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Risk estimation method of secondary water pollution in water supply system

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ABSTRACT

The functional safety of the water supply system should be implemented by using risk standards, available reliability methods or with the use of Water Safety Plans, which are dedicated to all water supply companies. The constantly updated knowledge and the ability to carry out risk analysis and assessment based on the available tools, allows for effective decision-making process in order to minimize the health risk and the negative effects posed by the risk of secondary water pollution in the water supply network. The main aim of the article was to propose an original model for estimating the risk of secondary water pollution in the water supply system. The proposed model is based on a four-parameter risk matrix. The presented methodology containing a matrix proposal and criteria on a descriptive-point scale can be used in risk analysis and assessment both in qualitative and quantitative terms. Additionally, it will have a positive impact on the effectiveness of the water supply security management process in water supply companies. For the proposed model, a calculation example for a water supply network operated in south–eastern Poland has been presented.

Keywords: Water safety; Secondary water pollution; Water supply system; Water quality; Risk

1. Introduction

1.1. Right to water

According to the latest estimates of the World Health Organization (WHO), 663 million people worldwide are still without access to water, and 842,000 deaths occurred from diseases of the digestive system in underdeveloped countries [1]. This fact is caused by the consumption of non-potable water, poor sanitary conditions and related personal hygiene, which is of great importance in diseases of the digestive system. Although – as the WHO admits – this number has decreased over the last decade, sanitation and water quality are still a huge problem. These results emphasize the importance of ensuring a microbiological and physicochemical safe water supply. For these reasons, the WHO Water Quality Guidelines recommend preventive, risk-based, water quality management covering the source of the exposure. The risk-based approach was first adopted by WHO in 1999 as the Stockholm Framework. Systematic risk assessment recommended in the guidelines refers to the clarification of the definition of health risk, its assessment and determination of the goals of risk management planning based on the result of its analysis. The WHO guidelines [2] are based on the Stockholm Framework and constitute a risk management plan for drinking water.

Over the past decade, international law and at the UN level have recognized the right to safe drinking water and sanitation. UN General Assembly Resolution 64/292 and the Human Rights Council state that: the right to access to safe and clean drinking water and sanitation is a human right necessary for the full enjoyment of life and the enjoyment of all human rights [3]. At European level, the Parliamentary Assembly of the Council of Europe has stated that: access

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to water must be recognized as a fundamental human right, because water is essential to life on Earth and is a common good that belongs to all mankind [4].

In recent years, the health safety of drinking water has become so important that this issue has been regulated under Community law by issuing key directives, namely: Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption [5]. This directive takes into account the results of the Regulatory Fitness and Performance (REFIT) [6] evaluation, is the European Commission's response to the European citizens' initiative Right2Water to improve access for all Europeans to safe and high-quality tap water, and contributes United Nations in achieving the Sustainable Development Goals (Rio + 20). Directives, and consequently also legal acts generally applicable in EU countries, indicate parameters (substances) that are important for the health safety of consumers, and also provide safe values for these parameters, the so-called parametric values. The proposed parametric approach for individual substances in the water allows to ensure a high level of health protection. Thus, it minimizes the health risk of service users related to the consumption of inadequate quality water.

The fact that access to safe drinking water and sanitation is inextricably linked to the right to life and human dignity and the requirement to ensure a fair standard of living has also been recognized by the WHO. This is confirmed by the opening words of the 4th edition of the WHO Guidelines on the Quality of Drinking Water, recommending the creation and implementation of Water Safety Plans [7]: The most effective means of consistently ensuring the safety of a drinking-water supply is through the use of a comprehensive risk assessment and risk management approach that encompasses all steps in the water supply from catchment to consumer. In these guidelines, such approaches are termed Water Safety Plans (WSPs) – The most effective way to consistently secure your drinking water supply is to use a comprehensive risk assessment and management method that covers all stages of the water supply from intake to consumer. These guidelines refer to such methods as Water Safety Plans (WSPs).

A collective water supply system (CWSS) is defined as a technical system (a system of technical devices), whose task is to supply water to the places of its use in a specified quantity, with appropriate quality and required pressure, at any time convenient for the water recipient [8–10]. In order for the water supply system to fulfil its function, it should: provide the population with water, which is a necessary livelihood, maintain healthy living conditions, ensure an adequate standard of living, provide water to economic units (industrial and service plants) for which water is the main raw material for production and factor of almost all technological processes of economic activity [11].

There is no technical system that is not exposed to risks. The occurrence of random events, manifested by negative effects in each technical system belonging to the critical infrastructure, is the basis for issues related to the security of systems. Hazards have certain characteristics, for example, source of origin, cause, frequency of occurrence, duration or effects of occurrence. The approach to risk analysis and assessment presented by WHO and EU legal acts concern risk management, that is, introducing the definition of risk assessment, that is, hazard identification and risk analysis carried out on the basis of applicable rules and standards.

The specialized scientific literature clearly shows the trend that quantitative and qualitative methods of risk analysis and assessment are the basis for managing the safety of technical systems, and thus the safety of their operation. The essence of the work is to propose a modified method of risk analysis and assessment for the purpose of estimating the risk of secondary water pollution in a collective water supply system. The proposed method presents a new approach to the subject of risk analysis, based on the introduction of new risk parameters for estimating the risk of secondary water pollution, along with a proposal of point scales description. This method can bring new standards in the analysis and assessment of water supply safety.

2. Main causes of changes in drinking water quality

Water supplied to recipients should be treated in such a way as to prevent the multiplication of pathogenic microorganisms, corrosion of water supply piping materials and to ensure that the piping interior does not overgrow with sediments. Ensuring the required quality of water supplied to recipients requires the removal of primary pollutants and the prevention of their secondary formation [12–16].

