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# Use of risk analysis as a tool for water quality safety

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**ABSTRACT**
This study aimed to use the risk assessment approach "Failure Mode and Effect Analysis" (FMEA) as a water quality safety methodology in the supply system of Belém/PA (Brazil). Eight water quality parameters were used as indicators. Analyzes were carried out at 46 points in the central supply zone, including treatment stations, reservoirs, and the network. The FMEA was applied to all indicators, and the points were divided into three groups: network, reservoirs, and treatment plants. For the network, 18 points of moderate and high risk were identified. For reservoirs and treatment plants, all points presented a moderate risk. In this research, there was no occurrence of negligible, low, or critical risk. The indicators fluoride, total coliforms, and E. coli were the most influential, 15% each, in the risk weights. The fluorine indicator contributed to an increase in the risk category, as it showed 100% non-compliance with Brazilian standards. A risk map was prepared, representing the risks related to water quality for each of the points studied. The risk assessment methodology proved to be an important water safety management tool.

**KEYWORDS:** Water quality safety. Water supply. Risk analysis.

## 1 INTRODUCTION

Risk assessment is an essential element and a systematic process of evaluating the impact, occurrence, and consequences of human activities on systems or activities with dangerous characteristics (van Duijne et al., 2008) and is an indispensable tool for the company's security policy.

In the 1990s, Covello and Merkhofer (1993) defined risk as "characteristic of a situation or action in which two or more effects are possible, but the particular effect that will occur is uncertain and at least one of the possibilities is undesirable". Another definition is from Woodruff (2005), who states that risk is the chance that someone or something that is valued will be adversely affected by the hazard. Hoj and Kroger (2002) also defined risk as uncertainty about the severity of danger, and Haimes (2009) as a measure of the probability and severity of undesirable effects. It should be emphasized, in all definitions, the probabilistic character expressed by the term possibility or chance and the undesirable character of possible effects. Hazard is broadly defined as an intrinsic characteristic of the substance or process that can potentially cause harm (Hoj and Kroger, 2002).

Risk analysis is a widely applied activity by risk management engineers and analysts in any industry (Garcia, 2013). The results provide information for decisions to be taken in a given critical point system (Fullwood, 2000). Risk analysis is based on several assumptions and concepts that characterize it as a flexible methodology that can be applied in different areas of knowledge, in addition to having the possibility of adaptation. In general, this methodology allows, based on the knowledge of possible factors, agents, or situations that may cause unwanted events, to outline intervention measures to control them (Bastos et al. 2009).

According to Brasil (2006), the control and surveillance of water quality are essential tools for protecting the health of consumers, therefore, there are fewer cases of diseases related to the poor quality of drinking water, which has a positive impact on the health system.

On the subject of quality and the search for improvements, risk analysis has recently been used in water supply systems to improve the production process. According to Brown (1998), risk analysis is the study of identification, evaluation, and recommendations applied to industrial installations or other activities that may generate risks. The supply of water for human

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consumption outside potability standards is associated with risks (for example, contamination by pathogens) - that is, the application of risk analysis methodologies to identify and predict the occurrence of undesirable effects in the system is possible.

The diversity of procedures for risk analysis and assessment is such that there are many techniques appropriate for all circumstances and the choice has become a matter of preference (Rouvroye and van den Bliek, 2002).

Given the numerous methodologies for analysis and risk assessment, the "Failure Mode and Effect Analysis" (FMEA) was chosen due to its simplicity of application and high flexibility to adapt to many situations. FMEA is a technique that aims to identify and eliminate failures, problems, and/or known or potential errors in a system, process, or service before they reach the final consumer (Stamatis, 1995). FMEA has been used in several areas of industry and knowledge, including automotive, aerospace, nuclear, electronics, chemical, mechanical, environmental, and others (Chang et al., 2001; Chin et al., 2009; Sharma et al., 2005; Zambrano and Martins, 2007).

