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Risk Assessment of Domestic Wastewater Treatment System Based on Constructed Wetlands

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Abstract: Risk assessment methods vary and have been applied to areas such as environmental, technological, and occupational safety, adapting to the complexities of the subjects under study. The objective of this work is to conduct a risk analysis of a domestic wastewater treatment system based on constructed wetlands (CW) and to evaluate actions to reduce the operational risk of the studied installation. The approach used is the three-dimensional risk matrix, which is a simplified version of the probabilistic risk evaluation method, making it more accessible and allowing for broader application. To apply the risk matrix method to a wastewater system based on CW, it was necessary to modify a risk model. This modification involved creating a process map and identifying accidental scenarios or sequences within each stage, including their initiating events, defenses, and consequences. The results enabled the identification of the most critical initiating events and defenses. Notably, human factors emerged as the primary contributors to the risk associated with wetland operation. The findings from this study can be used to enhance wetland security, including the prioritization of controls for the most critical defenses identified in this research.

Keywords: constructed wetland; subsurface horizontal flow; risk assessment; three-dimensional risk matrix; defense

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Citation: Pérez, Y.; García-Cortes, D.; Torres-Valle, A.; Jáuregui-Haza, U. Risk Assessment of Domestic Wastewater Treatment System Based on Constructed Wetlands. *Sustainability* **2023**, *15*, 15850. https://doi.org/10.3390/su152215850

Academic Editor: Andrea G. Capodaglio

Received: 4 October 2023
Revised: 6 November 2023
Accepted: 7 November 2023
Published: 11 November 2023

1. Introduction

Risk analysis has become a crucial tool for optimizing hazardous processes in different fields [1]. Although its use has been mostly deployed in high-risk technologies, such as nuclear and petrochemicals (technological risk analysis), its use has been generalized to environmental and occupational safety studies [2,3].

Wastewater treatment systems themselves can pose a significant source of environmental pollution due to the concentration of waste generated from various sources. Therefore, the occurrence of technological or operational problems in this type of facility can generate the uncontrolled dumping of pollutants into the environment with serious consequences for the area of influence of the treatment plant. This 'area of influence' refers to the hydrographic basin downstream of the treatment plant's location. Examples of these situations include accidents at the Warsaw city wastewater treatment plant in 2019 and 2020, when approximately 3.6 and 4.8 million cubic meters of raw wastewater were, respectively, discharged into the Vistula River. Another instance occurred at the wastewater treatment plant in the city of Fort Lauderdale, Florida, USA, where close to 1 million cubic meters were spilled [4,5].

Domestic wastewater treatment systems based on constructed wetlands (CW) are considered a technological process that simulate natural systems, exhibiting high efficiency in the degradation of organic matter and industrial pollutants. The use of CW has been extended from domestic to industrial wastewater treatment systems [6–10]. The domestic installations based on CW basically consist of three stages: a hydraulic system for collecting used water, septic tanks in homes before the CW, and the CW itself [6]. There are different types of constructed wetlands but the most used are the subsurface horizontal flow wetlands [11]. Like any treatment system, these systems can experience technological and operational (human) failures. In these cases, environmental contaminations of different severities could be produced depending on the spatial extent of the pollutant dispersion and the duration of the discharge of the pollutants into the environment.

There are different methods for conducting risk assessments of technological facilities. Notably, these include, in ascending order of complexity, checklists, "What if?" studies, Preliminary Risk Analysis (PRA), Hazard and Operability Analysis (HAZOP), Failure Modes and Effects Analysis (FMEA), and Probabilistic Safety Analysis (PSA). Among all those mentioned, the most complete is the PSA; however, it is associated with complex modelling needs for accidental sequences (use of event trees and fault trees, as well as reliability databases, as well as other disciplines such as dependent failures and human errors) [12].

The Three-Dimensional Risk Matrix (TDRM) method brings about a significant simplification of the PSA, particularly in terms of reliability data needs and system modelling by fault trees. Additionally, it substantially reduces the need for specialized human resources and study development time. With its origin in the PSAs, the risk matrix developed has a three-dimensional procedure, which is far superior to its two-dimensional predecessor based only on the frequency of initiating event and their consequences. This enhancement empowers the new method with a possibility of deploying the effects of defense measures, which is essential for its application to decision-making. The methodology has found successful application in areas such as biosafety practices during haemodialysis, the use of cytostatics, vaccine production, and studies of pathogen infections in fish farming [13,14].

Some studies have explored risk analysis in conventional plants using the two-dimensional risk matrix method [2,3,15]. However, a standardized methodology for addressing risk analysis in CWs using the approach proposed by this research has yet to be established. Many authors acknowledge the potential of CWs as sources of disease vectors and sources of unpleasant odors [16], as well as the possibility of direct physical contact with the surface of the wetland by pets, reckless users, and even children, if adequate measures are not taken to prevent it, including the risk of bacterial contamination with treated wastewater in densely populated areas [17,18]. This mention of risks has been more the result of the observation of wetland exploitation problems than the application of a scientific and systematic method of analysis. These situations constitute the core consequences within the postulated risk model.

Davila et al. [19] refer to the risks of odors and contact with untreated water due to problems with the wetland. It should be noted that the cases of very high risks in the current state of the constructed wetland, as well as the high ones in the event that it is improved with the proposed measures, coincide with the situations described before [16–18], although in the scenarios proposed in the risk model, a more explicit description of risky situations has been considered.

In the bibliography on CWs, there are references to different types of hazards to human health, mainly in surface flow constructed wetlands and rarely in vertical flow constructed wetlands, when these are not properly designed, becoming a focus for disease vectors and the emission of unpleasant odors [16,17]. Constructed wetlands are capable of reducing the population of faecal bacteria used as indicators of pathogenic microorganisms by 2–4 orders of magnitude, but these levels are still higher than the limits required by environmental regulations for reuse [20,21].

The aim of this work was to perform a technological and operational risk assessment of a domestic wastewater treatment system based on a constructed wetland of subsurface horizontal flow. The Three-Dimensional Risk Matrix method was employed for this purpose, aiming to identify and propose necessary measures for risk management. The study also encompassed an evaluation of the efficacy of implemented defense measures in risk mitigation. In this work, the domestic wastewater treatment system "El Dorado", located in the municipality of Jarabacoa, La Vega province, Dominican Republic, was used as a case study.

2. Theoretical Foundation of the Method

In this study, the environmental damage or undesired consequence is considered to be the pollution caused to the environment. Accordingly, the following types of damage will be considered: the emission of unpleasant odors and the discharge of wastewater containing contaminants surpassing permissible limits for effluent discharge.

In this context, an undesired consequence is postulated to occur with the continuous emission of unpleasant odors over multiple consecutive days. In relation to the domestic wastewater discharge, two scenarios were examined: when the values of the parameters established in the standards for the discharge of effluents of wastewater treatment facilities in Dominican Republic (based on the analysis of effluent samples analysis) exceed the accepted limits or when there is an uncontrolled discharge of wastewater due to a failure in the system.

The estimation of the risk of damage occurrence is conducted in accordance with the principles of a three-dimensional risk matrix. The advantage of this variant is the ability to incorporate the effect of defense measures into the risk estimation. The parameters linked in this three-dimensional variant of the contamination risk matrix are as follows: the frequency of the initiating event (F), the probability of the barrier failing (Pb), and the severity of the consequences (C). Each parameter is defined using a qualitative scale, illustrated in Figure 1.

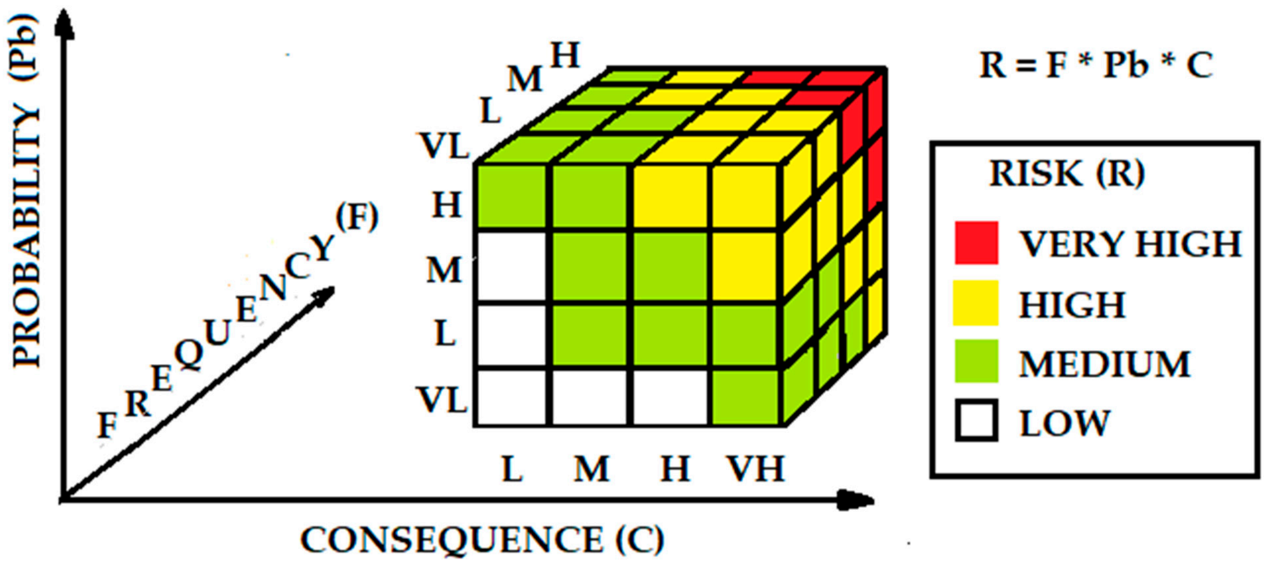


Figure 1. Diagram of the Three-Dimensional Risk Matrix. Probability and frequency (VH—Very high, H—high, M—medium, L—low, VL—very low).

Since the original TDRM was initially designed for radiological events and has later been adapted to other applications [13,22], it is necessary to modify it for risk assessment in domestic wastewater treatment systems based on constructed wetlands. In this context, while nearly all the approximations assumed in the original method's design were valid, it became necessary to distinguish between patterns in order to characterize frequencies and consequences. To apply the TDRM methodology, it is necessary to define the process map of the technology under study. The process map is a chronological representation of the different processes included in the technology. It should be noted that various sequences of events may occur in each process, influenced by natural events, technological failures, or human errors, which can result in undesirable consequences. These sequences of events are referred to as accidental sequences. Each accidental sequence is characterized by an initiating event, which serves as the trigger for the hazardous situation, and its defenses, which are the control measures established to prevent the progression toward unfavorable consequences [14]. Figure 2 schematically depicts an accidental sequence.

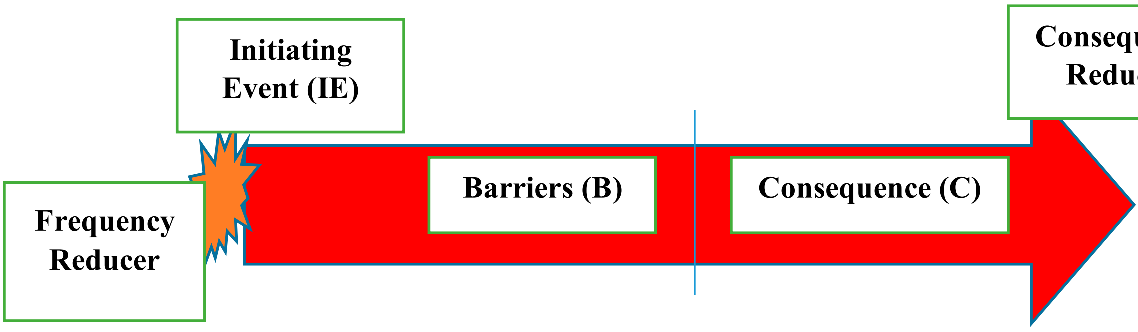


Figure 2. Accidental sequence in risk assessment.

