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Water supply safety assessment considering the water supply system resilience

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ABSTRACT

The paper assumes that the measure of the loss of safety in water distribution is the risk related to the occurrence of some undesired events such as the failure to meet certain (required) water quality conditions (that may have negative impacts on the consumer health), or a severe disruption of the water supply services. In this aspect, risk is assessed using the expected value of losses (hazardous effects) that may occur as a result of the occurrence of the undesirable events. A comparison of the determined values with the risk acceptability criteria is the basis for the safety assessment. The analysis was made based on the available operational data of the water supply subsystem. The analysis covered the period from 2011 to the third quarter of 2021 and was prepared on the basis of available physicochemical and microbiological analyses of water performed at the water and microbiology laboratory of the considered water supply system in Poland's Subcarpathian Province. A novel approach to risk analysis of the loss of safety in water supply system taking into account the occurrence of some undesired events was achieved. The estimated value of the risk level, under the given operating conditions, indicates that there is no real threat to water consumers.

Keywords: Water supply safety; Resilience; Water distribution system; Water quality; Water network failure; Risk

1. Introduction

Water supplied through the water distribution system (WDS) must be of the appropriate quality not only at the entrance of the water supply system, but also at the delivery point to the consumers [1–5]. During the transport of water to the consumer there is often a deterioration in its quality caused by the release of the material from which the network is made, the formation and detachment of biofilm, the accumulation, and the release of the deposited sediments.

Irregular changes in the quality of the supplied water can cause physicochemical and microbiological modifications in the pipeline material and the fouling formed in it. The result of this phenomenon may be the release of sediments, substances and microorganisms formed over decades, creating health risks and aesthetic problems related to the turbidity and the color of the tap water. Apart from the technical condition of the network itself, the lack of physical, biological, and chemical stability of the water leaving the water supply system is considered as the main cause of the deterioration in the quality of water during its transport [6–9].

The definition of the operational safety of the WDS is as follows: the safety of the functioning of the WDS is to ensure the continuity of water supply to the consumer while meeting the criteria of the reliability of the system in terms

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of quantity and quality, the societal acceptable level of price per m^3 of water supplied, taking into account the aspects resulting from the requirements of public safety, protection of the natural water environment and the quality of life standard [10,11].

Regarding WDSs, the producers' operational risks and the consumers' safety are distinguished but connected. The risk of a water producer can be defined as the quotient of the expected value of the losses incurred as a result of undesirable events by the expected value of the losses incurred as a result of undesirable events [11–13]. In the case of the producer, these may be losses related to the lack of water sales, the need to repair and flush the water supply network, possible compensation for water recipients, that is, losses in the expected financial profit of the water supply company resulting directly from the sale of water. However, in the case of an individual consumer, one can distinguish the risk associated with the possibility of disruptions in water supply and the risk associated with the possibility of consuming water of inadequate quality. The term "resilience" of water delivery systems refers to their capacity to withstand accidents, minimize disaster losses, manage efficiently, and recover promptly.

The article proposes a novel approach to risk analysis of the loss of safety in water supply system taking into account the occurrence of some undesired events. The analysis was made on the basis of the obtained operational data of the water supply system.

2. A measure of the loss of safety in the water distribution process

The primary and fundamental entity concerned by the concept of water safety is the consumer. The measure of "the loss of water safety" is the risk function, defined as the probability of an adverse event (cause), the effect of which may be a real threat to the health or life of water consumers (effect) [11,14].

The genesis of risk dates back to 1981, when Kaplan and Garrick [15] defined risk as a set of three interdependent parameters: a hazard scenario, the occurrence probability of the hazard scenario and the consequences.

ISO 31000 standard "Risk Management. Principles and Guidelines" [16] defines risk as the "effect of uncertainty on objectives" and an effect is a positive or negative deviation from what is expected. On the other hand, according to the ISO 9001:2015 standard "Quality Management Systems" [17], risk has been defined as the influence of uncertainty on the functioning of systems or projects.

Then, risk can be defined as a function $r(.)$ dependent on UES, P and C parameters [11,18]:

$$r = f\left(\text{UES}, P, C\right) \quad (1)$$

where $r(.)$ is the risk function, UES is the undesirable event scenario, P is the occurrence probability of an undesirable event scenario, C are the consequences (losses, effects).

In this way, it can be assumed that risk is the expected value $E(C)$ of the consequent loss C. The value of the estimated total risk [11,18–20] is:

$$E\left(C\right) = \sum_{(i=1)}^{N} P_i \cdot C_i = r\left(\text{UES}\right) = r \quad (2)$$

where $r(\text{UES}) = r$ is a risk of a representative accident scenario, P is the probability of an undesirable event scenario, $P = \{p_i\} = \{p_1, p_2, p_3, ..., p_n\}$, C is the set of possible loss values, $C = \{c_i\} = \{c_1, c_2, c_3, \ldots, n\}$, i is the i-th value of loss or adopted range of losses, n is the number of possible losses in the given scenario.

Assessing the functional safety of the water distribution subsystem and its impact on consumer safety requires, first of all, taking into account its vulnerability to various types of threats [21–23]. A water distribution subsystem is basically composed of: a water supply network and its auxiliaries, tanks, and network pumping stations and their emergency power generation units.

Vulnerability, in the absence of a normalised definition of vulnerability in system engineering science, we consider vulnerability as the characteristic of the system to resist (physically and/or functionally), absorb, mitigate or adapt to the actions of a threat [24–26]. The main vulnerability parameters are as follows:

- threat action intensity,
- exposure time,
- sensitivity, susceptibility (physical, functional, procedural),
- supporting human assets (organisational, managerial, professional).