The traditional FMEA consists, first, of the formation of a multidisciplinary team, followed by the identification of possible failures in the system or product, through systematic sessions of team discussions. After that, a review of these failure modes is carried out taking into account the factors of occurrence (O), severity (S), and detection (D). The objective is to quantify the failures to determine priorities in the allocation of resources or actions for the most critical risks (Liu et al., 2012).

Considering the presented context, the objective of the research was to use the risk analysis approach with the application of the FMEA methodology, to evaluate the water quality in the water supply system of Belém-PA. The application of the FMEA aims to allow a careful evaluation of possible critical points in the water supply system of Belém-PA, identifying potential failures and establishing priorities for the implementation of preventive and corrective actions. In addition, the research contributes to the improvement of water quality management, promoting water security.

## 2 METHODOLOGY

Data were collected at 46 supply points in the central zone, covering eight sectors (Figure 1). For each point, determinations of free residual chlorine (FRC), turbidity, apparent color, pH, fluoride, total iron, total coliforms, and E.coli were performed. To choose the points, geographic factors were considered, such as distance from the network to the treatment plant, reservoir exit, more densely populated areas, areas with populations in precarious health conditions, and vulnerable consumers.

10 campaigns were carried out, from March to December 2015. Totaling 460 collections and 3680 physical-chemical and microbiological determinations (8 parameters). Analytical procedures followed Standard Methods for Water and Sewage Analysis (APHA, 1998).

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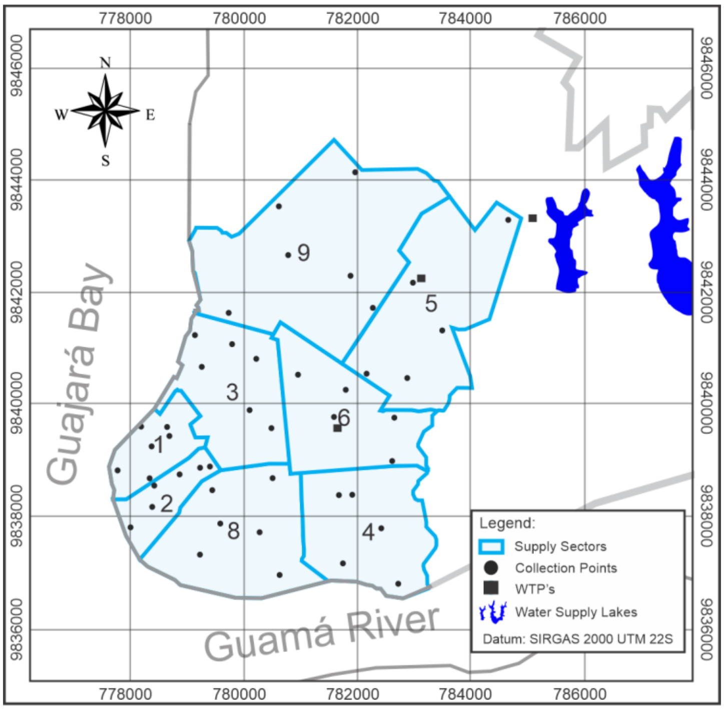
Figure 1. Location of collection points




Source: Authors, 2023.

To detect suspicious values (outliers that are not representative of the sample universe), the Grubbs test (1969) was applied. The outliers found were discarded.

## 2.1 Application of FMEA

The FMEA was carried out in five stages: planning, analysis of potential failures, assessment of potential failures, risk weighting, and calculation of the total risk.

The planning stage includes the study of the object, that is, the quality of the water supply system. In this phase, specialists were selected who participated in the multidisciplinary team, being responsible for the analysis and evaluation of possible failures. The team of experts was composed of five Masters of Science in the area.

For the analysis of possible failures, a meeting was held with the Failure Modes and Effects Analysis (FMEA) team to identify potential failures, and their sources and recommend mitigating measures, resulting in the preparation of a failure form. Additionally, a quantitative risk assessment table was built, which was essential to support the group's decision-making and provide subsidies for the subsequent stage.

The form consists of potential risks, their causes, severity (S), occurrence (O), detection (D), Scope (A), risk priority number (RPN), and mitigation measures.