An initiating event (IE) is any system failure, human error, or external/natural event that can lead to unintended consequences. To each initiating event is assigned a frequency of occurrence (F) and a consequence level (C), without considering the function of the barriers. Malfunctioning of the treatment system can result in damage either in the immediate vicinity of the wastewater treatment facility for a short or extended period or within the broader area affected by the installation, also for a short or long duration. The immediate area to the installation is defined as the space within the perimeter occupied by the entire domestic wastewater treatment system based on the CW, encompassing the area where the wastewater is generated. On the other hand, the "area of impact" refers to the basin where the domestic wastewater treatment system is situated, where contaminants from the residue might disperse if effective treatment does not occur or if there is a malfunction that leads to uncontrolled wastewater discharge. Considering the above, undesirable consequences are categorized into four levels, taking into account two factors: the duration of the impact and the severity of the damage (see Table 1).

Table 1. Classification of consequences for wastewater system based on constructed wetland.

Consequence Levels	Description
Very serious	There is a dispersion of contamination in the area of impact of the domestic wastewater treatment system, which contaminates surface or groundwater, soil, air (either individually or in combination), over an extended period. This contamination has the potential to harm human health or result in economic damage due to the unavailability of water supply sources for the population, agricultural, or industrial uses. Additionally, it can lead to undesirable odors, causing irritation and discomfort to those affected.
Serious	There is a dispersion of contamination in the area of impact of the domestic wastewater treatment system for a short period of time within that area or for an extended duration in the immediate vicinity of the system. This contamination eventually affects surface or groundwater, soil, or the air (either individually or in combination), resulting in moderate harm to people's health or limited economic damage due to temporary shutdown of water supply sources for the population, agricultural, or industrial use. Additionally, it may lead to tolerable unpleasant odors causing discomfort in those affected.
Moderate	There is contamination in the immediate vicinity of the domestic wastewater treatment system that does not affect surface or groundwater but does contaminate the soil or air within that area. This contamination does not result in harm to people's health or economic damage due to the unavailability of water supply sources for the population, agricultural, or industrial uses. However, there may be occasional or minor unpleasant odors that can cause discomfort for those affected.
Low	Slight contamination occurs in the immediate area of the treatment system with domestic wastewater, or it may not occur. In the latter case, there is a reduction in defense in depth, meaning that the facility's security has been compromised but this has not resulted in immediate consequences. It corresponds to failures in a security system that would not respond if its operation were necessary.

Frequency corresponds to the number of times that the initiating event is expected to occur within a specific period, regardless of whether the unintended consequences actually occur or whether the initiating event is detected and its consequences prevented. Four levels of initiating events will be considered: high (H), corresponding to more than one event per year; medium (M), when there are between one event per year and one event in five years; low (L), between an event every five years and an event every 20 years; and very low (VL), less than one event every 20 years.

On the other hand, defenses encompass all safety measures designed to avoid, prevent, detect, control, and mitigate the escalation of errors or failures in the process that could lead to accidents. Defenses are categorized into three types: barriers, which intervene once the initiating event has occurred to halt its progression; frequency reducers, which prevent the occurrence of the initiating event; and consequence reducers, which, once the consequences have occurred, can reduce their severity. The probability of failure of a barrier's failure depends solely on its robustness. However, as they work together in influencing the progression of the initiating event towards the consequences, their probabilities are multiplied, considering the redundancy with which they are arranged within the accidental sequence. The impact of the reducers on the parameters of frequency and severity of the consequences follows similar rules as described for barriers. Their effects are, respectively, the reduction in the frequency of the initiating events and the mitigation of the severity of the consequences.

The classification details of barriers, frequency reducers, and consequence reducers align with those previously reported [13,14]. Similarly, the rules governing the combination of barriers to calculate their failure probability and the influence of the respective reducers on the frequency and consequences are stipulated in the relevant documents associated with the risk matrix method [13,14].

3. Methodology

The methodology used to carry out the risk analysis of the wastewater system based on CW is shown in Figure 3.

The risk level was estimated by simulating the scenarios of the accidental sequences including the new defenses identified in the system's operation. For the elaboration of the process map, the chronological representation of the different sub-processes that are integrated for the work of the domestic wastewater treatment system based on CW was analyzed.

The domestic wastewater treatment system under study includes all wastewater collection points within the residential perimeter, as well as the hydraulic networks and systems designed to ensure its proper operation. There are two subsystems for collecting wastewater within homes: the gray water subsystem and the sewage subsystem. Grey water collection points include washbasins, sinks, showers, and drains located around the perimeter of the houses, all of which drain into the treatment system and are connected to a grease trap. In contrast, all toilets in the houses are connected to the sewage collection system. The gray water collection system, after passing through the grease trap, merges with the sewage system in cases where there is no gray water reuse system. All this wastewater is then directed to a sanitary manhole in each house. This facilitates maintenance of the underground sanitary sewer system without the need for destructive interventions and prevents any large solids from progressing further, allowing for their removal from the system. From this manhole, the wastewater passes to the septic tanks of the homes, and from there, the whole volume of wastewater to be treated in the wetland is collected and redirected to the septic tank of the wetland. Finally, the supernatant of this septic tank is treated in the wetland that constitutes the last stage of the treatment system.

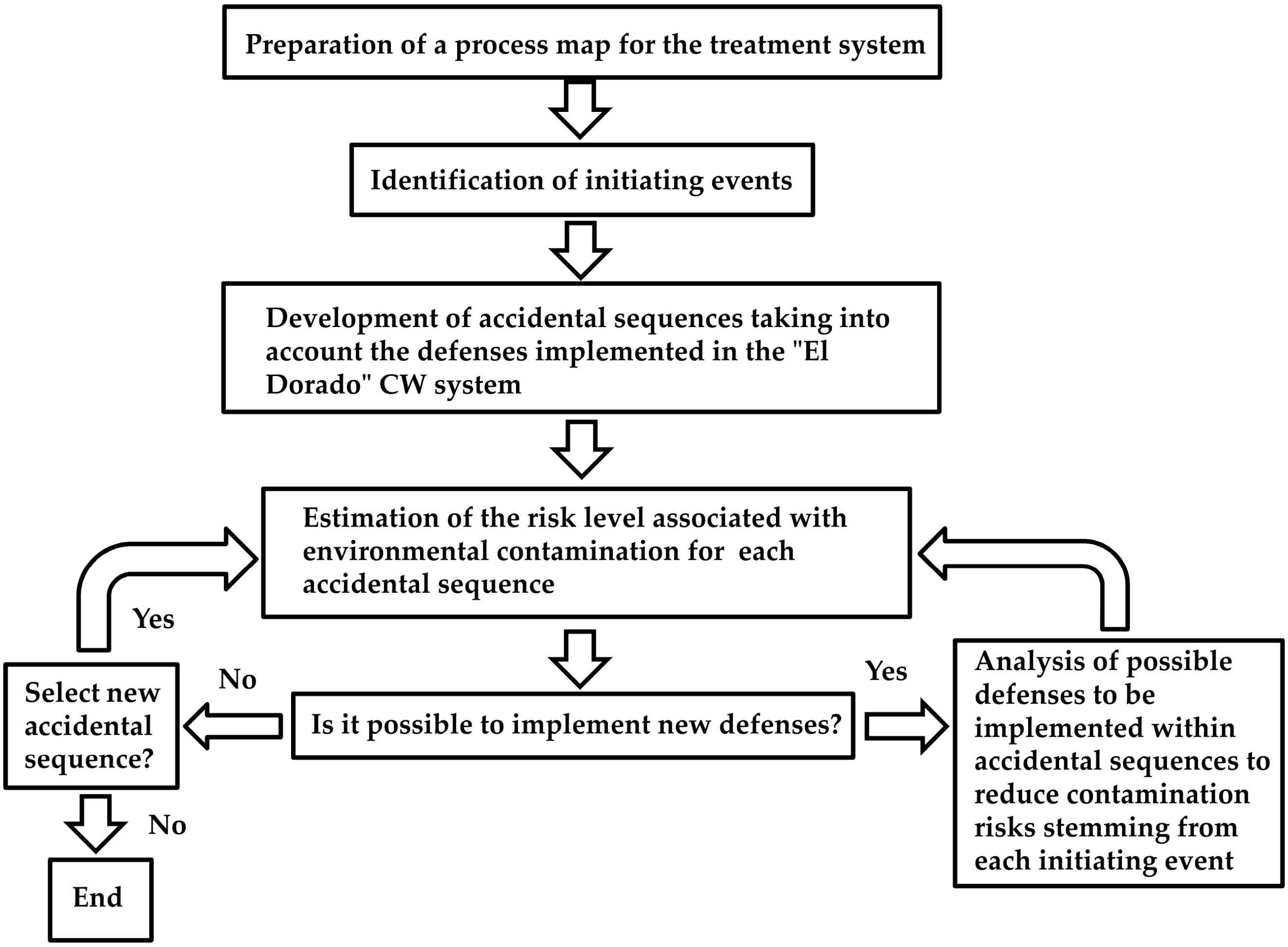


Figure 3. Flowchart for the methodology used for carrying out a risk analysis of the wastewater system based on constructed wetland.

On the other hand, initiating events were identified through a review of the bibliography [23], an examination of the constructed wetlands in the Jarabacoa municipality, La Vega province, Dominican Republic, and interviews with the operators of these treatment systems. This analysis considered potential causes of components failures within the treatment system and operational or management errors that could lead to initiating events. One distinctive feature of the initiating events in this analysis is that, in many cases, their occurrence is not an immediate process of failure and outcome, as is often the case in studies using these methods. Instead, their development corresponds to a gradual deterioration of the working conditions of wetland systems. In this study, for each initiating event, the defenses implemented in the “El Dorado” CW were analyzed. Subsequently, a new group of measures was introduced to reduce the environmental pollution risk. Following this, a new risk analysis was conducted to verify the reduction in risk within the studied system.

To estimate the risk level of each accident sequence scenario, considering the implemented defenses, the SECURE-MR-FMEA code version 1.0 was used [24]. This software facilitated the convolution of all scenario risks, helping identify the most critical accidental sequences and the most effective defenses.

4. Results and Discussion

4.1. Modelling of Technological, Natural and Operational Risks in the Domestic Wastewater Treatment System Based on Constructed Wetland "El Dorado"

The essential stages or sub-processes that were postulated in the process map of the domestic wastewater treatment system based on the CW are illustrated in Figure 4.

Figure 4. Process map of the domestic wastewater treatment system based on constructed wetlands.

From the analysis of the operation of each one of the stages, fifty-three initiating events were identified, two in the first stage, three in the second stage, and forty-eight in the third stage (Table A1 in Appendix A).

While initiating events associated with the first two stages have been fully explained, a list of 48 initiating events related to the CW has been summarized for the sake of document simplicity. Most of these events share similarities, with some specific characteristics setting them apart. For example, while many are related to plant biomass accumulation causing reversible obstruction, others relate to irreversible obstruction. Insufficient maintenance, a crucial aspect affecting the system's performance, has been extensively examined in this study.

