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ASSESSMENT AND MANAGEMENT OF HEALTH AND ENVIRONMENTAL RISKS OF INFRASTRUCTURES AND COMPLEX SYSTEMS OF THE INTEGRATED WATER SERVICE

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ABSTRACT

The use of risk assessment methodology in urban sanitation infrastructure systems is an important tool for the accurate anticipation and mitigation of risks. The general objective of this work is to assess the risks and vulnerabilities of these system components, analyze the efficiency of nutrient removal through a microalgae-based treatment system and evaluate the reuse risk of urban runoff water. To assess the vulnerability risk of water treatment system's internodes, the Analytic Hierarchy Process (AHP) methodology proposed by Marleni et al. (2022) was adapted. The risk assessment methodology for effluent reuse employed the Failure Modes and Effects Analysis (FMEA) method and a risk matrix stipulated by current legislation and international guidelines. The nutrient removal efficiency through microalgae was assessed using statistical methods and compared with the parameters established in current European and Italian effluent reuse legislation. The results of the vulnerability risk analysis applied in two Italian case studies demonstrate the methodology's applicability, yielding a measurable and easily interpretable index. In cases where the resulting risk is classified as vulnerable, a more detailed risk analysis must be conducted using a risk matrix to better identify hazards and implement mitigation measures. The urban runoff water risk analysis, from a study in Brazil, indicated high-risk values for parameters such as arsenic, surfactants, cadmium, sodium, barium, and thermotolerant coliforms, among others. To enable municipal-level reuse, it is essential to implement treatment technologies capable of removing these pollutants, thereby safeguarding environmental and public health. The Italian case study involving microalgae-based effluent treatment was conducted in three distinct phases. Across all phases, low phosphate and problematic ammonia removal efficiencies were observed, alongside pH fluctuations between phases, which ultimately compromised the process performance for reuse. Finally, the risk assessment applied to the two Brazilian wastewater treatment plants (WWTPs) was conducted based on Paraná State Council of Water Resources (CERH/PR) Legislation No. 122/2023. In the context of future interest in implementing treated water reuse practices, the Brazilian WWTPs under study, originally designed to meet the requirements for discharge into surface water bodies as per national legislation, will require a project revision to ensure compliance with the reuse parameters set forth in the specific reuse legislation. Regarding the Italian study, high risks were identified for total suspended solids (TSS), biochemical oxygen demand (BOD), and Escherichia coli necessitating the adoption of specific mitigation and control measures for these contaminants.

Keywords: climate change, risk assessment methodology, sanitation infrastructure, water reuse.

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GENERAL OBJECTIVE

To evaluate the risks and vulnerabilities of the urban sanitation infrastructure systems components, the efficiency of effluent treatment systems geared toward water reuse, and the associated risks of utilizing urban runoff water. This is undertaken with the overarching goal of ensuring the quality and quantity of water resources, thereby safeguarding public and ecosystem health, and promoting the adaptation of these systems to climate change.

RESEARCH PROBLEM, MOTIVATION AND JUSTIFICATION

Global climate change in recent years has significantly impacted the world, leading to a range of severe consequences, including rising temperatures and quantitative and qualitative water and food insecurity, among others. This scenario directly affects populations, ecosystems and urban infrastructures, consequently rendering them highly vulnerable to climatic shifts (IPCC, 2023; Biswas et al., 2023).

Climate change is particularly evident in urban centers, where compromises essential infrastructure systems, such as sanitation and energy. These systems frequently experience damage or destruction, leading to financial losses and service interruptions. These failures, in turn, produce adverse effects on the environment and public health (IPCC, 2023; Li et al., 2023). The occurrence of these extreme events has increased substantially Since 1950, resulting in mounting impacts on human health, ecosystems, and essential life-sustaining infrastructure (IPCC, 2023). Examples of such events include floods, droughts, landslides, earthquakes, and volcanic eruptions (Civil Protection, 2019; IPCC, 2023).

Hughes et al. (2018), for instance, detail cases of disruptions and damage to water supply and sewage treatment services following extreme events, primarily intense rainfall episodes. Crucially, they observed that sewage contamination can result from the combined overflow of stormwater and sewage, such as in cases where as Earthquake has damage the drainage system, subsequently releasing contaminated water.

Furthermore, and additional impact of extreme events, such as na earthquake, on sanitation systems, specifically water supply, is the interference with the hydrodinamic balance of the affected region (Checcucci et al., 2017).

[1] Note: The references cited in this chapter will be listed in the References section of Chapter 1.

Globally, approximately 3.3 to 3.6 billion people inhabit areas highly vulnerable to climate change (IPCC, 2023). In Europe, approximately 30% of the population resides in regions facing permanent water stress, while 70% experience water stress during the summer months (European Environment Agency, 2023).

This critical panorama underscores the urgent necessity of investigating effective alternatives to ensure a sustained availability of water resources, both in quantity and quality, thereby building resilience against scenarios of environmental and climatic vulnerability.

In this context, the risk-based methodology emerges as a valuable ally for sanitation initiatives, applicable to both water supply systems and wastewater treatment systems designed for reuse applications. The implementation of this methodology is well-established and integrated in Europe and Italy, confirming its relevance and legal necessity as an instrument to safeguard public health and environmental safety.

In contrast, the approach to risk assessment in water supply and wastewater reuse systems remains nascent in Brazil. While the federal government acknowledges the importance of this topic by merely mentioning the need for reuse and water conservation, it has not yet defined specific quality parameters for water reuse. Consequently, this regulatory task has been delegated to the states, wich have independently established their own quality standards for specific reuse classes.

At the European level, Directive 2000/60/EC was published on October 23, 2000, which aims to minimize the risks of water pollution. Another relevant regulation is Directive 91/271/EEC, currently undergoing revision, which seeks to protect the environment against discharges of urban wastewater.

Directive 2020/2184/EU, concerning the quality of water intended for human consumption, seeks to protect public health and enhance water access through risk-based prevention and control strategies, aligning with the principles of Water Safety Plans (WSP). Furthermore, Regulation (EU) 2020/741, enacted by the European Parliament and the Council on May 25, 2020, stipulates the minimum requirements for the reuse of treated urban wastewater.

Specifically within the Italian context, Legislative Decree No. 18, of February 23, 2023, mandates the adoption of a risk-based approach to ensure safety in water distribution, particularly concerning the quality of water intended for human consumption.

Complementing this legislation, various technical documents provide crucial support for risk assessment in sanitation infrastructures. These notably include: World Health Organization (WHO) Water Safety Plan Manual, which establishes the guiding principles and steps for ensuring water quality from source to consumer via a preventive risk management approach; the Italian Guidelines for the Implementation of the Water Safety Plan, developed by National Institute of Health – Istituto Superiore di Sanità – ISS, which adapt WHO principles to the domestic Italian regulatory framework; and the Technical Guidance Document (TGD) on Risk Assessment – Part 2, which supports European legislation in assessing chemical substance risks to human health and environment, thereby serving as a key reference for regulatory and environmental management practices.

One of the systems that have been extensively studied and have been identified as contributors to climate change are Wastewater Treatment Plants (WWTP). Although indispensable for ensuring environmental quality and public health, these systems are known sources of greenhouse gas (GHG) emissions, particularly during the biological treatment stage. the primary gases generated include carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), all of which are products of the microbiological reactions involved in effluent treatment (Ranieri et al., 2024).

Complementarily, the emergence of novel pollutants, such as pharmaceuticals and heavy metals, has spurred significant research aimed at optimizing treatment processes. This research seeks alternatives that mitigate environmental impacts, minimize gas emissions, and thus promote greater sustainability within the sanitation sector.

To mitigate the aforementioned challenges, the Utilization of microalgae for wastewater treatment has been extensively investigated in recent years. This interest stems primarily from its notable advantages, which include low energy demand, the ease of microalgae cultivation across diverse environmental conditions, and, crucially, its capacity to transform effluent, nutrients into high-value-added compounds (Abdelfattah et al., 2023).

Specifically, the application of microalgae for wastewater treatment offers several benefits, such as the efficient fixation of carbon dioxide (CO_2), a low environmental impact, the Utilization of solar energy for growth, and the effective removal of various pollutants, including nitrogen (N), phosphorus (P), heavy metals (HM), pharmaceutical compounds, and pesticides (Li et al., 2022; Kumar & Singh, 2021; Das et al., 2021).

Given the versatility of microalgae-based effluent treatments, their investigation is deemed highly relevant, as they align with the principles of the circular economy. This direct contribution supports the European Green Deal program and its objective of achieving the zero pollution target.

This necessity is further emphasize by the European Environment Agency document, "Beyond Water Quality – Wastewater Treatment in a Circular Economy", published by the European

Environment Agency (EEA – No. 5/2022). The document highlight that, within the framework of the eighth environmental action program, it is essential to enhance the recognition of wastewater's role. This recognition is essential to promote their sustainable management and effectively integrate them into the principles of the circular economy.

The present work is structured into individual chapters, each typically comprising a preamble, general and specific objectives, development (literature review), methodology, results and discussion, conclusion and/or recommendations, and references.

The appendices include a list of conference participation and published works, as well as the list of mandatory courses completed during the doctoral period.

INNOVATION PROPOSED BY RESEARCH

The risk-based approach, when applied to sanitation infrastructure, is considered particularly relevant because it enhances these systems' safety, efficiency, and resilience against climate change and increasingly frequent and intense extreme events.

The research proposed herein adopts the risk concept to systematically evaluate, identify, and mitigate potential threats across the entire water supply chain and the wastewater treatment system designated for reuse. This methodology fosters the engagement of diverse stakeholders, including government entities, the population, researchers, sanitation management bodies, and end-users of reused water, promoting a holistic view that integrates crucial technical, social, and environmental aspects.

Ultimately, sanitation infrastructures predicated on this concept are poised to become more resilient, enabling them to absorb and address disturbances, reduce uncertainty and unpredictability, and subsequently contribute effectively to water security (Collier et al., 2013).

CHAPTER 1 - CLIMATE CHANGE AND ITS IMPACTS ON URBAN WATER SUPPLY INFRASTRUCTURE

PREAMBLE

The consequences of climate change have increasingly impacted urban infrastructures, especially those of potable water supply systems. Such consequences directly compromise the basic services offered to the population, potentially leading to interruptions in water supply for hours and days. Given this scenario, it becomes essential to adopt vulnerability assessment methodologies that allow for measuring the quantification of risk, avoiding subjective estimates. This approach helps sanitation managers structure the risk matrix of the Water Safety Plan (WSP), identifying hazardous events that can affect these pipelines and defining preventive measures to avoid system shutdowns. In this context, the Analytic Hierarchy Process (AHP) methodology has been extensively studied in environmental themes related to water supply systems. A methodological proposal presented by Marleni et al. (2022) was adapted for vulnerability assessment within the scope of WSP and subsequently applied in case studies in Italy.

This methodological adaptation results in an important proposal for sanitation managers, as it helps to anticipate risks that may affect the internal components of the treatment system, avoiding problems of interruption in the treatment and distribution system and basic services for the population.

2. GENERAL OBJECTIVE

To study a methodology for assessing the vulnerability of pipelines that interconnect the various operational units within potable water treatment systems, considering the influence of extreme climate events observed in Italy.

2.1 SPECIFIC OBJECTIVE

To adapt a methodology for vulnerability analysis of pipelines (referred to as internal components) in water supply systems, aiming to enhance accuracy in risk identification and optimize mitigation strategies for the development of a Water Safety Plan (WSP).

3. STUDY DEVELOPMENT

3.1 BRIEF OVERVIEW OF CLIMATE CHANGE

Climate change can be defined as alterations in temperatures and climate patterns, identifiable through statistical testing. Such changes involve variations in the mean and/or variability of climatic properties and persist over extended periods (UN, n.d.; IPCC, 2023).

Data recorded since the 19th century indicate that global surface temperatures have reached unprecedented levels recently (Mokhov, 2022). Between 2011 and 2020, greenhouse gas (GHG) emissions resulting from human activities caused a global temperature increase of 1.1°C, a value higher than that recorded between 1850 and 1900 (IPCC, 2023).

The recorded temperature increase of 1.1°C may seem numerically insignificant; however, in practice, it has triggered tangible effects such as rising global temperatures, sea level rise, more frequent and severe storms, abrupt changes in precipitation patterns, flooding, and prolonged droughts—all of which have been increasingly observed (Rawat et al., 2024; Ebi & Hess, 2020).

The outcome of these effects directly impacts society and the environment and leads to Ebi & Hess (2020); IPCC (2023); Walinski et al., (2023):

- ✓ Food insecurity;
- ✓ Migration;
- ✓ Risk of death and injury caused by extreme events (e.g., heatwaves, storms, and floods);
- ✓ Precarious infrastructure not equipped to meet population needs;
- ✓ Infectious diseases and mental health impacts (e.g., foodborne and waterborne illnesses; vector-borne diseases; anxiety; post-traumatic stress);
- ✓ Water insecurity;
- ✓ Direct risk from the consequences of climate change for the most vulnerable populations.

The impacts of climate change on the issue of water insecurity were highlighted by the Intergovernmental Panel on Climate Change (IPCC, 2023), which reported that approximately half of the world's population has already experienced severe water scarcity during at least part of the year due to a combination of climatic and non-climatic factors.

The water scarcity scenario is also evident in several European countries currently facing severe water stress. According to the European Environment Agency, water scarcity affected 34% of the European Union's territory during at least one season in 2022. In Southern Europe,

approximately 30% of the population is already experiencing water stress-related issues (Agency, 2025).
Climate change has increased the frequency and intensity of extreme weather events such as floods, droughts, landslides, earthquakes, and volcanic eruptions (IPCC, 2023), and the resulting impacts have affected urban infrastructure systems—including water and wastewater treatment facilities, as well as energy networks.
Understanding extreme climate-driven events-including their variations and intensities—is critical for assessing their impacts and formulating effective adaptation strategies (ISPRA, n.d).
The overview presented above underscores the growing importance and urgency of exploring alternatives to ensure the availability of water in sufficient quantity and quality to support the well-being of both the population and the environment. Furthermore, it is essential to guarantee that water supply systems are adequately protected against scenarios of environmental and climate vulnerability.

3.2 CLIMATE CHANGE AND ITS CONSEQUENCES ON URBAN INFRASTRUCTURE

Extreme climate events of high intensity and prolonged duration have the potential to cause damage and disruptions to active urban infrastructure, which may last for hours or even days (OECD, 2024). These events are driven by a combination of multiple factors and/or hazards that contribute to increased social and/or environmental risk (IPCC, 2023). Under the pressure of such events, the various components of a water supply system, including intake, treatment, storage, distribution, and pipelines—previously regarded as secure—become increasingly vulnerable. This fragility heightens infrastructure exposure, promoting both chemical and biological contamination of water, thereby compromising its use for human consumption, food production, environmental preservation, and agriculture. Moreover, it increases the risk of waterborne disease transmission (Europe, 2011).
Cities' urban infrastructure needs to focus specifically on major adjustments to cope with and adapt to new patterns of disruption (Andersson et al., 2022).
The following are some examples of urban infrastructures affected by extreme events and which consequently suffered service interruptions:

a. In 2005, Hurricane Katrina hit New Orleans, causing destruction and affecting the energy, water, sanitation, and transportation infrastructure (Huck & Monstadt, 2019);

b. In 2017, two earthquakes hit Puerto Rico, affecting power distribution, since the distribution network was old and could not withstand the impacts (Andersson et al., 2022);

c. In September 2018, a combination of heavy rains and earthquakes caused landslides in northern Japan, triggering a cascading effect on its infrastructure (Andersson et al., 2022);
d. In 2020, in the region of Australia, drought and wildfire events impacted up to 95% of the state of New South Wales, and 85% of Sydney's water supply depended on rainfall during that period (Wang et al., 2022);
e. On July 17, 2021, the Chinese city of Zhengzhou was hit by heavy rains, affecting around 14.5 million people. Four days after this event, six (6) of the nine (9) water treatment plants were interrupted, compromising the water supply to 1864 homes [...] (Wang et al., 2022);
f. In 2024, in the state of Rio Grande do Sul (Brazil), extreme flooding contaminated multiple water sources, including those in rural areas—totaling 4,570 contaminated water sources, which left families without access to potable water (SDR, 2024);
g. In 2024, in the Valencia region (Spain), Storm Dana caused casualties and disrupted the potable water treatment services in the area (Cebrian, 2024).

Reversing the previously mentioned examples is virtually impossible. However, adapting to this new climatic phase has become urgent, and such adaptation must occur through the strengthening of the concept of resilience (Saneamento, 2025).

Resilience was addressed as a "driver of urban policy" (Collier et al., 2013), i.e., this type of approach requires integrated and multidisciplinary planning that involves stakeholders in the planning process.

McGill (2020), presents objectives and indicators for a city to become resilient to climate change. Some examples related to the theme of this chapter will be described in the following section.

- ✓ Health and well-being: minimal human vulnerability;
- ✓ Society and economy: social stability and security;
- ✓ Infrastructure and ecosystems: continuity of critical services.

The previously mentioned scenarios highlight the urgent need for cities to adapt to the consequences of climate change. Essential areas such as health, the economy, infrastructure, and ecosystems are being continuously affected, rendering cities and populations increasingly vulnerable.

3.3 VULNERABILITY OF WATER SUPPLY SYSTEMS TO EXTREME EVENTS

The potable water distribution system is subject to both direct and indirect damage to its pipelines, considered as an essential infrastructure for the population, particularly during extreme weather events, which renders it vulnerable under such conditions (Fan et al., 2023). Direct impacts on the water distribution system (WDS), within the context of climate change and extreme events, are easily identifiable and include supply interruptions, water contamination, and physical damage to infrastructure, among others. However, indirect impacts—such as those on public health, environmental degradation, economic and social disruptions, and population migration—tend to manifest over time and may not be immediately recognized as consequences of a specific extreme event (Khan et al., 2015; Dias & Matos, 2023).

Given the vulnerability of potable water supply infrastructure to extreme events, in November 2005, the European Commission adopted the so-called Green Paper addressing the European Programme for Critical Infrastructure Protection (EPCIP). The objective of this program is to enhance the protection of critical infrastructures within the European Union (EU) (European Comission, 2006).

Based on the EPCIP, urban potable water supply infrastructure can be considered critical, as any disruption or destruction of this system may lead to serious consequences for the population's health, safety, and economic well-being, thereby negatively impacting their quality of life (European Comission, 2010).

Based on the above-discussed scenarios, implementing a vulnerability assessment method can help prevent such scenarios, minimizing damage to the water supply and distribution network (Marleni et al., 2022).

3.3.1 Methodologies Applied to the Analysis of Vulnerabilities in Drinking Water Supply Infrastructures

The analysis of vulnerabilities in risk management of potable water supply infrastructure plays a key role in safeguarding these systems against potential threats (Borzì, 2023).

Over the years, several studies and methodologies have been developed, employing diverse approaches to better understand the risks and vulnerabilities inherent to this type of infrastructure.

Borzì (2023) introduced a methodology grounded in multiple indicators, wherein eight indicators were classified and organized into four distinct categories: soil characteristics, service inefficiencies for users due to infrastructure failures, pipeline route features, and physical characteristics of the aqueduct (Figure 1). Given the reliance on multiple indicators, processes of normalization and aggregation are essential to ensure data consistency and to mitigate potential imbalances when integrating them.

Figure 1 - Categories and indicators of vulnerability

Category	Vulnerability indicator name	Symbol
Physical characteristics of the pipe	Material Index	M
	Aging Index	A_{ge}
Lands and terrain characteristics	Corrosion Exposure Index by Aquifer	I_{CA}
	Exposure Index of the Pipe to Landslides	I_{EP}
Service inefficiencies for users	Index of Service Failure	F
	Uniqueness Index	U
Pipeline route	Accessibility index	A
	Exposure Index of Special Structures to Landslides	I_{SS}

Reference: Borzì (2023)

Marleni et al. (2022) developed a Seismic Vulnerability Index for Water Distribution networks (SVI-WDN), structured in three key stages. First, the criteria and sub-criteria are defined, including their respective value ranges and the scoring system for each sub-criteria. Second, the sub-criteria scores are normalized to ensure comparability across different measures. Third, the weights of the criteria and sub-criteria are determined through the application of the Analytical Hierarchy Process (AHP) methodology. Once these three stages are completed, the overall vulnerability index is calculated.

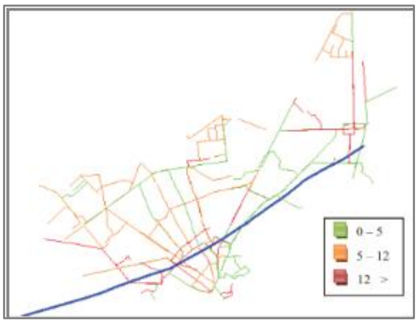
Tornyeviadzi et al. (2021) employed the Fuzzy AHP-TOPSIS methodology, which integrates selected topological, hydraulic, and water quality parameters to provide a holistic assessment of nodal vulnerability within water distribution networks (WDNs). The criteria applied in this framework included Proximity Centrality, Demand-Adjusted Proximity Centrality, and the Water Quality Index.

Laucelli et al. (2014) conducted an analysis grounded in the mechanical reliability of water distribution networks, taking into account system changes under multiple failure scenarios and the pipe failure probability law established by the American Lifeline Alliance. The proposed strategy is formulated as a multi-objective optimization problem, in which two functions are minimized simultaneously: (i) the number of simultaneous events (i.e., those that lead to the detachment of the segment(s)); (ii) the demand met by customers. The method is applied and discussed using the network of city C.

Zohra et al. (2012) proposed a methodology for assessing the seismic vulnerability of water pipelines through the application of Geographic Information Systems (GIS). The approach is grounded in the identification of parameters that influence pipeline behavior under seismic conditions. Each parameter is assigned a coefficient representing its relative impact on structural performance, and the product of these coefficients determines the seismic vulnerability of the section under analysis. The outcome is expressed as a vulnerability index ranging from zero to five, enabling the classification of sections as safe (green), unsafe (red), or intermediate (orange) (Figure 2).

Figure 2 - Classification of pipelines by severity and color scale, and vulnerability index results in GIS

Range VI	Evaluation	Colour
$0 < VI < 5$	Low vulnerability	Green
$5 \leq VI < 12$	Medium vulnerability	Orange
$12 \leq VI$	High vulnerability	Red



Reference: Zohra, et al. (2012)

The increasing intensity of extreme weather events has exposed potable water supply infrastructure to failures and damage, making it vulnerable. In this context, managers require reliable methods to support their risk assessments and, subsequently, decision-making by selecting the best alternative among various parameter options and/or decision contexts (Marleni et al., 2022; Stofkova et al., 2022).

4 METHODOLOGY

To conduct the study and proposed an adapted methodology for assessing the vulnerability risk of internal components within a potable water treatment system, the following steps were necessary.

4.1 LITERATURE REVIEW

Initially, a comprehensive review of technical and scientific literature was conducted. This review was based on academic articles, dissertations, technical standards, current legislation, and publications from official bodies such as environmental agencies, civil defense, and fire departments. Studies related to risk analysis associated with extreme climatic and geological events (such as floods, droughts, wildfires, earthquakes, and landslides) were also considered, alongside data from the European Union’s Earth Observation platform (Copernicus).

4.2 DEFINITION OF THE VULNERABILITY ANALYSIS METHODOLOGY

Building upon the literature review, technical discussions were held with experts in chemical engineering, environmental engineering, hydrology, and geology from the Università Politecnica delle Marche (UNIVPM). These deliberations focused on characterizing vulnerability risks in the internal components of the water treatment system under consideration, utilizing available data and historical records of structural, environmental, and safety failures.

4.3 PARAMETER SELECTION AND METHODOLOGICAL ADAPTATION

Methodological adaptations to specific sub-criteria of the original framework were performed, based on a selected reference scientific article. This process was conducted through a series of meetings involving university researchers and professionals from the regional sanitation company where the methodology was applied. This step was essential to ensure the technical feasibility and contextualization of the adapted methodology within the analyzed scenario.

4.4 METHODOLOGY APPLICATION

The adapted methodology was subsequently applied to case studies within sanitation companies to obtain a measurable vulnerability index for the internal networks comprising the water treatment system. Once this index is determined, it is incorporated into the risk assessment matrix utilized during in the development of the Water Safety Plan (WSP).

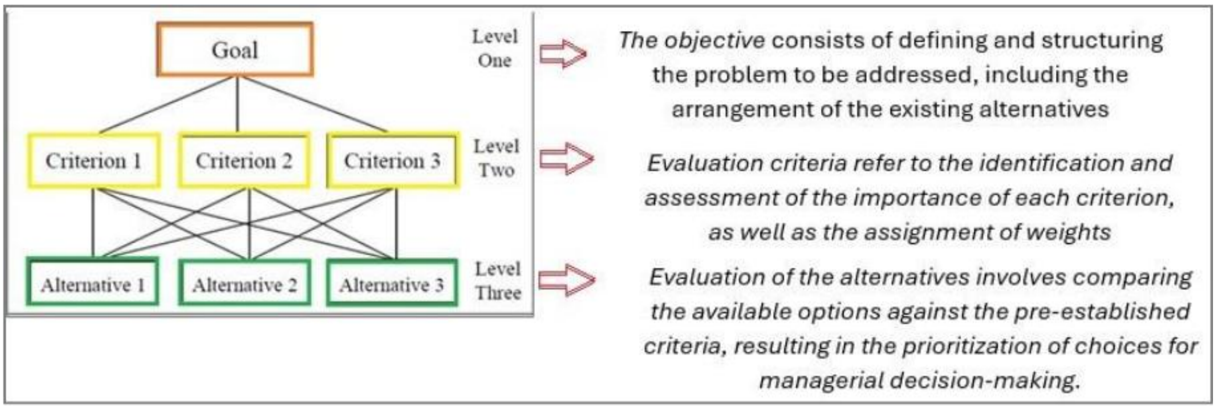
4.4.1 Presentation of the Reference Article's Methodology

Based on the literature review, the scientific article by Marleni et al. (2022) was selected as a key reference. It is methodological approach served as the foundation for adapting the vulnerability analysis methodology adopted in this study.

The methodology proposed by these authors refers to the Analytic Hierarchy Process (AHP), developed by professor and mathematician Thomas L. Saaty in 1980. The AHP is a multi-criteria decision-making (MCDM) support technique, applicable to both qualitative and quantitative criteria (Taherdoost, 2017).

The general structure of the AHP method is divided into three stages, as shown in Figure 3.

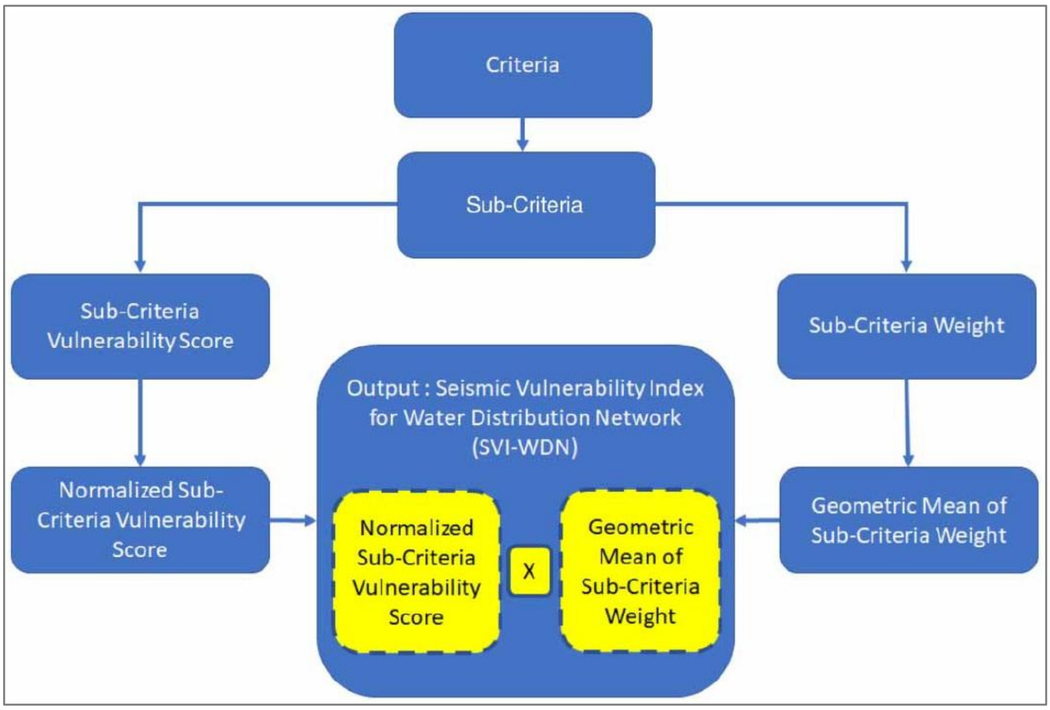
Figure 3 - Hierarchy of the first stage of the AHP method



Reference: Adapted from Taherdoost (2017); Stofkovva et al. (2022)

Based on the logic proposed by the AHP method, Marleni et al. (2022) developed the steps for vulnerability assessment (Figure 4).

Figure 4 - Diagram of the development phases of the methodology proposed by Marleni et al. (2022)



Reference: Marleni et al. (2022)

Based on the flow diagram presented by Marleni et al. (2022), the methodology was refined through the adaptation of specific sub-criteria, ranges, and scoring systems. This tailoring incorporated Italian legislation and local conditions, thus enabling sanitation company managers to accurately understand the level of risk to which the internal components of their water treatment systems are exposed. This analysis facilitates the structuring of the risk matrix within the Water Safety Plan (WSP), thereby supporting the proactive evaluation of mitigation actions anticipating potential hazardous events.

5 RESULTS

This section presents the key findings of the research. Initially, it demonstrated the relevance of the AHP methodology within environmental and sanitation studies, wich provides the rationale for its selection for vulnerability assessment. Subsequently, the stages of the AHP calculation process are described in detail, followed by the presentation of its application to the case studies conducted within sanitation company in Italy.

5.1 APPLICATION OF THE ANALYTIC HIERARCHY PROCESS (AHP) METHODOLOGY IN WATER SUPPLY INFRASTRUCTURE

Numerous environmental studies addressed the vulnerability risk of potable water supply infrastructure, particularly concerning extreme climatic conditions. These studies, conducted by various researchers, employed the AHP methodology, either independently or in conjunction with other mathematical models. The works are brief detailed in Table 1.

Table 1 – Environmental studies conducted using the AHP method

STUDY OBJECTIVE	YEAR	REFERENCE
Therefore, this study aimed to establish a multicriteria inventory classification for consideration while planning green infrastructure for a resilient stream ecosystem in response to climate change. It also aimed to establish the weights and ranks of various indicators considered in the multicriteria inventory classification and compare the results obtained through the AHP and fuzzy AHP.	2020	Park et al. (2020)
The present study aims to delineate the water resilience zones in Chennai city, Tamil Nadu, India, by effectively integrating the geographic information system, remote sensing, and AHP.	2021	Kaaviya & Devadas (2021)
This study proposes a methodological framework based on a hybrid Fuzzy AHP-TOPSIS (Analytical Hierarchical Process - Technique for Order Preference by Similarity to Ideal	2021	Tornyeviadzi et al. (2021)

STUDY OBJECTIVE	YEAR	REFERENCE
Solution) multi-attribute decision-making tool to systematically integrate the unique individual strengths of topological, hydraulic, and water quality vulnerability assessment methods in water distribution networks (WDNs).		
This research has shown the demarcated agricultural drought susceptibility zone in Bankura and Purulia districts by using analytic hierarchy process and weighted overlay techniques. First, different agricultural drought indices are estimated using remote sensing-based satellite imagery.	2021	Senapati et a. (2021)
Using the AHP method, a vulnerability analysis of saline intrusion in the potable water supply was conducted by integrating environmental and social factors of Rach Gia city, Vietnam.	2022	Phin et al. (2022)
Therefore, this study aimed to develop a framework to generate a Seismic Vulnerability Index for Water Distribution Network (SVI-WDN) for the Special Region of Yogyakarta, which has been known to be exposed to many earthquake incidences.	2022	Marleni et al. (2022)
This study presents a comprehensive method that combines Variable Weight Theory (VWT) with AHP to assess geo-environmental vulnerability based on susceptibility to various geohazards.	2023	Huang et al. (2023)
This study presents a comprehensive flood vulnerability assessment for Freetown, Sierra Leone, spanning the period from 2001 to 2022. The objective of this research was to assess the temporal and spatial changes in the flood vulnerability using Geographic Information System (GIS) tools and AHP-based Multi-Criteria-Decision-Making (MCDM) analysis.	2024	Koroma et al. (2024)

As demonstrated in Table 1, the selection of the AHP methodology for vulnerability assessment in this study is justified by its extensive applicability in various environmental studies focused on water supply systems. This makes the AHP a well-established and recognized method for this type of analysis.

Furthermore, the methodology facilitates the participation of experts in structuring the problem's hierarchy, where their technical judgments are critical in assigning weights and defining criteria, sub-criteria, ranges, and scores, in accordance with relevant legislation, guidelines, and their expertise. Its versatility also enables application across different thematic areas within the sanitation company.

Additionally, this methodology provides crucial support to sanitation management authorities in establishing maintenance and/or priority intervention strategies for pipelines requiring attention.

5.2 DESCRIPTION OF THE AHP METHODOLOGY FOR VULNERABILITY ASSESSMENT WITHIN THE WATER SAFETY PLAN

The vulnerability assessment employs a hierarchical structure based on three main criteria:

- ✓ Criteria 1: Physical;
- ✓ Criteria 2: Environmental;
- ✓ Criteria 3: Operational.

Each criteria is composed of a set of sub-criteria, which incorporate specific classification ranges and scoring systems. The flexibility of the methodology permits the addition or exclusion of these sub-criteria, depending on the specific nature of the problem being addressed. The physical criteria and its corresponding sub-criteria are presented in detail in Table 2.

Table 2 - Presentation of sub-criteria and their components for the physical criteria

Criteria	Physical (1)	Range	Score
Sub-criteria	**1.1 Pipe diameter**	Ø > 1,000 mm	1
		600 mm <Ø ≤ 1,000 mm	2
		450 mm < Ø < 600 mm	3
		250 mm < Ø < 450 mm	4
		150 mm < Ø < 250 mm	5
		100 mm < Ø < 150 mm	6
		Ø < 100 mm	7
	1.2 Pipe material	High-Density Polyethylene	1
		Polyvinyl Chloride	2
		Steel	3
		Asbestos cement	4

Criteria	Physical (1)	Range	Score
		Cast iron Ductile iron Galvanized steel	5 6 7
	1.3 Pipe age	< 10 years 10 ≤ years < 40 40 ≤ years < 75 75 ≤ years < 100 > 100 years	1 2 3 4 5
	1.4 Pipe lenght	< 100 m 100 ≤ m < 750 750 ≤ m < 2,000 >2,000 m	1 2 3 4
	1.5 Corrosion protection method	Present Absent	1 2
	1.6 Pipe fitting type	Seismic joint Steel with welded joints Standard ductile iron joint Polyvinyl Chloride Cast iron Asbestos cement Flanged steel	1 2 3 4 5 6 7
	1.7 Installation depth of the conduit	< 1 m 1 – 2 m 2 – 3 m	1 2 3

As presented in Table 2, the Physical criteria is composed of seven sub-criteria, each assigned respective range values and scores. Sub-criteria 1.7, "installation depth of the conduit", is highlighted in green, indicating its incorporation into the original framework utilized by Marleni et al. (2022). The inclusion of this sub-criteria is deemed highly relevant for vulnerability assessment, considering that internal pipelines within a water treatment and distribution system are often subjected to pressures from vehicular traffic, significant environmental thermal variations, and installation in areas classified as having periodic seismic activity.

The set of sub-criteria constituting the Environmental criteria is detailed in Table 3. It is noteworthy that the sub-criteria highlighted in green denote those specifically added to the original list proposed by Marleni et al. (2022).

Table 3 - Presentation of sub-criteria and their components for the environmental criteria

Criteria	Environmental (2)	Range	Score
Sub-criteria	**2.1 Ground fault**	No intersection 1 intersection with the buffer 1 intersection with the fault line >1 intersection with buffer/ line	1 2 3 4
	2.2 Landslides	Unclassified Area (No Risk) R1 Areas (Moderate Risk) R2 Areas (Medium Risk) R3 Areas (Hight Risk) R4 Areas (Very Hight Risk)	1 2 3 4 5
	2.3 Seismic intensity	ag < 0.05 0.05 < ag < a.15 0.15 < ag < 0.25 ag > 0.25	1 2 3 4
	2.4 Soil type	Hard exposed rock Moderately weathered rock Rock affected by erosion Eluvial-colluvial soil Alluvial soil	1 2 3 4 5
	2.5 Floods	No PAI* área R1 Moderate R2 Medium R3 High R4 Very High	1 2 3 4 5
	2.6 Thermal anomalies (consequences of a fire)	Low Medium High	1 2 3

*PAI: Hydrogeological Asset Plan

Table 3 illustrates the inclusion and/or adaptation of scales and values for four additional sub-criteria augmented to the original set, alongside a reassessment of the nomenclature and scores for sub-criteria 2.1. The four added sub-criteria, highlighted in green, address: landslides, seismic intensity, floods, and thermal anomalies (specifically related to wildfires). The respective ranges and scores were meticulously defined based on Italian legislation, technical reports, and official government agency documents, validated by the expertise of researchers from UNIVPM.

To effectively guide sanitation managers in assessing the vulnerability of internal structures, technical notes were concurrently developed. These notes contain necessary clarifications and guidelines for each classification range, aiming to facilitate the evaluation process. These guidelines are systematically presented in Table 4.

Table 4 – Presentation of technical notes for sub-criteria classification and scoring

Sub-criteria	Technical note
Seismic intensity	According to Italian legislation, the seismic classification of the territory is based on the maximum ground acceleration on rock; the territory is subdivided into zones. For this purpose, specific local studies, seismic hazard maps (Italian municipalities are categorized into four hazard classes[3]), regional hazard maps must be consulted for subclasses, and a reference seismic hazard map with a 0.02° step. The maps for reference are available on the website: <https://rischi.protezionecivile.gov.it/it/sismico/attivita/classificazione-sismica/> The National Cartographic Portal should also be consulted: < http://www.pcn.minambiente.it/>.
Ground fault	To assess the intersection of linear structures (such as the adduction and distribution network) with faults and other tectonic elements, relevant data must be obtained from the network operator (maps of adduction and distribution lines), the Italian Institute for Environmental Protection and Research (ISPRA) website (geological map at 1:50,000 scale), and regional websites (geological maps at 1:10,000 scale). It is essential to consider a danger "buffer" of approximately 100 meters around the tectonic structure. This is justified by the fact that the fault surface constitutes a zone of weakness in the rock, affecting not only the fracture zone itself but also a significant surrounding area. Consequently, the closer the network structure is to this fault zone, the higher its vulnerability will be. Such material can be retrieved from the:

Sub-criteria	Technical note
	• National Cartographic Portal: <http://www.pcn.minambiente.it/> • Regional websites and ISPRA website: <https://www.isprambiente.gov.it/it/progetti/cartella-progetti-in-corso/suolo-e-territorio-1/progetto-carg-cartografia-geologica-e-geotematica/index> • Websites of the District Basin Authorities for consultation.
Landslides	It is necessary to consult specific studies of the areas, as well as local or regional geological and geomorphological maps, and PAI. Based on the vulnerability classification present in these maps, a reclassification can be made for inclusion in the matrix (no risk, medium risk, significant risk). • Information regarding PAI can be researched on the National Cartographic Portal: <http://www.pcn.minambiente.it/> • On regional websites, on the ISPRA website: <https://www.isprambiente.gov.it/it/progetti/cartella-progetti-in-corso/suolo-e-territorio-1/progetto-carg-cartografia-geologica-e-geotematica/index> • The websites of the District Basin Authorities.
Soil type	Data regarding soil type should be obtained from specific studies and the ecopedological map of Italy (noting a level of detail and reclassification considered low). More detailed information can be found on the websites of regions or regional ARPA (Regional Agencies for Environmental Protection). An even higher level of detail is achievable through the transposition and analysis of data from lithological maps, available on regional websites (CARG) or the ISPRA

Sub-criteria	Technical note
	website, considering weathering phenomena and the mineralogical nature of pedological processes. • National Cartographic Portal: <http://www.pcn.minambiente.it/>
Floods	Drawing from previous planning experiences, the Decree of the President of the Council of Ministers (DPCM) of September 29, 1998, allows for the definition of four risk classes, according to the classifications outlined below. The various risk scenarios are aggregated into four classes of increasing severity to which the following definitions are attributed: • *R1 (Moderate Risk):* Characterized by marginal social, economic, and environmental damages; • *R2 (Medium Risk):* Indicates the possibility of minor damages to buildings, infrastructure, and environmental heritage, which, however, do not compromise personal safety, building habitability, or the functionality of economic activities; • *R3 (High Risk):* Suggests the possibility of risks to personal safety, functional damages to buildings and infrastructure resulting in their unsuitability for use, interruption of socioeconomic activities, and significant damage to environmental heritage; • *R4 (Very High Risk)*: Implies the possibility of loss of human lives and severe injuries, serious damage to buildings, infrastructure, and environmental heritage, in addition to the destruction of socioeconomic activities.
Thermal anomalies (consequences of a fire)	Fire data can be searched on the Copernicus platform via the following link: <https://effis.jrc.ec.europa.eu/>. Search for the region of interest and choose the scale that best represents the study area. It is important to consider in the analysis previous events that caused damage to the pipelines.

The third and final set of criteria constituting the methodology is the Operational criteria. The corresponding cub-criteria, along with their respective ranges and scores, are presented in Table 5. As in previous tables, text highlighted in green indicates the inclusion of new sub-criteria and/or adaptations made to existing terms, ranges, or scores.

Table 5- Presentation of sub-criteria and their components for the operational criteria

Criteria	Operational (3)	Range	Score
Sub-criteria	**3.1 Failure history**	Pipelines without a history of failures Pipeline with a history of failures	1 2
	3.2 Working pressure	< 6 atm 6 ≤ atm < 8 >8 atm	1 2 3
	3.3 Water Losses (%) (ARERA*/ISTAT basis)**	M1b < 25%: low 25% ≤ M1b < 45%: media M1b > 45%: high	1 2 3
	3.4 Water quality (based on FMEA* analysis)**	Risk 0% - 5%: excellent Risk 5% - 10%: very good Risk 10% - 20%: good Risk 20% - 50%: poor Risk > 50%: very poor	1 2 3 4 5
	3.5 Water supply condition	Intermittent water supply Continuous water supply	1 2

*ARERA: Regulatory Authority for Energy, Networks and Environment is the Italian regulatory body
** ISTAT: National Institute of Statistics is the Italian national statistical institute.
*** FMEA: Failure Mode and Effects Analysis

As detailed in Table 5, the two sub-criteria and their respective ranges and weights underwent reformulation. Specifically, the 'water losses' sub-criteria was structured based on the regulatory document "*Regolazione della qualità tecnica del servizio idrico integrato ovvero di ciascuno dei singoli servizi che lo compongono (RQTI)"* (Regulatory Authority for Energy, n.d.), issued by the Italian regulatory body ARERA/ISTAT.
The range utilized for this sub-criteria references the M1 macro-indicator, wich relates to water resource conservation and is applicable to all water service managers responsible for supply systems. Within this framework, M1b classified as the percentage indicator of water losses. For each range defined, a corresponding score was assigned, relying on the technical expertise of the researchers and other contributors involved in structuring the methodology.

The 'water quality' sub-criteria utilizes ranges defined through a water quality risk analysis employing the Failure Mode and Effects Analysis (FMEA) methodology. This methodology is established and regulated by the Italian national guideline ISTISAN 22/33, issued by the Istituto Superiore di Sanità (ISS). It is applied specifically to the analysis of historical water quality data.

The ranges adopted within the "water quality" sub-criteria are categorized into five classes, spanning from "*excellent*" (risk of 0%–5%) to "*very poor*" (risk greater than 50%). The "*excellent*" risk class signifies a system with high reliability in terms of water safety, presenting minimal risks. Conversely, the "*very poor*" quality class indicates that water quality may seriously compromise both public health and the operational integrity of the system.