During the evaluation of possible failures, each participant of the FMEA team received the form from the previous step along with a table of scores. Completion of the form was based on detailed discussions about the characteristics of the risks studied, their causes, effects, and possible mitigation measures. The score table was used to assign values to fields S, O, D, and A of the form, ranging from 1 to 3, where higher scores indicate greater risks. This approach

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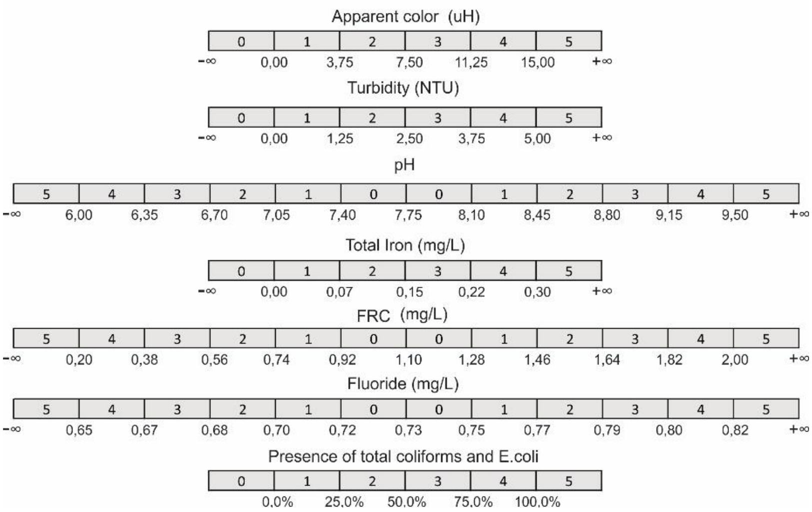
allowed for a systematic and quantitative risk assessment and was essential to support the group's decision-making process and provide input for the next stage of the process.

The indicators used in the survey were classified - from 0 to 5 - where values closer to zero represent less risk, while values closer to 5 represent greater risks, as shown in Figure 2.

Figure. 2. Classification of indicators.




Source: Authors, 2023.

The classification of the indicators was carried out considering the Brazilian standards of potability, but it could have been based on specific goals established by the supply company. The classification of the indicators was used in the total risk calculation stage.

After completing the scores (severity, occurrence, detection, and scope), the weighting of the risks was calculated, which defines the degree of relevance of each risk. The general risk was considered as the sum of all the risks raised in this research, thus calculating the percentage of the relevance of each risk concerning the total system, according to Equation 1.

$$P = \frac{R_1}{\sum_1^n R} \qquad \text{(Eq. 1)}$$

In Equation 1, the elements represented by the variables are the following: P corresponds to the weighting, $R_1$ represents the individual risk, n indicates the number of risks considered and $\sum_1^n R$ is the total sum of risks.

In the step of calculating the total risk, the maximum risk was first determined. This calculation is obtained through the sum of the product of the highest classification of each indicator by risk weighting. Then, risk categorization intervals were defined, ranging from negligible to critical.

Subsequently, the calculation of the total risk was performed for each monitored point. This calculation was performed using the product of the indicator classification and its respective risk weight. Finally, the sum of all products resulted in the total risk of the monitored point. This approach allowed a systematic and quantitative risk assessment.

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## 2.2 Risk map

As a final product, a risk map was generated based on the results of the indicators analyzed using mapping and geoprocessing software.

## 3 RESULTS

It was decided in a meeting with the FMEA team that the data would be divided into 3 groups; one group representing the points of the supply network (NET), another for the reservoir outlets (RV), and the third for the water treatment plants (WTP). The division was carried out in order not to ignore possible characteristic behaviors of each group. The NET group has 36 points, while the RV has 7 points and the WTP group has 3, totaling 46 points.

The hazards of high and low pH, high turbidity, high color, high and low concentration of free residual chlorine, high and low concentration of fluorine, presence of total coliforms and E. coli, and high concentration of total iron were considered. The form was completed for the three groups, considering severity (S), occurrence (O), detection (D), and Scope (A). Then, risk weighting was immediately carried out (Tables 1 and 2).

