

Article

Treatment Reliability When Reusing Reclaimed Water for Irrigation: A Risk Assessment, Ranking and Management Methodology

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Abstract

Water reuse may pose risks to the environment and human health due to pathogens or chemical pollutants (hazards) in reclaimed water arising from treatment or distribution system failures (hazardous events). In this context, the European Regulation EU 2020/741 requires the development of a Risk Management Plan (RMP) from the source to the irrigated fields. This study proposes a methodology to assess and manage the risk to guarantee a reliable treatment able to produce an effluent adequate for reuse. It combines Failure Mode and Effect Analysis (FMEA) with a Risk Priority Number (RPN) approach. FMEA identifies failure modes for the treatment components (hazardous events), their consequences for the system, and the hazards for environment and human health. The RPN measures the failure risk by the product of the likelihood of occurrence L, magnitude of effects M and ease of detection D for each failure. Due to a lack of data, L, M and D are estimated through scores. Failure risks are classified as low, medium, high and very high. The last step is the revision of existing corrective actions or the adoption of new ones to reduce the risk of critical failures (highest RPN). This methodology is applied to a large wastewater treatment plant (Class A technology, according to EU 2020/741). Out of the 303 failure modes identified for the 86 components, 12 are the most critical (very high risk) and the suggested additional corrective actions reduce L and/or D and thus M. This methodology supports an RMP for similar or more complex treatment plants.

Keywords: FMECA; hazardous events; risk analysis; treatment train; water reuse



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1. Introduction

Reusing reclaimed water is a practice aligned with the circular economy action plan [1] and the European new climate adaptation strategy [2]. The increasing attention to agricultural needs is related to the fact that this sector is particularly vulnerable to scarce or intermittent water resources. Therefore, reclaimed water, being climate-independent, could always meet quantitative water demands, particularly in areas classified as arid or semi-arid, and with increasingly frequent periods of drought.

For the safe use of reclaimed water, the European Regulation [3] identifies four water quality classes and lays down minimum requirements in terms of macropollutants (BOD₅, TSS, and turbidity) and indicator microorganisms (among them *E. coli*, *Legionella* spp. and intestinal nematodes).

Reclaimed water reuse may pose risks to the environment and human health due to the presence of contaminants—such as pathogens and/or chemical compounds—which constitute hazards. These hazards may arise from treatment failures or malfunctions, accidental leakages, or contamination of the reclaimed water distribution system, which represent hazardous events [3,4].

In this context, the European Regulation [3] requires the development of a Risk Management Plan (RMP), which includes an assessment of the risks to the environment and/or human health arising from the presence of hazards in reclaimed water, as well as the identification of measures to mitigate their adverse effects. Examples of risk assessment methodologies are provided in [4–6]. All of them are selected from those proposed by the Australian Guidelines [7], the ISO guidelines [8–10] and the WHO reports [11,12].

RMPs have recently been developed for pilot-scale systems [13], full-scale plants [14,15] and water distribution networks and crop irrigation systems [16]. However, in these studies the risk assessment focused on hazards—namely pathogens and chemical pollutants present in reclaimed water—while the underlying causes of their occurrence (the hazardous events) were not investigated in depth. As a result, the contribution of treatment failures, malfunctions, and distribution system issues to the overall risk remains insufficiently addressed. Their identification and analysis are fundamental to the risk assessment as their occurrence determines the likelihood of an occurrence of a hazard, as clearly stated in Section 5.2.1 of the ISO guidelines [10] and Annex III of the European guidelines [6].

This study aims to fill this gap by thoroughly investigating each treatment step of a wastewater treatment plant (WWTP), whose effluent is intended for reuse, at the level of individual components (e.g., valves, probes, sensors, and pipes), to identify potential hazardous events, hazards and the associated risks to humans and the environment. It proposes a methodology for the assessment, ranking and management of the risks related to the listed hazardous events by combining the Failure Mode and Effect Analysis (FMEA) [17] and the Risk Priority Number (RPN) approach [18]. This approach has been successfully utilized across numerous industrial sectors, as discussed in [18], including the electrochemical, computer, semiconductor, medical device, and automotive industries. FMEA identifies the failure modes which may occur during the treatment, their causes and their effects on the process performance, WWTP assets, final effluent quality, environment and human health, as well as their ease of detection. The RPN estimates the risk of each failure mode on the basis of its corresponding likelihood of occurrence, magnitude of consequences (effects) and ease of detection. Finally, a criticality analysis, performed by ranking the RPN values, allows the identification of the critical failure modes which must be properly managed in order to reduce their risk to a level as low as is reasonable. This implies the evaluation of the adequateness of the existing corrective actions, and the proposal of additional ones. The combination of the FMEA and the criticality analysis leads to the semiquantitative Failure Modes, Effects, and Criticality Analysis (FMECA). The developed methodology does not encompass compliance of the final effluent quality with legal limits for the regulated contaminants, but sheds light on the potential effects the failure modes have on it.

The described methodology is then applied to a real large urban WWTP in Italy whose reclamation facility consists of a rapid sand filter followed by a disinfection unit. This scheme is the indicative technology target for Class A of the EU Regulation [3] and has been adopted in many cases for agricultural and industrial reuse in Italy as reported in [19] and discussed in [5].

The scope of this study is to provide a framework to support the development of an RMP, focusing on potential failure modes (hazardous events) occurring at the source (influent), within the WWTP, and at the reclamation facility, which may result in the

presence of chemical or pathogenic hazards in the final effluent intended for agricultural reuse. The framework also offers guidance on reducing the associated risks to the lowest reasonably achievable level.

2. Materials and Methods

2.1. Definition of the Terms Used in the Development of the Methodology

The development of the proposed risk assessment methodology uses key terms, the definitions of which are reported in Table 1. They are aligned with the current terminology used in the fields of risk assessment in the chemical and process industries [17,18], and of RMP [3,12].

2.2. Rationale of the Developed Risk Assessment Methodology

A WWTP is designed to produce a final effluent that meets the quality standards (legal requirements) related to its destination (release into the environment, release into a sewage system, reuse or internal recycling). Normal working conditions are able to guarantee this aim. Deviations may occur to the influent (e.g., higher flow rate than the designed value, higher influent pollutant concentration than that designed); the operational conditions in the treatment steps (e.g., lower supplied oxygen than designed, lower added chemicals than requested); and the specific components of the system (e.g., a valve closed instead of open, uncalibrated probes). For the influent, deviations are related to what happens upstream, in the catchment area, whereas for the other components, deviations are mainly due to component failures. Any deviation leads to consequences for the system which may vary greatly in magnitude. It is thus crucial to know, predict and rapidly detect the failure modes of a system causing the deviations, and also, when necessary, to take proper actions to guarantee that the system returns to its normal conditions (correct working). At the same time, it is also important to identify the most critical failure modes (those leading to serious effects on the system, final effluent quality, environment or human health), to evaluate whether staff are quickly alerted, and to ascertain whether the planned actions are sufficient or whether new actions are necessary to return the system to its normal working conditions or mitigate the consequences.

In this context, different approaches are available. Among them is the qualitative FMEA, which identifies the potential failure modes of the whole system, their causes and consequences, and suggests corrective actions to respond to their occurrence [17].

