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Case Report

Approaches to Failure Risk Analysis of the Water Distribution Network with Regard to the Safety of Consumers

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Abstract: Contemporary risk assessment makes reference to current world trends, whereby there is increased emphasis on safety. This paper has thus sought mainly to present new approaches to failure risk assessment where the functioning of a water distribution network (WDN) is concerned. The framework for the research involved here has comprised of: (a) an analysis of WDN failure in regard to an urban agglomeration in south-east Poland; (b) failure rate analysis, taking account of the type of a water pipe (mains, distribution, service connections (SC)) and months of the year, with an assessment of results in terms of criterion values for failure rate; (c) a determination—by reference to analyses performed previously—of the compatibility of experts' assessments in terms of standards of failure and obtained results, through rank analysis; and (d) the proposing of a modified Multi-Criteria Decision Analysis with implementation of an Analytical Hierarchy Process, to allow failure risk assessment for the WDN to be performed, on the basis of the calculated additive value of obtained risk. The analysis in question was based on real operating data, as collected from the water distribution company. It deals with failures in the WDN over a period of 13 years in operation, from 2005 to 2017.

Keywords: safety of water supply consumers; risk; water supply system; failure risk analysis; decision making model; risk assessment methodology

1. Introduction

The second half of the twentieth century brought many major accidents and disasters relating to the functioning of public water supply systems (WSS) in urban and industrial agglomerations. In this regard, there can be no doubt that WSS operations are subject to risk [1–6], hence the key importance of risk analysis that determines the location and size of such risk, as well as the actions to be taken with a view to its reduction or elimination [7]. Activities allowing these relations to be studied fall under the heading of risk management, which should be organized and comprehensive, in relation to both the entire WSS and elements associated with it [8]. The risk function is a measure of security loss [9]. There is always the possibility of a domino effect, so events are related to risk escalation [7]. In this regard, the specialist scientific literature makes it clear that methods of quantitative analysis and risk assessment form the basis for safety management in regard to WSS [8,9]. Results of hybrid risk-based decision making gain implementation by reference to pipe design parameters, with authors in work [10] prioritizing pipes in line with their rehabilitation needs. Comparisons of the use of a vulnerability assessment model based on Bayesian Belief Networks and the related uncertainty assessment model were in turn performed in [11], with respect to the emergency management of systems supplying drinking water.

Research on risk in technical systems includes the class of cognitive and practical methods of analysis and assessment, which constitute important elements of comprehensive research into their safety [12]. The following trends of safety research can be distinguished, as risk analysis, where assessment models form the basis for building decision models; and risk engineering, where the assessment of design options in terms of safety is the basis for choosing the best solution [13–15]. A water supply system's (WSS) loss of safety may result directly from the failure of its individual subsystems or elements, such as water intakes, pumping stations, the water distribution network (WDN) or its utilities [16–20]; from the failure of other technical systems (e.g., sewerage, energy, water structures) [21]; from undesirable extreme natural phenomena like floods and droughts; or from the incidental pollution of water sources [22,23]. Risk analysis of the WSS should be preceded by analysis of the reliability of all subsystems in terms of interruptions to water supply [24,25], as well as failure to meet quality requirements for health posing threats to consumers of water [26].

In water supply companies, records of breaks should be gathered, as these come to represent the basic source of information for reliability and safety analyses. Water supply companies should thus have guidelines about the way they collect information, also in the form of expert opinions, so that these can be used in the decision-making model [27–30]. The registers concerned should not only relate to the number of undesirable events, but should also contain precise data on the locations and causes of failure, their duration, repair time, possible consequences and other information required if the basic indicators used in the analysis of the safety of the WSS are to be determined [31–34], with these inter alia including the numbers of failures over the examined period of operation of the WSS, average working time without failure, average repair time, etc. [35–37]. Failures may be due to mistakes in design, construction or operation [38]. On the other hand, the causes of failure can be classified on the basis of the phenomena giving rise to them [39]. The formation of failures in a WDN is in fact a complex problem and each time requires a detailed analysis of the root causes [40–42]. Failures of the WDN can arise from errors directly attributable to activities of the designer, the contractor or the operator of the water supply system, through incorrect assumptions in the design and shortcomings at the stage of performance, mismatched material or improper service [43,44]. Also, the failure of a WDN may be caused by factory defective materials, defective sealing or anti-corrosive coatings [45,46]. There are also environmental causes reflecting meteorological conditions, including sudden changes in temperature and landslides, as well as causes resulting from the functioning of the WDN in combination with improper monitoring [47,48].

The process of risk analysis in regard to the operational safety of the WDN takes place via steps comprising of: determination of the WDN type, limiting values for rates of failure of water supply and the nuisance of performed repairs. These are followed by determination of the types of protection related to the functioning of the WDN, as well as risk levels, where these are assigned to the categories of tolerated, controlled and unacceptable risks [3].

The literature review shows that analysis based on failure rate is suggested for a WDN, as a proper tool for decision support when it comes to managing failures in such a system. The main objective of the work detailed here has then been the proposing of methods by which to identify and assess the risks associated with the functioning of a WSS in Poland, in relation to different implemented approaches. The results of the research allowed for the identification of areas and procedures able to mitigate risk of failure effectively.

2. Legal Regulations Regarding Safety of the Water Supply for Consumers

It is important to underline that the main task of water supply companies is to provide consumers with water of adequate quantity and quality which meets the requirements of the Drinking Water Directive (Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption), with its latest amendments including Commission Directive (EU) 2015/1787 of 6 October 2015. In turn, in 2004, the World Health Organization (WHO) published guidelines for the application of water safety plans in which proposed analysis took in the chain of water supply intended for human consumption, inter alia, the water distribution network.

Analyses and assessments of WSS failure have been conducted in many countries since the second half of the last century [49–57], with obtained conclusions used to improve the programming, design, implementation and operation of the WSS; to inspire improvement and amendment of technical regulations, design standards, guidelines and instructions for the performance and acceptance of facilities; and to raise levels of technical knowledge and professional qualifications among designers, contractors and operators [58]. A very important issue is determination of the criterion value of risk, as a risk may be considered controlled when expected losses resulting from failure are acceptable to both a water company and the consumers of its water [2].

Risk acceptance criteria can be used in the decision-making process regarding the operation of such a system [3]. These criteria should take into account requirements relating to the reliability of subsystem operation, in terms of both quantity and quality, in accordance with applicable legal regulations, as well as social and economic conditions [59–61].

The management of the WSS should be improved constantly, through the pursuit of risk analysis and assessment and risk management in accordance with the recommendations of the WHO and existing regulations. The offer of water supply companies in terms of reliability of operation and water supply system safety should likewise improve constantly, notwithstanding changing economic and legal conditions, and not least in the circumstances of increasing pressure imposed by environmentalists and tougher quality standards relating to water for consumption [62,63].

For the purposes of Poland's Act on Crisis Management, a water supply system falls within the category of critical infrastructure, representing a system of key importance to the functioning of society and the state. As improper functioning of the above systems may pose a threat to human health or life, a high level of reliability and safety must be assured. The Crisis Management Act regulates the principles for the development of crisis management plans aimed at preventing crisis situations from arising, but also reacting should emergencies arise and ensuring the removal of consequences. Steps in the critical infrastructure protection process include risk assessment and indications as to priority activity, with a hierarchy being developed in line with the results of risk assessment carried out. The subject matter under consideration is thus of key importance in ensuring the proper functioning of a WSS.

3. Materials and Methods

3.1. The Failure Risk Approaches of Failure Framework and Data Source

The factors used in analyzing the failure rate among WDN were:

- type of a water pipe (mains, distribution or service connections),
- months in which the network was damaged.

The analysis presented represents a starting point for analysis of failure in a WDN. With this aim in mind, the research started with failure-rate analysis in respect of the aforementioned factors, with analysis of failure rates in line with risk acceptance criteria. To compare different criteria in the assessment of failure rates, and to establish the compatibility of expert assessments, a rank analysis was applied. After this, a proposal for modified Multi-Criteria Decision Analysis as regards assessment of the risk of failure in a WDN was presented.

Data regarding failures of the WDN cover a period of 13 years' operation, from 2005 to 2017. The analysis was carried out with Statsoft software [64]. Operational data were provided from the functioning of a real water supply system controlled by a municipal water company. Data on technical documentation and information obtained from the managers and services were also used.