Due to the fact that the water supply network is one of the potential sources of the spread of pathogenic organisms, their elimination is a key activity aimed at ensuring the required level of security of the supply of healthy water. The presence and growth of pathogenic microorganisms come from several sources. The main reasons stimulating the growth of bacteria in the water distribution system are: physico-chemical changes in water quality (temperature, availability of food substrates), low effectiveness of the disinfectant, wrong type of material and long age of the pipes, susceptibility of water pipes to corrosion and processes taking place at the end sections of the water supply network, favouring the formation of new bacterial colonies [17].

Another reason for changes in water quality is its irregular supply to the recipient, which results in pressure drop and contaminated water entering the water supply system through damage, cracks or leaks [2,18,19]. Noticeable changes in the speed of water in the pipes and its stagnation often cause its secondary pollution [17,20,21]. There are many reasons for secondary pollution of tap water, but the main one is the lack of biological and chemical stability of the water introduced to the tap-off network, insufficient amount of disinfectant administered and variable hydraulic conditions in the distribution system.

Water is considered to be biologically and chemically stable when it is in a state of carbonate calcium balance and is devoid of microorganisms and organic food substrates that condition the secondary development of microorganisms [16]. The lack of chemical stability causes corrosion of steel elements of the distribution system or precipitation of sparingly soluble compounds from water, mainly calcium carbonate $CaCO_3$. In turn, the lack of biological stability and the disinfectant results in the development of microorganisms forming the so-called biofilm on the inner surfaces of water pipes [20–23]. The increase in biofilm causes the unpleasant smell and taste of water, the increase in colour intensity, turbidity and the level of water pollution with organic substances, that is, ammonium nitrogen and metal corrosion products. It also increases the aggressive corrosivity of water [21,24,25]. The presence of biofilm in the water distribution system also creates operational problems. Biofilm and biological corrosion products can increase the roughness and hydraulic resistance of water pipes, which in turn reduces their internal cross-section and capacity. The intensity of destruction of home installation materials by biofilm increases the risk of failure in the water supply network and increases the costs of operating the water supply network and water losses. The activities to prevent biofilm formation include ensuring the chemical and biological stability of the water introduced into the water supply network and the presence of a disinfectant in the water throughout the system, as well as the proper operation of the network, including the prevention of the formation and accumulation of sediments, which are the main source of secondary water pollution in the water supply network.

Undoubtedly, it can be said that the quality of tap water is also influenced by the technical condition of devices, fittings and the network itself. Water pipes and utilities may corrode, which may lead to secondary pollution of the tap water. According to the publication [26], failures of pipes and utilities in the water supply network are an inherent phenomenon accompanying the process of network operation. The type of failure in the water supply depends mainly on the material of the pipes. These failures can be:

- in the case of grey cast iron pipes – loss of joint tightness, cracks and fractures,
- in the case of steel pipes – corrosion, cracks on welds,
- in the case of plastic pipes – longitudinal cracks.

As reported in the literature [27,28], in water pipes made, in particular, of cast iron and steel, there is a much greater risk of secondary water pollution. This is mainly due to the build-up of deposits and corrosion products that detach from the inner walls of the pipes and enter the flowing water. A particular risk of secondary water pollution is posed by breakdowns in the main pipes, due to the difficulty of ensuring the appropriate water flow velocity when rinsing the pipes after repair. Another equally dangerous cause of pollution are leaks in pipes and fittings. According to the authors of the works [28,29], a significant amount of water can flow through leaks in the form of micro cracks and pits in cast iron and steel pipes, which does not pose a threat when it flows out. Leaks can be a source of secondary pollution when a negative pressure occurs in the network, for example, as a result of a hydraulic shock, increased water intake or a sudden change in the direction of flow.The epidemiological risk caused by the presence of a biological membrane in the water supply network is related to both the water quality and the effectiveness of the treatment and disinfection processes carried out, taking into account the wrong dose of the disinfectant itself and the water treatment process at the water treatment plant [30].

3. Materials and methods

3.1. Methods of risk analysis and assessment

The concept of risk, which is its measure, is directly related to the loss of safety. The specialized scientific literature clearly shows the trend that quantitative and qualitative methods of risk analysis and assessment are the basis for managing the safety of water systems, and thus the safety of its operation. In terms of the functioning of the water system, the risk of lack of or limitation of water supply as a result of an undesirable event is inherent in both the producer and the water consumer. In the case of a water producer, it entails financial outlays that the company incurs when an undesirable event occurs. In relation to the water consumer, the risk is related to the loss of security of water supply due to the inconvenience related to the interruption in water supply, lack of it and possible loss of health or life as a result of consuming poor-quality water.

Therefore, the risk analysed in quantitative and qualitative terms can be defined as a measure of the loss of safety and must be interpreted as the probability of an undesirable event and the associated negative effects.

Regarding the mathematical aspect, in its simplest form, the risk r is defined as a function of two parameters: the probability of the occurrence of the undesirable event P and its negative consequences C [31–33]:

$$r = P \cdot C \tag{1}$$

Using Eq. (1), the numerical value of the risk is obtained. The next step is to categorize the risk according to the one of available category.

Research related to the municipal infrastructure risk analysis, has shown that its size (except the probability and the consequences parameter) is influenced by the protection parameter "O", which is inversely proportional to the risk size, or the vulnerability parameter "V". The numerical risk assessment is the product of the parameters listed below [33,34]:

$$r = \frac{P \cdot C}{O} \tag{2}$$

or $$r = P \cdot C \cdot V \tag{3}$$

where P – point weight related to probability of a given representative adverse event occurrence, C – point weight related to amount of losses, O – point weight related to protection of the system against threats, V – point weight related to vulnerability.