Another approach is the semiquantitative Failure Mode, Effects and Criticality Analysis (FMECA), which combines FMEA with the criticality analysis in order to rank the listed failure modes and identify the most critical ones (prioritization) [20] on the basis of defined risk levels. The most critical failure modes correspond to the ones with the highest risk. The risk is conventionally defined as the product between the likelihood of occurrence (L) of an event and the magnitude of its consequences (M). In the automotive sector [21] as well as in other fields in design and process FMEA [18], the Risk Priority Number (RPN) index (Equation (1)) is used to measure and prioritize the risks.

$$\text{RPN} = (\text{measure of L}) \times (\text{measure of M}) \times (\text{measure of D}) \quad (1)$$

where D is the ease of detection of a failure mode; that is, the visibility of the failure by controls and inspections.

Table 1. Definition of the key terms used in the proposed methodology.

Term	Definition
Component	Any part of the system that may be a source of hazard resulting from a failure mode, i.e., influent (raw wastewater), water stream (under treatment), tank containing a chemical, valve, sensor, and mixer. All of them may present deviations with respect to the characteristics defined by the project which are considered “normal conditions” (physical and chemical quality, operating conditions).
Consequences or effects	A description of the impact of a failure mode on the operation or status of the component, equipment, subsystem, system, final effluent, environment, or operators. Effects also include material loss, lost production, and recovery costs.
Corrective actions	Any device or action that would likely be able to return the system to its normal conditions. They are often called “safety measures”.
Detection	Ability of the current process control(s) to detect a failure mode or its causes.
Deviation	Process conditions which depart from their “normal conditions” (design intents) due to a failure mode.
Ease of detection	A measure of the ability of the design control to detect a failure mode or its cause.
Equipment	A general term used to refer to a subset of a system or a subsystem.
Failure	Cessation of a component/equipment/system to operate according to the design conditions (normal conditions). In the context of the current study, a failure is the manner in which a system (WWTP), subsystem (treatment step) or component (valve) fails to meet its intended purpose or function.
Failure mode	A condition in which a component/equipment/system does not work properly and a failure is observed. It is one of the possible hazardous events. A failure mode referring to the influent wastewater or stream under treatment corresponds to changes in its expected quantity and quality according to the design conditions.
Hazard	It may be physical, chemical or microbiological and corresponds to a situation (noise, overheating, vibrations), a contaminant or a pathogen with the potential to cause harm to humans and/or the environment (including the WWTP assets).
Hazardous event	Failure or malfunctioning within the WWTP causing a hazard for the environment, WWTP assets or people (WWTP staff members or resident population).
Item	One of the three parameters defining the Risk Priority Number (RPN); that is, the likelihood of occurrence, magnitude of the effects and ease of detection of a failure mode.
Level of detail of the risk assessment	Identification of all the components for which failures may happen. For instance, a valve may be considered as a whole or divided into a body and bonnet.
Likelihood of occurrence	A measure of the expected probability or frequency of occurrence of a failure mode.
Magnitude of consequences	A measure of the seriousness of the effects or consequences of a failure mode on the downstream processes or equipment of the process operation, system, final effluent quality, environment and human health.
Mitigate	Reduce the impact of the consequences.
Normal working conditions	Working conditions defined according to the design or the manual of system working procedures. As an example, they refer to the concentrations in the influent and in the water stream and operational conditions (redox, dissolved oxygen, pH, etc.).
Risk	The combination of the likelihood of a specified undesirable event occurring within a specified period and its consequences on the environment and/or human health. In this study the environment includes the system (WWTP assets) and what is present within the system boundaries.
Risk priority number (RPN)	Index defined for the prioritization of the different failure modes as the product of the likelihood of occurrence, ease of detection and magnitude of consequences.
Risk scenario	The situation in which a specific failure mode happens and its effects occur.
Subsystem	A set of interdependent equipment or parts organized to achieve a defined objective by performing a specified function. When referring to a WWTP, a subsystem corresponds to a treatment step.
System	A set of interdependent subsystems or components organized and linked in a coherent way to each other and to the whole. When referring to a WWTP, the system is the whole treatment plant.
System boundaries	The limits of the system under study.

The RPN can be evaluated by means of equations defined for the three items (L, M, D) [22] or more frequently by means of the assignment of scores S_i , where i stands for L, M and D, and which generally ranges between 1 and 5, or 1 and 10, with all the consecutive numbers used [18]. The resulting RPN is thus obtained by means of Equation (2):

$$\text{RPN} = S_L \times S_M \times S_D \quad (2)$$

The score corresponds to an expected level of $L(S_L)$, $M(S_M)$ and $D(S_D)$: the higher the score, the higher the likelihood of occurrence and magnitude of the effects and the lower the ease of detection. This means that the highest values of RPN correspond to the failure modes with the highest risk level (the most critical ones).

FMECA is often carried out by a team of experts on the processes and the system under study who, together with the plant staff, identify and analyze each failure mode, and assign the appropriate scores for RPN evaluation [23]. Helpful sources of information may include experienced data from similar equipment, recommendations from manufacturers and practitioners, and other expert judgments. Discussion among the experts is necessary to exchange know-how and to encourage a convergence of opinions on the scores to be assigned, as described in Section 2.3.3.

2.3. The Developed Methodology

The developed methodology is represented in Figure 1 and consists of four phases which are described in the following sections.

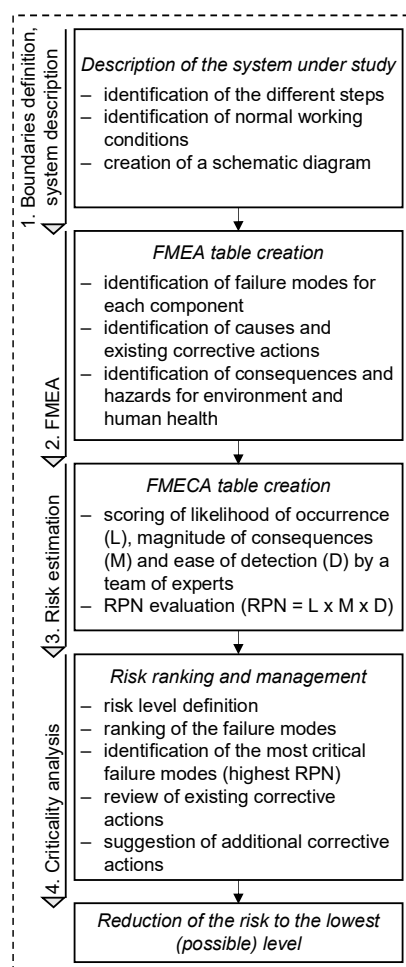


Figure 1. Flow chart of the developed methodology, including a description of the four phases.

2.3.1. Definition of the Boundaries and Description of the System

The first phase consists of the definition of the boundaries of the system under study (the treatment train) and its description. This implies a detailed analysis of the influent characteristics by means of a historical data series (flow rate and chemical composition in relation to the catchment area producing it), the different steps (the subsystems: treatment units, with their compartments and equipment, e.g., anaerobic/anoxic/aerobic compartments in the biological step), and their main components (e.g., probes/sensors, valves, pipes, chemicals to add). It must also identify the normal working conditions in each step (e.g., pH, temperature, redox potential, oxygen concentration) and the starting position of the different components (e.g., a valve must be opened).

A schematic diagram of the treatment train must be prepared, with all the subsystems being identified with a code (a capital letter), taking into consideration their position along the treatment train (the influent, treatment unit, remote control system). In this way, the subsystems can be identified as T1, T2, T3, ... Tn..., etc., with n being its position in the treatment train.