The analysis and safety assessment of the water supply system is performed according to the following algorithm:

- system recognition (construction, operation),
- identification of the purpose, scope and level of detail of the performed analysis,
- qualitative assessment of threats (action, intensity, severity),
- identifying threats that have an impact on the loss of system safety,
- selecting critical threats,
- selecting failures (adverse events) that may cause a domino effect (the so-called cascade damage),
- estimation of possible losses for each group of threats,
- estimation of the probability of exceeding a certain value of losses $P(C > C_{\lim})$,
- estimating the likelihood of adverse events,
- identification of safety barriers,
- estimation of the system's vulnerability to threats,
- determination of the number of inhabitants using the water supply system,
- determination of the risk function along with the characteristics of its parameters,
- assessment of the risk value, using the adopted three or five-point scale (tolerated, controlled, unacceptable risk),
- assessment of the costs incurred,
- development of emergency response plans,
- making decisions regarding the need to introduce corrective actions,
- setting strategic "milestones" regarding future goals of modernization, expansion of water supply system, in order to ensure the security of water supply.

The methods of risk analysis are divided into [18,19]:

- quantitative methods for risk analysis (QRA), methods that process quantitative (measurable) data and determine a specific risk value. These methods include methods based on mathematical statistics and the calculus of probability,
- qualitative methods of risk analysis (QLRA). Unlike quantitative methods, they do not take into account the numerical determination of risk using probabilistic methods (e.g., density distributions),
- quantitative–qualitative methods for risk analysis, which include, among others, matrix methods, Fault Tree Analysis (FTA) and Event Tree Analysis, networks Bayesian, fuzzy logic and neural networks,
- simulation methods using computer hydraulic models, control systems, data processing and recording, computer databases, etc.

A comparison of the determined values with the risk acceptability criteria is the basis for the safety assessment. At this stage, it is very important to define risk acceptability criteria so that they can be used in the decision-making process [27,28].

The acceptability criteria should take into account the requirements related to the reliability of the subsystem functioning, both in terms of quantity and quality, in accordance with the applicable legal regulations and social and economic conditions [29–31].

The risk assessment should include:

- ranking the adverse events,
- determining the level (value) of risk,
- proposing measures to minimize the risk,
- determining the period after which, as a result of various processes, for example, aging of materials, the risk may reach a critical value.

The most common is a three-level risk assessment scale [11,14]:

- ***tolerated*** – it can be assumed that the water supply system satisfactorily fulfils its functions in terms of operational reliability and safety,
- ***controlled*** – improvement of the operation of some elements of the system should be considered (e.g., network monitoring, protective stations or renovation of sections of the water supply network),
- ***unacceptable*** – means that the water supply system does not fulfil its functions both in terms of functioning and safety, that a thorough analysis of the main risk factors should be carried out, and the water supply system should be thoroughly modernized and even the possibility of its redesign should be considered.

3. Research methodology

In the paper, the risk of "loss of water safety" and of "water supply disruption" are measured by the occurrence probability of an adverse event. An adverse event can be a failure to meet certain requirements of water quality whose consequences may have a negative impact on the physicochemical and bacteriological quality of the supplied water. An alteration of the "supplied water quality" results systematically a "water supply disruption" event to protect the consumer.

Starting from the definition of the expected value, the risk defined in this way is defined as the probability of exceeding the assumed limit losses $C_{\lim}$ [19]. The risk value is described by the so-called risk function $f(r)$, defined as the expected value of losses under certain operating conditions of WDS, which determine the susceptibility (vulnerability) of the system to the adverse event:

$$r = E\left(C_i \mid C_i \geq C_{\lim}\right) = \sum_i P_i \cdot C_i \tag{3}$$

where $E(C_i \mid C_i \geq C_{\lim})$ is the expected value of losses C_i greater than the adopted limit losses $C_{\lim}$, and P_i is the probability of the occurrence of losses C_i.

and:

$$C_{\lim} = f\left(S_1, S_2, S_3\right) \tag{4}$$

where S_1 is the criterion corresponding to the possibility of exceeding the water quality standards, S_2 is the criterion corresponding to the failure rate of the water supply network, S_3 is the criterion corresponding to the vulnerability of the system to the existing adverse event.

The proposed base of rules regarding the quality of drinking water was developed on the basis of information provided by the Chief Sanitary Inspectorate in Poland, which supervises the quality of water intended for human consumption in accordance with the regulations [4,5].

The following evaluation criteria were assumed for individual parameters:

- the criterion corresponding to the possibility of exceeding the water quality standards is low (S_{1low}) – stating the suitability of the water for consumption:

I. If the microbiological parameters have not been exceeded and the parameters other than microbiological have not been exceeded, then S_1 is low.

- the criterion corresponding to the possibility of exceeding the water quality standards is medium ($S_{1medium}$) – confirmation of the conditional suitability of water for consumption in the analysed period (at least once).

II. If the microbiological parameters have not been exceeded and the non-microbiological parameters have not been exceeded in a significant way, then S_1 is medium,

- the criterion corresponding to the possibility of exceeding the water quality standards is high (S_{1high}) – stating that the water is unfit for consumption in the analysed period (at least once).

