ДГКМ
ДРУШТВО НА ГРАДЕЖНИТЕ КОНСТРУКТОРИ НА МАКЕДОНИЈА

Партизански одреди 24,
П. Фах 560, 1000 Скопје
Северна Македонија

MASE
MACEDONIAN ASSOCIATION OF STRUCTURAL ENGINEERS

Partizanski odredi 24,
P. Box 560, 1000 Skopje
North Macedonia

MMT-11

mase@gf.ukim.edu.mk
http://mase.gf.ukim.edu.mk

DELPHI-BASED RISK ASSESSMENT MODEL FOR WASTEWATER TREATMENT: TOWARD SUSTAINABLE DEVELOPMENT

Jovana TOPALIĆ[1], Vladimir MUČENSKI [2] , Maja PETROVIĆ[3]

ABSTRACT

Sustainable wastewater infrastructure is essential for achieving multiple global development objectives, yet its planning is often challenged by complex and interrelated project risks. This study builds upon a previously developed integrated risk assessment model for municipal wastewater treatment plants, designed to identify and evaluate 37 specific risks across six categories: legal, financial, logistical, environmental, managerial, and design-related. The aim of this paper is to assess how the model contributes to the implementation of key Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water). Using a structured SDG mapping approach, each risk was analyzed for its potential influence on relevant targets. The results show strong alignment, especially for environmental and design-related risks, highlighting the model's relevance in reducing uncertainty, supporting pollution control, and enhancing the resilience of water infrastructure in line with global sustainability priorities.

Keywords: risk, model, Delphi method, wastewater treatment, SDG mapping

[1] Research Associate, University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia
[2] Full Professor, University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia
[3] Associate Professor, University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

Corresponding author: Jovana TOPALIĆ, e-mail: jovanatopalic90@uns.ac.rs

1. INTRODUCTION

Every community generates liquid and solid waste as well as air emissions as a consequence of daily human activities and industrial processes. Liquid waste (wastewater) is essentially the water supply of the community after it has been used for various domestic, commercial, or industrial purposes [1]. Wherever there is human settlement, wastewater is inevitably produced. In this way, wastewater is a permanent and inseparable by-product of human habitation and development [2].

Historically, wastewater engineering has evolved in response to growing population densities and urbanization. As cities expanded, the necessity for engineered wastewater management systems became increasingly apparent, particularly in metropolitan areas [3]. Today, multidisciplinary teams of engineers and environmental professionals are engaged in the planning, design, operation, and optimization of wastewater treatment plants. Due to the scarcity of resources, population growth, and changes in freshwater consumption in daily activities, wastewater treatment is a global concern to ensure sustainable development [2]. Effective treatment of domestic and industrial wastewater, especially when integrated into sewer systems, plays a crucial role in protecting public health and enhancing environmental quality [3]. The uncontrolled release of untreated wastewater into natural water bodies poses serious threats to ecosystems, biodiversity, and human well-being [4]. One of the major challenges in wastewater management is the complex and heterogeneous composition of pollutants, which necessitates the use of advanced, adaptive, and energy-efficient treatment technologies to meet evolving water quality standards [5].

In this context, risk assessment and governance mechanisms in wastewater treatment are increasingly emphasized within the framework of the 2030 Agenda for Sustainable Development. This global agenda articulates a shared vision for peace, prosperity, and environmental sustainability, operationalized through 17 interconnected Sustainable Development Goals (SDGs). Among these, Goal 6 (Clean Water and Sanitation) and Goal 11 (Sustainable Cities and Communities) explicitly underscore the imperative of efficient water resource management, wastewater treatment, and pollution control. The SDGs recognize that efforts to eliminate poverty and ensure human well-being must be pursued in tandem with environmental protection, climate change mitigation, and the preservation of natural resources.

In alignment with SDG 6 which aims to ensure the availability and sustainable management of water and sanitation for all by 2030, recent studies indicate that approximately 3.5 billion people lack access to safely managed sanitation, while 2.2 billion remain without safely managed drinking water services [6]. Specific targets such as 6.3 (reducing water pollution), 6.4 (increasing water-use efficiency), and 6.5 (implementing integrated water resources management) directly reinforce the importance of advancing wastewater infrastructure and safe water reuse. These targets highlight the critical role of wastewater treatment as both a public health necessity and an environmental imperative.

Recent research further emphasizes a global shift toward circular economy principles in wastewater management, advocating for the recovery of valuable resources such as biogas, nutrients, and reclaimed water. In parallel, the integration of nature-based solutions such as constructed wetlands and vegetated infiltration systems has demonstrated substantial potential to reduce environmental burdens, improve cost-efficiency, and enhance resilience to climate induced water stress [7] [8]. Constructed wetlands offer multifunctional benefits including pollutant removal, biodiversity enhancement, and landscape restoration, often with favorable cost–benefit outcomes in decentralized or peri-urban contexts [9].