In the case of municipal systems, a four-parameter matrix can be used, which takes into account the number of inhabitants exposed to losses as a result of an adverse event (e.g., consumption of poor-quality water). The four-parameter risk estimation matrix is determined according to the equation [33,34]:

$$r = \frac{P \cdot C \cdot N}{O} \tag{4}$$

where P – point weight related to probability of a given representative adverse event occurrence, C – point weight related to amount of losses, N – point weight related to number of inhabitants affected by the risk, O – point weight related to the protection of municipal infrastructure against extraordinary threats.

To determine the risk associated with the failure of the water supply network, the equation has been proposed [33,34]:

$$r = \frac{S \cdot I \cdot U}{O} \tag{5}$$

where I – point weight related to the failure intensity λ, S – point weight related to the type of water supply network, U – point weight related to the inconvenience of damage repair, O – point weight related to the protection of the water supply network from undesirable event.

In the case of very extensive CWSS in large urban agglomerations, a five-parameter risk estimation matrix can be used used according to equation [33,34]:

$$r = \frac{P \cdot C \cdot N \cdot E}{O} \tag{6}$$

where P – point weight related to probability of a given representative adverse event occurrence, C – point weight related to amount of losses, N – point weight related to number of inhabitants affected by the risk, O – point weight related to protection of municipal infrastructure against extraordinary threats, E – point weight related to risk exposure.

When considering the risk in terms of quality, one should take into account the risk associated with the possibility of exceeding the normative values as well as the risk of changes in water quality parameters, which may adversely affect the physicochemical parameters of the water supplying the consumer.

In the work [30], the risk related to failure to meet certain values of physico-chemical parameters of water quality in the water supply network is a measure of the lack of bio stability. The value of the risk of biological instability of tap water under certain operating conditions of the CWSS is defined as the expected value of losses (effects) that may occur as a result of exceeding certain water quality parameters:

$$r = E\left(C_i \middle| C_i \geq C_{\text{gr}}\right) = \sum_i P_i \cdot C_i \tag{7}$$

where $E(C_i | C_i \geq C_{\text{gr}})$ – the expected value of losses C_i greater than the assumed limit losses C_{gr}, P_i – probability of losses C_i, wherein [30]:

$$C_{\text{gr}} = f\left(S_1, S_2, S_3\right) \tag{8}$$

where S_1 – criterion corresponding to the content BRWO (biodegradable dissolved organic carbon), g·C/m^3, S_2 – criterion corresponding to the content N_{norg}, g·N/m^3, S_3 – criterion corresponding to the content PO_4^{3-}, g·PO_4^{3-}/m^3.

On the other hand, the measure of the risk of loss of chemical stability of water is the expected value, related to exceeding water corrosivity indices (Langelier saturation index, Ryznar index, Strohecker index) taking into account the tendency to create protective layers as well as precipitation and dissolution of sediments. The value of the risk of losing chemical stability can be presented using Eq. (7) [30]:

$$C_{\text{gr}} = f\left(I_1, I_2, I_3\right) \tag{9}$$

where I_1 – criterion corresponding to the parameter value for the Langelier saturation index, I_2 – criterion corresponding to the parameter value for the Ryznar index, I_3 – criterion corresponding to the parameter value for the Strohecker index.

3.2. Novel method of risk estimation of secondary water pollution in water supply system

The analysis and assessment of the risk of secondary pollution in water supply system was performed using the proprietary risk matrix, based on the standard [33–36] and many years of research and collaboration between the authors and water companies. It is proposed to analyse and assess the risk in the following stages:

Stage 1. Determination of the probability of an adverse event (AE) – secondary water pollution in the water supply network (analysis based on operational data).

Stage 2. Identification of negative consequences caused by AE.

Stage 3. Determining the category of the water pipe on which the AE occurred.

Stage 4. Determination of the type of protection (protection) against secondary water pollution.

Stage 5. Determining the criteria values of risk.

Stage 6. Risk assessment based on the proposed risk categories.

A four-parametric risk matrix was used, using the proprietary, modified risk value equation:

$$r_{\text{wz}} = \frac{P_i \cdot V_i \cdot \text{WP}_i}{\text{Ptc}_i} \tag{10}$$

where P_i – point weight related to the probability of an adverse event (e.g., secondary pollution in water supply system), V_i – point weight related to the vulnerability of the occurrence of AE, in the case of qualitative analysis it means the predisposition of the water supply network to secondary water pollution, WP_i – point weight related to the category of the water pipe, Ptc_i – point weighting related to the protection of the system against the appearance of AE.

The proposed qualitative risk analysis method is of an expert method, therefore in such cases the values of risk estimation are used as descriptive measures of the parameters included in the formula for its determination. Each time the P_i, V_i, WP_i and Ptc_i parameters were assigned the criteria of a descriptive-point scale (Tables 1–4). The presented criteria were developed on the basis of own research and studies of the literature [2,7,37–45].

Using Eq. (10) for individual risk parameters, a risk matrix with numerical values ranging from 0.20 to 125 was obtained. The results were presented in the form of a matrix (Table 5).

Table 1
Descriptive-point scale criteria for the parameter P_i, i = 1, 2, 3, 4, 5

Point weight	Description of the P parameter
1	Very unlikely – once in 10 y and less
2	Unlikely – once in 5 y
3	Moderately likely – once every 2 y
4	Probable – once a year
5	Very likely – once every six months and more often

Table 6 shows the proposed risk categories.

After the process of identifying secondary water pollution, it is possible to determine the dose of organic, inorganic, carcinogenic substances to which the water consumer was exposed as a result of consuming poor-quality water [46].