III. If the microbiological parameters have not been exceeded and the non-microbiological parameters have been exceeded in significant values, then S_1 is high.
IV. If the microbiological parameters have been exceeded and the parameters other than microbiological have not been exceeded, then S_1 is high.
V. If the microbiological parameters have been exceeded and the non-microbiological parameters have not been exceeded in a significant way, then S_1 is high.
VI. If the microbiological parameters have been exceeded and the non-microbiological parameters have been exceeded in significant values, then S_1 is high.

Water supply failures often result in the reduction or suspension of water supply to consumers, therefore the failure rate was determined, which takes into account the number of failures and the length of the analysed pipes:

$$\lambda = \frac{n(\Delta t)}{L\Delta t}\text{km}^{-1}a^{-1} \tag{4}$$

where the $n(\Delta t)$ is the number of failures in the time interval Δt, the L is the length (km) of examined pipes in the time interval Δt and the Δt is the considered period of time in years.

The recommended values of failure rate indicators were adopted according to the criteria presented in the paper [32], as follows:

- mains of $\lambda_M \leq 0.3$ km/a,
- distribution pipes $\lambda_D \leq 0.5$ km/a,
- water connections $\lambda_W \leq 1.0$ km/a.

Therefore, the following evaluation criteria were adopted for parameter S_2 (λ_M is the failure rate of mains, and λ_D is the failure rate of distribution pipes):

- the criterion corresponding to the failure rate of the water supply network is low ($S_{2\text{low}}$) – the failure rate of the water pipes of the analysed city meets certain requirements:

I. If $\lambda_M \leq 0.3$ km/a and $\lambda_D \leq 0.5$ km/a, then S_2 is low.

- the criterion corresponding to the failure rate of the water supply network is medium ($S_{2\text{medium}}$) – the failure rate of the water pipes is slightly higher than the adopted criteria:

II. If $\lambda_M \leq 0.3$ km/a and $0.5 < \lambda_D \leq 1.0$ km/a, then S_2 is medium.
III. If $0.3 < \lambda_M \leq 0.5$ km/a and $\lambda_D \leq 0.5$ km/a, then S_2 is medium.

- the criterion corresponding to the failure rate of the water supply network is high ($S_{2\text{high}}$) – the failure rate of water pipes is very high, which proves the poor technical condition of these pipes,

IV. If $\lambda_M \leq 0.3$ km/a and $\lambda_D \geq 1.0$ km/a, then S_2 is high.
V. If $0.3 < \lambda_M < 0.5$ km/a and $0.5 < \lambda_D < 1.0$ km/a, then S_2 is high.
VI. If $0.3 < \lambda_M < 0.5$ km/a and $\lambda_D > 1.0$ km/a, then S_2 is high.
VII. If $\lambda_M \geq 0.5$ km/a and $\lambda_D \leq 0.5$ km/a, then S_2 is high.
VIII. If $\lambda_M \geq 0.5$ km/a and $0.5 < \lambda_D < 1.0$ km/a, then S_2 is high.
IX. If $\lambda_M \geq 0.5$ km/a and $\lambda_D \geq 1.0$ km/a, then S_2 is high.

Of course, it is impossible to eliminate all threats (e.g., heavy rains and the resultant deterioration of the quality of the abstracted water), but the effects can be limited. Therefore, the following evaluation criteria were adopted for the parameter S_3:

- the criterion corresponding to the resistance of the system to the existing threats is high, so the vulnerability to threats is low ($S_{3\text{low}}$): effective water treatment system; closed-loop network; complete monitoring and control of the water supply process; use of SCADA, GIS metering, hydraulic model; comprehensive emergency alert and response systems; full use of alternative water sources,
- the criterion corresponding to the resistance of the system to the existing threats is medium ($S_{3\text{medium}}$): effective water treatment system; a mixed looped system; standard monitoring and control process, alternative sources of water to cover the minimum needs of the city's population, but lack of adequate water transport logistic means,
- the criterion corresponding to the resistance of the system to the existing threats is low, so the vulnerability to threats is high ($S_{3\text{high}}$): exploitation of a treatment process with low coagulation efficiency; obsolete water treatment process, mainly in an open circuit; with minimal monitoring and control processes and equipment; the security level of the emergency water supply process, in case of a disruption of the water supply via the network,

In order to assess the levels of risk acceptability (tolerated risk, controlled risk, unacceptable risk), the loss limit value C_{lim} should be adopted. Fig. 1 presents the risk curve defined by the acceptable level of C_1 losses and the border level of C_2 losses.

The characteristic points of the curve are defined as [19]:

- r_1 (producer's risk) – it is a limit value of risk, under given operating conditions, below which there is no real threat to water consumers, the risk is tolerated for water consumers – acceptable safety level (ASL),
- r_2 (consumer's risk) – this is the limit value of the risk, under given operating conditions, above which there is a real risk to water consumers, the risk is unacceptable to water consumers – unacceptable safety level (USL),
- the range r_1 to r_2 is controlled safety level (CSL).

According to the risk curve shown in Fig. 1, for the discrete random variable of losses $C = c_i$, the conditional expected value of losses (risk function) was defined as [33]:

$$r = E\left(C / C \leq C_{\text{gr}}\right) = \int_0^\infty \text{Cp}(C)\text{dc} \tag{5}$$

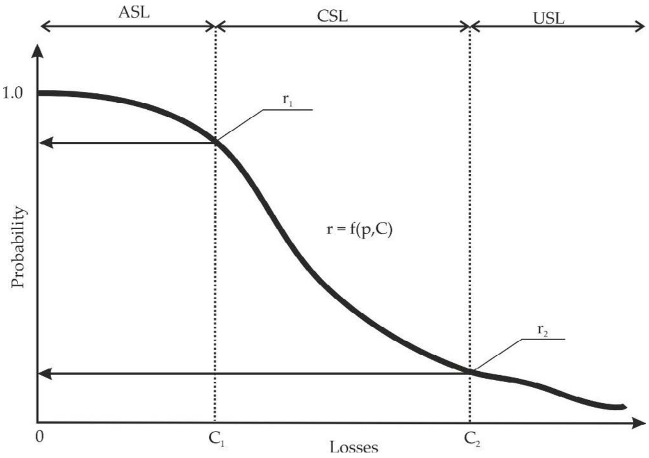

Fig. 1. Risk curve (based on the work Tchórzewska-Cieślak [19]).

