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The Failure Risk Analysis of the Water Supply Network

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Abstract: The primary objective of this work is to introduce a novel approach that modifies the method for analyzing and assessing the risk of water supply network failure. The approach aligns with recommendations from the World Health Organization and the European Union regarding the reliability and safety of water supply to consumers. The presented method for assessing the risk in the water distribution subsystem was based on the vulnerability identifying method (VIM) and involves the determination of the vulnerability index (VI). The VIM vulnerability factors considered encompass the failure rate, chemical stability of water, and issues related to water corrosion properties in water distribution subsystems. The obtained risk assessment includes parameters such as the probability of hazard occurrence, the consequences of these hazards, and vulnerability to them. This concept was evaluated using real operational data from the water distribution subsystem. The estimated risk level, under the given operating conditions, indicates its acceptability.

Keywords: water supply reliability; water distribution subsystems; risk assessment; vulnerability; operational data; risk level; consumer safety

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1. Introduction

The occurrence of water pipe failures poses a significant challenge to the operational functioning of the system [1]. It is crucial to bear in mind that the water supply network operates under fluctuating conditions, encompassing variations in both pressure and flow parameters [2]. These variations predominantly arise from the time-dependent distribution of water throughout the network [3]. A prevalent issue observed in numerous municipal water supply systems is the substantial oversizing of the network, leading to a reduction in water flow velocity, accumulation of sediment in pipelines, and, consequently, unfavorable flow conditions [4]. These conditions can potentially contribute to the deterioration of water quality within the water supply network [2,5–7]. Such occurrences can be attributed to either unpredictable incidents, deliberate human interference, or the cumulative effects of factors such as time, excessive pressure within pipes, unfavorable hydraulic conditions, and inadequate adaptation of water quality parameters to the local conditions and materials employed [5–8]. The malfunctioning of the water supply network can also be impacted by inadequately designed structural concepts for the network, improper selection of hydraulic conditions during network operations (such as an excessively high operating pressure or insufficient use of fittings to safeguard against water hammer), corrosive characteristics of the soil, fluctuations in temperature, and other related factors [9–13]. A framework for dynamic nodal vulnerability assessment in water distribution networks, considering demand variations, operational status, and multilayer networks, providing more realistic evaluations and insights for maintenance scheduling concerning the risk associated with water supply network failures was introduced among others in the studies [14]. The primary consideration revolves around safeguarding the health and safety of consumers. A dependable water supply is paramount in preventing waterborne diseases and sustaining daily life. Vulnerabilities leading to disruptions or contamination events can result in dire health consequences [15–17]. According to the findings presented in reference [18], the primary factors contributing to the approximately 600 emergency events that transpired in the water distribution subsystem within the United States from 1971 to 1998 were attributed to insufficient water treatment practices (accounting for 44.1% of incidents) and the occurrence of chemical and microbiological contamination within the water distribution subsystem (constituting 18.3% of incidents). These issues arose as a consequence of secondary water contamination.

Water quality within a water supply network is influenced by a range of factors, each capable of causing alterations and potential risks. These factors are pivotal to comprehend and manage in order to ensure a dependable and safe water supply [19–25]. The susceptibility to corrosion of the selected pipe material can significantly affect water quality. A cornerstone of vulnerability assessment is the availability of accurate and comprehensive data [26]. The challenge lies in collecting, maintaining, and updating these data to reflect the evolving network infrastructure adequately. A recorded collection of water main failures is accessible, but the ultimate data do not pinpoint the underlying reasons that led to those failures [27–29]. The question of what led to the failure, such as corrosion, transverse cracking, longitudinal cracking, etc., can be answered. However, identifying the root cause or origin of the failure is significantly more challenging [30,31]. An example that highlights the issue is a failure associated with pipeline corrosion. Potential factors contributing to this could include soil corrosion, insufficient passive and active corrosion protection measures, or corrosive properties of the water [32,33]. Furthermore, the duration of operation alone is not always the primary factor behind a network section's high failure rate. There are documented instances of grey cast iron water mains that have been in service for approximately 80, or even 100 years, maintaining good technical condition. Conversely, there are also relatively newer mains that require complete replacement despite their shorter lifespan [25,34,35]. A significant issue concerning the functioning of the water distribution subsystem is the mechanism for gathering, storing, and analyzing data regarding any disruptions in its operation and the statistical information pertaining to emergency situations that arise [36–38]. An uncertainty quantification framework for accurate failure rate prediction in water distribution networks was developed in [39] using a deep learning-based approach that considers the randomness and uncertainty of pipe failures, demonstrating superior prediction accuracy compared to a statistical regression model.

Sustainability approaches in the planning of network utilities' transmission and maintenance, which aim to enhance reliability and fairness in the allocation of maintenance teams, present decision-making challenges, and the utilization of the maximum-flow model is recommended for these utilities to consider reliability and stocks, emphasizing the importance of cooperation among zone owners to optimize transmission reliability and maintenance income [40]. An adequate and efficient data collection system for failures should encompass essential details such as the failure date, type of failure, and precise information identifying the water supply network [14,41,42]. A comprehensive and effective system for collecting failure data should encompass several crucial elements [43]. These include recording the failure date, specifying the type of failure, providing precise information to identify the water supply network, such as the type of water mains (mains, distribution, connections to buildings), material composition (steel, grey cast iron, ductile iron, plastic), pipeline diameter, age, and working pressure. Additionally, the system should gather data on the location of the water supply network, ground conditions, foundation depth, time taken for failure removal, potential causes of the failure, the resulting effects, and probable consequences [44–47]. This requires extensive databases and the use of IT systems such as SCADA [48,49].

Dynamic nature of the water networks are subject to constant change due to expansion, maintenance, and evolving demand patterns [50–52], therefore, keeping vulnerability models current is an ongoing challenge. It should be remembered that establishing and maintaining a reliable vulnerability model necessitates substantial resources, both in terms of technological infrastructure and expert proficiency, which may not always be readily accessible [53–55].

The objective of this research is to introduce an enhanced approach for analyzing and evaluating the risk associated with water supply network failures.

The proposed novel approach consists of three critical parameters: the probability of occurrence (P) of emergency events that pose a threat to the safety of the water distribution subsystem, the consequences (C) that would result from such events, and the system's vulnerability (V) under specific operational conditions. The vulnerability parameter (V) is inherently intricate, influenced by a multitude of factors, including the technical attributes of the network itself, such as the material used, as well as the specific type of hazard being analyzed for risk assessment.

Consequently, evaluating parameter V is a complex task. To address this challenge, we propose an innovative method known as the vulnerabilities identifying method (VIM). This approach revolves around identifying the factors that impact vulnerability levels within the water supply network. The method involves categorizing these vulnerability factors and assigning them ranking point values and w_{ij} point weights. Subsequently, these values are used to calculate the vulnerability index (VI). A detailed description of all the components are presented in Tables 1–3.

In the initial phase of the analysis, the aim is to identify the factors that can potentially affect the network's vulnerability to specific types of failures, such as water pipe ruptures leading to leakage, secondary water contamination, pipe leaks, or fittings failures. By employing this methodology, the study aims to provide a more comprehensive and accurate assessment of the potential risks and vulnerabilities associated with water supply network failures.