4. Results

4.1. Research object

The research object is the water supply network of one of the largest cities in south–eastern Poland. The analysed city is the seat of local and provincial authorities, as well as government and judiciary institutions. It plays the role of an important centre of the aviation, commercial and service and construction industries. According to the data of the city office from January 1, 2021, the city had 197,863 inhabitants. The analysed water supply network works in a closed system in 80%. The network cooperates with two groups of clean water tanks: ZB1 and ZB2, located in the eastern and western parts of the city. The scheme of the water supply network consists of four water mains transporting water from the pumping station located on the premises of the water treatment plant.

The pipes of the analysed water supply network are mostly made as a plastic pipes. PVC pipes account for 29.4%, and PE – 48.0% of the total length of the water supply network. Steel pipes account for 3.5% of all network, cast iron pipes account for almost 14.5%, and asbestos-cement pipes account for only 0.18%. Connections account for about 33.9% of the network (369.5 km), the main network for about 5.7% (62.2 km). The remaining part, ie approx. 60% of the networks, are distribution networks (656.8 km). In total, the water supply network is 1,088.5 km long (data from December 31, 2020).

Fig. 1 shows the location of the analysed water supply network.

The treated water transported from the water treatment plant (WTP) through five water main meets the quality requirements for drinking water in accordance with national requirements [46].

In the event of a crisis situation, such as water pollution or secondary water pollution in the water supply network, it is possible to supply water from a packer located on the premises of the water treatment plant (production capacity is about 1,500 bags with a capacity of 1 dm^3/h). When necessary, it is also possible to transport the packer to alternative sources (e.g., water tanks). The current possibilities of emergency water supply to the analysed urban agglomeration, taking into account all water sources operated by the enterprise, are as follows:

- water is stored in 11 water reservoirs on the supply network with a total capacity of 34 533 m^3,
- public wells with a total capacity of 689.4 m^3/d.

In recent years, a special economic zone has been established in the analysed area, where 4 clean water tanks with a total capacity of 3,000 m^3 have been put into operation. At the moment, the tanks are not working due to the lack of water demand in this zone (dedicated to investors), but they can be put into operation at any time. An alternative source of water in the event of a crisis situation, the company maintains two deep water intakes in the state of technical readiness, with the capacity of 1,008 and 432 m^3/d, respectively.

Separately, the possibility of using other alternative water sources located in the agglomeration, owned by business entities and public utilities, after signing contracts/consents for water abstraction in crisis conditions, should be considered. The signing of contracts for the supply of water in a crisis situation with neighbouring municipalities is of significant importance in increasing the security of water supply.

4.2. Analysis and assessment of the risk of secondary pollution in water supply system

The first stage of the research was to obtain operational data from a water supply company in the analysed urban agglomeration. These data concerned: determining the probability of an adverse event, resulting in a change in water quality in the water supply network, estimation of the predisposition of the analysed water supply network to the occurrence of a specific adverse event, determination of the category of a conduit (main, distribution, water supply connection), determination of the type of protection (protection) against secondary water pollution. The analysis also covered water quality data in the water supply network for the operational period, that is, 2016–2021. Some of the data that were not measured and made available by the enterprises was estimated on the basis of the literature and the experience of the authors of this study.

Before starting the analysis and assessment of the risk of secondary pollution in water system with the use of the proposed methodology, it was important to analyse the quality of water in the water supply network at selected points of water abstraction.

Table 7 presents the results of water quality monitoring tests in the water supply network for various water intake points located in the water supply network. The results below are based on materials obtained from the water utility.

The analysis took into account the results of tests carried out in the Accredited Central Laboratory from: 45 water points for the water supply system from 2016 (415 results), 55 water points from 2017 (316 results), 40 water points from 2018 (491 results), 40 water points from 2019 (520 results), 39 water points from 2020 (485 results) and 40 water abstraction points from 2021 (413 results).The analysis of the results

Table 2
Descriptive-point scale criteria for the parameter V_i, i = 1, 2, 3, 4, 5