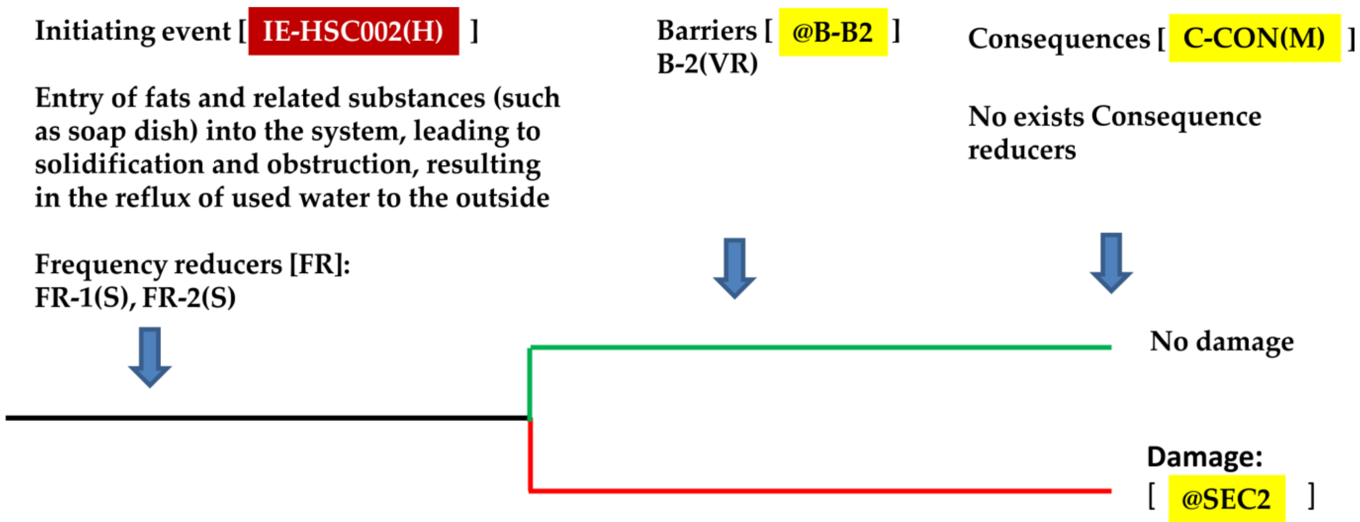
Insufficient maintenance often leads to anomalies in the waterproofing layer, allowing groundwater to enter the constructed wetland or allowing polluted water to drain into the groundwater. Anomalies in water levels and dikes can result from this lack of maintenance. Similar problems arise when there is insufficient maintenance of the vegetation cover, causing fluctuations in water levels and issues with the wetland dikes.

The accumulation of debris can attract rodent infestations, leading to damage in the waterproofing layer and problems with water levels, both high and low, as well as issues with the dikes. Suspended solids cause both reversible and irreversible obstruction, and the growth of microorganisms responsible for wastewater treatment can have the same effect, leading to blockages in the matrix pores.

Similar situations can also occur due to chemical precipitation and pore deposition. Inadequate maintenance, the improper regulation of the level control mechanism, and the incorrect use of sharp tools that lead to breaks in the waterproofing layer can result in high or low water levels, depending on the groundwater table at the wetland's location. To develop the accidental sequences, the defenses, including barriers and frequency and consequence reducers, implemented in the current treatment system were identified (Table A2 in Appendix A).

Figure 5 shows one of the accidental sequences for the wetland, depicting the interplay between initiating event, defenses, and consequences. In the tree of events, once the high frequency initiator IE-HSC-002 (H) occurs, a decision node emerges. If barrier B-2 (VR-Very Robust) succeeds (leading upward), no consequences follow. However, if the barrier fails (leading downward), sequence 2 (@SEC2) concludes with medium-magnitude contamination (consequences C-CON (M)). Frequency reducers FR-1 and FR-3, characterized by soft robustness (S), are applicable for this initiator. There are no consequence reducers (CR) in this sequence.

The initiator IE-HSC-002(H) corresponds to the entry of fats and related substances (such as soap dish) into the system, leading to solidification and obstruction, resulting in the reflux of used water to the outside.



Color Codes	Risks and Consequences	Frequencies and barriers
(green)	Low	Very Low
(yellow)	Medium	Low
(red)	High	Medium
(dark red)	Very High	High

FR-1(S): Awareness of the inhabitants of the houses of the negative behaviors of the people that cause a malfunction of the residual treatment system (S);
FR-2(S): Training of the inhabitants of the houses in the safe ways to evacuate used oils (S);
B-2(VR): Grease trap in the grey water hydraulic system (VR);
C-CON(M): Slight contamination of the soil or air for a long time / high level of contamination of the soil or air for a short time in the immediate area of the treatment system

Figure 5. Accidental sequence for the initiating event IE-HSC-002. The green line represents the accidental sequence's divergence toward a successful path without damage, while the red line indicates the sequence's progression towards damage due to the barriers' lack of success.

4.2. Evaluation of Technological, Natural, and Operational Risks in the Domestic Wastewater Treatment System Based on Constructed Wetland "El Dorado" Applying the Proposed Risk Model

Figure 6 displays the risk profile resulting from the application of the TDRM method to assess the technological, natural, and operational risks of the domestic wastewater treatment system based on a subsurface horizontal flow CW "El Dorado".

Out of the fifty-three identified initiating events for accidental sequences, six were determined to be of very high risk (Table 2), forty were of high risk, six were of moderate risk, and only one was of low risk. This allows for the classification of the studied system as a high-risk installation.

Besides the very high risks listed in Table 2, the presence of 40 high risks is also a concern. To enhance risk control in the wetland, the implementation of new defenses, including frequency reducers, barriers, and consequence reducers were proposed (Table 3). It is worth noting that these new proposals necessitate the regular presence of technical staff to manage the wetlands, a role that currently does not exist.

The simulation of how the implementation of the defenses listed in Table 3 would affect the variation in risk levels for contamination in the impact area and the immediate area of the domestic wastewater treatment system based on CW "El Dorado" is depicted in Figure 7.

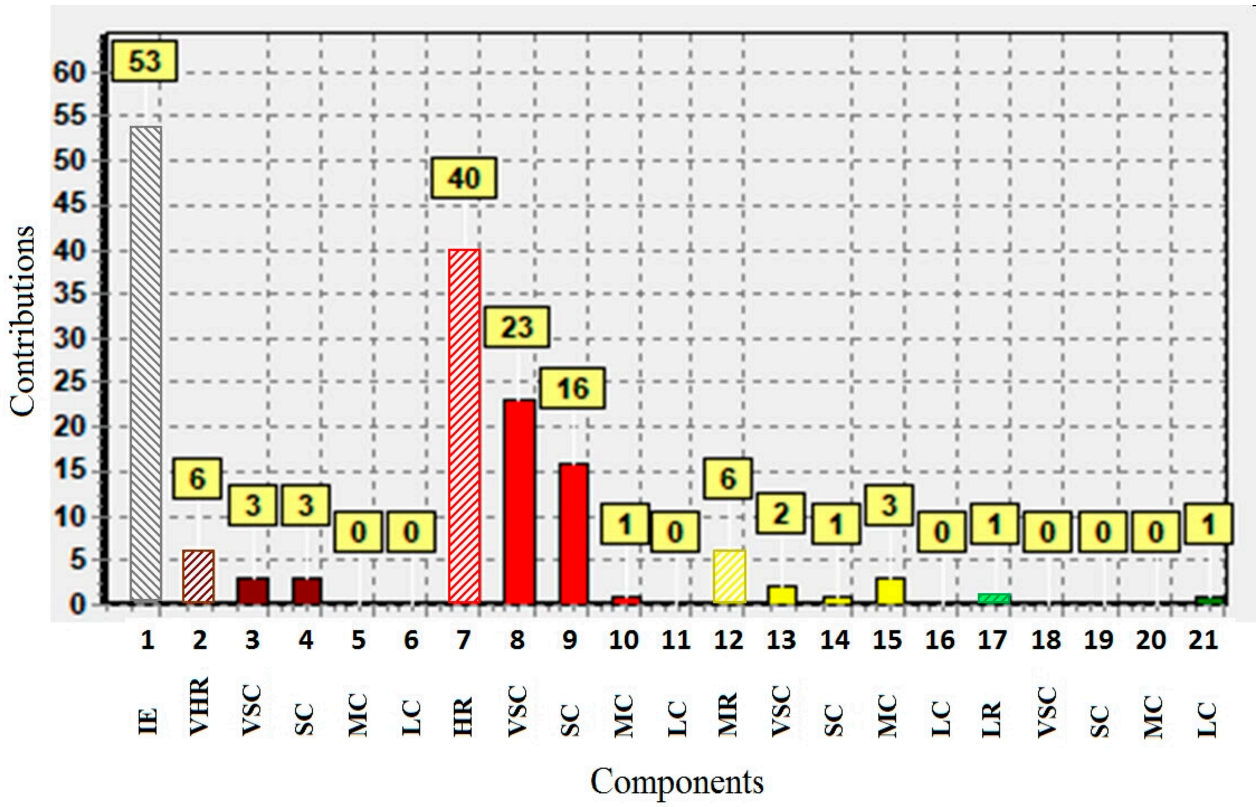


Figure 6. Risk profile of the current treatment system "El Dorado". Bar 1—total number of initiating events; striped bars 2, 7, 12, 17—distribution of initiating events by risk levels; full color bars 3–6, 8–11, 13–16, and 18–21 distribution of the initiating events corresponding to each risk level by consequence levels. Risk levels (VHR—very high risk, HR—high risk, MR—medium risk, LR—low risk); Consequences (VSC—very serious consequences, SC—serious consequences, MC—moderate consequences, LC—low consequences).

Table 2. Initiating events of accidental sequences identified as of very high risk in "El Dorado".

No.	Initiating Events of Accidental Sequences
1	IE-CW-004: Heavy rain or rain for a prolonged period that causes a rise in the water level, which in turn induces abnormal vegetation growth during start-up favoring the weeds' growth in the wetland.
2	IE-CW-019: Insufficiencies in the maintenance of the wetland vegetation cover that enables the growth of trees and/or shrubs that in turn causes anomalies in the wetland dikes. These anomalies induce a very low water level by allowing untreated water to drain into the subsoil, and the latter causes a low density or heterogeneous vegetation density and chlorosis of the plants.
3	IE-CW-023: Poor development of the rhizomes which causes the occurrence of chlorosis of the plants and their death.
4	IE-CW-031: Accumulation of suspended solids as a result of the reversible obstruction of the matrix pores and the clogging of the substrate, which in turn causes a very high water level or surface flow.
5	IE-CW-032: Accumulation of suspended solids as a result of the irreversible obstruction of the matrix pores and the clogging of the substrate, which in turn causes a very high water level or surface flow.
6	IE-CW-048: Inadequate maintenance of the fence and the gate of the facility which causes them to break and, as a consequence, the entry of animals that damage the plants and the structural components of the wetland

Table 3. New defenses (B—barriers; FR—frequency reducers; CR—consequence reducers) to be included in the domestic wastewater system based on CW "El Dorado" to improve the management of the risk of contamination of the impact area and the immediate area of the treatment system.