2. Method for Assessing the Risk in Water Distribution Subsystems

Risk value can be described by the so-called risk function f(r), the domain of which is a set of positive real numbers $\Omega \rightarrow R^+$ representing the dependence of the parameters: probability of occurrence of emergency events, constituting a threat to the safety of the water distribution subsystem (P), consequences (losses, effects) in the case of occurrence of an emergency (undesirable) event (C), vulnerability of the system (V). Therefore, it can be written that risk is a function of three parameters r = f(P, C, V). In risk analysis, the priority is to identify potential hazards and estimate the likely consequences of their occurrence [56–63]. Assume that, from a system safety perspective, we are primarily interested in the hazards likely to cause the most severe consequences [17,44,64–69].

The outcome of the risk analysis should be the expected values of specific loss values (e.g., risks to health or life of water consumers). From a mathematical point of view, the expected value is determined from the relationship [70–72]:

- or a continuous random variable:

$$\mathrm{E(C)} = \int_{\mathrm{C}=0}^{\infty} C \times \mathrm{dP(C)} = \int_{\mathrm{C}=0}^{\infty} \mathrm{C} \times \mathrm{P(C)dc} = r \tag{1}$$

- for the discrete variable:

$$\mathrm{E(C)} = \sum_{\mathrm{i,j}=1}^{\mathrm{n,m}} \mathrm{C_i} \times \mathrm{P_j} = \mathrm{r_{i,j}} \tag{2}$$

where:

- C_i—an independent variable describing the specific loss value;
- P(C)—the probability of the adverse events in the interval [0,C];
- P_j—the probability, that a loss will result from an adverse event;
- i = 1, 2, . . ., n and C_0 = 0;
- n—number of intervals describing the loss parameter C;
- j = 1, 2, . . ., m and P_0 = 0;

- m—number of intervals describing the probability parameter P.

Determining the risk based on the proposed three adopted parameters, the formula takes the form of Equation (3):

$$r = C_i \times P_j \times V_k \quad (3)$$

In the three-parameter risk matrix the parameters are:

- C_i—hazard consequences (assumed depending on the type of water supply network, according to Table 1);
- P_j—hazard occurrence probability (assumed depending on the failure rate λ, according to Table 2);
- V_k—vulnerability to hazards (adopted on the basis of the risk factors, according to Table 3 and Formula (5)).

Starting from the definition of risk (Formula (2)), the individual risk values can be represented as a $M_{r(i,j,k)}$ matrix. The elements of the $M_{r(i,j,k)}$ matrix are the risk values $[r_{i,j,k}]$.

For the parameters adopted in this way, the data matrix for the $M_{r(i,j,k)}$ water supply network risk analysis is as follows:

$$M_{r(i,j,k)} = \left[r_{i,j,k}\right] = \begin{bmatrix} r_{111} & r_{211} & r_{311} \\ r_{112} & r_{212} & r_{312} \\ r_{113} & r_{213} & r_{313} \\ r_{121} & r_{221} & r_{321} \\ r_{122} & r_{222} & r_{322} \\ r_{123} & r_{223} & r_{323} \\ r_{131} & r_{231} & r_{331} \\ r_{132} & r_{232} & r_{332} \\ r_{133} & r_{233} & r_{333} \end{bmatrix} \quad (4)$$

where:

- i—point weight for parameter C, i = {1,2,3};
- j—point weight for parameter P, j = {1,2,3};
- k—point weight for parameter V, k = {1,2,3}.

The values of Tables 1–3 were defined on the basis of interviews with the network operator and many years of observations of the water supply company's employees based on monitoring of the network operation. Additionally, these parameters were discussed by an independent expert from the water supply industry.

The following evaluation criteria were proposed for the individual parameters:

- For the loss parameter C_i. Evaluation criteria were adopted depending on the number of inhabitants (LM) exposed to the possibility of a hazard resulting in a shortage or restriction of a water supply according to Table 1.

Table 1. Evaluation criteria for parameter C_i.

Point Weight (i)	Parameter Description (Inhabitants LM)
1	1–5000
2	5001–50,000
3	>50,000

- For the probability parameter P_j the evaluation criteria i were adopted depending on the failure rate value λ of the water supply network or exceedances. Table 2 proposes a procedure for the evaluation of the parameter P_j depending on the range of the frequency of occurrence of a failure event or failure rate and the different types of water mains: mains (M), distribution (D), water supply connections (WC).

Table 2. Evaluation criteria for parameter P_j.

Point Weight (j)	Parameter Description	Range of Incidence Emergency Event/Exceedance f_i [Event/a]		λ [no. of Failures·km^{-1}·a^{-1}]		
				M	**D**	**WC**
1	unlikely	≤0.1	**OR**	≤0.3	≤0.5	≤1
2	medium probability	(0.1–2>		(0.3–0.5>	(0.5–1>	(1.0–2>
3	likely	>2		≥0.5	≥1	≥2

- For the vulnerability parameter V_k. The vulnerability parameter is complex and its magnitude can be influenced by various factors depending on the technical conditions of the network itself (e.g., type of material), but also on the type of hazard under consideration, for which the risk is analyzed. Therefore, the procedure to value this parameter is complex. For this purpose, an original method for the analysis of this parameter is proposed. The VIM method is based on the identification of factors influencing the degree of vulnerability. The proposed method is based on the classification of vulnerability factors on the water supply network and the assignment of R_i ranking point values and w_{ij} point weights to them, followed by the calculation of the vulnerability index (VI) according to Formula (5). In the first step of the analysis, the factors that can affect the vulnerability of the network to a given type of failure (e.g., water pipe failure resulting in water leakage, secondary water contamination in the network, pipe leakage, fittings failure) should be identified.

In this way, the value of the vulnerability index *VI* calculated according to Formula (5) is obtained:

$$VI = \sum_{i=1}^{n} R_i \times w_{ij} \tag{5}$$

where:

- VI—vulnerability index;
- R_i—rank of ith risk factor (degree of importance);
- w_{ij}—weight jth of this factor;
- i = 1, 2 . . . , n;
- n—number of factors taken into account;
- j = 1, 2, 3.

For each identified factor, depending on the degree of influence on the vulnerability index, a rank point value R_i is assigned as follows:

- (0–1]—neglected,
- [2–3]—low importance,
- [4–6]—moderately important,
- [7–8]—important,
- [9–10]—very important.

The values of the importance of the w_i factor are taken according to the so-called degree of exposure according to a scale: 1—low, 2—medium, 3—high.

Table 3 proposes classes of identified influencing factors for the analysis of the vulnerability of the water supply network to failure. The table can be modified for given operating conditions of the water distribution subsystem.

Table 3. Classes of factors and R_i and w_{ij} values for the determination of the parameter VI.