If the subsystem consists of more compartments, its code includes a subscript reflecting the position of the compartment in the subsystem (1, 2, 3, etc.). For instance, if the biological step is identified as subsystem T7 with the bioreactor divided into an anoxic (denitrification) and aerobic (nitrification) compartment, the codes will be: T7₁ for the anoxic tank and T7₂ for the aerobic tank.

It is important to clearly define the level of detail of the analysis which leads to the identification of the different components. For each step, a schematic diagram or a detailed description shows the components to which the analysis refers. For instance, in the air-fed ozonation step, FMEA might be limited to the prefiltration unit and the desiccant unit as a whole, or it might take into consideration the valves, sensors, compressor, pre-compressor filter, cooler and pre-desiccant filter.

2.3.2. FMEA

For each component of the subsystems, the expected failure modes (i.e., malfunctioning, leakage, breakage, etc.) must be identified by the team of experts together with the corresponding causes, the existing corrective actions and the consequences. The causes will provide guidance on the likelihood of failure mode occurrence. The existing corrective actions will provide suggestions for the expected magnitude of failure mode consequences for the treatment train, final effluent quality, working staff and surrounding environment.

Failure modes, their causes, existing corrective actions, consequences and resulting hazards for the environment and human health must be arranged and compiled in a table (called an FMEA table), and grouped according to the compartment or equipment and then the subsystem to which they belong (Table S1 in the Supplementary Materials).

Following the code assignment described in Section 2.3.1, each failure mode is identified with a (consecutive) number (identifier). For instance, the first failure mode listed for the aerobic tank will be coded as T7₂_1.

By means of the FMEA, Table S1 will be developed and will allow a qualitative analysis of all the failure modes and their consequences for the defined treatment train.

As the methodology under development aims to compare the risk associated with each failure mode and to identify the most critical risks, a (semi)quantitative analysis follows this phase.

2.3.3. Risk Estimation

The risk estimation is based on the RPN approach. This requires a quantification of L, M and D. Due to the lack of data in the literature regarding the likelihood of occurrence,

the magnitude of the consequences and the ease of detection, it was decided to estimate (measure) them through scores assigned on the basis of the experts' opinion as suggested by Rausand and Høyland [24]. In order to facilitate the effective integration of the collected opinions, different techniques are available including the Delphi method, Nominal Group Technique and Expert Panels as described in [25].

The scores vary in the ranges specific for each item (Tables 2–4). The assumed values and the corresponding descriptions were established by taking into consideration different sources [7,10,12,18,26]. In particular, the variability ranges and the scores selected for the magnitude differ from those selected for the other two items as the developed methodology aims to give more weight to the consequences, according to the approach outlined in [12].

Table 2. Score definition for the likelihood of occurrence L of a failure mode.

Score S_L	Descriptor	Description
1	Very unlikely/rare	It has not happened in the past and it is highly unlikely it will happen in the next 12 months.
2	Unlikely	It has not happened in the past and it may occur in exceptional circumstances in the next 12 months.
3	Possible	It may have happened in the past and it may occur under regular circumstances in the next 12 months.
4	Likely	It has been observed in the past and/or it is likely to occur in the next 12 months.
5	Almost certain	It has often been observed in the past and/or it is expected to occur in the next 12 months.

Table 3. Score definition for the magnitude of the consequences M of a failure.

Score S_M	Descriptor	Description
1	Insignificant	An insignificant or undetectable impact on the treatment train, and/or on the final effluent quality, which is suitable for reuse. No or negligible effects for workers' welfare (discomfort) and health, compared to the background levels.
2	Minor	Slight system damage. Slight effects on the quality of the final effluent which still remains suitable for reuse. Potential minor effects on welfare and health (for instance temporary symptoms of irritation).
4	Moderate	Moderate damage to the system. Moderate effects on the final effluent, which is not always suitable for reuse. Potential self-limiting health effects (upper respiratory tract infection, minor trauma).
8	Major	Relevant damage to the system. Relevant effects on the final effluent, which frequently becomes unsuitable for reuse. Potential illnesses or injuries may affect the workers.
16	Catastrophic	Severely damaged and compromised system. Severe effects on the quality of the final effluent, which is unsuitable for reuse. Potential serious illness or injuries and even death.

According to these definitions, it is possible to assign a score to the three items in each failure mode, and the FMEA table (Table S1) becomes the FMECA table (Table S2).

That being said, it is now possible to measure the risk for each failure mode by means of an RPN (Equation (2)). Based on the assumed scores for the three items, the RPN may vary between 1 and 400. There are 250 possible combinations for the three scores associated

with each failure mode (S_L , S_M , S_D) (Table S3), resulting in 38 different values for the RPN (Table S4).

Table 4. Score definition for the ease of detection D of a failure mode.

Score S_D	Descriptor	Description
1	Almost certain	Current controls will almost always detect the failure. Reliable detection controls are known and used in similar processes.
2	Likely	Current controls will detect the failure with a good likelihood.
3	Possible	Current controls will detect the failure with a modest/low likelihood.
4	Unlikely	Current controls will detect the failure with a very slight likelihood.
5	Very unlikely/rare	No known controls are available to detect the failure.

2.3.4. Risk Levels, Ranking and Criticality Analysis

It was decided to set four risk levels, as in [12]—low, medium, high and very high risks (Table 5)—through the identification of three thresholds carried out by analyzing the distribution of the whole list of RPN values (see Table S3) and giving more relevance to the magnitude score. It was assumed that:

- A failure mode with a rare likelihood of occurrence ($S_L = 1$), ease of detection ($S_D = 1$) but with catastrophic consequences ($S_M = 16$) corresponds to the first threshold (RPN = 16), separating the low risk level from the medium risk level;
- A failure mode with a rare likelihood of occurrence ($S_L = 1$), a possible ease of detection ($S_D = 3$) and catastrophic consequences ($S_M = 16$), or a possible likelihood of occurrence ($S_L = 3$), ease of detection ($S_D = 1$) and catastrophic consequences, corresponds to the second threshold (RPN = 48), separating the medium risk level from the high risk level;
- A failure mode with $S_L = 3$ and $S_D = 3$ and $S_M = 16$ corresponds to the third threshold (RPN = 144), separating the high risk level from the very high risk level.

At the same time, an analysis of the RPN value distribution shows that these thresholds correspond to the 30th, 54th and 90th percentiles considering the list of the 38 possible RPN values (Table S4) and the 30th, 60th and 90th percentiles considering the whole list of 250 combinations of the three items (Table S3).

The most critical failure modes are those with an $RPN \geq 144$ or, more generally, those with the highest RPN values. They are easily identified by ranking the whole list reported in the FMECA table (Table S2) according to the descending RPN values of the failure modes. In the case of more failures with the same RPN, those with the highest magnitude scores must be addressed first, then those with higher detection scores [18].

The last phase consists of the review of the existing corrective actions designed to face potential failures. In order to reduce the risk (the highest RPN), it could be necessary to suggest additional corrective actions that are able to improve the ease of detection, reduce the likelihood of the occurrence, or mitigate the effects on the system, the final effluent quality, the environment and human health. The goal is to reduce the risk to the lowest (possible/sustainable) level.

Table 5. Risk levels and their definition.