Following the definition of criteria and sub-criteria, the subsequent step involves the evaluation of a specific internal component within the distribution system. For each criteria and its corresponding sub-criteria, the appropriate range value related to the specific pipeline must be input. This process requires the technical team of the sanitation company to assign a score based on technical data, historical records, and their specialized expertise. The results of this initial evaluation are recorded in Table 6.

Table 6 - Score associated with the sub-criteria concerning the infrastructure installed for water distribution

Criteria	Physical (1)	Range	Score
Sub-criteria	1.1 Pipe diameter	Ø > 1000 mm	1
		600 mm <Ø ≤ 1000 mm	2
		450 mm < Ø < 600 mm	3
		250 mm < Ø < 450 mm	4
		150 mm < Ø < 250 mm	5
		100 mm < Ø < 150 mm	6
		Ø < 100 mm	7
	1.2 Pipe material	High-Density Polyethylene	1
		Polyvinyl Chloride	2
		Steel	3
		Asbestos cement	4
		Cast iron	5
		Ductile iron	6
		Galvanized steel	7
	1.3 Pipe age	< 10 years	1
		10 ≤ Years < 40	2
		40 ≤ Years < 75	3
		≤ Years < 100	4
		> 100 years	5
	1.4 Pipe lenght	< 100 m	1
		100 ≤ m < 750	2
		750 ≤ m < 2000	3
		>2000 m	4
	1.5 Corrosion protection method	Present	1
		No presente	

Score associated with the sub-criteria concerning infrastructure installed for water distribution

INTERNODI (internal component)			
Name or code of the internal element			

Following the initial evaluation, the resulting values must be normalized. This normalization is essential because the sub-criteria possess diverse measurement units and value ranges, making direct comparisons impractical.

The subsequent step involves constructing the comparison matrix. In the stage, the sub-criteria within each criteria group (Physical, Environmental, and Operational) must be evaluated through pairwise comparisons, considering the relative importance of each parameter compared to the others. For this evaluation, Table 7 should be consulted to verify the scale of importance levels utilized in the comparisons. Once defined, the selected values are then input into the comparison matrix (Table 8).

Table 7 - Importance level scale for pairwise comparison of sub-criteria in the matrix

Importance Level Scale for Pairwise Comparison of Sub-Criteria in the Matrix	
Definition	**Level of Importance**
Equally important	1
Slightly more important	2
More important	3
Extremely important	4
Slightly less important	1/2 = 0,5
Less important	1/3 = 0,33
Much less important	1/4 = 0,25

Table 8 - Example of comparison matrix

		PHYSICAL CRITERIA						
		Subcriteria 1.1: Pipe diameter	Subcriteria 1.2: Pipe material	Subcriteria 1.3: Pipe age	Subcriteria 1.4: Pipe lenght	Subcriteria 1.5: Corrosion protection method	Subcriteria 1.6: Pipe fitting type	Subcriteria 1.7: Installation depth of the conduit
PHYSICAL CRITERIA	Subcriteria 1.1: Pipe diameter	1	0.25	0.25	3	0.25	0.25	0.25
	Subcriteria 1.2: Pipe material	4	1	4	4	1	0.33	2
	Subcriteria 1.3: Pipe age	4	0.25	1	3	1	0.33	2
	Subcriteria 1.4: Pipe lenght	0.333333333	0.25	0.333333333	1	0.25	0.25	0.33
	Subcriteria 1.5: Corrosion protection method	4	1	1	4	1	0.5	3
	Subcriteria 1.6: Pipe fitting type	4	3.03030303	3.03030303	4	2	1	4
	Subcriteria 1.7: Installation depth of the conduit	4	0.5	0.5	3.03030303	0.333333333	0.25	1
AHP METODOlOGY	***SUM***	21.33333333	6.28030303	10.11363636	22.03030303	5.833333333	2.91	12.58

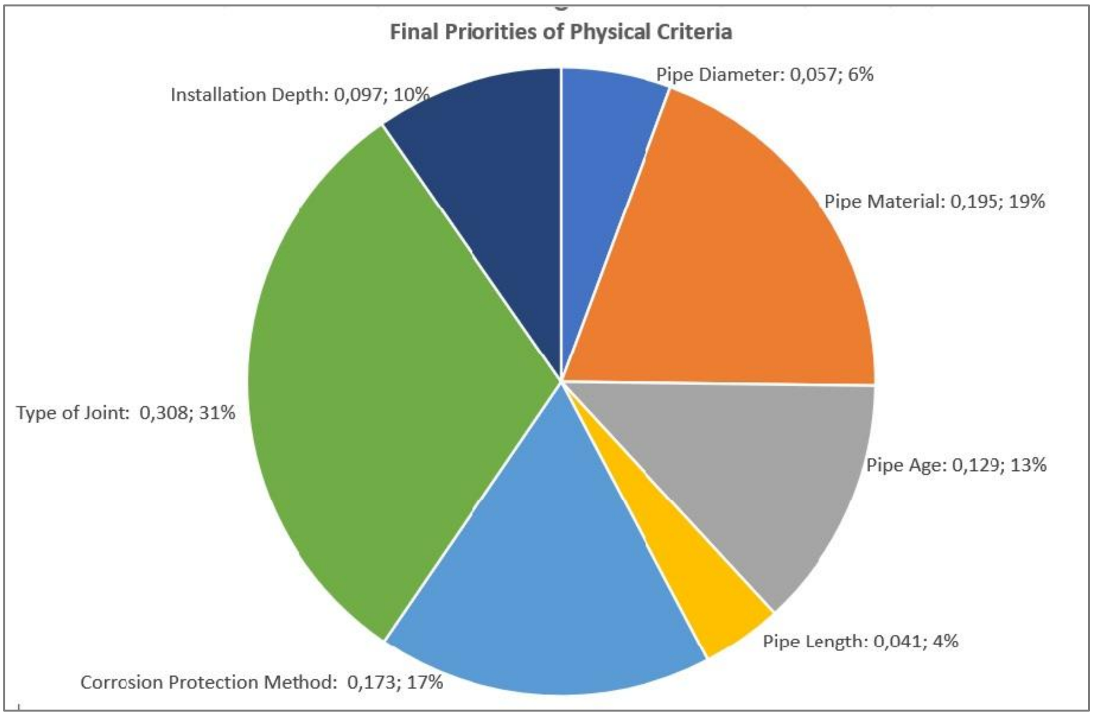
Following the analysis of the comparison matrix (Table 8) for each criteria, the sum of the column values for every evaluated sub-criteria is calculated. These columns sums are subsequently used to generate a normalized matrix (Table 9). This step is crucial, as the normalization process is necessary for the calculation of the priority vector (weights) for the criteria and sub-criteria.

Table 9 - Example of matrix with normalized values

	Sub-criteria 1.1: Pipe Diameter	Sub-criteria 1.2: Pipe Material	Sub-criteria 1.3: Pipe Age	Sub-criteria 1.4: Pipe Length	Sub-criteria 1.5: Protection Method (Corrosion)	Sub-criteria 1.6: Type of Joint	Sub-criteria 1.7: Installation Method of the conduit	Arithmetic mean **Final Priorities**
Sub-criteria 1.1: Pipe Diameter	0,046875	0,039806996	0,024719101	0,136176066	0,042857143	0,085910653	0,019872814	0,057
Sub-criteria 1.2: Pipe Material	0,1875	0,159227986	0,395505618	0,181568088	0,171428571	0,113402062	0,158982512	0,195
Sub-criteria 1.3: Pipe Age	0,1875	0,039806996	0,098876404	0,136176066	0,171428571	0,113402062	0,158982512	0,129
Sub-criteria 1.4: Pipe Length	0,015625	0,039806996	0,032958801	0,045392022	0,042857143	0,085910653	0,026232114	0,041
Sub-criteria 1.5: Protection Method (Corrosion)	0,1875	0,159227986	0,098876404	0,181568088	0,171428571	0,171821306	0,238473768	0,173
Sub-criteria 1.6: Type of Joint	0,1875	0,482509047	0,299625468	0,181568088	0,342857143	0,343642612	0,317965024	0,308
Sub-criteria 1.7: Installation depth of the conduit	0,1875	0,079613993	0,049438202	0,137551582	0,057142857	0,085910653	0,079491256	0,097
Sum of the normalized value of the columns	1	1	1	1	1	1	1	1

From the averaged values obtained from the normalized matrix (Table 9), the "Final Priority" column is derived (see Figure 9, where the column is distinctly emphasized by means of a red marker). This column, wich represents the priority vector (or weights) for the sub-criteria, provides the data necessary to generate a graph. This visualization effectively highlights the sub-criteria requiring greater attention or priority during the vulnerability assessment (Figure 5).

Figure 5 - Example of priority chart based on the normalized matrix of physical sub-criteria



The next step involves applying the normalization process to the results presented in Table 6, titled "internodes" (internal component). This procedure utilizes the normalization formula (Figure 6) to generate the standardized outcomes, which are subsequently entered into Table 10 "Normalized Score Result". Normalization is essential to transform the raw data into a dimensionless scale, allowing for meaningful comparison and integration with the weighted priority vector.

Table 10 - Normalization of the results obtained from the evaluation of each sub-criteria of the internal component

Scores Assigned to Sub-Criteria (Infrastructure) Installed for Water Distribution				Normalized Score Result			
INTERNODES (Internala component)				INTERNODES (Internala component)			
Identification of the Internal Component (Code)				Identification of the Internal Component (Code)			
4				1,5			
3				1			

Figure 6 - Normalization formula and scores applied to the results in Table 10

Normalized Sub-criteria Scores and Vulnerability Level of Selected Sub-criteria	
Vulnerability Level	**Sub-criteria Normalized Values**
Non-vulnerable	0
Low Vulnerability	1
Vulnerable	2
Very Vulnerable	3

$$N(x_i) = \frac{(x_i - \min(x)) \times (\max(y) - \min(y))}{(\max(x) - \min(x))} + \min(y)$$

N(xi) represents the normalized score assigned to each sub-criteria.

xi is the score of sub-criterion i based on the case study data; min(x) and max(x) are the minimum and maximum scores of sub-criteria *i*, respectively;

min(y) and *max(y)* represent the minimum and maximum expected values for the normalized sub-criteria.

Upon completion of the stage outlined in Figure 6, the final aggregation is performed. This involves multiplying the sum of the normalized column scores (from Table 10, “Normalized Score Result”) by the corresponding final priority value (the priority vector derived from Table 9).

Following this calculation, which adheres to the guidelines illustrated in Figure 6, the final vulnerability index value is obtained. This index corresponds to a defined scale ranging from zero to nine (Figure 7).

Figure 7 - Final vulnerability scale

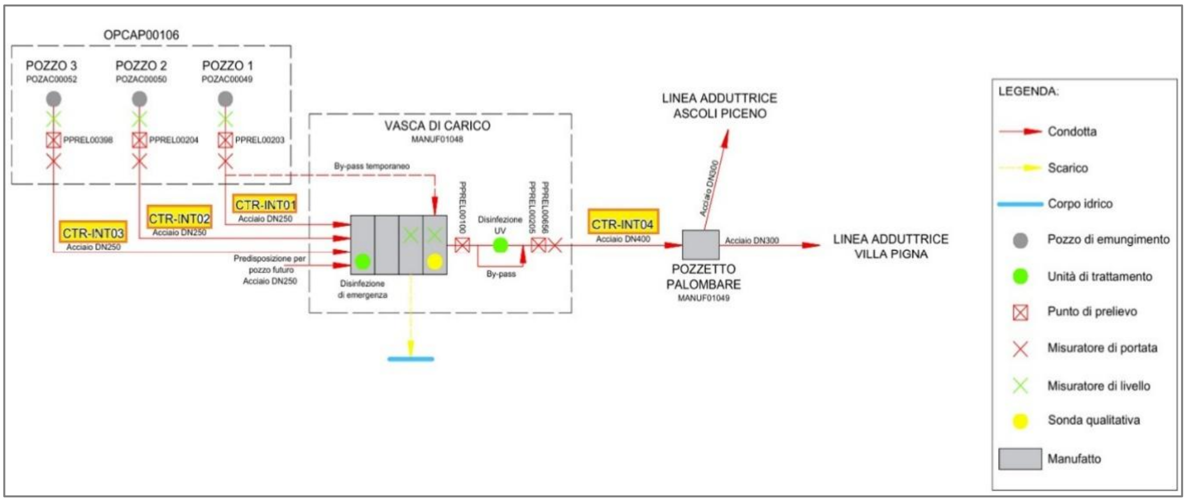
Vulnerability Scale	
0.00 - 0.99	Non-vulnerable
1.00 - 3.99	Low Vulnerability
4.00 - 7.99	Vulnerable
8.00 - 9.00	Very Vulnerable

5.3 APPLICATION OF THE METHODOLOGY

5.3.1 Case Study: Castel Trosino Water Supply System

De Simoni (2024/2025) applied the methodology proposed in this chapter to assess the vulnerability of four internodes within the Castel Trosino water supply and distribution system located in the Marche Region, Italy (Figure 8).

Figure 8 – Identification of the four internodes of the Castel Trosino system



Reference: De Simoni (2024/2025)

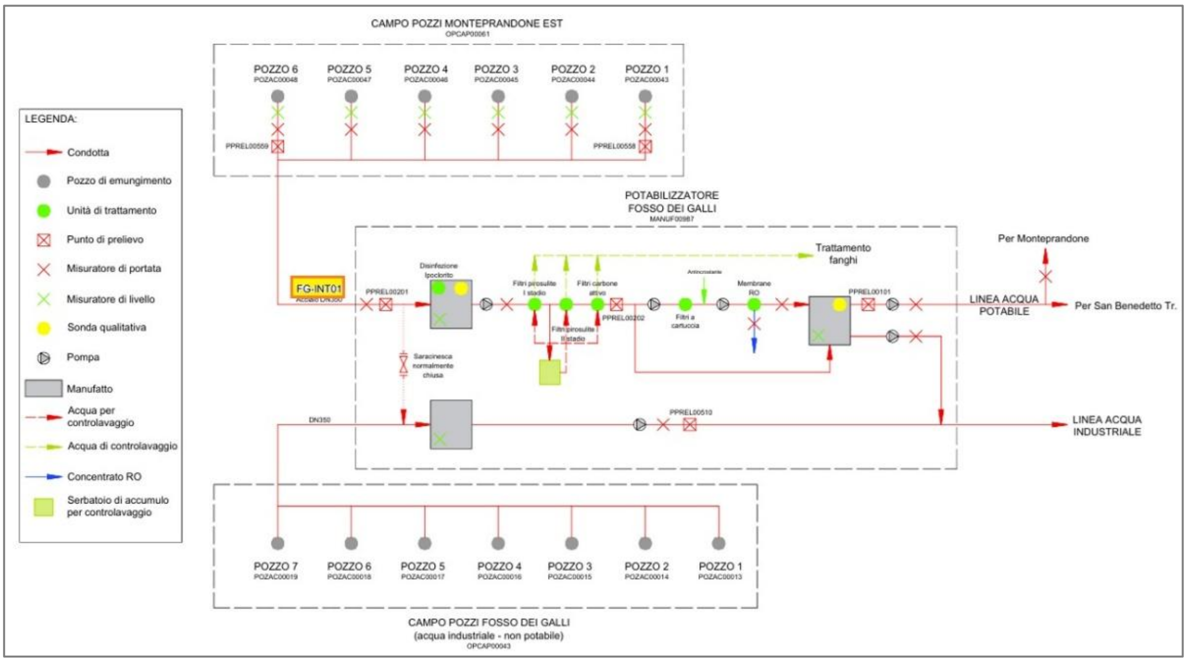
The assessment of the four internodes — CTR-INT01, CTR-INT02, CTR-INT03 and CTR-INT04 (visually represented in yellow in Figure 8), yielded a uniform classification of low vulnerability index. As a consequence of this findings, the Execution of a more comprehensive risk assessment via the standard risk matrix was considered redundant for the purpose of developing the (WSP).

5.3.2 Case Study: Fosso Dei Galli Water Treatment System

The second case study involves the application of the proposed methodology to the Fosso dei Galli water treatment system (Figure 9), also situated in the Marche region of Italy.

The internode evaluated, identified as FG-INT01 and highlighted in yellow in Figure 9, is specifically responsible for the conveyance of water captured from the wells to the treatment plant.

Figure 9 - Identification of internode of the Fosso dei Galli system



Reference: De Simoni (2024/2025)

The analysis conducted by De Simoni (2024/2025) yielded a vulnerability index of 4.20 for internode FG-INT01. According to the final vulnerability scale (Figure 7), this index classifies the internode as vulnerable. Based on this finding, a more detailed risk assessment was mandated ad performed utilizing a risk matrix.

The hazard and risk evaluation for this internode was detailed in the matrix, and the section corresponding to FG-INT01 is presented in Table 11.

Table 11 - Risk Matrix with hazard identification for internode FG-INT01

Water system component	Internode code	Hazardous event	Identification of the hazardous event	Hazard consequences	Hazard
Water adduction	FG-INT01	Nuclear and environmental disasters	Earthquake (Magnitude>5)	Loss of water availability	Physical: Interruption in water supply due to pipeline rupture

Reference: Adapted from De Simoni (2024/2025)

Table 11 summarizes the detailed risk analysis performed using the risk matrix. The hazardous event identified in the region encompassing the acqueduct corresponds (derived from the list suggested in the Rapporti ISTISAN 14/21 document) correponds to a “nuclear and environmental disasters”. Upon further investigation of this event, it is observed that an earthquake exceeding magnitude 5 could potentially impact the area, with the capacity to compromise the aqueduct’s infrastructure. Should such an occurrence materialize, the immediate consequence would be a water loss, and the primary risk would be associated with de interruption of potable water supply due to the aqueduct’s rupture.

The in-depth assessment of internod vulnerabilty using the risk matrix, within the scope of the WSP, constitutes an essential tool. It allows for the identification and classification of hazardous events, thereby substantianting both problem delineation and the implementation of preventive and mitigation measures. Furthermore, it enables the continuous monitoring of the risk level associated with each hazardous event, consequently contributing to water supply infrastructure systems becomig progressively more resilient in the face of challenges imposed by climate change.

CONCLUSION

The adapted and proposed methodology has proven to be applicable and highly valuable for sanitation company managers, enabling them to identify and anticipate potential hazards and risks that may impact the internod of water treatment system. This methodology facilitates the acquisition of a measurable, quantitative, and easily interpretable index, standing in contrast to merely subjective and qualitative analyses.

The detailed delineation of hazards and dengerous events, along with theirs associated probabilities and frequencies, streamlines the assessment process and provides clearer support for decision-making.

In conclusion, the proposed methodology represents a significant advancement in the technical and strategic assessment of component vulnerability, ultimately providing enhanced operational security and greater efficiency in decision-making.

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CHAPTER 2 - STORMWATER CHARACTERIZATION AND PRELIMINARY RISK ASSESSMENT: A BRAZILIAN CASE STUDY

PREAMBLE

Considering the escalating pressures on water resources, whether originating from anthropogenic, economic demands, or climate-change-related extreme events, the advancement of scientific research focused on alternative water sources has become increasingly imperative. Countries such as Australia and the United States, for instance, have already made progress in regulating stormwater management, establishing guidelines for its design, utilization, and/or reuse. In Brazil, however, this topic is still superficially addressed: there is no federal legislation defining quality standards for the reuse of treated water, thereby leaving individual states responsible for establishing their own parameters. Furthermore, the country lacks specific regulations governing stormwater management. Risk assessment methodologies have been widely employed as essential tools to ensure the environmental safety of affected compartments, such including soil, freshwater bodies, and coastal environments, as well as to protect human health to enable the direct or indirect reuse of urban drainage water. In manner, the responsible and safe utilization of rainwater as an alternative resource is promoted.

2. GENERAL OBJECTIVE

To investigate the feasibility of reusing rainwater as a sustainable source for agricultural, direct, and indirect applications.

2.1 SPECIFIC OBJECTIVE

To identify the physicochemical and microbiological risks associated with stormwater reuse, using the quality standards established by the current environmental regulations of the State of Paraná, Brazil, thereby ensuring environmental safety and regulatory compliance.

3. STUDY DEVELOPMENT

3.1 STORMWATER (URBAN RUNOFF WATER) AS AN ALTERNATIVE RESOURCE FOR WATER REUSE

Water is a vital resource for human survival and is closely linked to public health. It also provides benefits that drive the socioeconomic prosperity of nations, while being essential for food production and environmental preservation. In the United Nations' 2030 Agenda, the sixth

Sustainable Development Goal (SDG) estimates that more than 733 million people are affected by water stress (Raimondi et al., 2023).

According to UNESCO (2024), agriculture accounts for the highest global demand for water, utilizing approximately 70% of available freshwater. This is followed by the industrial sector, which consumes approximately 20%, while domestic use represents about 12%. However, water resources have been increasingly impacted over time by anthropogenic pressures, inadequate management practices, unequal distribution, and quality degradation.

The situation described above has become particularly concerning due to the intensification and severity of extreme climatic events worldwide, such as prolonged droughts, heavy rainfall, flooding, and earthquakes. These could potentially disrupt the hydrological behavior of an underground aquifer and other environmental disturbances (Szodrowska, Woka & Smol, 2025). In addition to the impacts on water resources, climate change may also negatively affect global agricultural productivity, compromising food supply and exacerbating nutritional problems in less developed countries (Richards et al., 2021).

There were well over 820 million people worldwide who suffered from malnutrition, according to the United Nations Development Program (UNDP) Thailand (2025). The effects of climate change were expected to intensify food insecurity in 2018.

As previously stated, the present situation necessitates the development of alternative water sources to resolve concerns regarding water scarcity, unequal distribution, and compromised quality. It is essential that these sources ensure safety for both the population and the environment to be effective.

Within this context, stormwater harvesting emerges as a promising solution. As an alternative source of water reuse, it possesses the potential to enhance water access in areas facing insufficient supply. Moreover, its utility extends to non-potable purposes, across small, medium and large scales, including applications in industrial settings, agriculture, and other relevant sectors (Reyneke et al., 2020).

The practice of rainwater harvesting and reuse is an ancient technique, with evidence tracing back to the Neolithic period. Throughout history, various civilizations have employed this method as a reliable means of securing a water supply. In recent years, rainwater collection and reuse have garnered increasing attention from the scientific community and governmental bodies. Consequently, these entities have been introducing legislation and public policies to encourage its adoption, recognizing its potential as a viable and sustainable for water management (Raimondi et al., 2023).

For example, rooftops, terraces, and other surfaces like parking lots or urban runoff areas can all yield stormwater that can be reused (Martins Vaz et al., 2023). Stormwater harvesting (or urban runoff), on the other hand, involves collecting runoff water from drainage pipes or streams (Natural Resource Management Ministerial Council, Environment Protection and Heritage Council & National Health and Medical Research Council, 2009).

Nevertheless, the reuse of stormwater requires careful consideration, as this source may contain various types of contaminants. Their presence is influenced by multiple factors contributing to pollution, such as the collection environment, atmospheric pollution levels, and land use patterns, among others (Singh et al., 2022).

Stormwater runoff may contain a wide variety of pollutants in its composition, resulting from its flow across diverse surfaces. These surfaces include urban, rural, industrial, residential, commercial areas, and vegetated spaces. Along this trajectory, the runoff can convey contaminants such as heavy metals, dust, pesticides and herbicides, pharmaceutical residues, salts, pathogenic microorganisms, and others (Cojoc et al., 2024).

In this context, it is imperative to perform a physicochemical and microbiological characterization of stormwater prior to its reuse. This assessment aims to identify the contaminants present and facilitate the selection of appropriate subsequent treatment technologies corresponding to the intended reuse purpose. Ultimately, this approach seeks to mitigate risks associated with public health and environmental integrity.

3.2 REGULATORY FRAMEWORK FOR WATER REUSE IN BRAZIL

Approximately 8% of the world's surface freshwater reserves are located in Brazil. However, these water resources are unevenly distributed throughout the country. For instance, 80% of the available surface water is concentrated in the Amazon Hydrographic Region (Figure 1) (FGVces, 2025), where the population density is ten times lower than the national average (ANA, n.d.). In 2022, the national population density was 23.86 inhabitants per square kilometer (IBGE, 2022).

Figure 1 - Amazon Watershed Region

Reference: ANA (n.d)

The topic of water reuse has been extensively studied in recent years and has garnered increasing attention due to its higher availability and low sensitivity to hydroclimatic factors. These characteristics establish it as a particularly relevant and promising approach in the current context, where multiple variables, previously discussed in Section 3.1, act as significant constraints on water availability (FGVces, 2025).

Brazil faces a significant regulatory gap regarding water reuse practices, as there is still no federal legislation that adequately addresses the issue. Essential components remain undefined, including use categories, specific quality parameters for each class, and risk assessment criteria associated with reuse activities.

At the federal level, Brazil has enacted the following legislation: Law No. 14.546, dated April 4, 2023, which amends Law No. 11.445, dated January 5, 2007 (the Basic Sanitation Law), establishing measures for waste prevention, rainwater harvesting, and non-potable reuse of greywater. Article 49-A of the amended law states:

"*Within the scope of the Federal Basic Sanitation Policy, the Union shall promote the use of rainwater and the non-potable reuse of greywater in new buildings and in landscaping, agricultural, forestry, and industrial activities, in accordance with regulations.*

§ 1 The plumbing system and the reservoir intended for the collection of rainwater and greywater from buildings must be separate from the public water supply system.

§ 2 (VETOED).

§ 3 Rainwater and greywater shall undergo a treatment process that ensures their safe use before storage and utilization within the building.”

Law No. 14.026, enacted on July 15, 2020, which updates Brazil’s legal framework for basic sanitation, addresses water reuse in its provisions as follows: *“Article 4, §1 – It shall be the responsibility of the National Water and Basic Sanitation Agency (ANA) to establish reference standards regarding: [...] IX – the reuse of treated sanitary effluents, in accordance with environmental and public health regulations.*”

Furthermore, Law No. 11,445 of January 5, 2007 was amended to include: *“[...] XIII – reduction and control of water losses, including in the distribution of treated water; promotion of rational water consumption; and encouragement of energy efficiency, reuse of sanitary effluents, and rainwater harvesting. Article 45, §11 – Non-residential buildings or condominiums governed by Law No. 4,591 of December 16, 1964 may utilize alternative sources and methods of water supply, including groundwater, reused water, or rainwater, provided they are authorized by the competent authority and subject to payment for water resource use, when applicable*”.

The National Water Resources Council (CNRH) has issued two key regulations addressing water reuse:

- ✓ CNRH Resolution No. 54, dated November 28, 2005 which establishes general guidelines and modalities for the practice of direct non-potable water reuse, and provides other provisions (Santos, Lima & Moraes, 2025);
- ✓ CNRH Resolution No. 121, dated December 16, 2010, which sets forth specific guidelines and criteria for the practice of direct non-potable water reuse in agricultural and forestry applications, as defined in Resolution No. 54, dated November 28, 2005 (Santos, Lima & Moraes, 2025).

The National Environmental Council (CONAMA) has issued the following regulation:

- ✓ Resolution No. 503, dated December 14, 2021, which defines criteria and procedures for the reuse of effluents in fertigation systems originating from food, beverage, dairy, meatpacking, and grease processing industries (Santos, Lima & Moraes, 2025).

In 2022, through the “Participa + Brasil” platform, the Federal Government launched Public Consultation No. 3/2022, which addresses the drafted resolution of the National Water Resources Council (CNRH). This proposal establishes modalities, general guidelines, and criteria to regulate and promote the practice of direct non-potable water reuse throughout the national territory. It also recommends minimum quality parameters for each reuse modality, aligned with the goals and directives of the National Water Resource Plan 2022–2040 (Governo Federal do Brasil, 2022).

As previously discussed, although a limited number of laws and resolutions have already addressed the issue of water reuse, Brazil remains at an early stage regarding technical discussions and research on this subject.

Brazil relies on the work of the Brazilian Association of Technical Standards (ABNT), related to technical standards, which is a private, non-profit organization. As a founding member of the International Organization for Standardization (ISO), ABNT is responsible for developing Brazilian standards applicable to a wide range of sectors throughout national activities (ABNT, n.d.). Among these standards is ABNT NBR 15527:2019, entitled "*Rainwater harvesting from roofs for non-potable uses—Requirements*," which establishes criteria for the safe use of rainwater in non-potable applications. Section 4.6 of the standard specifies the minimum quality parameters required for such use, limited to three indicators: *Escherichia coli*, turbidity, and pH.

The following regulations concerning water reuse have been identified at the state level:

- ✓ **Ceará:** COEMA Resolution No. 02, dated February 2, 2017, establishes standards and conditions for the discharge of liquid effluents generated by polluting sources. It repeals SEMACE Ordinances No. 154, dated July 22, 2002, and No. 111, dated April 5, 2011, and amends SEMACE Ordinance No. 151, dated November 25, 2002. The resolution also introduces guidelines and parameters for non-potable water reuse, in compliance with national environmental policies.
- ✓ **Rio Grande do Sul:** CONSEMA Resolution No. 419/2020 sets forth criteria and procedures for the use of reclaimed water for urban, industrial, agricultural, and forestry purposes within the state. It defines quality standards, monitoring requirements, and licensing procedures for the safe and sustainable application of treated effluents.
- ✓ **Rio Grande do Norte:** Law No. 11.332, dated December 30, 2022, establishes the policy for non-potable water reuse within the State of Rio Grande do Norte. The law aims to promote, regulate, and manage the practice of water reuse, providing definitions, modalities (urban, agricultural, industrial, environmental, and domestic), and outlines responsibilities for producers, distributors, and users of reclaimed water. It also

emphasizes sustainable water management and environmental protection, particularly in semi-arid regions.

- ✓ **Paraná:** CERH Resolution No. 122, dated June 19, 2023, sets forth general guidelines and criteria for the reuse of treated effluents from sanitary and industrial sources. The resolution covers multiple reuse modalities—urban, agricultural, forestry, environmental, and industrial—and establishes quality standards, licensing procedures, and monitoring requirements. It also mandates the use of separate and clearly marked distribution networks to prevent cross-contamination among potable water supplies.

The Municipality of Joinville, in the State of Santa Catarina, Brazil, enacted Complementary Law No. 220, dated October 3, 2006, which regulates the reuse of rainwater under specific conditions and establishes related provisions.

- ✓ Article 1 stipulates that "stormwater collected from roofs, balconies, terraces, eaves, and other open areas of buildings intended for residential, industrial, commercial, or service use—whether public or private—as well as horizontal and/or vertical residential condominiums with a total constructed area equal to or greater than 750 square meters, must be directed to a designated reservoir".
- ✓ Article 4, §1 further specifies that the water collected and stored in such reservoirs shall be used exclusively for non-potable purposes, in activities that do not require treated water supplied by the public water system, including: "I – flushing toilets; II – washing vehicles; III – laundering clothes; IV – irrigation of vegetable gardens, lawns, and crops".

However, it is noted that Complementary Law No. 220 stills requires regulatory implementation.

It is essential to emphasize that the Brazilian legislation discussed in this section exclusively addresses the reuse of previously treated water. Nevertheless, considering that the primary objective of this study is to characterize water originating from urban drainage systems, it becomes evident that Brazil lacks specific regulations governing the reuse of this alternative water source.

3.3 INTERNATIONAL REGULATORY FRAMEWORKS FOR STORMWATER MANAGEMENT (URBAN RUNOFF WATER)

In contrast to Brazil, the international context reveals the existence of regulatory frameworks and technical guidelines concerning the management and potential reuse of stormwater.

For example, in the United States, the Environmental Protection Agency (EPA) developed a technical guidance document in 2009 concerning the implementation of stormwater runoff requirements in federal projects. Although this document does not carry legal force—that is, it does not impose mandatory obligations on implementers—it serves solely as a technical reference to assist agencies and governmental departments in complying with the standards outlined therein (EPA, 2009). Moreover, in addition to federal regulations, individual states may establish their own rules. A case in point is Pennsylvania, where the city of Philadelphia published a Stormwater Management Guidance Manual in 2023, providing recommendations for the design of stormwater management systems (Philadelphia Water Department, 2023).

Similarly, Ontario, Canada, has a Stormwater Management Planning and Design Manual (2003), which provides technical and procedural guidance for the planning, design, and review of stormwater management practices (Queen's Printer, 2003).

In Europe, Directive 2000/60/EC of the European Parliament and of the Council, dated 23 October 2000, establishes practices related to stormwater management. Its main objective is to protect all water bodies, ensuring they achieve and maintain good ecological and chemical status (Jensen et al., 2020).

In Oceania, the Waikato Regional Council of New Zealand published the Waikato Stormwater Management Guideline in 2020, which is divided into two parts: the Waikato Stormwater Management Guideline (TR2020/07) and the Waikato Stormwater Runoff Modelling Guideline (TR2020/06).

The World Health Organization (WHO) (2001) released the guideline *Water Quality: Guidelines, Standards and Health*, which addresses risk assessment and management for water-related infectious diseases. The proposal is that the same principles used to ensure the safety of drinking water can also be applied to recycled water, through a unified risk management approach encompassing drinking water, recycled water, and recreational water (Natural Resource Management Ministerial Council, Environment Protection and Heritage Council & National Health and Medical Research Council, 2009).

Australia, by contrast, has developed specific guidelines focused on the management of urban runoff water. The document *Stormwater Harvesting and Reuse* (2009) provides guidance on health and environmental risk management related to the reuse of roof and urban runoff water, with an exclusive focus on non-potable applications.

The regulatory frameworks discussed here indicate that several countries have demonstrated increasing concern regarding stormwater management (urban runoff), aiming to strategically integrate it into urban planning with a focus on environmental sustainability, public health protection, local economic development, and public acceptance as a safe alternative source for reuse in specific activities.

Nonetheless, there remains an urgent need for more assertive governmental action, particularly in funding research aimed at characterizing the quality of urban runoff and evaluating its true potential for reuse at medium and large scales.

3.4 RISK ASSESSMENT TOOLS APPLIED TO WATER INFRASTRUCTURE SYSTEMS

Stormwater is regarded as viable alternative source for reuse, as previously discussed in Section 3.1. As a naturally available resource, rainwater has attracted growing interest from the scientific community, particularly in relation to its conservation and the diverse possibilities for reuse—ranging from small-scale to large-scale.

However, for such utilization to be both feasible and safe, it is essential that its management be effective, efficient, and, above all, capable of ensuring adequate safety levels for both the environment and the population potentially exposed to this water (Rentachintala, Reddy & Mohapatra, 2022; Natural Resource Management Ministerial Council, Environment Protection and Heritage Council & Australian Health Ministers Conference [NRMMC-EPHC-PAHMC], 2006).

The risk assessment process aims to prioritize hazardous events by classifying them according to their severity levels, thereby directing attention and efforts toward those that pose the greatest threat to the safety of water-reuse practices (WHO, 2023).

The risk level for stormwater reuse is estimated through a risk analysis, which involves (NRMMC-EPHC-PAHMC, 2006):

- ✓ Identifying chemical, physical, biological, and radiological hazards present in the water that may pose risks to human health, animals, and the environment—such as soil and bodies of water;
- ✓ Determination of hazardous events associated with these hazards, meaning situations or activities that may contribute to their occurrence or presence;
- ✓ Identification of potential sources of contamination in the urban-runoff-catchment area.

Environmental risks associated with water are primarily linked to the presence of chemical agents in its composition, which may vary depending on region, land use, sanitation practices, and the influence of local atmospheric pollutants. In stormwater-reuse projects, an initial screening-level risk assessment can be employed. This approach enables decision-makers to concentrate efforts on parameters that genuinely require attention (NRMMC-EPHC-PAHMC, 2006).

The screening-level risk assessment applies to the 95th percentile method to estimate risks associated with physical and chemical contaminants. Results are analyzed using a risk matrix (Figure 2), which helps classify the level of concern. If the risk is deemed unlikely, no further action is required. However, if the risk is classified as moderate or higher, a maximum risk assessment (assuming no preventive measures) must be conducted, followed by a residual risk assessment that accounts for the implementation of control measures (Natural Resource Management Ministerial Council, Environment Protection and Heritage Council & National Health and Medical Research Council, 2009; NRMMC-EPHC-PAHMC, 2006).

Figure 2 - Reference matrix to guide the interpretation of results from the screening-level risk assessment

Likelihood			Consequences		
	1-Insignificant	**2-Minor**	**3-Moderate**	**4-Major**	**5-Catastrophic**
A Rare	Low	Low	Low	High	High
B Unlikely	Low	Low	Moderate	High	Very high
C Possible	Low	Moderate	High	Very high	Very high
D Likely	Low	Moderate	High	Very high	Very high
E Almost certain	Low	Moderate	High	Very high	Very high

Reference: NRMMC-EPHC-PAHMC (2006), (Natural Resource Management Ministerial Council, Environment Protection and Heritage Council & National Health and Medical Research Council, 2009).

Beyond preliminary risk screening, a more in-depth assessment of health and environmental risks associated with water reuse projects can be conducted using the following methods (Seis, 2012):

- ✓ **Qualitative and semi-quantitative**: typically assessed by calculating the probability and magnitude/severity of a given hazard's impact on the exposed receptor, using a risk matrix;
- ✓ **Quantitative**: in terms of health, numerical risk assessment is based on the dose–response relationship of the individual, aiming to determine the effect of the hazard or hazardous event on human health. This calculation can be performed using the Quantitative Microbial Risk Assessment (QMRA) method.

For chemical risk assessment, the Quantitative Chemical Risk Assessment (QCRA) method typically employed. This methodology is founded on the ratio between the Predicted Environmental Concentration (PEC)— wich is calculated using models that simulate the fate and transport of a specific pollutant within environmental compartments—and the Predicted No-Effect Concentration (PNEC), or the maximum allowable concentration as defined by applicable legislation. The application of the QCRA method, however, requires a substantial volume of monitoring data; otherwise, its practical applicability becomes limited.

In addition to the methodology previously discussed, Failure Modes and Effects Analysis (FMEA) has also been applied in specific contexts related to environmental risk assessment. Prior to detailing its application in evaluating physical and chemical risks within environmental systems, a brief overview of the traditional structure of the methodology will be provided.

The traditional structure of the FMEA methodology comprises five main steps: (1) identifying potential failures and their impacts, (2) assessing severity, (3) analyzing the frequency of occurrence, (4) evaluating the ability to detect failures, and finally, (5) calculating the Risk Priority Number (RPN), wich is determined by the following formula (Subriadi & Najwa, 2020):

$$RPN = \text{severity} \times \text{detection} \times \text{occurrence}$$

The RPN value determines the priority of failures and is used to rank potential failures within a given process. Each component of the previously presented formula plays a specific role that ultimately leads to the calculation of the RPN. These components are shown in Table 1 (Suwandi, Zagloel & Hidayatno, 2020).

Table 1 - Parameters used to evaluate the Risk Priority Number (RPN) and to support decision-making prioritization

Severity	It refers to the assessment of the severity of effects on the process or product. In this context, each identified failure is analyzed based on its level of impact. A predefined scoring system and set of criteria are used to support this evaluation.
Occurrence (or event level)	Occurrence assessment is carried out to estimate how frequently such failures may arise in the production environment. A reference table containing scores, classifications, and failure rates should be consulted for this evaluation.

Detection	The purpose of the detection assessment is to estimate the likelihood that a failure will be effectively identified before it leads to significant consequences. A reference table containing the parameters of scoring, detection, and evaluation criteria is used during the assessment process.

Reference: Adapted by the author from Suwandi, Zagloel & Hidayatno (2020).

The three parameters listed in Table 1 must be identified during the evaluation of a given process or product. Then, the RPN is calculated, and the result will indicate the priority for action within that process or product (Suwandi, Zagloel & Hidayatno, 2020).

In the environmental field, the FMEA methodology has been employed to assess risks within the drinking water supply chain and in water reuse treatment systems, often coupled with a risk matrix. Based on that, the Instituto Superiore di Sanità (ISS) in Italy recommends, through the document *Rapporti ISTISAN 22/33* (2022), the application of the FMEA methodology for risk assessment in the drinking water supply chain.

This methodology is applied to chemical parameters for risk assessment within the drinking water supply chain, using limit values defined by legislation. To this end, historical water quality data must be analyzed to estimate the probability of occurrence of hazardous events. This estimation is typically performed using the 95th percentile, which represents the value exceeded in only 5% of the measurements performed (ISS, 2022).

The 95th percentile (P95) value of each physicochemical parameter is compared against the range defined between the Limit of Quantification (LOQ), which represents the lowest concentration of a substance that can be reliably measured through laboratory analysis, and the legal limit (LL), as established by current legislation and/or international guidelines (ISS, 2022; EFSA, n.d.). In summary, the methodology outlined in the ISTISAN report classifies the risk of each physicochemical parameter based on its P95 statistical value. The closer the P95 concentration is to the legal limit (LL), or if it exceeds it, the higher the assigned risk. Conversely, the nearer it is to the LOQ, the lower the associated risk.

This interval is systematically subdivided into five equally sized ranges (R1, R2, R3, R4, and R5), where R represents the detectability factor. In the context of chemical risk assessment, when the P95 value of a parameter falls within R1 or R2, the risk is considered low. If the value falls within R3, it is classified as moderate and mandates managerial attention. Conversely, parameters positioned in R4 or R5 are considered high-risk, requiring priority action by managers and, when necessary, the implementation of targeted control measures.

As previously established, the FMEA methodology has demonstrated significant robustness for risk assessment in processes and products, extending its utility to environmental applications—particularly within water supply chains and water reuse treatment systems. Nevertheless, its application in risk assessment related to rainwater reuse remains rather limited, as methodologies such as QCRA and QMRA are more commonly employed in this context. However, an interesting example demonstrating the potential of FMEA for analyzing risks in urban drainage water is the study conducted by Vidal et al. (2020). This research applied the methodology to identify and assess human health risks associated with drainage water in an urban watershed located in Campina Grande, in northeastern Brazil.

Although only one study has been identified by applying the FMEA methodology to stormwater risk assessment, this initiative has proven to be significant as it broadens the methodological scope and underscores the need for further research to scientifically and safely validate the feasibility of FMEA as an analytical tool for alternative water sources.

4. METHODOLOGY

Asa mandatory component of the doctoral program, a six-month international research placement was conducted in Brazil, in collaboration with the Universidade do Estado de Santa Catarina (UDESC – Joinville Campus), from November 2, 2024, to May 2, 2025. Within this context, the present study was developed as an initial and innovative contribution to the region, particularly given the absence of prior research of this nature in the study area, as previously reported. The study's relevance is rooted its capacity to characterize the current scenario regarding the reuse of urban drainage water sources, while simultaneously identifying opportunities for implementing this practice and developing future projects focused on the management and reuse of urban drainage water.

The ensuing section details the methodology employed of this study.

4.1 LITERATURE REVIEW

To develop the literature review, an extensive search was conducted for scientific articles addressing the use of stormwater as a reuse alternative, with emphasis on its environmental and social impacts. The investigation aimed to understand the approaches adopted in studies on this topic in Brazil—particularly in the region where the present research was carried out—with a focus on responses to climate change, the identification of major pollutants and their typical concentrations, as well as the potential risks associated with stormwater reuse.

Additionally, official websites of European projects related to the topic were consulted in order to understand ongoing studies and the results already achieved. This stage broadened the perspective on internationally adopted practices, as well as technological and regulatory advancements in the sector.

The research also encompassed a comprehensive analysis of international legislation and technical guidelines concerning stormwater Utilization. Concurrently, a detailed survey of Brazilian legislation was performed at the federal, state, and municipal levels. The focus of this review was placed on the required quality parameters and potential guidelines for reuse. Additionally, technical standards issued by the Brazilian Association of Technical Standards (ABNT) were examined, specifically those related to water reuse and stormwater harvesting.

Furthermore, a bibliographic review of international guidelines was conducted, concentrating on the tools employed in the assessment of environmental and health risks in water infrastructure systems.

