustainability-oriented risk governance framework at the earliest stages of municipal wastewater treatment plant (WWTP) planning and design. Through the Delphi-based identification of thirty-seven discrete risks and their systematic mapping to the United Nations Sustainable Development Goals (SDGs 6, 11

and 13), the research advances beyond conventional risk registers toward an integrated model that links infrastructure planning with global sustainability imperatives.

The analysis highlights the strong influence of legal, managerial, financial and design-related risks on achieving key targets for pollution reduction, integrated water resource management and the resilience of urban infrastructure. Placing these insights within national and EU regulatory contexts—such as the revised Urban Waste Water Treatment Directive and ISO 14091—clarifies the steps needed to align local planning processes with international standards and climate adaptation objectives.

Three strategic priorities emerge for policy makers and municipal authorities: (i) harmonise local regulatory and planning frameworks with evolving EU and international water governance requirements to minimise compliance uncertainty; (ii) strengthen institutional capacity and inter-agency coordination to reduce governance fragmentation and enable effective risk mitigation; and (iii) incorporate comprehensive, forward-looking risk assessment into the conceptual and design phases of WWTP projects to ensure long-term viability and adaptive capacity.

The proposed model thus serves as a decision-support mechanism that guides municipalities and utilities toward wastewater infrastructure that is technically and economically sound, resilient to future uncertainties, and fully aligned with the objectives of the 2030 Agenda for Sustainable Development.

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