Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.27879

247 (2022) 72–81
January

Hazardous event analysis of microbiological contamination in risk management of large water supply systems

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Received 2 August 2021; Accepted 28 September 2021

ABSTRACT

Effective risk management in water supply systems (WSS) is based on implementation of reasonable protective barriers for reducing frequency of hazardous events and/or minimizing their impact. Loss of biological and chemical stability of water contributes to secondary water contamination in WSS that determines safety of water consumers. Factors which affect secondary water contamination may also lead to growth of biofilm, these include: the quality of water entering the distribution network (its physicochemical composition), pipeline material and age, hydraulic conditions as well as the concentration of disinfectant in the tap water. Control of these aspects is important for ensuring biological stability of drinking water. However, under dynamic conditions of WSSs operation, it is difficult to include an effect of collective evaluation of those factors on formation of reasonable protective barriers in risk management procedures. Water stagnation and pipelines' age may affect the physicochemical water quality, which often results in biofilm growth. Therefore, the aim of this study is to identify hazardous events, which need to be considered during a risk assessment of secondary microbiological contamination of water. This paper presents an analysis of how the age of drinking water transported to the consumer and the age of pipelines affect the loss of microbiological stability of water.

Keywords: Microbiological stability; Secondary microbiological contamination; Water distribution network; Water pipeline age; Water age; Risk management

1. Introduction

The microbiological stability of water is an important factor to protect against secondary water contamination in water distribution substystem (WDS). Secondary microbiological contamination of water is caused by the presence of microorganisms both in treated water and in a biofilm accumulated on internal walls of the pipelines. To maintain microbiological stability of the disinfected water, it is significant not to exceed the permissible concentrations of biodegradable organic carbon, inorganic nitrogen and phosphate ions [1].

High risk of pathogens emerging in water during transport to the consumer may cause the microbiological stability of water to become a vital issue from the viewpoint of public health. There is evidence for a correlation between secondary microbiological contamination of water in WDS and the presence of assimilable organic carbon (AOC) [2]. Therefore, loss of biological stability of water is highly significant and is key in water health risk assessment.

The data presented by the World Health Organisation (WHO) indicates that ca. 1.1 billion people in the world drink contaminated water and that 88% of diarrhoeas is caused by contaminated water, poor hygiene, and poor sanitary conditions [3]. WHO report from 2014 includes a lot of evidence showing that improper management of potable water distribution in WSS leads to numerous disease outbreaks both in developed and developing countries, the

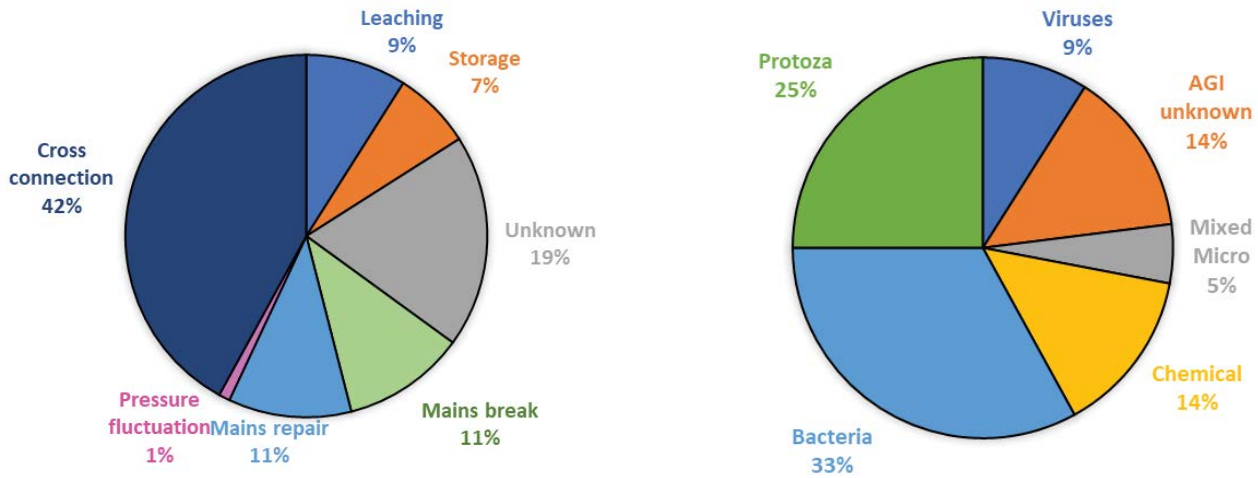

Fig. 1. Reasons of waterborne diseases in the US in years 1987–2010 [3].

causes of which are strongly diversified (Fig. 1). Between 1987 and 2010 in the US, 57 foci related to distribution system failures were reported, causing 9000 cases of disease [3]. Conducted studies showed that the most common reasons of water contamination include: cross connections and trapping, break or leak of water out of networks, contamination in network tanks, renovation of a main network and installation of a new water pipeline system, fluctuations of pressure, and washing of deposits (including biofilm) out of pipelines (Fig. 1a). The most common causes of diseases reported in 1987–2010 were intestinal pathogens, including bacteria ((Salmonella, Campylobacter, Shigella, Escherichia coli O157), protozoans (Cryptosporidium, Giardia) and viruses (Norovirus) (Fig. 1b).