4.2 DEFINITION OF SAMPLING POINTS

The definition of stormwater (urban runoff) sampling points was initiated through map analysis and technical discussions with experts from the Babitonga Bay Water Complex Management Committee (CHBB), the Municipality of Joinville (State of Santa Catarina, Brazil), and the University of the State of Santa Catarina (UDESC – Joinville Campus).

The primary objective was to identify representative urban areas of interest for stormwater characterization, considering the land use and land occupation patterns prevalent within the municipality.

Based on the initial analysis, three preliminary sampling points were selected in urban areas characterized by residential and commercial land use:

- ✓ the central-northern area near the northern industrial zone (Costa e Silva neighborhood);
- ✓ the southeastern area (Bucarein and Boa Vista neighborhoods); and
- ✓ another central-northern area (Jardim Sofia neighborhood).

Following the identification of these target regions, on-site meetings, technical consultations, and detailed analyses of both physical and digital maps were conducted. This work, including the review of the Municipality's Georeferenced Information System (SIMGeo), was performed in collaboration with technicians from the Urban Infrastructure Department, Urban Drainage Division (SEINFRA) of the Municipality of Joinville.

These activities were primarily aimed at locating existing stormwater drainage pipelines in the selected areas for subsequent sample collection.

With the sampling points defined, field visits were executed to pinpoint the urban drainage pipelines and assess potential obstacles that could hinder sample collection.

The main factors analyzed during the field survey included: the distance between pipelines and riverbanks or sidewalks; the presence of vegetation that might obstruct access to the pipelines; the height of bridges relative to the drainage infrastructure; and possible signs of groundwater infiltration or illegal wastewater connections - this latter being critically assessed during dry weather conditions.

This stage was essential to ensure that no interference or contamination from extraneous sources would occur during the collection of urban runoff water (Figures 3, 4, 5, and 6).

Figure 3 - Limited access to drainage pipelines due to vegetation along the riverbank

Figure 4 - Limited access due to the drainage pipeline base being close to the riverbed, which could lead to contamination with river water during rainwater sampling

Figure 5 – Inaccessible pipeline due to household waste deposited on the property adjacent to the drainage system

Figure 6 - Water discharge from one of the predefined sampling points during dry weather, possibly indicating groundwater seepage or an illegal sewage connection

Whenever obstacles were identified during field visits, additional formal meetings and/or informal discussions, often conducted via messaging applications, were held with technicians from the Urban Drainage Division of the Infrastructure Department (SEINFRA). The purpose of these interactions was to reassess the initially proposed sampling points and evaluate feasible alternatives. This iterative process continued until optimal locations for urban runoff water sampling were definitively determined.

Furthermore, SEINFRA technicians provide additional support by preparing indicative maps outlining the approximate rainwater catchment areas corresponding to the final sampling points, thereby contributing to the spatial delimitation and enhancing the understanding of runoff dynamics in the studied regions.

4.3 PREPARATORY STEPS FOR STORMWATER SAMPLING

The collection of stormwater necessitated continuous monitoring of weather forecasts, utilizing specialized digital platforms such as Climatempo, Windy, and Il Meteo, as well as alerts issued by the Civil Defense of the State of Santa Catarina.

This monitoring was essential to ensure that samples were collected immediately following the onset of the first rainfall. It is critical to note that this procedure does not refer to the collection of first-flush water, but rather to freshly discharged rainwater, thereby preserving its original characteristics.

Another relevant factor was the monitoring of the tidal chart for the Port of São Francisco do Sul (SC), covering the years 2024 and 2025, made available by the Brazilian Navy's Hydrography Center (Figure 7) and accessible via its official website.

To ensure the feasibility of sampling at the three previously established points, given that the port is located approximately 51 km from Joinville, it was necessary to estimate an interval of 20 to 30 minutes for the tide level, as indicated in the chart, to reach appropriate conditions in the sampling areas.

Adhering to the correct interval was crucial to preclude contamination of urban runoff water samples by saltwater, since high tide can induce the flooding of the drainage pipelines - an occurrence that would compromise sample quality (Figures 8 and 9).

Figure 7 - Example of tidal chart monitored at the Port of São Francisco do Sul (Brazil)

PORTO DE SÃO FRANCISCO DO SUL (ESTADO DE SANTA CATARINA) - 2025

Latitude 26° 14'.7 S | Longitude 48° 38'.5 W | Fuso UTC -03.0 horas

DHN-20 | 95 Componentes | Nível Médio 0.89 m | Carta 1804

Janeiro

	HORA	ALT(m)		HORA	ALT(m)
01 QUA	0357 0821 1155 1331 1701 2147	1.84 0.41 0.94 0.87 1.45 0.05	17 SEX	0549 0951 1404 1508 1732 2202	1.65 0.14 1.29 1.25 1.37 0.09
02 QUI	0444 0902 1227 1423 1747 2221	1.82 0.39 1.01 0.88 1.42 0.11	18 SÁB	0629 1023 1440 1606 1806 2238	1.52 0.15 1.31 1.25 1.33 0.15
03 SEX	0527 0942 1302 1516 1829 2301	1.76 0.40 1.09 0.87 1.38 0.20	19 DOM	0708 1102 1510 1701 1851 2310	1.38 0.22 1.28 1.21 1.27 0.24
04 SÁB	0614 1012 1342 1608 1914 2336	1.66 0.41 1.16 0.85 1.34 0.33	20 SEG	0302 0457 0755 1138 1542 1719 1949 2353	0.97 0.89 1.24 0.36 1.18 1.11 1.23 0.37
05 DOM	0702 1055 1414 1702 2006	1.54 0.44 1.19 0.81 1.32	21 TER	0325 0559 0844 1212 1602 1753 2049	1.02 0.83 1.11 0.52 1.05 0.96 1.22
06 SEG	0016 0755 1131 1455 1751 2102	0.47 1.40 0.51 1.18 0.74 1.31	22 QUA	0029 0359 0651 0938 1301 1604 1806 2147	0.52 1.04 0.77 1.03 0.67 0.89 0.79 1.25

Fevereiro

	HORA	ALT(m)		HORA	ALT(m)
01 SÁB	0510 0923 1259 1440 1759 2216	1.78 0.28 1.03 0.94 1.59 0.12	17 SEG	0212 0340 0640 1034 1802 2234	1.02 0.99 1.33 0.13 1.42 0.16
02 DOM	0601 1001 1334 1540 1844 2249	1.65 0.23 1.14 0.97 1.50 0.27	18 TER	0225 0455 0717 1104 1855 2304	1.13 0.93 1.18 0.26 1.32 0.30
03 SEG	0647 1034 1408 1636 1929 2316	1.48 0.24 1.20 0.93 1.39 0.44	19 QUA	0253 0551 0804 1140 1659 1957 2342	1.20 0.84 1.05 0.43 0.99 1.24 0.47
04 TER	0216 0408 0736 1108 1451 1727 2027 2359	0.81 0.69 1.29 0.29 1.22 0.82 1.29 0.63	20 QUI	0314 0634 0902 1210 1538 1732 2059	1.23 0.74 0.97 0.60 0.89 0.80 1.22
05 QUA	0253 0523 0827 1155 1523 1816 2140	0.96 0.67 1.13 0.40 1.16 0.67 1.25	21 SEX	0014 0344 0710 1006 1304 1502 1802 2201	0.66 1.20 0.65 0.96 0.77 0.82 0.59 1.27
06 QUI	0046 0321 0627 0934 1240 1601 1902 2255	0.84 1.06 0.62 1.02 0.55 1.06 0.51 1.28	22 SÁB	0104 0401 0746 1119 1831 2259	0.85 1.13 0.58 1.04 0.39 1.38

Março

	HORA	ALT(m)		HORA	ALT(m)
01 SÁB	0406 0831 1649 2114	1.85 0.23 1.81 0.00	17 SEG	0525 0936 1701 2129	1.42 0.00 1.63 0.04
02 DOM	0455 0902 1353 1727 2140	1.74 0.13 0.95 1.75 0.12	18 TER	0134 0340 0604 1004 1738 2201	1.15 1.04 1.26 0.10 1.55 0.12
03 SEG	0542 0936 1312 1501 1808 2204	1.56 0.09 1.09 0.97 1.63 0.26	19 QUA	0157 0447 0655 1040 1819 2227	1.27 0.94 1.11 0.25 1.44 0.27
04 TER	0116 0306 0625 1006 1353 1602 1901 2240	0.88 0.74 1.36 0.09 1.16 0.92 1.46 0.45	20 QUI	0217 0532 0749 1108 1910 2302	1.34 0.81 0.99 0.40 1.34 0.43
05 QUA	0157 0427 0716 1051 1429 1702 2002 2310	1.10 0.73 1.17 0.18 1.17 0.80 1.29 0.66	21 SEX	0246 0610 0847 1155 1504 1625 2010 2338	1.35 0.68 0.94 0.58 0.80 0.77 1.28 0.65
06 QUI	0229 0534 0816 1127 1504 1801 2112 2350	1.25 0.65 1.02 0.33 1.13 0.63 1.20 0.88	22 SÁB	0302 0646 0949 1302 1406 1710 2112	1.32 0.57 0.97 0.75 0.76 0.58 1.28

Abril

	HORA	ALT(m)		HORA	ALT(m)
01 TER	0012 0157 0514 0906 1240 1423 1753 2136	0.83 0.74 1.44 0.02 0.98 0.87 1.70 0.36	17 QUI	0125 0425 0627 1016 1801 2202	1.33 0.93 1.05 0.26 1.57 0.27
02 QUA	0055 0312 0606 0949 1316 1525 1844 2206	1.10 0.77 1.24 0.07 1.03 0.82 1.51 0.50	18 SEX	0155 0510 0721 1101 1846 2236	1.39 0.78 0.97 0.41 1.48 0.44
03 QUI	0131 0425 0702 1025 1401 1625 1942 2251	1.31 0.71 1.07 0.19 1.03 0.72 1.33 0.69	19 SÁB	0214 0549 0821 1202 1936 2306	1.38 0.65 0.96 0.56 1.40 0.63
04 SEX	0208 0527 0806 1112 1444 1723 2055 2331	1.43 0.63 0.97 0.35 1.00 0.60 1.22 0.88	20 DOM	0234 0614 0921 1608 2036 2349	1.34 0.53 1.03 0.52 1.36 0.84
05 SÁB	0253 0617 0912 1208 1514 1814 2208	1.42 0.57 0.97 0.54 0.93 0.48 1.23	21 SEG	0249 0638 1021 1704 2138	1.27 0.44 1.15 0.35 1.38
06 DOM	0040 0325 0702 1017 1329 1553 1902 2323	1.06 1.27 0.56 1.06 0.68 0.82 0.41 1.34	22 TER	0032 0255 0701 1116 1753 2246	1.05 1.20 0.37 1.30 0.19 1.45

Reference: Marinha do Brasil (2025)

Figure 8 - Image of the Cachoeira River in Joinville-SC (Brazil) during high tide, with limited visibility of drainage pipeline outlets

Reference: Zschornack & Oliveira (2017)

Figure 9 - Image of the Cachoeira River in Joinville-SC (Brazil) during low tide, showing drainage pipelines not submerged

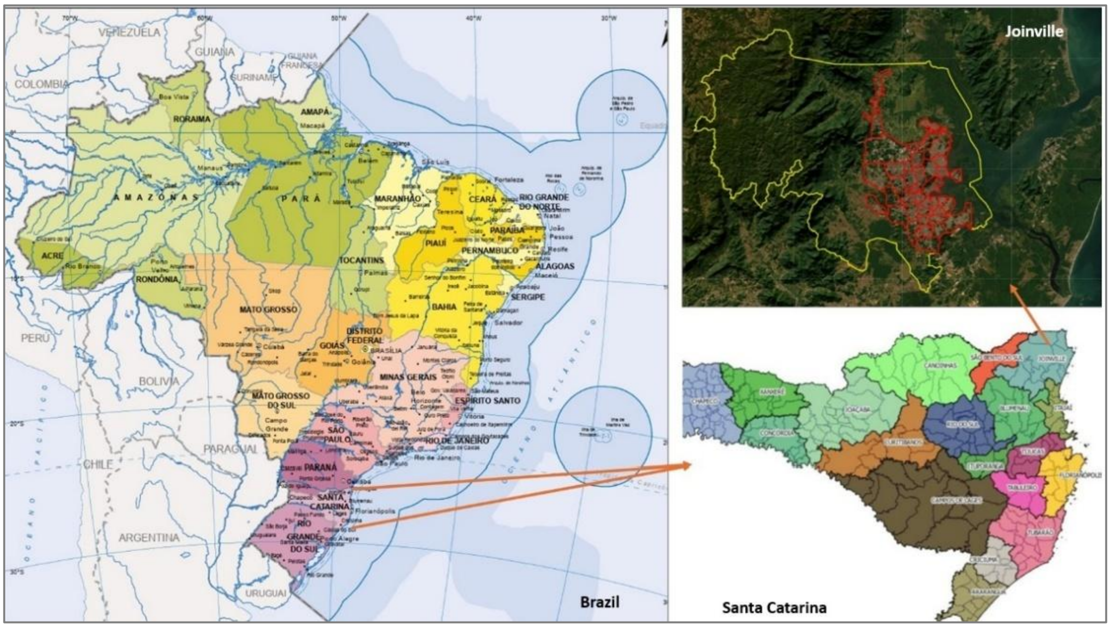
Reference: Saavedra (2025)

Based on daily monitoring of weather forecasts and tidal charts, once precipitation was confirmed for a specific date and time range, the outsourced laboratory responsible for the analyses was promptly notified. This notification ensured the advance preparation of sterilized sampling bottles and insulated containers, thereby guaranteeing proper sample preservation. Immediately following collection, the sample bottles were delivered to the laboratory, where analytical procedures were promptly initiated.

4.4 STUDY AREA

Joinville, located in the State of Santa Catarina in southern Brazil, is one of the 5,570 municipalities that comprise the Federative Republic of Brazil (IBGE, 2024) (Figure 10).

Figure 10 - Location of the state of Santa Catarina within the national context, and of the Municipality of Joinville in relation to the state of Santa Catarina



Reference: IBGE (s.d); (Lima, et al., 2011); (Prefeitura Municipal de Joinville, 2025)

Joinville covers a territorial area of 1,127.837 km². The estimated population for 2024 is 654,888 inhabitants, while the population density recorded in 2022 was 546.41 inhabitants per square kilometer.

Notably, the municipality's Human Development Index (HDI) stands at 0.809 (IBGE, 2023). The local economy encompasses a diverse range of activities, including artisanal agroindustry, rural tourism, industrial production, services, commerce, freelance professionals, and individual micro-entrepreneurs (MEI) (Joinville Municipal Government, 2024a).

From a hydrological perspective, Joinville is considered a privileged municipality, as nearly all river sources are located within its own territorial boundaries.

This condition results from the interaction of several factors, including the clay-rich composition of the soil—which has low permeability and hinders rainwater infiltration—and the region's high rainfall index (Maia et al., n.d.).

The elevated precipitation levels are influenced by a combination of elements: the presence of a mountain range with altitudes exceeding one thousand meters, proximity to the Atlantic Ocean, and the action of atmospheric systems—particularly frontal systems, which are meteorological phenomena that affect weather patterns across the extratropical and subtropical latitudes of South America (Mello & Oliveira, 2016; Souza, 2016).

Figure 11 presents climatological data for the municipality spanning the period from 1991 to 2021, enabling the visualization of both general climate characteristics and recorded precipitation volumes (in millimeters) throughout this interval (Joinville Municipal Government, 2024b).

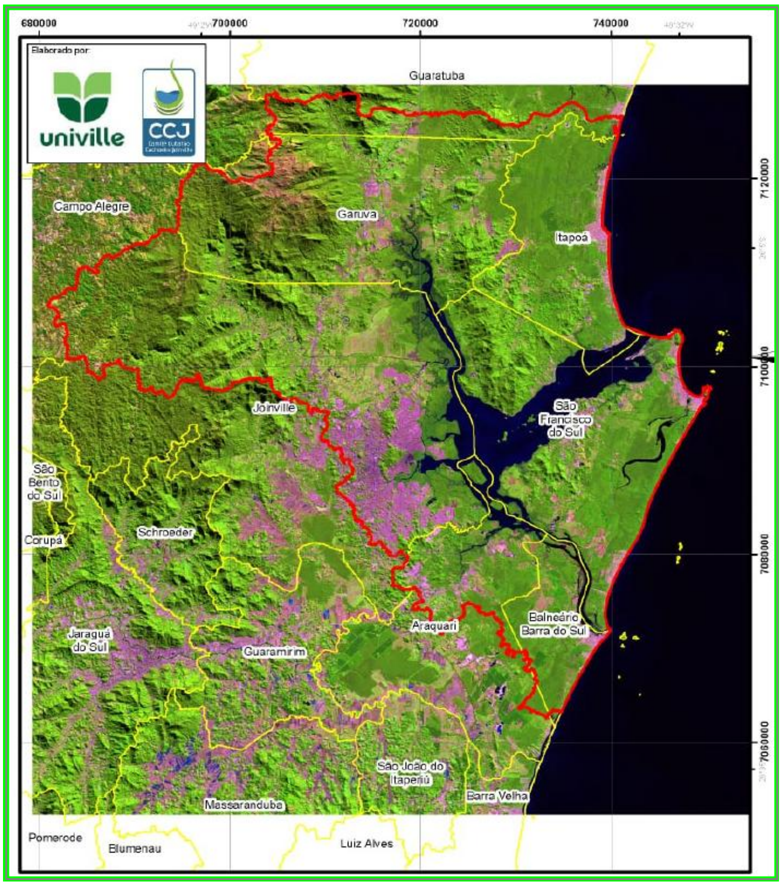
Figure 11 - Climatological data for the period from 1991 to 2021

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Average temperature (°C)	24.7	24.8	23.9	22.1	19	17.3	16.5	17.3	18.6	20.4	21.8	23.7
Minimum temperature (°C)	21.9	22	21.3	19.2	16	14.2	13.2	14	15.7	17.7	18.9	20.8
Maximum temperature (°C)	28.3	28.4	27.4	25.7	22.8	21.4	20.7	21.7	22.5	24.1	25.4	27.4
Rain (mm)	290	262	211	126	112	108	100	94	154	157	166	196
Humidity (%)	82%	84%	84%	83%	81%	84%	84%	83%	82%	82%	81%	81%
Rainy days (d)	18	16	17	12	10	7	8	7	11	14	14	15
Sunny hours (h)	6.4	6.5	5.7	5.6	5.6	5.6	5.5	5.2	4.4	4.1	4.9	5.7

Reference: Adapted by the author from Prefeitura Municipal de Joinville (2024b).

In terms of watershed governance and water resource management, it is important to highlight that the river watershed within the Municipality of Joinville are part of the Watershed Management Committee for the Babitonga Bay Hydrological Complex and Adjacent Basins (Babitonga Committee – CHBB), established by State Decree No. 834 on September 15, 2020. In addition Joinville, the committee includes five other municipalities: São Francisco do Sul, Araquari, Balneário Barra do Sul, Garuva, and Itapoá (Figure 12).

Figure 12 - Area of operation of the Watershed Management Committee of the Babitonga Bay Hydrological Complex



Reference: (CHBB, n.d.)

The study area encompasses the Municipality of Joinville, within which seven river watershed are located (Figure 13) (Oliveira et al., 2017). These include:

1) Palmital River Watershed;

2) Cubatão (North) River Watershed;

3) Piraí River Watershed;

4) Itapocuzinho River Watershed;

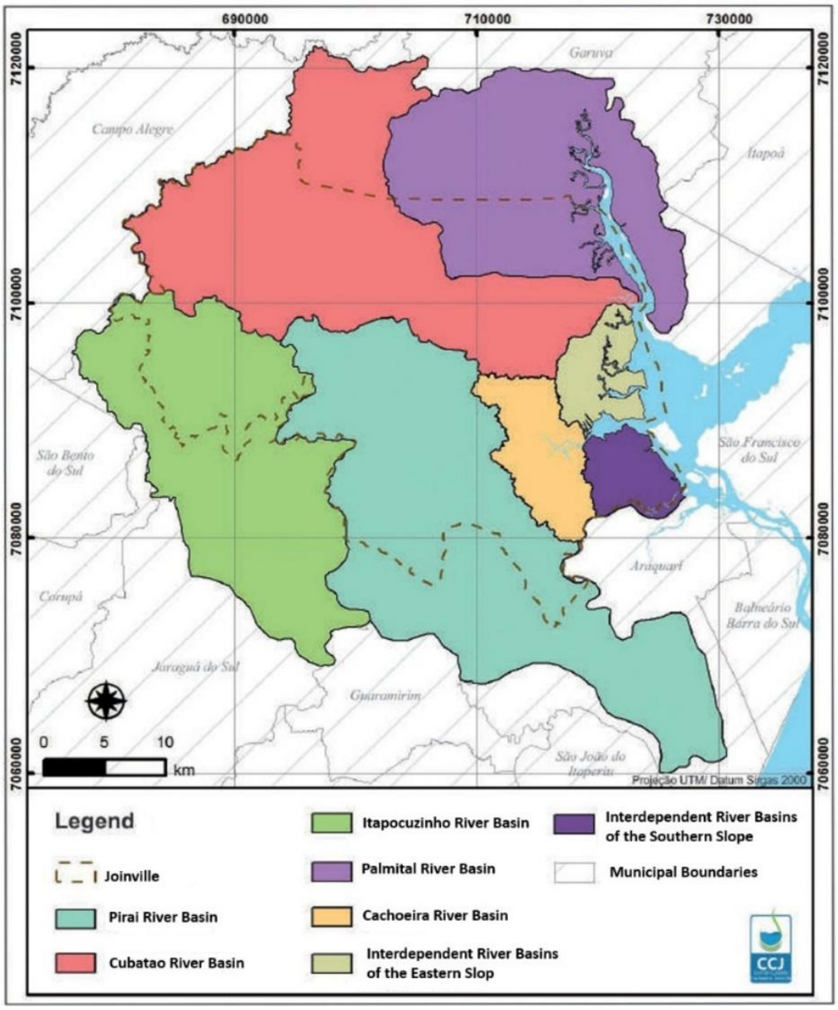
5) Cachoeira River Watershed;

6) Independent River Watershed of the Eastern Slope; and

7) Independent River Watershed of the Southern Slope.

Urban stormwater samples were collected exclusively within two specific areas: the Cubatão (North) River Watershed - highlighted in salmon in Figure 13 - and the Cachoeira River Watershed, marked in yellow in the same figure. Both are briefly described in the following section.

Figure 13 - Hydrographic regions of the Municipality of Joinville-SC, Brazil



Reference: Adapted by the author from Oliveira, et al. (2017)

Approximately 75% of the Cubatão (North) River Watershed is located within the Municipality of Joinville, while the remaining 25% lies within the municipality of Garuva. The watershed spans a total area of 492 km², with a perimeter of 159.16 km, and its main channel extends for 88 km. Its source is located in the Serra Queimada, at an altitude of 1,100 meters. This watershed contains Joinville's primary water treatment plant, which supplies approximately 70% of the city's public water. Additionally, it includes water intake points for industrial and agricultural use (Maia et al., n.d.).

The Cachoeira River Watershed is classified as urban, as it is entirely situated within the built-up area of the municipality. Covering a drainage area of 83.12 km², the watershed has a channel length of 14.9 km and a perimeter of 59.31 km. Approximately 49% of the municipal population resides within its boundaries. Its sources are located at an altitude of 40 meters, and its mouth opens into an estuarine region under direct tidal influence.

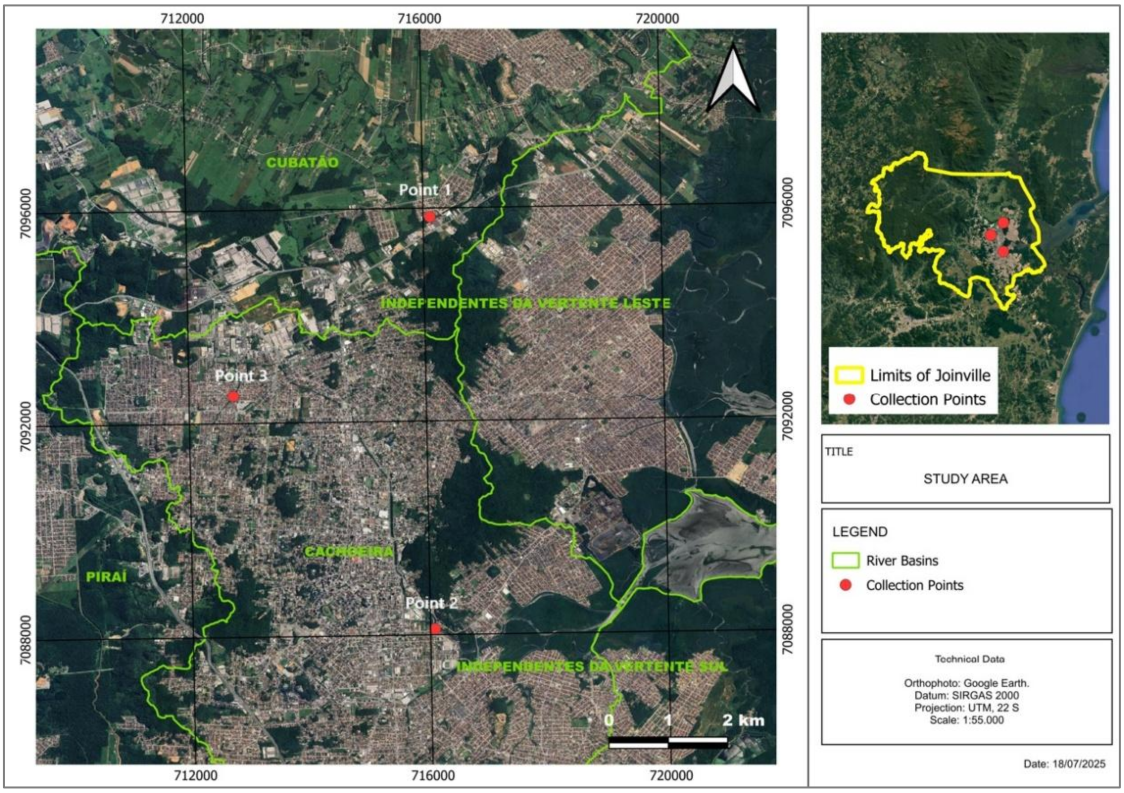
During high tide periods, flow reversal is observed, with saltwater intrusion reaching up to half the length of the river.

The low elevation of the watershed near its mouth—combined with the influence of astronomical and meteorological tides, as well as episodes of intense rainfall—significantly contributes to recurrent flooding in the city's central area (Maia et al., n.d.).

4.5 CHARACTERIZATION OF SAMPLING POINTS AND SAMPLE COLLECTION METHODOLOGY

As previously established, three sampling points were selected for the preliminary study on urban runoff water characterization: one located in the Cubatão (North) River Watershed and two in the Cachoeira River Watershed. Their respective locations are illustrated in Figure 14.

Figure 14 - Geographical distribution of the three sampling points



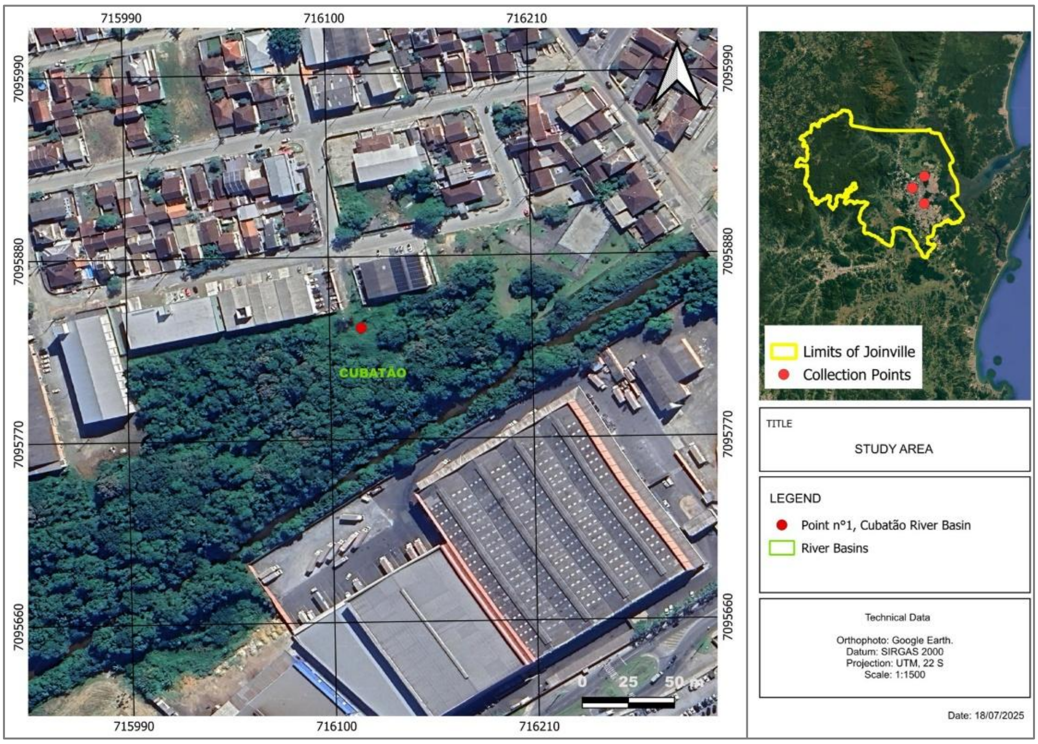
Reference: Prefeitura Municipal de Joinville: SIMGeo (2025)

Sampling Point 1, situated at the terminous of Rua José Josmar da Silva in the Jardim Sofia neighborhood, is located within a mixed residential and commercial area in the central-northern region of the Cubatão River Watershed.

According to Municipal Complementary Law No. 470 (dated January 9, 2017), this area is officially classified as an Urban Macrozone of Controlled Densification (AUAC).

These zones are characterized by occasional environmental vulnerabilities, limited infrastructure, constraints on road system improvements, and deficiencies in access to public transportation, public facilities, and essential services. Such conditions inherently restrict the area's capacity to accommodate new residents or economic activities (Figure 15).

Figure 15 - Spatial Location of Sampling Point 1 – Neighborhood: Jardim Sofia



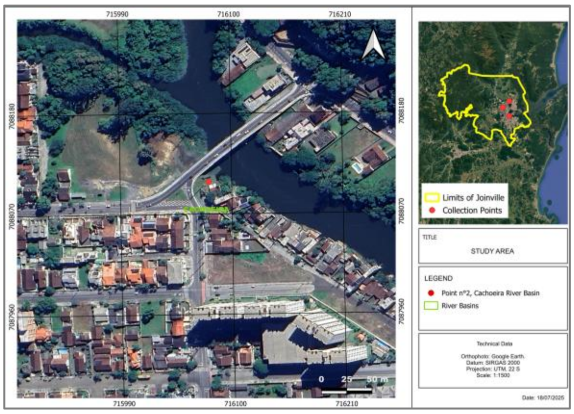
Reference: Prefeitura Municipal de Joinville: SIMGeo (2025)

Sampling Points 2 and 3 were established within the Cachoeira River Watershed. Sampling Point 2 is located along Rua Dr. Plácido Olímpio de Oliveira, between the Bucarein and Boa Vista neighborhoods, in an area classified under the urban macrozoning plan as a Priority Urban Densification Area (AUAP).

This category encompasses regions that generally do not exhibit environmental fragility and are characterized by consolidated infrastructure, a well-structured road network, efficient public transportation, and public facilities capable of supporting projected population growth. Additionally, these AUAP areas tend to concentrate tertiary sector activities with low environmental impact and contain extensive urban voids (Joinville, 2017).

Sampling Point 3, located on Rua Promotor Ary Silveira de Souza in the Costa e Silva neighborhood, is also situated within an AUAP macrozone, similar to Point 2 (Figure 16).

Figure 16 - Spatial Location of Sampling Points 2 and 3, respectively



Reference: Prefeitura Municipal de Joinville: SIMGeo (2025)

Reference: Prefeitura Municipal de Joinville: SIMGeo (2025)

Two distinct sampling campaigns were executed at each designated point, resulting in a total of twelve collected samples.

To acquire the stormwater samples, simple and readily accessible instruments were employed, selected based on the previously observed field conditions. Specifically, a container was utilized for the direct capture of water at the drainage pipe outlet; ropes were necessary to lower the container into the drainage system; and a funnel was used to facilitate the transfer of the collected water into sampling bottles.

4.6 RISK CHARACTERIZATION BASED ON LEGAL THRESHOLDS AND FMEA METHODOLOGY

In this study, risk assessment was initially conducted through a preliminary screening, comparing the physicochemical and microbiological results obtained from the characterization of urban drainage water against the limits established by Resolution CERH/PR No. 122/2023. Although this resolution is not specifically designated for the reuse of urban drainage water, it was adopted due to its extensive coverage of relevant physicochemical and microbiological parameters for environmental evaluation, particularly when contrasted with the ABNT NBR 15227:2019 standard, which has a narrower scope focused exclusively on rooftop rainwater harvesting.

Following the initial screening, physicochemical parameters will be evaluated using the Failure Mode and Effects Analysis (FMEA) methodology for risk quantification. In this study, Limit of Quantification (LOQ) values were obtained directly from the laboratory reports. A human health risk assessment will not be conducted at this stage, as the study is exploratory and not linked to any concrete engineering projects aimed at water reuse.

Instead, these results will serve to identify action priorities, allowing parameters classified as moderate or high risk to be considered by decision-makers should a reuse project be developed in the future.

The FMEA methodology adopted in this study strictly follows the approach described in ISTISAN Report 22/33 (2022), published by the *Instituto Superiore di Sanità* (Italy), as referenced in Section 3.4.

Figure 17 presents the table detailing the intervals corresponding to the five risk levels defined in the same report.

Figure 17 - Risk classification intervals derived from the 95th percentile (P95), legal limit (LL), and limit of quantification (LOQ)

FMEA Index	Calculation Formula (95th Percentile Interval)	Risk Level
I. FMEA = 1	P95 < LOQ + (LL - LOQ)/5	Very low
I. FMEA = 2	LOQ + (LL - LOQ)/5 ≤ P95 < LOQ + (2/5) x (LL - LOQ)	Low
I. FMEA = 3	LOQ + (2/5) x (LL - LOQ) ≤ P95 < LOQ + (3/5) x (LL - LOQ)	Moderate
I. FMEA = 4	LOQ + (3/5) x (LL - LOQ) ≤ P95 < LOQ + (4/5) x (LL - LOQ)	Hight
I. FMEA = 5	LOQ + (4/5) x (LL - LOQ) ≤ P95 < LL	Very hight
I. FMEA = 5	P95 > LL	Critical

Resolution CERH/PR No. 122, dated June 9, 2023, establishes three categories for the reuse of treated water, classified as follows:

- ✓ **Class A—Unrestricted non-potable reuse:** intended for landscape irrigation in areas with unrestricted access, floor, and public space washing, vehicle cleaning, ornamental purposes, firefighting, and building applications;
- ✓ **Class B—Restricted non-potable reuse:** intended for landscape irrigation in areas with limited or controlled access, particulate emission control, civil construction activities, and the unclogging of sewage, stormwater, and/or wastewater networks;
- ✓ **Reuse for agricultural and forestry purposes**.

5 RESULTS AND DISCUSSION

Sample collection at the three defined points was conducted during two distinct campaigns, which were not necessarily simultaneous across all locations.

This non-simultaneity was a direct consequence of the irregular distribution of rainfall observed in the Municipality of Joinville from November 2024 to February 2025, which prevented concurrent precipitation throughout the regions selected for this study. In other words, rainfall did not occur on the same days or within the same time frames at all sampling points.

Field monitoring was rigorously carried out to verify the occurrence of precipitation in accordance with meteorological forecasts and to confirm that the required minimum rainfall volume for sample collection had been reached.

The following section presents the initial screening calculations and the application of the FMEA methodology for risk assessment.

5.1 EXPLORATORY STUDY WITH A QUALITATIVE METHODOLOGY

As previously described in the methodology section, the three sampling points are in distinct regions, and the water collected at the drainage pipe outlets represents the flow originating from their respective catchment areas, which are illustrated in Figures 18, 19, and 20.

Figure 18 - Sampling point Nº 1 (Jardim Sofia Neighborhood – Cubatão River Watershed) and its corresponding approximate drainage area (Estimated surface area: 57,119 m²)

Figure 19 - Sampling point Nº 2 (Bucarein and Boa Vista Neighborhoods – Cachoeira River Watershed) and its corresponding approximate drainage area (Estimated surface area: 88,119 m²)

Figure 20 - Sampling point Nº 3 (Costa e Silva Neighborhood – Cachoeira River Watershed) and its corresponding approximate drainage area (Estimated surface area: 148,576 m²)

Understanding the approximate boundaries of the sampling area is a key element, as it facilitates terrain characterization and the identification of anthropogenic activities that may serve as potential sources of pollution.

This information is also essential for municipal managers when planning future treatment strategies aimed at stormwater reuse.

In this context, the results of the urban runoff water characterization are systematically presented in Figure 21.

Concentrations of thirty-nine parameters were analyzed and grouped into four categories: physical, chemical, metal, and microbiological.

The data were extracted from laboratory test reports identified by the following reference numbers: 2334/2025.0.A and 13507/2025.0.A (Sampling Point 1); 2345/2025.0.A and 13508/2025.0.A (Sampling Point 2); 85/2025.0.A and 6706/2025.0.A (Sampling Point 3).

Figure 21 - Results of stormwater quality analysis

			Sampling Campaign n° 1			Sampling Campaign n° 2		
Analyzed parameters	**Unit of measurement**	**Parameter Category**	**Point 1 01/17/25**	**Point 2 01/17/25**	**Point 3 01/06/25**	**Point 1 04/03/25**	**Point 2 04/03/25**	**Point 3 02/18/25**
pH		Physical	6.59	6.88	7.16	6.28	6.8	6.37
Conductivity	µS/cm	Physical	284.5	313.0	125.2	243.00	2386.0	39.73
Total Hydrocarbons (Mineral Oils)	mg/L	Chemical	< 10.0	<10.0	<10.00	< 10.0	< 10.0	< 10.0
Vegetable Oils and Animal Fats	mg/L	Chemical	< 10.0	<10.0	<10.00	< 10.0	< 10.0	< 10.0
Surfactants	mg/L	Chemical	< 0.20	<0.20	<0.20	< 0.20	< 0.20	< 0.20
Dissolved Aluminum	mg/L	Metals	0.0715	0.0761	0.1738	0.0645	0.067	0.085
Arsenic	mg/L	Chemical	< 0.0080	<0.0080	<0.0080	< 0.0080	< 0.0080	0.026
Barium	mg/L	Metals	0.0916	0.0433	0.0387	< 0.0010	0.030	0.0255
Bicarbonate Alkalinity	mg/L	Chemical	92.00	88.00	40.00	46.00	84.00	14.00
Boron	mg/L	Chemical	0.0207	0.0292	<0.0050	0.018	0.260	0.010
Cadmium	mg/L	Metals	< 0.0010	<0.0010	<0.0010	< 0.0010	< 0.0010	< 0.0010
Carbonate Alkalinity	mg/L	Chemical	< 2.00	<2.00	<2.00	< 2.00	< 2.00	< 2.00
Lead	mg/L	Metals	< 0.0100	<0.0100	<0.0100	< 0.0100	< 0.0100	< 0.0100
Total Chlorine	mg/L	Chemical	0.33	<0.05	0.19	0.20	< 0.05	0.12
Chloride	mg/L	Chemical	9.39	15.73	8.06	12.93	19.09	4.25
Cobalt	mg/L	Metals	< 0.0050	<0.0050	<0.0050	< 0.0050	< 0.0050	< 0.0050
Dissolved Copper	mg/L	Metals	< 0.0050	<0.0050	<0.0050	< 0.0050	< 0.0050	< 0.0050
Hexavalent Chromium	mg/L	Metals	< 0.020	<0.020	<0.020	< 0.020	< 0.020	< 0.020
Trivalent Chromium	mg/L	Metals	< 0.030	<0.030	<0.030	< 0.030	< 0.030	< 0.030
Sulfide	mg/L	Chemical	< 0.030	<0.030	<0.030	< 0.030	< 0.030	< 0.030
Sulfate	mg/L	Chemical	30.71	17.15	11.50	0.89	14.93	4.28
Dissolved Iron	mg/L	Metals	0.6139	0.306	0.5113	0.592	0.1805	0.082
Dissolved Manganese	mg/L	Chemical	0.0896	0.0473	0.0409	0.2095	0.1695	< 0.0050
Mercury	mg/L	Metals	< 0.00020	<0.00020	<0.00020	< 0.00020	< 0.00020	< 0.00020
Molybdenum	mg/L	Metals	< 0.0050	<0.0050	<0.0050	< 0.0050	< 0.0050	< 0.0050
Nickel	mg/L	Metals	< 0.0060	<0.0060	<0.0060	< 0.0060	< 0.0060	< 0.0060
Sodium Adsorption Ratio (SAR)		Chemical	< 0.20	<0.20	<0.20	< 0.20	< 0.20	< 0.20
Calcium	mg/L	Metals	20.20	27.78	13.18	9.269	56.84	3.52
Magnesium	mg/L	Metals	3.81	6.24	2.20	3.157	61.90	0.7205
Selenium	mg/L	Chemical	< 0.0070	<0.0070	<0.0070	< 0.0070	< 0.0070	< 0.0070
Sodium	mg/L	Metals	7.52	15.40	8.11	11.996	205.55	3.30
Fluoride	mg/L	Chemical	0.130	0.195	0.065	0.368	0.354	0.09
Zinc	mg/L	Metals	0.0480	0.0854	0.0322	0.044	0.189	0.168
Cyanide	mg/L	Chemical	< 0.001	<0.001	<0.001	< 0.001	< 0.001	< 0.001
Vanadium	mg/L	Metals	< 0.0050	<0.0050	<0.0050	< 0.0050	< 0.0050	< 0.0050
Total Phenols	mg/L	Chemical	< 0.003	<0.003	<0.003	< 0.003	< 0.003	< 0.003
Thermotolerant Coliforms	UFC/100 mL	Microbiological	< 10.0	3400.00	70.00	240.0	2700.00	< 100.0
BOD (5 days)	mg/L	Chemical	< 3.0	<3.0	<3.0	< 3.0	< 3.0	< 3.0
COD	mg/L	Chemical	< 30.0	<30.0	<30.0	< 30.0	< 30.0	< 30.0

Legend: BOD- Biochemical Oxygen Demand (5 days)
COD- Chemical Oxygen Demand

Given the limited number of samples collected and the absence of prior studies on water quality in the analyzed area, an exploratory approach was adopted for this initial stage. This approach was based on a visual assessment of the main variations among the analyzed parameters and a qualitative description of these variations (Amaro, 2023).

The variation analysis conducted in this study focuses on parameters obtained during distinct sampling campaigns that corresponded to the same collection points. This strategy is designed to enable the evaluation of temporal changes at each sampling location.

In the first campaign (Sampling Campaign No. 1), high concentrations of alkaline bicarbonate were observed at Point 1 (92.0 mg/L) and Point 2 (88.0 mg/L), elevated sulfate levels at Point 1 (30.71 mg/L), and a significant presence of thermotolerant coliforms at Point 2 (3400.0 CFU/100 mL).

In the second campaign (Sampling Campaign No. 2), significant variations were observed in several parameters at Point 2. These included conductivity (2386.0 µS/cm), alkaline bicarbonate (84.0 mg/L), sodium (205.55 mg/L), calcium (56.84 mg/L), and magnesium (61.90 mg/L), with values substantially exceeding those recorded at other points and in the previous campaign.

The parameter exhibiting the most pronounced variation between campaigns was the concentration of thermotolerant coliforms (2700.0 CFU/100 mL).

The recurring detection of elevated concentrations of thermotolerant coliforms at Point 2 in both sampling campaigns may suggest the presence of illegal sanitary sewage connections within the urban drainage network.

Furthermore, the possibility of brackish water interference during sampling cannot be ruled out, which may have also contributed to the observed results. The sustained presence of this parameter is a clear indicator of fecal contamination.