3.2. Description of the Study Area

The distinguished water supply system is located in Poland's Subcarpathian province. The supplied city is located on the right bank of the Vistula, in south-eastern Poland, where it covers a total area of 86 km^2 and is located at 50°34′ N and 21°40′ E (Figure 1). The city has an urbanization rate of 555 inhabitant/km^2 and is at 160 m above sea level. The area within the city boundary is dominated by arable land, which accounts for some 5500 ha or as much as 65% of the total. About 3000 ha (36% of the area) is genuinely urban in character. The most limited form of cover (accounting for just 140 ha) in turn involves industrial areas, which thus represent no more than about 2% of the city. Climatically, this city is in the zone of lowlands and foothills. This denotes hot summers, relatively small amounts of rainfall (circa 600 mm) and winters that are not especially severe.

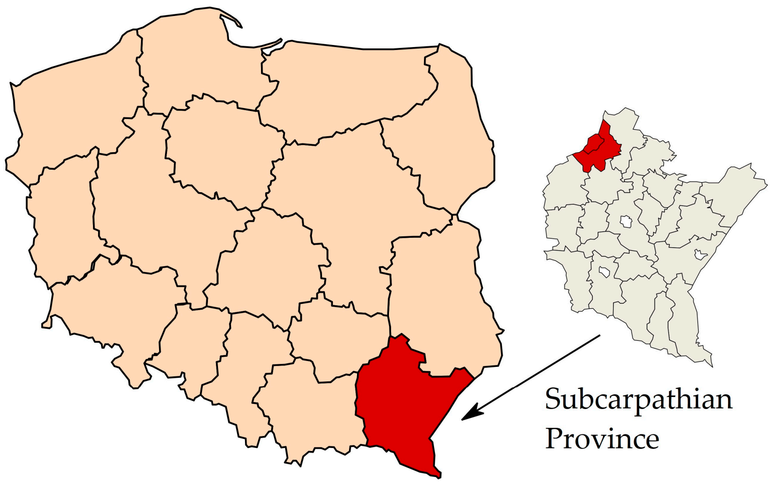

Figure 1. Location of the examined water supply system in Poland's Subcarpathian Province.

3.3. Characteristics of the Research Object

The urban water supply under study is currently used by the entire population of the distinguished city of some 51,000 people, as well as by some 3000 people living in other localities. Currently, the coverage by this water supply is close to 100%, with only single houses not being covered by the collective municipal water supply. In total, the length of the WDN is of 309.95 km.

The transmission of water from the clean water tanks takes place via two mains of diameters 400 and 500 mm. As the sections of mains connect twice in connection chambers, switch offs are possible in case of emergency. The water intake consists of two pumping intakes: the first consists of five drilling wells with a capacity of Q_{emax} = 183 m^3/h and the other consisting of 22 drilling wells with a capacity of Q_{emax} = 715 m^3/h. Expressed per day, this gives a value of 17,160 m^3/day. The volume of water taken from the intake is 2.92 million m^3/year. The Water Treatment Plant (WTP) is fed from a Quaternary aquifer with a free water table from a depth of about 15 m below ground level (BGL). The designed maximum capacity of the WTP is 715 m^3/h. The treated water flows from a clean tank to two water mains by means of three pumps. Two of these have a capacity of 440 m^3/h and a third one of 280 m^3/h. Their lifting capacity is 58 m.

The city's WDN consists of 16.8 km of mains and 191.7 km of distribution network. The water household connections network consists of 5000 connections and has a length of 100.85 km. The WDN is characterized by a mixed structure. The city center has a network with many loops, thanks to which, when a failure occurs, there is a possibility of residents continuing to be supplied with water thanks to a changing in the direction of water flow and inflow from another water line. The areas of suburban housing estates, in which there are single-family houses, are mostly supplied from a branched network. Investment activities in the area of construction and modernization of the WDN have been engaged in over the last few years, thanks to which more and more settlements are characterized by a looped system.

The largest share, about 43% of the entire WDN, is in the form of pipes less than 20 years old, but more than 11 years old. Approximately 90.2 km of the network is made of materials less than 10 years old, and this represents 31% of the entire WDN. The material structure of WDN is as follows: grey cast iron (37.7%), polyvinyl chloride (24.7%), galvanized steel (19.7%) and polyethylene (17.9%). The majority of house connections are made of cast iron and steel. It is only recently that pipes made of PVC (polyvinyl chloride) and PE (polyethylene) have been used. At present, no pipes forming the WDN are more than 40 years old. About 30.09% of the entire WDN is made up of pipes less than 10 years old, while about 42.7% is 11–20 years old and 26.4% of the entire WDN is above 20 years old.

3.4. Methods

3.4.1. Failure Rate Analysis

The analysis of failure rate in the WDN was performed by reference to the following formula [65,66]:

$$\lambda_j = \frac{n_j(t, t + \Delta t)}{N_j \times \Delta t} \tag{1}$$

where $n_j(t, t + \Delta t)$ is the number of all failures in the time interval Δt for the jth type of network; N_j is the length of the WDN of the jth type of network (km) and j is the type of WDN (e.g., for M—mains, R—distribution pipes, SC—service connections).

Standards as regards failure rate were proposed in the following works [6,67]. The former standards [6] provide that failure rates should not exceed criterion values as follows. In the case of mains λ_{Mcrit} is of less than 0.3 failures/(km^{-1}·year^{-1}), as compared with less than 0.5 for the distribution pipe $\lambda_{D\text{crit}}$, and $\leq$1.0 failures/(km^{-1}·year^{-1}) for service connections λ_{SCcrit}. In [67], proposals for the classification of criteria values of failure rates for the whole WDN were presented and classified in terms of reliability, with a high failure rate concerning low reliability when $\lambda_{lr\_crit} \geq$ 0.5 failures/(km^{-1}·year^{-1}), high reliability when $\lambda_{hr\_crit} \leq$ 0.1 failures/(km^{-1}·year^{-1}), and average reliability between the criteria values mentioned 0.1 < λ_{ar_crit} < 0.5 failures/(km^{-1}·year^{-1}).

3.4.2. A Rank Analysis of Failure-Rate Criteria

To check the correlation between levels of compliance for individual criteria used to assess monthly failure rates, a rank analysis was applied, with its task being to determine correlations between two failure-rate criteria. Prior to the correlation calculation, data were sorted according to the degree of specific statistical characteristic, expressing them on ordinal scales, in line with the limit failure criteria given in Section 3.4.1.

The Spearman correlation coefficient is calculated as follows [1,68]:

$$r_S = 1 - \frac{6 \times \sum d_i^2}{n(n^2 - 1)} \tag{2}$$

where d_i is the difference between the two ranks of each observation and n the number of observations.

The failure rates for each month were ordered from the lowest to the highest for each year, with a rank assigned, whereby unity denotes the lowest failure rate and non-exceeded criterion of failure rate. The two separate assessments accorded with criteria presented in either [27] or [67].

3.4.3. Seasonal Analysis of Failure Rates

To assess variability due to the action of the factor of season, seasonal analysis was carried out after [69], by reference to:

- the seasonal index S_i given by:

$$S_i = \frac{\overline{y_i} \times d}{\sum_{i=1}^{d} \overline{y_i}}, \tag{3}$$

where the arithmetic mean for failure rate in homonymous sub-periods (January, February,..., December) ($\overline{y_i}$) is:

$$\overline{y_i} = \frac{\sum_{i=1}^{d} k_i}{12}, \tag{4}$$

where d is an annual cycle of fluctuations within which the monthly sub-periods were distinguished (d = 12, e.g., in January, February, etc.), and k_i the failure rate in a given month and year.

- absolute levels of seasonal fluctuations for individual sub-periods, calculated using:

$$g_i = S_i \times \overline{y} - \overline{y} \tag{5}$$

where g_i is the absolute level of seasonal fluctuation and $\overline{y}$ the average value given by:

$$\overline{y} = \frac{\sum \overline{y}_i}{d \times t}, \tag{6}$$

where t is the number of years of observation.

- the standard deviation (SD) characterizing absolute levels of seasonal variation, with these representing an assessment of variability due to the factor of season over a period of 13 years in operation:

$$SD(g_i) = \sqrt{\frac{\sum_{i=1}^{d} g_i^2}{d}}. \tag{7}$$

With these dependent relationships taken account of, seasonal fluctuations in the occurrence of failures around WDNs were determined.