For individual risk levels, Eq. (5) takes the form [33]:

- tolerable risk r_T:

$$r_T = E\left(C / \left(0 < C_{\text{gr}} \leq C_1\right)\right) \quad (6)$$

- controlled risk r_K:

$$r_K = E\left(C / C_1 < C_{\text{gr}} \leq C_2\right) \quad (7)$$

- unacceptable risk r_N:

$$r_N = E\left(C / C_{\text{gr}} \geq C_2\right) \quad (8)$$

The following base of rules has been proposed:

- ASL – acceptable safety level:

I. ASL: If S_1 is **low**, *S_2 is* **low** *and S_3 is* **low**, *then the risk level is tolerated.*
II. ASL: If S_1 is **low**, *S_2 is* **low** *and S_3 is* **medium**, *then the risk level is tolerated.*
III. ASL: If S_1 is **low**, *S_2 is* **low** *and S_3 is* **high**, *then the risk level is tolerated.*
IV. ASL: If S_1 is **medium**, *S_2 is* **low** *and S_3 is* **medium**, *then the risk level is tolerated.*
V. ASL: If S_1 is **medium**, *S_2 is* **low** *and S_3 is* **high**, *then the risk level is tolerated.*
VI. ASL: If S_1 is **low**, *S_2 is* **medium** *and S_3 is* **medium**, *then the risk level is tolerated.*
VII. ASL: If S_1 is **low**, *S_2 is* **medium** *and S_3 is* **high**, *then the risk level is tolerated.*

- CSL – controlled safety level:

I. CSL: If S_1 is **medium**, *S_2 is* small *and S_3 is* **low**, *then the risk level is controlled.*
II. CSL: If S_1 is **low**, *S_2 is* **medium** *and S_3 is* **low**, *then the risk level is controlled.*
III. CSL: If S_1 is **medium**, *S_2 is* **medium** *and S_3 is* **low**, *then the risk level is controlled.*
IV. CSL: If S_1 is **medium**, *S_2 is* **medium** *and S_3 is* **medium**, *then the risk level is controlled.*
V. CSL: If S_1 is **medium**, *S_2 is* **medium** *and S_3 is* **high**, *the risk level is controlled.*
VI. CSL: If S_1 is **low**, *S_2 is* **high** *and S_3 is* **medium**, *then the risk level is controlled.*
VII. CSL: If S_1 is **low**, *S_2 is* **high** *and S_3 is* **high**, *then the risk level is controlled.*
VIII. CSL: If S_1 is **medium**, *S_2 is* **high** *and S_3 is* **high**, *then the risk level is controlled.*

- USL – unacceptable safety level:

I. USL: If S_1 is **high**, *S_2 is* **low** *and S_3 is* **low**, *the risk level is unacceptable.*
II. USL: If S_1 is **high**, *S_2 is* **low** *and S_3 is* **medium**, *the risk level is unacceptable.*
III. USL: If S_1 is **high**, *S_2 is* **low** *and S_3 is* **high**, *the risk level is unacceptable.*
IV. USL: If S_1 is **high**, *S_2 is* **medium** *and S_3 is* **low**, *the risk level is unacceptable.*
V. USL: If S_1 is **high**, *S_2 is* **medium** *and S_3 is* **medium**, *the risk level is unacceptable.*
VI. USL: If S_1 is **high**, *S_2 is* **medium** *and S_3 is* **high**, *the risk level is unacceptable.*
VII. USL: If S_1 is **high**, *S_2 is* **low** *and S_3 is* **high**, *the risk level is unacceptable.*
VIII. USL: If S_1 is **low**, *S_2 is* **high** *and S_3 is* **low**, *the risk level is unacceptable.*
IX. USL: If S_1 is **medium**, *S_2 is* **high** *and S_3 is* **low**, *the risk level is unacceptable.*
X. USL: If S_1 is **medium**, *S_2 is* **high** *and S_3 is* **medium**, *the risk level is unacceptable.*
XI. USL: If S_1 is **high**, *S_2 is* **high** *and S_3 is* **low**, *the risk level is unacceptable.*
XII. USL: If S_1 is **high**, *S_2 is* **high** *and S_3 is* **medium**, *the risk level is unacceptable.*
XIII. USL: If S_1 is **high**, *S_2 is* **high** *and S_3 is* **high**, *the risk level is unacceptable.*

4. Research object

The source of water for the water treatment plant (WTP) is the surface water. In the 1990s, the facility was modernized, introducing preliminary ozonation of raw water. The total production capacity of the WTP is Q_{maxd} = 84,000 m^3/d. The WTP consists of two independent water treatment plants (WTP I and WTP II), located in one area, with a common intake.

The current possibilities of emergency water supply to the city, taking into account all available water sources, are as follows:

- water stored in 11 equalizing reservoirs within the water supply network, with a total capacity of 34,533 m^3,
- public wells with a total capacity of 689.4 m^3/d that gives a total of 35,222.4 m^3/d.