Code	Barriers
B-8	Record of periodic inspection of the state of the drain grates (N)
B-9	Checking the periodic inspection plan for the state of the drain grates (N)
B-10	Periodic grease trap maintenance (N)
B-11	Filling in the record of periodic maintenance activities of the grease trap (N)
B-12	Check of the periodic maintenance plan of the grease trap (N)
B-13	Periodic maintenance to the flow meter (N)
B-14	Filling in the periodic maintenance record of the flow meter (N)
B-15	Record of evacuation of sludge from septic tanks (N)
B-16	Periodic monitoring of the flow and pollutant load in the inlet to the wetland. Filling in the corresponding records (N)
B-17	Periodic checking of the facility records to detect deviations from the parameters established for the proper functioning of the wetland (N)
B-18	Existence of a reserve cell "functional redundancy" (VR)
B-19	Inspect the wetland in an extraordinary way to check the water level until the rains stop (N)
B-20	Periodically measure the concentration of suspended solids in the fluid and the feed flow of the wetland. Fill in the corresponding records (N)
B-21	Weekly inspection to verify the status and operation of the wetland and filling out the corresponding record (N)
Code	**Frequency reducers**
FR-5	Daily cleaning maintenance of existing washbasins, sinks, showers, and drains to remove solid materials (N)
FR-6	Semi-annual review of the sludge level in the septic tanks of the houses (S)
FR-7	Checking compliance with the program for checking the levels of septic tanks in homes (N)
FR-8	Preventive maintenance of the septic tank and filling of the corresponding record (N)
FR-9	Periodic check of facility's records to detect breaches of maintenance, training, and inspection plans (N)
FR-10	Perform periodic maintenance on the wetland cover and fill out the corresponding record (N)
FR-11	Training of workers who attend the installation and filling out the corresponding record (S)
FR-12	Plant selected grasses on dikes to prevent the growth of trees and shrubs (N)
FR-13	Maintenance of septic tanks and filling of the corresponding record (N)
FR-14	Maintenance of the wetland through periodic cycles of filling and draining and filling out the corresponding record (N)
FR-15	Cleaning maintenance of the areas surrounding the wetland and filling out the corresponding record (N)
FR-16	Select a suitable tool to perform wetland maintenance (N)
FR-17	Use only seeds certified "weed-free" to plant in the wetland (N)
FR-18	Maintenance of the residual water distribution system (N)
FR-19	Periodic maintenance of the perimeter fence and the access door to the wastewater treatment facility and fill out the corresponding record (N)
Code	**Consequence reducers**
CR-6	Advertising of the contact number of specialists or companies that address problems related to sewage in the community (S)
CR-7	Establishment of a contact number for attention to vulnerable low-income families in the community that allows them to cover emergency expenses due to the risk of environmental contamination (S)
CR-8	Advertising of the contact number of specialists who deal with problems of damage to the internal hydraulic networks of drinking water in the community (S)

Table 3. *Cont.*

Code	Barriers
CR-9	Septic tank emergency maintenance (N)
CR-10	Perform cycles of filling and draining the wetland (N)
CR-11	Operate the level control to regulate the water level if necessary (R)
CR-12	Lower the water level using the level control system (R)
CR-13	Repair the waterproofing layer (N)
CR-14	Repair the damaged dikes (N)
CR-15	Repair the damaged perimeter fence or access gate (N)
CR-16	Consult a plant expert to solve the problem of chlorosis (S)
CR-17	Superficially apply low concentrations of iron-rich compost (for example with iron sulphate (N)
CR-18	Replant the wetland with efficient plants with respect to iron uptake (S)
CR-19	Stimulate root growth by lowering the water level to 20–30 cm below the surface for 15–30 days (S)
CR-20	Repair holes made by rodents in the waterproofing geomembrane (N)
CR-21	Carry out a campaign for the application of rodenticide substances (N)
CR-22	Clean plant residues and/or residues from pre-treatments, treatments, and pruning from the areas surrounding the wetland (N)
CR-23	Cover up detected caves in the wetland bed (N)
CR-24	Recirculate treated water to dilute inflow (N)
CR-25	Remove solids from the surface if it is detected that this is the cause of the increase in suspended solids (N)
CR-26	If more than 75% of the surface remains flooded and there is an unpleasant odor or proliferation of mosquitoes and poor quality of the effluent, replace the substrate (N)
CR-27	Clean the water distribution pipe (N)
CR-28	Repair or replace the level control mechanism (N)
CR-29	Correct position of level control mechanism (N)
CR-30	Repair the protective coating from solar radiation (N)

Note: The values in parentheses correspond to the robustness of the barriers (VR—Very robust; R—Robust, N—Normal; S—Soft).

As observed, the implementation of the proposed defenses reduces the risks to lower levels. Very high levels initiating events are no longer identified, and high-risk events decrease from forty to six, with an increase in moderate (from six to thirty-one) and low-risk events (from one to sixteen). Consequently, the system transitions from a high-risk to a moderate-risk installation. Figure 8 provides a clearer visualization of this shift towards less significant risks resulting from the incorporation of defense measures presented in Table 3. Notably, only six high risks would remain in this scenario, with the others falling into the moderate and low categories. Additionally, these histograms depict the distribution of consequences severity for each risk level. For example, in Figure 6, among the six high risks displayed, three entail very serious consequences and thus demand the most attention. Table 4 presents the initiating events of the six accidental sequences identified as high risks in the study after the implementation of new defenses.

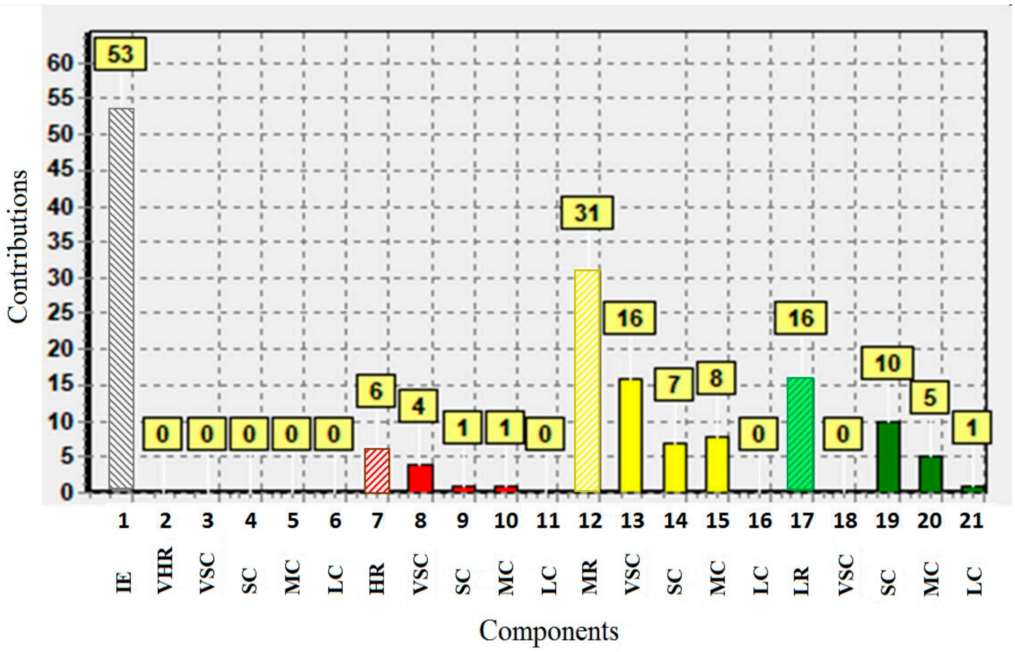


Figure 7. Risk profile for the constructed wetland "El Dorado" after implementing the defenses proposed to improve risk management. Bar 1—total number of initiating events; striped bars 2, 7, 12, 17—distribution of initiating events by risk levels; full color bars 3–6, 8–11, 13–16, and 18–21—distribution of the initiating events corresponding to each risk level by consequence levels. Risk levels (VHR—very high risk, HR—high risk, MR—medium risk, LR—low risk); Consequences (VSC—very serious consequences, SC—serious consequences, MC—moderate consequences, LC—low consequences).

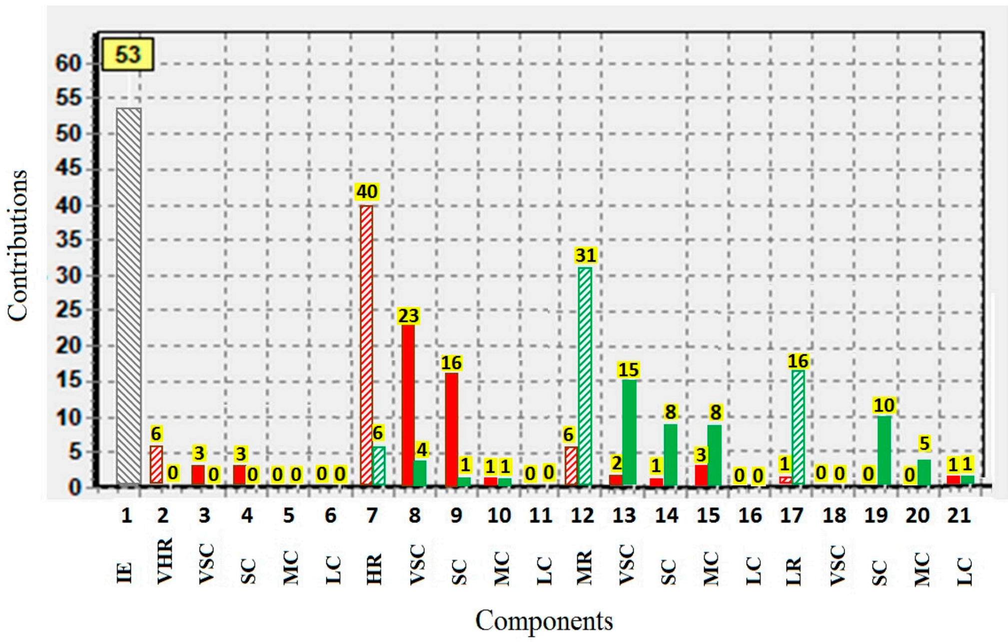


Figure 8. Comparative histogram. Red bars: magnitude of the technological risks of the current treatment system; green bars: estimated magnitude of the risks if the proposed defenses are implemented. Bar 1—total number of initiating events; striped bars 2, 7, 12, 17—distribution of initiating events by risk levels; full color bars 3–6, 8–11, 13–16, and 18–21 distribution of the initiating events corresponding to each risk level by consequence levels. Risk levels (VHR—very high risk, HR—high risk, MR—medium risk, LR—low risk); Consequences (VSC—very serious consequences, SC—serious consequences, MC—moderate consequences, LC—low consequences).

Table 4. Initiating events of the accidental sequences with high risk in "El Dorado", considering the implementation of the new defenses.

No.	Initiating Events of Accidental Sequences
1	IE-ST-001: Entry into the system of disinfectant chemical substances that cause the death of microorganisms responsible for the degradation of organic substances
2	IE-CW-004: Heavy rain or rain for a prolonged period that causes a rise in the water level, which in turn induces abnormal vegetation growth during start-up, favoring the weeds' growth in the wetland.
3	IE-CW-019: Insufficiencies in the maintenance of the wetland vegetation cover that enables the growth of trees and/or shrubs, which in turn causes anomalies in the wetland dikes. These anomalies induce a very low water level by allowing untreated water to drain into the subsoil, and the latter causes a low density or heterogeneous vegetation density and chlorosis of the plants.
4	IE-CW-021: Low organic load in the feed of the wetland which causes the occurrence of chlorosis of plants and their death
5	IE-CW-023: Poor development of the rhizomes which causes the occurrence of chlorosis of the plants and their death.
6	IE-CW-038: Growth of the rhizomes and roots which causes an irreversible obstruction of the matrix pores and clogging of the substrate, which in turn induces a very high level of water or surface flow.