In the analyses conducted during Campaign 1 (Points 1 and 2) and Campaign 2 (Point 2), notably high concentrations of alkaline bicarbonate were consistently observed.

These findings suggest possible interference from anthropogenic activities, such as illegal domestic and/or industrial sewage connections to the urban drainage network, or even the influence of brackish water during sample collection.

The bases of the drainage pipes at Points 1 and 2 are in areas very close to river courses, making them susceptible to tidal influence during flood periods.

Moreover, episodes of heavy rainfall may directly affect the quality of the collected water. These conditions may have significantly contributed to the observed results (Figures 18 and 19).

In Campaign 2, Point 2 exhibited elevated values for conductivity, sodium, calcium, and magnesium, as previously noted.

In a study conducted in 2009, Santos, J.S.; Santos, M.J.S.; and Santos, M.L.P. attributed the presence of sodium to effluents from irrigation practices, sanitary sewage, and urban stormwater, while calcium was considered an indicator of domestic sewage and urban runoff contributions to natural water bodies.

The presence of magnesium in the environment may be associated with industrial activities, soil composition, agricultural practices (such as fertilizer application), urban traffic, construction activities, and even magnesium particulates already present in rainwater before contact with the soil surface (CASQA, 2020).

Taneez et al. (2023) further reported that interaction between rainwater and concrete drainage pipes might also have contributed to the presence of dissolved magnesium.

Although alkaline bicarbonate values varied among the three sampling points throughout both campaigns, all remained within the typical limits observed in surface waters - below 200 mg/L (Dias, 2016).

At the national level, although some studies have addressed the quality of surface runoff water - including those conducted by Silva et al. (n.d.), Silva Filho et al. (1998), Campana & Bernardes (2010), Honório, Horbe & Seyler (2010), Cerqueira et al. (2014), Braga (2017), Da Silva et al. (2020), Santos et al. (2022), De La Cruz et al. (2024), and Birelo et al. (2025)—the number of investigations on this topic remains modest and limited.

This underscores the need to expand research efforts in this area.

Studies identified in the Joinville region primarily focused on small-scale domestic reuse solutions, flood control methodologies, and initiatives aimed at environmental sustainability and energy efficiency in stormwater treatment.

However, a significant gap persists regarding the analysis of water quality parameters for reuse at medium and large scales—particularly considering the region's industrial profile and high rainfall incidence—as well as the risks associated with this type of reuse.

Supporting this observation, several studies can be cited. Custódio & Ghisi (2019) evaluated the potential for potable water savings through rainwater use in the residential sector of Joinville.

Bertolazzi & Custódio (2020) analyzed economically viable strategies to reduce potable water consumption in households and assessed the feasibility of rainwater harvesting in Joinville, SC.

Morais (2006) investigated the use of rainwater for non-potable purposes in a single-family residence in the Joinville region.

Gonçalves et al. (2018) examined how low-impact development (LID) techniques could mitigate flood risk in a coastal area with high rainfall in southern Brazil (Joinville-SC).

Cureau & Ghisi (2020) proposed a method to estimate electricity savings in water supply and sanitation systems resulting from reduced potable water consumption at the urban scale in Joinville, in southern Brazil.

The initial results highlight the spatial variability of certain parameters throughout the different sampling regions, as well as the temporal variability observed at the points throughout the campaigns.

Following this exploratory analysis, a more in-depth evaluation of the collected data will be carried out through a preliminary screening, comparing the recorded values with the limits established by Resolution CERH/PR No. 122/2023.

This step aims to identify which reuse categories analyzed stormwater—that originated from urban drainage—could potentially fall under, considering that no prior treatment was applied before sample collection.

5.2 PRELIMINARY RISK EVALUATION THROUGH THE APPLICATION OF FMEA

The results obtained in the two sampling campaigns would be analyzed based on each reuse class, following the quality standards established for the three reuse categories defined in CERH Resolution No. 122/2023.

This step aims to identify which parameters comply with the legal limits for each reuse class, to verify the results of the risk levels identified for each parameter, and, additionally, to propose nature-based solutions that are appropriate for eliminating the parameters that have resulted in high levels of risk.

In the column dedicated to assessing the feasibility of reuse, green-highlighted parameters indicate compliance; those highlighted in red indicate that the values exceed the defined concentration limits; and those marked as N.D. (not determined) or N.A. (not applicable, due to values below the detection limit) have not been analyzed.

For this study, the "helminth eggs" parameter was intentionally not evaluated, as priority was accorded to variables considered more directly representative of stormwater characterization of stormwater within the scope of this research. Nevertheless, the relevance of this parameter for public health is fully recognized, and its inclusion in more comprehensive assessments of water reuse is recommended for subsequent studies.

Tables 2, 3, and 4 present the results of urban drainage water characterization at sampling Point 1, based on two sampling campaigns conducted within the Cubatão River Watershed (see Figure 18).

Table 2 – Risk analysis for sampling point No. 1 – Class A: Unrestricted Non-Potable Reuse

Parameter	**Unit of measurement**	**Class A water reuse limits**	**Campaign 1 01/17/25**	**Campaign 2 04/03/25**	**P95**	**Risk level**
pH	-	6 a 9	6.59	6.28	6.57	1
Thermotolerant Coliforms or E. coli	CFU/100 mL	200	9.99	240	228.5	-
Total Chlorine*	mg/L	0.5 < CRT < 2	0.33	0.2	0.32	1
Conductivity	mS/cm	3200	0.2845	0.24	0.28	1

* The total chlorine parameter was used as a reference for this analysis

As detailed in Table 2, for reuse Class A, the pH parameter yielded a P95 of 6.57, wich is below the established legal limit for this class. The parameters for total chlorine and conductivity also exhibited the same level of risk, considered very low.

The thermotolerant coliform parameter, whose risk analysis via FMEA is not recommended, was assessed separately. A concentration of 240 CFU/100 mL was recorded during the second campaign, a value that exceeds the legal limit for reuse Class A, reaching a P95 of 228.5. Consequently, prior treatment is unequivocally required for the thermotolerant coliforms parameter to enable the reuse of stormwater from this point in Class A applications.

For reuse in Class B, classified as Restricted Non-Potable Reuse, the results are presented in Table 3 below.

Table 3 - Risk analysis for sampling point No. 1 – Class B: Restricted Non-Potable Reuse

Parameter	**Unit of measurement**	**Class B water reuse limits**	**Campaign 1 01/17/25**	**Campaign 2 04/03/25**	**P95**	**Risk level**
pH	-	6 a 9	6.59	6.28	6.57	1
Thermotolerant Coliforms or E. coli	CFU/100mL	1000	9.99	240	228.5	-
Total Chlorine*	mg/L	0.5 < CRT < 2	0.33	0.2	0.32	1
Conductivity	mS/cm	3200	0.28	0.24	0.28	1

*The total chlorine parameter was used as a reference for this analysis

Table 3 reports the same risk results shown in Table 2 for the pH, total chlorine, and conductivity parameters – all of which were classified as very low in risk level 1 for Class A (unrestricted non-potable reuse).

Regarding thermotolerant coliforms parameter, considering that the reuse limit for Class B is 1000 CFU/100 mL, the stormwater met the required standards for this type of reuse. It is crucial to highlight that the analyzed water had not undergone any prior treatment.

Subsequently, Table 4 reports the risk assessment values for sampling point No. 1, designated for agricultural and forestry reuse.

Table 4 - Risk analysis for sampling point No. 1 – Class: Reuse for Agricultural and Forestry Purposes

Parameter	Unit of measurement	Reuse for Agricultural and Forestry Purposes	Campaign 1 01/17/2025	Campaign 2 04/03/2025	P95	Risk level
pH		5 a 9	6.59	6.28	6.57	2
Thermotolerant Coliforms or E. coli	CFU/100 mL	1000	<10.0	240	228.5	-
Conductivity	mS/cm	3200	0.284	0.24	0.282	1
Total Hydrocarbons (Mineral Oils)	mg/L	Up to10	9.99	9.99	9.99	1
Vegetable Oils and Animal Fats	mg/L	Up to 30	9.99	9.99	9.99	1
Surfactants	mg/L	0.5	0.19	0.19	0.19	5
Dissolved Aluminum	mg/L	0.2	0.0715	0.064	0.071	5
Total Arsenic	µg/L	0.03	8.00	8.00	8.00	5
Total Barium	mg/L	1	0.0916	0.001	0.087	1
Alkalinity Bicarbonate	meq/L	10	1.51	0.754	1.51	5
Total Boron	mg/L	0.75	0.02	0.018	0.020	5
Cadmium	µg/L	0.01	1.00	1.00	1.00	5
Carbonate Alkalinity	meq/L	0.1	0.067	0.067	0.067	1
Total Lead	mg/L	0.033	0.01	0.01	0.01	3
Chloride	mg/L	30	9.390	12.93	12.75	1
Cobalt	mg/L	0.2	0.01	<0.0050	0.005	1
Dissolved Copper	mg/L	0.013	0.0050	0.0050	0.01	1
Hexavalent Chromium	mg/L	0.1	0.019	0.019	0.019	1
Trivalent Chromium	mg/L	1	0.029	0.029	0.029	1

Parameter	Unit of measurement	Reuse for Agricultural and Forestry Purposes	Campaign 1 01/17/2025	Campaign 2 04/03/2025	P95	Risk level
Sulfide	mg/L	1	0.029	0,029	0.029	1
Sulfate	mg/L	250	30.71	0.89	29.21	1
Dissolved Iron	mg/L	5	0.613	0.592	0.613	3
Dissolved Manganese	mg/L	0.5	0.089	0.209	0.203	1
Total Mercury	mg/L	0.002	0.00019	0.00019	0.00019	1
Molybdenum	mg/L	0,5	0.0049	0.0049	0.0049	1
Total Nickel	mg/L	0.025	0.0059	0.0059	0.0059	1
Sodium Adsorption Ratio (SAR)	-	15	0.19	0.19	0.19	1
Total Selenium	mg/L	0.05	0.0070	0.0070	0.007	1
Sodium	meq/L	40	0.3270	0.52	0.51035	1
Total Fluoride	mg/L	10	0.13	0.368	0.3561	1
Total Zinc	mg/L	5	0.05	0.044	0.0478	1
Cyanide	mg/L	0,022	0.001	0.001	0.001	1
Vanadium	mg/L	0.1	0.0050	0.005	0.005	1
Total Phenols	mg/L	0.01	0.0030	0.003	0.003	1
BOD (5 days)	mg/L	60	2.90	2.90	2.9	1

The thermotolerant coliform parameter yielded results below the legal limit (LL) of 1000 CFU/100 mL in both campaigns, thereby meeting the standards for agricultural and forestry reuse.

The pH was classified as risk level 2, indicating low risk, as all measurements remained below the legal threshold throughout both campaigns.

In contrast, total lead and dissolved iron were assigned risk level 3, considered moderate. This classification represents an alert level that warrants ongoing monitoring to better understand the parameter behavior in the studied area.

Meanwhile, dissolved aluminum, surfactants, alkaline bicarbonate, total boron, and barium were all classified at risk level 5, indicating a very high risk. Notably, arsenic presented a concentration of 8.0 µg/L, substantially exceeding the legal limit of 0.03 µg/L. Cadmium, with a legal limit of 0.01 µg/L, showed consistent results of 1.0 µg/L in both campaigns.

Sampling Point No. 2, situated in the Bucarein and Boa Vista neighborhoods within the Cachoeira River Watershed, yielded the following results for Reuse Class A (Tables 5, 6, and 7).

Table 5 - Risk analysis for sampling point No. 2—Class A: Unrestricted Non-Potable Reuse

Parameter	Unit of measurement	Class A water reuse limits	Campaign 1 01/17/25	Campaign 2 04/03/25	P95	Risk level
pH	-	6 a 9	6.88	6.80	6.87	2
Thermotolerant Coliforms or E. coli	CFU/100mL	200	3400.00	2700.00	3365	-
Total Chlorine*	mg/L	0.5 < CRT < 2	<0.05	<0.05	0.049	1
Conductivity	mS/cm	3200	0.313	2.386	2.28	1

Table 5 presents the results for urban runoff water intended for Class A reuse. The parameters of residual chlorine and electrical conductivity, with 95th percentile values of 0.049 and 2.28, respectively, were below the legal limits established for Class A, resulting in a risk level 1 - classified as very low.

The pH parameter was assigned to a risk level 2, indicating low risk. This result poses no concern for reuse and remains within the acceptable limit.

In contrast, the thermotolerant coliform parameter showed elevated values in both monitoring campaigns, unequivocally indicating fecal contamination at the sampling point. Considering that the FMEA methodology is not recommended for this parameter, it is noted that the P95 value is significantly above the permitted legal limit, thereby prohibiting the reuse of urban runoff water for this class type.

Table 6 presents the results of runoff water sampling compared to the legal limits for Class B - restricted non-potable reuse.

Table 6 - Risk analysis for sampling point No. 2—Class B: Restricted Non-Potable Reuse

Parameter	Unit of measurement	Class B water reuse limits	Campaign 1 01/17/25	Campaign 2 04/03/25	P95	Risk level
pH	**-**	**6 a 9**	**6.88**	**6.80**	**6.87**	**2**
Thermotolerant Coliforms or E. coli	**CFU/100mL**	**1000**	**3400.00**	**2700.00**	**3050**	**-**
Total Chlorine*	**mg/L**	**0.5 < CRT < 2**	**<0.05**	**<0.05**	**0.05**	**1**
Conductivity	**mS/cm**	**3200**	**0.313**	**2.386**	**2.28**	**1**

For Class B –-Restricted Non-Potable Reuse, the same conditions observed in Table 5 for Class A reuse are reiterated.

The parameters of total chlorine and electrical conductivity were assigned as risk level 1, classified as very low, indicating no threat to reuse practices. The same applies to the pH parameter, which was classified with a risk level 2, considered low.

Once again, the thermotolerant coliform parameter showed an extremely high P95 value, far exceeding the legal limit, thereby confirming the comprise to the feasibility of reuse without prior treatment.

The results for the agricultural and forestry reuse class are presented in Table 7 below.

Table 7 - Risk analysis for sampling point No. 2—Class: Reuse for Agricultural and Forestry Purposes

Parameter	Unit of measurement	Reuse for Agricultural and Forestry Purposes	Campaign 1 01/17/2025	Campaign 2 04/03/2025	P95	Risk level
pH		5 a 9	6.88	6.80	6.87	3
Thermotolerant Coliforms or E. coli	CFU/100 mL	1000	3400,00	2700,00	3365	
Conductivity	mS/cm	3200	0.313	2.386	2266.71	5
Total Hydrocarbons (Mineral Oils)	mg/L	Up to10	<10.0	<10.0	10	5
Vegetable Oils and Animal Fats	mg/L	Up to 30	<10.0	<10.0	10	1
Surfactants	mg/L	0.5	<0.20	<0.20	0.2	1
Dissolved Aluminum	mg/L	0.2	0.0761	0.0670	0.075	1
Total Arsenic	µg/L	0.03	8.0	8.0	8.0	5
Total Barium	mg/L	1	0.0433	0.0300	0.042	5
Alkalinity Bicarbonate	meq/L	10	1.44	1.377	1308.22	5
Total Boron	mg/L	0.75	0.0292	0.2600	0.248	5
Cadmium	µg/L	0.01	<10.0	1.0	9.55	5
Carbonate Alkalinity	meq/L	0.1	0.067	<0.066	0.066	5
Total Lead	mg/L	0.033	<0.0100	<0.0100	0.01	5
Chloride	mg/L	30	15.73	19.09	18.92	5
Cobalt	mg/L	0.2	<0.0050	<0.0050	0.005	1
Dissolved Copper	mg/L	0.013	<0.0050	<0.0050	0.005	1
Hexavalent Chromium	mg/L	0.1	<0.020	<0.020	0.02	1

Parameter	Unit of measurement	Reuse for Agricultural and Forestry Purposes	Campaign 1 01/17/2025	Campaign 2 04/03/2025	P95	Risk level
Trivalent Chromium	mg/L	1	<0.030	<0.030	0.03	5
Sulfide	mg/L	1	<0.030	< 0.030	0.03	1
Sulfate	mg/L	250	17.15	14.93	17.039	5
Dissolved Iron	mg/L	5	0.3060	0.1805	0.299	2
Dissolved Manganese	mg/L	0.5	0.0473	0.1695	0.163	1
Total Mercury	mg/L	0.002	<0.00020	<0.00020	0.0002	1
Molybdenum	mg/L	0.5	<0.0050	<0.0050	0.005	1
Total Nickel	mg/L	0.025	<0.0060	<0.0060	0.006	5
Sodium Adsorption Ratio (SAR)	-	15	<0.20	<0.20	0.20	2
Total Selenium	mg/L	0.05	<0.0070	<0.0070	0.007	1
Sodium	meq/L	40	0.669	8.937	8490.18	5
Total Fluoride	mg/L	10	0.195	0.354	0.346	5
Total Zinc	mg/L	5	0.0854	0.1890	0.183	1
Cyanide	mg/L	0,022	<0.001	<0.001	0.001	1
Vanadium	mg/L	0.1	<0.0050	<0.0050	0.005	1
Total Phenols	mg/L	0.01	<0.003	<0.003	0.003	1
BOD (5 days)	mg/L	60	<3.0	<3.0	3.0	1

According to Table 7, the parameters classified with risk level 1 (very low) presented values well below the legal limits (LL), indicating no threat to this type of reuse.

At risk level 2 (low), the parameters dissolved iron and SAR were identified. Although these values are not currently concerning, it is recommended that they be monitored to better understand their behavior over time.

Risk level 3 (moderate) was assigned to the pH parameter. The result falls within the established limit range, and the P95 value did not exceed the LL. However, it warrants attention, although the water can still be used for the proposed reuse.

The remaining parameters, classified as very high or critical risk, showed values significantly above the LL, posing a serious threat to both the environment and public health. Therefore, the use of this water in agricultural and forestry activities is not recommended without appropriate prior treatment to remove heavy metals, salinity, and thermotolerant coliforms.

The results of the urban runoff water characterization analyses for Point 3, derived from the study conducted in the Rio Cachoeira Watershed, located in the Costa e Silva neighborhood (See Figure 20), are presented in Tables 8, 9, and 10 below.

Table 8 - Risk analysis for sampling point No. 3—Class A: Unrestricted Non-Potable Reuse

Parameter	Unit of measurement	Class A water reuse limits	Campaign 1 01/06/25	Campaign 2 02/18/25	P95	Risk level
pH	-	6 a 9	7.16	6.37	7.12	2
Thermotolerant Coliforms or E. coli	CFU/100mL	200	70.00	99.99	98.49	-
Total Chlorine*	mg/L	0.5 < CRT < 2	0.19	0.12	0.186	1
Conductivity	mS/cm	3200	0.125	0.039	0.120	1

The results of the analysis to assess the potential for reuse in Class A indicate that both sampling campaigns yielded parameter values below the legal threshold established for unrestricted non-potable use. The parameters for total chlorine and conductivity showed a very low risk (risk level 1), while the pH parameter presented a low risk (risk level 2).

The thermotolerant coliform parameter remained within the legal limits predefined for Class A reuse. This scenario suggests that, under the observed conditions, urban runoff water could be reused within Class A standards.

Table B presents the results related to the evaluation of reuse in Class B.

Table 9 - Risk analysis for sampling point No. 3– Class B: Restricted Non-Potable Reuse

Parameter	Unit of measurement	Class B water reuse limits	Campaign 1 01/06/25	Campaign 2 02/18/25	P95	Risk level
pH	-	6 a 9	7.16	6.37	7.12	2
Thermotolerant Coliforms or E. coli	CFU/100mL	1000	70.0	99.99	98.49	
Total Chlorine*	mg/L	0.5 < CRT < 2	0.19	0.12	0.186	2
Conductivity	mS/cm	3200	0.125	0.0397	0.120	1

The analysis of the results regarding the potential for reuse in Class B indicated that the pH and total chlorine parameters remained within the range permitted by legal limits, although classified as risk level 2, considered very low. While this does not pose an immediate concern, continuous monitoring is recommended to better understand the behavior of these parameters over time.

The conductivity parameter showed a risk level 1, also considered very low, presenting no restrictions for reuse.

Crucially, the maximum legal limit for thermotolerant coliforms in Class B is 1000 CFU/100 mL, and the results from both sampling campaigns remained below this threshold, indicating the absence of fecal contamination and confirming the feasibility of reuse in Class B.

Table 10 - Risk analysis for sampling point No. 3—Class: Reuse for Agricultural and Forestry Purposes

Parameter	**Unit of measurement**	**Reuse for Agricultural and Forestry Purposes**	**Campaign 1 01/06/25**	**Campaign 2 02/18/25**	**P95**	**Risk level**
pH	-	5 a 9	7.16	6.37	7.120	-
Thermotolerant Coliforms or E. coli	CFU/100 mL	1000	70.0	99.99	98.490	
Conductivity	mS/cm	3200	0.125	0.039	0.120	1
Total Hydrocarbons (Mineral Oils)	mg/L	Up to10	<10.0	<10.0	10	1
Vegetable Oils and Animal Fats	mg/L	Up to 30	<10.0	<10.0	10	1
Surfactants	mg/L	0.5	0.20	0.199	0.199	1
Dissolved Aluminum	mg/L	0.2	0.17	0.085	0.169	5
Total Arsenic	µg/L	0.03	8.0	26.00	25.1	5
Total Barium	mg/L	1	0.038	0.025	0.038	5
Alkalinity Bicarbonate	meq/L	10	0.656	0.23	0.634	1
Total Boron	mg/L	0.75	0.01	0.01	0.009	5
Cadmium	µg/L	0.01	1.0	1.0	1	5
Carbonate Alkalinity	meq/L	0.1	0.066	0.067	0.066	1
Total Lead	mg/L	0.033	0.01	0.01	0.01	1
Chloride	mg/L	30	8.06	4.25	7.869	2
Cobalt	mg/L	0.2	0.005	0.005	0.005	1
Dissolved Copper	mg/L	0.013	0.005	0.005	0.005	1
Hexavalent Chromium	mg/L	0.1	0.02	0.02	0.02	1
Trivalent Chromium	mg/L	1	0.03	0.03	0.03	1
Sulfide	mg/L	1	0.03	0.03	0.03	1
Sulfate	mg/L	250	11.50	4.28	11.139	1
Dissolved Iron	mg/L	5	0.51	0.082	0.489	1

Parameter	Unit of measurement	Reuse for Agricultural and Forestry Purposes	Campaign 1 01/06/25	Campaign 2 02/18/25	P95	Risk level
Dissolved Manganese	mg/L	0.5	0.040	0.005	0.039	1
Total Mercury	mg/L	0.002	0.0002	0.0002	0.0002	1
Molybdenum	mg/L	0.5	0.01	0.005	0.005	1
Total Nickel	mg/L	0.025	0.006	0.006	0.006	1
Sodium Adsorption Ratio (SAR)	-	15	0.20	0.20	0.20	1
Total Selenium	mg/L	0.05	0.007	0.007	0.007	1
Sodium	meq/L	40	0.352	0.143	0.341	1
Total Fluoride	mg/L	10	0.065	0.09	0.088	1
Total Zinc	mg/L	5	0.032	0.168	0.161	1
Cyanide	mg/L	0,022	0.001	0.001	0.001	1
Vanadium	mg/L	0.1	0.005	0.005	0.005	1
Total Phenols	mg/L	0.01	0.003	0.003	0.003	1
BOD (5 days)	mg/L	60	3.00	3.00	3.00	1

Unlike the other sampling points, Point 3 exhibited less variation in risk level results in the reuse analysis for forest and agricultural classes when compared to the remaining collection sites.

Twenty-seven parameters were classified as risk level 1, considered very low, which does not pose concern for reuse in this category. Only one parameter, chloride, was classified as risk level 2, indicating low risk. Thermotolerant coliforms were not detected in the collected samples, suggesting the absence of fecal contamination in the study area. The pH also remained within the predefined legal limits, posing no risk.

On the other hand, the parameters dissolved aluminum, total barium, and total boron were classified as risk level 5, considered very high, while arsenic and cadmium were present in the samples with risk level 5, classified as critical. Since these parameters exceed the legally permitted limits, the urban runoff water is not suitable for reuse without prior adequate treatment.

As shown in the previously presented tables, the very high and critical risk levels will be addressed first, based on their potential anthropogenic sources that may have contributed to the presence of such parameters at each sampling point.

For Class A reuse at sampling points 1 and 2, located in the Jardim Sofia neighborhood (Cubatão River Watershed) and at the boundary between the Bucarein and Boa Vista neighborhoods (Cachoeira River Watershed), the thermotolerant coliform parameter was detected in the results. This detection, for example, may indicate contamination from domestic and/or industrial sewage, suggesting possible deficiencies in the basic sanitation infrastructure or the presence of illegal connections to the drainage system.

Although stormwater drainage systems are designed in urban planning projects as absolute separators - intended exclusively for rainwater runoff - the Brazilian context reveals a recurring practice of clandestine sewage discharges into the drainage network. This irregularity significantly contributes to the presence of contaminants such as thermotolerant coliforms, which are widely recognized as classical indicators of fecal pollution (Henriques et al., 2021). Rodrigues et al. (2025) further emphasize that thermotolerant coliforms are commonly used as bioindicators for detecting water contamination by the feces of homeothermic animals.

The same condition of microbial contamination was observed at Point 2 for Class B reuse, where thermotolerant coliform levels exceeded the legal limit established for this class. In contrast, for forest and agricultural reuse classes, a greater variation in risk levels was noted across the sampling points due to the larger number of parameters analyzed.

For instance, arsenic, cadmium, and boron were detected at all sampling locations. The presence of arsenic in water may stem from both natural and anthropogenic sources.

Anthropogenic contributions are linked to atmospheric deposition from industrial activities, improper effluent disposal, trace amounts in fresh leachate, and certain pharmaceutical practices (Sultan et al., 2025).

Chaudhary et al. (2024) further identify human-related sources of arsenic contamination, including metal smelting, waste incineration, pesticide application, non-ferrous metal mining, wood burning, and coal combustion.

In addition to these, relevant natural sources such as dust storms and wildfires may contribute to the environmental dispersion of arsenic.

Bhat et al. (2024) categorize the primary anthropogenic sources as follows:

- ✓ Mining and smelting activities, through waste disposal, residue discharge, and airborne dispersion;
- ✓ Industrial effluents from sectors such as chemicals, metals, and semiconductors, involving unregulated disposal and the cumulative impact of multiple arsenic-generating operations concentrated in the same region;
- ✓ Agricultural practices involving arsenic-based pesticides and herbicides, which contribute to contamination via surface runoff, leaching, and residue accumulation.

The presence of parameters such as cadmium, lead, and nickel may be associated with traffic activity in the studied regions (Stinshoff et al., 2025).

Barium, another parameter detected at sampling points 2 and 3, is a compound naturally found in igneous and sedimentary rocks. However, under anthropogenic influence, barium is widely used in the plastic, rubber, electronics, and textile industries - industrial activities present in the city of Joinville (Government of Canada, 1990).

Boron was detected at all three sampling points, and its presence may occur naturally via groundwater and seawater intrusion, for example (Bolan et al., 2023).

Anthropogenic sources that may have contributed to its presence in urban runoff water, even in trace amounts, include herbicides and insecticides leached from landfills, as well as bleaching agents in detergents and cleaning products that may be improperly discharged into the drainage system (Hasenmueller & Criss, 2013).

Dissolved aluminum was found at sampling points 1 and 3, located near the northern industrial area of the city. Its presence in the environment primarily occurs through the erosion of rocks and minerals. However, anthropogenic contributions stem from atmospheric emissions, wastewater effluents, and solid waste - mainly originating from industrial processes such as metallurgical and plastic manufacturing, construction and demolition materials via leaching, vehicle traffic, and cleaning products that may contain aluminum salts in their composition (ATSDR, n.d.)

The presence of mineral oil at sampling point 2, located in the central area of the city, may indicate a high volume of vehicular activity in the region, considering the recent construction of a new bridge connecting the Bucarein and Boa Vista neighborhoods to improve urban mobility (ND Mais, 2024). Mineral oil may originate from motor oil leaks, fuel and lubricant residues, and oil spills, which plausibly explain its presence (Müller et al., 2020; Akhtar et al., 2021).

Bicarbonate, detected at sampling points 1 and 2, and carbonate, found at point 2, are alkaline substances commonly dispersed through leaching processes (Kriech & Osborn, 2022). Anthropogenic influences contributing to these parameters include global warming, acid precipitation, and the use of concrete materials (Raymond & Hamilton, 2018). Chlorides, present at sampling point 2, may be linked to the proximity of the sea and potential interference from tidal conditions and coastal winds affecting the watershed where the sampling was conducted (Medeiros-Junior, 2018). This situation may contribute to the presence of chlorides in the drainage water collection area under study. Nava et al. (2020) also associate chloride presence with untreated and treated wastewater, human and animal waste, solid waste, and fertilizers. Sodium may originate from anthropogenic sources such as household cleaning products and materials used in road paving, while fluorides may derive from effluents generated by metallurgical processes.

As observed, several parameters presented very high and critical risk levels, particularly in the assessment of reclaimed water for agricultural and forestry activities. In light of this scenario, and to support the development of an effective urban runoff reuse project, it is essential to implement long-term monitoring activities to thoroughly understand the origin and impact of the parameters that exceeded the legal limits, as well as those that resulted in very high and critical risk levels. This approach will guide the selection of appropriate treatment methods for reuse and ensure both environmental and public health protection.

CONCLUSION AND RECOMMENDATIONS

As previously established certain sampling points suggested the potential for the utilization of urban runoff water, specifically, Point No. 1 for Class B and Point No. 3 for both Classes A and B. Nevertheless, given the limited number of analyses performed, it is not yet prudent to affirm the long-term consistency of such conditions. This emphasizes importance of long-term and continuous monitoring to capture the synergic interactions between community practices and local use, account for seasonal variations in sampling, and evaluate the impacts of climate change, thereby facilitating a more holistic understanding of the dynamics underpinning water characterization.

These influences collectively demonstrate the complexity of urban runoff water management and emphasize the importance of selecting appropriate pre-treatment methods to enable safe reuse, ensuring both public health and environmental protection.

Furthermore, the preliminary study is relevant as it demonstrates the pressing need for the federal government to establish parameter standards, ensuring that this practice gains institutional support and visibility within the legislative framework.

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CHAPTER 3 - EVALUATION OF NUTRIENT REMOVAL EFFICIENCY IN MICROALGAE-BASED WASTEWATER TREATMENT: AN ITALIAN CASE STUDY

PREAMBLE

Conventional wastewater treatment plants (WWTPs), while essential for environmental preservation and public health, operate under a linear model primarily focused on water purification, environmental discharge, and sludge separation. Crucially, these systems were not originally conceived to consider resource life cycles or reuse practices. Today, this approach is increasingly incompatible with the principles of the circular economy, which advocates for pollution reduction, byproduct recovery, energy efficiency, and greenhouse gas emissions (GHG) mitigation.

In this context, microalgae-based wastewater treatment has gained significant attention as a sustainable alternative, exhibiting the potential to remove nutrients, generate valuable biomass, and support low-carbon strategies. Studies have been conducted using various types of effluents - domestic, industrial, mixed, and agricultural – thereby highlighting the technological versatility of this approach. However, operational and ecological challenges persist, necessitating a deeper understanding of the interactions between biotic and abiotic factors to ensure process balance and efficiency. Consequently, this chapter presents a case study conducted in Italy, contributing to the advancement of innovative solutions in environmental sanitation.

2. GENERAL OBJECTIVE

To evaluate the performance of a microalgae-based treatment system regarding pollutant removal efficiency, considering the influential role of both biotic and abiotic factors.

2.1 SPECIFIC OBJECTIVE

To determine the nutrient removal efficiency of the microalgae-based treatment system by analyzing the influence of key abiotic factors - namely pH, temperature, and light intensity - and subsequently comparing the obtained results with current wastewater legislation in Italy, within the scope of presented a case study.

3. STUDY DEVELOPMENT

3.1 SUSTAINABLE EFFLUENT MANAGEMENT THROUGH MICROALGAE CULTIVATION

Over the past 150 years, the implementation of wastewater treatment systems has led to significant advancements in public health, contributing to reduced mortality rates and the prevention of disease outbreaks. These systems have also played a crucial role in mitigating environmental pollution by removing contaminants such as organic matter, nitrogen (N), and phosphorus (P) (Hughes et al., 2021; Kan et al., 2021).

In addition to these commonly targeted pollutants, wastewater (WW) also harbors heavy metals (HM) and emerging contaminants - synthetic organic compounds that pose significant potential risks to both human health and the environment. These emergent contaminants notably include, but are not limited to, per- and polyfluoroalkyl substances (PFASs), flame retardants, pharmaceutical compounds (PCs), pesticides, and artificial sweeteners (Abdelfattah et al., 2023).

Despite their essential role in safeguarding public and environmental health, conventional wastewater treatment plants (WWTPs), primarily designed to remove pollutants without considering the potential reuse of by-products, have come under increasing scrutiny. This is largely due to their high energy consumption, greenhouse gas emissions throughout various stages of the treatment process, generation of solid waste (e.g., sludge), and the discharge of treated water into natural water bodies such as rivers, without further utilization.

To integrate sustainability into these systems, it is imperative that they adopt more efficient practices aligned with the principles of the circular economy (EEA, 2022).

Of the total electricity generated in developed countries, approximately 0.6% to 3% is consumed by the wastewater treatment process.

In terms of carbon emissions, it is estimated that the carbon dioxide (CO_2) resulting from electricity usage in this sector reaches around 2.2 million tonnes annually in Germany, approximately 2.1 million tonnes in the United Kingdom, and about 11.5 million tonnes in the United States (Mohsenpour et al., 2021).

Considering these scenarios, and the fact that the wastewater treatment sector contributes approximately 1.57% of global greenhouse gas emissions, its integration into sustainability strategies becomes increasingly vital (UN Environment Programme, 2023).

As noted by Hernández-Chover et al. (2023), the circular economy (CE) emerges as a viable alternative to the prevailing linear model, which is still dominant in current WWTP operations and is based on the extract–produce–use–dispose paradigm.

The core principle of the circular economy (CE) is to maximize the lifecycle of products and materials by promoting their reuse, recovery, and recycling. This approach seeks to reduce the extraction of natural resources, minimize waste generation, and thereby mitigate the environmental impacts associated with pollution.

When applied to wastewater treatment plants (WWTPs), circular economy principles enable the recovery of several valuable by-products (EEA, 2022), including:

- ✓ Nitrogen and phosphorus, which can be repurposed for fertilizer production;
- ✓ Thermal energy, which can be utilized for heating or electricity generation;
- ✓ Reusable water, suitable for irrigation and sanitary flushing systems.

In this context, nature-based solutions, such as microalgae-based treatment systems, have gained prominence due to their potential to close resource loops and enhance sustainability. Building on this progress, microalgae-based wastewater treatment has recently emerged as an environmentally sustainable and economically viable alternative (Song et al., 2022). This approach facilitates the reuse of treated water and the generation of high-value by-products, such as biofuels and biofertilizers (Hernández-Cuenca et al., 2025).

González-Camejo et al. (2024) argue that microalgae-based wastewater treatment can make a significant contribution to the circular economy framework by addressing key goals such as decarbonization, zero pollution, resource circularity, and environmental protection.

Scientific interest in microalgae-based effluent treatment has been growing steadily. For example, Mantovani et al. (2020) investigated the use of microalgae for treating anaerobic rejected liquor in a 1,200-liter outdoor raceway reactor pilot plant located in northeastern Italy. In addition, Vaz et al. (2023) conducted a comprehensive review of studies focused on the operation and performance of microalgae-based reactors in open systems.

Microalgae treatment systems can be implemented in either open or closed pond configurations, each offering distinct advantages and limitations (Figure 1).

Figure 1 - Operational advantages and disadvantages of open and closed microalgae cultivation systems

Pond systems	Advantages	Disadvantages
Open pond	Low cost and easy to construct	Microalgae are more exposed to contamination by external organisms
	Use of natural sunlight for algae growth	Low control over environmental conditions
	Easy maintenance	System exposed to high water evaporation rates
	Effective gas exchange with the atmosphere (release of oxygen)	Limited to resistant species and low algae productivity
Closed pond	Improvement and possibility of controlling environmental conditions	Artificial lighting sources are necessary for growing algae
	Low risk of contamination	Biofilm formation on the internal surfaces of the system
	Increased algae productivity	Significant increase in capital and operating expenses
	System is considered compatible and use in various climatic conditions	Maintaining the pH or oxygen gradients (PBRs of the horizontal tube) can be challenging

Reference: Gaurav et al. (2024)

From a legislative standpoint, the transition toward a Circular Economy (CE) in Italy is supported by key regulatory instruments. Notably, Ministerial Decree No. 185 of June 12, 2003 establishes the "*Technical standards for wastewater reuse*," while Law Decree No. 39 of April 14, 2023 introduces "*Urgent measures to address water scarcity and strengthen water infrastructure*."

At the European level, Directive (EU) 2024/3019 on urban wastewater treatment reinforces this transition by emphasizing the gradual reduction of greenhouse gas emissions, improvements in energy efficiency throughout wastewater collection and treatment processes, and the implementation of stricter monitoring protocols to control nutrient concentrations—particularly nitrogen and phosphorus—in treated effluents. These measures aim to mitigate environmental impacts and foster resource recovery.

As previously discussed, microalgae-based wastewater treatment represents a sustainable alternative to conventional methods, especially in light of legal frameworks that support the adoption of emerging technologies. In this context, further research is essential to identify existing challenges and address them, thereby contributing to the development of a safe and effective solution.

3.2 MICROALGAE AND THE FACTORS INFLUENCING THEIR PERFORMANCE IN WASTEWATER TREATMENT PROCESSES

Algae are considered aquatic photosynthetic organisms (Nguyen et al., 2022), typically visible only at the microscopic scale, and encompassing both eukaryotic microalgae and prokaryotic cyanobacteria (González-Camejo, 2019).

Recently, the use of microalgae in the treatment of municipal, industrial, agro-industrial, and livestock wastewater has been tested and validated for the bioremediation of nutrients, heavy metals (HM), emerging pollutants, and pathogens. Species such as *Scenedesmus*, *Chlorella*, *Botryococcus*, *Phormidium*, *Limnospira* (formerly *Arthrospira*, *Spirulina*), and *Chlamydomonas* have demonstrated effectiveness in these processes. Additionally, species that exhibited efficient growth under such environmental conditions include *Scenedesmus*, *Chlorella*, *Euglena*, *Oscillatoria*, *Chlamydomonas*, and *Ankistrodesmus* (Abdelfattah et al., 2023).

Microalgal organisms can be classified into three main metabolic categories: photoautotrophs, which utilize inorganic carbon and light as energy sources; photoheterotrophs, which rely on organic carbon in combination with light; and mixotrophs, capable of alternating between or combining autotrophic and heterotrophic metabolisms depending on substrate availability and lighting conditions (González-Camejo, 2019).

In general, pollutant removal by microalgae occurs through specific mechanisms that vary according to the nature of the contaminant. Most microalgae are photoautotrophic, using light as an energy source and carbon dioxide (CO_2) —derived from natural or artificial sources, or bicarbonates (HCO_3^-) present in the culture medium as a carbon source. Through photosynthesis and CO_2 fixation, these compounds are converted into energy storage molecules, such as carbohydrates, which support cellular growth and metabolic activity (Amaro et al., 2023).

During the treatment process, microalgae require a balanced environment to ensure proper growth and performance. To achieve this, it is essential to monitor key factors, both biotic and abiotic, which will be described below.

a) **Abiotic factors:**

- ✓ **pH:** This is a crucial factor in the removal of nitrogen and phosphorus. In environments with elevated pH levels, there is greater availability of carbon dioxide (CO_2), which facilitates its absorption by microalgae. However, excessively high pH values can inhibit microalgal metabolism, compromising nutrient assimilation (Amaro et al., 2023). It is important to note that each microalgal species has an optimal pH range for ideal performance. For green microalgae, this range lies between 7.0 and 8.0, whereas cyanobacteria are favored in environments with pH levels above 9.0 (González-Camejo, 2019).

During the management of microalgae-based treatment systems, it is essential to consider that the assimilation of inorganic carbon, when not occurring at the same rate as its consumption, may lead to an increase in the medium's pH, rendering it excessively alkaline (pH > 9.0), which can compromise process efficiency (Amaro et al., 2023).

- ✓ **Light intensity and temperature**: The quality, intensity, and duration of light, along with water temperature, exert a demonstrable influence on microalgae (Lage, Toffolo & Gentili, 2021). The optimal temperature range for microalgal growth lies between 15 °C and 30 °C. Temperatures deviating significantly below or above this range may detrimentally affect nutrient removal, primarily because they affect the optimal activity of enzymes essential to microalgal metabolism (Amaro et al., 2023).

  Regarding light intensity, the energy captured from sunlight drives the oxygen (O_2) release process and promotes the generation of adenosine triphosphate (ATP), a molecule responsible for energy storage, which is used by microalgae to fix CO_2 during the treatment process (Mohsenpour et al., 2021). Microalgal growth is directly proportional to light intensity; however, when intensity falls below the optimal threshold, growth becomes limited. In outdoor environments, the culture medium is directly influenced by sunlight, making it essential to manage this condition carefully. Optical path depth, microalgal biomass growth, and pigment coloration are key factors that significantly contribute to light attenuation within the culture system (González-Camejo, 2019).

- ✓ **Nutrients:** Essential for microalgal growth, nutrients play a fundamental role in various metabolic processes. Nitrogen (N), for instance, is indispensable for the synthesis of proteins, photosynthetic pigments, and nucleic acids, and can be assimilated in different forms, such as ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-). Phosphorus (P) is primarily assimilated by microalgae in the form of orthophosphates (PO_4).

  Moreover, microalgae have the ability to absorb excess phosphorus, storing it as polyphosphates, a phenomenon known as luxury uptake, which also depends on other factors such as optimal light intensity and temperature ranges (González-Camejo, 2019).

b) **Biotic Factors:**

- ✓ **Microalgae bioreactor configuration**: System configuration directly influences treatment efficiency. Bioreactors can operate in open or closed systems (Figure 1), encompassing the following cultivation types: I) immobilized cell system: these include configurations such as flat-panel reactors or rotating algal biofilm reactors, as well as those employing active entrapment in gel matrices; and II) suspended culture systems: in this setup, microalgae remain free in the liquid phase, exemplified by continuous flow tanks (raceway ponds), high-rate algal ponds (HRAP), and photobioreactors (PBR) (González-Camejo, 2019; Mohsenpour et al., 2021).

- ✓ **Hydraulic Retention Time (HRT):** The duration of the treatment is a fundamental criteria for evaluating the performance of a bioreactor and must ensure compliance with legislation (Mohsenpour et al., 2021). Specifically, hydraulic retention time (HRT) can be defined as the average period required for a defined volume of substrate (wastewater) to pass through all stages of a treatment reactor before being discharged (Arimi et al., 2015).

As observed, the balance between biotic and abiotic factors is crucial for the performance of microalgae-based treatment systems and is essential for achieving high efficiency in contaminant removal.

In this context, several researchers have conducted studies aimed at gaining a more precise understanding of the interactions between these factors, considering that treatments based on natural processes are highly complex and not yet fully understood, particularly when evolving biological, chemical, and biochemical interactions (Abdelfattah et al., 2023).

Tan et al. (2023) evaluated the removal efficiency of the microalgal species *Scenedesmus sp.*, *Chlorococcum aquaticum*, *Ankistrodesmus augustus*, and *Haematococcus pluvialis* under varying concentrations of non-sterilized wastewater (0%, 10%, 25%, 50%, 75%, and 100%, v/v). In summary, the results demonstrated that all species were capable of removing more than 90% of nitrogen, ammonium, and phosphorus under conditions of 5% and 10% wastewater concentration.