Point weight	Description of the V parameter
1	Very small predisposition No health risk to water consumers. Water quality that fully meets the requirements for the quality of water for human consumption in accordance with the applicable standards [46]. Biologically and chemically stable water. Organoleptic properties without reservations. A well-chosen water treatment process at the water treatment plants. Selection of an appropriate/sufficient dose of the disinfectant, in accordance with the recommendations of an accredited laboratory. Inability to act by third parties that could affect the quality of the water supplied. The network is made of new pipes, the material and quality of which are adapted to the quality of the water supplied. In the case of the existing networks, the old pipes of the water supply network, made of cast iron and steel, are successively replaced with new ones.
2	Small predisposition No health risk for consumers. Local deterioration of organoleptic parameters, including taste, colour and smell. No exceeding of the microbiological, chemical, indicator and radioactive parameters. Existing risk of further deterioration of water quality with the existing water treatment process. Biologically and chemically stable water. There is no significant presence of organic compounds that feed the microorganisms in the water. Non-aggressive water, with a slight tendency to precipitate $CaCO_3$. There is no information about the possibility of pollution of water from the ground due to leaks in the water supply pipes. Selection of an appropriate/sufficient dose of the disinfectant, in accordance with the recommendations of an accredited laboratory. Old water pipes made of cast iron and steel, successively replaced with plastic pipes. Inability to act by third parties that could affect the quality of the water supplied.
3	Medium predisposition Local deterioration of organoleptic parameters, including taste, colour and smell. Numerous complaints. No exceeding of the micro-biological, chemical, indicator and radioactive parameters. Trace amounts of biofilm in water pipes. There is a significant risk of secondary water pollution in the water supply network. Moderately aggressive water, and the value of the Strohecker stability index in the range of 0.5–2.0. Threshold values of parameters determining the biological stability of water, that is, BRWO (biodegradable dissolved organic carbon), PWO (bioavailable organic carbon), nitrogen and phosphorus compounds [46], not exceeded. Selection of an appropriate/sufficient dose of the disinfectant, in accordance with the recommendations of an accredited laboratory. An unfavourably designed water distribution system, but not adversely affecting the hydraulic conditions of water transmission. Old water pipes made of cast iron and steel, successively replaced with plastic pipes. Inability to act by third parties that could affect the quality of the water supplied.
4	High predisposition Considerable organoleptic nuisance (smell, changed colour and turbidity). Numerous complaints. Exceeding physicochemical indices, no pathogenic and drug-resistant microorganisms. There are numerous clusters of biofilm in individual fragments of the water supply network. The threshold values of parameters determining the biological stability of water, that is, BRWO, PWO, nitrogen and phosphorus compounds [46], were exceeded. Moderately aggressive water, and the value of the Strohecker stability index in the range of 0.5–2.0. Chemically unstable water, with a tendency to precipitate $CaCO_3$. Selection of an insufficient dose of disinfectant or water treatment process. An unfavourably designed water distribution system with unfavourable hydraulic conditions. No renovation activities aimed at replacing corroded water pipes. Possible pollution of water from the ground, for example, due to leakage at connections of water pipes. No protection against the possibility of third party actions.
5	Very high predisposition No response to numerous complaints from water consumers. Very high organoleptic nuisance (odour, changed colour and turbidity). Exceedance of physicochemical and/or microbiological parameters of pathogenic organisms, indicator and/or radioactive parameters. In larger parts of the water supply network numerous clusters of biofilm. The threshold values of parameters determining the biological stability of water, that is, BRWO, PWO, nitrogen and phosphorus compounds [46], were significantly exceeded. Chemically unstable water, characterized by a strong tendency to dissolve $CaCO_3$. Aggressive water, and the value of the Strohecker stability index in the range of 2.0–4.0. Choosing the wrong dose of disinfectant or the entire water treatment process. Poorly designed water distribution system, with unfavourable hydraulic conditions. No renovation activities aimed at replacing corroded water pipes. Possible pollution of the water from the ground, for example, by leakage at the connections of water pipes. No protection against the possibility of third party actions.

Table 3
Descriptive-point scale criteria for the parameter WP_i, i = 1, 2, 3, 4, 5

Point weight	Description of the WP parameter
1	Water connection to a single-family house or several single-family houses – DN25–DN80
2	Distribution pipes – DN100–DN150
3	Distribution pipes – DN200–DN280
4	Main pipes – DN300–DN1500 AE location at a distance of ≤5 km from the water treatment plant
5	Main pipes – DN300–DN1500 AE location at a distance of ≥5 km from the water treatment plant

Table 4
Descriptive-point scale criteria for the parameter Ptc_i, i = 1, 2, 3, 4, 5

Point weight	Description of the Ptc parameter
1	Standard monitoring of the quality of water supplied to consumers, meeting the requirements of the regulation [46].
2	Standard monitoring of the quality of water supplied to consumers. Location of additional measurement points on the network. Water consumers equipped with anti-pollution valves installed behind the water meter set on the side of the internal installation.
3	Above-standard water quality monitoring – using specialized software, for example, SCADA. Water consumers equipped with anti-pollution valves installed behind the water meter set on the side of the internal installation.
4	Fully utilized SCADA software. Developed emergency response plan. Possibility of supplying people with water from active, alternative water sources. Water consumers are equipped with anti-pollution valves installed behind the water-meter set from the side of the internal installation.
5	Specialist monitoring of water treatment technology along with the operation of the entire CWSS. Using a multi-barrier system [45] with bio-monitoring of raw water. Consideration of test results on indicator organisms. A comprehensive emergency response plan developed. Continuous coordination and supervision of the AE removal action. Possibility of switching the water supply network. System of notifying the city's population about the incident. Water consumers are equipped with anti-pollution valves installed behind the water-meter set from the side of the internal installation.

of tests of physicochemical, bacteriological and organoleptic indicators of water samples taken from the water supply network showed that the water in the analysed water supply network meets the requirements for the quality of water intended for human consumption in accordance with the standards in the country [46].

Based on the results obtained from the water quality analysis carried out and on the basis of consultations with the employees of the water supply company, the last stage of the research was carried out, which consisted in estimating the individual parameters of the proposed matrix for the risk of secondary water pollution in the water supply network.

In order to determine the risk value, individual parameters, in accordance with the proposed Eq. (10), assume the following values:

- parameter P (probability of occurrence of AE, which is secondary water pollution in the water supply network): for main and distribution pipes it was assumed at level 1, because: the probability of an event related to the consumption of poor-quality water in accordance with Table 1 happen once in 10 y or less.
- parameter V (vulnerability of the system to the occurrence of undesirable event, which is secondary water pollution in the water supply network): for main pipes i was adopted at level 2, because: the system's predisposition to AE according to Table 2 is small.
- WP parameter (water pipe category): for main pipes it is assumed at level 5, because: the analysed pipes are within the DN300–DN1500 diameters and the AE location is at a distance of ≥5 km from the water treatment plant.
- Ptc parameter (protection of the system against AE): for the analysed network, the value of the parameter was set at 5, because: the system is equipped with comprehensive, specialized monitoring of water treatment technologies, monitoring of the water supply network and bio-monitoring of raw water, a comprehensive response plan has been developed in a crisis situation, there is a continuous coordination and supervision of each action related to the removal of all AE, a system for notifying the city's population about AE has been developed and a multi-barrier system has been implemented.