Influencing Factor	**Rank R_i**	**Weight of the Factor w_{ij}**		
		Low = 1	**Medium = 2**	**High = 3**
Age of the water supply network	9	to 10 years	(10–30) years	>30 years
Network material	6	plastics	steel	grey cast iron
Hydrogeological factors influencing the network	8	good	average	bad
Monitoring of the network operations	5	above standard comprehensive monitoring of the water distribution network through the measurement of water pressure and flow rates. possession of specialized equipment for detecting water leaks using acoustic methods, unrestricted 24-h communication with the public via a dedicated phone line, monitoring of water quality within the WDN through a protection and warning system	standard simplified monitoring of the water distribution network, primarily through pressure measurements, inability to promptly respond to minor leaks. periodic water quality testing within the water distribution network	none lack of monitoring of network and water quality
Measures taken to prevent corrosion	4	full	standard	none
Network location—including factors such as dynamic loads and density of underground components	3	small pipeline in the not urbanized areas	average pipeline in the street	big pipeline in the pedestrian traffic
Hydraulic conditions within the network	7	good favorable working conditions of the water supply network: v = 1.0–1.5 m/s, water age < 24 h, smooth pressure regulation depending on hourly water consumption	average average conditions of waterworks network operation: network in mixed, v = 0.5–1.0 m/s, water age < 24–48 h, pressure regulation depending on hourly water consumption	bad unfavorable conditions of waterworks network operation: network in open system, v < 0.5 m/s, water age > 48 h, no pressure regulation depending on hourly water consumption
Chemical stability of the water supplied by the network *	8	low water is chemically stable with the following parameters: Langelier saturation index I_L = 0, or Ryznar index I_R = 6.2–6.8, or Strohecker index I_{st} < 0.5) [73–75]	medium mild corrosion, does not produce protective $CaCO_3$ layers, with the following parameters: Langelier Saturation Index I_L = −3 to 4, or Ryznar Index I_R = less than 8.5, or Strohecker Index I_{st} > 0.5, except when there is low susceptibility (Langelier Saturation Index I_L = 0 and Ryznar Index I_R = 6.2–6.8) and high susceptibility (Langelier Saturation Index I_L = 3 to 4 and Ryznar Index I_R = less than 5.5) [73–75]	high rapid corrosion, does not produce protective $CaCO_3$ layers, with the following parameters: Langelier Saturation Index I_L = −4 to −5, or Ryznar Index I_R = more than 8.5 and less than 5.5 or Strohecker Index I_{st} > 0.5, or Langelier Saturation Index I_L = 3 to 4, or Ryznar Index I_R = less than 5.5, or Strohecker Index I_{st} > 0.5 [73–75]

Notes: * A single corrosivity parameter is sufficient to meet a given chemical stability condition, or, if all designated parameters are available, the parameter with the most acceptable value [76].

Table 4 proposes a procedure to value the parameter V_k depending on the VI determined according to Equation (5).

Table 4. The value of vulnerability index VI.

Point Weight (k)	Value of VI
1	<100
2	101–160
3	>160

For each risk value, point range and corresponding risk levels are proposed in Table 5, according to Equations (3) and (4).

Table 5. Proposed risk categories.

Risk Level	Point Range
Accepted	1–8
Controlled	9–18
Unacceptable	19–27

Figure 1 summarizes the process of applying the vulnerability identification method. The subsequent sections provide explanations for each of the procedures illustrated in Figure 1.

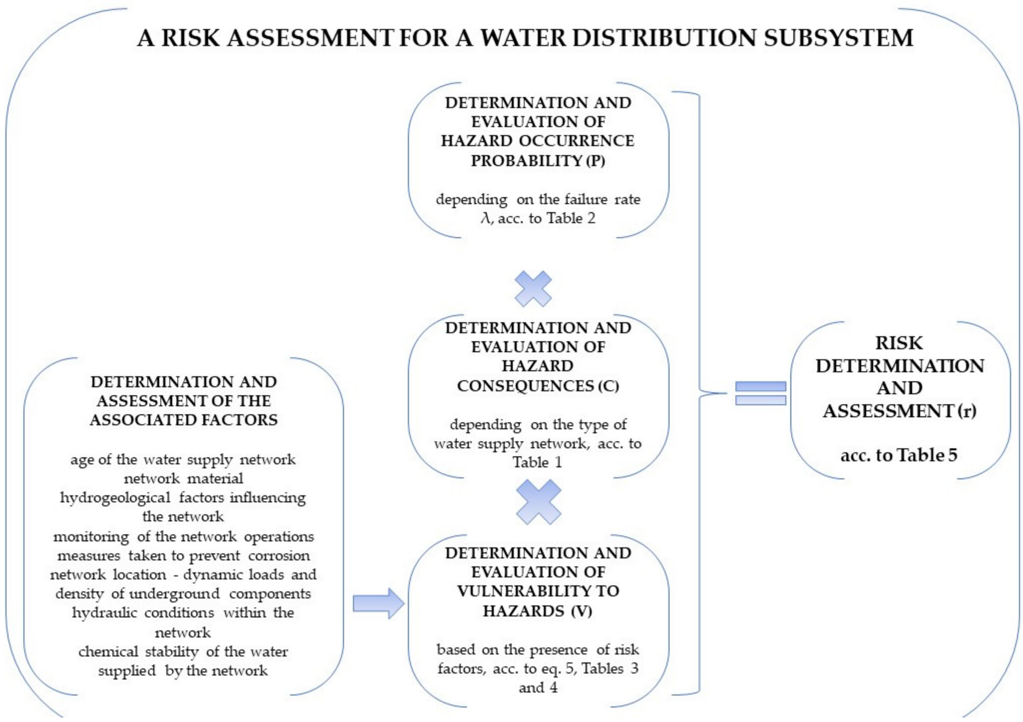

Figure 1. Flowchart for assessing the risk for a water distribution subsystem.

3. Characteristics of the Study Object

A collective water supply system (CWSS) is defined as a technical system (system of technical devices) whose task is to deliver water to places of use in a specific quantity, of appropriate quality and required pressure, at any time convenient for the water recipient. For the water supply system to fulfil its purpose function, it should: supply the population with water, which is an essential means of life, maintain healthy living conditions, ensure appropriate comfort of life, supply water to economic units (industrial and service plants) for which water is the main raw material for production and a factor in almost all technological processes of economic activity. Each water supply system has its own specificity and consists of interrelated subsystems that form an integral whole.

CWSS includes the following subsystems:

- Water intake and pumping subsystem.
- Water treatment subsystem.
- Water transmission subsystem.
- Water storage subsystem.
- Water distribution subsystem (water supply network with utilities).

The basic subsystem ensuring the safety and reliability of water supply to consumers is the water distribution subsystem. In accordance with the definition given in PN-EN-805:2002: Water supply. Requirements for systems external and their components [77], the water distribution subsystem begins at the outlet from the water treatment plant (or the source in the absence of treatment) and ends at the point of connection to the water recipient's installation. The water distribution subsystem includes a network of water supply pipes and water pumping stations located at selected points (possibly hydrophore plants) and water storage tanks.

In the water distribution subsystem, which is one of the subsystems that make up the CWSS, adverse events are divided into three basic categories:

- Accident events causing losses on a small scale, but occurring relatively frequently. These types of events include failures of the water distribution network and water supply connections, failures of individual devices.
- Emergency events causing medium-scale losses that occur relatively rarely. These include failures in water mains, incidental contamination in the source of intake water.
- Catastrophic events that occur relatively rarely but cause significant losses.
- Adverse events in the water distribution subsystem can therefore be divided into:
- Failures of water supply lines and fittings (e.g., material defects, corrosive soil, too high pressure, age of the pipes).
- Secondary water pollution in the water supply network.
- Failures of water supply pumping stations.
- Incidental events, i.e., contamination of water sources, failures of water treatment plants, water contamination in network water supply tanks.
- Action of forces of nature (droughts, landslides, rainfall).
- Actions of third parties (acts of vandalism, terrorist and cyberterrorist attacks).
- The effects of the above-mentioned events are:
- Interruptions in water supply or its complete lack.
- Secondary contamination of tap water.
- Loss of safety of water consumers due to consumption of poor quality water.
- Financial losses related to the purchase of bottled water, medical costs.
- Water losses and financial losses incurred by the water supply company related to network flushing, network disinfection, costs of repairing failures, lack of water sales.
- Compensation paid to water consumers.
- Washing out of the bottom layer of the substrate due to the action of water flowing from the damaged pipe, which results in unsealing of subsequent sections of the network.
- Loss of trust in the water recipient–water supplier relationship.