In the study conducted by Abdelfattah et al. (2023), microalgae-based systems with high bioremediation capacity were presented, achieving removal rates between 45% and 65% for biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Additionally, microalgae showed potential for the removal of heavy metals and pharmaceutical compounds present in wastewater, such as 17α-estradiol, which was biodegraded by 85% using *Scenedesmus dimorphus*. Compounds such as paracetamol and ibuprofen were also biodegraded by *Chlorella sorokiniana*.

A high-rate algal pond (HRAP) was employed by Velásquez Orta et al. (2024), achieving a removal efficiency of 90% for ammonium (NH_4^+), 70% for COD, and 50% for phosphate (PO_4^{3-}).

In light of the studies presented, it is evident that microalgae-based systems constitute a highly sustainable and promising alternative. However, challenges related to operational conditions, specifically, those raising from the comlexity and inherent variability of the biotic and abiotic factors involved, and more critically, their interplay and equilibrium persist. This necessitates further in-depth investigation to achieve a more comprehesive understanding.

4. METHODOLOGY

The experimental work conducted at the pilot wastewater treatment station utilizing microalgae between late January and July 2024. This study was performed within the framework of the European project Microalgae 4.0 (HORIZON-MSCA-2021-PF-01).

The detailed methodological steps employed in the execution of this study will be delineated in the following sections.

4.1 LITERATURE REVIEW

As an initial stage of the research, a comprehensive literature review was conducted to identify existing studies on microalgae-based wastewater treatment. The analysis considered variables such as experimental scale (laboratory or pilot), type of effluent used (synthetic or real, industrial, domestic, or mixed), reactor configuration, microalgal species employed, and reported removal efficiency values. Additionally, current wastewater treatment regulations in Italy were reviewed to establish comparative parameters for the case study.

4.2 OPERATION OF THE PILOT PLANT AND SAMPLING PROCEDURES

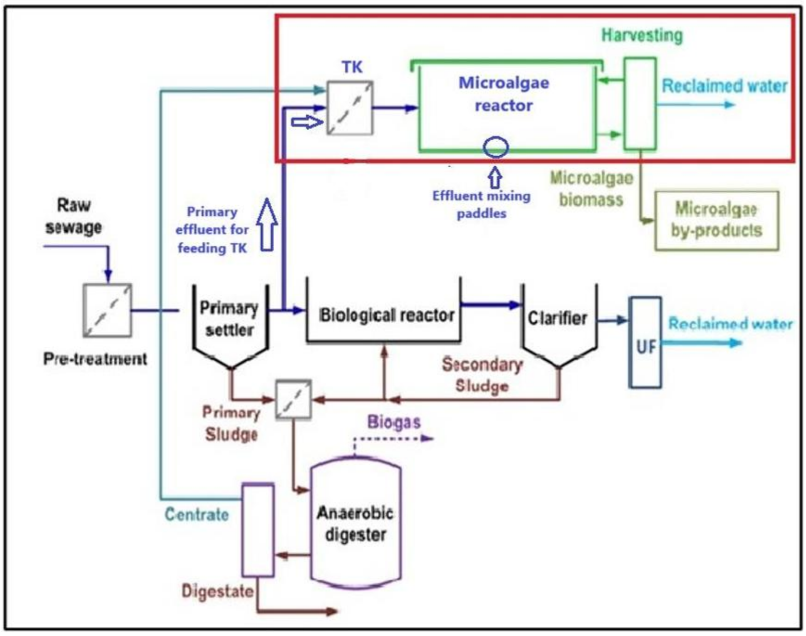
In this case study, the pilot plant operated from January to July 2024, totaling 198 days of continuous operation. The unit was installed on the premises of a full-scale municipal wastewater treatment plant (WWTP) located in Jesi, central Italy.

The microalgae reactor was equipped with all essential components required for its sustained operation. Once or twice a week, the primary effluent from the WWTP was transferred to a 1000 L reservoir (TK), which served as the feed tank for the reactor. The effluent was subsequently pumped from the TK to the reactor using a peristaltic pump.

Figure 2 shows the operational layout of the pilot plant, with the components responsible for system functionality highlighted in red.

On-site monitoring of key parameters was conducted using dedicated pH, temperature, and dissolved oxygen probes. A solar radiation sensor was subsequently installed.

Figure 2 – Pilot Plant Layout



Additionally, maintenance and operational management activities were performed during each visit to pilot plant. These activities included cleaning the feed tank (TK) prior to refilling with fresh effluent, cleaning the microalgae reactor and paddle wheels, verifying and cleaning the monitoring probes, and conducting on-site control of operational parameters. The pilot plant (Figures 3 and 4) operated under the following specifications:

- ✓ Total reactor volume: 125 L;
- ✓ Configuration: Open-type (raceway pond);

- ✓ Surface area: 1.28 m²;
- ✓ Reactor depth: 10 cm;
- ✓ The Hydraulic Retention Time (HRT): Ranged from 1.4 to 6.7 days during the study periods;
- ✓ The microalgae employed: Belonged to the *Chlorophyta* group, commonly known as green algae.

Field activities at the pilot station involved several key tasks, including: verification of the functionality of the dissolved oxygen (DO) probe, measurement of pH and solar radiation, cleaning of the microalgae reactor and paddle wheels; replacement of the effluent feeding the reactor; control of the flow rate; and recording of *in situ* parameters such as algal density.

Figure 3 - Pilot station for wastewater based on microalgae

Figure 4 - Sample of algae for laboratory analysis

Influent samples (collected from the TK reservoir) and effluent samples (collected from the microalgae reactor) were systematically collected once or twice a week.

Following collection, all samples were transported to the Water Laboratory of Marche Polytechnic University (UNIVPM) for physicochemical analysis. The analysis of the parameters adhere to international procedures (APHA, 2017), and were performed in duplicate. The instruments utilized for the analysis of these the parameters in this study are listed as follows:

- ✓ UV-Vis Spectrophotometer (UV-1900i): used for total phosphorus quantification;
- ✓ Hanna Edge pH Meter (HI2022-02): for pH determination;
- ✓ Ion Chromatograph (Dionex AS-DV): responsible for the analysis of nitrite, nitrate, and phosphate;
- ✓ Orion Star A214 Ammonia Meter: used to measure ammonia concentration.

4.3 STUDY PHASES

The study was conducted in three distinct phases, considering different operational conditions, as follows:

- ✓ **Phase 1:** in this phase, the pilot plant was fed with primary settled wastewater effluent from the full-scale wastewater treatment plant. Flow rates ranged from 18.4 L/day to 91 L/day. The average influent concentrations were: pH = 7.72; N-NH_3 = 42.9 mg/L; and P-PO_4 = 6.3 mg/L.
- ✓ **Phase 2:** the same matrix used in Phase 1 was maintained. Additionally, 300 mg $CaCO_3$/L of sodium bicarbonate was added to the feed stream. Flow rates during this phase varied between 50 L/day and 75 L/day. The average influent concentrations in Phase 2 were: pH = 8.44, N-NH_3 = 17.15 mg/L, and P-PO_4 = 6.63 mg/L, and;
- ✓ **Phase 3:** The influent fed into the system during this phase consisted of 85% pre-settled wastewater and 15% anaerobic reject liquor, resulting in a total flow rate of 73 L/day. The average influent concentrations were: pH = 7.95, N-NH_3 = 9.92 mg/L, and P-PO_4 = 7.60 mg/L.

The results obtained in each phase will be presented in Section 5 (Results and Discussion).

5 RESULTS AND DISCUSSION

5.1 PHASE 1: PRE-SETTLED WASTEWATER FEEDING

This experimental phase was carried out over the winter and early spring periods, exhibiting average removal efficiency, as detailed in Figure 5.

Figure 5 - Average removal efficiency achieved during phase 1

Parameters	Influent (mg/L)	Effluent (mg/L)	Removal efficiency (%)	Average temperature (°C)
pH	7.72± 0.1475	9.59±8.56	-	13,17
$N\text{-}NH_3$	42.9±6.63	4.3±4.22	89.9%	
$P\text{-}PO_4$	6.3±0.82	5.6±0.433	11.1%	

As illustrated in Figure 5, the average effluent concentration of ammoniacal nitrogen was 4.3 ± 4.22 mg/L. However, according to Italian Ministerial Decree No. 185/2003, which governs wastewater reuse, the maximum allowable concentration of ammoniacal nitrogen at the outlet of water recovery treatment plants is 2 mg NH_4/L. consequently, the observed value exceeds the regulatory limit. In terms of removal efficiency, the ammoniacal nitrogen parameter achieved 89.9%.

The literature review conducted by Vaz et al. (2023) reported high removal efficiencies, citing values of 88.9–98% for $N\text{-}NH_3$ and 99.7–100% for $P\text{-}PO_4$. Mohsenpour et al. (2021) also provided a review of removal efficiency values in suspended high-rate algal ponds, with the following divergent findings: Study 1 reported 79% removal for $N\text{-}NH_3$ and 22% for $P\text{-}PO_4$ under control conditions of 13 °C and pH 9.7; Study 2 achieved 99% removal for $N\text{-}NH_3$ and 94% for $P\text{-}PO_4$ under conditions of 25 °C and pH ranging from 6.5 to 7.2.

Mohsenpour et al. (2021) explicity noted that low nutrient removal efficiencies were associated with lower temperatures (13 °C) and elevated pH (9.7). This scenario closely mirrors the conditions observed in our study, where the average ambient temperature was 13.17 °C and the pH was not controlled, ranging from 7.72 to 9.59 (average inlet and outlet values). This low-temperature condition was confirmed by field observations and recorded in the field log on January 31, 2024, when a thin layer of ice was noted on the algal reactor in the morning, thus confirming that the temperature factor was directly influenced by the winter season.

According to Dinh et al. (2022), the optimal temperature range for microalgae-based treatment processes is between 15°C and 25°C. Mérida and Padrón (2023) further identified 22°C as the ideal temperature for achieving efficient nutrient removal. It is well established that cultivation temperature directly influences nutrient uptake by microalgae.

Furthermore, the absence of pH control may have contributed to the lower removal efficiency of $P\text{-}PO_4$ (though $P\text{-}PO_4$ results are not detailed here, this links factors). The optimal pH range for green algae is between 7 and 8 (González-Camejo, 2019), which was exceeded in our study, as a pH value of 9.59 was recorded. According to Santos (2017), the growth rate of microalgae does not vary significantly within a pH range of 6.5 to 8.5; a marked decline is observed at higher pH levels.

Light is a paramount parameter in microalgal systems, as it is required for the synthesis of essential molecules, including adenosine triphosphate (ATP) (Katam et al., 2022). In this pilot study, light exposure within the reactor was irregular, particularly during the winter and early spring months, when the reactor remained shaded for extended periods. According to González-Camejo (2019), inconsistent light availability can significantly limit microalgal growth.

5.2 PHASE 2: PRE-SETTLED WASTEWATER FEEDING AND SODIUM BICARBONATE ADDITION

Maintaining the same influent matrix as in the previous phase, with the addition of sodium bicarbonate, Phase 2 demonstrated removal efficiency as illustrated in Figure 6.

Figure 6 – Removal efficiency observed in phase 2

Parameters	Influent (mg/L)	Effluent (mg/L)	Removal efficiency (%)	Average temperature (°C)
pH	8.44±0.4685	10.51±0.62	-	
$N\text{-}NH_3$	17.15±7.04	0.11±0.25	99.36%	19,34
$P\text{-}PO_4$	6.63±0.1473	5.21±0.613	21.41%	

This phase was conducted by adding sodium bicarbonate to the feed stream and took place during the spring season. The addition of sodium bicarbonate was intended to address issues related to the alkalinity of the culture medium.

During this period, the study demonstrated improved efficiency in the removal of ammoniacal nitrogen and a slight enhancement in phosphate removal. As shown in Figure 6, the average effluent concentration of ammoniacal nitrogen complied with the legal limit of 2 mg/L established by Ministerial Decree No. 185/2003. However, regarding the pH parameter, the effluent concentration increased compared to Phase 1 and exceeded the acceptable range defined by the same decree (6.0 – 9.5). Sodium bicarbonate also served as a source of inorganic carbon. As microalgae can absorb it due to their ability to interconvert it intracellularly and extracellularly (Latagan et al., 2024). However, its use causes the medium's pH to increase, as verified in this case study.

Tango et al. (2023) investigated microalgal growth and nutrient uptake under varying nitrogen-to-phosphorus ratios (5:1, 10:1, and 20:1), with the addition of bicarbonate. Their findings indicated that, across all three ratios, ammoniacal nitrogen removal efficiency exceeded 95.97% ± 6.9%, reaching up to 100%. In contrast, phosphate removal efficiency varied significantly: 5:1 yielded −30.60% ± 162.25, 10:1 achieved 73.32% ± 21.78, and 20:1 reached 98.33% ± 2.58.

The pH values observed in this study were higher than those reported by Latagan et al. (2023). In addition to pH, the average temperature during this phase was 19.34 °C, slightly higher than in Phase 1. However, according to Mérida & Padrón (2023), the optimal temperature for microalgal process efficiency is approximately 22 °C.

As in the previous phase, the uneven light distribution within the reactors hypothesized to have continually contributed to the low removal efficiency of P-PO_4. Although previous studies have reported high phosphate removal efficiencies, this was not substantiated in the current phase. The combined effect of several factors, specifically, the elevated pH, which promotes $CaCO_3$ formation and sequesters Ca^{2+} íons, thereby hidering the precipitation of $Ca_3(PO_4)_2$, coupled with low temperatures and limited natural light, may have contributed to the persistently low phosphate removal efficiency, despite a marginal improvement compared to Phase 1.

Regarding light exposure, on April 4, 2024, the algal reactor was slightly repositioned to increase sunlight incidence, as the wall of one of the treatment tanks at the wastewater treatment plant (WWTP) was partially shading the system. This repositioning was undertaken to mitigate light limitations.

Several operational occurrences were recorded in the field log and may have influenced the reactor's performance during this phase. On April 5 and 8, 2024, the pump responsible for feeding the algal reactor was found to be non-operational, either due to system malfunctions or power outages - such as the one that occurred on May 13, 2024. Once these issues were identified by the team, corrective actions were promptly taken. Additionally, on May 28, the feed tube connected to the control panel was found to be clogged with biomass, which could have compromised the flow rate set in the system.

5.3 PHASE 3: PRE-SETTLED WASTEWATER AND ANAEROBIC REJECTED LIQUOR FEEDING

Phase 3 was conducted using a composition of 85% pre-settled wastewater and 15% anaerobic reject liquor. The average removal efficiency results obtained during this stage are presented in Figure 7.

Figure 7 – Average removal efficiency achieved in phase 3

Parameters	Influent (mg/L)	Effluent (mg/L)	Removal efficiency (%)	Average temperature (°C)
pH	7.95±0.1105	9.68±0.77	-	
N-NH_3	9.92±0.0	4.56±0.0	50.54%	26,214
P-PO_4	7.06±0.271	6.93±1.01	1.325%	

This phase was conducted during the summer, starting on June 24, 2024, with an average temperature of 26.214 °C.

Significantly, among the three phases, this one exhibited the lowest efficiency in the removal of ammoniacal nitrogen and phosphate. Both the pH and the concentration of ammoniacal nitrogen exceeded the legal limits established by Ministerial Decree No. 185/2003.

Mantovani et al. (2020) evaluated a microalgae-based wastewater treatment system applied to the supernatant from blackwater dehydration. The average nutrient removal efficiency achieved was 86% ± 7% for ammoniacal nitrogen and 71% ± 10% for phosphate. The pH observed in the study was 8.2 ± 0.3, with temperatures of 26 °C in August and 17 °C in September.

The results presented in Figure 7 clearly indicate that the performance of this phase was inferior to the results obtained by Mantovani et al. (2020). It is hypothesized that, in this stage of the study, the external addition of carbon may have caused a system imbalance, potenttially in the system, possibly subjecting the microalgae to stress conditions which resulted in low nutrient removal efficiency.

During the development of this phase, it was found that the algae exhibited a light green coloration, less intense than usual throughout the study. Crucially, on July 9, 2024, it was confirmed in the field that the anaerobic reject liquor had been depleted, consequently interrupting the feed flow to algal reactor. Due to logistical constraints, it was not possible to continue the operation, which resulted in an unusually short experimental period. Furthermore, the instability in the liquor flow, which ceased during the process, may have contributed to algal stress and impeded their successful adaptation to the new environment. For a more robust comprehensive evaluation, it is recommended that future studies be conducted over a longer period to better elucidate microalgal performance under these conditions.

CONCLUSION

The study demonstrated that the microalgae-based wastewater treatment system can operate under different configurations, either by treating exclusively urban wastewater or by incorporating external sources of carbon and/or nutrients, such as bicarbonate and anaerobic reject liquor. To determine the optimal operational parameters, a longer study period is required, during which field-level operational interferences can be better understood. Throughout the study, occasional failures in the feed pump, power supply interruptions, and blockages in the reactor's feed system were recorded—factors that may have affected overall process performance.

Meanwhile, numerous scientific studies on this type of treatment have been conducted, progressively contributing to the understanding of the system's optimal performance. Additionally, seasonal effects were observed in the nutrient removal efficiency of the pilot system.

However, this study presented some limitations: a) the location of the pilot plant, particularly the microalgae reactor, was affected by shading from one of the tanks at the municipal wastewater treatment facility; b) the short duration of the study periods hindered a comprehensive understanding of the abiotic and biotic factors influencing the process; c) further investigation is needed into the metabolic interactions between microalgae and environmental factors; d) the parameter control strategy should be improved by employing probes capable of monitoring a broader range of variables to ensure optimal process performance.

With the implementation of the new European Directive on urban wastewater treatment, microalgae-based systems show potential to meet the objectives outlined in the legislation by aligning with the principles of circular economy and treated water reuse.

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CHAPTER 4 - RISK ANALYSIS AND PROPOSED REUSE PLAN FOR TREATED WASTEWATER: BRAZILIAN AND ITALIAN CASE STUDIES

PREAMBLE

The reality of water scarcity in various regions of the world, combined with the growing demand for sustainable solutions, deploys the reuse of treated wastewater as a strategic approach to advancing the circular economy and conserving natural resources. This chapter presents a reuse plan grounded in risk analysis, emphasizing environmental safety and public health protection. While the European Union has established consolidated guidelines, Brazil still lacks a unified federal regulation defining quality standards for reuse categories. As a result, several Brazilian states have developed their own legal frameworks. The methodology adopted in this study is based on well-established European and Italian models, including the Failure Mode and Effect Analysis (FMEA) approach and the risk matrix, both of which were applied, where feasible, to the Brazilian and Italian case studies.

2. GENERAL OBJECTIVE

This study aims to assess the physicochemical risks associated with treated effluent derived from municipal wastewater treatment plants, focusing on two case studies, one in Brazil and the other in Italy, in order to evaluate the effluent's suitability for potential water reuse applications.

2.1 SPECIFIC OBJECTIVE

To conduct a comparative analysis of the characteristics of treated effluents against the current reuse regulations in Brazil and Italy, to identify potential physicochemical risks associated with the existing treatment systems, and to propose improvements to treatment processes with the aim enhancing or implementing reuse practices that ensure both environmental safety and efficiency.

3. STUDY DEVELOPMENT

3.1 RISK MANAGEMENT PLAN FOR TREATED WASTEWATER REUSE

Treated wastewater is increasingly recognized as a viable alternative, offering a safe and dependable source of water that alleviates pressure on natural water resources, especially in the face of rapid urbanization and accelerating climate change. When properly and safely treated, its reuse extends the water lifecycle and supports Sustainable Development Goal 6 (SDG 6), which promotes circular economy principles by advocating universal access to safe drinking water and sanitation (European Commission, n.d.; Michalopoulos & Kalavrouziotis, 2025).

The reuse of treated water from urban wastewater treatment plants aims to minimize waste, enhance water conservation, and facilitate the recovery of nutrients present in the treated effluent (Regulation EU 2020/741).

Risk assessment within a management plan must ensure that reclaimed water is used and distributed safely, without posing risks to the environment, human health, or animal health (Regulation EU 2020/741).

Broadly speaking, reclaimed water can be applied in various contexts, including potable uses (provided it complies with drinking water standards) and non-potable uses such as agricultural irrigation, industrial cooling, and urban landscaping, depending on its suitability for the intended purpose (Bauer & Wagner, 2022; Michalopoulos & Kalavrouziotis, 2025).

Recent studies indicate that the implementation of water reuse systems, covering both potable and non-potable applications, has enabled certain cities to reduce freshwater demand by up to 54%, underscoring the potential and advantages of these practices in advancing sustainable water management (Michalopoulos & Kalavrouziotis, 2025).

According to Maffettone & Gawlik (2022), risk management activities primarily aim to identify, assess, and control the risks inherent to a given system. In the context of reclaimed water treatment systems, these risks are defined by hazards and hazardous events associated with their use, considering both the exposed population and the impacted environmental compartments, such as surface water, groundwater, and soil.

A comprehensive risk management plan is structured around eleven key elements, as outlined in the KRM framework (Maffettone & Gawlik, 2022; Decree-Law No. 39/2023), namely:

- ✓ **Key elements:**

1. KRM 1: Description of the entire water reuse system;
2. KRM 2: Identify all stakeholders involved in the water reuse system, such as the treatment plant manager, environmental authorities, end users, and other relevant actors;
3. KRM 3: Identification of potential hazards (microbiological, chemical, physical, and radiological) as well as hazardous events, such as treatment failures, associated with the water reuse treatment system;
4. KRM 4: Identify the risks associated with the exposure of the population and environmental compartments to water reuse;

5. KRM 5: Identification of the risks associated with each previously defined receptor, such as end users, animals, terrestrial and aquatic organisms, soil, and the environment as a whole, taking into careful consideration the respective exposure pathways. For humans, these pathways include direct or indirect ingestion, dermal contact, and inhalation of aerosols; for environmental receptors, they include soil infiltration, bioaccumulation in organisms, and root uptake by plants, among others. Based on this identification, a health and/or environmental risk assessment should be conducted using qualitative, semi-quantitative, or quantitative methods, depending on the availability and robustness of the supporting data.

✓ **Supplementary provisions**:

6. KRM 6: The outcomes of the risk assessment may indicate the need for a more in-depth investigation of specific water quality parameters, including, among others, heavy metals, pesticides, and emerging contaminants, depending on their relevance to the identified receptors and exposure pathways.

✓ **Preventive measures**:

7. KRM 7: Identify the preventive measures or barriers, either existing or additional, to be implemented within the water reuse system, for the aim of mitigating or minimizing the previously identified risks;
8. KRM 8: Establish appropriate quality control measures, such as reclaimed water monitoring protocols, equipment maintenance schedules, and standardized operational procedures, to ensure the consistent performance and integrity of the water reuse system;
9. KRM 9: Establish an environmental monitoring system to assess the presence and behavior of identified pollutants in environmental receptors exposed to water reuse;
10. KRM 10: Establish protocols for the management of incidents and emergencies, aiming to ensure a rapid, effective, and safe response to unexpected events within the water reuse system;
11. KRM 11: Define the communication and coordination mechanisms among the various stakeholders involved in the water reuse system for the aim of ensuring effective information exchange, integrated decision-making, and safe system management.

The risk management plan, grounded in the comprehensive identification of the key elements previously outlined, is designed to provide managers with a thorough understanding of each stage of the water reuse process, facilitate proactive system oversight to prevent unforeseen events, and ensure that reclaimed water is safe for both environmental reuse and public health protection (Decree-Law No. 39/2023).
Moreover, the risk management process can serve as a strategic instrument for safeguarding water quality in countries that have already implemented specific regulations and adopted water reuse practices. Since its core objective is to ensure the highest possible water quality, this approach contributes to the ongoing enhancement of safety and efficiency standards within reuse systems. It is essential to emphasize that this process must remain dynamic, regularly updated and revised, to maintain its effectiveness and alignment with evolving regulations and technological advancements (Bauer & Wagner, 2022).

3.2 ITALIAN AND BRAZILIAN REGULATORY FRAMEWORK

In Italy, the use of wastewater, particularly for agricultural irrigation, is specifically governed by Regulation (European Union—EU) 2020/741 of the European Parliament and of the Council dated May 25, 2020, which sets out minimum requirements for water reuse. This regulation is complemented by Article 7 of Decree-Law No. 39 dated April 14, 2023, subsequently converted, with amendments, into Law No. 68 dated June 13, 2023.
For other uses, such as non-agricultural irrigation, civil and industrial applications, Ministerial Decree (MD) No. 185, dated June 12, 2003, applies.
In particular, Decree-Law (DL) No. 39/2023 "*Urgent provisions to address water scarcity and to strengthen and upgrade water infrastructure*" establishes that, to obtain authorization for water reuse, the operator must prepare a risk management plan.
This plan must be developed by the person responsible for the wastewater treatment plant, in collaboration with those responsible for the transport and storage of the reclaimed water.
The content of the plan is detailed in Annex A of the decree, in accordance with Regulation (EU) 2020/741 - *which sets minimum requirements for water reuse* - and with the technical standards developed by the Joint Research Centre (JRC) of the European Commission. Decree-Law No. 39/2023 defines the quality classes of treated water intended for different types of crops (Table 1), as well as the quality parameters that must be met for the production of such water within each defined class (Table 2).

Table 1 - Quality classes of reclaimed water, irrigation techniques, and permitted agricultural uses (DL No. 39/2023)

Quality classification of treated wastewater	Crop category (*)	Irrigation techniques
A	All food crops intended to be consumed raw whose edible parts are in direct contact with reclaimed water, as well as root crops to be consumed raw	All irrigation techniques
B	Food crops intended to be consumed raw, whose edible parts grow above ground and are not in direct contact with reclaimed water, processed food crops, and non-food crops, including those used for feeding dairy or meat-producing animals	All irrigation techniques
C	Food crops intended to be consumed raw, whose edible parts grow above ground and are not in direct contact with reclaimed water, processed food crops, and non-food crops, including those used for feeding dairy or meat-producing animals	Drip irrigation (**) or other irrigation techniques that avoid direct contact with the edible part of the crop
D	Industrial, energy, and seed crops	All irrigation techniques (***)
(*) If the same type of irrigated crop falls under multiple categories in Table 1, the requirements of the most stringent category shall apply. (**) Drip irrigation (also known as localized irrigation) is a micro-irrigation system capable of delivering water to plants in the form of droplets or thin streams. Water is supplied at a very low flow rate (2–20 liters/hour) onto the soil surface or directly beneath it through a network of small-diameter plastic tubing equipped with nozzles called "emitters" or "drippers." (***) In the case of irrigation techniques that simulate rainfall, particular attention must be paid to protecting the health of workers and bystanders. Appropriate preventive measures must be implemented for this purpose.		

Table 2 - Quality classes and quality requirements for reclaimed water intended for agricultural irrigation – highlighted variations compared to the European Regulation

<table>
<tr><th>Quality class</th><th>Indicative technological objective</th><th>Escherichia coli § (n/100 mL)</th><th>Biochemical Oxygen Demand - BOD_5 (mg/L O_2)</th><th>Total Suspended Solids - TSS (mg/L)</th><th>Turbidity (NTU)</th><th>Legionella spp. § (CFU/L) (*)</th><th>Intestinal nematode § (**)</th><th>Ntot (mg/L) ‡</th><th>Ptot (mg/L) ‡</th><th>Salinity (psu) (***)</th><th>Salmonella spp.</th></tr>
<tr><td>A</td><td>Secondary treatment, tertiary treatment, filtration, and disinfection</td><td>≤ 10</td><td>≤ 10</td><td>≤ 10</td><td>≤ 5</td><td>≤ 1000</td><td>≤ 1 egg /L</td><td rowspan="4">In accordance with Legislative Decree 152/2006 (Table 2 where applicable, Table 3, Annex 5, Part III)</td><td rowspan="4">In accordance with Legislative Decree 152/2006 (Table 2 where applicable, Table 3, Annex 5, Part III)</td><td>≤ 10</td><td>Absent</td></tr>
<tr><td>B</td><td>Secondary treatment, tertiary treatment, and disinfection</td><td>≤ 100</td><td rowspan="3">In accordance with Directive 91/271/EEC (Annex I, Table 1)</td><td rowspan="3">In accordance with Directive 91/271/EEC (Annex I, Table 1)</td><td>-</td><td>≤ 1000</td><td>≤ 1 egg /L</td><td>≤ 10</td><td>Absent</td></tr>
<tr><td>C</td><td>Secondary treatment, tertiary treatment, and disinfection</td><td>≤ 1000</td><td>-</td><td>≤ 1000</td><td>≤ 1 egg /L</td><td>≤ 10</td><td>Absent</td></tr>
<tr><td>D</td><td>Secondary treatment, tertiary treatment, and disinfection</td><td>≤ 10.000</td><td>_</td><td>≤ 1000</td><td>≤ 1 egg /L</td><td>≤ 10</td><td>Absent</td></tr>
</table>

(*) Legionella spp.: if there is a risk of airborne transmission;
(**) Helminth eggs: for irrigation of pastures or forage crops;
§ The values indicated for E. coli, Legionella spp., and intestinal nematodes are met in at least 90% of the samples; none of the sample values exceed the maximum allowable deviation of 1 logarithmic unit from the indicated value for E. coli and Legionella spp., and 100% of the indicated value for intestinal nematodes
° For the Salmonella parameter, the limit value must apply to 100% of the samples;
(***) Standard value to be assessed according to soil type and crop within the risk management plan;
‡ For storage in reservoirs and discharge into permeable irrigation channels, the applicable limits are 10 mg/L for total nitrogen (Ntot) and 1 mg/L for total phosphorus (Ptot); more stringent values may be defined based on the risk management plan.

Decree-Law No. 39/2023 also establishes the minimum frequencies for monitoring activities of treated water used in agricultural irrigation (Table 3).

It should be noted that, in cases where treated water is stored in reservoirs or released into permeable irrigation channels, specific limits for total phosphorus and total nitrogen must be observed, as indicated in the note of Table 2 in Annex A of DL 39/2023: Total phosphorus (Ptot) = 1 mg/L and total nitrogen (Ntot) = 10 mg/L.

Table 3 – Minimum monitoring frequencies for reclaimed water used for agricultural irrigation (Decree-Law No. 39/2023)

Water quality class	**E. coli**	**BOD_5**	**TSS**	**Turbidity**	**Legionella spp. (where applicable) (*)**	**Intestinal nematodes**	**Ntot**	**Ptot**	**Salinity**	**Salmonella spp.**
A	Once a week	Once a week	Once a week	Continuous	Twice a month	Twice a month or as determined by the operator of the reclamation plant, based on the number of eggs present in the wastewater entering the treatment facility	Once a week or in accordance with Directive 91/271/EEC	Once a week or in accordance with Directive 91/271/EEC	Twice a month	Twice a month
B	Once a week	In accordance with Directive 91/271/EEC	In accordance with Directive 91/271/EEC	-					Twice a month	Twice a month
C	Twice a month			-					Twice a month	Twice a month
D	Twice a month			-					Twice a month	Twice a month

(*) According to the irrigation method

Regulation (EU) 2020/741 also specifies that reclaimed water is considered compliant with the requirements set out in Table 2 if the measurements for the reclaimed water meet all of the following criteria:

— the values indicated for *E. coli*, *Legionella spp.*, and intestinal nematodes are respected in at least 90% of the samples; none of the sample values exceed the maximum allowable deviation of 1 logarithmic unit from the indicated value for *E. coli* and *Legionella spp.*, and 100% of the indicated value for intestinal nematodes;

— the values indicated for BOD_5, TSS, and turbidity in Class A are respected in at least 90% of the samples; none of the sample values exceed the maximum allowable deviation of 100% of the indicated value.

The Table 4 presents the limit values for other constituents of wastewater intended for reuse, as defined by Ministerial Decree 185/2003.

Table 4 - Limit values for water at the outlet of the recovery plant (Ministerial Decree 185/03)

Category	Parameter	Unit of measurement	Limit value
Physicochemical parameters	pH		6 - 9.5
	Sodium Adsorption Ratio (SAR)		10
	Coarse materials		Absent
	Total Suspended Solids (TSS)	mg/L	10
	Biochemical Oxygen Demand (BOD_5)	mg O_2/L	20
	Chemical Oxygen Demand (COD)	mg O_2/L	100
	Total phosphorus (Ptot)	mg P/L	2
	Total nitrogen (Ntot)	mg N/L	15
	Ammoniacal nitrogen	mg NH_4/L	2
	Electrical conductivity (EC)	µS/cm	3000
	Aluminum	mg/L	1
	Arsenic	mg/L	0.02
	Barium	mg/L	10
	Beryllium	mg/L	0.1
	Boron	mg/L	1.0
	Cadmium	mg/L	0.005
	Cobalt	mg/L	0.05
	Total chromium	mg/L	0.1
	Hexavalent chromium	mg/L	0.005
	Iron	mg/L	2
	Manganese	mg/L	0.2
	Mercury	mg/L	0.001
	Nickel	mg/L	0.2
	Lead	mg/L	0.1
	Copper	mg/L	1
	Selenium	mg/L	0.01
	Tin	mg/L	3
	Thallium	mg/L	0.001
	Vanadium	mg/L	0.1
	Zinc	mg/L	0.5
	Litihium	mg/L	-
	Molybdenum	mg/L	-
	Total cyanide (as CN)	mg/L	0.05
	Sulfides	mg H_2S/L	0.5
	Sulfites	mg SO_3/L	0.5

Category	Parameter	Unit of measurement	Limit value
	Sulfates	mg SO_4/L	500
	Carbonates	mg/L	-
	Active chlorine	mg/L	0.2
	Chlorides	mg Cl/L	250
	Fluorides	mg F/L	1.5
	Animal and vegetable fats and oils	mg/L	10
	Mineral oils *[Note 1]*	mg/L	0.05
	Total phenols	mg/L	0.1
	Pentachlorophenol	mg/L	0.003
	Total aldehydes	mg/L	0.5
	Tetrachloroethylene, Trichloroethylene (sum of specific concentrations)	mg/L	0.01
	Total chlorinated solvents	mg/L	0.04
	Trihalomethanes (sum of concentrations)	mg/L	0.03
	Total aromatic organic solvents	mg/L	0.01
	Benzene	mg/L	0.001
	Benzo(a)pyrene	mg/L	0.00001
	Total nitrogenous organic solvents	mg/L	0.01
	Total surfactants	mg/L	0.5
	Chlorinated pesticides (each) *[Note 2]*	mg/L	0.0001
	Organophosphorus pesticides (each)	mg/L	0.0001
	Other total pesticides	mg/L	0.05
Microbiological parameters	Escherichia coli *[Note 3]*	CFU/100 mL	10 (80% of the samples) 100 (Maximum point value)
	Salmonella		Absent
	Helminths	Eggs/100 mL	-
Radiological	Total alpha radiation	pCi/L	-
	Total beta radiation	pCi/L	-

[Note 1] This substance must be absent from recovered wastewater intended for reuse, in accordance with paragraph 2.1 of Annex 5 of Legislative Decree No. 152 of 1999 concerning discharges onto soil. This requirement is considered fulfilled when the substance is present at concentrations not exceeding the detection limits of the reference analytical methods, as defined and updated by a specific ministerial decree pursuant to paragraph 4 of Annex 5 of Legislative Decree No. 152 of 1999. Pending such definition, the detection limits indicated in the table shall apply.

[Note 2] The parameter value refers to each individual pesticide. For Aldrin, Dieldrin, Heptachlor, and Heptachlor epoxide, the parametric value is equal to 0.030 µg/L.

[Note 3] For recovered wastewater originating from lagooning or phytoremediation, the applicable limits are 50 CFU/100 mL (80% of the samples) and 200 CFU/100 mL (maximum point value).

Ministerial Decree No. 185/2003 also establishes that the limits for pH, ammoniacal nitrogen, specific electrical conductivity, aluminum, iron, manganese, chlorides, and sulfates at the outlet of the recovery plant, (listed in the annexed table) are to be considered guideline values. Regional authorities may authorize alternative limits for specific uses, subject to approval by the Ministry of the Environment and the Protection of Territory, provided that such values do not exceed the discharge thresholds into surface waters defined in Table 3 of Annex 5 of Legislative Decree No. 152/2006. For specific electrical conductivity, the value must not exceed 4000 μS/cm.

All physicochemical parameters must refer to annual average values or, when applied to irrigation reuse, to the average values of the specific irrigation season. Reuse must be immediately suspended if, during monitoring, the instantaneous value of any parameter exceeds 100% of the established limit. It may only resume once the parameter(s) fall below the threshold in at least three consecutive and successful measurements.

In Brazil, there is currently no federal legislation specifically addressing the reuse of treated water. Nonetheless, certain regulatory instruments have begun to acknowledge the relevance of this practice, although they do not establish quality standards or define reuse categories.

In response to this legislative gap, several Brazilian States, including Ceará, Rio Grande do Norte, Rio Grande do Sul, and Paraná, have enacted their regulations to promote water reuse practices, establishing quality parameters and classification systems.

One of the most recent regulatory frameworks is Resolution No. 122, dated July 19, 2023, issued by the State Water Resources Council of Paraná (CERH/PR). This resolution outlines general guidelines and criteria for water reuse within the state.

According to Article 1, the regulation establishes directives and general standards for the reuse of water derived from treated sanitary or industrial effluents, intended for urban, agricultural, forestry, environmental, and industrial applications.

Article 10 defines the quality parameters and classification of reused water for urban purposes, which are categorized as follows:

1. **Class A:** Reused water designated for landscape irrigation in areas with unrestricted public access, floor washing, cleaning of public spaces, vehicle washing, ornamental use, fire suppression, and building-related applications;
2. **Class B:** Reused water intended for landscape irrigation in areas with either unrestricted or restricted access, particulate emission control, civil construction activities, and maintenance of sewage, stormwater, and/or wastewater networks;

3. **Water reuse in agricultural and forestry applications**.

The specific quality standards applicable to each class are detailed in Table 5 of the Resolution.

Table 5 - Quality standards for reclaimed water in Classes A and B (Resolution CERH/PR No. 122/2023)

Water quality standards		Reclaimed water use categories	
Parameter	**Unit of measurement**	**Class A Unrestricted non-potable reuse**	**Class B Restricted non-potable reuse**
pH	-	6 to 9	6 to 9
Thermotolerant coliforms or Escherichia coli	CFU/100 mL	200	1000
Viable helminth eggs	Eggs/L	< 1	< 1
Total residual chlorine (TRC) [(1)]	mg/L	0.5 < TRC < 2	0.5 < TRC < 2
Electrical conductivity (EC) [(2)]	mS/cm	3200	3200

[(1)] Post-treatment effluent
[(2)] Parameter required only for use in landscape irrigation

The quality and standards for water reuse intended for agricultural and forestry purposes shall comply with the maximum values established in Table 6.

*Table 6 - Maximum permissible value for agricultural and forestry reuse (*Resolution CERH/PR No. 122/2023)

Parameter	Unit of measurement	Maximum limits
pH	pH units	5 to 9
Electrical conductivity (EC)	mS/cm	3200
Mineral oils	mg/L	Up to 10
Animal and vegetable fats and oils	mg/L	Up to 30
Surfactants (MBAS)	mg/L	0.5
Dissolved aluminum	mg/L	0.2
Total arsenic	µg/L	0.03
Total barium	mg/L	1.0
Bicarbonates	meq/L	10.00
Total boron	mg/L	0.75
Total cadmium	µg/L	0.01
Carbonates	meq/L	0.10
Total lead	mg/L	0.033
Chlorides	mg/L	30.00
Cobalt	mg/L	0.2

Parameter	Unit of measurement	Maximum limits
Dissolved copper	mg/L	0.013
Hexavalent chromium	mg/L	0.10
Trivalent chromium	mg/L	1.0
Sulfide	mg/L	1.0
Sulfate	mg/L	250.00
Dissolved iron	mg/L	5.0
Dissolved manganese	mg/L	0.5
Total mercury	mg/L	0.002
Molybdenum	mg/L	0.50
Total nickel	mg/L	0.025
Sodium adsorption ratio (SAR)	$(mmolc/L)^{1/2}$	15.00
Total selenium	mg/L	0.05
Sodium	meq/L	40.00
Total fluoride	mg/L	10.00
Total zinc	mg/L	5.0
Cyanide	mg/L	0.022
Vanadium	mg/L	0.1
Total phenols	mg/L	0.01
Thermotolerant coliforms	MPN/100 mL	1000
Viable helminth eggs	Egg/L	1.0

According to Article 13, regarding Biochemical Oxygen Demand (BOD), the following considerations apply:
I – When reused water originates from domestic wastewater treatment and is intended for agricultural and forestry purposes, a maximum limit of 60 mg/L of BOD_5 must be observed;
II – When reused water originates from industrial effluent treatment plants and is intended for agricultural and forestry purposes, the standards established in Annex 7 of Resolution CEMA/PR No. 70, dated October 1, 2009, shall apply.

It is necessary to note the following when addressing water reuse for agricultural and forestry purposes. Article 16 of Resolution CERH/PR No. 122/2023 outlines specific prohibitions regarding the use of reclaimed water in the following situations:

- ✓ In the cultivation of fruits, vegetables, roots, and tubers intended for raw human consumption when the edible portion is in direct contact with the soil;
- ✓ In areas where groundwater is abstracted from wells located within a radius under 70 meters;
- ✓ Within a radius of less than 200 meters from population centers;
- ✓ In locations characterized by rocky outcrops or the presence of shallow or poorly developed soils;

- ✓ In flood-prone areas;
- ✓ In permanent preservation areas;
- ✓ In aquifers classified as highly vulnerable.

3.3 ANALYTICAL CRITICALITY: DATA ANALYSIS USING THE FAILURE MODE AND EFFECT ANALYSIS (FMEA) METHODOLOGY

The analytical assessment of parameter criticality is conducted using the Failure Mode and Effect Analysis (FMEA) methodology in a risk management plan, focusing on parameters for which threshold values have been established, whether the analysis is temporal or spatial in nature (ISTISAN, 2022).

The FMEA methodology is employed to identify potential failures, along with their causes and effects on the performance of a given process. This approach, when expanded, may include a criticality analysis aimed at prioritizing failure modes. Such prioritization is based on factors such as severity, frequency of occurrence, and the Risk Priority Number (RPN), which is calculated as the product of severity, occurrence, and detection ratings. Guided by this methodology, actions are developed and implemented to eliminate or reduce the likelihood of failures and associated safety risks (Nolan & McDermott, 2025).

In the field of water and wastewater management, particularly in water safety planning and the reuse of treated wastewater, this semi-quantitative methodology can be applied to chemical water quality parameters, except for those lacking legally defined limit values or those for which only an acceptable range is provided. It is important to note that this methodology is not applicable to microbiological parameters, as they typically exhibit a non-Gaussian distribution (ISTISAN, 2022).

As previously established, the FMEA methodology considers the values of parameters for which Legislative Limits (LL) have been established. In addition to these, two other factors are incorporated into the historical data assessment: the 95th percentile (P95), defined as the value of the random variable exceeded in only 5% of cases, and the Limit of Quantification (LOQ) (Hernández-Cuenca et al., 2025; ISTISAN, 2022).

Based upon these outlined factors, the resulting interval is subsequently subdivided into five subintervals of equal width, to which the values R1, R2, R3, R4, and R5 are assigned (R = detectability factor). Table 7 presents the calculation methodology used to define these subintervals.

Table 7 – Risk classification subintervals

Detectability factor (R)	Detectability interval	Risk level
R1	P95 < LOQ + (LL-LOQ) /5	Very low (1 – 2)
R2	LOQ + (LL-LOQ) /5 ≤ P95 < LOQ + (2/5) x (LL-LOQ)	Low (3 – 4)
R3	LOQ + (2/5) x (LL-LOQ) ≤ P95 < LOQ + (3/5) x (LL-LOQ)	Medium (5 – 9)
R4	LOQ + (3/5) x (LL-LOQ) ≤ P95 < LOQ + (4/5) x (LL-LOQ)	Moderate (10 – 17)
R5	LOQ + (4/5) x (LL-LOQ) ≤ P95 < LL	Non acceptable (18 – 36)
R5	P95 > LL	Critical

Reference: Adapted from Hernández-Cuenca et al. (2025)

The rationale underpinning the FMEA methodology is to determine, for each parameter, the detectability category (R1 - R5) into which its 95th percentile falls. Parameters whose 95th percentile of historical concentration values fall within the highest detectability levels (R4 and R5) should be considered high-risk from a monitoring perspective, even if they do not exceed Legislative Limits (LL).