3.4.4. A Proposed Modified Multi-Criteria Decision Analysis Implementing an Analytic Hierarchy Process for Risk Assessment as Regards Failures in a WDN

Modified Multi-Criteria Decision Analysis (mMCDA) entails a choice of criteria influencing the risk of failure in a WDN, and the future occurrence thereof. The method suggested is based on risk-criteria grouping as regards failure in a WDN, with assessment then carried out by reference to determined points values under the Analytic Hierarchy Process (AHP) method [1,40,70,71]. It was assumed that risk means a measure by which to assess a hazard or threat resulting either from probable events beyond our control or from the possible consequences of a decision. Impacts are distinguished through the additive value of risk, which includes the category criterion of the size of possible financial losses resulting where failures arise. Evaluation criteria weights, as criterion of financial losses. The risk is interpreted by us in terms of expected losses.

In this way, the appropriate risk measure is calculated using Equation (8).

$$rA = \sum_{j=1}^{m} w_j \times F_j(A), \tag{8}$$

where r is the additive value of risk, w_j the point weight for each subcategory criterion j relating to design, performance or operation, or social or financial environment or surroundings, where j = {1, 2, . . . , m}, and F_j means category preference for alternatives taken into account by the method considered.

Depending on its influence on the risk index, each category was assigned a percentage weight that took account of importance in line with the Analytic Hierarchy Process (AHP), introduced by Thomas L. Saaty [72]. The procedure for using the AHP involves definition and analysis of the decision problem and goal-setting decisions. A set of criteria that have to be comparable are then established. The method also accepts criteria expressed quantitatively and qualitatively. Another important step in the procedure overall is the selection of relevant alternatives and the determination of implications of variations in the defined criteria. It is then possible to structure the hierarchical model. Input data are subject to comparisons of selected elements in pairs, with the advantage of one element over another determined in this way, in line with a nine-point pairwise comparison scale. The final decision is based on a synthesis of partial evaluation and selection of the best variant, through the creation of overall assessment scales using criteria and partial evaluation of alternatives. This relative preference is determined on a linear scale and verbally, taking into account the same significance or the strength of any advantage. Individual preferences and specific degrees of advantage in line with the Saaty scale are as shown in Table 1 [72,73].

Table 1. Scale of relative importance (after Saaty).

Interpretation		Value of a_{ij}	Definition
1	1	*i* and *j* are equally important	equal importance
3	1/3	*i* is slightly more important than *j*	moderate importance
5	1/5	*i* is more important than *j*	strong importance
7	1/7	*i* is far more important than *j*	very strong or demonstrated importance
9	1/9	*i* is absolutely more important than *j*	extreme importance
2, 4, 5, 8	1/2, 1/4, 1/5, 1/8	intermediate values	for comprise between the above values

Giving a relative preference means that the selection and evaluation of individual parameters are closer to reality. An expert's opinion is used to increase the substantive correctness of results. In the first place, the pairwise comparison of criteria allows them to be ordered qualitatively and as a matrix is being constructed in a quantitative way from the value of 1/9 to that of 9, with seventeen possible evaluations thus provided for.

In pairwise comparison by reference to an n by n matrix (A), so-called reversible pairwise comparisons are made, as already mentioned, and can be written as [72,73]:

$$A = [a_{ij}] \text{ for } i, j = 1, \ldots, n \tag{9}$$

where

$$a_{ij} = \frac{1}{a_{ji}}, \tag{10}$$

and

$$a_{ii} = 1 \tag{11}$$

the matrix is consistent, if:

$$a_{ij} = \frac{w_i}{w_j} \tag{12}$$

The matrix takes the following form:

$$A = \begin{bmatrix} 1 & a_{12} & \ldots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \ldots & a_{2n} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \ldots & 1 \end{bmatrix} \tag{13}$$

As a result of calculations of the comparison matrix in pairs, vectors of the priorities $w = (w_1, \ldots, w_n)$, concerning the significance of elements, are obtained.

The obtained priority vectors can be presented in the form of a matrix of normalized grades, using Saaty's fundamental comparison scale:

$$Aw = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \cdot \\ \cdot \\ \cdot \\ w_n \end{bmatrix} = n \times \begin{bmatrix} w_1 \\ w_2 \\ \cdot \\ \cdot \\ \cdot \\ w_n \end{bmatrix} \quad (14)$$

hence equality occurs:

$$Aw = nw \quad (15)$$

To check if the matrix is consistent, the principal eigenvalue λ_{max} corresponding to the greatest value of the eigenvector, should be calculated in line with Equation (16):

$$\lambda_{\max} = \frac{1}{w_i} \sum_{j}^{n} a_{ij} w_j, \quad (16)$$

The matrix of pairwise comparisons $A = (a_{ij})$ is said to be consistent when its principal eigenvalue is close to n. To assess the compatibility of deviations, a Consistency Index (CI) is determined, in line with the dependence relationship:

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \quad (17)$$

Next, a Consistency Ratio (CR) is determined, defining the degree to which comparison of the validity of characteristics is characterized by incompatibility. This is given by:

$$CR = \frac{CI}{RI}, \quad (18)$$

where RI is the Random Index, depending on the number of comparable items, according to the matrix dimensions listed in Table 2.

Table 2. *RI* values corresponding to matrix dimensions.

n	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
RI	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54

To calculate weighting factors and consistency indexes, with a view to calculations performed being checked for their accuracy, use was made of methods involving the arithmetic and geometric means, as well as matrix multiplication. Depending on the designated consistency ratio, preferential information can be adopted or rejected. If the value of CR is greater than the permitted 0.1, an inconsistent matrix is present, and preferential information will need to be verified by decision makers. In such a case, actions will need to be taken to reduce low-quality observations and inconsistencies relating to them. It is very important that a decision problem taken up should not be too difficult and should be in line with assumptions adopted.

What is described here can combine with the experience and knowledge of experts to form a basis for expert opinions as regards the risk of failure. Indeed, the preparation of the categories and subcategories of criteria presented in Table 3 involved cooperation with designers, contractors and operators of the studied WDN. The key variables were also based on the relevant literature cited in the text. Expert opinion provides an opportunity for the experience of experts in a given field to be brought together, such that all the most important factors affecting the risk values associated with failures in a WDN may then be taken into account. Values for assessment subcategories of criteria are adopted in line with the importance of the damaged pipe, using a scale whereby a low hazard is on 1, a moderate hazard on 2 and a severe hazard on 3. If a given factor is not present in an analysis, a value of 1 for the subcategory is assumed.

Table 3 sets out proposed categories and subcategories of criteria for the analysis and identification of areas at risk of WDN failure [6,10,23,71].

For the mMCDA method a three-step scale to obtain the additive value of a risk category was adopted, risk assessment thus being provided for via implementation of AHP in line with a scale comprising tolerable risk (2.567 ÷ 3.06), controlled risk (3.06 ÷ 6.02) and unacceptable risk (6.02 ÷ 7.701). The proposed scale was based on the opinions of experts, who on the basis of their knowledge, experience and data in litteris assess risk categories. Assessment of the additive value of risk obtained supports the taking of decisions that relate to the operation or modernization of the system. Should a value indicating tolerable risk be obtained, no extra actions are required and the system is running in a proper and reliable way, with no preventive actions in the system needed either. Controlled risk means that the system is permitted to function but under the condition that modernization or renovation will commence. If an unacceptable level is found to have arisen, an immediate undertaking should be given, to the effect that the additive value of the risk category will be reduced. It should be noted that the consequences of failure to the water distribution subsystem are what cause periodic breaks in the delivery of water supply that is anyway of inadequate quality.

Table 3. Evaluation criteria weights.