RPN Threshold	Risk Level	Descriptor
RPN < 16	Low risk	The existing risk management is sufficient to handle any reported risk scenario. No action is needed, in particular for: RPN = 15 corresponding to negligible consequences for the system, the final effluent quality, and human health and discomfort; a possible (or almost certain) likelihood of occurrence of the failure; and very unlikely detection (or possible). RPN = 12 corresponding to moderate consequences for the system, human health and discomfort with a possible (or very unlikely) likelihood of occurrence and almost certain (or possible) detection.
$16 \leq \text{RPN} < 48$	Medium risk	The existing risk management might be reviewed. Attention must be paid to the risk scenarios characterized by catastrophic, major and moderate consequences for the system, the final effluent quality and human health, and actions are necessary to mitigate them. Other actions might be added for those scenarios with minor consequences but with certain (likely) occurrence and unlikely (very unlikely) detection.
$48 \leq \text{RPN} < 144$	High risk	The existing risk management requires revision. If the consequences are major or catastrophic for the system, the final effluent quality and the environment and human health, actions are requested to mitigate them. In the other cases, actions are required in order to reduce the likelihood of occurrence of a failure or increase its detectability.
$144 \leq \text{RPN} \leq 400$	Very high risk	The existing risk management is not adequate and immediate additional actions are required to reduce the risks resulting in relevant system damage, deterioration of the final effluent quality, and inadequateness for the expected destination; injuries, acute and/or chronic illness or loss of life for the workers; and risks for the release of contaminants into the environment.

3. Results

3.1. The Treatment Train Under Study

The described methodology was applied to a real urban WWTP in a flat area of Italy, fed by a gravity-drained combined sewer that collects the wastewater of a catchment area of 120,000 person equivalent (300 L/s on average) and its effluent should be reused for irrigation needs. The WWTP is represented in Figure 2 and consists of coarse screening (5 cm space between the rods, automatic cleaning); a pumping station (equipped with four identical pumps running in rotation and on demand); a fine screening unit (25 mm space between the rods, automatic cleaning); an aerated grit and fat/oil/grease (FOG) removal unit (two circular aerated tanks equipped with an airlift for the withdrawal of the collected sand, sand washing and grease skimmer); and a primary sedimentation unit (four circular tanks, 20 m diameter each). The treatment then includes a biological stage consisting of a conventional activated sludge system divided into two identical lines, each including denitrification and nitrification compartments, followed by four secondary settlers ($V = 5400 \text{ m}^3$). The denitrification compartment has a total volume of 4000 m^3 and is equipped with four submerged mixers. In the nitrification, which has a volume of 6100 m^3 , air is supplied by a timer-controlled blower and eight submerged aerators, and the oxygen concentration in the tank is kept at 2 mg/L. Phosphorus is removed by coprecipitation in the biological step. The biological unit operates at a low-to-medium load, at an average hydraulic retention time of 9 h, a sludge age of around 10 d and a mixed liquor concentration of approximately 3.5 kg/m^3 .

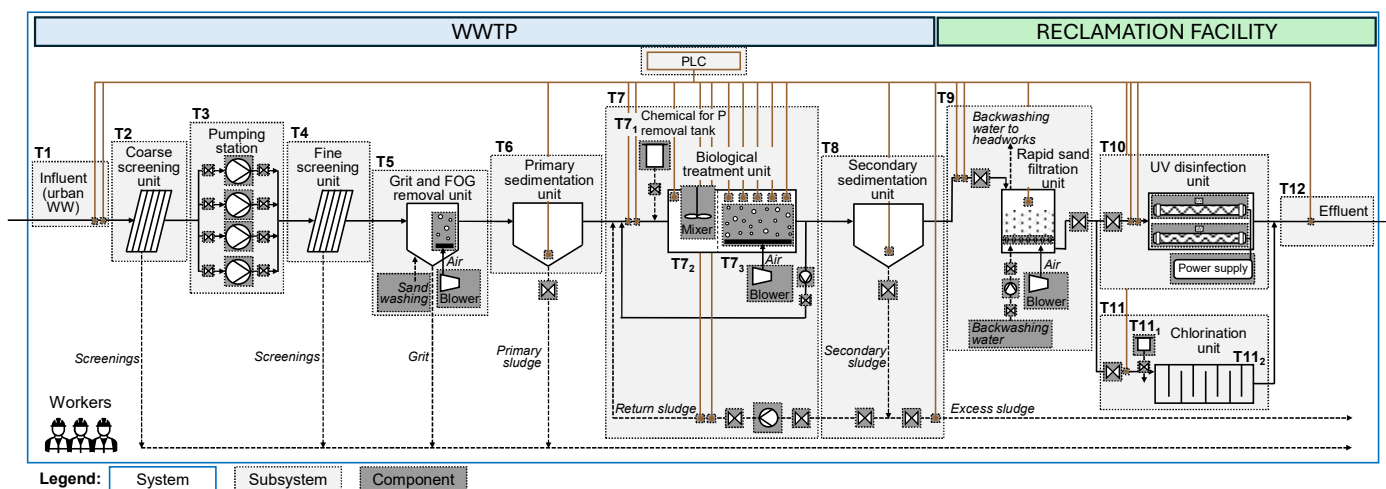


Figure 2. Schematic diagram of the WWTP under study with the different units and the corresponding code T#. Regarding the PLC, only the main components are reported; the full list is included in the risk assessment (Table S5).

The treatment then includes a reclamation facility. It consists of a gravity rapid sand filter (three 1 m deep filters operating at a filtration rate of 7 m/h at the average flow rate of 300 L/s, with water backwashing and auxiliary air scouring every 12 h) and a UV disinfection reactor (100 mW s/cm²) that requires a turbidity < 10 NTU and a transmittance > 55% in the influent in order to meet the reuse water quality standards (set by the Italian legislation [27] in force). The plant also includes an emergency disinfection unit achieved by the addition of 8–10 mg/L of NaClO (stored in a tank as a solution at 14% of available chlorine). The filtered effluent is directed to the chlorine contact basin only when the UV unit is out of order.

Many probes and sensors are present along the treatment train (brown lines in Figure 2) in order to monitor the representative variables of the processes. They are connected to the Programmable Logic Controller (PLC), which controls the operations and allows the main process variables to be regulated remotely according to the design intents.

According to Table 2 of Annex I, Section II of the EU 2020/741 [3], the treatment train in Figure 1 is considered the indicative technology for Class A (unrestricted use of the reclaimed water, any irrigation method) and it is frequently adopted for the reuse of reclaimed water [19,28,29].

3.2. FMEA and Risk Estimation for the WWTP Under Study

Table S5 reports the results of the FMEA for the WWTP under study. The system is composed of 13 subsystems (first column in Table S5): influent (T1); coarse screening (T2); pumping station (T3); fine screening (T4); gritting and FOG removal (T5); primary sedimentation (T6); biological treatment (T7) (with its three compartments: phosphorus co-precipitation T7₁, denitrification T7₂, nitrification T7₃); secondary sedimentation (T8); rapid sand filtration (T9); UV disinfection (T10); chlorination for emergency situations (T11, with the distinction between the equipment chemical tank T11₁ and the compartment chlorine contact basin T11₂); the effluent (T12); and the final subsystem including miscellaneous issues related to the whole system (T13).

Regarding the influent (T1), it may cause many potential deviations to the system's processes and must be accurately and regularly monitored and analyzed. As for the effluent (T12), the FMEA refers to the failures occurring in the sensors that monitor its quality. As for the whole system (T13), the list contains failure modes common to many components in

the system (for instance, pipes conveying wastewater under treatment, PLC, or temporary shutdown of the plant).

Eighty-six components were identified with 303 potential failure modes listed for the whole system. As shown in Figure 3, below the X-axis, it emerges that the bioreactor (T7) accounts for 90 failures, followed by rapid sand filtration (T9, 51 failures), UV (T10, 28) and chlorination (T11, 27). The subsystems with the lowest numbers of failure modes are the effluent (T12) with 3 modes, and coarse (T2) and fine screening (T4) with 6 modes each.