Thus, the primary objective of the FMEA analysis is to identify the most critical parameters for risk management, those that require more frequent and rigorous monitoring strategies.

3.4 IDENTIFICATION OF HAZARDS AND HAZARDOUS EVENTS FOR PRELIMINARY RISK ASSESSMENT

Hazard identification constitutes a fundamental element in risk assessment, being essential both for defining the implementation of appropriate control measures and for identifying the necessary treatment requirements.

According to the guidelines provided by the Joint Research Centre (JRC) in its technical manual for the development of risk management plans for the reuse of treated wastewater in agriculture (Maffettone & Gawlik, 2022), all potential hazards to be considered must encompass pathogenic agents and chemical pollutants present in the treated water that may pose risks to human health, animal health, and/or the environment.

In this context, it is recommended to utilize, as the list of relevant hazards the set of microbiological, chemical, and physical parameters regulated by national and/or international standards mandated for the protection on water quality and human health, as detailed in Section 3.2.

Hazardous events may vary in nature and consist of either a single process failure or a sequence of interconnected occurrences. Such events may arise during standard system operation, as a result of a failure or accident, or they may be related to adverse meteorological conditions. The occurrence of a hazardous event ultimately leads to direct or indirect exposure to a hazard.

For example, a plant malfunction at the treatment facility may result in non-compliance with legislative limits for certain regulated physicochemical and microbiological parameters, potentially causing contamination of the receiving environmental compartment and posing a health risk to individuals who come into contact with the effluent.

The identification of hazardous events must be conducted through the analysis of each node in the flow diagram representing the water reuse system.

Furthermore, each hazardous event introduces a specific hazard at different stages of the treated effluent production and distribution chain. These hazards must be identified and appropriately associated with each potential hazardous event.

3.5 IDENTIFICATION OF EXPOSED POPULATION GROUPS AND MAIN EXPOSURE PATHWAY

Hazards, specifically, the presence of contaminants at concentrations exceeding legally established limits (LL), resulting from hazardous events may cause detriment to the health of exposed population groups.

In the context of irrigation reuse, the population groups potentially exposed to the identified hazards within a reuse system, for the purpose of health risk assessment, include the following:

- ✓ Wastewater treatment plant (WWTP) personnel or those operating the distribution network;
- ✓ Agricultural works (Farmers);
- ✓ Local communites (Residents of nearby areas).

In addition to identifying the exposed population, the contamination pathways are also crucial for understanding the mechanisms by which exposure may occur.

The main pathways include:

- ✓ Inhalation of aerosols;
- ✓ Accidental ingestion;
- ✓ Consumption of raw or inadequately washed vegetables;
- ✓ Dermal contact, particularly through broken or damaged skin.

3.6 HEALTH AND ENVIRONMENTAL RISK ASSESSMENT

The methodology for calculating health risk is based on the previously identified hazards and hazardous events, employing a semi-quantitative approach.

According to this approach, risk is calculated by determining the product of the probability of occurrence of a given hazardous event and the severity of the resulting hazard, as expressed below:

$$R = P \text{ (Probability of Occurrence)} \times S \text{ (Severity of Hazard)}$$

It is the prerogative and responsibility of the team in charge of developing the risk management plan to assign a probability of occurrence to each identified hazardous event, as well as a severity level to the resulting hazard.

The "Probability of Occurrence" is quantified using a discrete integer value, selected within the range of 1 to 5, based on the frequency of past occurrences or the plausibility of the event, according to the criteria defined in Table 8.

Table 8 - Criteria for Assigning the Score Related to the Probability of Occurrence of a Hazardous Event

Score	Categorization	Description
Probability of Occurrence (P)		
1	Rare	***Frequency:*** not occurred in the past (observation period: no less than 5 years). ***Plausibility:*** highly unlikely to occur in the future.
2	Unlikely	***Frequency:*** occurred rarely (observation period: 3 years). ***Plausibility:*** cannot be ruled out that it may occur in the future.
3	Moderate	***Frequency:*** occurred in the past (observation period: 1 year). ***Plausibility:*** plausible, especially under certain circumstances that may realistically occur.
4	Likely	***Frequency:*** occurred in the past (observation period: 3 months). ***Plausibility:*** plausible that the conditions may recur.

Score	Categorization	Description
5	Almost Certain	***Frequency:*** occurred repeatedly (observation period: 1 month). ***Plausibility:*** likely to continue occurring.

The frequency of occurrence of a hazardous event can be determined by consulting the operational records of the wastewater treatment plant.

If such frequency cannot be established through this method, it is possible to estimate the plausibility of occurrence. In this regard, the following actions are particularly effective:

- ✓ **Completion of checklists:** conducting on-site inspections at the treatment plant allows for the recording of relevant information to assess the functional condition of equipment and treatment processes.
- ✓ **Monitoring data analysis:** the FMEA method can be applied to parameters with defined limit values. These analyses allow for the identification of elevated concentrations of specific analytical parameters that warrant attention in relation to the limits established by current regulations.
- ✓ **Functional checks and analysis of operational parameters:** these are carried out through comparison with technical specifications available in the literature for the various treatment units. These analyses aid in identify potential critical points within the purification process;
- ✓ **Modeling analysis:** this is aimed at simulating the impact of load variations and operational parameters on the behavior and performance of treatment processes.

The "Severity" score is also quantified using a discrete integer value, selected within the range of 1 to 5, and is determined based on the potential consequences for human health.

The criteria for defining the severity score are presented in Table 9.

Table 9 - Criteria for Assigning the Score Related to the Probability of Occurrence of a Hazardous Event

Score	Categorization	Description
Severity of Hazard (G)		
1	Not Significant	Hazard related to a chemical, physical, or microbiological parameter not regulated by current legislation, which entails null or negligible health effects compared to background

Score	Categorization	Description
		levels. The hazard does not affect the acceptability of the water resource for use.
2	Low	Hazard related to a chemical, physical, or microbiological parameter not regulated by current reuse legislation, which entails null or negligible health effects, but may slightly alter certain physical properties of the water (e.g., color, temperature etc.), thereby affecting the acceptability of the water resource for use.
3	Moderate	Hazard related to a chemical, physical, or microbiological parameter regulated by current reuse legislation. The hazard may result in minor health effects (e.g., temporary symptoms such as irritation, nausea, or headache). The hazard or hazardous event may lead to regulatory non-compliance subject to administrative penalties.
4	High	Hazard related to a chemical, physical, or microbiological parameter regulated by current reuse legislation. The hazard may result in minor health effects (e.g., temporary symptoms such as irritation, nausea, or headache). The hazard or hazardous event may lead to the accumulation of toxic substances in the environment, with potential repercussions on human health. It may also result in regulatory non-compliance subject to administrative penalties.
5	Very High	Hazard related to a chemical, physical, or microbiological parameter regulated by current reuse legislation. The hazard may cause human diseases (e.g., malaria, acute diarrhea, vomiting, upper respiratory tract infections etc.). Its presence and accumulation in the environment may lead to carcinogenic effects or other non-negligible impacts on human health. The hazard or hazardous event will trigger serious investigations by regulatory authorities, with likely legal action.

Once the values assigned to *Probability* and *Severity* have been defined, they are multiplied together to yield a numerical value representing the final risk. This resultant value ranges from 1 to 25 and corresponds to the structure of a 5 X 5 risk matrix (Table 10).

Table 10 – Risk matrix

Risk Matrix			Severity of Hazard (G)				
			Insignificant	Low	Moderate	High	Catastrophic
			1	2	3	4	5
Probability of Occurrence (P)	Rare	1	1	2	3	4	5
	Unlikely	2	2	4	6	8	10
	Moderate	3	3	6	9	12	15
	Likely	4	4	8	12	16	20
	Almost Certain	5	5	10	15	20	25
R = P x G			< 6	6 - 9	10 - 15	> 15	
Level risk			Low Risk	Medium Risk	High Risk	Very High Risk	

Risks that, following calculation using the semi-quantitative method, are classified as "Very High," "High," or "Medium" must be reassessed considering the validation results of the currently implemented control measures. If these measures are deemed to be inadequate, an improvement program (supported by appropriate investments) must be implemented to ensure that all risks are properly managed and controlled. Risks classified as "Low" must nevertheless be documented and subjected to regular review to ensure that any future systemic changes do not lead to an increase in their rating.

Environmental risk assessment follows the methodology proposed by the Australian Guidelines for Water Recycling (NRMMC-EPHC-AHMC, 2006), as subsequently adopted by the JRC guidelines. According to these methodologies, environmental risk is calculated by assigning descriptors or ratings to both the likelihood of occurrence of a hazardous event and the severity of the resulting environmental damage. Figure 1 deadlines the criteria used to define the likelihood of occurrence of an environmentally hazardous event.

Figure 1 - Criteria for Assigning the Likelihood Categorization

Likelihood of Occurrence		
Level	**Categorization**	**Description**
A	Rare	It may occur only under exceptional circumstances and is estimated to happen once every 100 years.
B	Unlikely	It could occur within 20 years or under unusual circumstances.
C	Possible	It could occur, or is expected to occur, within a 5–10 year timeframe.
D	Likely	It is likely to occur within a timeframe of 1 to 5 years.
E	Almost certain	It is expected to occur with a probability of multiple occurrences within one year

Reference: Australian Guidelines for Water Recycling (2006)

Figure 2 presents the criteria used to assign the severity descriptor to the resulting hazard.

Figure 2 - Criteria for Assigning the Severity Descriptor (Australian Guidelines for Water Recycling, 2006)

Severity of Hazard (G)		
Level	**Categorization**	**Description**
1	Insignificant	Impact not significant or not detectable
2	Minor	Potentially harmful to the local ecosystem, with site-contained impacts. Environmental effects are short-term and reversible, with no detectable ecological change. The situation can be readily managed but still requires prompt action to minimize impacts. For example, a minor release of recycled water (suitable for forest irrigation) into a nearby stream may cause limited adverse effects (e.g., odor) or slight stress to native vegetation (e.g., phosphorus-sensitive native plants). Some manageable alterations to normal use or discharge may occur.
3	Moderate	Potentially harmful to ecosystems at the regional level, with impacts confined to the surrounding site. Minor effects may extend to adjacent areas. Environmental impacts are medium-term and generally reversible. Should the event occur, the impacts could be promptly contained or mitigated (e.g., eutrophication of a watercourse caused by runoff during irrigation with recycled water). Represents a significant deviation from normal conditions, with consequences for typical use or discharge patterns and an increase in monitoring requirements.
4	Major	Potentially lethal to the local ecosystem, with possible off-site impacts. Environmental effects may be medium- to long-term and potentially reversible over several years. The event would cause significant disruption to ecosystems. If it were to occur, environmental impacts would be difficult to contain or mitigate (e.g., large-scale fish kills, widespread mortality of flora and fauna). Represents a major deviation from normal conditions, with consequences for typical use or discharge. Possible cessation of use may be required. A high level of monitoring is necessary.
5	Catastrophic	Potentially lethal to regional ecosystems or to threatened species; widespread on-site and off-site impacts. Catastrophic damage—should the event occur, environmental consequences would be extremely difficult, if not impossible, to contain or mitigate (e.g., catastrophic impacts on World Heritage areas, or on species, populations, or ecological communities identified as threatened). Represents a severe system failure leading to cessation of use.

Reference: Australian Guidelines for Water Recycling (2006)

By cross-referencing the descriptors/ratings assigned to the likelihood of occurrence and the severity of the resulting hazard, it is possible to determine the environmental risk rating, as defined in Figure 3.

Figure 3 - Criteria for Environmental Risk Assessment

Likelihood of Occurrence	Severity				
	Insignificant	**Minor**	**Moderate**	**Major**	**Catastrophic**
Rare (1)	Low	Low	Low	High	High
Unlikely (2)	Low	Low	Moderate	High	Very High
Possible (3)	Low	Moderate	High	Very High	Very High
Likely (4)	Low	Moderate	High	Very High	Very High
Almost Certain (5)	Low	Moderate	High	Very High	Very High

Reference: Australian Guidelines for Water Recycling (2006)

3.7 CONSTRUCTION OF A RISK MATRIX

The risk assessment process must encompass every identified hazardous event, and this process must be thoroughly documented through the Risk Matrix (RM), which serves as the principal tool utilized during the implementation of a Risk Management Plan in a wastewater reuse system.

The RM functions as the central document of the management plan, providing a clear and schematic summary all information and evaluations related to the reuse system under analysis, the control measures applied, and the supplementary actions planned. It is an operational tool highly suitable for conducting a systematic and rigorous study of the entire system, effective in ensuring immediate traceability of the entire risk analysis process. Furthermore, it ensures that no element is overlooked during the system review phase and, in the event of an incident, provides documentary evidence of the decision-making process, thereby facilitating the identification of potential gaps.

The construction of the Risk Matrix (RM) comprises the following essential elements (Table 11):

Table 11 - Elements of the Risk Matrix

Matrix component	Description
Identification of the Reuse System	It is important to identify the code of each node within the treatment system, possible sub-systems, and a description of each node.
Description of Hazardous Events and Associated Hazards	Hazardous event and consequences: provides a concise description of the identified hazardous event and its potential consequences.

Matrix component	Description
	Evidence supporting the assignment of probability/likelihood of occurrence: gathers information to establish the frequency or plausibility of occurrence, aimed at assigning a “Probability of Occurrence” score to the hazardous event in question. Evidence supporting the assignment of impact severity (worst-case scenario): presents the parameters or groups of parameters regulated by legislation, whose concentrations in the treated effluent may exceed legal limits as a result of the hazardous event. Additionally, it is possible to specify whether the parameter type is related to a biological, chemical, or physical hazard. Exposure pathways: lists the exposure routes associated with the hazardous event.
Preliminary Risk: This element summarizes the results of the risk assessment under worst-case conditions, that is, in the absence of control measures.	Probability of Occurrence (P1): numerical value assigned to the likelihood of the selected event occurring in the absence of control measures, based on the evaluations conducted. Severity of Hazard: numerical value assigned to the severity of the hazard’s consequences, according to the assessments carried out. Risk (R1): numerical value representing the risk, obtained through the mathematical operation P1 × G.
Existing Control Measures: Presents the control measures currently	Existing Control Measures: provides a description of the control measures already implemented and

Matrix component	Description
implemented in the wastewater reuse system, linking them to the various hazardous events and associated hazards identified at the nodes of the treated water supply system under analysis.	linked to the hazardous event identified in the previous section. Supporting Observations: offers a concise assessment of the effectiveness of the existing control measures in preventing the occurrence of the associated and previously identified hazard. Effectiveness must be evaluated based on documented evidence, such as the results of FMEA analysis and functionality checks of the treatment facility. This section is essential to justify a revised assignment of the "Probability of Occurrence" value for the hazardous event in question.
Residual Risk: This section contains the results of the residual risk assessment. The probability of occurrence of the various hazardous events may be modified by the presence of control measures and, depending on their effectiveness, subsequently reassessed. However, existing control measures do not alter the evaluation of G (Severity of Hazard). Therefore, the previously assigned G value is used in the risk calculation. The fields in this section are:	Probability of Occurrence (P2): numerical value assigned to the likelihood of the selected event occurring in the presence of a specific control measure. Severity of Hazard: numerical value assigned to the severity of the hazard's consequences, which remains unchanged in the presence of control measures. Risk (R2): numerical value representing the residual risk, obtained through the mathematical operation P2 × G.
Improvement Plan: This section lists the additional control measures identified to improve the system in	Need/opportunity for additional control measures: Describes the supplementary control measures identified to minimize the probability of

Matrix component	Description
cases where the risk is not sufficiently minimized by the existing control measures. The fields in this section are:	occurrence of the hazardous event outlined in the previous sections.
Validation of Supplementary Measures and Complementary Monitoring This section describes the actions required to evaluate the effectiveness of the proposed supplementary control measures and to calculate the expected residual risk after intervention. The associated fields are:	Validation of Supplementary Measures and Complementary Monitoring: describes the actions required to verify the effectiveness of the newly adopted control measures and the actual reduction of risk. Responsible for Implementing Supplementary Measures: identifies the entity responsible for executing the defined supplementary measures. Probability of Occurrence (theoretically estimated – P3): numerical value assigned to the likelihood of the selected event occurring in the presence of supplementary measures, estimated based on theoretical projections. Severity of Hazard: numerical value associated with the severity of the hazard's consequences, which remains unchanged despite the adoption of supplementary control measures. Final Expected Residual Risk Post-Intervention (R3): numerical value representing the residual risk, obtained through the mathematical operation $P3 \times G$.

4. METHODOLOGY

As part of the mandatory training component of the doctoral program, a six-month international research period was carried out in Brazil, in collaboration with the Universidade do Estado de Santa Catarina (UDESC), from November 2, 2024, to May 2, 2025.

During this period, for the development of Case Study 1, two municipal wastewater treatment plants were selected, along with their respective managers, to conduct a comprehensive risk analysis of the treatment processes. This topic is considered innovative for the region and is specifically aimed at assessing the physicochemical risks associated with wastewater treatment, focusing on the feasibility of reusing treated water.

For Case Study 2, the analysis focused on treated effluent intended for reuse from a wastewater treatment plant located in the Marche Region, Italy.

The following section delineates the specific methodology adopted for the development of this study.

4.1 LITERATURE REVIEW

The literature review aimed to explore the planning of treated wastewater reuse, emphasizing the importance of developing a structured reuse plan, its key technical components, and the regulatory frameworks governing this practice in both Italy and Brazil.

Furthermore, risk assessment approaches were examined based on the methodology established by the Italian directive issued by the *Istituto Superiore di Sanità*, as outlined in the ISTISAN Report 22/33 (2022), European and Italian legislation, regulation of the State of Paraná, Brazil, for the reuse of treated effluent complemented by additional bibliographic sources addressing the application of the Failure Mode and Effect Analysis (FMEA methodology) and risk matrix structuring for the prioritization of mitigation strategies.

4.2 STUDY AREA: BRAZIL

Municipal treatment plants located in Southern Brazil were selected to assess the risks associated with the wastewater treatment system, based on the sanitation company's designation of the facilities under its management.

Wastewater Treatment Plant (WWTP No. 1), considered the city's main facility, is located in the Southern part of the municipality and is responsible for treating approximately 90% of the collected sewage. It serves approximately 190,000 residents from the North, East, Central, and South regions, with a full operational capacity of 600 L/s (Figure 4). The treated effluent is discharged into a local river in compliance with current legislation. WWTP No. 1 is situated within the Independent Hydrographic Basins of the Southern Watershed.

The facility is located in the urban macrozone classified as a Controlled Urban Densification Area (AUAC), specifically within the Controlled Densification Sector (SA-04), according to Complementary Law (2017).

The treatment system employed at this unit is the *Intermittent Cycle Extended Aeration System* (ICEAS) with activated sludge, achieving an average efficiency of 83% (PROSAJ, 2022).

Figure 4 - Wastewater Treatment Plant No. 1 – Brazilian Case Study

Reference: SimGEO (2025)

WWTP No. 2, located in the Northern region of the city, serves approximately 17,200 residents and has a treatment capacity of 41 L/s (Figure 5) (Prefeitura de Joinville, 2021).

This facility utilizes the *Upflow Anaerobic Sludge Blanket* (UASB) system combined with activated sludge, achieving an average efficiency of around 86% (PROSAJ, 2022). The treated effluent is discharged into a local river in full compliance with current legislation.

WWTP No. 2 is located within the Cubatão River Basin, and the facility is located in the urban macrozone classified as a Controlled Urban Densification Area (AUAC), specifically within the Controlled Densification Sector (SA-04) (Complementary Law, 2017).

Figure 5 - Aerial View of WWTP No. 2 – Brazilian Case Study

Reference: SimGEO (2025)

Overall, both WWTPs follow the standardized treatment stages delineated in Table 12.

Table 12 - Concise description of the treatment process stages implemented at the two Wastewater Treatment Plants (WWTPs) examined in this case study

Identification of the Wastewater Treatment Plant (WWTP)	Wastewater Treatment Phases
WWTP No. 1	Preliminary Treatment; Secondary Treatment; Distribution Tower; Tertiary Treatment (Ultraviolet Disinfection – UV) Sludge Treatment; Support Structures: Chemical Dosing, Structural Maintenance, and Quality Control.
WWTP No. 2	Pre-treatment; Secondary Treatment; Tertiary Treatment (Disinfection using Sodium Hypochlorite); Sludge Treatment;

Identification of the Wastewater Treatment Plant (WWTP)	Wastewater Treatment Phases
	Support Structures: Chemical Storage, Structural Maintenance.

Reference: Personal communication, management company of the WWTPs (2024), Prefeitura de Joinville (2021)

The time frame considered for the historical analysis of treatment parameters spans from June 9, 2022, to December 19, 2024, encompassing both evaluated treatment plants (WWTP).

4.3 CASE STUY: ITALY

The Italian case study refers to the wastewater treatment plant located in the city of San Benedetto del Tronto (Figure 6), in the Marche region, near the Sentina Regional Nature Reserve.

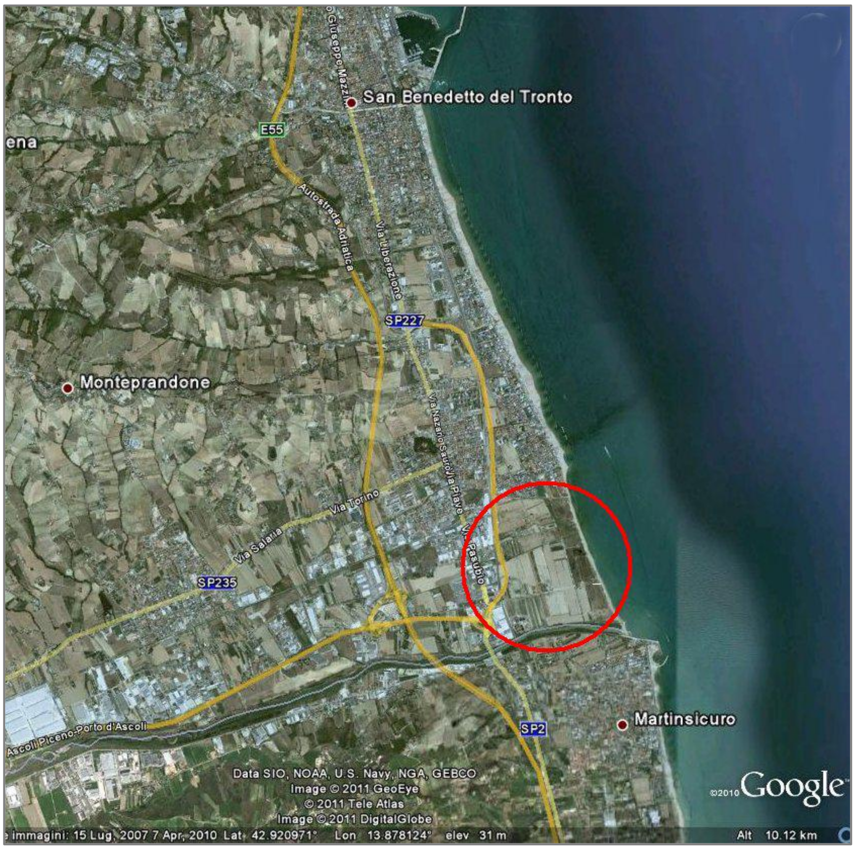
Figure 6 - Aerial view of the San Benedetto del Tronto wastewater treatment plant

Reference: Google Earth (2024)

Established on December 14, 2004, the Sentina Regional Nature Reserve is the smallest protected area in the Marche region, yet it holds significant environmental importance (Council Resolution No. 156).

It is a landscape of water and sand spanning approximately 180 hectares within the municipality of San Benedetto del Tronto, situated between the urban center of Porto d'Ascoli to the north and the Tronto River to the south (Figure 7) (Riserva Sentina, n.d).

Figure 7 - Location of the Sentina Regional Nature Reserve



Reference: Google Maps (2024)

The habitats that make up the Sentina Reserve include (Riserva Sentina, n.d):

- ✓ **Dune environment**: The Sentina Regional Nature Reserve features approximately 1,700 meters of coastline, along which a small dune system has developed, hosting various plant and bird species. The observed plant species include sea rocket (*Cakile maritima*), *Spartina*, and *Salsola*. These plants, like other psammophilous species (adapted to sandy coastal environments), exhibit unique adaptations that allow them to survive in this seemingly harsh setting; deep roots, salt tolerance, and sturdy leaves are just a few examples. The bird species include the Kentish plover (*Charadrius alexandrinus*) can be observed—a migratory bird that lays its eggs directly on the beach;
- ✓ **Wet interdunal environment**: it is considered the most important habitat within the reserve. It was once severely degraded and later restored thanks to the Life+ Re.SCWe

project.
The interdunal wetland is highly heterogeneous, characterized by small bodies of fresh or brackish water, both perennial and seasonal. This environment serves as a habitat for migratory birds such as herons (e.g., cattle egret), ducks, as well as amphibians and reptiles;

- ✓ **Salt meadow**: also known as saline steppe, this environment is characterized by soils with high salt concentration. These areas also feature various surface water bodies, but unlike wetland habitats, they are temporary and therefore dependent on heavy rainfall or storm tides capable of breaching the dune barrier. Plant species commonly found in this habitat include *Salicornia*, sea fennel (*Crithmum maritimum*), and licorice (*Glycyrrhiza*);
- ✓ **Agricultural area**: this is the habitat most affected by human activity. Hedges and rows of vineyards have almost entirely disappeared. Crop rotation is no longer practiced, and agricultural techniques are intensive. The management plan for this area aims to restore traditional farming practices in order to sustain the high level of animal and plant biodiversity.

The San Benedetto del Tronto treatment plant (Brodolini, DEPUR00198), managed by the company CIIP Spa, is authorized with a nominal capacity of 180,000 population equivalents (PE) and an average raw sewage flow of 24,000 m^3/day.
The plant serves the urban clusters of San Benedetto del Tronto and the Lower Tronto Valley, and is subject to significant seasonal variations, mainly due to the area's tourism activity, which results in predominantly domestic wastewater discharges.
The treatment capacity allocated to industrial wastewater corresponds to approximately 10%.
The current water treatment line consists of the following stages:

- ✓ Pumping;
- ✓ Preliminary treatments;
- ✓ Primary sedimentation;
- ✓ Secondary biological treatments;
- ✓ Secondary sedimentation;
- ✓ Final chemical disinfection (disinfection is carried out through two operational units, referred to as the “new line” and the “old line,” using peracetic acid);

- ✓ Tertiary filtration (the new filtration section consists of a dual unit of semi-submerged disc filters. Depending on operational needs, the filtered water can be directed either to the Ultraviolet (UV) disinfection section or to disinfection with peracetic acid);
- ✓ UV disinfection (currently, both treatment lines are in the implementation phase).

Currently, the San Benedetto treatment plant operates with two water treatment lines, referred to as the east line and the west line.
The treated effluent is discharged into a surface water body (the Tronto River), in compliance with the limits established in Tables 1, 2, and 3 of Legislative Decree 152/2006.
Two mixed sewage lines converge at the San Benedetto plant: one along the coastal stretch (IS10) and another along the mountainous stretch (Basso Tronto).
The treatment plant is authorized to process approximately 17,000 population equivalents (PE) of industrial origin.
In terms of flow rate (m^3/day) and mass load of major pollutants (kg/day), industrial discharges account for, at most, 10% of the total treated volume.

4.3.1 The Reuse System: Description of the Irrigated Perimeter and the Canalization/Distribution System

The irrigated perimeter of the Tronto extends throughout the entire valley of the Tronto River, starting from the intake structure located in Brecciarolo (Ascoli Piceno).
Through a main channel — operating as a free-flow system — the water drawn from the river flows to the section just before the Sentina Regional Nature Reserve. In this specific case, the final stretch consists of an underground steel pipeline that crosses the railway via a siphon.
After this route, the water enters the distribution system within the Sentina Reserve area, with an approximate flow rate of 100 L/s, which varies depending on climatic conditions and user demand.
If the flow exceeds 100 L/s, the surplus is discharged through an overflow into a drainage channel that leads the water back to the Tronto River.
A structure located immediately downstream of the aforementioned siphon allows the division of the incoming water (100 L/s) into three branches of the distribution system, namely:

1. **Left branch:** composed of a section of buried pipeline and free-flow channels of Type A (maximum flow rate of 25 L/s) and Type B (maximum flow rate of 40 L/s). The left branch transports water intended exclusively for agricultural reuse.

2. **Central branch:** composed of free-flow channels of Type A (maximum flow rate of 25 L/s) and Type B (maximum flow rate of 40 L/s). The central branch distributes water for agricultural purposes and is responsible for collecting water for the replenishment of the Sentina ponds. The water demand for pond replenishment is 30 L/s.
3. **Right branch:** composed of a buried pipeline with a diameter of Ø300 mm that supplies Type B free-flow channels (maximum flow rate of 40 L/s). This pipeline is fed by a pump installed at the water distribution structure that divides the flow among the three branches. The right branch transports water intended exclusively for agricultural reuse.

For the implementation of treated wastewater reuse practices, CIIP Spa has planned the construction of a pressurized pipeline that will convey the water directly from the treatment plant to the distribution system's branching structure.

A pumping station will be installed at the Brodolini Treatment Plant in San Benedetto del Tronto, which will be responsible for driving the water through the pressurized pipeline.

The pumps to be installed will draw water from the outlet of the treatment plant's disinfection channel and direct it into the pressurized pipeline, without the need for constructing storage tanks.

A flow regulation system based on water levels will ensure the required supply (maximum 100 L/s) of treated wastewater to the distribution system.

The Brodolini plant, with an average dry-weather flow of 22,900 m^3/day (equivalent to 265 L/s), is capable of providing the full flow required by the distribution system throughout the entire calendar year.

In the event of implementing wastewater reuse practices, the entire flow destined for the distribution system would be supplied by the treatment plant.

Water from the intake structure in Brecciarolo would be used only in case of interruption in the supply of treated wastewater. Or in other specific situations related to the operational management of the distribution system across the entire Tronto irrigation perimeter. Therefore, il would supply the need to channel water through the Sentina facilities.

The buried pipelines were constructed using asbestos-cement. For this reason, the monitoring plan includes control measures for the release of asbestos fibers.

The free-flow channels are elevated above ground level to prevent contamination from agricultural surface runoff.

Type B channels (maximum flow rate of 40 L/s) are 40 cm wide at the top and 40 cm high. Type A channels (maximum flow rate of 25 L/s) are 30 cm wide at the top and 30 cm high. Agricultural reuse practices are seasonal, whereas environmental reuse would be carried out continuously throughout the year.

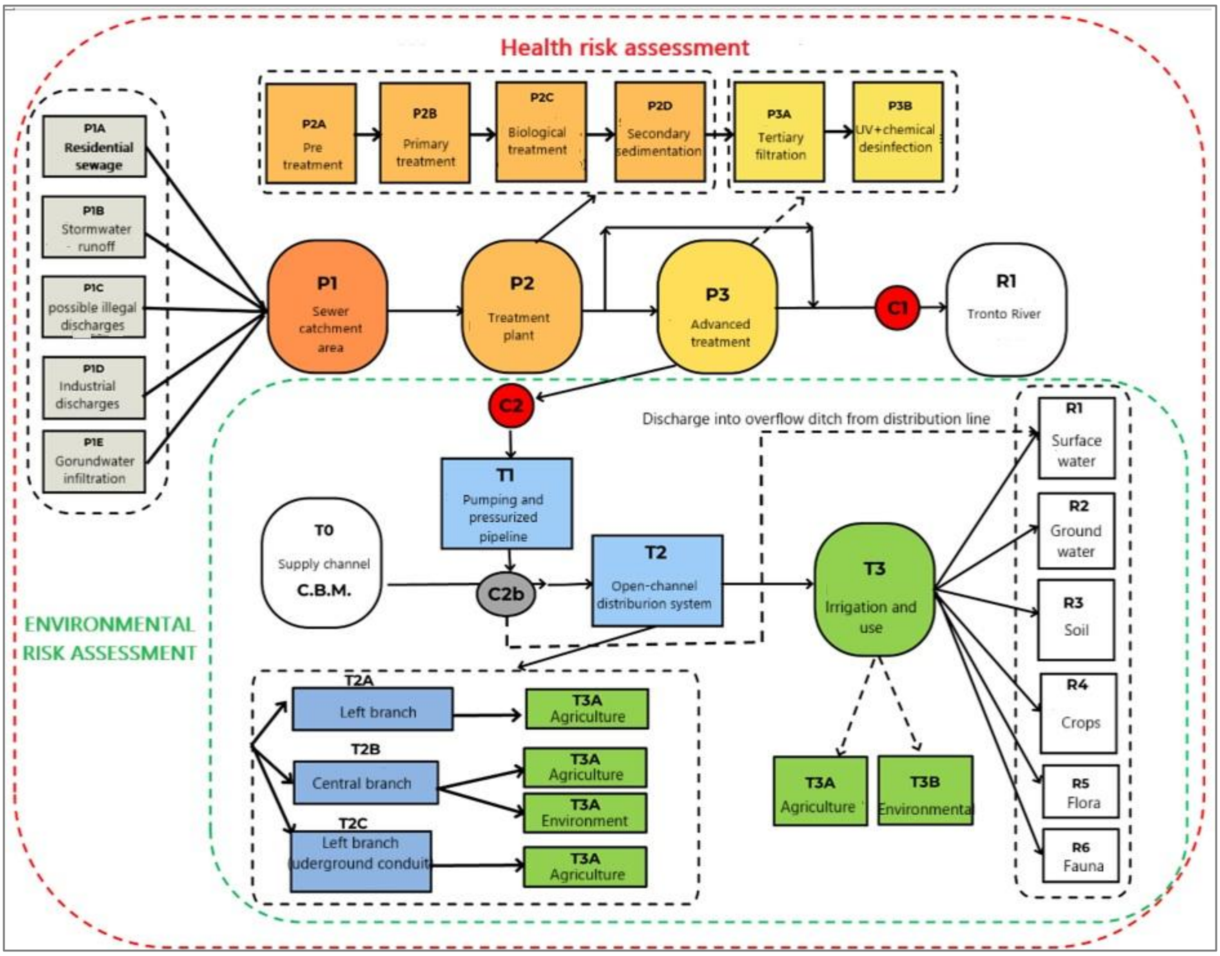
The replenishment of the Sentina ponds requires a flow rate of 30 L/s, whereas during periods when water availability for agricultural irrigation becomes necessary, the demand for treated water can reach up to 100 L/s.

The presence of manually operated shut-off valves allows the interruption of treated water supply to the right and left branches of the distribution system, ensuring exclusive supply to the central branch. This is essential for the replenishment of the Sentina ponds even during the winter season.

4.3.2 Block Diagram of the Reuse System

The diagram presented below (Figure 8) illustrates the entire treated water reuse system, including the wastewater treatment process and the management by the Benfica Consortium, which is responsible for distributing the reclaimed water for agricultural use.

Figure 8 - Block diagram of the San Benedetto del Tronto reuse system



The following section describes the meaning of each letter indicated in the block diagram in Figure 8.

The letter P refers to process nodes, T to transport nodes, R to environmental receptors, and C to the delivery point of the treated water resource.

The subsequent tables provide detailed information regarding the nodes in the reuse system block diagram (Table 13), the discharges into the sewer network (Table 14), the treatment plant (Table 15), and the distribution network (Table 16). Tables 17 and 18 present the details of the reuse network and the environmental receptors, respectively.

Table 13 - Detailed Node Diagram of the San Benedetto del Tronto Reuse System

Subsystem	Node	Description
Catchment Area / Sewer Network	P1	Sewer System and Related Inputs: Includes domestic discharges (P1A), stormwater runoff (P1B),

Subsystem	Node	Description
		potential illegal discharges (P1C), industrial discharges (P1D), and marine intrusion (P1E).
Wastewater Treatment Plant	P2	Treatment Plant: composed of preliminary treatments (P2A), primary treatments (P2B), a biological reactor with pre-anoxic phase + alternating cycles + phosphorus removal (P2C), and secondary sedimentation (P2D).
Tertiary Treatment Plant	P3	Polishing Plant: tertiary filtration (P3A), UV disinfection and emergency disinfection using peracetic acid (P3B).
Compliance Point	C1	Control Point for the Discharge of Treated Water into Surface Waters (Tronto River).
Compliance Point	C2	Control Point for Treated Wastewater Intended for Agricultural Reuse for Irrigation or Environmental Purposes.
Supply Channel	T0	Open Channels Managed by the Aso, Tenna, and Tronto Consortium, Collecting Rainwater and Surface Runoff.
Pumping and Conveyance Pipeline	T1	Pumping Station and Pressurized Conveyance Pipeline Delivering Polished Water to the Canal Distribution System.
Delivery Point to the Distribution System	C2b	Structure for Collecting Water from the Conveyance Pipeline and Entry Point for Reclaimed Effluent into the Canal Distribution System.
Canal-Based Distribution System	T2	Irrigation Distribution Network: Right, Central, and Left Branches (T2A, T2B, T2C).
Irrigation and Utilization System	T3	Irrigation and Agricultural Use System (T3A) and Use for Environmental Purposes (T3B)

Table 14 - Details on Sewer Discharges from the San Benedetto del Tronto Treatment Plant

Discharge Type	Sub-Node	Description/Notes
Domestic Discharges	P1A	The Basso Tronto collector, a sanitary sewer, collects wastewater from the following municipalities: areas of Spinetoli, Monsampolo, Monteprandone, and Colli del Tronto. The effluent flows into the internal lift station of the treatment plant known as Basso Tronto. The San Benedetto del Tronto collector gathers wastewater from the municipalities of San Benedetto and Acquaviva.
Stormwater Runoff	P1B	With regard to the San Benedetto del Tronto collector, two separate sewer lines converge at the treatment plant: a sanitary sewer pipeline that flows into lift station IS10, and a stormwater sewer pipeline that connects to station IS.
Potential Illegal Discharges	P1C	Originating from unauthorized industrial discharges or illegal dumping into sewer manholes.
Industrial Discharges	P1D	The Brodolini treatment plant is also authorized to process approximately 17,000 PE of industrial origin. In terms of flow rate (m^3/day) and mass loads of major pollutants (kg/day), industrial discharges account for up to a maximum of 10% of the total treated.
Marine Intrusion	P1E	Conductivity and chloride values in the wastewater suggest a suspected infiltration of brackish water into the sewer network.

Table 15 - Overview of the San Benedetto del Tronto Treatment and Refinement Facility

Treatment Type	Sub-Node	Description/Notes
Preliminary Treatments	P2A	Preliminary treatments include coarse and fine screening, as well as grit removal.
Primary Treatments	P2B	Four Parallel Primary Sedimentation Lines.
Biological Process and Chemical Phosphorus Removal	P2C	The biological treatment consists of a pre-anoxic tank followed by two alternating-cycle treatment lines, with chemical reagent dosing for phosphorus removal.

Treatment Type	Sub-Node	Description/Notes
Secondary Sedimentation	P2D	Five Circular Secondary Sedimentation Tanks.
Tertiary Filtration	P3A	Two Tertiary Filters.
UV Disinfection	P3B	UV lamp disinfection system. Emergency disinfection system using peracetic acid dosing.

Table 16 - Details on the Distribution Network

Distribution System	Sub-Node	Description/Notes
Right Branch	T2A	Underground
Central Branch	T2B	Flow-through
Left Branch	T2C	Underground

Table 17 - Details on the Utilization Network

Authorized Uses	Sub-Node	Description/Notes
Agriculture	T3A	Use for Irrigation and Agricultural Purposes
Environmental	T3B	Environmental Applications

Table 18 - Details on Environmental Receptors

Environmental Receptors	Sub-Node	Description/Notes
Surface Waters	R1	Tronto River
Groundwater	R2	Aquifers
Soil	R3	--
Crops	R4	Vegetables, Orchards, Olive Groves
Flora	R5	Vegetation Present in the Sentina Nature Reserve
Fauna	R6	Fauna and Animal Biota Present in the Sentina Nature Reserve

4.4 RISK ASSESSMENT

The risk assessment for the Brazilian case was conducted based on two municipal Wastewater Treatment Plants (WWTPs).

In the Brazilian context, due to the absence of federal legislation establishing quality standards for water reuse, the current State regulation in Paraná - Resolution CERH/PR No. 122/2023 - was adopted as the reference framework. Accordingly, only a system-level risk assessment was carried out using the FMEA methodology, since certain parameters required for environmental evaluation were not available.

In contrast, for the Italian case, both a system-level risk assessment and an environmental evaluation were performed for the reuse system of the San Benedetto del Tronto WWTP, considering the applicable European and Italian legislation.

5 RESULTS AND DISCUSSION

This section presents a detailed overview of the results concerning physicochemical parameters classified as risk levels R4 and R5, based on the findings of the FMEA analysis. The assessment of limit exceedance for thermotolerant coliforms and/or *E. coli* is addressed separately, as these parameters are excluded from the scope of the FMEA methodology. The risk analysis was conducted using the available physicochemical parameters for the two wastewater treatment plants (WWTPs) examined in the case study. Crucially, not all quality parameters defined by the reuse classes in the State of Paraná's resolution were applied. This exclusion is because this is a regional regulation whose adoption is not mandatory in other states, such as the one where the present study is situated, further exacerbated by the absence of a national legal framework in Brazil mandating the practice of treated wastewater reuse.

5.1 CASE STUDY: BRAZIL

5.1.1 Risk Assessment for Quality Class *A* And *B*

When applying the FMEA analysis for Reuse Classes A and B, it was found that, out of the five parameters defined by Resolution CERH/PR No. 122/2023 – namely, pH, thermotolerant coliforms or *E. coli*, helminth eggs, total residual chlorine, and electrical conductivity - only two were available for evaluation: pH, which exceeded the permitted reuse limit for both classes, and thermotolerant coliforms/*E. coli*, a parameter explicity excluded from risk assessment via FMEA according to the ISTISAN report (2022).

Due to this constraint, and the insufficient availability of relevant data, the risk assessment for these reuse classes was definitively excluded concerning the two wastewater treatment plants analyzed in the study.

5.1.2 Risk Assessment for the Reuse of Treated Wastewater in Agricultural and Forestry Applications

Only six of thirty-five parameters listed for agricultural and forestry reuse (Table 6), were absent from WWTP No. 1. These missing parameters were: sodium, sodium adsorption ratio (SAR), molybdenum, carbonates, vegetable oils, and animal fats. The remaining parameters were assessed using the FMEA methodology, with those classified as high-risk (R5) presented in Table 19.

Table 19 - Outcome of the FMEA assessment for parameters identified with an R5 risk level at WWTP No. 1

Parameter	Number of analyses	Mean	95th percentil	Limit for agricultural and forestry reuse (CERH/PR	LOQ	Risk level
Mineral oil	76	10.61	13.6	Up to 10 mg/L	10	R5
Surfactants	22	0.1369	0.6416	0.5 mg/L	0.1	R5
Dissolved aluminum	1	0.01	0,01	0.2 mg/L	0.01	R5
Total arsenic	22	10	10	0.03 µg/L	0.001	R5
Total cadmium	22	0.9091	1.0	0.01 µg/L	0.0001	R5
Chlorides	1	313.66	313.66	30.0 mg/L	5	R5
Total phenols	22	0.0268	0.06715	0.01 mg/L	0.002	R5

At WWTP No. 2, ten parameters were unavailable for risk analysis: vegetable oils and animal fats, bicarbonates, carbonates, chlorides, cobalt, dissolved copper, molybdenum, sodium adsorption ratio (SAR), sodium, and vanadium. Risk analysis was conducted for the available parameters, and those that reached the highest risk level (R5) are presented in Table 20.