Table 8 summarizes the values of individual risk parameters related to secondary water pollution in water supply network.

Substituting the obtained value into the proposed Eq. (10), the value of the risk of secondary water pollution

Table 5
Four parametric risk matrix of the occurrence of an adverse event in the water supply system – secondary pollution in water supply system

Ptc – Protection	P – Probability																								
	1																								
	V – Vulnerability																								
	1					2					3					4					5				
	WP – Water pipe																								
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	1.00	2.00	3.00	4.00	5.00	2.00	4.00	6.00	8.00	10.00	3.00	6.00	9.00	12.00	15.00	4.00	8.00	12.00	16.00	20.00	5.00	10.00	15.00	20.00	25.00
2	0.50	1.00	1.50	2.00	2.50	1.00	2.00	3.00	4.00	5.00	1.50	3.00	4.50	6.00	7.50	2.00	4.00	6.00	8.00	10.00	2.50	5.00	7.50	10.00	12.50
3	0.33	0.67	1.00	1.33	1.67	1.67	1.33	2.00	2.67	3.33	1.00	2.00	3.00	4.00	5.00	1.33	2.67	4.00	5.33	6.67	1.67	3.33	5.00	6.67	8.33
4	0.25	0.50	0.75	1.00	1.25	0.50	1.00	1.50	2.00	2.50	0.75	1.50	2.25	3.00	3.75	1.00	2.00	3.00	4.00	5.00	1.25	2.50	3.75	5.00	6.25
5	0.20	0.40	0.60	0.80	1.00	0.40	0.80	1.20	1.60	2.00	0.60	1.20	1.80	2.40	3.00	0.80	1.60	2.40	3.20	4.00	1.00	2.00	3.00	4.00	5.00
Ptc – Protection	P – Probability																								
	2																								
	V – Vulnerability																								
	1					2					3					4					5				
	WP – Water pipe																								
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	2.00	4.00	6.00	8.00	10.00	4.00	8.00	12.00	16.00	20.00	6.00	12.00	18.00	24.00	30.00	8.00	16.00	24.00	32.00	40.00	10.00	20.00	30.00	40.00	50.00
2	1.00	2.00	3.00	4.00	5.00	2.00	4.00	6.00	8.00	10.00	3.00	6.00	9.00	12.00	15.00	4.00	8.00	12.00	16.00	20.00	5.00	10.00	15.00	20.00	25.00
3	0.67	1.33	2.00	2.67	3.33	1.33	2.67	4.00	5.33	6.67	2.00	4.00	6.00	8.00	10.00	2.67	5.33	8.00	10.67	13.33	3.33	6.67	10.00	13.33	16.67
4	0.50	1.00	1.50	2.00	2.50	1.00	2.00	3.00	4.00	5.00	1.50	3.00	4.50	6.00	7.50	2.00	4.00	6.00	8.00	10.00	2.50	5.00	7.50	10.00	12.50
5	0.40	0.80	1.20	1.60	2.00	0.80	1.60	2.40	3.20	4.00	1.20	2.40	3.60	4.80	6.00	1.60	3.20	4.80	6.40	8.00	2.00	4.00	6.00	8.00	10.00
Ptc – Protection	P – Probability																								
	3																								
	V – Vulnerability																								
	1					2					3					4					5				
	WP – Water pipe																								
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	3.00	6.00	9.00	12.00	15.00	6.00	12.00	18.00	24.00	30.00	9.00	18.00	27.00	36.00	45.00	12.00	24.00	36.00	48.00	60.00	15.00	30.00	45.00	60.00	75.00
2	1.50	3.00	4.50	6.00	7.50	3.00	6.00	9.00	12.00	15.00	4.50	9.00	13.50	18.00	22.50	6.00	12.00	18.00	24.00	30.00	7.50	15.00	22.50	30.00	37.50
3	1.00	2.00	3.00	4.00	5.00	2.00	4.00	6.00	8.00	10.00	3.00	6.00	9.00	12.00	15.00	4.00	8.00	12.00	16.00	20.00	5.00	10.00	15.00	20.00	25.00
4	0.75	1.50	2.25	3.00	3.75	1.50	3.00	4.50	6.00	7.50	2.25	4.50	6.75	9.00	11.25	3.00	6.00	9.00	12.00	15.00	3.75	7.50	11.25	15.00	18.75
5	0.60	1.20	1.80	2.40	3.00	1.20	2.40	3.60	4.80	6.00	1.80	3.60	5.40	7.20	9.00	2.40	4.80	7.20	9.60	12.00	3.00	6.00	9.00	12.00	15.00

Table 1 (Continued)