The occurrence of water supply network failures is a complex process that requires a thorough analysis of the causes of their occurrence. Failure tests of the water supply network carried out so far in scientific units throughout Poland have enabled the development of a program of operational reliability tests, which can specify:

- Preliminary stage (research preparation).
- Analysis of the structure of facilities and the process of their operation and functioning.
- Obtaining and verifying operational data.
- Processing the collected data and determining reliability characteristics objects.
- Use of processed data (research results).

The water distribution subsystem is exposed to the constant occurrence of adverse events that have a direct impact on the reliability and safety of water supply to recipients.

It is difficult to provide a clear classification of the causes causing damage to the water supply network. Generally, factors increasing the failure rate can be identified as errors at the design stage, errors and omissions during construction, operation of the network, and material defects, and also incidentally as a result of other factors (e.g., works carried out in the vicinity without taking appropriate protective measures, excessive loads from road traffic). A measurable, negative effect of a water supply network failure is water loss due to leaks, which occurs in virtually all waterworks. They are one of the basic elements of assessing the technical condition of the water supply system.

The analyzed object is the water distribution subsystem in a major city in south-eastern Poland. This city serves as the hub for local and regional government offices, as well as governmental and judicial institutions. Additionally, it plays a crucial role in the aviation, commercial, service, and construction sectors. As of 31 December 2021, the city's population, as reported by the municipal office, was 198,609 residents. The water supply network being analyzed functions primarily as a ring water supply network, with 80% of its operations contained within. Two separate sets of clean water tanks, namely water tank 1 (WT1) and water tank 2 (WT2), are situated in the eastern and western parts of the city. The network consists of four primary pipelines that transport treated drinking water from the stage II pumping station located at the water treatment plant.

The majority of pipes within the water supply network being studied are constructed from plastic materials. Specifically, PVC pipes make up approximately 29.4% of the total pipe length, while PE pipes account for around 48.0%. In contrast, steel pipes constitute a mere 3.5% of the overall pipe length, while cast iron pipes make up nearly 14.5%, and asbestos cement pipes represent a mere 0.18%. Connections within the network make up approximately 33.9% (369.5 km), with the mains network comprising approximately 5.7% (62.2 km). The remaining 60% of the network consists of distribution networks, amounting to approximately 656.8 km in length. Overall, the water supply network managed by the water utility has a total length of 1088.5 km, as of 31 December 2020.

The water supply pipes in the city under analysis vary in diameter, ranging from Φ 25 to 1200 mm. Water that has been treated at the water treatment plant (WTP), situated in the southern part of the city, is transported to the city through several main pipes.

These main pipes include:

- Main line No. "0", with a diameter ranging from Φ 1200 to 800 mm, made of steel.
- Mains No. "1" and No. "2", both with a diameter of Φ 400 mm, constructed from steel and cast iron.
- Pipe line No. "3", also with a diameter of Φ 400 mm, made from a combination of steel and cast iron materials.

Figure 2 presents the location of the study site.

The water treatment plant (WTP) sources its water from surface water and underwent modernization in the 1990s, incorporating preliminary ozonation of the raw water. The WTP has a maximum daily production capacity of Q_{maxd} = 84,000 m^3. It comprises two independent water treatment plants, namely WTP I and WTP II, situated in a shared location with a common intake.

Regarding emergency water supply options for the city, considering all available water sources, the current possibilities are as follows: the presence of water stored in 11 equalizing reservoirs within the water supply network, with a combined capacity of 34,533 m^3, along with public wells with a total daily capacity of 689.4 m^3, resulting in a cumulative capacity of 35,222.4 m^3 per day.

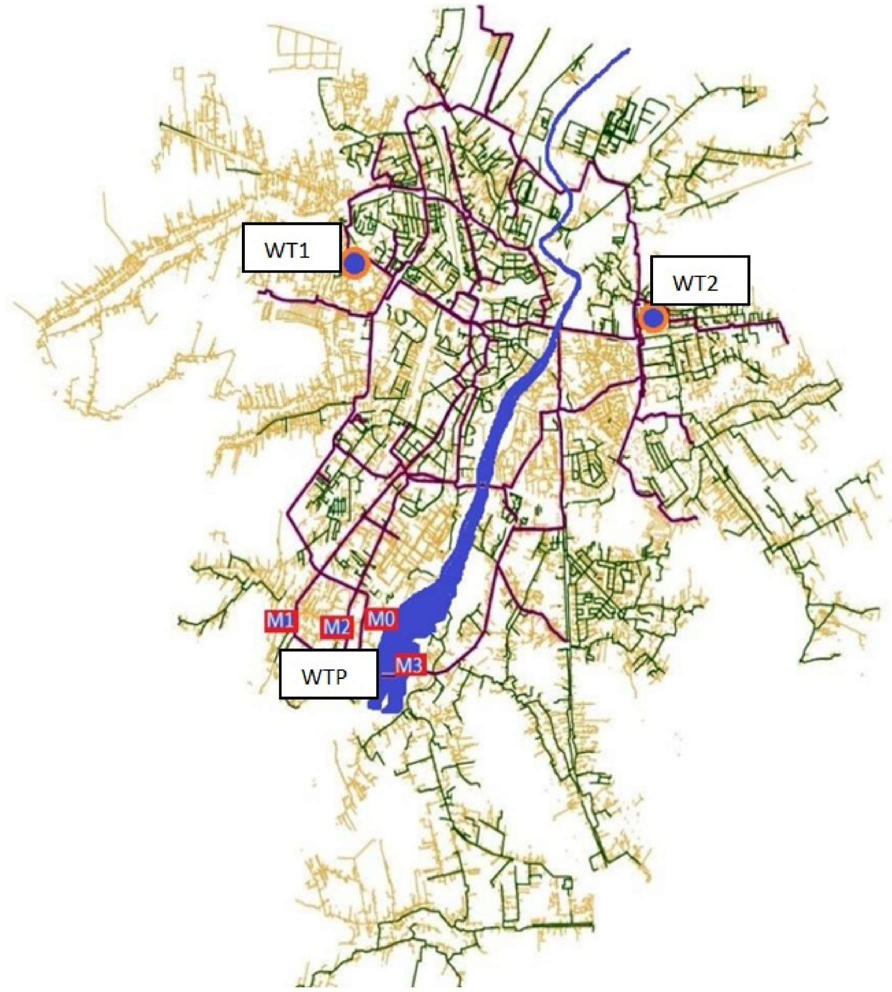

Figure 2. Diagram of the water supply network generated in the GEOMEDIA program (purple color—main pipes).

At present, the water treatment processes involve several stages, including the removal of large contaminants using grates, water ozonation, coagulation, slow mixing, flocculation, sedimentation in horizontal sedimentation tanks with continuous sludge scraping, filtration through a sand bed at WTP I station, and anthracite-sand filtration at WTP II station. Additionally, the treatment includes indirect ozonation, filtration through a carbon bed, preliminary disinfection using UV, final disinfection using chlorine compounds (chlorine gas and chlorine dioxide), and adjustment of water pH as required.