In support of SDG 11, which aims to make cities and human settlements inclusive, safe, resilient, and sustainable, wastewater treatment infrastructure plays an important role in addressing the interconnected challenges of urbanization, environmental degradation, and public health disparities. Rapid population growth, the proliferation of informal settlements, and aging infrastructure especially in low- and middle-income countries have increased the risk of untreated wastewater exposure, particularly in underserved communities [10]. These vulnerabilities disproportionately affect marginalized populations lacking access to centralized sewer systems and basic sanitation.

Moreover, other SDGs complement and reinforce the imperative for sustainable wastewater management. SDG 12 (Responsible Consumption and Production), particularly targets 12.4 and 12.5, calls for the environmentally sound management of chemicals and all wastes throughout their life cycle and promotes reduction, recycling, and reuse, key principles integrated in modern wastewater reuse and

sludge valorization practices. SDG 13 (Climate Action), though indirectly connected, encourages climate-resilient infrastructure development, including adaptive water and sanitation systems that respond to changing precipitation patterns, droughts, and extreme weather events. In addition, SDG 14 (Life Below Water), especially target 14.1, emphasizes the need to prevent marine pollution from land-based sources, including untreated or poorly treated wastewater and nutrient runoff. These interlinked goals collectively position wastewater treatment as a cross-sectoral driver of environmental, social, and economic sustainability.

In this context, the development of structured and systematic approaches to risk management in wastewater infrastructure becomes increasingly important, particularly during the early phases of project development.

This study introduces a comprehensive risk assessment model specifically designed for application during the planning and design of municipal wastewater treatment plants (WWTPs). It builds upon that foundation by empirically validating the model's central hypothesis namely, that structured risk assessment during the early stages of WWTP planning can contribute meaningfully to the achievement of the SDGs. The main objective of this paper was to determine the extent to which the structured identification and evaluation of project risks contributes, directly or indirectly, to the implementation of the selected SDGs.

2. METHODOLOGY

2.1. Analytical Basis

The initial development of model was undertaken as part of a doctoral research project [11] and serves as the foundation for the present study. The model identifies and classifies 37 risks relevant to the planning and design phases of WWTPs. These risks are organized into six categories: Legal, Financial and economic, Logistical, Environmental, Managerial, Design-related.

Each risk was previously assigned a relative weight using expert consensus, allowing the model to serve as a structured tool for early-stage project risk prioritization. In the present study, this established model forms the analytical starting point for evaluating how risk assessment practices in WWTP planning relate to the achievement of selected SDGs.

The list of all identified risks for the risk assessment model with specified groups is shown in Table 1 [12]:

Table 1. Identified risks by category

Category	Risk ID	Risk Description
Legal	1.1	Frequent changes and modifications of laws and by-laws
Legal	1.2	Incompatibility of foreign investor regulations with local regulations
Legal	1.3	Ignorance of actual laws and by-laws
Legal	1.4	Delays in resolving contract disputes in the design phase
Legal	1.5	Untimely issuance of design permits from public agencies
Legal	1.6	Inadequate terms for connecting WWTP to existing infrastructure
Legal	1.7	Poor estimation of public procurement impacts on project lifecycle

Legal	1.8	Inadequate criteria for project dealer selection
Legal	1.8a	Inadequate criteria for project designer selection
Legal	1.8b	Inadequate criteria for contractor selection
Legal	1.9	Poor definition of optimal project contracting approach
Financial	2.1	Insufficient budget for construction of modern WWTPs
Financial	2.2	Uncontrolled cash flow during project phases
Financial	2.3	Inflation and unexpected price fluctuations
Financial	2.4	Incomplete or incorrect estimation of financial benefits
Financial	2.5	Incomplete or incorrect estimation of economic benefits
Logistical	3.1	Poor communication with public companies
Logistical	3.2	Lack of qualified WWTP designers
Environmental	4.1	Inadequate plant location from an environmental standpoint
Environmental	4.2	Inadequate plant location with respect to populated areas
Managerial	5.1	Lack of qualified staff in public companies
Managerial	5.2	Poor communication among project participants
Managerial	5.3	Unprofessional behavior of investor in providing design information
Managerial	5.4	Slow decision-making by the investor delaying design
Managerial	5.5	Inadequate team structure for project implementation
Managerial	5.6	Lack of a designated project leader by the investor
Managerial	5.7	Unrealistic deadline planning by the investor
Design	6.1	Lack of data on wastewater quantity
Design	6.2	Lack of data on the recipient (quality, flow, level)
Design	6.3	Inadequate demographic assessment
Design	6.4	Insufficient data on existing sewer systems