Table 1. Risk weights of the NET and RV groups

| Danger Parameter | S | O | D | A | Risk RPN | % |
|---|---|---|---|---|---|---|
| Low pH | 2 | 1 | 2 | 3 | 12 | 6,67 |
| High pH | 2 | 1 | 2 | 3 | 12 | 6,67 |
| High turbidity | 3 | 1 | 1 | 3 | 9 | 5,00 |
| High apparent color | 3 | 1 | 1 | 3 | 9 | 5,00 |
| Low concentration of CRL | 3 | 1 | 2 | 3 | 18 | 10,00 |
| High concentration of CRL | 3 | 1 | 1 | 2 | 6 | 3,33 |
| High concentration of fluoride | 3 | 1 | 3 | 3 | 27 | 15,00 |
| Low concentration of fluoride | 1 | 3 | 3 | 3 | 27 | 15,00 |
| Presence of total coliforms | 3 | 1 | 3 | 3 | 27 | 15,00 |
| Presence of E. coli | 3 | 1 | 3 | 3 | 27 | 15,00 |
| High concentration of total iron | 2 | 1 | 1 | 3 | 6 | 3,33 |
| **Total Risk** | | | | | **180** | **100,00** |

Source: Authors, 2023.

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Table 2. WTP group risk weightings

| Danger Parameter | S | O | D | A | Risk RPN | % |
|---|---|---|---|---|---|---|
| Low pH | 2 | 1 | 2 | 3 | 12 | 6,74 |
| High pH | 2 | 1 | 2 | 3 | 12 | 6,74 |
| High turbidity | 3 | 1 | 1 | 3 | 9 | 5,06 |
| High apparent color | 3 | 1 | 1 | 3 | 9 | 5,06 |
| Low concentration of CRL | 3 | 1 | 2 | 3 | 18 | 10,11 |
| High concentration of CRL | 2 | 1 | 1 | 2 | 4 | 2,25 |
| High concentration of fluoride | 3 | 1 | 3 | 3 | 27 | 15,17 |
| Low concentration of fluoride | 1 | 3 | 3 | 3 | 27 | 15,17 |
| Presence of total coliforms | 3 | 1 | 3 | 3 | 27 | 15,17 |
| Presence of E. coli | 3 | 1 | 3 | 3 | 27 | 15,17 |
| High concentration of total iron | 2 | 1 | 1 | 3 | 6 | 3,37 |
| **Total Risk** | | | | | **178** | **100,00** |

Source: Authors, 2023.

To calculate the maximum risk, the maximum score (5) was used for all indicators, respecting the excluding risks (for example, high and low pH, high and low concentration of FRC or fluorides). The criterion used was to disregard the exclusionary risks that did not occur during monitoring (Tables 3 and 4).

Table 3. Maximum risk for the NET and RV groups

| Parameter | Maximum Rating | Risk % | Risk Total | Risk Interval | Risk Classification |
|---|---|---|---|---|---|
| Low pH | 5 | 6,67 | 33,00 | 0,00 ≤ x ≤ 0,94 | Negligible |
| High turbidity | 5 | 5,00 | 25,00 | 0,94 < x ≤ 1,87 | Moderate |
| High apparent color | 5 | 5,00 | 25,00 | 1,87 < x ≤ 2,81 | High |
| Low concentration of CRL | 5 | 10,00 | 50,00 | 2,81 < x ≤ 3,75 | Critical |
| Low concentration of fluoride | 5 | 15,00 | 75,00 | | |
| Presence of total coliforms | 5 | 15,00 | 75,00 | | |
| Presence of E. coli | 5 | 15,00 | 75,00 | | |
| High concentration of total iron | 5 | 3,33 | 16,67 | | |
| **Total** | | | **375** | | |
| **Maximum Risk** | | | **3,75** | | |

Source: Authors, 2023.