4. Results

4.1. Failure Analysis of Water Supply Network

The first stage of the research work was to carry out detailed analyses of the failure rate of the water supply network. The basis for the research presented in this study was operational data on the functioning of the water supply network, compiled on the basis of failure records obtained from the water supply company in the analyzed city. The analysis of the failure rate of the main and distribution network was carried out taking into account the cause of the failure, the material of the pipes, and the type of network. The analyzed period of operation covered the years 2010–2020. It should be noted that the following boundary conditions were assumed, necessary for carrying out the failure rate analysis:

- the mains consist of pipes with diameters $\geq$ 300 mm;
- the distribution network consists of tpipes with diameters of 90–280 mm.

Figures 3–5 and Tables 6 and 7 show the number of water mains failures, specifying the diameters and materials of the distribution pipes and mains.

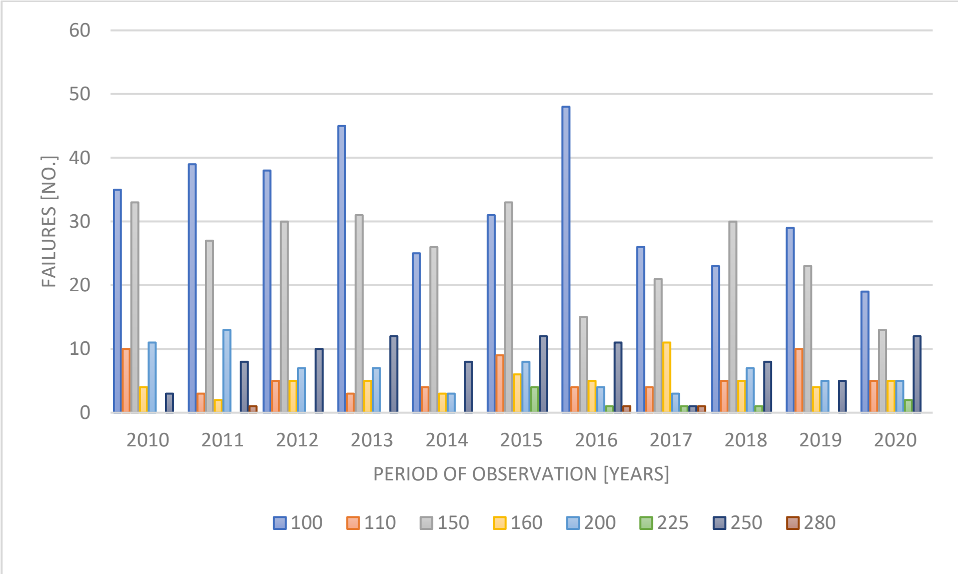

Figure 3. Summary of number of distribution pipes failures depending on diameter (2010–2020).

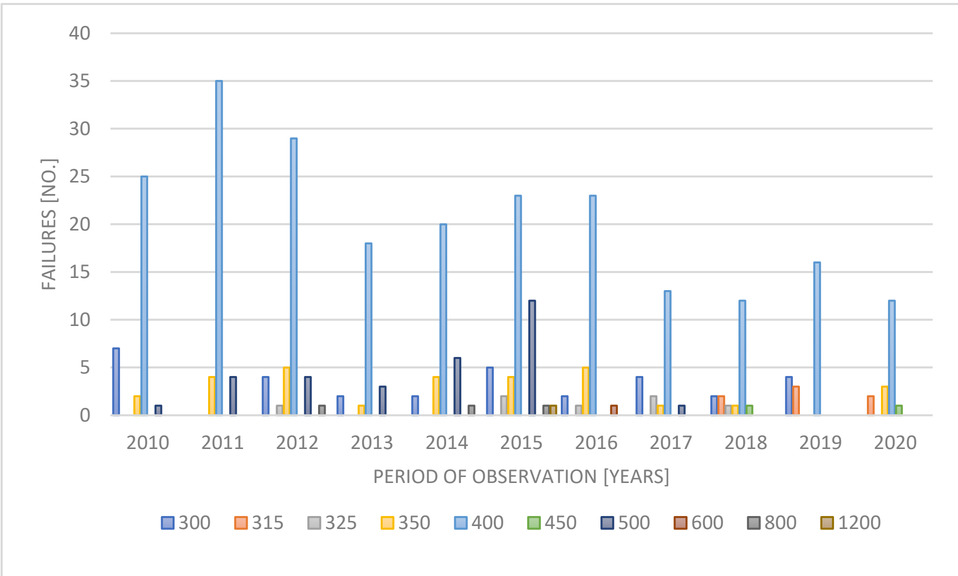

Figure 4. Summary of number of main pipes failures depending on diameter (2010–2020).

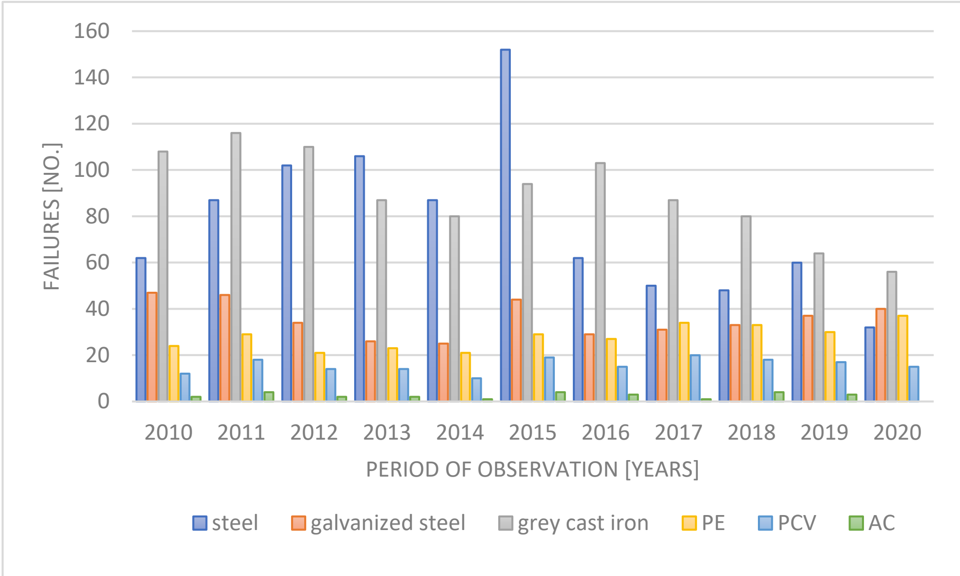

Figure 5. Summary of number of failures by the material structure of pipelines (years 2010–2020).

Table 6. Descriptive statistics for the number of distribution pipe failures depending on diameter (2010–2020).

Statistical Characteristics	Diameter							
	100	110	150	160	200	225	250	280
Std. Dev.	8.85	2.57	7.14	2.17	3.02	1.19	3.61	0.45
Median	31.00	5.00	27.00	5.00	7.00	0.00	8.00	0.00
Avg. value	32.55	5.64	25.00	5.00	6.64	0.82	8.18	0.27
Variance	78.25	6.60	50.91	4.73	9.14	1.42	13.06	0.20
perc. 0.25	25.50	4.00	18.50	4.00	4.50	0.00	6.50	0.00
perc. 0.55	33.00	5.00	28.50	5.00	7.00	0.50	9.00	0.00
perc. 0.75	38.50	7.00	30.50	5.00	7.50	1.00	11.50	0.50

Table 7. Descriptive statistics for the number of main pipe failures depending on diameter (2010–2020).