At present, the water treatment processes are the removal of large contaminants on the grates, water ozonation, coagulation, slow mixing, flocculation, sedimentation in horizontal sedimentation tanks (continuous sludge scraping), filtration through a sand bed (WTP I station) and anthracite-sand (WTP II station), indirect ozonation, filtration through a carbon bed, preliminary disinfection with UV and final disinfection with chlorine compounds (chlorine gas and chlorine dioxide) and the correction of the pH of the water (depending on the needs).

Water supply pipes are mostly made of plastic pipes. Polyvinyl chloride (PVC) pipes account for 29.4% and polyethylene (PE) – 48.0% of the total length of the water supply networks. Pipes made of steel account for 3.5% of the length of all pipes, cast iron pipes account for almost 14.5%, and pipes made of asbestos-cement only 0.18%. Water connections constitute approximately 33.9% of the network (369.5 km), the main network approximately 5.7% (62.2 km). The remaining part, approx. 60% of the networks, are distribution networks (656.8 km). In total, the water supply network administered by Water Company is 1,088.5 km long. Water pipelines are constructed in diameters from 25 to 1,200 mm.

5. Results

5.1. Water physico-chemical quality assessment

The analysis covered the period from 2011 to the third quarter of 2021 and was prepared on the basis of available physicochemical and microbiological analyses of water performed at the water and microbiology laboratory of the considered water and Sewage Company.

The results of the chosen parameters of the water quality for individual quartiles of the analysed years covered by the analysis were shown on box charts presented on Figs. 2–6, which also presents basic statistical characteristics.

In the last year of the analysis the following average values for parameters were obtained: pH (7.7), conductivity (561 µS/cm), nitrates (8.8 mg/L), nitrites (<0.05 mg/L), chlorides (31 mg/L), chromium (<0.5 mg/L), aluminium (<40 µg/L), cadmium (<0.5 µg/L), magnesium (10.1 µg/L), manganese (<20 µg/L), copper (0.003 µg/L), nickel (<4.0 µg/L), lead (<4.0 µg/L), sulphates (32 µg/L), total iron (<20 µg/L), oxidisability (0.7 µg/L), chloroform (<1.0 µg/L), total THMs (5.9 µg/L), total alkalinity (4.8 mval/L), total organic carbon (1.7 mg/L), total hardness (240 mg/L).

After analysing the quality water parameters of treated water no exceedances were found in the analysed period.

The water treatment technology at the water treatment plant is selected in the right way, and the treated water transported to the water supply network of the city meets the requirements for the quality of water intended for human consumption in accordance with the applicable ordinance on the quality of water intended for human consumption [4,5] as evidenced by the conducted analysis.

5.2. Failure data assessment

The study covered a sample of 2,731 failures from January 2010 to the December 2020. The following boundary conditions, necessary to conduct the failure rate analysis, were adopted:

- the main network consists of pipes with diameters ≥300 mm,
- the distribution network consists of pipes with a diameter of 100–250 mm,
- water supply connections form pipes with diameters in the range of 25–90 mm.

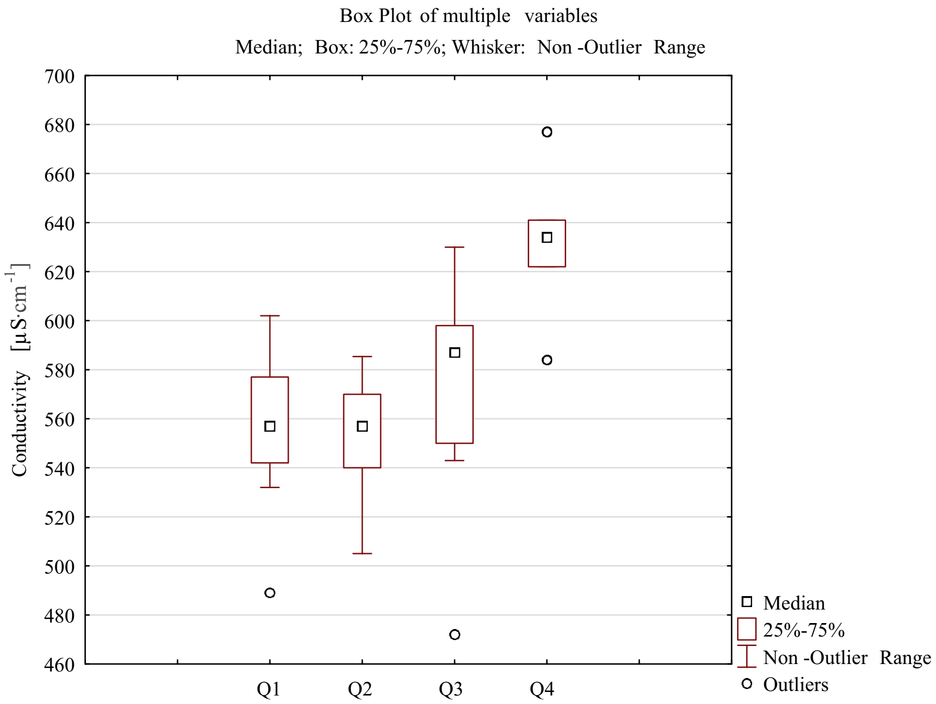

Fig. 2. Conductivity of the treated water in the period 2011–2021.