No.		Categories and Subcategories of Criteria			Point Weighting of Subcategories
1	2	3	4		5
I	Ia)	Design	a reputable design office with a quality certificate, having completed projects on the reference list, and engaging in design using proven computer programs,		1
	Ib)		design office has certified designs and legitimizes itself by virtue of a list of references,		2
	Ic)		a person engaging in business activity, having in his portfolio partial projects for the expansion of WDN,		3
	Id)		network monitoring *	above-standard,	1
	Ie)			standard,	2
	If)			none,	3
	Ig)		corrosion protection	full,	1
	Ih)			standard,	2
	Ii)			none,	3
II	IIa)	Performance	construction company is certified and has completed investments in the reference list, procedures related to the acceptance of investments, pipes laid in accordance with the best available technology,		1
	IIb)		construction company has a reference list of completed investments, verification of material specifications and acceptance procedures is performed,		2
	IIc)		construction company is entering the water supply market, but has no experience in this area,		3
III	IIIa)	Operation	type of WDN according to higher priority to repair	SC,	1
	IIIb)			distribution network,	2
	IIIc)			mains,	3
	IIId)		failure rate, λ	to 0.5 $km^{-1} \cdot year^{-1}$,	1
	IIIe)			from 0.5 $km^{-1} \cdot year^{-1}$ to 1.0 $km^{-1} \cdot year^{-1}$,	2
	IIIf)			>1.0 $km^{-1} \cdot year^{-1}$,	3
	IIIg)		dynamic loads, including difficulty of repairs in area in which a network is situated	pipeline in non-urbanized areas,	1
	IIIh)			pipeline in pedestrian traffic (under pavements),	2
	IIIi)			pipeline in the street,	3
	IIIj)		WDN age	to 20 years,	1
	IIIk)			from 20 to 50 years,	2
	IIIl)			above 50 years,	3
	IIIm)		WDN material	plastics,	1
	IIIn)			steel,	2
	IIIo)			grey cast iron,	3
IV	IVa)	Social	nuisance resulting from road occupation and green area	pipeline in non-urbanized area,	1
	IVb)			pipeline in pedestrian traffic,	2
	IVc)			pipeline in street,	3

Table 3. *Cont.*

No.		Categories and Subcategories of Criteria			Point Weighting of Subcategories
V	Va)	Financial	size of possible losses arising should failure occur	financial loss of up to 10^4 EUR,	1
	Vb)			financial loss from 10^4 to 10^5 EUR,	2
	Vc)			financial loss above 10^5 EUR,	3
	Vd)		difficulty of repairing damage	repair brigades are organized and equipped appropriately and are in full readiness for 24 h,	1
	Ve)			basic equipment to repair a failure, one-shift work,	2
	Vf)			lack of mechanized equipment to repair a failure,	3
VI	VIa)	Environment and surroundings	hydrogeological conditions	good,	1
	VIb)			average,	2
	VIc)			poor,	3
	VId)		density of underground infrastructure in the vicinity of the network	low,	1
	VIe)			average,	2
	VIf)			high.	3

Notes: * Above-standard network monitoring: full monitoring of the WDN through measurement of water pressure and flow rate, possession of specialized apparatus to detect water leaks by acoustic methods, unrestricted communication with the public via a phone line active 24 h a day, monitoring of water quality in a WDN by means of a protection and warning system. Standard: simplified monitoring of WDN by way of pressure measurement, inability to respond to minor leaks, water quality tests in WDN conducted. None: lack of monitoring of network and water quality.

4. Results and Discussion

4.1. Failure Rate Analysis

The failure risk analysis is found to contribute significantly to a reduction of failure overall, and a limiting of their consequences. The analysis question was based on operational data obtained over 13 years of observation. The λ_{WN} values for failure rates over the network as a whole (Figure 2), and for mains λ_M (Figure 3), distribution pipes λ_D (Figure 4), and SCs λ_{SC} (Figure 5), were determined in line with Equation (1). The failure rate for WDN pipes in subsequent months of the analyzed 2005–2017 period was then determined. To show seasonal fluctuations, Figure 6 was presented, with this supplying basic statistical characteristics for monthly values where failure rates are concerned. Results from seasonal calculations are as shown in Figure 7.

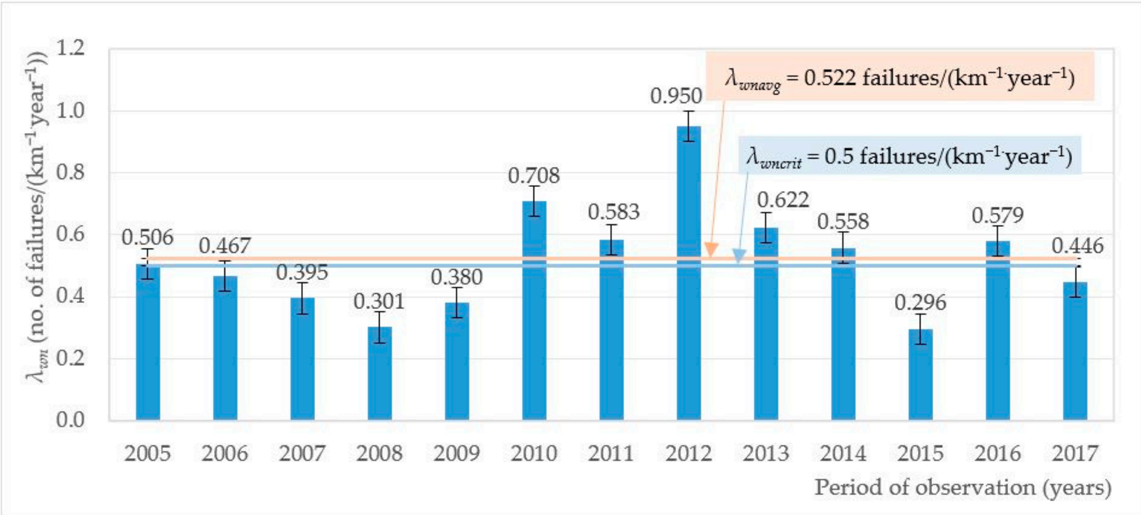

Figure 2. The failure rate for the whole network over the distinguished 2005–2017 time period.

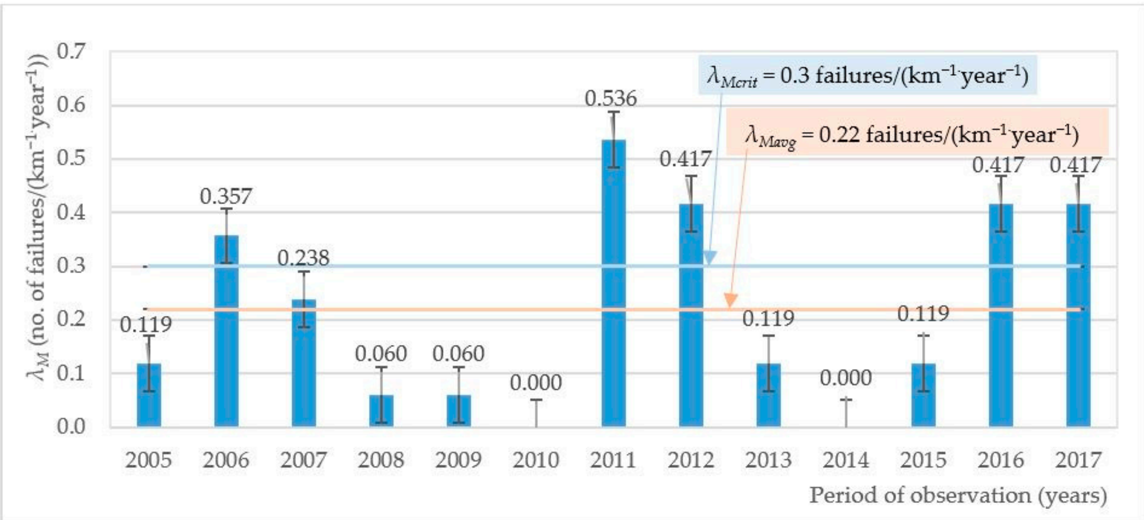

Figure 3. The failure rate for mains over the distinguished 2005–2017 period.

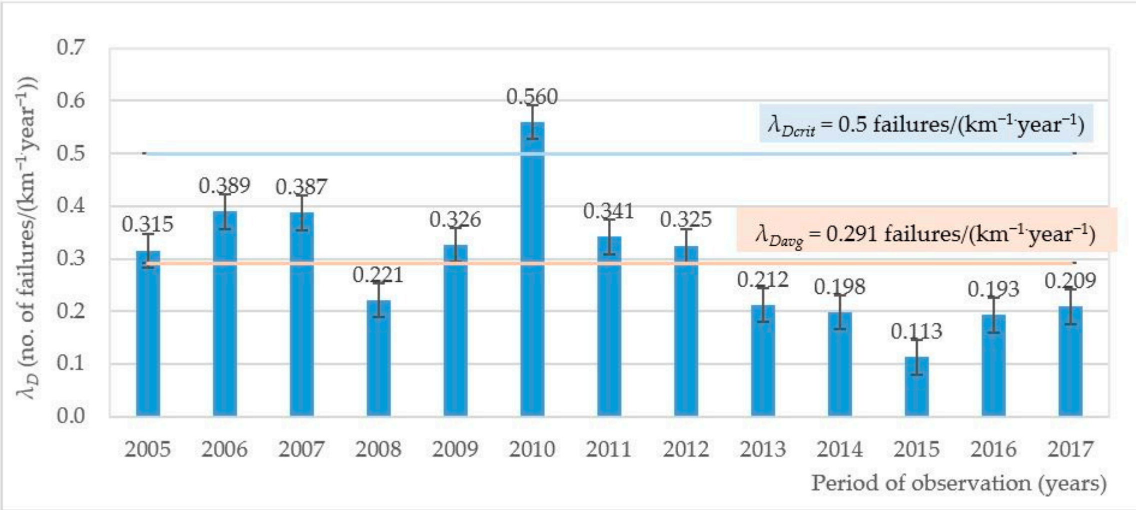

Figure 4. The failure rate for distribution pipes over the distinguished 2005–2017 period.