Statistical Characteristics	No. of Failures									
	Diameter									
	300	315	325	350	400	450	500	600	800	1200
Std. Dev.	2.02	1.07	0.77	1.71	7.02	0.39	3.51	0.29	0.45	0.29
Median	2.00	0.00	0.00	3.00	20.00	0.00	1.00	0.00	0.00	0.00
Avg. value	2.91	0.64	0.64	2.73	20.55	0.18	2.82	0.09	0.27	0.09
Variance	4.08	1.14	0.60	2.93	49.34	0.15	12.33	0.08	0.20	0.08
perc. 0.25	2.00	0.00	0.00	1.00	14.50	0.00	0.00	0.00	0.00	0.00
perc. 0.55	3.00	0.00	0.50	3.50	21.50	0.00	2.00	0.00	0.00	0.00
perc. 0.75	4.00	1.00	1.00	4.00	24.00	0.00	4.00	0.00	0.50	0.00

Table 8 shows the number of failures of water pipes by material.

Table 8. Descriptive statistics for the number of failures by the material structure of pipelines (years 2010–2020).

Statistical Characteristics	No. of Failures					
	Material					
	Steel	Galvanized Steel	Grey Cast Iron	PE	PCV	AC
Std. Dev.	32.51	7.44	18.17	5.12	2.93	1.30
Median	62.00	34.00	87.00	29.00	15.00	2.00
Avg. value	77.09	35.64	89.55	28.00	15.64	2.36
Variance	1056.81	55.32	330.25	26.18	8.60	1.69
perc. 0.25	55.00	30.00	80.00	23.50	14.00	1.50
perc. 0.55	74.50	35.50	90.50	29.00	16.00	2.50
perc. 0.75	94.50	42.00	105.50	31.50	18.00	3.50

Over the analyzed years 2010–2020, there is a clear tendency that the most common failures occurred in pipes with diameters of Φ 150 and 400 mm. This is due to the corrosiveness of the materials from which the pipes were made (steel, cast iron). The smallest number of failures occurred in pipes with diameters of Φ 225 and 280 mm (for the distribution network) and Φ 450, 600, 800, and 1200 mm. This is due to the fact that there are fewer of these pipes in the network. Analyzing the test results in accordance with Table 8, it can be concluded that the most frequently damaged pipes were those made of steel (848 failures) and gray cast iron (985 failures). Currently, the water supply company is successfully carrying out modernization works in order to replace the defective material with a more damage-resistant one, such as PE or PVC.

4.2. Analysis of the Chemical Stability of Water

In order to adopt a weight and rank for the influence factor "chemical stability of water", an analysis and evaluation of the stability of tap water in the study area was carried out. The parameter values of the Langelier index (I_L), Ryznar index (I_R), and Stohecker index (I_{st}) were used to carry out the analysis. The samples were gathered from the whole network and each sample was carefully examined also. The 120 samples were collected from 3 years in equal intervals. The results of the detailed analyses for the water supply network are shown in Figures 6–8.

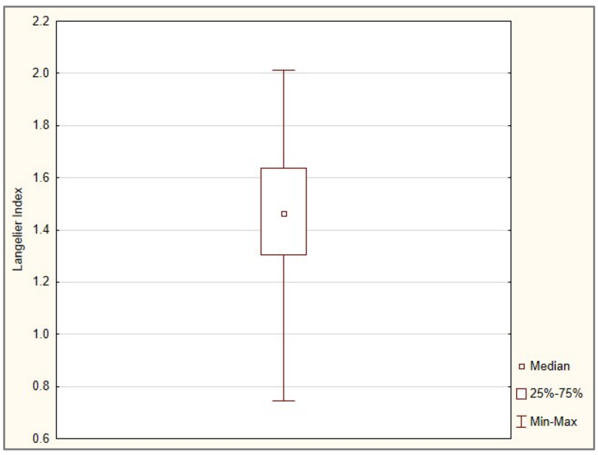

Figure 6. Values of water corrosivity indices for the whole examined network—Langelier index (I_L).

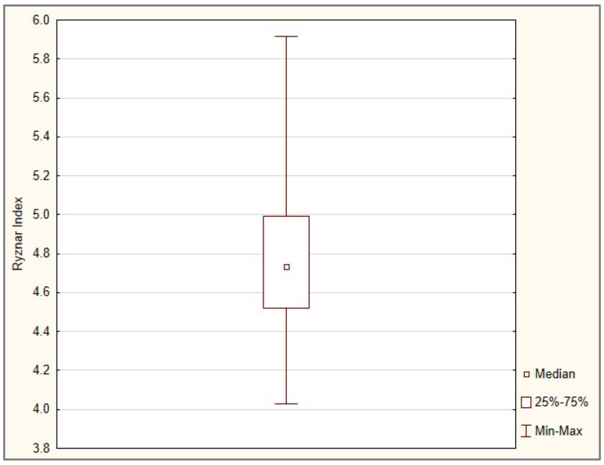

Figure 7. Values of water corrosivity indices for the whole examined network—Ryznar index (I_R).

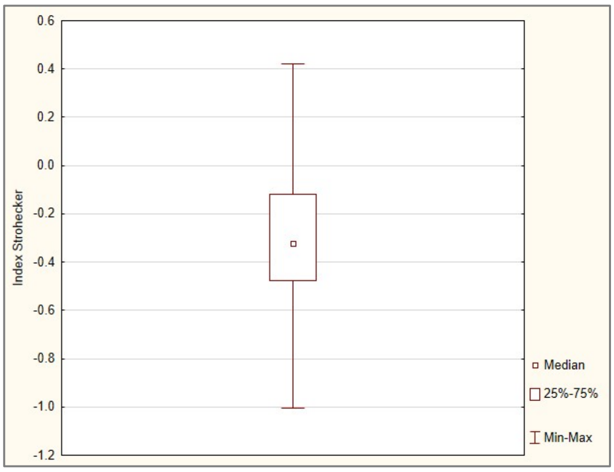

Figure 8. Values of water corrosivity indices for the whole examined network—Stohecker index (I_{st}).

The Strohecker index values obtained for the entire water supply network under consideration indicate non-aggressive water (I_{st} < 0.5) and therefore low susceptibility to pipeline corrosion for all samples tested and the Langelier index values were positive in the range from 0.743 to 2.011 (medium susceptibility), which is characterized by a tendency to precipitate $CaCO_3$ sediments, which is confirmed by the Ryznar index results obtained for 93% of water samples indicating medium susceptibility and for 7% of water samples indicating high susceptibility. According to the adopted criterion values, the susceptibility of the pipeline is low because the water is chemically stable, at least one of the criteria was met, in this case 100% of samples met the following criteria I_{st} < 0.5.

4.3. Failure Risk Analysis of Water Supply Network

The first stage of the study was to select a pipe, which was subjected to a preliminary analysis in order to adopt impact factors (as shown in Table 3) and to determine the vulnerability index (VI). The analysis of the risk of failure of water pipes was carried out for two cases likely to occur in the water distribution subsystem. Two cases were selected for analysis concerning different type, material, and diameter.

In order to graphically present the conducted analyses, available modern GIS tools were used—the GEOMEDIA Professional program. This is a commercial GIS software (QGIS 3.32.3 'Lima') package from Intergraph Corp. The program can be used, for example, as a tool for analyzing spatial data. In the analyzed cases, the GEOMEDIA software (16.8) runs in Windows and has an interface based on it. It is equipped with a set of tools for conducting analyses, such as: queries regarding the attributes and location of objects, determining buffer zones, spatial overlay of information layers, or thematic analysis. The software used allowed us to generate maps intended to present the results of the analyses which were carried out. Such a presentation of data may constitute a source of knowledge and information for the network operator and may be used in planning renovation and repair activities.