Table 5

Ptc – Protection	P – Probability																								
	4																								
	V – Vulnerability																								
	1					2					3					4					5				
	WP – Water pipe																								
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	4.00	8.00	12.00	16.00	20.00	8.00	16.00	24.00	32.00	40.00	12.00	24.00	36.00	48.00	60.00	16.00	32.00	48.00	64.00	80.00	20.00	40.00	60.00	80.00	100.00
2	2.00	4.00	6.00	8.00	10.00	4.00	8.00	12.00	16.00	20.00	6.00	12.00	18.00	24.00	30.00	8.00	16.00	24.00	32.00	40.00	10.00	20.00	30.00	40.00	50.00
3	1.33	2.67	4.00	5.33	6.67	2.67	5.33	8.00	10.67	13.33	4.00	8.00	12.00	16.00	20.00	5.33	10.67	16.00	21.33	26.67	6.67	13.33	20.00	26.67	33.33
4	1.00	2.00	3.00	4.00	5.00	2.00	4.00	6.00	8.00	10.00	3.00	6.00	9.00	12.00	15.00	4.00	8.00	12.00	16.00	20.00	5.00	10.00	15.00	20.00	25.00
5	0.80	1.60	2.00	3.20	4.00	1.60	3.20	4.80	6.40	8.00	2.40	4.80	7.20	9.60	12.00	3.20	6.40	9.60	12.80	16.00	4.00	8.00	12.00	16.00	20.00
Ptc – Protection	P – Probability																								
	5																								
	V – Vulnerability																								
	1					2					3					4					5				
	WP – Water pipe																								
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	5.00	10.00	15.00	20.00	25.00	10.00	20.00	30.00	40.00	50.00	15.00	30.00	45.00	60.00	75.00	20.00	40.00	60.00	80.00	100.00	25.00	50.00	75.00	100.00	125.00
2	2.50	5.00	7.50	10.00	12.50	5.00	10.00	15.00	20.00	25.00	7.50	15.00	22.50	30.00	37.50	10.00	20.00	30.00	40.00	50.00	12.50	25.00	37.50	50.00	62.50
3	1.67	3.33	5.00	6.67	8.33	3.33	6.67	10.00	13.33	16.67	5.00	10.00	15.00	20.00	25.00	6.67	13.33	20.00	26.67	33.33	33.33	8.33	25.00	33.33	41.67
4	1.25	2.50	3.75	5.00	6.25	2.50	5.00	7.50	10.00	12.50	3.75	7.50	11.25	15.00	18.75	5.00	10.00	15.00	20.00	25.00	6.25	12.50	18.75	25.00	31.25
5	1.00	2.00	3.00	4.00	5.00	2.00	4.00	6.00	8.00	10.00	3.00	6.00	9.00	12.00	15.00	4.00	8.00	12.00	16.00	20.00	5.00	10.00	15.00	20.00	25.00

Table 6
Proposed risk categories of secondary water pollution in the water supply network

Risk level	Risk value
Acceptable	$0.20 \le r \le 10$
Tolerated	$11 \le r \le 40$
Controlled	$41 \le r \le 65$
Not tolerated	$66 \le r \le 99$
Not accepted	$100 \le r \le 125$

Table 8
Values of parameters related to the risk of secondary pollution in water supply system

Parameter	Numerical value of the parameter
P	1
V	2
WP	5
Ptc	5

Table 7
Results of water quality monitoring studies in the water supply network for selected water collection points in the water supply network in 2021

Parameter	Water collection points				Highest allowed value
	No. 1	No. 2	No. 3	No. 4	
	Average values				
Colour, mg/L	<5	<5	<5	<5	Accepted by consumers and no abnormal changes
Turbidity, NTU	<0.24	<0.21	<0.20	<0.26	1
pH value	7.6	7.5	7.7	7.6	6.5–9.5
Conductivity, µS/cm	583	619	600	620	2,500
Ammonium ion, mg/L	<0.032	<0.032	<0.032	<0.032	0.5
Nitrates V, mg/L	8.1	6.7	8.2	5.5	50
Nitrates III, mg/L	<0.050	<0.050	<0.050	<0.050	0.5
Chlorides, mg/L	34.1	40.8	36.6	34.1	250
Fluorides, mg/L	<0.13	0.128	<0.11	0.127	1.5
Aluminium, µg/L	<45	<45	<45	<46	200
Magnesium, mg/L	19.6	14.3	16.3	16.8	7–125
Manganese, µg/L	<15	<15	<15	<15	50
Sulfate SO_4, mg/L	32	–	29.6	36.3	250
Total iron, µg/L	<20	<20	<20	<20	200
Permanganate index, mg/L	0.83	0.76	–	0.84	5
Temperature, °C	17.5	17.6	16.7	16.2	–
Calcium, µg/L	72.9	76.2	52.8	84	–
Total organic carbon, mg/L	1.69	1.62	1.25	1.3	No invalid changes
Overall hardness, mg/L	256	273	231	279	60–500
Taste	<1	<1	<1	<1	Accepted by consumers and no abnormal changes
Smell	<1	<1	<1	<1	Accepted by consumers and no abnormal changes
Free chlorine, mg/L	0.19	0.12	<0.07	<0.05	0.3
Bromates, µg/L	<4.0	<4.0	<4.0	<4.0	10
Sum of chlorites and chlorates, mg/L	<0.24	<0.19	<0.23	<0.166	0.7
UV absorbance (260–280 nm), mg/L	2.0	2.2	1.5	2.0	–
Dissolved oxygen, mg/L	11.5	12.4	10.8	10.4	–
Dissolved oxygen, %	124	135	121	115	–
Coliform bacteria, jtk/100 mL	0	0	0	0	0
Escherichia coli, jtk/100 mL	0	0	0	0	0
Clostridium perfringens, jtk/100 mL	0	0	0	0	0
Faecal streptococci, jtk/100 mL	0	0	0	0	0
Total number of microorganisms at 22°C, jtk/1 mL	1	Not found	Not found	Not found	No invalid changes