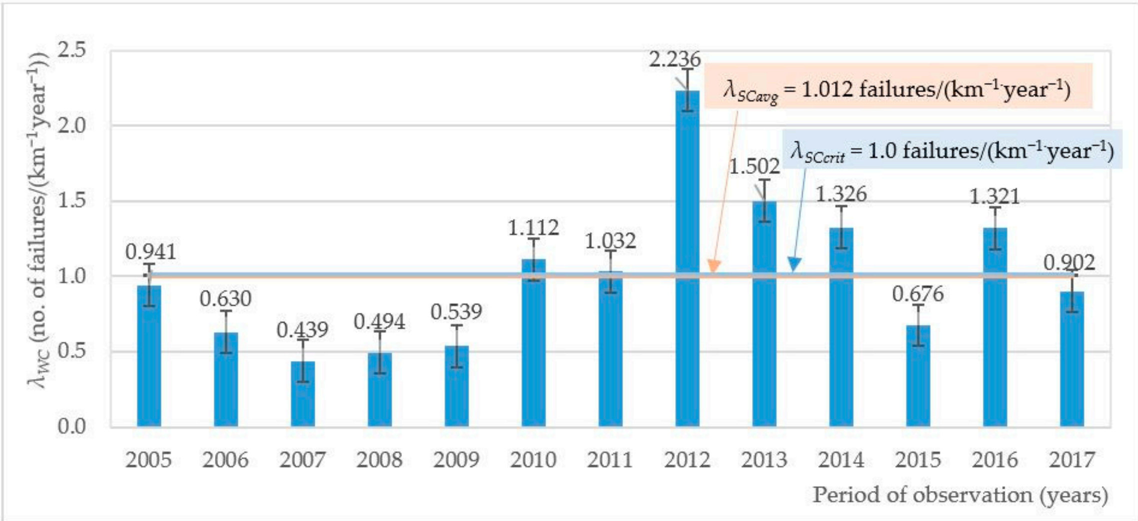

Figure 5. The failure rate for SCs over the distinguished 2005–2017 period.

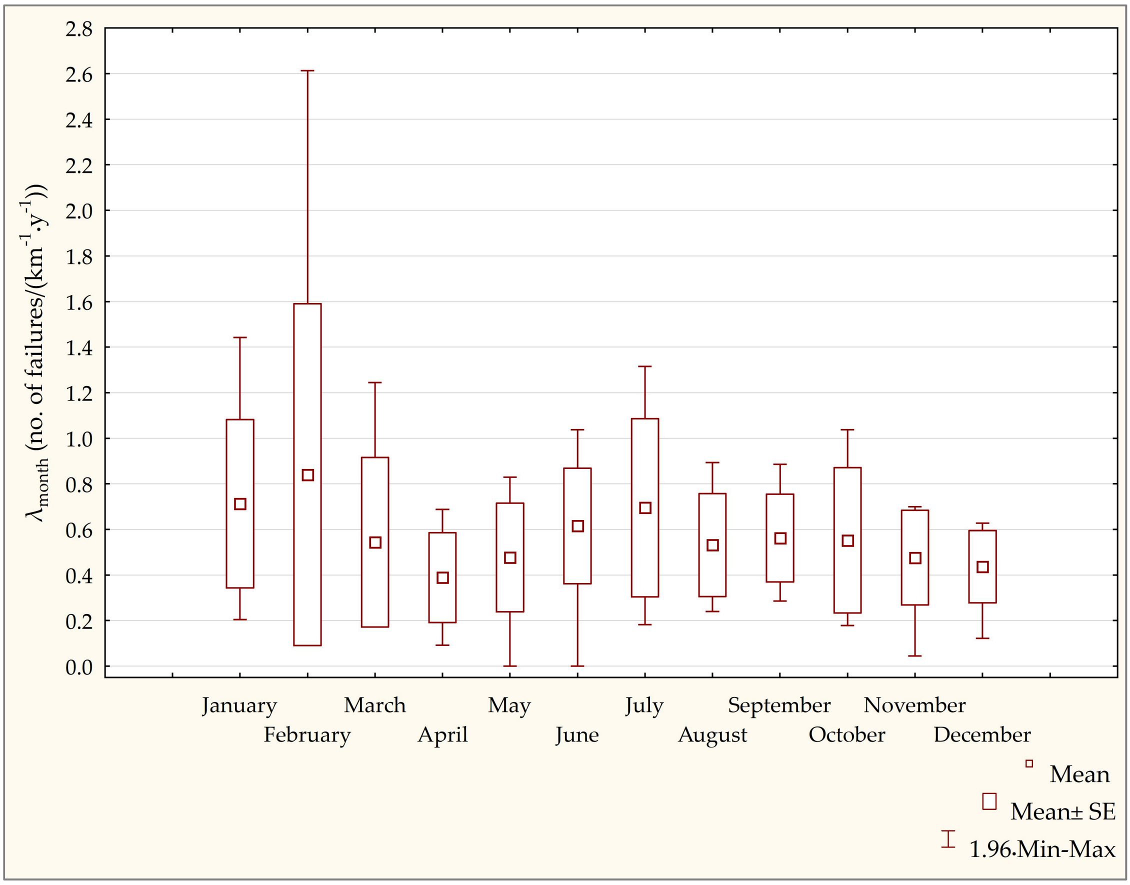

Figure 6. A box-whisker plot of the mean values for failure rates along the WDN in each month of the year and in line with the following operational data for the 2005–2017 period.

Figure 7. Relative seasonal fluctuations of failure rates in WDN.

Over the analyzed period of time, the average number of failures amounted to 1862 (on average 143 failures per year of observation), while the corresponding average failure rate is 0.522 failures/(km^{-1}·year^{-1}). Before the analysis was commenced, verification of operational data was performed, in respect of the classification of data on the failure rate of individual types of pipes and changes resulting from repairs and modernizations. The determined SD for the whole network was of 0.171 failures/(km^{-1}·year^{-1}), as compared with 0.178 failures/(km^{-1}·year^{-1}) for the mains, 0.113 for distribution pipes, and 0.483 failures/(km^{-1}·year^{-1}) for SCs. Where the whole network is taken into account (in line with the data presented in Figure 2), the highest failure rates were found to have occurred in 2010 and 2012, with 199 and 260 failures. The lowest failure rates occurred in 2008 and 2015, with 78 and 85 failures respectively. The highest failure rate in 2010 may be related to flooding, which took place twice that year and gave rise to consequences as regards liquidation that caused the number of failures to increase. The detailed analysis in turn indicated that the high failure rate in 2012 reflected low temperature, which caused the freezing of SC. Dependence is observed in failure-rate distribution over the month-long span of time in the analyzed years, and this is primarily seen to be due to changes in ground temperature in the winter-spring period. In 2012, about 24% of all failures (about 63 in absolute terms) occurred in February, with this mainly reflecting changes in ground temperature during periods of the winter season. An increased number of failures also occurs in July, with this probably owing to heat-driven drying of soil leaving pipes more prone to cracking. Such a situation arises with the superficial laying of pipes and low water flow at night then causing the freezing of water in the pipes more prone to frost. Over the last few years, the length of distribution pipes and SCs has increased significantly. Since 2005, about 22.2 km of water-supply connections and 45.8 km of distribution pipes have been constructed. It is worth underlining that failures of the main network do not cause a break in water supply because the mains consists of two pipelines. According to data presented (Figures 3 and 5), water supply connections (λ_{SCavg} = 1.012 failures/(km^{-1}·year^{-1}) are most often damaged, while the main network is least often damaged (λ_{Mavg} = 0.22 failures/(km^{-1}·year^{-1}). The occurrence of more failures in distribution pipes and SCs is related to the age and type of material from which they are made. Over the years, the failure rate of distribution pipes has declined; attesting to modernization work on the WDN in the city. According to the data presented in Figure 4, in recent years there has been a tendency for the failure rate along distribution pipes to decrease. The significant reduction in failure rate occurred after 2010, it was due to the start of the modernization of the WDN. The distribution network meets the criteria that the failure rate should be less than 0.5 failures/(km^{-1}·year^{-1}), except in the year 2010 when the criterion value of about 12% was slightly exceeded. In the case of SC there was a decrease in the failure rate after 2012. In that period SCs have met the standards ($\lambda_{SC} \leq 1.0$ failure/(km^{-1}·year^{-1}), and, as was mentioned above, this reflects modernization and a change in the material from which the network is made, given the use of the PVC and PE pipes less prone to failure and characterized by lower failure rates than pipes made from steel or cast iron. Taking into account the criteria presented in work [67] and the mean failure rate, the network as a whole is characterized by low reliability, with $\lambda \geq 0.5$ failures/(km^{-1}·year^{-1}), while distribution pipes and SCs are of average reliability, with mean values for failure rates between 0.1 and 0.5 failures/(km^{-1}·year^{-1}). The results of calculations show that, in every year of the analyzed period, due to seasonal fluctuations (as Figure 6 shows), the total number of failures in February was higher than the monthly average (100%) by approximately 47.6%, in January by 25.3% and in July by 22.2%. In turn, in April the value is lower than the average by 31.7%, and so on (Figure 7). Such tendencies are also present in other systems [44]. Absolute seasonal fluctuation in g_i informs us that, in January, the total number of failures is higher than in an average month (at $\overline{y}$ = 0.569 failures/(km^{-1}·year^{-1})), and therefore by 0.271 failures/(km^{-1}·year^{-1}). In turn, in April, the figure is lower than the average by 0.18 failures/(km^{-1}·year^{-1}) (Figure 8). SD for absolute seasonal variation levels, over the period of 13 years in operation is at the level of 0.123 failures/(km^{-1}·year^{-1}).