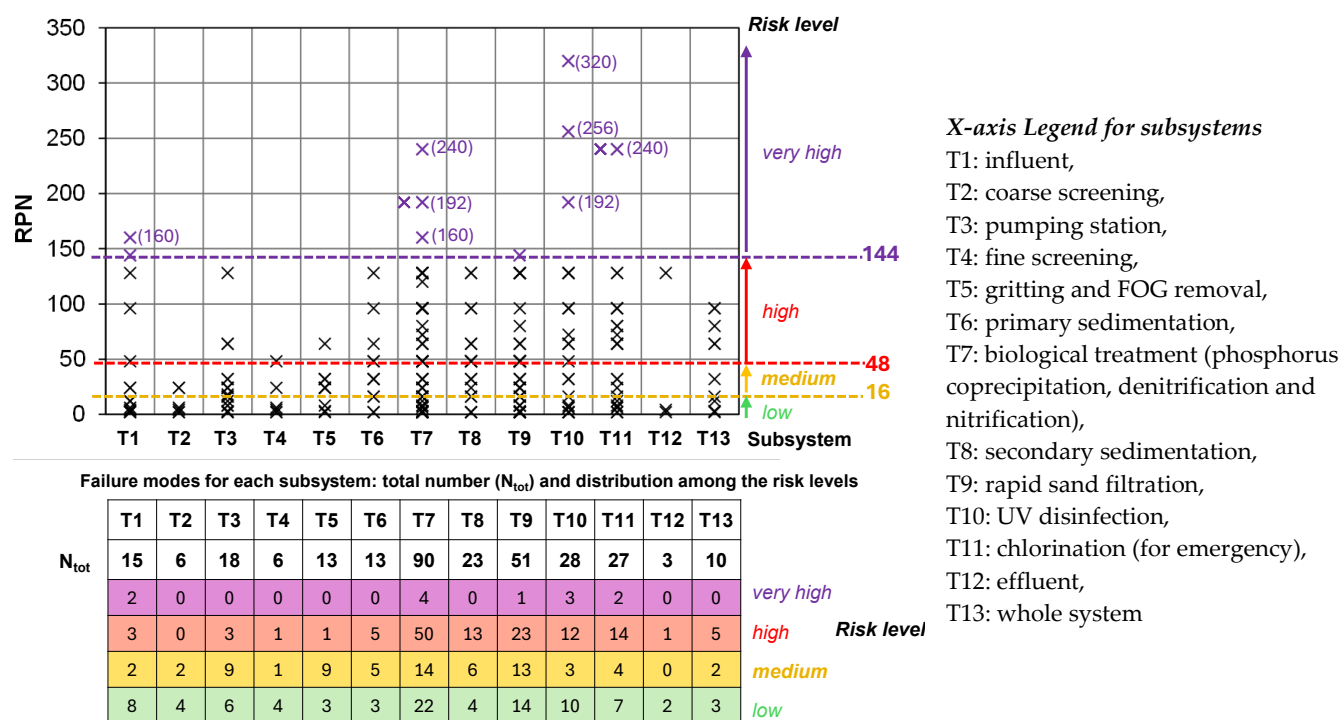


Figure 3. RPN values identified for the thirteen subsystems (T1–T13) and in brackets, near the symbol x, the RPN values for the hazardous events with very high risk (graph); legend for the subsystem reported on X-axis (right side); summary of the total number of failure modes per subsystem and distribution among the 4 risk levels (colored rows in the table below the X-axis); and description of the failure modes exhibiting a very high risk ($RPN \geq 144$) grouped according to the subsystem (below the table).

The consequences were identified, bearing in mind the existing corrective actions (see Table S5). Most of the failure modes refer to the bad performance (lower/insufficient removal of macro- or micropollutants) of the specific treatment (subsystem) where the failure occurs. It is also possible that the failure affects the final effluent quality or involves waste chemicals or energy, leading to economic losses. The listed failures affecting working staff (9 out of 303) are due to losses of chlorine-based disinfectant (T11, chlorination), flooding in the equipment room and the overheating of mechanical equipment (T3 pumping station, T7 biological treatment, T9 rapid sand filtration and T13 the whole system). Those

affecting the environment are due to losses of wastewater, backwashing water, sludge and disinfectant due to leakage/breakage of pipes or valves (T3, T6, T7, T8, T9, T11 and T13).

For each failure mode, the expected microbiological, chemical and physical hazards are identified with regard to the environment and human health (see Table S5).

Table S5 also reports the results of the FMECA, which are the scores assigned to L, D and M for each failure mode and the resulting RPN values (Equation (2)). The scores were assigned according to the definitions (Tables 1–3), by interviewing different experts and using the Delphi method [30] to reach a consensus. This is an iterative process based on successive rounds of questioning and feedback. It first collects the opinions of the experts through individual interviews and then allows them to re-evaluate their initial responses in light of insights from their peers, with the aim of converging on shared results [25,31].

The Delphi panel in this study consisted of two WWTP staff members, a design engineer, and a treatment equipment supplier. The experts first assigned scores to L, D, and M independently. Regarding the failure modes of valves, pumps, and pipes, historical data were available, and experts assigned the S_L values based on this information. The facilitators (the authors) then collected the responses and encouraged the participants to review their initial assessments in light of the other experts' evaluations or following clarifications. Reaching consensus required three rounds, with the most significant discrepancies occurring for the biological treatment, UV disinfection and chlorination units.

More specifically, discrepancies $\Delta_{i,j}$, for the i -th item and the j -th failure mode, among the scores assigned by the four experts, were evaluated by means of Equation (3):

$$\Delta_{i,j} = \begin{cases} \max S_{i,j} - \min S_{i,j} & i = L, D \\ \max \log_2 S_{i,j} - \min \log_2 S_{i,j} & i = M \end{cases} \quad j = 1, 2, 3, \dots 303 \text{ failure modes} \quad (3)$$

The percentages of failure modes exhibiting $\Delta \geq 3$ at the end of the three Delphi rounds are reported in Table 6.

Table 6. Percentages of failure modes for which discrepancies $\Delta \geq 3$ for the three items in the Delphi rounds.

Round	L, %	D, %	M, %
1	12	9	23
2	5	3	8
3	0	0	0

Table S6 reports the distribution of the shared scores for the three items. It emerges that the most frequent values are 2 for S_L (164 failure modes) and S_D (92), and 16 for S_M (108). The maximum score for S_L occurs only in one case: the lamp fouling in T10, as it is unavoidable that the lamps get dirty, and automatic cleaning is not able to completely remove the built-up scaling. For S_D , the maximum value was assigned to 11 failure modes, which concern the presence of unexpected recalcitrant substances in the influent (T1), different (concentrations of) supplied chemicals (T7_1; T11), the nozzle clogging in T9 and errors in PLC/sensors (T13).

Regarding the consequences, the maximum score was assigned to 108 out of 303 failure modes, as at any step of the treatment, all the failures leading to a worsening of the final effluent quality were considered critical in the context of the sanitation safety plan/RMP (according to Table 2, this corresponds to catastrophic effects). The maximum score was also assigned in the case of serious effects for the environment and human health. According to EU 2024/1765 [4], the protection of human health and the environment can be achieved via a multi-barrier approach, including treatment or non-

treatment measures applied before or after the point of compliance (where treated water is delivered to the next user). Typical barriers include drip or surface irrigation, suspended irrigation before harvest, post-harvest washing and peeling, and forage drying [8]. Where such barriers exist downstream of the reclamation facility, S_M for failures degrading effluent quality could be below 16. For precautionary reasons, this study adopts the maximum score.