4.3.1. Case One Assumes Failure on the Main, Diameter Φ 400 Made of Cast Iron

Figure 9 shows the location of the main that was analyzed.

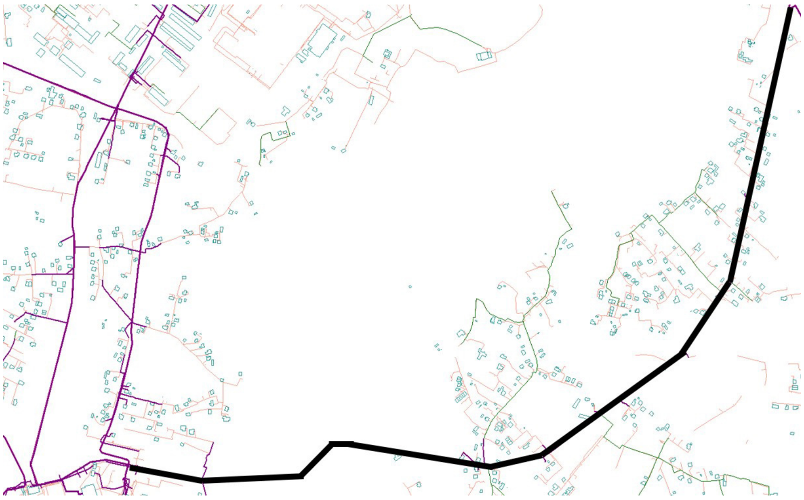

Figure 9. The analyzed main pipe (map generated in the GEOMEDIA program—black color—analyzed pipe Φ 400).

Data necessary for the analysis:

- main water supply pipe located in the southern part of the city, Φ 400 mm made of cast iron;
- according to the Table 2, the value of the P parameter has been assumed at P = 1 because, based on the number of failures recorded in 2020, i.e., <20 failures per year, the failure frequency parameter has been assumed as $f_i \leq 0.1$ events/year;
- according to Table 1, the value of the C parameter has been assumed at the level of C = 2;
- in accordance with Table 3, the following impact factors presented in Table 9 (weight and their rank) necessary for determining the vulnerability index VI were adopted on the basis of the water network operation analysis in order to determine the parameter V.

Table 9. Classes of factors and R_i and w_{ij} values for the first case study.

Influencing Factor	Weight of the Factor w_{ij}	Rank R_i
	3	9
Network material: grey cast iron	3	6
Good hydrogeological factors influencing the network	1	8
Above standard monitoring of the network operations	1	5
No measures taken to prevent corrosion	3	4
Average dynamic loads and average density of underground utilities	2	3
Good hydraulic conditions within the network	1	7
Low susceptibility for the chemical stability of the water supplied by the network	1	8

The obtained statistical values of individual indices allowed use of Formula (5) and Table 9 to determine the value of the vulnerability index VI:

$$\begin{aligned} VI &= R_1 \times w_1 + R_2 \times w_2 + R_3 \times w_3 + R_4 \times w_4 + R_5 \times w_5 + R_6 \times w_6 + R_7 \times w_7 \\ &\quad + R_8 \times w_8 \\ &= 3 \times 9 + 3 \times 6 + 1 \times 8 + 1 \times 5 + 3 \times 4 + 2 \times 3 + 1 \times 7 + 1 \times 8 \\ &= 91 \end{aligned}$$

Based on the determined value of the vulnerability index, VI, the value of the risk vulnerability parameter was assumed to be V = 1, according to Table 4.

After taking into account all the determined risk parameters (P, C, V), according to Formula (3), the risk value of the distribution network failure was determined to be r = 2, which corresponds to the accepted risk.

4.3.2. Case Two Assumes the Failure of the Distribution Network Pipe, Diameter Φ 90 Made of PE Plastic

Figure 10 shows the location of the pipe that was analyzed.

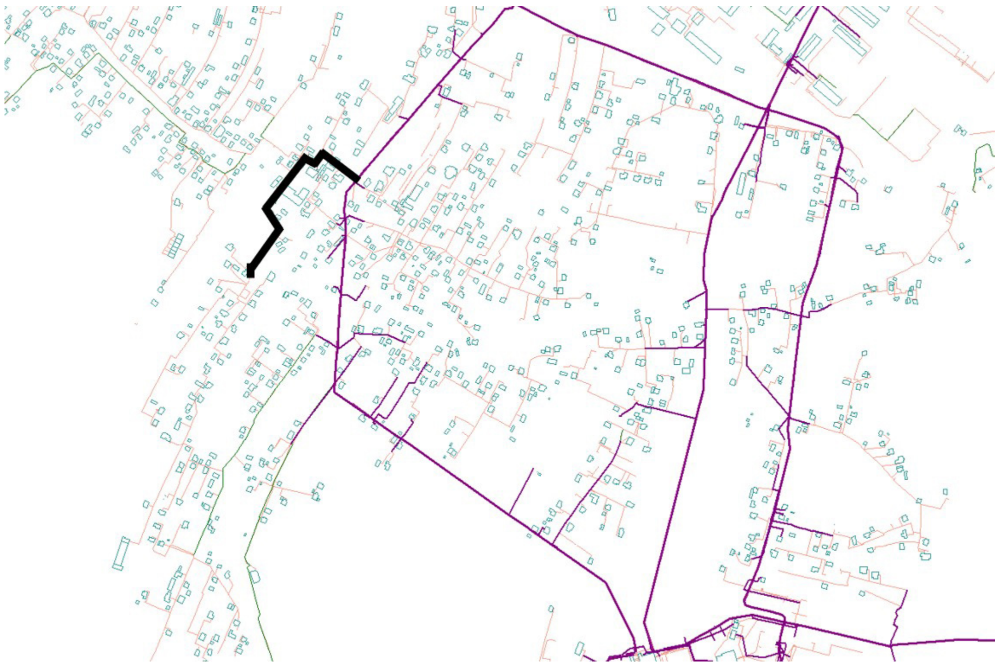

Figure 10. The analyzed distribution pipe (map generated in the GEOMEDIA program—black color—analyzed pipe Φ 90).

Data necessary for the analysis:

- water distribution pipe located in the south-western part of the city, Φ 90 made of PE plastic;
- according to Table 2, the value of the P parameter has been assumed at P = 1 because, based on the number of failures recorded in 2020, i.e., <20 failures per year, the failure frequency parameter has been assumed as $f_i \leq 0.1$ events/year;
- according to Table 1, the value of the C parameter has been assumed at the level of C = 1;
- according to Table 3, in order to determine the parameter V, the following influence factors presented in Table 10 (weight and their rank), necessary for determining the vulnerability index VI, were adopted on the basis of the water network operation analysis.

Table 10. Classes of factors and R_i and w_{ij} values for the second case study.

Influencing Factor	**Weight of the Factor w_{ij}**	**Rank R_i**
Age of the water supply network: 10–30 years	2	9
Network material: plastic	1	6
Good hydrogeological factors influencing the network	1	8
Above standard monitoring of the network operations	1	5
Standard measures taken to prevent corrosion	2	4
Low dynamic loads and low density of underground utilities	1	3
Good hydraulic conditions within the network	1	7
Low susceptibility for the chemical stability of the water supplied by the network	1	8

The obtained statistical values of individual indices allowed use of Formula (5) and Table 10 to determine the value of the vulnerability index VI:

$$\begin{aligned} VI &= R_1 \times w_1 + R_2 \times w_2 + R_3 \times w_3 + R_4 \times w_4 + R_5 \times w_5 + R_6 \times w_6 + R_7 \times w_7 + R_8 \times w_8 \\ &= 2 \times 9 + 1 \times 6 + 1 \times 8 + 1 \times 5 + 2 \times 4 + 1 \times 3 + 1 \times 7 + 1 \times 8 = 63 \end{aligned}$$

On the basis of the determined value of the vulnerability index *VI*, the value of the risk vulnerability parameter was assumed to be VI = 1 according to Table 4.