Design	6.5	Uncoordinated work among different designers
Design	6.6	Lack of knowledge of desired equipment by designer
Design	6.7	Large distances between municipalities to be connected to WWTP
Design	6.8	Frequent changes in WWTP technology selection

2.2. SDG Mapping Approach

The central methodological approach in this study is a qualitative SDG mapping of the identified risks. The following goals and their corresponding targets were selected based on their recognized relevance to wastewater infrastructure, environmental protection, and human health:

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 12: Responsible Consumption and Production (Targets 12.4, 12.5)

SDG 13: Climate Action (relevant to climate-resilient infrastructure)

SDG 14: Life Below Water (Target 14.1)

2.3. Mapping Procedure

The mapping was carried out in three steps:

Thematic Alignment

Each of the 37 risks was reviewed in relation to the content and indicators of the selected SDG targets. The aim was to identify conceptual or operational linkages between specific risks and sustainability goals, e.g., risks involving pollution, water reuse, emissions, or system failure were examined considering SDG 6.3, 12.4, or 14.1.

Contribution Classification

For risks with identified relevance to one or more SDGs, a qualitative assessment was performed to determine the level of contribution, based on the perceived potential of each risk (if unmitigated) to obstruct or if addressed, to support the fulfillment of the SDG target. A simple three-level scale was used:

Strong: Direct and clear contribution to the target's achievement

Moderate: Indirect or enabling influence on the target

None: No significant contribution or impact observed

Synthesis and Interpretation

The final step involved synthesizing the individual risk–SDG relationships into a risk–SDG mapping matrix, allowing for an aggregated analysis of how different risk categories intersect with sustainability priorities. This facilitated identification of SDG targets that are most strongly supported by comprehensive risk management in WWTPs, as well as those less represented, pointing to areas for potential model improvement.

2.4. Limitations

It is acknowledged that the mapping was based on authorial analysis and thematic interpretation, without empirical field validation or stakeholder consultation in this phase. While the approach provides valuable strategic insight into the alignment between risk governance and sustainable development,

future studies may benefit from triangulation through expert panels, stakeholder feedback, or case-based quantitative assessments.

3. RESULTS AND DISCUSSION

The results of the SDG mapping reveal that the integrated risk assessment model for wastewater WWTPs exhibits strong alignment with key sustainability targets, particularly within SDG 6, SDG 11, SDG 12, SDG 13 and SDG 14. These findings suggest that risk governance in the early planning and design phases of WWTPs can significantly support national and global efforts toward sustainable development.

3.1. Risk category contributions to SDGs

The mapping results, summarized in Table 2, show that each of the six identified risk categories, legal, financial and economic, logistical, environmental, managerial, and design-related contributes to at least three of the five selected SDGs. Environmental and design-related risks show the strongest and most consistent alignment across all five SDGs. These categories include risks associated with ecosystem disturbance, proximity to populated areas, insufficient baseline data, uncoordinated design processes, and technology selection. Such risks are directly relevant to Targets 6.3 and 6.5 (wastewater treatment and integrated water resources management), 11.5 (reducing disaster-related risks), 12.4 (chemical waste management), and 14.1 (reducing marine pollution).

Table 2. Risk–SDG mapping matrix

Risk Category	SDG 6 (6.3, 6.4, 6.5)	SDG 11 (11.5, 11.6)	SDG 12 (12.4, 12.5)	SDG 13 (Climate Action)	SDG 14 (14.1)
Legal	Strong	Moderate	Moderate	Moderate	Moderate
Financial and Economic	Strong	Strong	Strong	Moderate	None
Logistical	Moderate	Moderate	Moderate	None	None
Environmental	Strong	Moderate	Strong	Strong	Strong
Managerial	Strong	Strong	Moderate	Moderate	Moderate
Design-related	Strong	Strong	Strong	Strong	Moderate

3.2. SDG specific insights

The strongest overall alignment was observed with this goal. All risk categories contribute to the three selected targets (6.3, 6.4, 6.5), underlining the relevance of comprehensive risk assessment in achieving pollution reduction, water efficiency, and integrated water management.

Strong alignment was observed with Targets 11.5 and 11.6, particularly through financial, managerial, and design risks. These risks affect the development of inclusive and resilient sanitation services in growing urban areas.

SDG 12 is supported by risk categories that influence lifecycle planning, waste handling, and reuse potential. Design-related and environmental risks were most relevant for Targets 12.4 and 12.5.