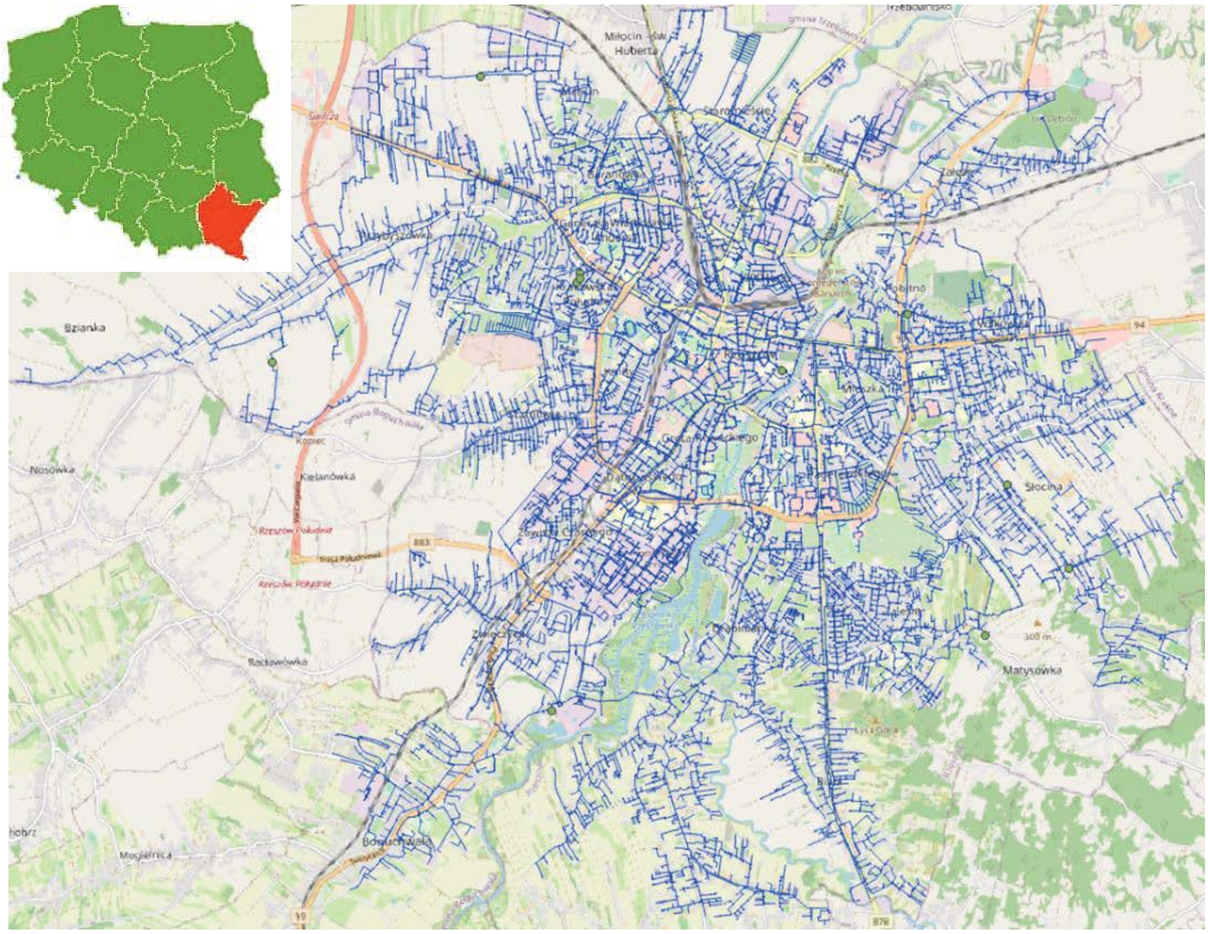

Fig. 1. Location of the analysed urban agglomeration in Poland and a scheme of the water supply network.

in water supply system is $r = 2$, which, in accordance with the proposed risk categories included in Table 6, corresponds to the acceptable level.

5. Conclusions

Collective water supply systems belonging to the critical infrastructure must be subject to special protection both in terms of quantity and quality. The process of proper design, construction and operation of water supply systems should be supplemented with risk analyses of the risk of lack or limitation of water supply as a result of occurrence of adverse events occurring in the system. One of the most important aspects related to the safety of water consumers is access to safe tap water, taking into account the quality aspect [12,13,24,27,28]. The new Water Directive [5] sets new tasks for the water sector. One of the challenges will be to adapt water quality monitoring to the new Water Directive, these changes will concern parametric indicators for lead, an endocrine disruptor (bisphenol-A) and placing beta estradiol, nonylphenol and microplastic on the watch list. One of the adverse events resulting in the delivery of poor quality water to the consumer is the phenomenon of secondary water pollution during its transport [13]. The age of water is one of the main factors in the deterioration of water quality in water supply systems. Water in pipes undergoes various chemical, physical and biological changes. The implementation of the hydraulic model in each water supply company will allow for flow modelling and checking the age of water, thus it will be a tool for monitoring the effects of secondary water pollution in the water supply network [10,12]. The methodology of risk assessment presented in the work can be used in the daily operation of water supply systems, contributing to the increase in the safety of water consumers. The proposed matrix method for estimating the risk of secondary water pollution and the proposed criteria of the descriptive-point scale can be used for the analysis and assessment of risk in the qualitative aspect. Also can be part of the risk analysis as part of the procedures implemented in accordance with the Water Safety Plan (WSP) [47,48]. The conducted analysis and risk assessment showed that for the analysed city the risk of secondary water pollution in the water supply network is at an acceptable level. The risk assessment criteria proposed in the paper have been developed on the basis of operational tests carried out by the authors and literature research and can be modified after taking into account the specificity of a given water supply system [30–33,38,39]. The presented research methodology is a new approach to the methods of estimating the risk of water quality changes in the water supply network. In the available literature on the subject, there is a gap in research on the analysis and assessment of the risk of secondary water pollution in the water supply network. A novelty in the proposed modified method are four risk parameters that take into account the water quality aspect, in particular the "*V*" parameter – vulnerability of the occurrence of adverse event (in the case of qualitative analysis it means the predisposition of the water supply network to secondary water pollution), based on the results of water quality in the water supply network. The proposed method may be a supplement to the existing studies and the basis for further research in the field of methods of estimating and managing the risk of water quality changes in the water supply network.

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