As part of the analysis, an assessment of the significance of defenses was conducted. This assessment was conducted on an improved version of the "El Dorado" domestic wastewater treatment system based on CW. One approach for evaluating the importance of defenses is to determine their percentage participation in accidental sequences. In this case, we focused on barriers and identified those with the highest participation in the accidental sequences, as illustrated in Figure 9.

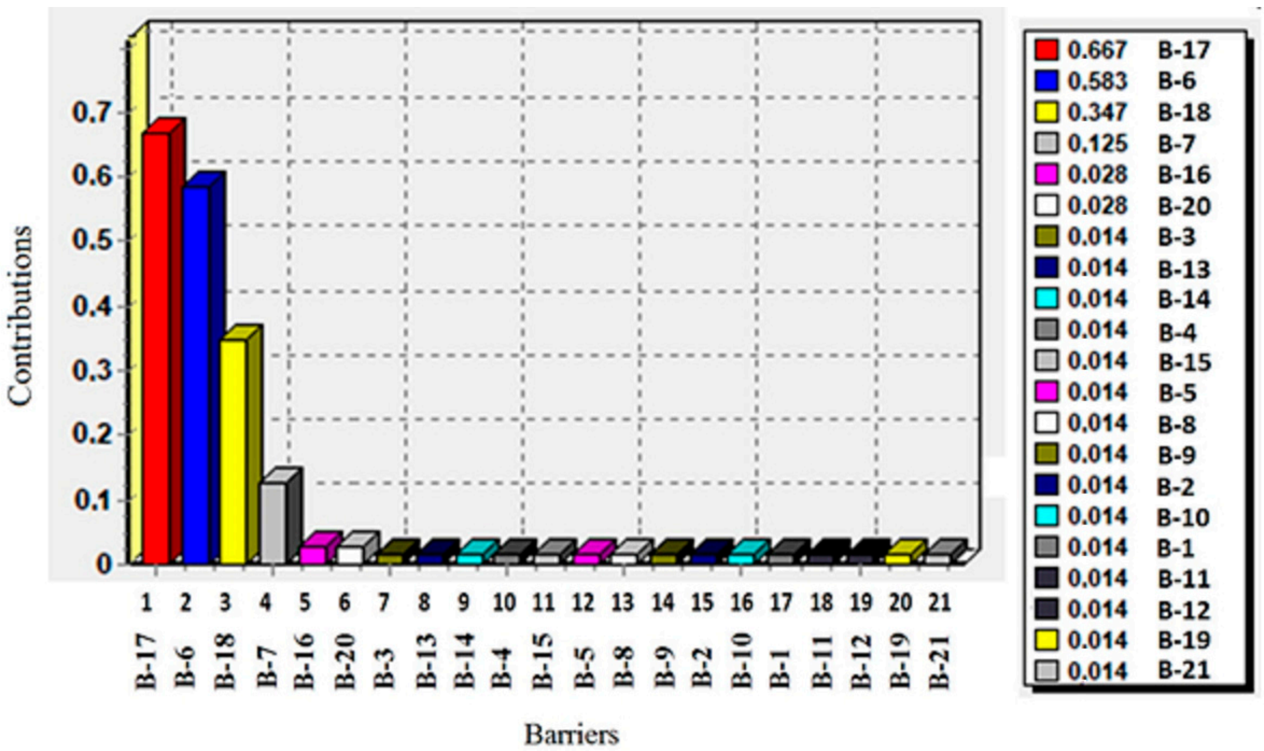


Figure 9. Importance of the barriers by their percentage participation in the different accidental sequences.

The three barriers with the highest percentage participation turned out to be the following:

1. B-17 Periodic checking of the facility records to detect deviations from the parameters established for the proper functioning of the wetland.

2. B-6 Periodic inspection to verify the status and operation of the wetland, the status of the surrounding areas, and the completion of the corresponding records.
3. B-18 Existence of a reserve cell (functional redundancy).

However, this measure of importance does not account for the impact of additional redundant barriers within each sequence. A barrier may participate in multiple sequences but have minimal significance because it is supported by others. To address this, a complementary study was carried out using the measure of importance called "increased risks when defenses disappear".

Figure 10 displays the results of the risk assessment study when removing barriers, indicating the number of accidental sequences that experience increased risk when a specific barrier is eliminated. Similarly, Figure 11 pertains to the study involving the removal of frequency reducers, while Figure 11 addresses the removal of consequence reducers.

The first study confirmed the importance of barriers B-6, B-17, and B-18, as previously identified by the percentage method. In this case, there were no significant differences, given the low redundancy of barriers in the analyzed sequences. However, it is worth noting that the order of importance changed between the percentage participation and increased risks for subsequent barriers. Therefore, more attention should be given to barriers B-3 (Parshall channel to monitor the flow rate at the system's output) and B-21 (weekly inspection to verify the wetland's status and operation, along with record-keeping), which are considered insignificant in the percentage representation.

The second study, shown in Figure 11, allowed the identification that the most important frequency reducers are as follows:

1. FR-9 Periodic check of the facility's records to detect breaches of maintenance, training, and inspection plans.
2. FR-11 Training of workers who attend the installation and filling out the corresponding record.

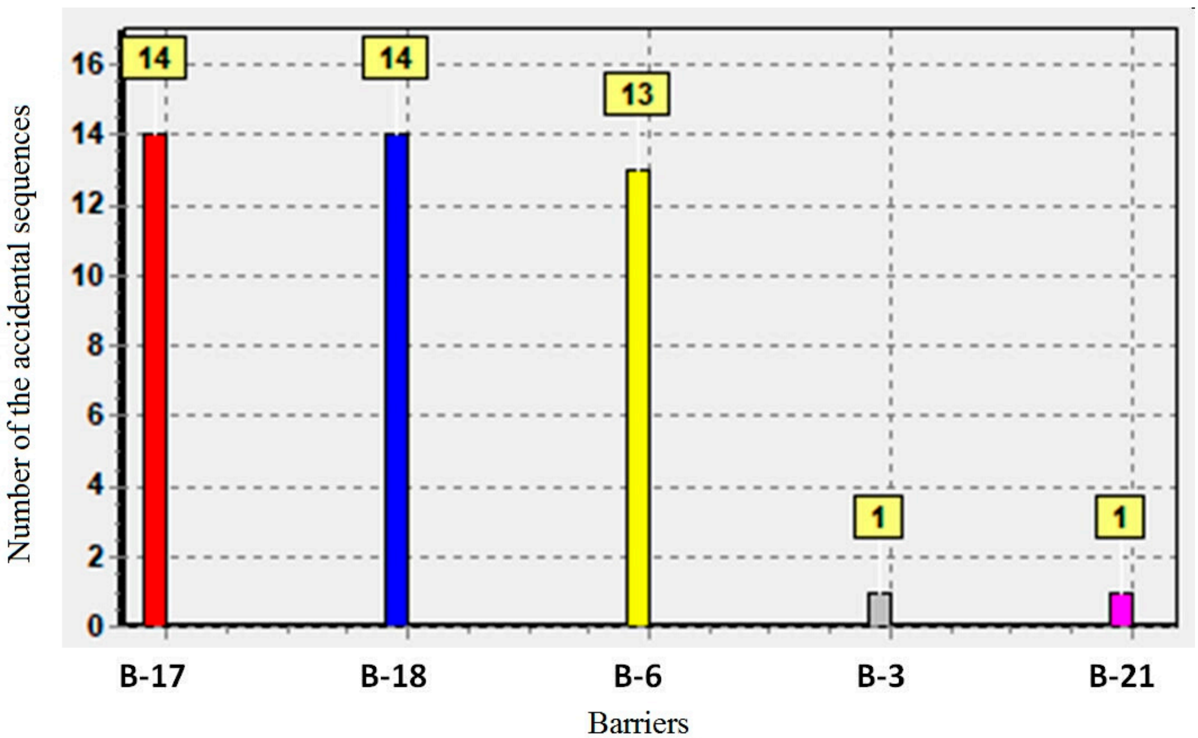


Figure 10. Barriers that increase the risk of the greatest number of accidental sequences when they are eliminated. Different color corresponds to a different barrier.

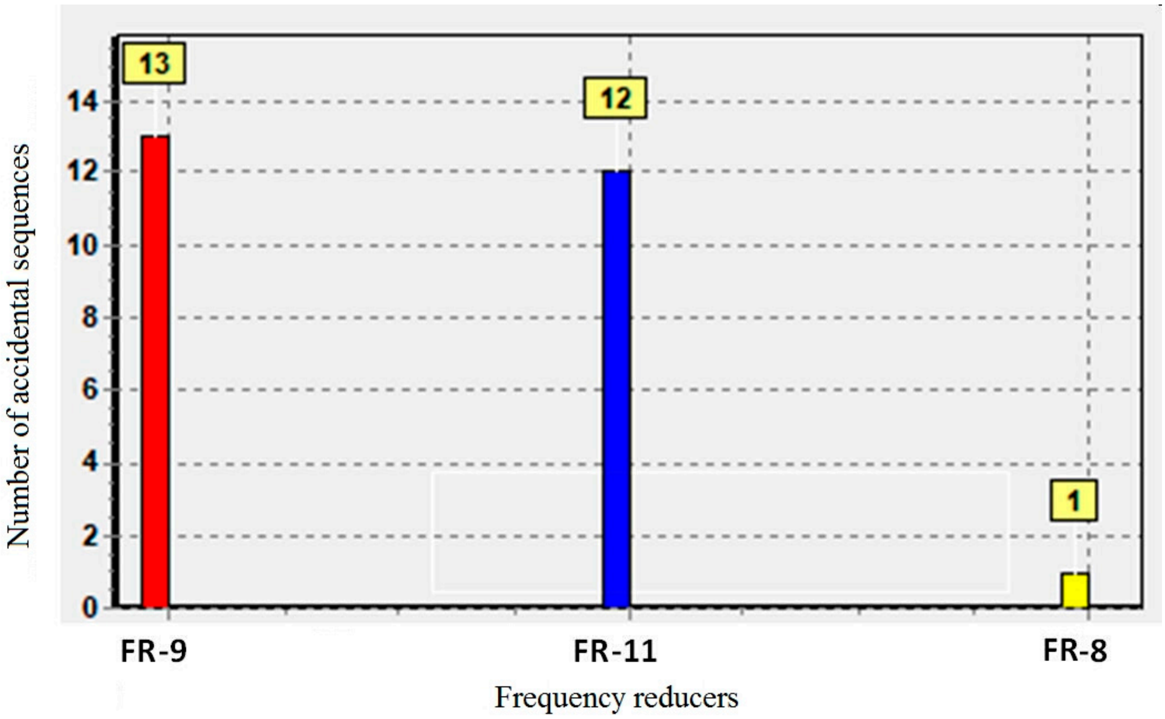


Figure 11. Frequency reducers that increase the risk of the greatest number of accidental sequences when they are eliminated. Different color corresponds to a different barrier.