Table 4. Maximum risk for the WTS group

| Parameter | Maximum Rating | Risk % | Risk Total | Risk Interval | Risk Classification |
|---|---|---|---|---|---|
| Low pH | 5 | 6,74 | 33,71 | 0,00 ≤ x ≤ 0,95 | Negligible |
| High turbidity | 5 | 5,06 | 25,28 | 0,95 < x ≤ 1,89 | Moderate |
| High apparent color | 5 | 5,06 | 25,28 | 1,89 < x ≤ 2,84 | High |
| Low concentration of CRL | 5 | 10,11 | 50,56 | 2,84 < x ≤ 3,79 | Critical |
| Low concentration of fluoride | 5 | 15,17 | 75,84 | | |
| Presence of total coliforms | 5 | 15,17 | 75,84 | | |
| Presence of E. coli | 5 | 15,17 | 75,84 | | |
| High concentration of total iron | 5 | 3,37 | 16,85 | | |
| **Total** | | | **379,21** | | |
| **Maximum Risk** | | | **3,79** | | |

Source: Authors, 2023.

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The risk at each point was calculated (obtained through the product of the classification - obtained in Fig. 2 - by the weight parameter), resulting in 28 points of moderate risk and 18 of high risk. The NET group scored 18 points for moderate and high risk. The RV group scored 7 points for moderate risk. The WTP group scored 3 moderate risk points (Table 5).

From the risk data obtained in the previous step, it was possible to construct the risk map of the water supply system in the central area of Belém (Fig. 3).

According to the risk map, it was observed that the 2nd sector presented the highest risk. Following the 2nd sector, the highest risk sectors were the 8th and 3rd, both neighbors of the 2nd sector. The higher risk in these sectors was mainly due to the presence of total coliforms and E.coli. For the 2nd sector, there were 10 occurrences of total coliforms and 4 of E.coli, while for the 3rd and 8th sectors, there were 10 and 8 occurrences of total coliforms, respectively, and no occurrence of E.coli.

Another factor that led to increased risk was the low concentration of fluoride at all points in the survey, causing the indicator to be rated at maximum (5), increasing the risk.

The methodology allowed qualitatively classifying the risks in the studied system, so that, based on the results and data generated, it was possible to visualize the risks and identify where they might occur. The FMEA made it possible to quantify, categorize and map risks, facilitating their management. The use of risk maps provides more comprehensive information, becoming a great advantage in management, allowing the manager, through the definition of goals and the implementation of a continuous cycle of improvement, to attack exactly the critical areas, risks, and their causes, gradually reducing them and providing better quality water for the population.

Another advantage of risk assessment is the easy adaptation of the methodology to the needs of the system, that is, it is possible to change the parameters that the manager considers most relevant for the analysis or change the factors of severity (S), occurrence (O), detection (D) and Scope (A), according to the reality of each system. Thus, the FMEA proved to be a powerful tool for managing water quality in supply systems.

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Table 5. Risks of the NET, RV and WTP groups

| Point | Group | Risk | Point | Group | Risk |
|---|---|---|---|---|---|
| P1.0 | RV | Moderate | P5.0 | WTP | Moderate |
| P1.1 | NET | Moderate | P5.1 | NET | Moderate |
| P1.2 | NET | Moderate | P5.2 | NET | High |
| P1.3 | NET | Moderate | P5.3 | NET | Moderate |
| P1.4 | NET | High | P5.4 | NET | High |
| P1.5 | NET | High | P5.5 | NET | High |
| P2.0 | RV | Moderate | P6.0 | RV | Moderate |
| P2.1 | NET | Moderate | P6.1 | WTP | Moderate |
| P2.2 | NET | High | P6.2 | NET | Moderate |
| P2.3 | NET | High | P6.3 | NET | Moderate |
| P2.4 | NET | High | P6.4 | NET | Moderate |
| P2.5 | NET | High | P8.0 | RV | Moderate |
| P3.0 | RV | Moderate | P8.1 | NET | High |
| P3.1 | NET | High | P8.2 | NET | High |
| P3.2 | NET | Moderate | P8.3 | NET | High |
| P3.3 | NET | High | P8.4 | NET | Moderate |
| P3.4 | NET | Moderate | P8.5 | NET | Moderate |
| P4.0 | RV | Moderate | P9.0 | RV | Moderate |
| P4.2 | NET | Moderate | P9.1 | NET | Moderate |
| P4.1 | NET | High | P9.2 | NET | High |
| P4.3 | NET | Moderate | P9.3 | NET | Moderate |
| P4.4 | NET | Moderate | P9.4 | NET | High |
| | | | P9.5 | NET | High |
| | | | WTP Bolonha | WTP | Moderate |