After taking into account all the determined risk parameters (P, C, V), according to Formula (3), the risk value of the distribution network failure was determined at the level of r = 1, which corresponds to the accepted risk.

The values of the individual risk parameters and the final value are shown in Table 11.

Table 11. Results of the risk analysis.

Type of Failure/Risk	**P**	**C**	**V**	**r**
Failure of the main	1	2	1	2
Failure of the distribution network	1	1	1	1

The value of the risk obtained through a comprehensive analysis serves as a vital tool in making informed decisions regarding the operation and modernization of the system. By conducting a thorough risk assessment, key stakeholders can gain valuable insights into the potential hazards and vulnerabilities associated with the system's current state.

In both analyzed cases, the failure of the main pipe, with a diameter of Φ 400 made of cast iron, and the failure of the distributional pipe, with a diameter of Φ 90 made from PE, resulted in an acceptable risk level. In this particular situation, it is advisable to continuously monitor and uphold the present level associated with water network failure and the quality of drinking water.

Alongside monitoring water quality, it is equally important to sustain an acceptable level of failure rate within the network. This involves implementing strategies to minimize the occurrence of failures, such as leaks, bursts, or disruptions in the distribution system. By actively managing and addressing these issues, the network can operate reliably, minimizing interruptions in the water supply.

It is worth highlighting that the mean annual failure rate in the main pipelines remains below the recommended threshold [65], specifically less than 0.3 no. of failures·km^{-1}·a^{-1}. Similarly, for distribution pipes, the acceptable limit was not exceeded (0.5 no. of failures·km^{-1}·a^{-1}), as well as for water connections, it was less than 1.0 no. of failures·km^{-1}·a^{-1}. To maintain the acceptable failure rate, it is recommended to implement preventive maintenance programs.

These programs can include periodic inspections, routine maintenance tasks, and proactive repairs to address potential vulnerabilities before they escalate into serious failures. By identifying and resolving issues in a timely manner, the overall reliability of the network can be preserved.

The controlled risk approach acknowledges that, while the system is currently operating within acceptable parameters, proactive measures are necessary to ensure its long-term sustainability. By prioritizing modernization and repair activities, potential risks can be mitigated, operational efficiency can be improved, and the overall lifespan of the system can be extended. Ultimately, embracing a controlled risk mindset allows for continuous evaluation, improvement, and optimization of the system, leading to enhanced reliability, reduced downtime, and an overall better service for users.

In the event of encountering an unacceptable level of risk, it is essential to address and mitigate it. Immediate action should be taken to reduce the risk, which may involve modifying the processes in accordance with the hydraulic conditions and employing suitable materials for constructing water supply systems. By implementing these necessary changes, the aim is to establish a safer and more resilient system that can effectively manage and minimize potential risks.

By implementing these recommended changes, it is possible to effectively mitigate the unacceptable risk level and ensure the long-term functionality and safety of the water supply infrastructure.

5. Conclusions and Perspectives

The failure risk analysis method proposed in this paper serves as the foundation for the risk management process and aids in making informed decisions regarding the modernization and renovation of water supply companies. The method outlined conforms with the guidelines outlined in the recent European Parliament and Council Directive (EU) 2020/2184 [78], specifically in the context of safeguarding the quality of water supplied to consumers and mitigating water losses amidst the challenges posed by climate change. As per the Directive's provisions, the responsibility for conducting risk assessment and risk management within the water supply system lies with the European Member States. Also, the suggested approach aligns with the recommendations provided in the World Health Organization (WHO) guidelines for Water Safety Plans (WSPs) [79], which affirms that the most reliable way to consistently ensure the safety of a drinking water supply is through the adoption of a comprehensive risk assessment and risk management approach in the water supply to consumers. The proposed method can be used for different water supply systems and adjusted to their specific characteristics in consultation with the water supply company. Conducting failure risk analysis is pivotal in ensuring the safety of water consumers, a standard that should be upheld in water supply systems. Water companies, being the primary knowledge holders in risk analysis, should establish guidelines for collecting information, which may include expert opinions, to facilitate the risk analysis approach. Furthermore, operators should actively participate in designing and operating water distribution subsystems to ensure their proper functioning and the maintenance of an adequate level of safety from the water source to the end user.

It is crucial for stakeholders in the water supply service industry to be proficient in estimating risks, informing users about service quality, implementing measures to mitigate risks, and initiating actions to minimize the impact of failures.

The method introduced here relies on operational and failure data from the water supply network and has been applied to address the shortcomings of the conventional matrix approach, in which fewer parameters are considered. Compared to existing failure risk assessment methods and conventional matrix approaches, the proposed method incorporates various vulnerability factors that can influence the network's susceptibility to specific types of failures. These factors include failure analysis, operational parameters, and the chemical stability of water.

It is important to emphasize that the choice of risk analysis method in each case should be tailored to the specific system under analysis, considering the available database and the expertise of the analysts conducting the assessment. Due to the relative versatility of the method presented here, it can also be applied to other critical infrastructure systems, such as energy or gas supply networks.

Assessing vulnerabilities in water distribution networks is an imperative undertaking, particularly for consumers. The ramifications extend from health and economic well-being to resource conservation and resilience. However, the complexity and challenges intrinsic to modeling these vulnerabilities cannot be understated. Addressing data constraints, network intricacies, dynamism, multifaceted vulnerabilities, and resource limitations are central to advancing the reliability of vulnerability assessments, thus fortifying the foundations of water distribution network management and consumer-centric well-being.

Future research on this topic should focus on leveraging modern information and communication technologies for risk analysis and assessment, developing decision models for water supply network operators, and establishing criteria, metrics, and indicators for quantifying risk assessments and measuring risk reduction. In addition to the previously discussed recommendations, it is crucial to consider the following perspectives, such as developing AI-Driven Predictive Models, which can play a pivotal role in anticipating vulnerabilities in water distribution subsystems. These models can utilize historical data, real-time monitoring, and machine learning algorithms to predict potential failures or weaknesses in the system. By proactively identifying and addressing these issues, water utilities can reduce the likelihood of disruptions and enhance the efficiency of maintenance efforts. Future research should focus on refining and expanding the capabilities of such models, making them even more accurate and applicable to various types of distribution systems. Also, an important issue constitutes the climate change impact assessment. As climate change continues to pose significant challenges to water resources, it is imperative to investigate its impact on water supply reliability. Future research should aim to understand how changing climate patterns, such as increased droughts, extreme weather events, and altered precipitation patterns, affect water availability and quality. Moreover, researchers should explore the development of adaptive infrastructure solutions that can mitigate the impact of climate change on water distribution subsystems. This may include strategies such as increased water storage capacity, advanced water treatment technologies, and alternative water sources. By pursuing these research directions, we can better equip our water distribution subsystems to withstand future challenges and ensure a sustainable and reliable water supply for communities. These proactive measures will not only enhance the resilience of our infrastructure but also contribute to the overall well-being and prosperity of society.

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