Table 20 - Outcome of the FMEA assessment for parameters identified with an R5 risk level at WWTP No. 2

Parameter	Number of analyses	Mean	95th percentil	Limit for agricultural and forestry	LOQ	Risk level
Mineral oil	91	10.32	13.15	Up to 10 mg/L	10	R5
Total arsenic	23	10	10	0.03 µg/L	0.001	R5
Surfactants	48	0.16	0.5192	0.5 mg/L	0.1	R5
Total barium	23	0.03	0.03	1.0 mg/L	0.001	R5
Total boron	23	0.08	0.228	0.75 mg/L	0.0001	R5
Total cadmium	23	0.96	1	0.01 µg/L	0.0001	R5
Sulfate	15	1209.92	5308.3	250.0 mg/L	1	R5
Total phenols	49	0.024	0.099	0.01 mg/L	0.002	R5

Following the initial stage of identifying parameters classified as risk level R5, a statistical analysis was conducted on the data presented in Tables 19 and 20 to assess compliance with the legal limits established for agricultural and forestry reuse classes (Tables 21 and 22). This approach is justified exclusively for these reuse categories, as the FMEA assessment for Reuse Classes A and B did not include three of the five parameters required for a comprehensive evaluation of that quality standard. Tables 21 and 22 present the monitoring results for parameters identified as risk level 5, including the number of occurrences exceeding the legal threshold, as well as cases where values surpassed the limit by more than 100%. Based on this analysis, the cumulative compliance frequency was also calculated to determine which parameters remained within regulatory standards throughout the study period.

Table 21 – Compliance analysis of the parameters from WWTP No. 1 for the period between June 9, 2022 and December 19, 2024

Parameter	**No. of analyses**	**Mean**	**95th percentil**	**Limit**	**No. of exceedance**	**Exceedances above 100% of the legal limit**	**Cumulative compliance frequency**
Mineral oil	76	10.61	13.6	Up to 10 mg/L	11	1	85.5
Surfactants	22	0.1369	0.6416	0.5 mg/L	2	0	90.9
Dissolved aluminum	1	0.01	0,01	0.2 mg/L	0	0	100
Total arsenic	22	10	10	0.03 µg/L	22	22	0
Total cadmium	22	0.9091	1.0	0.01 µg/L	20	20	9.1
Chlorides	1	313.66	313.66	30.0 mg/L	1	1	0
Total phenols	22	0.0268	0.06715	0.01 mg/L	4	4	81.8

Table 22 - Compliance analysis of the parameters from WWTP No. 2 for the period between June 9, 2022 and December 19, 2024

Parameter	**No. of analyses**	**Mean**	**95th percentil**	**Limit**	**No. of exceedance**	**Exceedances above 100% of the legal**	**Cumulative compliance frequency**
Mineral oil	91	10.32	13.15	Up to 10 mg/L	7	0	92.3
Total arsenic	23	10	10	0.03 µg/L	23	23	0
Surfactants	48	0.16	0.5192	0.5 mg/L	4	0	91.7
Total barium	23	0.03	0.03	1.0 mg/L	0	0	100

Parameter	No. of analyses	Mean	95th percentil	Limit	No. of exceedance	Exceedances above 100% of the legal	Cumulative compliance frequency
Total boron	23	0.08	0.228	0.75 mg/L	0	0	100
Total cadmium	23	0.96	1	0.01 µg/L	0	0	100
Sulfate	15	1209.92	5308.3	250.0 mg/L	1	1	93.3
Total phenols	49	0.024	0.099	0.01 mg/L	4	2	91.8

As evidenced in Table 21, the surfactants and dissolved aluminum parameters exhibit high cumulative compliance frequencies, with rates ranging from 90.9% to 100%, respectively. In contrast, mineral oil and total phenols show slightly lower compliance levels, ranging from 81.8% to 85.5%. These results suggest that the treatment system may benefit from operational adjustments, such as increased sampling frequency and the implementation of continuous monitoring, to ensure greater system stability and alignment with legal standards. On the other hand, total arsenic (0%), chlorides (0%), and total cadmium (9.1%) demonstrate extremely low compliance frequencies, highlighting the urgent ncessity for corrective measures within the treatment process.

Table 12 refers to the Wastewater Treatment Plant (WWTP) No. 2, reveals a superior cumulative compliance performance compared to WWTP No. 1 (Table 21). Most of the evaluated parameters showed high-quality results, with compliance rates exceeding 90%, indicating the overall efficacy of the adopted treatment process. The sole exception was total arsenic, which recorded 0% compliance, pointing to a complete failure in its removal. This outcome underscores the urgent need for targeted revisions and specific improvements in the treatment system, particularly regarding the efficiency of arsenic removal.

An annual evaluation was conducted for parameters classified as risk level R5 in each WWTP analyzed to deepen the investigation into the definition and subsequent of compliance with established legal limits. Tables 23, 24, and 25 present the results of this annual cumulative compliance analysis for WWTP No. 1.

*Table 23 – Annual evaluation of the cumulative compliance performance for Wastewater Treatment Facility No. 1, year 2022**

2022*							
Parameter	**No. of analyses**	**Mean**	**95th percentil**	**Limit**	**No. of exceedances**	**Exceedances above 100% of the legal limit**	**Cumulative compliance frequency (%)**
Mineral oil	16	12.05	20	Up to 10 mg/L	1	0	93.75
Surfactants	6	0.16	0.55	0.5 mg/L	1	0	83.33
Dissolved aluminum	0	0	0	0.2 mg/L	0	0	Data not available
Total arsenic	6	10	10	0.03 µg/L	6	6	0.0
Total cadmium	6	1	1	0.01 µg/L	6	6	0.0
Chlorides	0	0	0	30.0 mg/L	0	0	Data not available
Total phenols	6	0.0716	0.3155	0.01 mg/L	1	1	83.33

* Data available from June 2022 onwards

As presented in Table 23, during the six-month period with available data for the year 2022, the parameters total arsenic and total cadmium exhibited 100% of analyses exceeding the established legal limit for agricultural and forestry reuse. In the same period, no analytical data was recorded for dissolved aluminum and chlorides, which precluded their statistical evaluation. Furthermore, the analysis of the 95th percentile revealed that the values of the parameters listed in Table 23 remained elevated, consistently surpassing the legal threshold – thus indicating a recurrent and critical risk scenario.

Table 22 - Annual evaluation of the cumulative compliance performance for Wastewater Treatment Facility No. 1, year 2023

2023							
Parameter	**No. of analyses**	**Mean**	**95th percentil**	**Limit**	**No. of exceedances**	**Exceedances above 100% of the legal limit**	**Cumulative compliance frequency (%)**
Mineral oil	35	10.20	12.12	Up to 10 mg/L	5	0	85.71
Surfactants	11	0.08	0.555	0.5 mg/L	0	0	100
Dissolved aluminum	0	0	0	0.2 mg/L	0	0	Data not available
Total arsenic	11	10	10	0.03 µg/L	10	10	9.09
Total cadmium	11	1	1	0.01 µg/L	11	11	0.0
Chlorides	0	0	0	30.0 mg/L	0	0	Data not available
Total phenols	11	0.01	0.039	0.01 mg/L	1	1	90.91

As shown in Table 24, the parameters total arsenic and total cadmium remained critical in 2023, with 100% of the analyses exceeding the legal limit and consistently presenting values above the established threshold for agricultural and forestry reuse. The 95th percentile analysis reinforces this scenario, indicating that the levels of these contaminants remained consistently elevated throughout the period.

Mineral oil exhibited only five data points above the legal limit, with a 95th percentile value of 12.12 mg/L, suggesting a moderate recurrence of non-compliance.

Although the mean concentration of total phenols remained within the legal limit, the 95th percentile was slightly elevated, with at least one instance exceeding the established threshold. Surfactants remained in overall compliance, despite a slight exceedance in the 95th percentile. Meanwhile, no data was available for the dissolved aluminum and chloride parameters, precluding their statistical evaluation.

Table 25 - Annual evaluation of the cumulative compliance performance for Wastewater Treatment Facility No. 1, year 2024

2024							
Parameter	**No. of analyses**	**Mean**	**95th percentil**	**Limit**	**No. of exceedances**	**Exceedances above 100% of the legal limit**	**Cumulative compliance frequency (%)**
Mineral oil	25	10.24	10	Up to 10 mg/L	1	0	96.0
Surfactants	5	0.24	0.697	0.5 mg/L	1	0	80.0
Dissolved aluminum	1	0.010	0.01	0.2 mg/L	0	0	100
Total arsenic	5	10	10	0.03 µg/L	5	5	0.0
Total cadmium	5	0.60	1	0.01 µg/L	3	3	40.0
Chlorides	1	313.66	313.66	30.0 mg/L	1	1	0.0
Total phenols	5	0.01	0.03	0.01 mg/L	2	2	60.0

As exhibited in Table 25, the total arsenic and chloride values exceeded the legal limits in 100% of the analyses, indicating complete non-compliance. The total cadmium parameter, in turn, recorded three exceedances out of five analyses, all surpassing 100% of the legal threshold, resulting in a compliance rate of only 40% during the evaluated period. A similar situation was observed for total phenols, with two out of five analyses exceeding the legal limit by more than 100%, corresponding to a compliance frequency of 60%.

Tables 26, 27, and 28 present the results of the annual analysis of cumulative compliance frequency for Wastewater Treatment Plant No. 2.

*Table 26 - Annual evaluation of the cumulative compliance performance for Wastewater Treatment Facility No. 2, year 2022**

2022*							
Parameter	**No. of analyses**	**Mean**	**95th percentil**	**Limit**	**No. of exceedances**	**Exceedances above 100% of the legal limit**	**Cumulative compliance frequency (%)**
Mineral oil	26	10.49	14.5	Up to 10 mg/L	2	0	93.31
Total arsenic	7	10	10	0.03 µg/L	7	7	0.0
Surfactants	23	0.24	0.534	0.5 mg/L	3	0	86.96
Total barium	7	0.03	0.03	1.0 mg/L	0	0	100
Total boron	7	0.12	0.28	0.75 mg/L	0	0	100
Total cadmium	7	1	1	0.01 µg/L	7	7	0.0
Sulfate	7	33.41	73.7	250.0 mg/L	0	0	100
Total phenols	23	0.049	0.099	0.01 mg/L	2	0	91.30

* Data available from June 2022 onwards

The total barium, total boron, and sulfate parameters demonstrated a cumulative compliance frequency of 100%, with 95th percentile values consistently below the legal limits (LL), indicating excellent control and stability in the concentrations of these substances. Conversely, the mineral oil and total phenol parameters did not exhibit exceedances above 1the LL; however, their 95th percentile values marginally surpassed the established thresholds, suggesting the need for continued monitoring. Surfactants showed a compliance rate of 86.96%, with only three instances of exceedance, reflecting relatively stable performance, though regular oversight remains necessary.

In contrast, the total cadmium and total arsenic parameters require immediate attention, as 100% of the analyses conducted throughout the year exceeded the legal limits, with values entirely surpassing the reference thresholds. This resulted in a cumulative compliance frequency of 0.0%, highlighting a critical scenario that demands urgent corrective measures.

Table 27 - Annual evaluation of the cumulative compliance performance for Wastewater Treatment Facility No. 2, year 2023

2023							
Parameter	**No. of analyses**	**Mean**	**95th percentil**	**Limit**	**No. of exceedances**	**Exceedances above 100% of the legal limit**	**Cumulative compliance frequency (%)**
Mineral oil	40	10.13	10.86	Up to 10 mg/L	3	0	92.50
Total arsenic	12	10	10	0.03 µg/L	12	12	0.0
Surfactants	22	0.06	0.226	0.5 mg/L	0	0	100
Total barium	12	0.03	0.03	1.0 mg/L	0	0	100
Total boron	12	0.07	0.197	0.75 mg/L	0	0	100
Total cadmium	12	1	1	0.01 µg/L	12	12	0.0
Sulfate	6	2966.38	13125.25	250.0 mg/L	1	1	83.33
Total phenols	22	0.008	0.0165	0.01 mg/L	1	1	95.45

According to Table 27, the total barium, total boron, and surfactant parameters exhibited a cumulative compliance frequency of 100%, with 95th percentile values remaining below the legal limit (LL), thereby indicating stability and effective control of these compounds throughout the analyzed period.

Total phenols and mineral oil recorded compliance rates of 95.45% and 92.50%, respectively. Although none of the analyzed samples exceeded the LL, the 95th percentile values slightly surpassed the established thresholds, signaling the necessity for continued attention, particularly considering their potential environmental and public health impacts. In contrast, the total arsenic and total cadmium parameters showed 100% of analyses with values above the legal limit, all exceeding the LL by more than 100%.

This condition resulted in a cumulative compliance frequency of 0.0%, characterizing a critical scenario that mandates rigorous monitoring, identification of contamination sources, and immediate intervention in the treatment system.

Table 28 - Annual evaluation of the cumulative compliance performance for Wastewater Treatment Facility No. 2, year 2024

2024							
Parameter	**No. of analyses**	**Mean**	**95th percentil**	**Limit**	**No. of exceedances**	**Exceedances above 100% of the legal limit**	**Cumulative compliance frequency (%)**
Mineral oil	25	10.46	14.16	Up to 10 mg/L	2	0	92
Total arsenic	4	10	10	0.03 µg/L	4	4	0.0
Surfactants	4	0.18	0.537	0.5 mg/L	1	0	75
Total barium	4	0.02	0.03	1.0 mg/L	0	0	100
Total boron	4	0.03	0.04	0.75 mg/L	0	0	100
Total cadmium	4	0.75	1	0.01 µg/L	3	3	25
Sulfate	2	58.30	74.32	250.0 mg/L	0	0	100
Total phenols	4	0.022	0.022	0.01 mg/L	1	1	75

As shown in Table 28, the total barium, total boron, and sulfate parameters exhibited a cumulative compliance frequency of 100%, with all values remaining within the legally established limits. The mineral oil parameter recorded only two samples above the legal threshold, with no exceedances greater than 100%, resulting in a compliance rate of 92%, which reflects satisfactory performance, though continued attention is warranted.

Surfactants and total phenols showed a compliance rate of 75%, with 95th percentile values slightly exceeding the legal limits, suggesting notable variability that requires ongoing monitoring due to the potential environmental impact of these compounds. In contrast, total arsenic, with 0% compliance, and total cadmium, with only 25%, demonstrated the poorest performance. These results indicate a critical scenario that mandates rigorous oversight, identification of contamination sources, and potential intervention in the treatment system.

A detailed annual analysis for the E. coli parameter was also conducted to assess the quality class attributable to the effluent from the station following the disinfection treatment applied at both wastewater treatment plants (Tables 29 and 30).

The comprehensive annual assessment confirms that the disinfection system successfully ensure reuse quality is suitable for the agricultural and forestry class.

Table 29 - Annual Statistical Analysis of Post-Treatment E. coli Levels for Reuse in Forestry and Agricultural Activities (WWTP nº 1)

Year	No. of analyses	Mean	95th percentil	Limit (MNP/100 mL)	No. of exceedance	Exceedances above 100% of the legal limit	Cumulative compliance frequency (%)
2022*	15	38624.00	128000	1000	13	13	13.33
2023	32	28600,875	57900	1000	6	23	59.57
2024	24	143405,00	803000	1000	1	23	71.83

* Data available from June 2022 onwards

An analysis of Table 29 reveals a progressive improvement in compliance over the years, although the 95th percentile values remained above the legally established limit.
In 2022, of the 15 analyses conducted, 13 exceeded 100% of the legal threshold, resulting in a compliance rate of only 13.3%.
In 2023, 32 analyses were performed, with 6 surpassing the limit and 23 exceeding 100% of the permitted value, raising the cumulative compliance rate to 59.57%.
By 2024, among the 24 monitored samples, only one exceeded the legal limit, although 23 still surpassed 100% of that value, leading to an annual compliance rate of 95.83%.
Despite the gradual improvement in compliance indicators, the 95th percentile values remained above the legal threshold in all evaluated years, indicating the persistence of contamination peaks that still warrant attention.

Table 30 - Annual Statistical Analysis of Post-Treatment E. coli Levels for Reuse in Forestry and Agricultural Activities (WWTP nº 2)

Year	No. of analyses	Mean	95th percentil	Limit (MNP/100 mL)	No. of exceedance	Exceedances above 100% of the legal limit	Cumulative compliance frequency (%)
2022*	26	435.87	940	1000	0	0	100
2023	37	885.87	2384.25	1000	2	4	89.2
2024	23	564.48	1938	1000	1	1	95.7

* Data available from June 2022 onwards

For Wastewater Treatment Plant No. 2, the treatment system demonstrated superior performance compared to Plant No. 1 (Table 29).

In 2022, full compliance was achieved, with no samples exceeding the legal limits. Although the 95th percentile value approached the established threshold, the six months of monitoring indicated excellent system performance.

In 2023, among the 37 analyses conducted, two samples directly exceeded the legal limit (LL), and four surpassed 100% of the LL, resulting in a cumulative compliance rate of 89.2%. This scenario revealed isolated peaks in E. coli concentration that were not fully mitigated by the treatment system.

In 2024, a significant improvement in compliance was observed compared to the previous year. Of the 23 analyses performed, only one exceeded the LL and one surpassed 100% of the LL, yielding an annual compliance rate of 95.7%.

5.1.3 Proposal of Additional Treatment Measures for Controlling the Identified Risks

Following the results of the risk analysis for both WWTPs, it was found that several parameters presented elevated risk, which prevents the reuse of water for forestry and agricultural activities as defined in CERH/PR Resolution No. 122/2023. In this regard, control measures will be proposed that can ensure the reduction of the risk level for the aforementioned parameters.

Table 31 - Proposals for upgrading WWTPs 1 and 2 to lower the risk level of parameters categorized as Risk Level 5.

Hazard	Parameter identification	Suggested measures	Treatment stage to be improved
Chemical	Mineral oil	Optimization of the OWS (Oil-Water Separator) unit; Identify potential sources of contamination and the raw effluent.	Pre-treatment
Chemical	Surfactants	Granular activated carbon (GAC) + sand filtration;	Tertiary treatment

Hazard	Parameter identification	Suggested measures	Treatment stage to be improved
		Identification of point sources and control of the raw effluent.	
Metal	Dissolved aluminium, Total arsenic, Total cadmium	Clariflocculation + reverse osmosis; Identification of industrial discharge sources.	Tertiary treatment
Chemical	Chlorides	The adoption of desalination technologies, such as reverse osmosis, would still necessitate robust pre-treatment.	Tertiary treatment
Microbiological	E.coli	Addition of filtration, GAC, RO, and chlorination as a safety measure.	Tertiary treatment

5.2 CASE STUDY: ITALY

The proposed water reuse scenarios for irrigation within the Sentina Regional Nature Reserve are as follows:

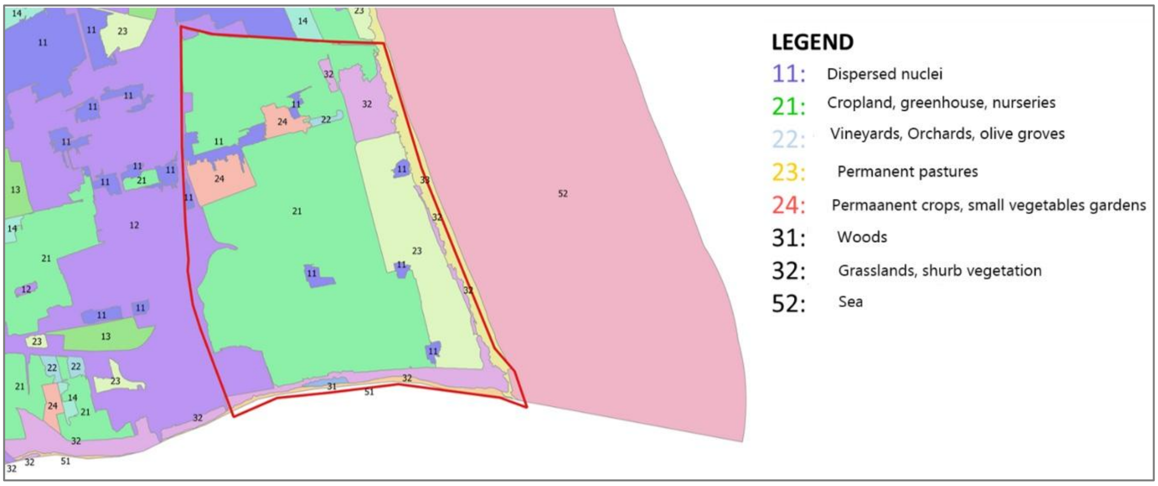
- ✓ **Scenario 1- Lake replenishment**: Reuse of treated water for the replenishment of the Sentina lakes, with a continuous annual water demand of 30 L/s;
- ✓ **Scenario 2 - Environmental and seasonal irrigation**: Reuse of treated water for environmental purposes (30 L/s) and seasonal agricultural irrigation (approximately from May to September), with a total water demand of 100 L/s;
- ✓ **Scenario 3 - Occasional blending:** Occasional blending of treated wastewater with water abstracted from Brecciarolo intake structure, strictly limited to cases of operational necessity related to the Tronto irrigation distribution system. The proportion of blending is not predictable, as it depends on technical requirements. Under no circumstances shall the total flow exceed 100 L/s, and any surplus would be discharged into the drainage channel;

- ✓ **Scenario 4 - Emergency supply exclusive use**: use of water abstracted from the Brecciarolo intake structure only in the event of an interruption in the supply of treated water from the Brodolini treatment plant.

The water distribution system within the Sentina Reserve serves a relatively limited area, and the average water residence time in the canals is on the order of a few hours (estimated to be a maximum of six hours). Water is supplied directly to end-users, namely, farmers for agricultural irrigation, through these canals, in addition to being used for lake replenishment. Crucially, there are no storage reservoirs along the distribution network.

The water demand for the environmental restoration of the lakes in the Sentina Reserve is approximately 1 million cubic meters per year (1 M m^3/year), while the demand for agricultural irrigation is also around 1 x 10^6 m^3/year, focusing exclusively during the irrigation period. intensive agricultural activities are present within the Reserve, as indicated in 2007 Land Use Map of the Marche Region (Figure 9).

Figure 9 - Agricultural area within the Sentina Reserve



The agricultural area covers about 90 hectares, mainly consisting of grain cultivation areas and permanent crops/small vegetable gardens.

The predominant crop in the Sentina Reserve area is horticultural, and irrigation is carried out by flooding or through pressurized rotors. Moreover, seasonal and/or periodic changes in crops and irrigation methods are highly probable. For this reason, treated water intended for agricultural reuse must comply with Class A quality standards, as established by European Regulation EU 741/2020.

Based on Figure 8 and with input from system managers, hazards were identified through an analysis of each point in the block diagram. Each identified risk is associated with a potential hazardous event, which is detailed in Table 32.

Table 32 - Hazardous events identified in the reuse system

Node Code	Node Description	Hazardous Event and Consequences	Evidence supporting the assignment of likelihood/possibility of occurrence	Evidence supporting the assignment of impact severity
All nodes	All nodes	Service interruptions; Inefficiency of units requiring electrical power due to blackout; Power outage lasting at least one hour	Occurred in the past	Failure to comply with regulatory limits for all regulated parameters
All nodes	All nodes	Service interruption caused by catastrophic events or natural disasters	Unlikely event, but one that cannot be ruled out in the future. The trends regarding climate change can have an impact on repeatability (for example, flood)	Failure to comply with regulatory limits for all regulated parameters
All nodes	All nodes	Risk of lack of communication between the different parties responsible for the reuse system	Plausible event, especially in certain circumstances that can realistically occur	Possibility of using refined water without complying with regulatory limits for parameters classified as: pathogens, macro-pollutants
P1+P2 +P3	Sewer network and wastewater treatment plant	Effect of climate change: a greater number of extreme precipitation events could be observed in the future. Extreme precipitation events compromise the efficiency of the entire purification process	Moderate-high frequency of occurrence. Plausible event, especially under certain circumstances that can realistically occur.	Failure to comply with regulatory limits for all parameters regulated by standards
P1	Sewage system	Effect of climate change: Increase in drought phenomena and water stress could have repercussions on the groundwater level with an increase in salinity intrusion phenomena. This can cause high levels of chlorides, salinity, and	Not having happened in the past, it cannot be ruled out that it will happen in the future	Failure to comply with regulatory limits for salinity, conductivity, SAR (macro-pollutants), chlorides (ions with medium-low toxicity)

Node Code	Node Description	Hazardous Event and Consequences	Evidence supporting the assignment of likelihood/possibility of occurrence	Evidence supporting the assignment of impact severity
		conductivity in the treated water		
P1	Stormwater runoff / Sewer network	Hydraulic overload due to stormwater runoff resulting in treatment and removal inefficiencies	Occurred in the past, event very likely in the future	Non-compliance with regulatory limits for the following classes of parameters: Macro-pollutants; Nutrients; Microbiological parameters
P1	Stormwater runoff / Sewer network	Possible increase in TSS concentrations and turbidity at the plant inlet due to solid overload after rainfall events, with a possible consequent increase in microbiological agents due to the vector effect and a possible reduction in disinfection efficiency due to the screening effect on the lamps, and possible non-compliance with E. coli, pathogens, and/or TSS at the plant outlet	Occurred in the past, event very likely in the future	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants; Microbiological parameters
P1B	Stormwater runoff	At the intersections with rainwater collectors and urban drainage, urban run-off after dry periods (washing of roads, parking lots, and paved urban areas) with possible presence of hazardous chemical compounds and potential non-compliance	Having happened in the past, it cannot be ruled out that it will happen in the future	Failure to comply with regulatory limits for the following parameter classes: Heavy metals; Organic contaminants
P1E	Groundwater infiltration / seawater intrusion	Overload of Chlorides, non-compliance with SAR index, Conductivity/salinity caused by seawater intrusion	Not having happened in the past, it cannot be ruled out that it will happen in the future	Failure to comply with regulatory limits for conductivity, salinity, SAR (macro-pollutants)

Node Code	Node Description	Hazardous Event and Consequences	Evidence supporting the assignment of likelihood/possibility of occurrence	Evidence supporting the assignment of impact severity
P1C	Industrial/productive connections Illegal connections	Abnormal concentrations of one or more dangerous chemical parameters at the plant inlet and possible purification inefficiency due to abnormal industrial or production-type discharges	Having happened in the past, it cannot be ruled out that it will happen in the future	Failure to comply with regulatory limits for the following parameter classes: Heavy metals; Organic contaminants; Cyanides
P1C	Industrial/productive connections and Illegal connections	Overloads of one or more macro-pollutants (organic material, nutrients) caused by discharges and/or illegal connections	Occurred in the past, especially in certain circumstances that can realistically happen (specific periods of the year during intense work periods)	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants, Nutrients
P2A	Pretreatments – Screening	Outflow of coarse solids due to damage/contamination of the grid. The coarse solids that escaped can damage downstream electromechanical equipment, causing inefficiencies in the entire purification process.	Occurred in the past, especially under circumstances of significant hydraulic influx	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants, Nutrients, Pathogens
P2A	Pretreatments – Grit removal	Insufficient sedimentation of sands due to excessive Q causing insufficient HRT, due to malfunctioning blowers and/or compressors, due to malfunctioning sand extractors. This event causes the failure to remove the sands, leading to their accumulation in the subsequent basins. Problems of abrasion of electromechanical components and clogging of air diffusers can occur. Such issues can	Occurred in the past, especially under certain circumstances that can realistically happen.	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants, Nutrients, Pathogens

Node Code	Node Description	Hazardous Event and Consequences	Evidence supporting the assignment of likelihood/possibility of occurrence	Evidence supporting the assignment of impact severity
		compromise the entire purification process		
P2B	Primary treatments	Inefficiency in primary sedimentation due to sludge sedimentability issues caused by electromechanical malfunctions (e.g., sludge discharge problems).	Occurred in the past, they might happen again but rarely.	-
P2C	Biological	insufficient/limited biological nitrogen removal due to low [Carbon/Nitrogen] ratio	Occurred in the past, especially under certain circumstances that can realistically happen.	Failure to comply with regulatory limits for the following parameter classes: Nutrients
P2C	Biological	Malfunction of recirculation (sludge and/or aerated mixture) with exceedances of COD, BOD, Nitrogen, and Phosphorus due to insufficient oxidation-nitrification-denitrification. Problems (solid accumulation) in sludge sedimentation and difficult solid control in the tank	Occurred in the past, especially under circumstances of significant hydraulic influx	Failure to comply with regulatory limits for the following parameter classes: Macro-pollutants; Nutrients
P2C	Biological	Elevated concentrations of phosphorus in the plant effluent, exceeding the legal thresholds for reuse, due to uncontrolled dosing of the dephosphatizing agent.	Occurred in the past, particularly under certain circumstances that may realistically arise (incorrect dosing due to mechanical failure or shortage of dephosphatizing agent)	Non-compliance with regulatory limits for the following parameter classes: Nutrients.
P2C	Biological	High concentrations of phosphorus in the effluent from the plant exceeding legal reuse limits due to uncontrolled dosing of phosphate remover. Exceedances of COD, BOD, nitrogen, and phosphorus due to insufficient	Occurred in the past, especially under certain circumstances that can realistically happen (breakdown / deterioration)	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants, Nutrients

Node Code	Node Description	Hazardous Event and Consequences	Evidence supporting the assignment of likelihood/possibility of occurrence	Evidence supporting the assignment of impact severity
		oxidation/nitrification and sludge sedimentation problems caused by low dissolved oxygen levels linked to insufficient aeration or malfunctioning diffusers/blowers/compressors.		
P2D	Secondary separation	High TSS in the effluent from secondary sedimentation due to sedimentability issues of biological sludge (bulking, foaming, or rising)	Occurred in the past, especially under circumstances of significant hydraulic influx	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants, Nutrients, Pathogens
P2D	Secondary separation	High TSS in the effluent from secondary sedimentation due to sludge settleability issues caused by electromechanical malfunctions (e.g., sludge discharge problems).	Occurred in the past	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants, Nutrients, Pathogens
P3A	Filtration	Malfunctions of tertiary filtration and excess suspended solids during disinfection linked to irregular filter fouling due to solid leaks from secondary sedimentation	Not occurred in the past but plausible, especially in certain circumstances that can realistically happen (malfunctions of electromechanical - e.m. - devices)	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants, Pathogens
P3A	Filtration	Hydraulic overload resulting in treatment inefficiencies and solid removal	Not happened in the past but plausible, especially in certain circumstances that can realistically occur	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants, Pathogens
P3B	UV disinfection	Loss of radiant power of UV lamps due to lamp breakage or end of life	Not occurred in the past but plausible, especially in certain circumstances that can realistically happen (malfunctions of e.m. devices)	Failure to comply with regulatory limits for microbiological indicator parameters

Node Code	Node Description	Hazardous Event and Consequences	Evidence supporting the assignment of likelihood/possibility of occurrence	Evidence supporting the assignment of impact severity
P3B	UV disinfection	Soiling of UV lamps and reduction of disinfection efficiency related to calcium hardness, presence of substances such as iron and manganese, biofilm formation, suspended solids	Not occurred in the past but plausible, especially in certain circumstances that can realistically happen (defosfating agent overdose)	Failure to comply with regulatory limits for microbiological indicator parameters
P3B	UV disinfection	Failure to achieve the Reuse Class due to reduced disinfection efficiency	Not happened in the past but plausible	Failure to comply with regulatory limits for the following parameter classes: Pathogens
P2+P3	Wastewater treatment plant and tertiary treatment	Lack of telecontrol connection that could lead to improper management of the system	Moderately likely event	Possibility of non-compliance with regulatory limits for all regulated parameters
P2+P3	Wastewater treatment plant and tertiary treatment	Cyber attack, malfunction of the computer system that could compromise the remote control system. Such an event could affect the proper management of the plant and could cause it to go out of service.	Event that occurred in the past but is unlikely, plausible in the future	Possibility of non-compliance with regulatory limits for all regulated parameters
P2+P3	Wastewater treatment plant and tertiary treatment	Presence of specific pollutants at the plant's inlet and/or outlet (e.g. Surfactants	Occurred in the past, especially under certain circumstances that can realistically happen.	Metals, emerging organic micro-contaminants, phenols, hydrocarbons, surfactants
P2+P3	Analysis cabin / Plant monitoring system	Reduction in the reliability of online data on final effluent quality and alert systems related to probe malfunctions.	Event that occurred in the past, not very frequent, plausible in the future	Failure to comply with regulatory limits for the following classes of parameters: Macro-pollutants, Nutrients, Pathogens
T2A	Right branch (underground duct)	Sediment accumulation	Plausibility: it cannot be ruled out that it will happen in the future	Deterioration of the quality of accumulated water. Loss of quality requirements for any of the regulated parameters

Node Code	Node Description	Hazardous Event and Consequences	Evidence supporting the assignment of likelihood/possibility of occurrence	Evidence supporting the assignment of impact severity
		Development of biomass in networks (Formation of biofilm/bacterial regrowth) and/or algal growth	Plausible, especially in certain circumstances that can realistically occur	Deterioration of the quality of accumulated water. Loss of quality requirements regarding microbiological parameters
		Loss or unintentional release due to network breakage and/or leaks	Plausible that the conditions that generated the event will be repeated.	Entry of water or contaminants from other sources that could deteriorate its water quality. Loss of quality requirements for any of the regulated parameters
		Cross-contamination during mixing with water from another source	Plausibility: it cannot be ruled out that it will happen in the future	Entry of water or contaminants from other sources that could deteriorate its water quality. Loss of quality requirements for any of the regulated parameters
		Release of asbestos from pipes	Plausibility: it cannot be ruled out that it will happen in the future	-
T2B	Central branch	Accumulation of sediments	Plausibility: it cannot be ruled out that it will happen in the future	Deterioration of the quality of accumulated water. Loss of quality requirements for any of the regulated parameters
		Development of biomass in networks (Formation of biofilm/bacterial regrowth) and/or algal growth	Plausible, especially in certain circumstances that can realistically occur	Deterioration of the quality of accumulated water. Loss of quality requirements regarding microbiological parameters

Node Code	Node Description	Hazardous Event and Consequences	Evidence supporting the assignment of likelihood/possibility of occurrence	Evidence supporting the assignment of impact severity
		Loss or unintentional release due to network breakage and/or leaks	Plausible that the conditions that generated the event will be repeated.	Entry of water or contaminants from other sources that could deteriorate its water quality. Loss of quality requirements for any of the regulated parameters
		Cross-contamination during mixing with water from another source	Plausibility: it cannot be ruled out that it will happen in the future	Entry of water or contaminants from other sources that could deteriorate its water quality. Loss of quality requirements for any of the regulated parameters
T2B	Left branch (underground duct)	Accumulation of sediments	Plausibility: it cannot be ruled out that it will happen in the future	Deterioration of the quality of accumulated water. Loss of quality requirements for any of the regulated parameters
		Development of biomass in networks (Formation of biofilm/bacterial regrowth) and/or algal growth	Plausible, especially in certain circumstances that can realistically occur.	Deterioration of the quality of accumulated water. Loss of quality requirements regarding microbiological parameters
		Loss or unintentional release due to network breakage and/or leaks	Plausible that the conditions that generated the event will be repeated.	Entry of water or contaminants from other sources that could deteriorate its water quality. Loss of quality requirements for any of the regulated parameters
		Cross-contamination during mixing with water from another source	Plausibility: it cannot be ruled out that it will happen in the future	Entry of water or contaminants from other sources that could deteriorate its water quality. Loss of quality requirements for any

Node Code	Node Description	Hazardous Event and Consequences	Evidence supporting the assignment of likelihood/possibility of occurrence	Evidence supporting the assignment of impact severity
				of the regulated parameters
		Release of asbestos from pipes	Plausibility: it cannot be ruled out that it will happen in the future	-

Regarding the population exposed to reused water, Table 33 presents the groups exposed by type of pollutant and the predominant exposure route.

Table 33 - Identified exposure pathways and corresponding exposed groups for health risk assessment

Hazard group	Exposed groups	Exposure pathways
Macro-pollutants Nutrients Metals Cyanides Highly toxic ions Moderately to low toxic ions Fats and oils Mineral oils Organic contaminants Pesticides	Farmers; Local community	Accidental ingestion of small amounts of reclaimed wastewater; Accidental ingestion of small amounts of soil irrigated with reclaimed wastewater; Accidental contact of reclaimed wastewater with open skin wounds; Consumption of raw and unwashed vegetables that have been in contact with reclaimed wastewater.
Microbiological parameters	Farmers; Local community	Inhalation of aerosols; Accidental ingestion of small amounts of reclaimed wastewater; Accidental ingestion of small amounts of soil irrigated with reclaimed wastewater;

Hazard group	Exposed groups	Exposure pathways
		Accidental contact of reclaimed wastewater with open skin wounds; Consumption of raw and unwashed vegetables that have been in contact with reclaimed wastewater.

Regarding environmental matrices exposed to reclaimed water, the soil and directly irrigated crops may be subject to environmental risks, such as: phytotoxicity, reduced productivity, or the deterioration of soil characteristics.

Surface waters are also considered, given that they receive these waters. As well as the eventual presence of underground aquifers beneath the irrigated lands, into which the reused water can infiltrate.

In Table 34, it is possible to identify environmental and animal receptors, as well as the exposure pathways identified for environmental risk analysis purposes.

Table 34 - Identified exposure pathways and receptors for environmental risk assessment

Hazard	Environmental receptors	Exposure pathways	Effects
Salinity (TDS, Conductivity)	Surface water	Runoff	Increase in salinity
Chlorides			Toxicity to aquatic biota
Nutrients			Eutrophication
Disinfection by-products			Toxicity to aquatic biota
Organic micro-contaminants			
Salinity (TDS, ECw)	Aquifer / groundwater	Infiltration into the soil and percolation into the groundwater	Increase in salinity
Chlorides			Toxicity to aquatic biota
Nutrients			Eutrophication
Disinfection by-products			Toxicity to aquatic biota

Hazard	Environmental receptors	Exposure pathways	Effects
Organic micro-contaminants			
Salinity (TDS, ECw)	Soil	Runoff	Soil damage due to salinization
Chlorides			Soil contamination from salinization
Nutrients			Nutritional imbalance in crops; toxic effect on terrestrial biota
Boron			Crop toxicity
Sodium			Toxic effects
Inorganic compounds			
Disinfection by-products			Toxicity to terrestrial biota
Organic micro-contaminants			
Nutrients (N,P)	Culture	Absorption thru the root system of purified water or absorption thru "spraying"	Nutritional imbalance in crops
Chlorides			Crop toxicity
Sodium			
Organic micro-contaminants			
Salinity (TDS, ECw)	Flora / vegetation	Absorption of refined water through the root system	Contamination and alteration of plant biodiversity / Toxicity
Chlorides			
Nutrients (N,P)			
Boron			
Sodium			
Inorganic compounds			
Disinfection by-products			

Hazard	Environmental receptors	Exposure pathways	Effects
Organic micro-contaminants			
Salinity (TDS, ECw)	Fauna / aquatic biota / birds	Ingestion of purified water or contact with purified water	Contamination and alteration of animal biodiversity / Toxicity
Chlorides			
Nutrients (N,P)			
Boron			
Sodium			
Inorganic compounds			
Disinfection by-products			
Organic micro-contaminants			

Na analysis of the severity of each hazard present in the reuse system was conducted for the risk assessment. The points assigned to the hazards (contaminants present in the water) are presented in Table 35.

Table 35 - Assignment of severity scores to hazards identified in the wastewater reuse system

Group	Parameter	Type of hazard	Severity score
Macro-pollutants	pH	Chemical/Physical	3
	RAS		
	Electrical conductivity		
	Salinity		
	Coarse materials		
	Total suspended solids (TSS)		
	BOD_5		
	COD		
	Turbidity		

Group	Parameter	Type of hazard	Severity score
	Total surfactants		
Nutrients	Total phosphorus	Chemical	3
	Total nitrogen		
	Ammoniacal nitrogen		
Metals	Aluminum	Chemical	5
	Arsenic		
	Barium		
	Beryllium		
	Boron		
	Cadmium		
	Cobalt		
	Total chromium		
	Chromium VI		
	Iron		
	Manganese		
	Mercury		
	Nickel		
	Lead		
	Copper		
	Selenium		
	Tin		
	Thallium		
	Vanadium		
	Zinc		
Cyanides	Total cyanides (as CN)	Chemical	5
Highly toxic ions	Sulfides	Chemical	4
	Sulphites		
	Active chlorine		
Moderately toxic ions	Sulfates	Chemical	3
	Chlorides		

Group	Parameter	Type of hazard	Severity score
	Fluorides		
Animal/vegetable fats and oils	Animal/vegetable fats and oils	Chemical	3
Mineral oils	Mineral oil	Chemical	5
Organic contaminants	Total phenols Pentachlorophenol	Chemical	5
	Total aldehydes		
	Tetrachloroethylene, trichloroethylene (sum of specific parameter concentrations)		
	Total chlorinated solvents		
	Trihalomethanes (sum of concentrations)		
	Total aromatic organic solvents		
	Benzene		
	Benzo(a)pyrene		
	Total nitrogenous organic solvents		
Pesticides	Chlorinated pesticides (each one)	Chemical	5
	Organophosphorus pesticides (each one)		
	Total other pesticides		
Microbiological parameters	Escherichia coli	Microbiological	5
	Salmonella		
	Legionella spp		
	Intestinal nematodes		

After assigning the values of “Probability” (P) and “Severity” (S), they are multiplied together, generating a numerical value associated with a risk scale in a 5 x 5 matrix. The risk matrix (RM) for all the nodes in the irrigation system can be partially visualized in Figure 10.

Figure 10 - Risk matrix: irrigation water distribution network

IDENTIFICAZIONE DEL SITO			IDENTIFICAZIONE DEGLI EVENTI PERICOLOSI E DEI PERICOLI ASSOCIATI							RISCHIO PRELIMINARE			MISURE DI CONTROLLO ESISTENTI	RISCHIO RESIDUALE			PIANO DI MIGLIORAMENTO	VALIDAZIONE MISURE INTEGRATIVE E MONITORAGGIO INTEGRATIVO	
CODICE NODO	SUB-SISTEMA	DESCRIZIONE NODO	EVENTO PERICOLOSO + CONSEGUENZE	Evidenze a supporto dell'attribuzione della probabilità/possibilità di accadimento	Evidenze a supporto dell'attribuzione della gravità dell'impatto (scenario peggiore)	BIOLOGICO	CHIMICO	FISICO	VIE DI ESPOSIZIONE	PROBABILITÀ DI ACCADIMENTO	GRAVITÀ DEL PERICOLO	RISCHIO	MISURE DI CONTROLLO	PROBABILITÀ DI ACCADIMENTO	GRAVITÀ DEL PERICOLO	RISCHIO	NECESSITÀ DI MISURE INTEGRATIVE	Validazione Misure Integrative e Monitoraggio integrativo	Responsabile dell'attuazione delle Misure Integrative
P3B		DISINFEZIONE UV	Non raggiungimento della Classe di riuso causa ridotta efficienza in disinfezione	Non avvenuto in passato ma plausibile	Mancato rispetto dei limiti normativi per le seguenti classi di parametri: Patogeni	x			1. contatto dermico 2. Ingestione 3. Inalazione	4	5	20	1. Monitoraggio e manutenzione periodica del sistema 2. Procedure e istruzioni operative 3. Telecontrollo 4. serie pompe dosatrici acido peracetico	3	5	15	Potenziamento sistema di disinfezione mediante aumento del dosaggio di acido peracetico	Monitoraggio dei parametri E. Coli, Salmonella spp, Legionella spp, Nematoidi intestinali - Validazione del processo mediante verifica rimozioni logaritmiche di E. Coli, Colifagi, Spore di Clostridium perfringens	Gestore impianto di depurazione
P2+P3		IMPIANTO DI DEPURAZIONE+ AFFINAMENTO	Mancato collegamento telecontrollo che potrebbe comportare una gestione non corretta dell'impianto	Evento mediamente probabile	Possibilità di mancato rispetto dei limiti normativi per tutti i parametri regolamentati	x	x	x	1. contatto dermico 2. Ingestione 3. Inalazione	2	5	10	1. Batteria Tampone 2. Procedure interne per la tempestiva riabilitazione del servizio. 3. Presenza di personale/reperibilità che può operare in campo in modalità manuale	1	5	5			
P2+P3		IMPIANTO DI DEPURAZIONE+ AFFINAMENTO	Attacco informatico, malfunzionamento sistema informatico che potrebbe compromettere il sistema di telecontrollo. Tale evento potrebbe influire sulla corretta gestione dell'impianto e potrebbe causarne il fuori servizio	Evento verificatosi in passato ma poco probabile, plausibile in futuro	Possibilità di mancato rispetto dei limiti normativi per tutti i parametri regolamentati	x	x	x	1. contatto dermico 2. Ingestione 3. Inalazione	1	5	5	1. Antivirus 2. Presenza di personale/REPERIBILITA' che può operare in campo in modalità manuale	1	5	5			
P2+P3		IMPIANTO DI DEPURAZIONE+ AFFINAMENTO	Presenza di inquinanti specifici in ingresso e/o uscita impianto (es. Tensioattivi)	Avvenuto in passato, soprattutto in certe circostanze che possono realisticamente verificarsi	Metalli, Micro-contaminanti organici emergenti, fenoli, idrocarburi, tensioattivi		x		1. contatto dermico 2. Ingestione	2	5	10	1. Programmi di monitoraggio	1	5	5	Interruzione riuso in caso di rilevamento misure anomale Pianificazione monitoraggio lungo la filiera di trattamento del depuratore di Brodolini Pianificazione campagna di monitoraggio su bacino fognario al fine di ottenere informazioni su origine	Monitoraggio del parametro in ingresso/uscita impianto al fine di ottenere informazioni su origine	Gestore impianto di depurazione

Table 36 presents the results of the FMEA analysis, referring to the data series from 2018 to April 2024, for the parameters total suspended solids (TSS), Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total Nitrogen (Ntot), Total Phosphorus (Ptot), and E.coli.