A score equal to 8 was assigned when the failure modes lead to economic losses and a score of 1 when electrical interruptions occur, but the presence of an internal generator immediately copes with the undesired situation and guarantees the proper (and continuous) working of the affected components.

The resulting RPN values vary between 2 and 320 and their ascending order distribution is shown in Figure S1. It emerges that most of the failures fall into the high risk area (131 failure modes, corresponding to 43% of the total), followed by low risk (90, corresponding to 30%), medium risk (70, corresponding to 23%) and very high risk (12, corresponding to 4%).

Figure 3 reports RPN distribution with regard to the thirteen different subsystems (T1–T13). The dotted colored lines define the risk levels and the numbers in brackets report the RPN values for the failure modes exhibiting a very high risk ($RPN \geq 144$). As some failures of the same subsystem may exhibit the same RPN, some crosses may overlap (see Table S5 for the details), except failures whose RPN is ≥ 144 : this is the case for T7 with an RPN equal to 192, and T11 with an RPN equal to 240 (two crosses are present in Figure 2 for each RPN value).

As regards failure modes with a low risk, RPN values of 2, 3, 4, 6, 8, and 12 were identified, with 2 being the most frequent (52 out of 90 cases, corresponding to 58%). The RPN value of 2 was caused by electricity interruption ($S_L = 2$, $S_M = 1$, and $S_D = 1$). However, the presence of an existing and promptly implemented corrective action (i.e., a backup generator) ensures proper and continuous operation. Regarding failure modes with a medium risk, RPN values of 16, 18, 24, and 32 were found. The most frequent was 24 (27 out of 70, 39%), followed by 32 (24 out of 70, 34%). As for high-risk failure modes, RPN values of 48, 64, 72, 80, 96, 120, and 128 were recorded. The most frequent value was 48 (35 out of 131 cases, 27%), followed by 128 (32 out of 131 cases, 24%) and 96 (31 out of 131 cases, 24%).

Attention is now paid to failures with a very high risk listed below the graph in Figure 2, summarized in Table 6. The numbers in brackets correspond to their RPN values. The result is that they are 4 for T7 (biological reactor), 3 for T10 (UV), 2 for T11 (emergency chlorination) as well as T1 (influent) and 1 for T9 (rapid sand filtration). The highest value of RPN is 320; it refers to UV (T10) and is due to lamp fouling. The resulting hazards to the environment and human health are microbiological (failures associated with T1, T9, T10, and T11) and chemical (failures associated with T1 and T9). Failures at T7 (biological treatment) result in chemical hazards to the environment, such as increased concentrations of phosphorus and/or BOD, as indicated by the description of the consequences of the corresponding failure modes reported in Table S5.

3.3. Criticality Analysis and Risk Mitigation

The criticality analysis here refers to the twelve failure modes characterized by a very high risk level. They are listed in Table 7 with their details and the additional control actions identified to manage and reduce the risks to a level as low as is reasonable, as requested. The proposed actions may affect L, M, or D, as indicated by the item reported in brackets in the “Additional Corrective Actions” column in Table 7. The last four columns present the corresponding updated scores (highlighted in green) and the re-evaluated RPN values.

Table 7. Details of the failure modes with a very high risk together with the additional corrective actions suggested and the items (L, D, M, reported in brackets) the actions intend to reduce. In the first column, the components are shown in italics to better distinguish them from the subsystem to which they belong. “x” means that the failure mode will result in a hazard for the environment and/or the human health. The hazard can be microbiological (Micro), chemical (Chem) or physical (Phys). Cells in green highlight new score values as a result of the additional corrective actions.

Subsystem Component	Identifier Failure Mode	Causes	Existing Corrective Actions	Consequences	Hazard for Environment		Hazard for Human Health			S _L	S _D	S _M	RPN	Additional Corrective Actions (Affected Items)	Revised Scores			Re- Evaluated RPN
					Micro	Chem	Micro	Chem	Phys						S _L	S _D	S _M	
Influent <i>Flow rate</i>	T1_3 (Magnetic) Flow rate sensor malfunctioning	Air may be entered during maintenance operations; gases may be released during spontaneous degradation processes.	Alarms on the PLC. The control system can exclude the values provided by the instrument guaranteeing continuity of the feeding to the treatment train.	The measured flow rate value does not correspond to the real one and it is not possible to know the flow rate fed to the plant.	x	x	x	x		3	3	16	144	Consider adopting external flow meters to avoid the problems due to the presence of bubbles which may disturb internal (magnetic) flow meters. (D, M)	3	1	1	3
Rapid sand filtration <i>Filling material</i>	T9_51 Saturated filling material	Higher content than expected in the influent.	Scheduled backwashing can clean the filter.	The effluent does not meet the standards for release or reuse.	x	x	x	x		3	3	16	144	Consider immediately activating the backwashing operations. (L, M)	2	3	2	12
Influent <i>Chemical composition and load</i>	T1_11 Presence of new and recalcitrant substances (unexpected)	Unauthorized discharges in the sewer network, urban runoff, major industrial accidents leading to a release.	Multiparametric sensors may alert in the case of unexpected values (of the surrogates).	The effects are strongly related to the substances and their ecotoxicological characteristics.	x	x	x	x		2	5	16	160	Consider monitoring the sewer network by means of very sensitive sensors, in particular downstream to the release of industrial effluents. (D)	2	1	16	32
Biological treatment (P coprecipitation compartment) <i>Chemical tank (alum or iron salts)</i>	T7_8 Different chemical	Different supplier, human error.	Accurate control with the supplier and at the delivery.	Insufficient removal of phosphate, final effluent not meeting the legal limits.		x				2	5	16	160	Consider adding intermediate control on the P concentration during the treatment (D) and, if necessary, to complete the P removal in the rapid sand filtration step by the addition of the appropriate chemical (M).	2	3	1	6
Biological treatment (P coprecipitation compartment) <i>Electrovalve for chemical dosage regulation (orthophosphate precipitation)</i>	T7_14 Lower dosage of chemical	Non-calibrated valve, human error.	Remote control of the tank containing the chemical.	Phosphorus concentration in the effluent exceeds the legal limits.		x				3	4	16	192	Consider guaranteeing a timely maintenance (of the valve) (L), to add intermediate control on the P concentration during the treatment (D) and to complete the P removal in the rapid sand filtration step by the addition of the appropriate chemical (M).	2	2	1	4

Table 7. Cont.