While this SDG 13 is not directly targeted in the model, indirect contributions were identified through risks that influence infrastructure adaptability and environmental robustness.

Risks associated with effluent quality, pollutant emissions, and ecosystem sensitivity were mapped to Target 14.1. Design and environmental risks in particular influence nutrient runoff and the potential degradation of aquatic ecosystems downstream.

3.3. Strategic implications

The analysis confirms that structured risk management tools designed for engineering projects can provide significant value beyond technical decision-making. When risk categories are evaluated through a sustainability lens, they offer clear pathways for aligning infrastructure projects with international development priorities. The strong overlap between model categories and SDG targets affirms the importance of embedding risk assessment into early-stage infrastructure planning.

At the same time, the results highlight areas for future model improvement. Risks related to climate resilience, digital infrastructure, nature-based solutions, and social acceptance were not covered in the original model but are becoming increasingly relevant. Expanding the model to include such dimensions may further enhance its applicability to long-term sustainability and SDG alignment.

4. CONCLUSION

This study demonstrates that the integrated risk assessment model developed for WWTP planning and design aligns closely with several critical Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water). By systematically evaluating 37 identified risks across six core categories, the model reveals its utility not only as a technical planning instrument but also as a strategic framework for advancing sustainability objectives.

The SDG mapping confirmed that structured risk assessment contributes to reducing operational uncertainties, enhancing environmental protection, and promoting more resilient and inclusive urban infrastructure. Legal, design-related, and environmental risks demonstrated strong thematic alignment with multiple SDG targets, underscoring the critical importance of integrating risk governance into early-stage infrastructure planning.

The model exhibits considerable potential for further refinement. By integrating complementary methodologies, such as SWOT and PESTEL analyses, as well as emerging tools including machine learning and big data analytics, the model could evolve into a more dynamic and adaptable decision-support instrument. Additionally, expanding the model's scope to include emerging risk categories, such as climate resilience, cybersecurity in digital infrastructure, and community acceptance would enhance its relevance in addressing the evolving challenges of sustainable wastewater management.

ACKNOWLEDGEMENT

This research was supported by the City Administration for Environmental Protection of the City of Novi Sad (Contract No. Vl-501 -2/2024-14B-8), Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contracts No. 451-03-136/2025-03/200156 and 451-03-137/2025-03/200156), the Faculty of Technical Sciences, University of Novi Sad (Project No. 01-50/295).

5. REFERENCES

[1] Tchobanoglous G., Burton, F. L., Stensel, H. D. (2003). Wastewater Engineering, Treatment and Reuse, 4th ed, New York: Mc-Graw-Hill Education

[2] L'Agenda 2030 en France “ODD6 - Garantir l’accès de tous à l’eau et à l’assainissement et assurer une gestion durable des ressources en eau,” France, 2024.

[3] Obaideen K., Shehata N., Taha Sayed E., Ali Abdelkareem M., S.Mahmoud M., Olabi A.G. (2022). The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline,” *Energy Nexus,* vol. 7

[4] Alwadani N., Fatehi P. (2018). “Synthetic and lignin-based surfactants: challenges and opportunities,” *Carbon Resour. Convers.*, vol. 1, pp. 126-138

[5] Kakavandi B., Ahmadi M. (2019). “Efficient treatment of saline recalcitrant petrochemical wastewater using heterogeneous UV-assisted sono-Fenton process,” *Ultrason. Sonochem.,* vol. 56, pp. 25-36

[6] UNICEF and WHO, “Progress on household drinking water, sanitation and hygene 2000-2022: Special focus on inequalities.,” WHO and UNICEF Joint Monitoring Programme (JMP).

[7] Karakulski K, Leszczyński, S., Luczak, J. (2022). “Circular economy in wastewater treatment: Energy and resource recovery perspectives,” *Renewable and Sustainable Energy Reviews*

[8] Lv, T., Cheng, W., Lu, W., Chen, X. (2023). “Constructed wetlands as nature-based solutions for sustainable wastewater management: Integration with circular economy and climate resilience,” *Environmental Research,* vol. 225

[9] Vymazal J, (2022). “Constructed wetlands for wastewater treatment: Five decades of experience,” *Environmental Science and Technology ,* vol. 11

[10] UN-Habitat (2020). “World cities Report 2020: The value of Sustainable Urbanization,” United Nations Human Senttlements Programme

[11] J. T. Marković (2022). “Preliminary risk assessment model of wastewater treatment plant construction”. Serbia

[12] Topalić Marković J., Mučenski V., Savić D., Velkovski T., Peško I., Tomaš L. (2020). “Risk Assessment Model for Planning and Design Processes of Watewater Treatment Plants,” *Periodica Polytechnica Civil Engineering*