The box-whisker plot for mean values of failure rates allowed for assessment overall, and the most marked variation was shown for the winter month of January, which is characterized by a SD equal to 0.75. The most limited differentiation in turn occurs in the summer month of July, for which the SD value is at the level of 0.39. The detailed analysis in the last year of observation indicates that the highest indicator values for failure rate characterizes pipes made of steel, representing 0.23 failures/(km^{-1}·year $^{-1}$), as compared with the lowest failure rate determined for PE, at the level of about 0.09 failures/(km^{-1}·year $^{-1}$).

The Spearman's rank correlation coefficient was used to compare the assessment of the different criteria in regard to each monthly failure rates. When the obtained values for coefficients were compared, a high level of agreement regarding the assessment and classification of failure rate was only found in the case of mains (at the level of 0.589, and hence significant at $p < 0.05$). In the case of service connections, the average value achieved for the relationship was of 0.395. The lack of failure rates below 0.1 failures/(km^{-1}·year $^{-1}$), caused the same assessment according to two criteria for the whole network and for the distribution pipes, and there was also functional dependence noted between these two assessments.

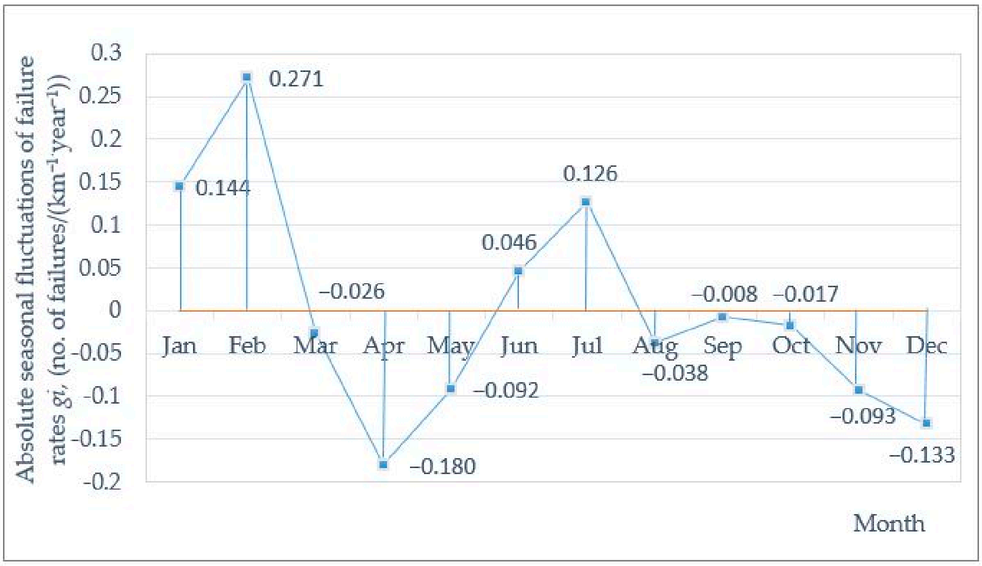

Figure 8. Absolute seasonal fluctuations of failure rates in WDN, in (no. of failures/(km^{-1}·year^{-1})).

4.2. Results of Failure Risk Assessment for WDN

The performed analysis focused in on a section of the distribution network along with traffic difficulties caused by repairs of the WDN which arise very often. The examined section is of total length 2.4 km, and forms part of the WDN in the city under consideration supplying 50,000 inhabitants. The expert analysis revolved around six main criteria, which were compared in terms of pairs of individual criteria, in line with the scale developed that is presented in Table 4.

Table 4. Matrix construction and weighting calculation for categories associated with the failure risk assessment.

Category	I	II	III	IV	V	VI	Weight
I	1	2	2	4	4	3	0.3262
II	0.5	1	2	4	4	3	0.2589
III	0.5	0.5	1	4	3	3	0.1959
IV	0.25	0.25	0.25	1	2	2	0.0856
V	0.25	0.25	0.333	0.5	1	2	0.0712
VI	0.333	0.333	0.333	0.5	0.5	1	0.0622
Total	2.833	4.333	5.917	14	14.5	14	0.3262
λ_{max} = 6.3071; *CI* = 0.0614; *RI* = 1.25; *CR* = 0.0491							

As the determined *CR* is acceptable (<0.1), the results obtained may be adopted. The preference vectors determined on this basis are shown in Table 5 [72].

Table 5. A characterisation of the network.

No.		Categories and Subcategories of Criteria			Weight	
					Point Weight of Subcategories	Categories
1	2	3	4		5	6
I	Ib)	Designing	design office has certified designs and legitimizes itself by virtue of a list of references,		2	0.3262
	Ie)		network monitoring	standard, simplified monitoring of water- WDN with the use of pressure measurement,	2	0.3262
	Ii)		corrosion protection	not applicable	3	0.3262
II	IIb)	Performance	construction company has a reference list of completed investments, verification of material specifications and acceptance procedures is performed,		2	0.2589
III	IIIb)	Operation	type of WDN	distribution network,	2	0.1959
	IIId)		failure rate, λ	to 0.5 $km^{-1} \cdot year^{-1}$,	1	0.1959
	IIIg)		dynamic loads	pipeline in not urbanized areas,	1	0.1959
	IIIk)		WDN age	from 20 to 50 years,	2	0.1959
	IIIm)		WDN material	plastics,	1	0.1959
IV	IVa)	Social	nuisance of road and green area users	pipeline in non-urbanized area,	1	0.0856
V	Va)	Financial	size of possible losses arising should failure occur	financial loss of up to 10^4 EUR,	1	0.0712
	Ve)		difficulty of repairing damage	basic equipment to repair a failure, one-shift work,	2	0.0712
VI	VIc)	Environment and surroundings	hydrogeological conditions	poor,	3	0.0622
	VId)		density of underground infrastructure in the vicinity of the network	low.	1	0.0622

According to Table 2, the value of $r(A)$ was 4.72, which corresponds to the category of a controlled risk level. The obtained value indicates that some improvement in the work of the WDN, or repair of certain sections of the WDN, should be considered to minimize risk of failure. Directions proposed for the WDN operator responsible for the monitoring of proper functioning Included the introduction of preventive measures, with a view to conditions leading directly to a WDN threat not arising. At this stage, the possibilities of undesirable events occurring should be analyzed from the point of view of the reliability of the water supply system, through water reserving, and the monitoring of failure around the WDN–as can be achieved by introducing repair brigades that are properly organized and fully ready 24 h a day. Introduction of a satisfactory level of protection, with a view to protecting the consumers of drinking water using the public WSS, also seeks to minimize possible losses. Minimizing the effects of unintentional events is also advocated, with water taken from alternative sources if necessary and the process of informing the public about interruptions in water supply checked for its effectiveness.