Subsystem Component	Identifier Failure Mode	Causes	Existing Corrective Actions	Consequences	Hazard for Environment		Hazard for Human Health			S _L	S _D	S _M	RPN	Additional Corrective Actions (Affected Items)	Revised Scores			Re- Evaluated RPN
					Micro	Chem	Micro	Chem	Phys						S _L	S _D	S _M	
Biological treatment (nitrification compartment) <i>Air diffusers</i>	T7 _{3_22} Clogging of the air outlet nozzles	Settled materials on the nozzles.	Periodic maintenance.	Reduced air quantity supplied, lower oxidation rate.		x				3	4	16	192	Consider cleaning the diffuser system with alkaline solutions or formic acid (L). Consider regularly monitoring the oxygen concentration in the tank and adjusting the supplied air (L), if necessary, to maintain the desired dissolved oxygen concentration (M).	2	4	2	16
UV disinfection <i>Automatic mechanical cleaning system</i>	T10_24 Cleaning system malfunctioning	Dirty collars unable to remove deposits on the lamp surface.	Periodic maintenance.	Lower UV irradiation, lower disinfection efficiency.	x		x			3	4	16	192	Consider sending the filtered effluent to the chlorination unit, bypassing the UV unit (M). Consider chemically cleaning the lamps immediately (L).	1	4	1	4
Biological treatment (P coprecipitation compartment) <i>Chemical tank (alum or iron salts)</i>	T7 _{1_10} Different concentration of chemicals in the supplied solution	Different supplier, human error.	Accurate control with the supplier and at the delivery.	Insufficient removal of phosphate, final effluent not meeting the legal limits.		x				3	5	16	240	Consider adding intermediate control on the P concentration during the treatment (D) and, if necessary, to complete the P removal in the rapid sand filtration step by the addition of the appropriate chemical (M).	3	3	1	9
Chlorination <i>Chemical tank (disinfectant, NaClO)</i>	T11_3 Different concentration of chemicals in the supplied solution	Different supplier, human error.	Accurate control with the supplier and at the delivery.	Failure to provide the requested dosage/dose of disinfectant. Insufficient disinfection, final effluent not complying with the legal limits.	x		x			3	5	16	240	Consider controlling the supplied solution before using (L) and adjusting the dosage, if necessary (M). Consider adopting a fast E. coli detection test (D).	1	3	4	12
Chlorination <i>Chemical tank (disinfectant, NaClO)</i>	T11_4 Different concentration of chemicals in the supplied solution	Different supplier, human error.	Accurate control with the supplier and at the delivery.	Failure to provide the requested dosage/dose of disinfectant. Excess (waste) chemical added. Higher costs. Potential formation of disinfection byproducts.	x		x			3	5	16	240	Consider controlling the supplied solution before using (L) and adjusting the dosage, if necessary (M). Consider adopting a fast E. coli detection test (D).	1	3	4	12

Table 7. Cont.

Subsystem Component	Identifier Failure Mode	Causes	Existing Corrective Actions	Consequences	Hazard for Environment		Hazard for Human Health			S _L	S _D	S _M	RPN	Additional Corrective Actions (Affected Items)	Revised Scores			Re- Evaluated RPN
					Micro	Chem	Micro	Chem	Phys						S _L	S _D	S _M	
UV disinfection Lamps	T10_18 Reduction in the lamp intensity	Lamp aging.	Periodic maintenance.	Lower disinfection efficiency.	x		x			4	4	16	256	Consider increasing the control of the lamp intensity (L) and being ready with a timely replacement of the old lamp with a stand-by UV lamp/modules available at the WWTP (M). Consider activating the emergency chlorine-based disinfection (M). Consider intensifying the chemical cleaning (L). Consider activating the emergency chlorine-based disinfection (M).	2	4	1	8
UV disinfection Lamps	T10_17 Reduction in the lamp intensity	Lamp fouling.	Periodic maintenance.	Lower disinfection efficiency.	x		x			5	4	16	320	Consider intensifying the chemical cleaning (L). Consider activating the emergency chlorine-based disinfection (M).	1	4	1	4

It emerges that in nine cases, the additional control actions aim at reducing the likelihood of occurrence by increasing the frequency of maintenance and/or carrying out accurate controls on the supplied chemicals. In seven cases, they allow the improvement of the ease of detection of the failures and suggest adopting new or more accurate monitoring systems along the treatment train. Finally, in 12 cases, additional corrective actions reduce the magnitude of the consequences and thus the final effluent quality fulfills the legal requirements. In particular, in 10 situations, they involve changes in operation (mainly the addition of appropriate chemicals in the following step to complete the removal of the specific contaminants or the activation of the emergency chlorine-based disinfection) and in two situations they involve the improvement of the ease of detection (T1_3) or the reduction in the occurrence of the failure (T9_51) (indirect effect).

The implementation of certain suggested additional measures is straightforward (e.g., reviewing the maintenance plan and scheduling more frequent inspections), whereas others require a longer timeframe (e.g., planning and implementing prompt and appropriate changes to operating conditions) and may also entail higher costs (e.g., the replacement or installation of more robust instrumentation; upgrading the remote control system through the addition of alarm systems and highly sensitive pollutant detection sensors).

A multi-barrier treatment system makes it possible to mitigate the consequences of the occurrence of a failure mode on the final effluent quality by exploiting the removal capacity of the treatment steps that come after where the failure occurred. This is the case of the removal of P compounds if something goes wrong in the dedicated step (T7₁) as their removal might be completed in the rapid sand filtration. This is a reliable strategy and can significantly reduce the risk. However, it is important to underline that disinfection is achieved only in the last step and for this reason this process must be carefully monitored, remotely controlled and frequently maintained, and an emergency disinfection system (chlorination in this study) should be available to face any critical situations that may arise.

On the basis of the suggested additional corrective actions, the scores have been reassigned and the RPN re-evaluated (last column in Table 7). All the final 12 RPN values are significantly reduced, with nine in the low risk area and two in the medium area (RPN = 16 and 32). In the case of the presence of unexpected recalcitrant compounds in the influent that are not removed during the treatment (T1_11), for the sake of prudence, it was preferred to maintain a very high S_M as the WWTP could not have the proper treatment to remove the (micro)pollutant load resulting from unauthorized release/accidents in the catchment area. Regarding the clogging of the air nozzles in the nitrification tank, leading to a lower oxidation rate of organic compounds in the bioreactor (T7_{3_22}), it is still quite difficult to improve the ease of detection as they cannot be inspected.

The attention here is paid to the failure modes with the highest risk, but it should be extended to the failure modes with medium and high risks (RPN ≥ 16).

4. Discussion

4.1. Risk Measure

Referring to the treatment system (WWTP + reclamation facility) under study and the listed failure modes in Table S5, a comparison is carried out between the results achieved by the outlined methodology (risk measured by the RPN and classified according to the levels in Table 5) and the risk R defined as the product of L and M , and classified with the following four levels according to the thresholds set by the WHO in [12]: $R < 6$ low risk; $6 \leq R \leq 12$ medium risk; $12 < R \leq 32$ high risk; $R > 32$ very high risk.

Figure 4 reports the R and RPN values for the different subsystems with the proposed levels. Thresholds proposed by [12] correspond to the 30th, 50th and 75th percentiles considering the list of the 17 possible R values and to the 33rd, 55th and 80th percentiles

considering the whole list of the 25 combinations of the items (L and M), which are slightly different from those proposed in this study (see Section 2.3.4).