Finally, the third study showed that the most important consequence reducers identified were the following (Figure 12):

1. CR-1 Replant the vegetation coverage and remove dead plants, if they exist.
2. CR-13 Repair the waterproofing layer.

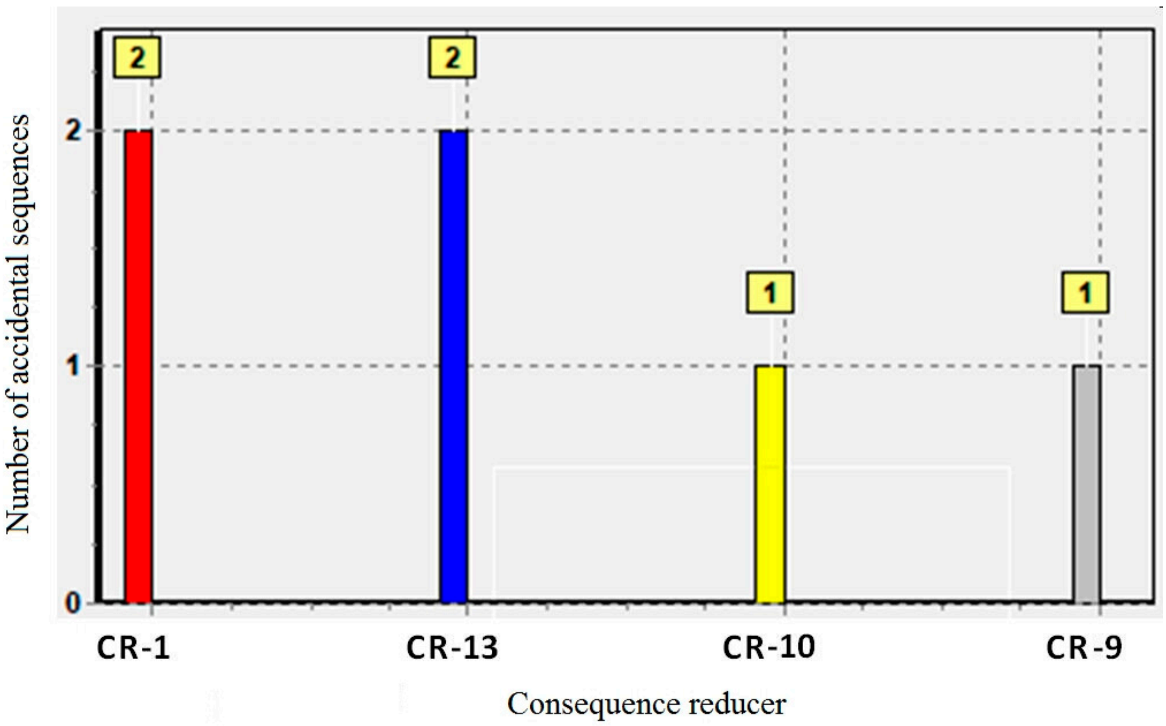


Figure 12. Consequence reducers that increase the risk of the greatest number of accidental sequences when they are eliminated. Different color corresponds to a different barrier.

Through this study, the most crucial defenses that need to be implemented to control the risk of the "El Dorado" treatment system were identified.

As far as we know, there has not been any study of the risk management of wastewater treatment plants based on constructed wetlands. Nevertheless, recently, Analouei et al. have performed a risk assessment of a wastewater treatment and reclamation plant not fulfilling the effluent requirements by applying the bow-tie method [25] and the dynamic Bayesian network [26]. However, these proposed methodologies are more complex than the Three-Dimensional Risk Matrix. On the other hand, they concluded that human errors were responsible for the most risks in WWTP failure, while in the wastewater treatment plants based on constructed wetlands with all the new defenses implemented, the high risks identified were mostly related with natural processes.

4.3. Discussion on the Proposed Model for Risk Management in Domestic Wastewater Treatment Systems Based on Constructed Wetland

The Federal Roundtable on Remedial Technologies (FRTR) recognizes that the long-term effectiveness of constructed wetlands in containing or treating certain contaminants is not well understood [27]. This publication also emphasizes that, like other biological methods, constructed wetlands are constrained by the biota's ability to withstand exposure to its environmental factors, such as weather events, wildlife, and pollutant concentrations. The challenges in establishing these systems align with the findings in [28]. These situations were considered in the risk model designed for the wetland in this investigation.

Another issue highlighted in the reference [27] is the limitation of remediation for metals in constructed wetlands. Wetlands do not destroy metals; instead, they restrict their mobility through sorption or plant bioaccumulation. In the context of this investigation, the treatment is specifically designed for domestic wastewater, so the situation described earlier is not anticipated. It is important to avoid using exotic and invasive species when developing a CW, and a plan should be in place for their removal if they appear [25]. This aspect is taken into account in the proposed risk model, which is designed based on defenses implemented through an appropriate wetland vegetation cover maintenance policy.

Another aspect to consider is the control measures suggested by [27], which must be implemented in the wetland and that were included as part of the defense measures in the model [27,29]:

- Maintenance of any water distribution system, including clogging prevention;
- Frequency and type of vegetation monitoring;
- Need for vegetation management, odor control, and pest control;
- Frequency and scope of monitoring of conventional parameters and contaminants.

On the other hand, the US Environmental Protection Agency notes that using constructed wetlands as a treatment technology entails certain risk for several reasons [30]. Firstly, constructed wetlands are not uniformly accepted by all state regulators. Some authorities encourage their use based on misconceptions regarding their proven efficiency, simultaneous aerobic and anaerobic treatment capacity, and their potential for oxygen and phosphorus treatment due to insufficient modeling data. In this regard, this research considers the wetland as a proven treatment technology for the pollutants that require treatment, as supported by previous experimental research [31]. Secondly, although there is no evidence of harm to the environment associated with the use of CW, some regulators have raised significant concerns about these systems attracting wildlife. Unfortunately, there has been limited research on the potential risks to wildlife when constructed wetlands are used. Despite their distinct habitat type, there is also a lack of evidence regarding wildlife risks in treatment pond systems. The risk model developed in this research does not specifically address harm to wildlife. However, it does recognize that such interactions can act as initiators affecting the wetland's operation.

Finally, the absence of a substantial body of scientifically validated data makes the design process complex. It relies primarily on empirical observations rather than scientific theories. Because many factors in CW, such as climatic effects, influent wastewater characteristics, design configurations, construction techniques, and operation and maintenance practices, exhibit variability, disagreements may persist regarding certain design issues and performance over time. Coincidentally, this research aims to comprehensively address various aspects of risk that remain to be investigated. It employs a multidimensional model that incorporates multiple variables related to risk and the factors listed. This provides the model with a unique characteristic, allowing us to examine risks from a simulation perspective. Through this approach, we can execute tests involving changes in the configuration of inputs, simulating alterations in risk-related variables.

The US Environmental Protection Agency's reference document, "EPA, Risk Assessment, 2000" [32], outlines a sequence of activities for conducting risk assessments related to human health from environmental effects. The stages considered are as follows:

- Harm identification: to identify the types of adverse health effects that may be caused by exposure to any agent(s) in question, and to characterize the quality and weight of evidence supporting this identification.
- Dose response to document the relationship between dose and toxic effect. A dose-response relationship describes how the probability and severity of adverse health effects (responses) are related to the amount and conditions of exposure to an agent.
- Exposure assessment: the process of measuring or estimating the magnitude, frequency, and duration of human exposure to an agent in the environment.
- Risk characterization: to summarize and integrate the information from the previous steps of the risk assessment to synthesize an overall conclusion about the risk.

It should be clarified that the previous analysis combines deterministic and probabilistic approaches, to which experimental results are added. While there are similarities, it's important to emphasize that the developed risk model primarily follows a probabilistic approach. In the EPA methodology, the identification of harm involves explicit studies of toxicokinetics and toxicodynamics, which analyze how damages occur in interaction with humans. All of this research is incorporated into the risk model developed for the domestic wastewater treatment system based on a constructed wetland, particularly in the determination of consequences.

The questions related to dose response are implicit in the descriptive definition of the model concerning accidental consequences. The results are reflected in the varying magnitudes of modeled consequences, with probabilities of harm established based on the magnitude of the doses received. To define these consequences, the corresponding step as described in the EPA methodology must have been completed. It is worth noting that the relationship between dose and the probability of harm may require experimental data, possibly involving animal studies, in the absence of human data. All of these aspects are implicitly incorporated into the definition of consequences within the designed risk framework in this research. Exposure assessment is achieved by modeling various scenarios (accidental sequences), which illustrate different risk exposure situations. This modeling allows us to determine the magnitude and duration of exposure (grouped as consequences) as well as frequency (captured by the parameter of the same name associated with the initiating event). Notably, the method employed in this research incorporates management capabilities through the inclusion of defenses within the model.

The convolution of the results of the three previous stages makes it possible to calculate the individual risk, as well as the collective risk. The manner in which results are presented here differs from the approach taken in the probabilistic risk model of this research. These are two distinct risk assessment methodologies, each with its unique perspective on risk. It's worth noting that once the probabilistic risk pattern of the wetland has been established, obtaining its results is a relatively quick process, which underscores the model's practicality.

Wu, Gao, Wu, Zhu, Xiong, and Ye [33] argue that the risk of groundwater contamination increases in areas where constructed wetlands are utilized. They suggest considering the use of waterproofing layers to protect groundwater and strengthening management. These issues are considered among the defenses suggested by the risk model developed.

Finally, many of the references consulted deal with cases of wetlands built for the treatment of pollutants other than domestic ones [34,35]. It should be clarified that these wetlands necessitate specific risk models tailored to their required treatment capacities. These scenarios are beyond the scope of the risk model for the treatment system based on a constructed wetland presented in this research.

Current environmental regulations in the US demand a level of detail that has not been applied to the studied wetland. However, if it becomes necessary to seek authorization using a method similar to the one discussed in this work, it is advisable to establish strict controls for very high risks as a guideline regarding risk levels. These risk levels can be achieved through the additional defense measures proposed in the previous section (refer to the improved case). This approach is optimistic and draws inspiration from the field of radiation safety [13], where prolonged exposure to high risks is not permitted. Considering the challenges associated with achieving such a goal for facilities of this nature, it is recommended to focus solely on prohibiting very high risks within the scope of this issue.

While matrix methods for estimating risk have been used in water treatment facilities (see references [2,3,15]), they have not been widely applied to treatment facilities using constructed wetlands. One limitation of the two-dimensional approach in the risk matrix, as seen in these references, is its lack of systematicity in studying the impact of defenses. This study employs a three-dimensional risk matrix, addressing this limitation and distinguishing it from the approach found in the international standard ISO-31000 [34], explicitly dedicated to risk management but similarly limited when considering defenses.

The use of TDRM in this investigation implicitly integrates defenses into the prioritization of the most critical sequences, enhancing the objectivity of the analysis, which has not been achieved in similar studies [2,3,15,36]. Moreover, this method identifies the most effective defense measures for controlling technological risks in the wetland. The application of this approach to the results reveals that specialized defense measures should be prioritized for very high-risk accident sequences. These sequences, as indicated by the results, primarily result from inadequate maintenance and surveillance (IE-CW-04, IE-CW-019, IE-CW-048), along with insufficient operational policies (IE-CW-023, IE-CW-031, IE-CW-032).

The measures recommended in Table 3 effectively reduce the risk to lower levels, demonstrating their efficacy. Among these measures, those depicted in Figures 9–11 should be highlighted. These measures primarily address operational issues (B-17: Periodic checking of the facility records to detect deviations from the parameters established for the proper functioning of the wetland, B-6: Periodic inspection to verify the status and operation of the wetland, the status of the surrounding areas, and the completion of the corresponding records, FR-9: Periodic check of the facility's records to detect breaches of maintenance, training, and inspection plans, CR-1: Replant the vegetation coverage and remove dead plants, if they exist), maintenance (CR-1: Replant the vegetation coverage and remove dead plants, if they exist), installation design (B-18: Existence of a reserve cell), and personnel training (FR-11: Training of workers who attend the installation and filling out the corresponding record).