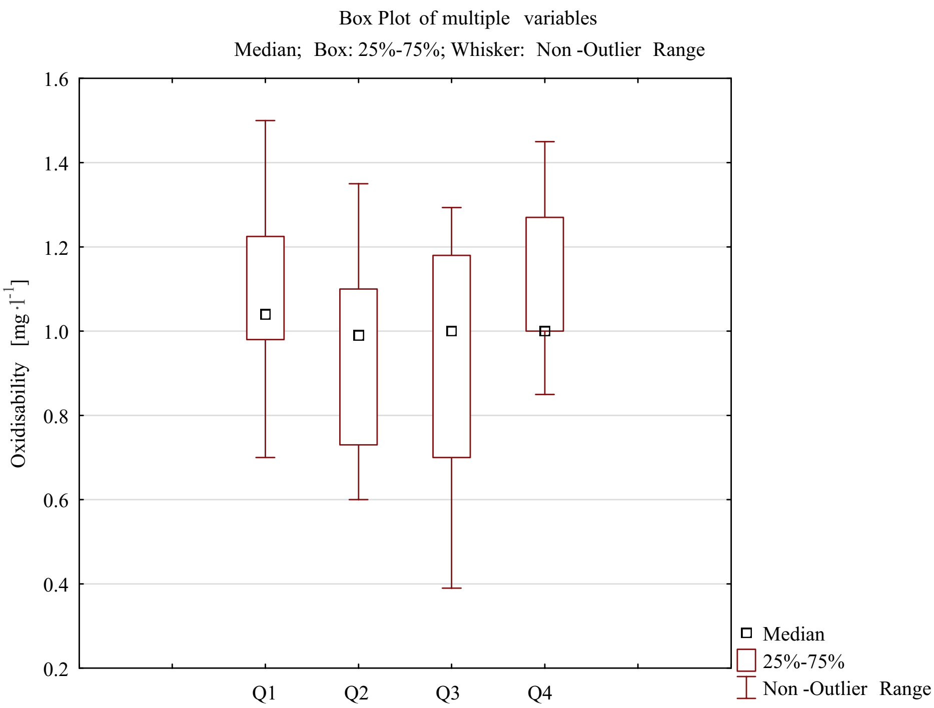

Fig. 3. PV of the treated water in the period 2011–2021.

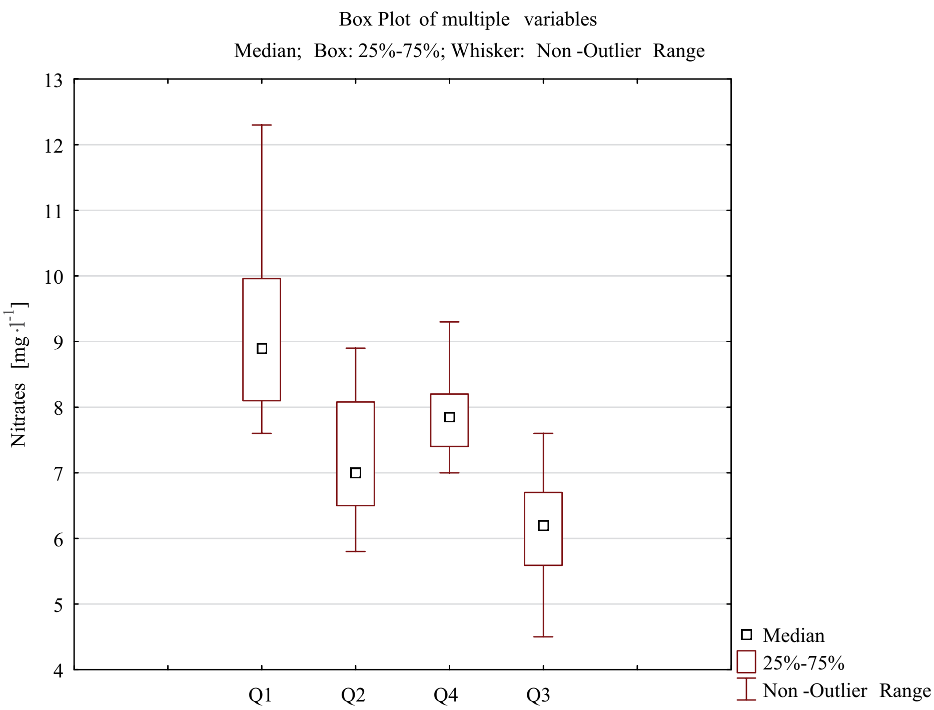

Fig. 4. Nitrates of the treated water in the period 2011–2021.

When interpreting the results, it can be seen that the most failures over the analysed years occurred on distribution lines (931 recorded failures) and on water supply connections (1,464 recorded failures). The distribution network constitutes the largest percentage of the total size of the water supply network (as for December 2020 – 60.34%). In total, in the analysed years there were 2,731 failures, which is: 12.5% on the main network, 34% on the distribution