The FMEA analysis was conducted considering the regulatory limit for the production of refined water of class A quality.

For total phosphorus and total nitrogen, the limits established in Annex A of Decree-Law 39/2023 were considered (Ptot = 1 mg/L and Ntot = 10 mg/L).

Table 36 - Results of the FMEA analysis applied to historical chemical-physical parameters (SST, BOD_5, Ntot, Ptot, and E.coli) prior to the start-up of advanced treatment processes for Class A water production

Parameter	**Unit of measurement**	**DM 185/2003**	**DL 39/2023 (Classe A)**	**95th percentile**	**LL (Legal limit)**	**UoM (Unit of Measure)**	**LOQ (Limit of Quantification)**	**Risk level**
TSS	mg/L	10	10	21	10	mg/L	1	5
BOD_5	mgO_2/L	20	10	25	10	mg/L	2	5
COD	mgO_2/L	100	-	45	100	mg/L	20	2
Total phosphorus	mgP/L	2	1	1.7	1	mg/L	0.04	5

Parameter	Unit of measurement	DM 185/2003	DL 39/2023 (Classe A)	95th percentile	LL (Legal limit)	UoM (Unit of Measure)	LOQ (Limit of Quantification)	Risk level
Total nitrogen	mgN/L	15	10	13	10	mg/L	1	5
Escherichia coli	CFU/100mL	10	10	1730	10	mg/L	0	5

It should be noted that the results presented in Table 36 refer to a plant configuration that is not yet suitable for the reuse of effluent water, as the refinement treatments (tertiary filtration and UV disinfection) are not yet fully operational.

Specifically, for each year analyzed (from 2018 to April 2024), the subsequent tables (37 through 41) present the compliance with Decree-Law 39/2023, highlighting the number of exceedances of the limit value, the number of exceedances exceeding 100% of the limit value, and the calculation of the accumulated compliance frequency.

It is observed that, for BOD_5 and TSS, the limits must be respected in at least 90% of the samples, and none of the values should exceed the maximum allowable variation of 100% of the indicated value. For nitrogen (N) and phosphorus (P), the annual average must comply with the limit. For E. coli, the limit values must be respected in at least 90% of the samples, and none of the values should exceed the maximum allowable variation of one logarithmic unit.

Table 37 - Number of exceedances relative to the legal limit (DL 39/2023) observed for the SST parameter during the reference years (prior to the start-up of advanced treatment processes) and cumulative compliance frequency

TSS							
Year	Number of measurement	Average (mg/L)	95th percentile (mg/L)	DL 39/2023 limit (mg/L) – Class A	Exceedances	Exceedances > 100% of legal limit	Cumulative compliance frequency (%)
2018	11	8	14.5	10	2	0	82%
2019	14	10.1	24.25	10	5	1	64%
2020	10	19	46.85	10	8	2	20%
2023	35	7.9	18.3	10	7	1	80%
2024	8	9.1	19.38	10	3	1	63%

Table 38 - Number of exceedances relative to the legal limit (DL 39/2023) observed for the BOD_5 parameter during the reference years (prior to the start-up of advanced treatment processes) and cumulative compliance frequency

BOD5							
Year	**Number of measurements**	**Average (mg/L)**	**95th percentile (mg/L)**	**DL 39/2023 limit (mg/L) – Class A**	**Exceedances**	**Exceedances > 100% of legal limit**	**Cumulative compliance frequency (%)**
2018	11	6	11	10	1	0	91%
2019	13	5.1	13.2	10	1	1	92%
2020	10	10	19.4	10	2	1	80%
2023	35	16.2	27.7	10	30	4	14%
2024	9	15.1	26.2	10	6	3	33%

Table 39 - Compliance with the legal limit (DL 39/2023) for the Ntot parameter (prior to the start-up of advanced treatment processes)

Total nitrogen (N_{tot})					
Year	**Number of measurements**	**Annual average (mg N/L)**	**95th percentile (mg N/L)**	**DL 39/2023 limit (mg N/L)**	**Compliance with the legal limit**
2018	11	9.5	12.5	10	Yes
2019	14	8.8	12.4	10	Yes
2020	10	11	18.19	10	No
2023	35	7.4	13.16	10	Yes
2024	9	7.5	11.24	10	Yes

Table 40 - Compliance with the legal limit (DL 39/2023) for the Ptot parameter (prior to the start-up of advanced treatment processes)

Total phosphorus (P_{tot})					
Year	**Number of measurements**	**Annual average (mg P/L)**	**95th percentile (mg P/L)**	**DL 39/2023 limit (mg N/L)**	**Compliance with the legal limit**
2018	11	0.3	0.565	1	Yes
2019	14	0.5	1.415	1	Yes

Total phosphorus (P_{tot})					
Year	**Number of measurements**	**Annual average (mg P/L)**	**95th percentile (mg P/L)**	**DL 39/2023 limit (mg N/L)**	**Compliance with the legal limit**
2020	10	1	3.11	1	Yes
2023	35	0.5	1.465	1	Yes
2024	6	0.2	0.28	1	Yes

Table 41 - Compliance with the legal limit (DL 39/2023) for the E.coli parameter (prior to the start-up of advanced treatment processes)

Year	**Number of measurements**	**Average (mg/L)**	**95th percentile (mg/L)**	**DL 39/2023 limit (mg/L) – Class A**	**Exceedances**	**Exceedances of 1 logarithmic unit**	**Cumulative compliance frequency (%)**
2018	21	921	1414	10	8	7	62%
2019	34	206	1731.05	10	17	16	50%
2020	42	150	420.3	10	12	11	71%
2023	35	1442	3880	10	33	33	6%
2024	8	62	100	10	5	5	38%

Following the partial initiation of tertiary treatments, which occurred in July 2024, an FMEA analysis was conducted covering the periods from July 2024 to April 2025, utilizing a total of eight samples. The primary purpose of the tertiary treatment (Table 42).

Table 42 - FMEA results for physicochemical parameters requiring attention

Parameter	**Unit of measurement**	**DM 185/2003**	**DL 39/2023 (Class A)**	**95th percentile**	**LL (Legal Limit)**	**LOQ (Limit of Quantificatio**	**Risk Level**
Total nitrogen	mgN/L	15	10	**7.565**	10	1	4

Parameter	Unit of measurement	DM 185/2003	DL 39/2023 (Class A)	95th percentile	LL (Legal Limit)	LOQ (Limit of Quantificatio	Risk Level
Ammoniacal nitrogen	$mgNH_4/L$	2	-	**3.9**	2	0.2	5
Turbidity	NTU	-	5	**11.6**	5	0.4	5
Total phosphorus	mgP/L	2	1	**1.88**	1	0.04	5
Chlorides	mgCl/L	250	-	**199**	250	0.03	4
Total surfactants	mg/L	0.5	-	**1.258**	0.5	0.55	5

From the FMEA analysis of the physicochemical parameters evaluated in the refined water effluent produced after the initiation of tertiary treatments, it is observed that continued attention is still required for the following parameters:

- ✓ Total nitrogen (N_{tot});
- ✓ Ammoniacal nitrogen (NH_4^+);
- ✓ Turbidity;
- ✓ Total phosphorus (P_{tot});
- ✓ Chlorides;
- ✓ Total surfactants.

For the parameters mentioned above, a detailed analysis concerning compliance with legal limits (LL), was conducted. Given the limited size of the samples set (only eight samples), all the data obtained during the monitoring campaign following the commissioning of the tertiary treatments were utilized in the compliance analysis.

Table 43 - Compliance with the legal limit (DL 39/2023) for the Ntot parameter (following the start-up of advanced treatment processes)

Total nitrogen (N_{tot})					
Year	**Number of measurements**	**Average (mg N/L)**	**95-percentile (mg N/L)**	**DL 39/2023 limit (mg N/L)**	**Compliance with the legal limit**
2024-2025	8	6.9	7.6	10	Yes

Table 44 presents the results of the regulatory compliance analysis conducted for the ammoniacal nitrogen parameter, for wich no criticalities were identified. Furthermore, it is important to highlight that DM 185/2003 only suggests a guideline value for ammoniacal nitrogen, while the limit that must not be exceeded under any circumstances is that defined by Legislative Decree 152/2006.

Table 44 - Compliance with the legal limit (DM 185/2003) for the ammoniacal nitrogen parameter (following the start-up of advanced treatment processes)

Ammoniacal nitrogen										
Year	**Number of measurements**	**Average (mg/L)**	**95-percentile (mg/L)**	**Guideline value DM 185/2003 (mg/L)**	**Limit D.Lgs. 152/2006 (mg/L)**	**Exceeds DM 185/2003**	**Exceeds 100% of DM 185/2003**	**Exceeds D.Lgs. 152/2006**	**Complies with DM 185/2003**	**Complies with D.Lgs. 152/2006**
2024 - 2025	8	2.0	3.9	2	15	7	0	0	Yes	Yes

Table 45 presents the results of the normative compliance analysis conducted for the turbidity parameter are presented. The turbidity parameter exhibit values slightly above the normative limit. It should be noted, however, that this parameter should be continuously monitored at the station using a dedicated process probe.

Table 45 - Compliance with the legal limit (DL 39/2023) for the parameter Ntot (following the initiation of tertiary treatment processes)

Turbidity							
Year	**Number of measurement**	**Average (mg/L)**	**95-percentile (mg/L)**	**DL 39/2023 limit (mg/L) – Class A**	**Exceedances**	**Exceedances > 100% of the legal limit (LL)**	**Cumulative compliance frequency (%)**
2024 - 2025	8	6.8	11.6	5	5	1	38%

Table 46 presents the results of the normative compliance analysis conducted for the total phosphorus parameter, for which no critical issues were identified.

Table 46 - Compliance with the legal limit (DL 39/2023) for the Ptot parameter (following the start-up of advanced treatment processes)

Total phosphorus (P_{tot})					
Year	**Number of measurements**	**Average (mg/L)**	**95-percentile (mg/L)**	**DL 39/2023 limit (mg/L) – Class A**	**Compliance with the legislative limit**
2024 - 2025	7	0.75	3.9	1	Yes

Table 47 presents the results of the regulatory compliance analysis conducted for the chloride parameter. It is emphasized that DM 185/2003 provides a guideline value for the concentration of chlorides in treated waters, stipulating that, in no case, this concentration should exceed the limits for discharge into surface waters defined in Table 3 of Annex 5 of Legislative Decree No. 152 of 2006.

Based on the analysis of Table 47, it can be stated that there are no critical issues related to the chloride parameter.

Table 47 - Regulatory compliance for the chloride parameter

Chlorides									
Year	**Number of measurements**	**Average (mg/L)**	**95-percentile (mg/L)**	**Guideline Value – DM 185/2003 (mg/L Cl)**	**Limit – D.Lgs. 152/2006 (mg/L Cl)**	**Exceeds DM 185/2003**	**Exceeds D.Lgs. 152/2006**	**Complies with DM 185/2003**	**Complies with D.Lgs. 152/2006**
2024 - 2025	8	173.8	199.0	250	1200	0	0	Yes	Yes

Table 48 presents the results of the regulatory compliance analysis conducted for the total surfactants parameter. Regarding DM 185/2003, the surfactant parameter is currently non-compliant with the legal limits.

This result highlights the necessity to conduct an investigation into the efficiencies of surfactant removal throughout the treatment chain of the Brodolini station, with special attention given to the oil separation compartment.

Furthermore, if necessary, monitoring of the sewage network should be carried out to identify the source of surfactant discharges into the system.

However, it should be considered that DM 185/2003 will soon be revoked with the approval of the new Presidential Decree on national reuse. The draft DPR currently in circulation, which incorporates the guidelines of Regulation EU 741/2020, does not set limits for the total surfactants parameter. For this parameter, reference should then be made to D. Lgs 152/2006 regarding the discharge into surface waters, the limit currently required by the station for the discharge into the Tronto River.

Based on this latter limit, the total surfactants parameter is deemed to be in compliance.

Table 48 - Regulatory compliance for the Total Surfactants parameter

Total surfactants										
Year	**Number of measurements**	**Average (mg/L)**	**95-percentile (mg/L)**	**Limit – DM 185/2003 (mg/L)**	**Limit – D.Lgs. 152/2006 (mg/L)**	**Exceeds DM 185/2003**	**Exceeds 100% of DM 185/2003**	**Exceeds D.Lgs. 152/2006**	**Complies with DM 185/2003**	**Complies with D.Lgs. 152/2006**
2024 - 2025	8	0.9	1.3	0.5	2	7	3	0	No	Yes

During the monitoring campaign conducted after the initiation of tertiary treatments, the disinfection system was operated under different configurations. In particular, during the period when the initial samples were taken (up until October 2024), only UV lamps were used for disinfection.

However, under these conditions, the reduction of E. coli reduction for Class A defined by Regulation EU 741/2020 was not achieved.

Consequently, it was decided to apply peracetic acid after UV disinfection, with the aim of achieving an E. coli concentration below 10 CFU/100 mL in the treated waters.

The results of the monitoring of microbiological parameters are presented in Table 49.

Table 49 - Regulatory compliance for microbiological parameters governed by DL 39/2023

Parameter	**Unit of Measurement**	**DL 39/2023 (Class A)**	**Effluent 07/10/24**	**Effluent 08/22/24**	**Effluent 08/28/24**	**Effluent 10/01/24**	**Effluent 11/12/24**	**Effluent 12/03/24**	**Effluent 12/11/24**	**Effluent 04/22/25**
			UV Disinfection Only				**UV Disinfection and Peracetic Acid Dosing**			
E. coli	CFU/ 100mL	**10**	42	40	33	20	**0**	**3**	**0**	**0**
Salmonella	-	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent
Legionella spp	UFC/L	**1000**	<100	<100	<100	<100	**<100**	**<100**	**<100**	**<100**
Intestinal Nematodes	Eggs/L	**1**	<2	<2	<2	<2	**<2**	**< 2**	**< 2**	**< 2**

It is observed in Table 49 that the parameters Salmonella, Legionella spp, and intestinal nematodes were consistently in compliance with legal limits in all samples collected between July 2024 and April 2025, irrespective of the addition of peracetic acid.

It should be noted that the detection limit for intestinal nematodes is 2 eggs/L, and all samples showed values below this limit. Although the detection limit is higher than the legal limit, the lowest value that could be present is 1 egg/L, which exactly corresponds to the legal limit. However, in none of the collected samples was a concentration higher than 1 egg/L recorded.

When disinfection was carried out solely using UV lamps, the concentrations of E. Coli never fell below the limit required for class A (10 CFU/100 mL). Conversely, after the addition of peracetic acid, E. coli values were consistently observed below 10 CFU/100 mL.

After the regulatory compliance analysis of the physicochemical and microbiological parameters measured in the effluent produced by the San Benedetto del Tronto treatment plant, following the initiation of tertiary treatments, it is possible to highlight specific elements and risks that require targeted intervention. The measures and interventions to be adopted for the management of the identified risks are detailed in Table 50.

Table 50 - Identified Risks and List of Supplementary Measures to be Implemented for Risk Management

Parameter	Identified Risk	Planned Mitigation Measure	Validation Method
Turbidity	Turbidity measurements are close to the legal limit	Continuous turbidity monitoring via probe and interruption of reuse in case of abnormal readings; More frequent cleaning of sand filters; Cleaning to prevent solid accumulation in the disinfection compartment.	Continuous monitoring of turbidity parameter
Total Surfactants	Presence of total surfactant concentrations at the plant outlet close to the legal limit	Interruption of reuse in case of detection of anomalous measurements; Planning of monitoring along the wastewater treatment chain of the Brodolini plant, with particular	Monitoring of the total surfactant parameter at the plant inlet/outlet

Parameter	Identified Risk	Planned Mitigation Measure	Validation Method
		attention to the oil separation compartment; Planning of a monitoring campaign on the sewer basin to obtain information on the origin.	
Total Phosphorus	Total phosphorus concentrations sporadically exceeding the legal limit	Monitoring algal growth in the distribution system; Process management control in the treatment plant.	Monitoring the Ptot parameter at the plant outlet and in the distribution network
Microbiological Parameters (E. Coli; Intestinal Nematodes)	Failure to achieve Class A standards	Enhancement of the co-disinfection system through the dosing of peracetic acid.	Monitoring of E. coli, Salmonella spp, Legionella spp, and intestinal nematodes parameters; Process validation through verification of logarithmic removals of E. coli, coliphages, and Clostridium perfringens spores.

Regarding the distribution and irrigation systems, the environmental risks were assessed for surface waters, groundwater, soil, crops, vegetation, and fauna within the study area covered by the reuse project were assessed.

Table 51 presents the severity score is assigned to the hazards selected for the environmental risk analysis, considering the previously defined attribution criteria.

Table 51 - Assignment of severity scores to the hazards/contaminants identified for environmental risk assessment

Hazard	Severity
Nitrogen	3 - Moderate
Phosphorus	3 - Moderate

Hazard	Severity
Disinfection by-products	3 - Moderate
Salinity (TDS, Conductivity)	3 - Moderate
Boron	3 - Moderate
Chloride	3 - Moderate
Sodium	3 - Moderate
Inorganic compounds (e.g., metals)	3 - Moderate
Organic micro-contaminants (e.g., emerging pollutants, pesticides)	3 - Moderate

The risks that, after calculation using the previously described semiquantitative method, are classified as "Very high," "High," or "Moderate," must be re-evaluated considering the results of the validation of the existing control measures in the system.

If these measures still prove inadequate, it will be necessary to implement additional actions or protective barriers to ensure that all risks are properly managed and controlled.

Risks classified as "Low" must nonetheless be documented and subjected to periodic reviews, in order to ensure that any systemic changes over time do not elevate their classification.

The results of the environmental risk analysis are partially presented in the environmental risk matrix (Figure 11).

Figure 11 - Environmental risk assessment of internal units T2A, T2B, and T2C

IDENTIFICAZIONE DEL SITO			IDENTIFICAZIONE DEGLI EVENTI PERICOLOSI E DEI PERICOLI ASSOCIATI						RISCHIO PRELIMINARE			MISURE DI CONTROLLO ESISTENTI	RISCHIO RESIDUALE			PIANO DI MIGLIORAMENTO	VALIDAZIONE MISURE INTEGRATIVE E MONITORAGGIO INTEGRATIVO		RISCHIO RESIDUALE FINALE		
CODICE NODO	SUB-SISTEMA	DESCRIZIONE NODO	EVENTO PERICOLOSO	VIE DI ESPOSIZIONE	RECETTORE AMBIENTALE		EFFETTO POTENZIALE	PERICOLI ASSOCIATI	PROBABILITÀ DI ACCADIMENTO	GRAVITÀ DEL PERICOLO	RISCHIO	MISURE DI CONTROLLO ESISTENTI	PROBABILITÀ DI ACCADIMENTO	GRAVITÀ DEL PERICOLO	RISCHIO	NECESSITÀ / OPPORTUNITÀ DI MISURE INTEGRATIVE	Validazione Misure Integrative e Monitoraggio integrativo	Responsabile dell'attuazione delle Misure Integrative	PROBABILITÀ DI ACCADIMENTO* (* Probabilità di accadimento valutata su stime teoriche)	GRAVITÀ DEL PERICOLO	RISCHIO RESIDUALE FINALE ATTESO POST INTERVENTO
T2A	Rete di distribuzione irrigua	RAMO DESTRO (condotta interrata)	Deterioramente della qualità delle acque distribuite (dovuto a malfunzionamento impianto di depurazione/ o cross-contaminazione con altro tipo di acqua o a fenomeni di riscrescita batterica/algale)	infiltrazione su suolo e percolazione in falda	ACQUE SOTTERRANEE	R2	Aumento della salinità, eutrofizzazione, tossicità biota acquatico	Salinità, cloruri, nutrienti, sodio,boro, contaminanti inorganici, micro-inquinanti organici	3	Moderato	ALTO	Il depuratore garantisce acqua di classe A; Ispezioni periodiche visive da parte del personale del consorzio; manutenzione delle	3	Moderato	ALTO	Piano di monitoraggio sull'effluente dell'impianto di depurazione, lungo la rete di distribuzione e attuazioni di protocolli di arresto della fornitura	Condivisione dei dati ottenuti	Gestore dell'impianto di depurazione; gestore della rete di distribuzione.	1	Moderato	BASSO
				contaminazione acque superficiali o ruscellamento sul suolo	ACQUE SUPERFICIALI SUOLO	R1-R3	Aumento della salinità, eutrofizzazione, tossicità biota acquatico; tossicità biota terrestre	Salinità, cloruri, nutrienti, sodio,boro, contaminanti inorganici, micro-inquinanti organici	3	Moderato	ALTO	Il depuratore garantisce acqua di classe A; Ispezioni periodiche visive da parte del personale del consorzio; manutenzione delle	3	Moderato	ALTO	Piano di monitoraggio sull'effluente dell'impianto di depurazione, lungo la rete di distribuzione e attuazioni di protocolli di arresto della fornitura	Condivisione dei dati ottenuti	Gestore dell'impianto di depurazione; gestore della rete di distribuzione.	1	Moderato	BASSO
				assorbimento delle specie vegetali	COLTURE	R4	Squilibrio nutrizionale nelle colture; tossicità delle colture	Salinità, cloruri, nutrienti, sodio,boro, contaminanti inorganici, micro-inquinanti organici	3	Moderato	ALTO	Il depuratore garantisce acqua di classe A; Ispezioni periodiche visive da parte del personale del consorzio; manutenzione delle	3	Moderato	ALTO	Piano di monitoraggio sull'effluente dell'impianto di depurazione, lungo la rete di distribuzione e attuazioni di protocolli di arresto della fornitura	Condivisione dei dati ottenuti	Gestore dell'impianto di depurazione; gestore della rete di distribuzione.	1	Moderato	BASSO
				assorbimento delle specie vegetali	FLORA	R5	alterazione della biodiversità vegetale e/o Tossicità	Salinità, cloruri, nutrienti, sodio,boro, contaminanti inorganici, micro-inquinanti organici	3	Moderato	ALTO	Esistono piani di monitoraggio sull'abbondanza delle specie vegetali	2	Moderato	MODERATO	Ripristino piano di monitoraggio già adottato in passato e aumento della frequenza in caso di necessità	Condivisione dei dati ottenuti	Comune di San Benedetto del Tronto	1	Moderato	BASSO
				contatto diretto o indiretto: ingestione di acque e/o ingestione di vegetali a contatto con le acque	FAUNA	R6	alterazione della biodiversità animale e/o Tossicità	Salinità, cloruri, nutrienti, sodio,boro, contaminanti inorganici, micro-inquinanti organici	3	Moderato	ALTO	Esistono piani di monitoraggio sull'abbondanza delle specie animali	2	Moderato	MODERATO	Ripristino piano di monitoraggio già adottato in passato e aumento della frequenza in caso di necessità	Condivisione dei dati ottenuti	Comune di San Benedetto del Tronto	1	Moderato	BASSO

Following a detailed analysis within the risk matrix, the internal units T2A, T2B, and T2C were classified as having a low final residual risk. The measures outlined therein, which are to be

implemented, are deemed appropriate to maintain the low level of risk in the context of environmental risk assessment.
Subsequent to the risk assessments, it is essential to implement a comprehensive monitoring program to ensure the efficiency of the treatment system and the quality of the treated water prior to distribution and irrigation of agricultural plots, including analyses of soil and irrigated agricultural production.
The Regulation of the European Parliament and of the Council 741/2020 establishes the minimum monitoring frequencies for the regulated parameters (E. coli, BOD5, TSS, Turbidity, Legionella, and intestinal Nematodes).
Supplementary monitoring prescriptions may be added to these, when necessary and appropriate, to ensure an adequate level of protection for the environment and human and animal health, especially when there is clear scientific evidence that the risks arise from the treated waters, for the following parameters: heavy metals, pesticides, disinfection by-products, pharmaceuticals, other substances of emerging concern (including microcontaminants) and microplastics, and antimicrobial resistance agents.
The Ministerial Decree of June 12, 2003, No. 185 establishes that the wastewater treatment plant is subject to the control of the competent authority, with the aim of verifying compliance with the requirements contained in the reuse authorization. This control, as determined by the competent authority and based on the monitoring program provided for in Article 49, paragraph 1, of Legislative Decree No. 152 of 1999, can be carried out by the person responsible for the recovery station. Furthermore, the person in charge of the station must, in any case, ensure the performance of a sufficient number of self-checks at the station's exit, never less than those required by regional regulations, according to specific uses.
Article 11 also establishes that the person responsible for the distribution network conducts monitoring with the aim of verifying the chemical and microbiological parameters of the reclaimed wastewater that is distributed, as well as the environmental, agronomic, and pedological effects of reuse.
The health authority, in the exercise of its preventive activities and in accordance with the provisions of Article 4, paragraph 2, evaluates any hygienic-sanitary effects associated with the use of reclaimed wastewater.
The monitoring results are transmitted to the region on an annual basis. It is specified, therefore, that at the national level, mandatory monitoring frequencies are not established, which must be defined at the regional level, according to the specific uses of the treated effluent.

The new national decree project for the transposition of the European Regulation establishes minimum frequencies for the monitoring activities of treated water, according to the type of reuse (agricultural, industrial, urban, or environmental). In particular, the following parameters are regulated for wastewater intended for agricultural irrigation: E. coli, BOD5, TSS, Turbidity, Legionella, intestinal nematodes, total nitrogen (Ntot), total phosphorus (Ptot), Salinity, and Salmonella. For water intended for other uses, only the following parameters are required: E. coli, BOD5, TSS, TKN, and TP.

Table 52 presents the monitoring frequency of the parameters defined in this new legislation.

Table 52 - Minimum frequencies of monitoring activities for reclaimed water intended for agricultural irrigation

Water Quality Class	Monitoring Frequencies									
	E.coli(4)	BOD(4)5	TSS(4)	Turbidity(4)	Legionella spp. where applicable to Legionella) (4)	Intestinal nematodes	N_{tot}	P_{tot}	Salinity	Salmonella spp.
A	Once a week	Once a week	Once a week	Continuous	Twice a month	Twice a month, or as determined by the operator of the tertiary treatment plant based on the number of eggs present in the influent wastewater	Once a week or in accordance with Directive 91/271/EEC	Once a week or in accordance with Directive 91/271/EEC	Twice a month	Twice a month
B	Once a week	In accordance with Directive 91/271/EEC	In accordance with Directive 91/271/EEC	-					Twice a month	Twice a month
C	Twice a month			-					Twice a month	Twice a month
D	Twice a month			-					Twice a month	Twice a month

CONCLUSIONS

This study conducted a comprehensive risk analysis for wastewater reuse in two distinct Geographical contexts: Brazil (WWTPs No. 1 and 2) and Italy (San Benedetto del Tronto WWTP), drawing specific conclusion regarding regulatory compliance, high-risk parameters, and necessary system upgrades.

The risk analysis of effluents demonstrated that the current Brazilian WWTP configurations cannot meet the requirements of CERH/PR Resolution No. 122/2023 for agricultural and foresty activities. It should be noted that the primary operational objective of these two WWTPs is strictly limited to effluent discharge into surface water bodies, in compliance with federal and state legislation, and not the production of water for reuse purposes.

The principal parameters presenting a high risk in the FMEA (Failure Mode and Effects Analysis) were chlorides, sulfates, arsenic, cadmium, boron, phenols, surfactants, and mineral oil.

To comply with CERH/PR Resolution No. 122/2023 and reduce the risk level associated with these parameters, a system upgrade is mandated. A suggest about optimization of the oil-water separator unit and the addition of a advanced tertiary processes: filtration system, granular activated carbon (GAC), and reverse osmosis (RO) for the comprehensive removal of chemical compounds. For *E. coli* removal, the suggested additions include filtration, granular activated carbon, reverse osmosis, and emergency chlorine dosing.

In the Italian case, the refined effluent is destined for the irrigation of crops within the Sentina Regional Nature Reserve, in the Marche region.

The treated effluent currently undergoes tertiary treatment. However, even after its installation, some parameters were still observed to require attention: total nitrogen, ammoniacal nitrogen, turbidity, total phosphorus, chlorides, and surfactants.

These parameters were subjected to detailed compliance analysis with the legal limits of DL 39/2023. Of all the parameters assessed, only the turbidity parameter was slightly above the normative limit, suggesting that the parameter must be continuously monitored by means of a dedicated probe.

Furthermore, following the initiation of UV lamp disinfection, the *E. coli* parameter did not achieve the reduction mandated by the legislation. Consequently, peracetic acid was subsequently dosed after UV disinfection to ensure that the normative limit was successfully attained, validating the combined disinfection strategy.

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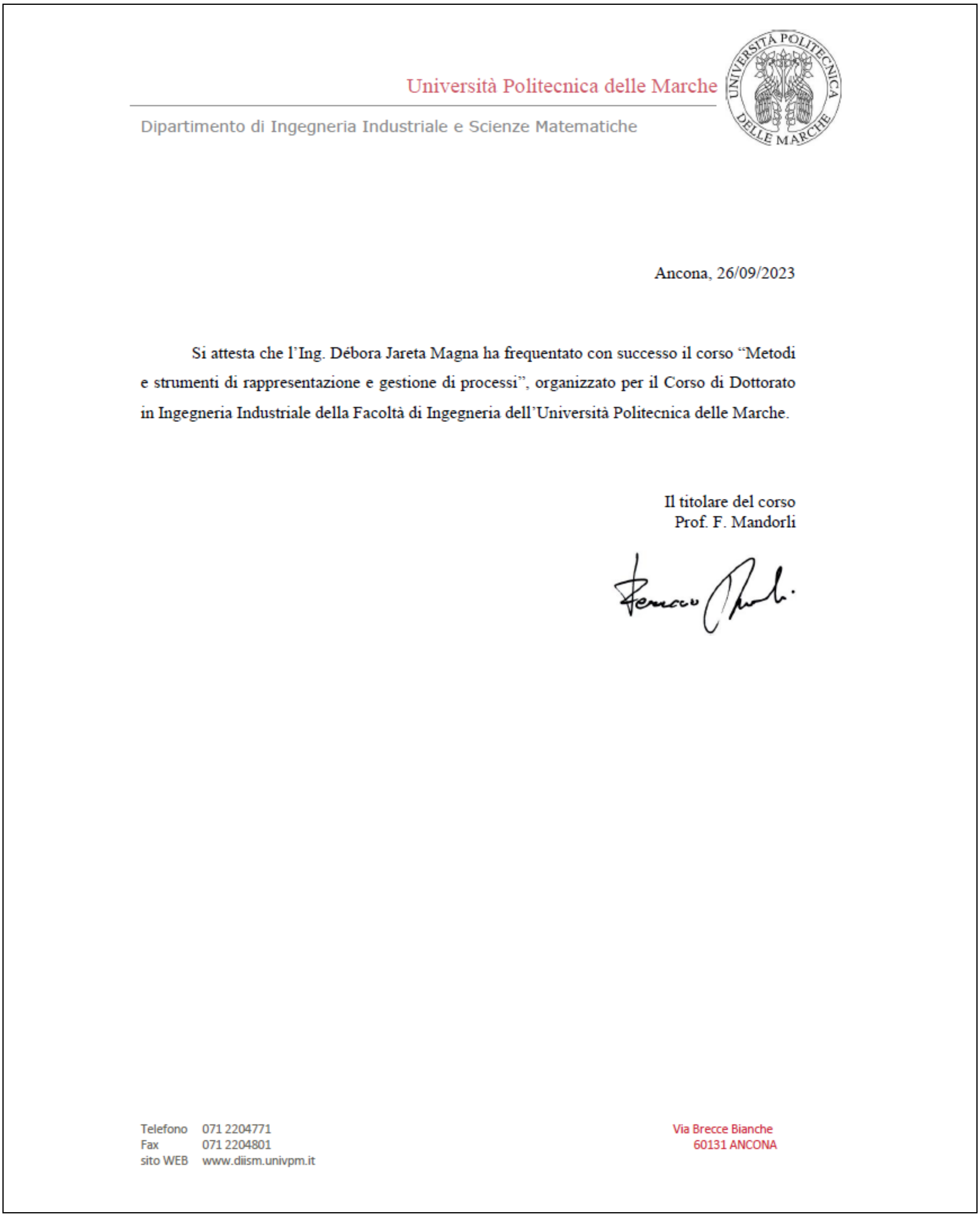
APPENDIX - LIST OF PUBLICATIONS

Title	Authors	Type of publication	References
Development of methodologies and tools of risk assessment for wastewater and stormwater reuse	L. De Simoni, S. Radini, A. Foglia, M. Sgroi, **D. J. Magna**, B. Szelag, A. Kiczko, A. L. Eusebi, F.Fatone	Poster	6th IWA International Conference on eco-Technologies for Wastewater Treatment. Girona-Spain 26th-29th June (2023)
Quantitative Microbial Risk Assessment Applied to Wastewater-Based Microalgae Biorefinery	J. González-Camejo, S. Hernández-Cuenca, **D. J. Magna**, A. L. Eusebi, M. Pachés, F. Fatone	Oral presentation	Photorefineries 2024 1st International Conference on Novel Photorefineries for Resource recovery. Valladolid-Spain 9, 10, 11 September (2024) DOI: 10.5281/zenodo.13476761
Implementation Of Microalgae-Based Recovery Facility To Improve Circularity In Urban Wastewater Treatment	Josue Gonzalez Camejo, Ignacio Ortega Pérez, Luisa Vera, Francesco Fatone, **Débora Jareta Magna**	Oral presentation	Proceedings of the 17th IWA Conference on Small Water and Wastewater Systems and the 9th IWA Conference on Resource-Oriented Sanitation Curitiba, Paraná, Brazil, 10–14 November (2024) ISBN: 978-65-990271-9-2
Wastewater Treatment through Microalgae Cultivation: a Pilot Case Study in Italy	**Débora J. Magna**, Alessia Foglia, Maria Grazia Chieti, Virginia G. Barros, Anna Laura Eusebi, Josue G. Camejo, Francesco Fatone	Oral presentation	Chemical Engineering Transactions VOL. 117, 2025, p 133-138. Guest Editors: Fabrizio Bezzo, Flavio Manenti, Gabriele Pannocchia, Almerinda di Benedetto Copyright © (2025) AIDIC Servizi S.r.l. ISBN 979-12-81206-17-5; ISSN 2283-9216 DOI: 10.3303/CET25117023
Artificial intelligence in wastewater treatment plants: a review of current trends and adaptation strategies in the face of climate-driven rainfall floctuations	Selda Murat Hocaoglu, Bardia Roghani, Hande Gulcan, **Débora Jareta Magna**, Cihangir Aydöner, Virginia Grace Barrosc, Sebnem Koyunluoglu Aynur, Harsha Ratnaweera, Francesco Fatone, Anna Laura Eusebi and Zakhar Maletsky	Scientific article	Journal of Water and Climate Change Vol 00, 2025, No 0, 1 DOI: 10.2166/wcc.2025.849
Alternative Water Sources, Reuse, and Management of Health and	Massimiliano Sgroi, Lucia De Simoni, **Débora Jareta Magna**, Serena	Technical paper	Servizi a Rete, Luglio - Agosto 2023

Title	Authors	Type of publication	References
Environmental Risks – From Horizon2020 Digital Water City to Horizon Europe WATERUN	Radini, Anna Laura Eusebi, Enrico Marinelli, Francesco Fatone		

ANNEX 1 - CERTIFICATE ATTENDANCE: MANDATORY COURSES

Figure 1 – Certificate of attendance: Course-Methods and Instruments for Process Representation and Management



Università Politecnica delle Marche

Dipartimento di Ingegneria Industriale e Scienze Matematiche

Ancona, 26/09/2023

Si attesta che l'Ing. Débora Jareta Magna ha frequentato con successo il corso "Metodi e strumenti di rappresentazione e gestione di processi", organizzato per il Corso di Dottorato in Ingegneria Industriale della Facoltà di Ingegneria dell'Università Politecnica delle Marche.

Il titolare del corso
Prof. F. Mandorli

Telefono 071 2204771
Fax 071 2204801
sito WEB www.diism.univpm.it

Via Brecce Bianche
60131 ANCONA

Figure 2 - Certificate of attendance: Course-Technology Transfer and Innovation

UNIVERSITÀ
POLITECNICA
DELLE MARCHE

Dipartimento
di Ingegneria
dell'Informazione
DII

Ancona, 19 ottobre 2023

OGGETTO*: attestator di frequenza.*

Attesto che la dottoranda Débora Jareta Magna, dottoranda presso il Dottorato di Ricerca Nazionale "Difesa dai rischi naturali e transizione ecologica del costruito" presso l'University of Catania (UNICT) e Marche Polytechnic University (UNIVPM), ha frequentato l'insegnamento per le scuole di dottorato dell'Ateneo dal titolo: "TECHNOLOGY TRANSFER AND INNOVATION" svoltosi nel periodo 01/03 – 03/05 2023.

Il docente

Prof. Donato Iacobucci

SEDE
Via Brecce Bianche 12
Monte Dago
60131 Ancona / Italia
www.univpm.it

Figure 3 - Certificate of attendance: Course-Electron microscopy techniques and microanalysis

Università Politecnica delle Marche

Dipartimento di Scienze e Ingegneria
della Materia, dell'Ambiente ed Urbanistica

Ancona, 11/10/2024

Con la presente si ATTESTA che la dottoressa **Débora Jareta Magna** ha frequentato nel 2024 il corso di dottorato dal titolo "Electron microscopy techniques and microanalysis", per un totale di 24 ore corrispondenti a 3 CFU, all'interno della Scuola di Dottorato della Facoltà di Ingegneria dell'Università Politecnica delle Marche.

Il titolare del corso
Prof. Gianni Barucca
Gianni Barucca

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Figure 4 - Certificate of attendance: Course-Scientific writing and communication

Università Politecnica delle Marche

Scuola di Dottorato in Scienze dell'Ingegneria

CERTIFICATE OF ATTENDANCE

I, the undersigned Gianluca Coccia, Professor of the teaching "Scientific writing and communication", provided within the Doctoral School in Engineering Sciences, Faculty of Engineering, Università Politecnica delle Marche,

CERTIFY

that Dr./Eng. Débora Jareta Magna, student code ---, enrolled in the XVIII cycle of the Doctoral School/Course DEFENSE AGAINST NATURAL RISKS AND ECOLOGICAL T RANSITION OF BUILT ENVIRONMENT, University of Catania, attended classes, for a total of 15 hours, as indicated in the following schedule.

Date	Starting time	Ending time
20/01/2025	13:30	16:30
27/01/2025	09:30	12:30
06/02/2025	09:30	12:30
10/02/2025	09:30	12:30
17/02/2025	09:30	12:30

Dr./Eng DEBORA JARETA MAGNA

- ☑ has passed
- o has not passed

the final exam.

This certificate is issued upon the request of the interested party for the uses permitted by Law.

Ancona, 13/03/2025

Signature
Prof. Gianluca Coccia
Gianluca Coccia

OFFICE ADDRESS
Presidenza Facoltà di Ingegneria,
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ANEXX 2 - CERTIFICATE ATTENDANCE: COMPLEMENTARY COURSES

Figure 1 -Certificate of attendance: Course - The importance of experimental research for seismic risk mitigation

PhD course on: **The importance of experimental research for mitigation of seismic risk**

Organization and Introduction
Prof. Edoardo M. Marino and Francesca Barbagallo, University of Catania, Italy

Lectures:
Development of new experimental technologies
Prof. Peng Pan, Tsinghua University, China

Multi-Disciplinary Approach on Earthquake Reconnaissance and Large-Scale Testing for Seismic Assessment and Monitoring of Medical Facilities
Prof. Masahiro Kurata, Kyoto University, Japan

Shaking table test on 1000kV ultra-high voltage power grid infrastructures in China
Prof. Qiang Xie, Tongji University, China

Experimental tests for seismic prequalification of steel beam-to-column joints
Prof. Mario D'Aniello, University of Naples "Federico II", Italy

Seismic resilience assessment of engineering systems
Prof. Tao Wang, Institute of Engineering Mechanics, China

Certificate of attendance

This is to certify that

Ms. Débora Jareta Magna

*attended online the PhD course on: The importance of experimental research for mitigation of seismic risk held at University of Catania, Italy, 4 October 2023, for a total amount of **5 hours** of lecture.*

Catania, 18 October 2023

Prof. Antonino Cancelliere

Prof. Massimo Cuomo

Prof. Edoardo M. Marino

Prof. Francesca Barbagallo

SICILIAE STVDIVM GENERALE 1434

PhD Course in Evaluation and mitigation of urban and territorial risks
Coordinator: Prof. Antonino Cancelliere

National PhD Course in Defense against natural risks and ecological transition of built environment
Coordinator: Prof. Massimo Cuomo

Figure 2 - Certificate of attendance: Course – English course

UNIVERSITÀ degli STUDI di CATANIA

CLA

Centro Linguistico di Ateneo

Rep. 1189

Catania, 27/10/2023

SI ATTESTA CHE

Debora Jareta Magna

- nata a Nova Andradina, Brasile il 15/06/1982 - ha frequentato online tramite la piattaforma Microsoft Teams, nel periodo che va dal 09/03/2023 al 26/05/2023, un corso di lingua inglese di 40 ore e di livello A2/A2+, organizzato dal Centro Linguistico d'Ateneo per i dottorandi dell'Università degli Studi di Catania, superando la verifica interna al corso.

Il Presidente del CLA
Prof. Marco Mazzone

"Il presente certificato non può essere prodotto agli organi della pubblica amministrazione o ai privati gestori di pubblici servizi (art. 40, comma 2 DPR 445/2000, come modificato dall'art. 15 della Legge 183/2011)."

Centro Linguistico d'Ateneo
Piazza Dante n. 32 - 95124 - Catania
email: infoclma@unict.it - web: www.cla.unict.it

Figure 3 - Certificate of attendance: Summer school on Strategies for adapting to and mitigating the effects of climate change in the agricultural sector

SMART4ENV

Summer School on Strategies for adapting to and mitigating the effects of climate change in the agricultural sector

24th, 25th and 26th of April 2024

Certificate of Participation

This certificate is awarded to

Debora Jareta Magna

For attending the SMART4ENV 2nd Summer School in person.

The Summer School is organised by the Beta Technological Center from the University of Vic – Universitat Central de Catalunya in the framework of the SMART4ENV Horizon Europe Project. It offered conferences from high-level experts to gain valuable insights from their practices, projects and experience related to strategies and innovations related to the sustainable management of nutrients, fertilisers, and water.

Sergio Ponsá

Director of the Beta Technological Center

Beta
UVIC