Finally, we want to express how our research contributes to sustainability. Constructed wetlands represent a nature-based solution for water treatment, and this paper's risk assessment methodology, particularly the three-dimensional risk matrix approach, offers a novel and practical means to enhance the sustainability of such systems. By identifying the most critical initiating events and defenses, with a focus on human factors, the research highlights the vulnerabilities within constructed wetland operation. The suggested defense measures and the transition from a high-risk to a moderate-risk facility demonstrate a path towards improving the reliability and effectiveness of wastewater treatment. This, in turn, contributes to environmental sustainability by reducing the potential risks and impacts associated with the discharge of inadequately treated wastewater, ultimately safeguarding water quality and ecosystem health. Moreover, this paper introduces the concept of using risk analysis as a tool for optimizing the operation of wastewater treatment technology based on constructed wetlands. This innovative approach can lead to more efficient and cost-effective water treatment processes, contributing to the sustainability of water resources and the preservation of natural ecosystems. In conclusion, the research offers a valuable framework for enhancing the sustainability of wastewater treatment systems based on constructed wetlands, addressing an urgent problem of humanity while emphasizing the role of nature-based solutions in environmental stewardship and open new directions for further research on the risk analysis of constructed wetlands for wastewater treatment and water purification.

5. Conclusions

The results of the risk analysis have identified the most critical initiating events and defenses within the domestic wastewater treatment system based on a constructed wetland of subsurface horizontal flow, "El Dorado", located in Jarabacoa, Dominican Republic. Notably, human factors emerge as the primary contributors to the risks associated with the operation of this constructed wetland. The benefits of implementing the newly suggested defense measures have been determined. With these measures in place, the constructed wetland would achieve an acceptable technical state of operation, transitioning from a high-risk to a moderate-risk facility. From a methodological perspective, the use of a three-dimensional risk matrix for this type of study proves valuable due to its ability to incorporate the effectiveness of defense measures into risk quantification. Having risk models for a domestic wastewater treatment system based on a constructed wetland, along with the use of specialized computer code, enables sensitivity analysis. This analysis considers the gradual or partial incorporation of defense measures, turning the tool into a risk monitor for the studied system. In these conditions, there is potential to optimize the operation of wastewater treatment technology based on constructed wetland using risk analysis. The developed models and available tools illustrate the generalization possibilities created through this research. The application presented in the research is novel, as there are no precedents for using it to manage the risk associated with domestic wastewater treatment systems based on constructed wetlands as point pollution sources for the environment.

Author Contributions: Conceptualization, D.G.-C., A.T.-V. and U.J.-H.; methodology, Y.P., D.G.-C. and A.T.-V.; software: A.T.-V.; validation, D.G.-C. and A.T.-V.; formal analysis, Y.P., D.G.-C., A.T.-V. and U.J.-H.; investigation, Y.P., D.G.-C., A.T.-V. and U.J.-H.; resources, U.J.-H.; data curation, Y.P., D.G.-C. and A.T.-V.; writing—original draft preparation, Y.P., D.G.-C. and A.T.-V.; writing—review and editing, U.J.-H.; supervision, U.J.-H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funds from Instituto Tecnológico de Santo Domingo (INTEC, grant number: CBA-330810-2020-P-1) and the Ministry of Higher Education, Science and Technology of Dominican Republic (MESCYT) through FONDOCYT (grant number: 2022-2B2-161).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data may be available upon request.

Acknowledgments: The authors thank Enmanuel Vargas from the Plan for the Sustainable Development of the Yaque del Norte River Basin, Inc. (Plan Yaque), for his valuable comments. This work has been undertaken in the framework of INTEC's Doctorate program on Environmental Sciences.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Initiating events of the accidental sequences in the "El Dorado" treatment system (IE—initiating event; HSC—hydraulic system for domestic wastewater collection; ST—Septic tank; CW—constructed wetland).

Code	Initiating Events
Initiating events associated with the hydraulic system for collecting domestic wastewater	
IE-HSC-001	The entry of large solids, such as pieces of cloth, into the system can cause hydraulic clogs and result in the used water overflowing to the outside
IE-HSC-002	The entry into the system of fats and related substances (e.g., soap, etc.) that solidify causing clogs, resulting in used water overflowing to the outside.
Initiating events associated with septic tanks	
IE-ST-001	The entry into the system of disinfectant chemical substances that cause the death of microorganisms responsible for the degradation of organic substances.
IE-ST-002	A continuous and excessive water supply into the system, beyond its design parameters, can wash out the microorganisms responsible for organic substance degradation.
IE-ST-003	The overflow of sludge from the septic tanks of the houses towards the collection pipe that goes to the septic tank of the wetland
Initiating events associated with the constructed wetland	
IE-CW-001	The overload of organic matter in the wetland inlet that causes a low density or heterogeneous vegetation density, which in turn favors the weeds' growth in the wetland.
IE-CW-002	The overload of organic matter in the wetland inlet that causes the reversible obstruction of the matrix pores and clogging of the substrate that in turn induces a very high water level or surface flow.
IE-CW-004	Heavy rain or rain for a prolonged period that causes a rise in the water level, which in turn induces abnormal vegetation growth during start-up, favoring the weeds' growth in the wetland.
IE-CW-005	The accumulation of plant biomass that falls naturally on the vegetation cover and decomposes.
IE-CW-006	The accumulation of plant biomass that falls naturally on the vegetation cover causing reversible obstruction of the matrix pores and clogging of the substrate, which in turn induces a very high water level or surface flow.
IE-CW-008	Inadequacies in the maintenance of the area surrounding the wetland which favors the weeds' growth in the wetland, which in turn induces abnormal vegetation growth during start-up.
IE-CW-009	Insufficiencies in the maintenance of the areas surrounding the wetland that allows the growth of trees and/or shrubs in them, which in turn cause anomalies in the waterproofing layer that allows the entry of water from the groundwater table and the occurrence of a very high water level or superficial flow. This favors a low density or heterogeneous vegetation density and the chlorosis of the plants.
IE-CW-010	Inadequacies in the maintenance of the areas surrounding the wetland that allows the growth of trees and/or shrubs in them, which in turn causes anomalies in the waterproofing layer. These anomalies induce a very low water level by allowing untreated water to drain into the subsoil, and the latter causes a low density or heterogeneous vegetation density and chlorosis of the plants.
IE-CW-011	Insufficiencies in the maintenance of the areas surrounding the wetland that enables the growth of trees and/or shrubs in them, which in turn causes anomalies in the wetland dikes. These anomalies induce a very high water level or surface flow when water enters from outside, and the latter causes a low density or heterogeneous vegetation density and chlorosis of the plants.
IE-CW-013	Insufficiencies in the maintenance of the area surrounding the wetland that allows the growth of trees and/or shrubs in them, which in turn causes anomalies in the perimeter fence and/or the access gate and allows the entry of animals that damage the wetland plants.
IE-CW-014	Insufficiencies in the maintenance of the wetland vegetation cover which enables the growth of trees and/or shrubs, which in turn causes a heterogeneous distribution of water in the wetland and a reduction in retention time.
IE-CW-015	Insufficiencies in the maintenance of the wetland vegetation cover that enables the growth of trees and/or shrubs whose shade causes a low density or heterogeneous vegetation density.

Table A1. *Cont.*

Code	Initiating Events
IE-CW-016	Insufficiencies in the maintenance of the wetland vegetation cover that enables the growth of trees and/or shrubs that in turn causes anomalies in the waterproofing layer. These anomalies allow the entry of water from the groundwater table and the occurrence of a very high water level or surface flow. This favors a low density or heterogeneous vegetation density and the chlorosis of the plants.
IE-CW-018	Insufficiencies in the maintenance of the wetland vegetation cover that enables the growth of trees and/or shrubs that in turn causes anomalies in the wetland dikes. These anomalies induce a very high water level or surface flow when water enters from outside causing a low density or heterogeneous vegetation density and chlorosis of the plants.
IE-CW-020	Insufficiencies in the maintenance of the wetland vegetation cover that allows the weeds growth, which in turn induces an abnormal growth of the vegetation during the start-up.
IE-CW-021	Low organic load in the feed of the wetland which causes the occurrence of chlorosis of plants and their death.
IE-CW-022	A lack of nutrients in the wetland's feed (mainly iron but also other nutrients, such as nitrogen and sulfur, can lead to chlorosis and plant death). This scarcity may result from low concentrations or non-assimilable forms.
IE-CW-023	The poor development of the rhizomes which causes the occurrence of chlorosis of the plants and their death.
IE-CW-024	Waste accumulation in the areas surrounding the wetland that favors the occurrence of rodent pests, which in turn causes anomalies in the perimeter fence and/or the gate. These anomalies allow the entry of animals that damage the wetland plants.
IE-CW-025	Waste accumulation in the areas surrounding the wetland that favors the occurrence of rodent pests, which in turn causes damage to the waterproofing layer allowing the entry of water from the groundwater table and the occurrence of a very high water level or surface flow that provokes a low density or heterogeneous vegetation density and the chlorosis of the plants.
IE-CW-027	Waste accumulation in the areas surrounding the wetland that favors the occurrence of rodent pests, which in turn causes damage to the wetland dikes, inducing a very high-water level or surface flow when water enters from outside. This causes a low density or heterogeneous vegetation density and chlorosis of the plants.
IE-CW-029	Waste accumulation in the areas surrounding the wetland that favors the occurrence of rodent pests, which in turn causes damage to the vegetation cover during start-up, causing its abnormal growth, which favors the weeds' growth.
IE-CW-030	Waste accumulation in the areas surrounding the wetland that favors the occurrence of rodent pests, which in turn causes damage to the vegetation cover during operation, causing abnormal growth of the latter, which favors the weeds' growth.
IE-CW-031	The accumulation of suspended solids as a result of the reversible obstruction of the matrix pores and the clogging of the substrate, which in turn causes a very high-water level or surface flow.
IE-CW-033	The accumulation of plant debris around the wetland in a state of putrefaction.
IE-CW-034	The growth of the microorganisms responsible for the treatment of residuals, which causes a reversible obstruction of the matrix pores and clogging of the substrate, which in turn induces a very high level of water or surface flow.
IE-CW-036	Chemical precipitation and deposition in the pores which causes a reversible obstruction of the matrix pores and clogging of the substrate which induces a very high level of water or surface flow.
IE-CW-038	Growth of the rhizomes and roots which causes an irreversible obstruction of the matrix pores and clogging of the substrate which in turn induces a very high level of water or surface flow.
IE-CW-039	The accumulation of solids transported by wastewater that has not been eliminated in the pretreatment, causing anomalies in the distribution or collection system, which in turn induces a low density or heterogeneous vegetation density and the obstruction of the matrix pores and clogging of the substrate.
IE-CW-040	The inadequate maintenance of the level control mechanism that induces a very high water level or superficial flow causing the low density or heterogeneous vegetation density and their chlorosis.
IE-CW-042	The inadequate regulation of the level control mechanism that induces a very high water level or superficial flow causing the low density or heterogeneous vegetation density and their chlorosis.
IE-CW-044	Breaks in the protective layer against solar radiation that causes anomalies in the waterproofing layer on the edge of the dikes, which in turn allows residual water to drain into the subsoil.