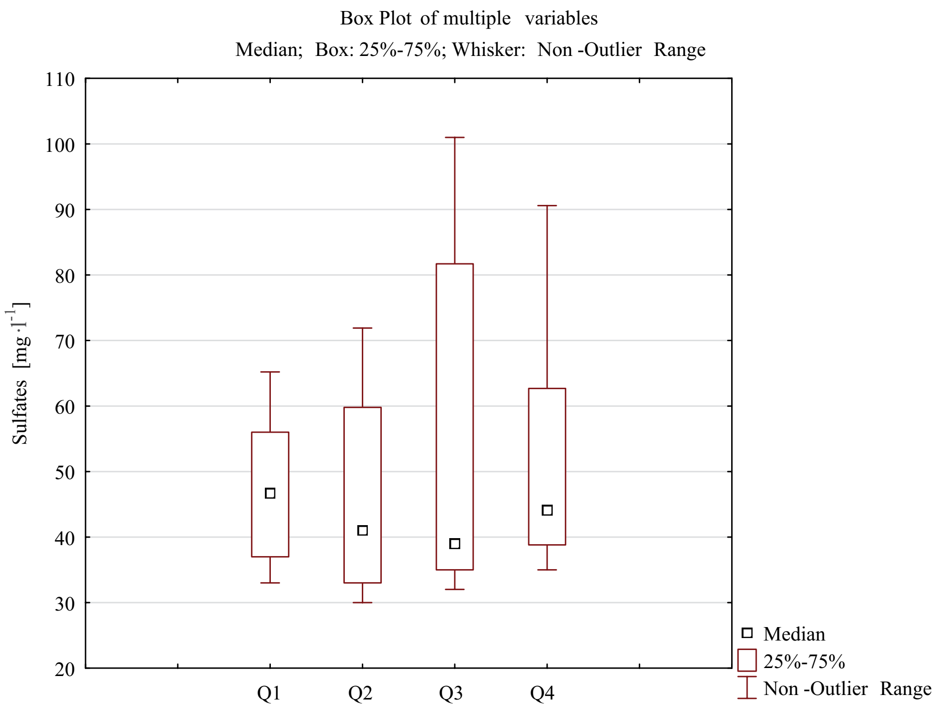

Fig. 5. Sulfates of the treated water in the period 2011–2021.

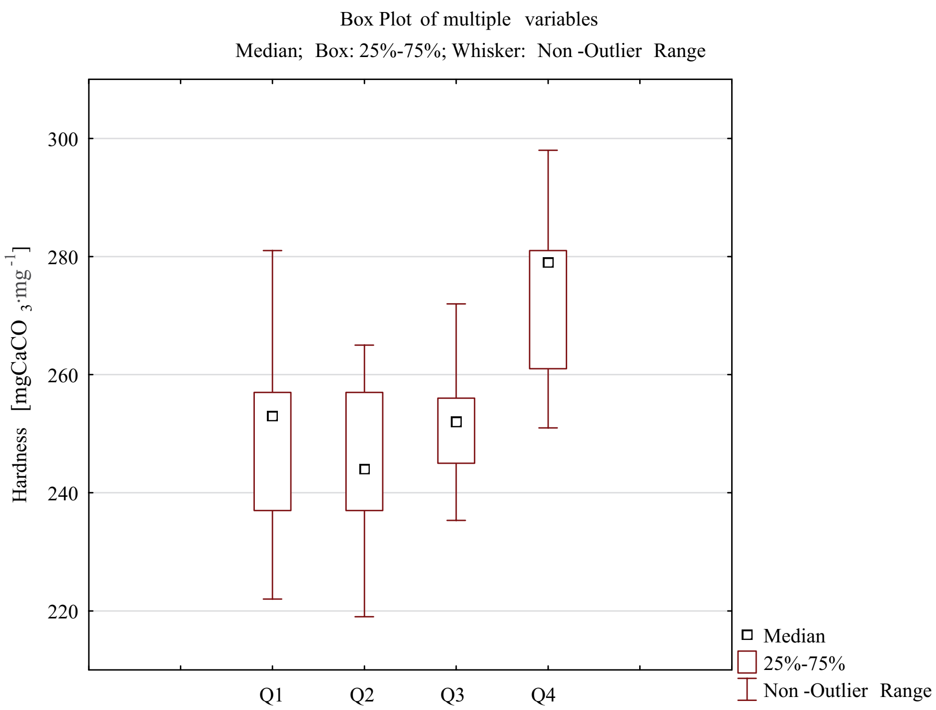

Fig. 6. Hardness of the treated water in the period 2011–2021.

network, and 53.5% of all failures on water supply connections. The most common cause of failure of the water supply system is corrosion, which most often occurs on steel pipes (1,240 failures), and unsealing on pipes made from cast iron (576 failures). Pipes made of PE and PVC are characterized by the lowest number of failures. Pipes made of plastic are characterized by high resistance to changing soil conditions and corrosion-causing microorganisms.

Fig. 7 presents the values of failure rate, calculated with the formula 3 in the years 2010–2020 and their basic statistics (Table 1).

For the main, the highest recorded failure rate was in 2015 (λ_{mh} = 0.91 km/a) and the lowest in 2020 (λ_{ml} = 0.29 km/a). For the distribution, the highest failure rate was recorded in 2010 and 2013 (λ_{dh} = 0.20 km/a) and the lowest in 2020 (λ_{dl} = 0.09 km/a). As for the connections, the highest was recorded in 2015 (λ_{ch} = 0.59 km/a) and the lowest in 2020 (λ_{cl} = 0.27 km/a). The analysis shows that the average value of the failure rate of the main is 0.593 km/a and higher than the adopted standard value of 0.3 km/a. For the distribution, the average failure rate is 0.153 km/a which is lower than the standard of 0.5 km/a. As for the connection, the average failure rate is 0.391 km/a, which is also lower than the adopted standard of 1.0 km/a.

5.3. Analysis of the loss of safety in water distribution system

Having analysed the loss of safety in a water supply system the following criteria were obtained.