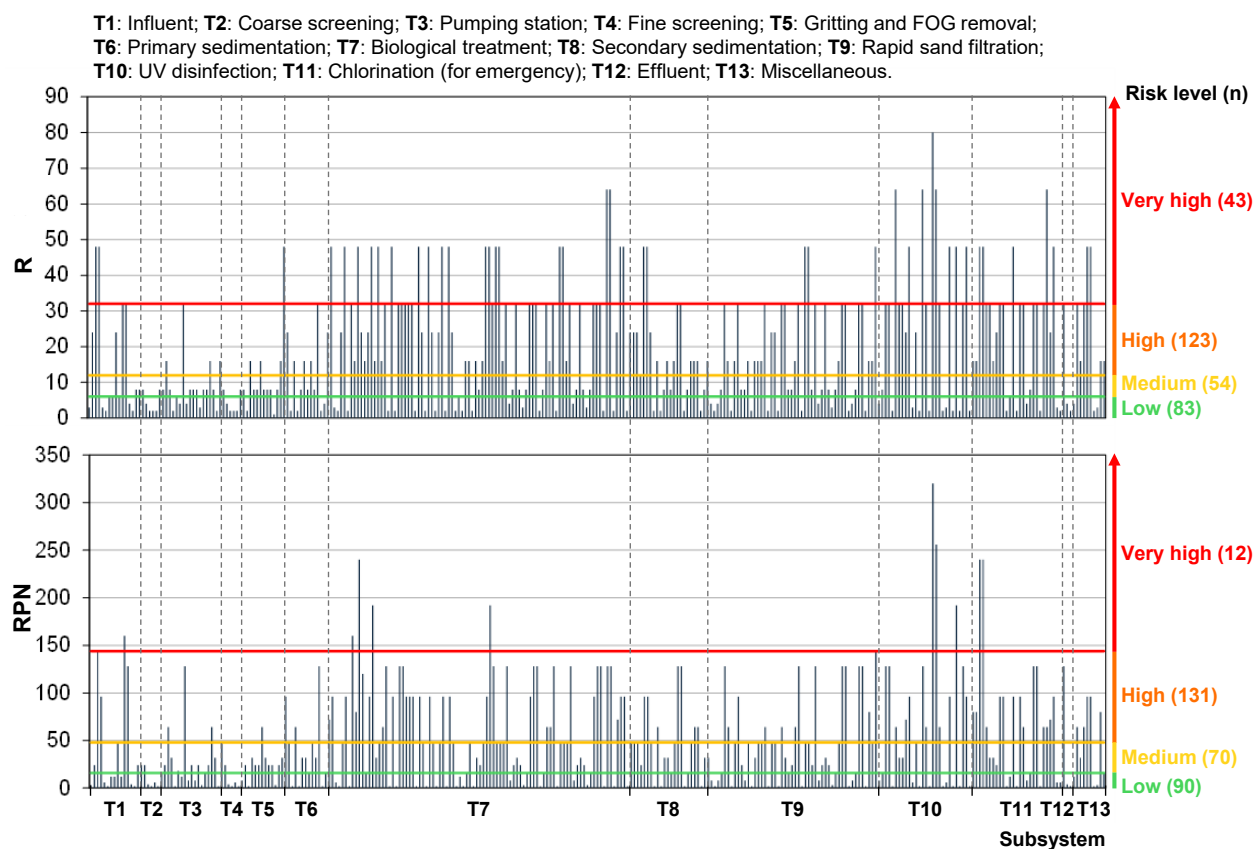


Figure 4. Comparison of the risk evaluation using the R ($L \times M$) and RPN ($L \times M \times D$) approaches for the different components identified within the 13 subsystems listed at the top of the figure. Numbers in brackets for the different risk levels indicate the number of failure modes falling within the corresponding risk level under the two approaches.

It emerges that the number of failure modes with a very high risk reduces from 43 cases (R approach) to 12 (RPN approach). This can be explained by the fact that item D (ease of detection) strongly influences the evaluation of the risk level as, once a failure mode occurs, if it is rapidly detected (low values for the score S_D), the existing corrective actions may immediately activate and try to lead the system to normal working conditions.

In the case of $S_D = 5$, there is no known control to detect the failure, and the associated risk may be higher according to the RPN approach rather than the R approach. This happens for the failure modes T1_11 (Presence of new and recalcitrant substances (unexpected) in the influent) and T7_1_8 (Different chemical for P coprecipitation in the bioreactor) which rise from high risk to very high risk (Table S5).

4.2. Score Values and Uncertainties in Their Assignment

The methodology presented here assumes the same range and a uniform distribution of values for L and D (Tables 1 and 3), whereas a wider range with non-consecutive values is adopted for M (Table 2). This choice reflects the intention to assign greater relevance to the magnitude of the consequences, while simultaneously improving the accuracy and precision of the risk-ranking quantification.

In previous studies on the risk assessment of WWTPs, the three parameters generally range from 1 to 5, as in [26,32,33], or from 1 to 10, as in [34,35]. In these studies, the scores are typically expressed as consecutive integers. Much wider ranges are generally

not recommended, as they are difficult to interpret and may hinder the assignment of appropriate values [18].

In some cases, non-uniform distributions (i.e., non-consecutive scores) have been preferred [36], whereas in others the use of consecutive values has been recommended [37]. If different variability intervals and (discrete) values within those ranges are assumed for the scores of the three items, different RPN values will result, and the risk thresholds will change accordingly (see Section 2.3.4). If a wider score range is assigned to one item, that item will carry greater weight in the corresponding RPN value.

Some authors have proposed weighting the three parameters using fuzzy-based multi-criteria decision-making methods [38]. Finally, other studies suggest incorporating additional factors into the risk measure, such as linking the occurrence of a failure mode to its causes or accounting for economic aspects associated with failures [37]. In this context, a meaningful revision of the index could involve the inclusion of a factor representing the economic losses arising from a failure.

The scores reported in Table S5 are based on expert judgments. This approach, common in this kind of analysis [36,39] and suggested by the European, Australian and WHO guidelines [6,7,12], is affected by uncertainties mainly related to data gaps, experts' know-how, methods adopted to aggregate the different opinions, and the complexity of the system under study. Uncertainties are analyzed in detail in [25], and in [37] they are addressed by an analytical hierarchy process combined with an entropy technique.

5. Conclusions

The study at hand aims to be an example of an FMECA applied to a WWTP (including a reclamation facility) whose effluent is intended for (agricultural) reuse. Despite the identified components being plant-specific and the listed failures depending on their characteristics, it represents the baseline for a semiquantitative analysis of the reliability of a wastewater treatment train.

This study fits in the context of the RMP, which encompasses many elements from the source (influent and its catchment area) to the final destination (irrigation field) [5,7]. It allows the hazardous events to be identified (related to the production of reclaimed water intended for reuse) which can cause the exposure of people or the environment to a hazard (a pathogen or a macro- or micropollutant). The development of an RMP in a specific study case can be based on the application of the FMECA approach to the WWTP, the reclamation facility as well as the reclaimed water distribution and storage system, in order to find the corresponding hazardous events and related risks. Bearing in mind the list of hazards characterizing the study case and their correlation with the identified hazardous events, the following steps consist of the environmental and human health risk assessment referring to them [4] and preventive measures and further barriers (according to [8]) in planning to reduce or mitigate the assessed risks.

This analysis provides a template for Class A technology; however, for its appropriate application, the failure modes and corresponding scores need to be tailored to the specific characteristics of each plant. The same methodology may be extended to different treatment technologies, resulting in a different list of failure modes. In addition, it can be useful not only for the reliability assessment of treatment plants, to guarantee the adequateness of the final effluent for its final destination, but also for designing a new treatment train (design FMECA), in a process evaluation related to under-developed technologies (process FMECA). It can also be used in the case of a new technology under development in order to find changes or improvements during its Technology Readiness Level (TRL) scaling up (re-engineering FMECA) and in the control system design of an existing WWTP (control FMECA).

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18050627/s1>, Table S1: FMEA table format; Table S2: FMECA table format; Table S3: RPN values and the corresponding scores for L, M, D ($RPN = SL \times SM \times SD$); Table S4: The values RPN may assume according to the defined scores of the three items, defined in Tables 1–3 of the main text; Table S5: FMECA table with all details for each failure mode (Excel file); Table S6: Distribution of the scores for the three items L, D and M; Figure S1: Distribution of the RPN values in ascending order.

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