5. Conclusions and Perspectives

The issues presented may prove of great interest to authorities managing the operation of a WSS in water supply companies, as well as to the scientific community, doctoral students and students of technical and agricultural universities, employees of design companies and people who deal with water treatment technologies, and the operation of WDN and internal installations.

The methodology in question can gain direct application even in relation to water supply systems, given the relative universality of the approach presented here. Moreover, the presented method by which to pursue failure analysis should be a major element of any comprehensive management. If numerous failures arise in a WDN, the water company is obliged to modernize and renovate, so as to minimize pipeline failures. In its initial stages, managing of WDN safety entails creating a database of weak points of system functioning, with particular emphasis placed on frequency of occurrence and associated negative effects. In safety management, decisions are made as regards the selection of risk protection measures, implementation into operational practice and checks needing to be carried out in regard to the effectiveness of applied solutions.

Further work in this area will be focused on researching exposure to failure using operational data, field investigations and analyses of experts, with this facilitating identification of particular areas with high and unacceptable failure rates, in this way achieving a classification of sections of the network risk-mapped as in need of renovation. A further important aspect will entail analysis of failure assessment in the context of the determination of acceptance criteria vis-à-vis failure. The suggested method of failure risk assessment for WDNs is among expert methods that may be deployed, and may form part of the decision making process as regards plans for the modernization of a WSS. It can also be used where operational data prove insufficient and can be combined with the experience and knowledge of experts as a basis for opinions regarding the risk of failure. Furthermore, this type of analysis is very helpful in classifying those segments of a WDN that need repairing. The multi-criteria methods in failure risk assessment involve cooperation between designers, contractors and operators of the WDN, so this denotes an opportunity to combine the experience of experts in given fields. The methods proposed here from work based on operational data and expert knowledge can form a basis for a comprehensive risk management program that forms part of the water safety plans recommended by the WHO, which will be obligatory, given the need for modern standards regarding the safety of drinking water to be met.

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References

1. Rak, J.R.; Tchórzewska-Cieślak, B. *Risk in Operation of Collective Water Supply Systems*; Publishing House of Seidel Przywecki: Warsaw, Poland, 2013.
2. Rak, J. *Safety of Water Supply System*; Polish Academy of Science: Warsaw, Poland, 2009.
3. Rak, J.; Tchórzewska-Cieślak, B. *Risk Factors in the Operation of Water Supply Systems*; Publishing House of Rzeszow University of Technology: Rzeszow, Poland, 2007.
4. Rak, J. *Fundamentals of Water Supply System Safety*; Polish Academy of Science: Lublin, Poland, 2005.
5. Rak, J. A study of the qualitative methods for risk assessment in water supply systems. *Environ. Prot. Eng.* **2003**, *29*, 123–133.
6. Rak, J.R. Some aspects of risk management in waterworks. *Ochr. Sr.* **2007**, *29*, 61–64.
7. Rak, J.; Tchórzewska-Cieślak, B. The possible use of the FMEA method to ensure health safety of municipal water. *J. Konbin* **2010**, *3*, 143–154. [CrossRef]
8. Rak, J.R. Methods of reliability index determination concerning municipal water quality. *J. Konbin* **2008**, *5*, 157–173. [CrossRef]
9. Tchórzewska-Cieślak, B. *Methods for Analysis and Assessment of Risk of Failure in Water Distribution Subsystem*; Publishing House of Rzeszow University of Technology: Rzeszow, Poland, 2011.
10. Salehi, S.; Tabesh, M.; Ghazizadeh, M.J. HRDM method for rehabilitation of pipes in water distribution networks with inaccurate operational-failure data. *J. Water Res. Plan. Manag.* **2018**, *144*. [CrossRef]
11. Pagano, A.; Pluchinotta, I.; Giordano, R.; Petrangeli, A.B.; Fratino, U.; Vurro, M. Dealing with uncertainty in decision-making for drinking water supply systems exposed to extreme events. *Water Res. Manag.* **2018**, *32*, 2131–2145. [CrossRef]
12. Tchorzewska-Cieslak, B.; Rak, J. Method of identification of operational states of water supply system. Environmental Engineering III. In Proceedings of the 3rd Congress of Environmental Engineering, Pafos, Cyprus, 13–16 September 2009; pp. 521–526.
13. Izquierdo, J.; López, P.A.; Martinéz, F.A.; Pérez, R. Fault detection in water supply systems using hybrid (theory and data-driven) modeling. *Math. Comput. Model.* **2007**, *46*, 341–350. [CrossRef]
14. Khomsi, B.D.; Walters, G.A.; Thorley, A.R.D.; Ouazar, D. Reliability tester for water distribution networks. *J. Comput. Civ. Eng.* **1996**, *10*, 10–19. [CrossRef]

15. Tchorzewska-Cieslak, B.; Wlodarczyk-Makula, M.; Rak, J. Safety analysis of the wastewater treatment process in the field of organic pollutants including PAHs. *Desalin. Water Treat.* **2017**, *72*, 146–155. [CrossRef]
16. Bergel, T.; Pawełek, J. Quantitative and economical aspects of water loss in water-pipe networks in rural areas. *Environ. Prot. Eng.* **2008**, *34*, 59–64.
17. Zimoch, I. Pressure control as part of risk management for a water-pipe network in service. *Ochr. Sr.* **2012**, *34*, 57–62.
18. Kuliczkowski, A.; Kuliczkowska, E.; Kubicka, U. Design of the pipelines considering exploitative parameters. Underground Infrastructure of Urban Areas. In Proceedings of the International Conference on Underground Infrastructure of Urban Areas, Wroclaw, Poland, 22–24 October 2008; pp. 165–170.
19. Pozos-Estrada, O.; Sanchez-Huerta, A.; Brena-Naranjo, J.A.; Pedrozo-Acuna, A. Failure analysis of a water supply pumping pipeline system. *Water* **2016**, *8*. [CrossRef]
20. Wąsik, E.; Chmielowski, K.; Cupak, A.; Kaczor, G. Stability monitoring of the nitrification process: Multivariate statistical analysis. *Pol. J. Environ. Stud.* **2018**, *27*, 2303–2313. [CrossRef]
21. Królikowska, J. Application of PHA method for assessing risk of failure on the example of sewage system in the City of Krakow. *Rocz. Ochr. Sr.* **2011**, *13*, 693–710.
22. Berardi, L.; Ugarelli, R.; Rostum, J.; Giustolisi, O. Assessing mechanical vulnerability in water distribution networks under multiple failures. *Water Resour. Res.* **2014**, *50*, 2586–2599. [CrossRef]
23. Kozłowski, E.; Mazurkiewicz, D.; Kowalska, B.; Kowalski, D. Application of a multidimensional scaling method to identify the factors influencing on reliability of deep wells. *Adv. Intell. Syst.* **2019**, *835*, 56–65. [CrossRef]
24. Tchórzewska-Cieślak, B.; Boryczko, K.; Eid, M. Failure scenarios in water supply system by means of fault tree analysis. In *Advances in Safety, Reliability and Risk Management*; Taylor & Francis Group: Abingdon, UK, 2012; pp. 2492–2499.
25. Zimoch, I. Method of risk analysis and assessment of water supply system exploitation in agricultural areas. *Ochr. Sr.* **2016**, *38*, 33–38.
26. Puri, D.; Borel, K.; Vance, C.; Karthikeyan, R. Optimization of a water quality monitoring network using a spatially referenced water quality model and a genetic algorithm. *Water* **2017**, *9*. [CrossRef]
27. Jung, D.; Yoo, D.; Kang, D.; Kim, J. Linear model for estimating water distribution system. *J. Water Res. Plan. Manag.* **2016**, *142*, 04016022. [CrossRef]
28. Moglia, M.; Davis, P.; Burn, S. Strong exploration of a cast iron pipe failure model. *Reliab. Eng. Syst. Saf.* **2008**, *93*, 863–874. [CrossRef]
29. Wang, Y.; Zayed, T.; Moselhi, O. Prediction models for annual break rates of water mains. *J. Perform. Constr. Fac.* **2009**, *23*, 47–54. [CrossRef]
30. Zimoch, I.; Łobos, E. Application of the theil statistics to the calibration of a dynamic water supply model. *Environ. Prot. Eng.* **2010**, *36*, 105–115.
31. Mamo, T.G. Risk-based approach to manage aging urban water main infrastructure. *J. Water Supply Res. Technol.* **2015**, *64*, 260–269. [CrossRef]
32. Shahata, K.; Zayed, T. Data acquisition and analysis for water main rehabilitation techniques. *Struct. Infrastruct. E* **2012**, *8*, 1054–1066. [CrossRef]
33. Scheidegger, A.; Scholten, L.; Maurer, M.; Reichert, P. Extension of pipe failure models to consider the absence of data from replaced pipes. *Water Res.* **2013**, *11*, 3696–3705. [CrossRef] [PubMed]
34. Tabesh, M.; Soltani, J.; Farmani, R.; Savic, D. Assessing pipe failure rate and mechanical reliability of water distribution networks using data-driven modeling. *J. Hydroinform.* **2009**, *11*, 1–17. [CrossRef]
35. D'Ercole, M.; Righetti, M.; Raspati, G.S.; Bertola, P.; Ugarelli, R.M. Rehabilitation planning of water distribution network through a reliability-based risk assessment. *Water* **2018**, *10*. [CrossRef]
36. Iwanejko, R.; Bajer, J. Determination of the optimum number of repair units for water distribution systems. *Arch. Civ. Eng.* **2009**, *55*, 87–101.
37. Martinez-Codina, A.; Castillo, M.; Gonzales-Zeas, D.; Garrote, L. Pressure as a predictor of occurrence of pipe breaks in water distribution networks. *Urban Water J.* **2016**, *13*, 676–686. [CrossRef]
38. Królikowska, J. Damage evaluation of a town's sewage system in southern poland by the preliminary hazard analysis method. *Environ. Prot. Eng.* **2011**, *37*, 131–142.
39. Szpak, D.; Tchórzewska-Cieslak, B. Assessment of the failure rate of water supply system in terms of safety of critical infrastructure. *Chemik* **2014**, *6*, 862–867.