Source: Authors, 2023.

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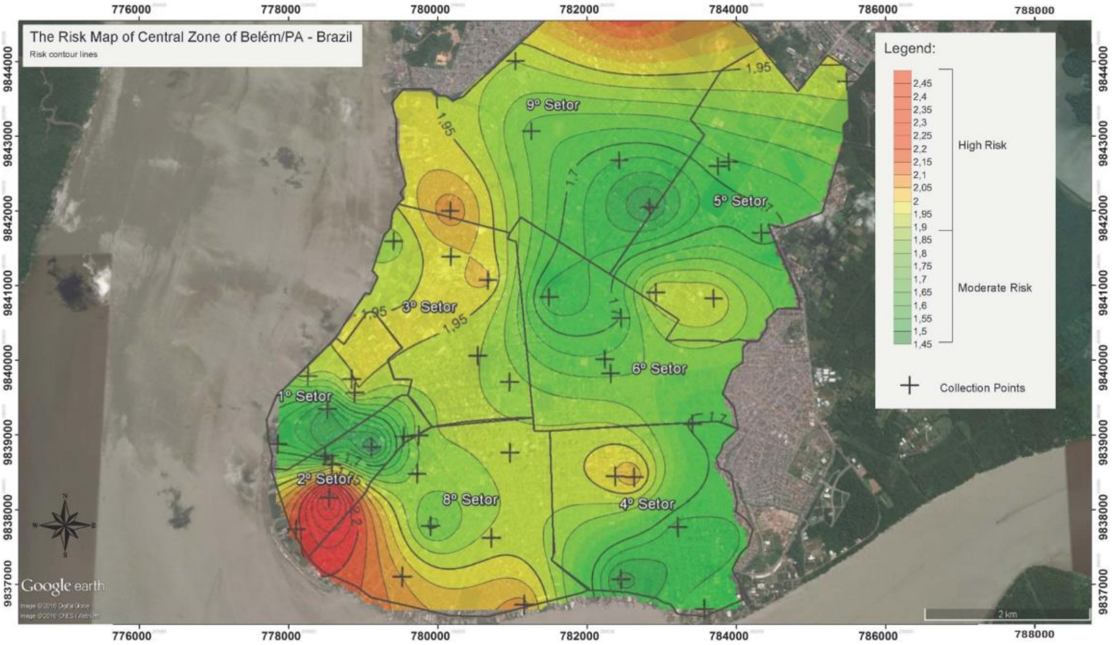
Figure. 3. Risk Map




Source: Authors, 2023.

## 4 CONCLUSIONS

The risk for the central supply zone was considered moderate by the methodology, with 28 points of moderate risk, 18 points of high risk, and no points of negligible risk. Fluoride contributed to an increase in risk at all points. If this deficiency is corrected, there will be a risk reduction, resulting in 28 points of moderate risk and 18 points of negligible risk.

In addition, the risk map created during the FMEA process is an extremely important visual tool for understanding the identified risks and their respective categorization. This graphical representation facilitates the visualization of the most critical points and allows management teams to make decisions in a more objective and agile way, directing their efforts to the most critical points.

Thus, the FMEA methodology proved to be highly efficient for categorizing risks at all points studied and can be used as an important control tool for monitoring water quality. Additionally, it can complement existing monitoring systems or be deployed in locations without management tools. The FMEA is easy to use, improves management, and helps reduce risks, making it a recommended methodology for water quality management.

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