Table A1. *Cont.*

Code	Initiating Events
IE-CW-045	The incorrect use of cutting tools that causes anomalies in the waterproofing layer which allow the entry of water from the groundwater table and the occurrence of a very high-water level or surface flow. This favors a low density or heterogeneous density of the vegetation and the chlorosis of the plants.
IE-CW-047	The use of seeds without certification of being free of weeds, which causes abnormal vegetation growth during the start-up of the wetland.
IE-CW-048	The inadequate maintenance of the fence and the gate of the facility, which causes them to break and, as a consequence, the entry of animals that damage the plants and the structural components of the wetland.

Table A2. Defenses implemented (B—barriers; FR—frequency reducers; CR—consequence reducers) in the wastewater system based on constructed wetland "El Dorado".

Code	Barriers
B-1	Grids at the inlets of the grey water collectors (VR)
B-2	Grease trap in the grey water hydraulic system (VR)
B-3	Parshall channel to monitor the flow rate located at the output of the system (R)
B-4	Evacuation of the sludge from the septic tanks of the houses once levels above the permissible levels are detected (N)
B-5	Presence of the septic tank of the wetland (redundancy of functions) (VR)
B-6	Periodic inspection to verify the status and operation of the wetland, the status of the surrounding areas, and the completion of the corresponding records (N)
B-7	Periodic characterization of the wetland effluent and notification of its ineffectiveness if it exists. Filling in the corresponding records (N)
No.	**Frequency reducers**
FR-1	Awareness of the inhabitants of the houses of the negative behaviors of the people that cause a malfunction of the residual treatment system (S)
FR-2	Training of the inhabitants of the houses in the safe ways to evacuate the used oils (S)
FR-3	Elimination of weeds as soon as they are detected (N)
FR-4	Cleaning debris from the ground cover after pruning (N)
No.	**Consequence reducers**
CR-1	Replant the vegetation cover and remove dead plants, if they exist (N)
CR-2	Eliminate weeds present in the wetland (N)
CR-3	Replace substrate (N)
CR-4	Remove dead plant debris from the surface of the wetland (N)
CR-5	Remove trees and shrubs present in the wetland (N)

Note: The values in parentheses correspond to the robustness of the barriers (VR—Very robust; R—Robust, N—Normal; S—Soft).

References

1. Derradji, R.; Hamzi, R. Multi-criterion analysis based on integrated process-risk optimization. *J. Eng. Des. Technol.* **2020**, *18*, 1015–1035. [CrossRef]
2. Tušer, I.; Oulehlová, A. Risk assessment and sustainability of wastewater treatment plant operation. *Sustainability* **2021**, *13*, 5120. [CrossRef]
3. Łój-Pilch, M.; Zakrzewska, A. Analysis of risk assessment in a municipal wastewater treatment plant located in upper Silesia. *Water* **2019**, *12*, 23. [CrossRef]
4. Trávníček, P.; Junga, P.; Kotek, L.; Vítěz, T. Analysis of accidents at municipal wastewater treatment plants in Europe. *J. Loss Prev. Process Ind.* **2022**, *74*, 104634. [CrossRef]
5. Jaskulak, M.; Sotomski, M.; Michalska, M.; Marks, R.; Zorena, K. The effects of wastewater treatment plant failure on the gulf of gdansk (southern baltic sea). *Int. J. Environ. Res. Public Health* **2022**, *19*, 2048. [CrossRef] [PubMed]

6. Gorgoglione, A.; Torretta, V. Sustainable management and successful application of constructed wetlands: A critical review. *Sustainability* **2018**, *10*, 3910. [CrossRef]
7. Kochi, L.Y.; Freitas, P.L.; Maranho, L.T.; Juneau, P.; Gomes, M.P. Aquatic macrophytes in constructed wetlands: A fight against water pollution. *Sustainability* **2020**, *12*, 9202. [CrossRef]
8. Qian, G.; Wang, C.; Gong, X.; Zhou, H.; Cai, J. Design of Constructed Wetland Treatment Measures for Highway Runoff in a Water Source Protection Area. *Sustainability* **2022**, *14*, 5951. [CrossRef]
9. Younas, F.; Bibi, I.; Afzal, M.; Niazi, N.K.; Aslam, Z. Elucidating the Potential of Vertical Flow-Constructed Wetlands Vegetated with Different Wetland Plant Species for the Remediation of Chromium-Contaminated Water. *Sustainability* **2022**, *14*, 5230. [CrossRef]
10. Chen, J.; Wei, X.D.; Liu, Y.S.; Ying, G.G.; Liu, S.S.; He, L.Y.; Yang, Y.Q. Removal of antibiotics and antibiotic resistance genes from domestic sewage by constructed wetlands: Optimization of wetland substrates and hydraulic loading. *Sci. Total Environ.* **2016**, *565*, 240–248. [CrossRef]
11. Vymazal, J. The historical development of constructed wetlands for wastewater treatment. *Land* **2022**, *11*, 174. [CrossRef]
12. Salomón Llanes, J.; Perdomo Ojeda, M. *Análisis de Riesgo Industrial*; Instituto Superior de Investigación y Desarrollo, Centro de Altos Estudios Gerenciales ISID: Caracas, Venezuela, 2001.
13. IAEA. Application of the Risk Matrix Method to Radiotherapy. In *IAEA-TECDOC-1685*; IAEA: Vienna, Austria, 2016.
14. Sierra Gil, K.; Torres Valle, A. Matriz de riesgo tridimensional aplicada a una evaluación de Bioseguridad en una práctica de hemodiálisis. *Rev. Cuba. Salud Trab.* **2020**, *21*, 13–21.
15. Falakh, F.; Setiani, O. Hazard identification and risk assessment in water treatment plant considering environmental health and safety practice. *E3S Web Conf.* **2018**, *31*, 06011. [CrossRef]
16. Pérez-Salazar, R.; Mora-Aparicio, C.; Alfaro-Chinchilla, C.; Sasa-Marín, J.; Scholz, C.; Rodríguez-Corrales, J.Á. Biogardens as constructed wetlands in tropical climate: A case study in the Central Pacific Coast of Costa Rica. *Sci. Total Environ.* **2019**, *658*, 1023–1028. [CrossRef] [PubMed]
17. Bydalek, F.; Myszograj, S. Safe surface concept in vertical flow constructed wetland design to mitigate infection hazard. *J. Environ. Sci. Health Part A-Toxic/Hazard. Subst. Environ. Eng.* **2019**, *54*, 246–255. [CrossRef] [PubMed]
18. Rajan, R.J.; Sudarsan, J.S.; Nithiyanantham, S. Efficiency of constructed wetlands in treating *E. coli* bacteria present in livestock wastewater. *Int. J. Environ. Sci. Technol.* **2019**, *17*, 2153–2162. [CrossRef]
19. Davila, P.A. The Evaluation of a Subsurface-Flow Constructed Wetland for On-Site Wastewater Treatment under the NSF/ANSI Standard 40 Protocol Design Loading. Doctoral Dissertation, Baylor University, Waco, TX, USA, 2007.
20. Grinberga, L. Water Quality Assurance with Constructed Wetlands in Latvia. In *Water Resources Quality and Management in Baltic Sea Countries*; Springer Nature Switzerland AG: Cham, Switzerland, 2020; pp. 87–103.
21. Khan, Z.M.; Kanwar, R.M.A.; Farid, H.U.; Sultan, M.; Arsalan, M.; Ahmad, M.; Shakoor, A.; Aslam, M.M.A. Wastewater Evaluation for Multan, Pakistan: Characterization and Agricultural Reuse. *Pol. J. Environ. Stud.* **2019**, *28*, 2159–2174. [CrossRef]
22. Torres, A.; Montes de Oca, J. Nuevo algoritmo para análisis de riesgo en radioterapia. *Nucleus* **2015**, *58*, 39–46.
23. Turon Planella, C. *EDSS-Maintenance Prototype: An Environmental Decision Support System to Assess the Definition of Operation and Maintenance Protocols for Horizontal Subsurface Constructed Wetland*; Universidad de Girona: Girona, Spain, 2006.
24. Torres Valle, A.; Amador Balbona, Z.; Alfonso Laguardia, R.; Elías Hardy, L.L. SECURE-MR-FMEA código cubano para análisis integral de riesgo de prácticas con radiaciones ionizantes. *Nucleus* **2021**, *69*, 44–56.
25. Analouei, R.; Taheriyoun, M.; Safavi, H.R. Risk assessment of an industrial wastewater treatment and reclamation plant using the bow-tie method. *Environ. Monit. Assess.* **2020**, *192*, 33. [CrossRef]
26. Analouei, R.; Taheriyoun, M.; Amin, M.T. Dynamic Failure Risk Assessment of Wastewater Treatment and Reclamation Plant: An Industrial Case Study. *Safety* **2022**, *8*, 79. [CrossRef]
27. FRTR Constructed Wetlands. Available online: https://www.frtr.gov/matrix2/section4/4-43.html (accessed on 22 March 2023).
28. Mueller, B.; Payer, F.; Goswami, D.; Kastury, S.; Kornuc, J.; Harman, C.; Eger, P.; Patel, M.; Cates, D.; Talkington, D. *Technical and Regulatory Guidance Document for Constructed Treatment Wetlands*; Interstate Technology and Regulatory Council Wetlands Team: Washington, DC, USA, 2003.
29. Tilley, E.; Ulrich, L.; Luethi, C.; Reymond, P.; Zurbruegg, C. *Compendium of Sanitation Systems and Technologies*, 2nd ed.; Swiss Federal Institute of Aquatic Science and Technology Eawag: Duebendorf, Switzerland, 2014.
30. Brown, D.S.; Kreissl, J.F.; Gearhart, R.A.; Kruzic, A.P.; Boyle, W.C.; Otis, R.J. *Manual—Constructed Wetlands Treatment of Municipal Wastewaters*; EPA/625/R-99/010 (NTIS PB2001-101833); Science Inventory, US EPA: Cincinnati, OH, USA, 2000.
31. Pérez, Y.A.; García-Cortés, D.; Jauregui-Haza, U.J. Humedales construidos como alternativa de tratamiento de aguas residuales en zonas urbanas: Una revisión. *Ecosistemas* **2022**, *31*, 2279. [CrossRef]
32. EPA Conducting a Human Health Risk Assessment. Available online: https://www.epa.gov/risk/conducting-human-health-risk-assessment#tab-1 (accessed on 21 March 2023).
33. Wu, H.; Gao, X.; Wu, M.; Zhu, Y.; Xiong, R.; Ye, S. The efficiency and risk to groundwater of constructed wetland system for domestic sewage treatment-A case study in Xiantao, China. *J. Clean. Prod.* **2020**, *277*, 123384. [CrossRef]
34. Ilyas, H.; van Hullebusch, E.D. Performance comparison of different constructed wetlands designs for the removal of personal care products. *Int. J. Environ. Res. Public Health* **2020**, *17*, 3091. [CrossRef] [PubMed]

35. Omondi, D.O.; Navalia, A.C. *Constructed Wetlands in Wastewater Treatment and Challenges of Emerging Resistant Genes Filtration and Reloading*; Book Inland Water: Frankfurt, German, 2020.
36. *ISO 31000*; Gestión de Riesgo—Directrices. ISO: Geneva, Switzerland, 2018. Available online: https://dgn.isolutions.iso.org/obp/ui#iso:std:iso:31000:ed-2:v1:es (accessed on 23 February 2023).