40. Darvini, G. Comparative analysis of different probability distributions of random parameters in the assessment of water distribution system reliability. *J. Hydroinform.* **2014**, *14*, 272–287. [CrossRef]
41. Boxall, J.B.; O'Hagan, A.; Pooladsaz, S.; Saul, A.J.; Unwin, D.M. Estimation of burst rates in water distribution mains. *Proc. Inst. Civ. Eng.-Water Manag.* **2007**, *160*, 73–82. [CrossRef]
42. Shin, H.; Kobayashi, K.; Koo, J.; Do, M. Estimating burst probability of water pipelines with a competing hazard model. *J. Hydroinform.* **2016**, *18*, 126–135. [CrossRef]
43. Arai, Y.; Koizumi, A.; Inakazu, T.; Watanabe, H.; Fujiwara, M. Study on failure rate analysis for water distribution pipelines. *J. Water Supply Res. Technol.* **2010**, *59*, 429–435. [CrossRef]
44. Hotloś, H. *Quantitative Assessment of the Effect of Some Factors on the Parameters and Operating Costs of Water-Pipe Networks*; Wrocław University of Technology Publishing House: Wrocław, Poland, 2007.
45. Estokova, A.; Ondrejka Harbulakova, V.; Luptakova, A.; Stevulova, N. Performance of fiber-cement boards in biogenic sulphate environment. *Adv. Mater. Res.* **2014**, *897*, 41–44. [CrossRef]
46. Hotlos, H. Quantitative assessment of the influence of water pressure on the reliability of water-pipe networks in service. *Environ. Prot. Eng.* **2010**, *36*, 103–112.
47. Bogardi, I.; Fülöp, R. A Spatial probabilistic model of pipeline failures. *Period Polytech.-Civ.* **2011**, *55*, 161–168. [CrossRef]
48. Debón, A.; Carrión, A.; Cabrera, E.; Solano, H. Comparing risk of failure models in water supply networks using ROC curves. *Reliab. Eng. Syst. Saf.* **2010**, *95*, 43–48. [CrossRef]
49. Kleiner, Y.; Rajani, B. Comprehensive review of structural deterioration of water mains: Statistical models. *Urban Water J.* **2001**, *3*, 131–150. [CrossRef]
50. Kowalski, D.; Kowalska, B.; Kwietniewski, M. Monitoring of water distribution system effectiveness using fractal geometry. *Bull. Pol. Acad. Sci.* **2015**, *63*, 155–161. [CrossRef]
51. Kutyłowska, M. Comparison of two types of artificial neural networks for predicting failure frequency of water conduits. *Period Polytech.-Civ.* **2017**, *61*, 1–6. [CrossRef]
52. Kwietniewski, M.; Rak, J. *Reliability of Water and Wastewater Infrastructure in Poland*; Polish Academy of Science: Warsaw, Poland, 2010.
53. Mays, W.L. *Reliability Analysis of Water Distribution Systems*; American Society of Civil Engineers: New York, NY, USA, 1998.
54. Pelletier, G.; Mailhot, A.; Villeneuve, J.P. Modeling water pipe breaks-three case studies. *J. Water Res. Plan. Manag.* **2003**, *129*, 115–123. [CrossRef]
55. Shamir, U.; Howard, C.D.D. An analytical approach to scheduling pipe replacement. *J. Am. Water Works Assoc.* **1979**, *71*, 248–258. [CrossRef]
56. Toumbou, B.; Villeneuve, J.P.; Beardsell, G.; Duchesne, S. General model for water-distribution pipe breaks: Development, methodology, and application to a small city in Quebec, Canada. *J. Pipeline Syst. Eng.* **2014**, *5*, 04013006. [CrossRef]
57. Xu, Q.; Chen, Q.; Li, W. Application of genetic programming to modeling pipe failures in water distribution systems. *J. Hydroinform.* **2011**, *13*, 419–428. [CrossRef]
58. Shuang, Q.; Liu, Y.S.; Tang, Y.Z.; Liu, J.; Shuang, K. System reliability evaluation in water distribution networks with the impact of valves experiencing cascading failures. *Water* **2017**, *9*. [CrossRef]
59. Rak, J.R.; Kucharski, B. Sludge management in water treatment plants. *Environ. Prot. Eng.* **2009**, *35*, 15–21.
60. Walski, T.M.; Pelliccia, A. Economic analysis of water main breaks. *J. Am. Water Works Assoc.* **1982**, *74*, 140–147. [CrossRef]
61. Tchórzewska-Cieślak, B.; Pietrucha-Urbanik, K.; Urbanik, M.; Rak, J.R. Approaches for safety analysis of gas-pipeline functionality in terms of failure occurrence: A case study. *Energies* **2018**, *11*, 1589. [CrossRef]
62. Nowacka, A.; Wlodarczyk-Makula, M.; Tchorzewska-Cieslak, B.; Rak, J. The ability to remove the priority PAHs from water during coagulation process including risk assessment. *Desalin. Water Treat.* **2016**, *57*, 1297–1309. [CrossRef]
63. Seo, J.; Koo, M.; Kim, K.; Koo, J. A study on the probability of failure model based on the safety factor for risk assessment in a water supply network. *Procedia Eng.* **2015**, *119*, 206–215. [CrossRef]
64. StatSoft, Inc. STATISTICA (Data Analysis Software System), Version 12. Available online: www.statsoft.com (accessed on 15 July 2018).
65. Kwietniewski, M.; Roman, M.; Kłos-Trębaczkiewicz, H. *Relaibility of Water Supply and Sewage Systems*; Arkady: Warsaw, Poland, 1993.

66. Wieczysty, A. *Reliability of Water and Wastewater Systems I and II*; Publishing House of Cracow University of Technology: Kraków, Poland, 1990.
67. Kwietniewski, M. Failure of water supply and wastewater infrastructure in Poland based on the field tests. In Proceedings of the XXV Scientific-Technical Conference, Międzyzdroje, Poland, 24–27 May 2011; pp. 12–140.
68. Corder, G.W.; Foreman, D.I. *Nonparametric Statistics: A Step-by-Step Approach*; Wiley: Hoboken, NJ, USA, 2014.
69. Sobczyk, M. *Statistics: Theoretical and Practical Aspects*; Maria Curie-Sklodowska University (UMCS): Lublin, Poland, 2006.
70. Figueira, J.; Greco, S.; Ehrgott, M. *Multicriteria Decision Analysis: State of the Art Surveys*; Springer: New York, NY, USA, 2005. [CrossRef]
71. Tchórzewska-Cieślak, B.; Pietrucha-Urbanik, K. Methods for integrated failure risk analysis of water network in terms of water supply system functioning management. *J. Pol. Saf. Reliab. Assoc.* **2017**, *8*, 157–166.
72. Saaty, L.T. A scaling method for priorities in hierarchical structures. *J. Math. Psychol.* **1977**, *15*, 234–281. [CrossRef]
73. Saaty, L.T. *The Analytic Hierarchy Process*; McGraw-Hill: New York, NY, USA, 1980.