Regarding the first criterion (S_1) none of the examined water parameter is exceeding the standards values. According to the first rule: If none of the microbiological and the chemical-physical parameters exceeds the standard values, then S_1 is low. The supplied water is then safe according to the regulations [4,5].

The following failure rates (parameter S_2) were estimated as: λ_M = 0.29 km/a for the mains (λ_M), and 0.09 km/a for the distribution pipes (λ_D). It can be concluded, that the criterion corresponding to the overall failure rate of the water distribution network is low (S_{2low}), complying with the following standard requirements: If $\lambda_M \leq 0.3$ km/a, and $\lambda_D \leq 0.5$ km/a, then S_2 is low. It should be noted, that main pipes failure have the greatest impact on the water supply service. Therefore, when planning renovation and repair works, the mains and distribution pipes with the highest failure rate should be eliminated in the first place.

The considered water supply system is characterised by the effective water treatment system with standard monitoring of the water supply network of measurements of pressure and flow rate in hydrophore plants. Also

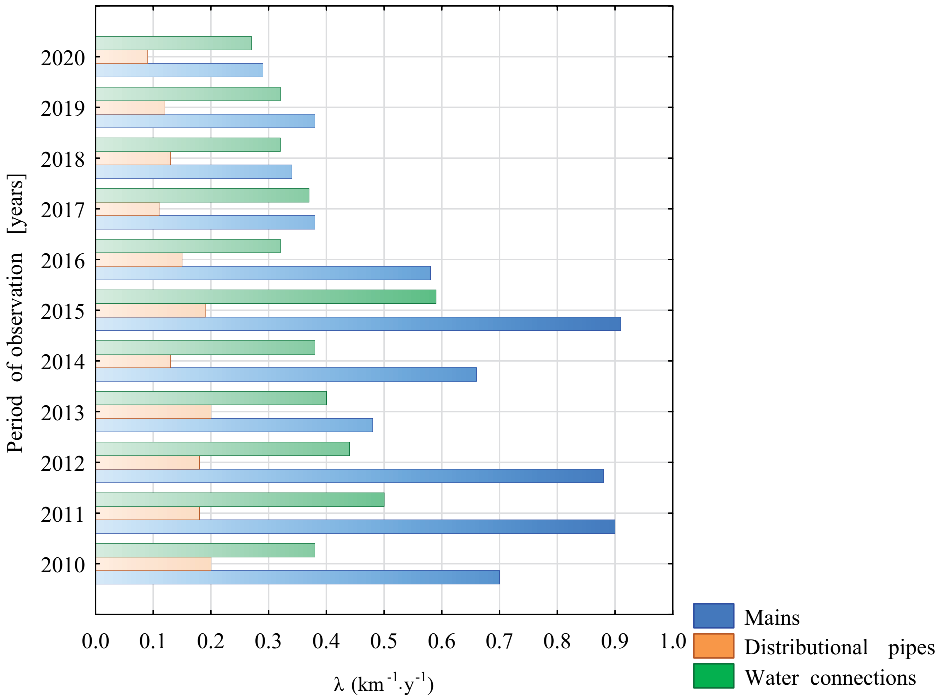

Fig. 7. Failure rates of the considered network.

Table 1
Descriptive statistics of the failure rates of the considered network

Descriptive statistics of failure rates (km/a)							
Variable	Mean	Median	Minimum	Maximum	Percentile 25%	Percentile 75%	Std. Dev.
Mains	0.59	0.58	0.29	0.91	0.38	0.88	0.235051
Distributional pipes	0.15	0.15	0.09	0.2	0.12	0.19	0.03901
Water connections	0.39	0.38	0.27	0.59	0.32	0.44	0.091869

comprehensive emergency alert and response system, as well as full use of alternative water sources are implemented. At the moment, the company does not have software for night flow tracking. Also lacks the analysis of their components and correlation of pressure changes in the water supply network, which would be a source of information about leakages on the network. Regarding the vulnerability criterion (S_3) its value is estimated as medium ($S_{3medium}$).

The acceptable safety level was determined (in compliance with the second-rule of the ASL): *If S_1 is low, S_2 is low and S_3 is medium, then the risk level is tolerated.* The estimated value of the risk level, under the given operating conditions, indicates that there is no real threat to water consumers. Of course, it is recommended to continue monitoring and maintaining the current level related to the quality of drinking water.

The presented method is based on operation and failure data of the water supply network and has been used to overcome the limitations of the conventional matrix method [31]. In the conventional matrix method the different combinations of parameters give the same risk value, but with different risk significances, what his leads to inappropriate decision makings. In comparison with the conventional matrix method, the proposed method does not require users to assign specific point values.

6. Conclusions

Future implementation of a monitoring and control smart systems will allow efficient mapping in real time of the network operational state. The implementation will then provide spatial and dynamic numerical mapping data. The project will enhance the reliability of the water supply system and maintain water quality at the highest standards levels.

It should be noted that the key aspect is monitoring undesirable events that may impact the nominal operation of the water supply system. Operators can then take appropriate actions in time and in the right place.

The increased risk in the long-term of large-scale power failures (blackouts), makes it necessary to develop alternative solutions for drinking water supply in crisis situations. The water supply system is an important critical infrastructure. It is increasingly subjected to restrictive requirements in terms of resilience and business continuity in crisis situations.

The presented new approach related to the modification of matrix methods is based on linguistic analysis procedure. That does not require users to assign specific point values. This assessment is based on the operational data. Besides, it relies on the expert judgements of the operator when operational data are unavailable. In the perspective research the presented approach will constitute the basis for neuro-fuzzy hybridization of AI simulation.

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