The pathogens that may be transmitted through contaminated drinking water in Water Supply System are diverse in characteristics, behavior (persistence in tap water) and resistance to chlorine. The selection of reference pathogens may vary across different regions in the world. It depends on a local condition of WSS operation, incidence and severity of waterborne disease, the living conditions, and consumers' health traits. The pathogen indicator is undoubtedly Escherichia coli, characterized by medium persistence in tap water and low resistance to chlorine, and thus low relative infectivity above 104 CFU. On the other hand, for Campylobacter jejuni bacteria has similar persistence in WSS and resistance characteristics, however, the relative infectivity index is in the medium group (as opposed to low), for which 102 to 104 CFU causes health consequences for the water consumer. Yet another pathogen indicator is Cryptosporidium, characterized by a long persistence in water delivered to the consumer and high resistance to disinfectants, which consequently leads to high relative infectivity index, that from 1 to 102 CFU can cause a disease entity. Studies have shown that for water containing 10 CFU of Cryptosporidium per 1 L, the risk of diarrhea infection has a high probability of 0.7. Epidemiological studies, carried out worldwide, indicate high difficulty of defining unique single reference value covering all pathogenic microorganisms, because of the complexity of microbiological hazards [3].

Li et al. [4] reviewed factors determining secondary water contamination by analysing numerous scientific studies as presented in 1809 papers published since January 1998. Studies took into account effects of the residual disinfectant (chlorine and chloramine) both on microbiological quality of water and on the level of the generated disinfection by-products. Key factors determining the stability of water disinfectants were identified, these included: temperature, water age, pipeline material, corrosion products, pH, hydraulic conditions of operation of the water distribution system, type of deposits of disinfectants and their amount, and microbiological activity. Based on the review, it was assessed that what has the strongest impact on the activity of microorganisms in water is the type and dose of disinfectant [4].

Water disinfection allows selective neutralisation of bacteria in the water treatment plant and should protect water against secondary microbiological contamination under dynamically changing conditions of WSS operation. However, according to numerous literature reports [5–12], water stagnation, water age and reduced water flow rate are factors significantly affecting the level and scope of secondary water contamination and the intensity of biofilm formation. Therefore, when building the system for risk managing of the water consumer's health, which limits occurrence of microbiological threats, it is necessary to determine the critical areas of water distribution. These critical areas require implementation of effective protective barriers guaranteeing maintenance of reasonable hydraulic conditions of operation of the water pipeline network and limiting water stagnation. Using data from over 800 water supply companies from around the world, the Water Industry Database determined the recommended water retention time in the supply subsystem at 40 h. The same organisation informs that the permissible water age limiting the risk of waterborne disease, is 72 h [13].

Decrease in water consumption by consumers led to the situation where most current WSSs use an oversized water pipeline network, where numerous physical, chemical and biological processes occur. An extensive water pipeline network is a type of a bioreactor, so to speak, with conditions favourable for microorganisms, including pathogens, forming the biofilm. The state of equilibrium appears between the biofilm and water mass. Therefore, any change in the hydraulic conditions of operation of WSSs disrupts the microbiological equilibrium of water and increases the amount of natural organic matter in water, which translates into elevated risk for the water consumer's health. Under such circumstances, it is essential not only to monitor the microbiological condition of water, but also to manage the risk of secondary microbiological contamination of water [14].

Quantitative microbiological risk assessment (QMRA) is one of the methods for risk management, it facilitates the decision-making process in extensive water pipeline systems. This method allows to assess threats to human life resulting from the presence of pathogens in water. There are two types of QMRA modelling: static and dynamic. Difference between the two lies in the approach to treating disease resistance and their secondary dissemination among people [15,16]. In majority of countries where WSS management based on Water Safety Plans was put in place, [17–21] it has been shown that the microbiological quality of water supplied to the consumer is a fundamental aspect when it comes to building protective barriers in risk management procedures. Dutch Water Supply Companies, which follow rules of Water Safety Plans, conduct quantitative microbiological risk assessment once every 4 y for the so-called marker pathogens. The conducted studies on the effect of water stagnation on water quality [22], showed that both the temperature (range of water temperature variability in the consumer's tap is from a few °C in winter to 20°C in summer) and reduced water flow rates, which caused stagnation of up to 168 h, determined both chemical and microbiological quality of tap water. Tests were conducted in a system imitating the standard Dutch domestic water pipeline system. The conducted tests found that the content of general organic carbon went down during stagnation during both summer and winter and the strongest reduction (30%) was detected after 168 h of water stagnation in the internal, domestic water pipeline system. Proteobacteria dominates the examined biofilm (from 61% to 80%). Night water stagnation affected the microbiological parameters of water expressed by HPC (heterotrophic plate counts), ATP (total adenosine triphosphate concentration) and FCM (flow cytometry measurements) [22].

The commonly used standard methods for microbiological water quality assessment are burdened with threat of late detection of threat to the water consumer's health (because microbiological parameters are analysed at the laboratory site for a long time). Therefore, in the risk management system, it is important to direct the actions related to the use of WSSs to the detection of potentially hazardous events generating risk of pathogen development in water so as to limit the causes that may lead to the loss of microbiological stability of water.

According to the results of numerous tests conducted both in the laboratory setting and in the actual WSS setting [23–27], the lack of biological stability of water led to considerable threats to water consumer's health. In the US, an idea has emerged to develop common frameworks of risk management for the water intended for human consumption (Shared Risk Framework), which would strengthen the safety of water supplies to the consumer and minimise risks related to the use of WSS as a critical infrastructure. A correct risk assessment is the basis for their classification and for developing of a list of the weakest points in the system [28,29] that require introduction of effective protective barriers. The above American concept of WSS risk management was also fully confirmed by a benchmark conducted by the Water Losses Task Force of IWA. IWA proposed four most significant areas of WSS management covering: assessment of risk of damage to linear water pipeline infrastructure, promptness and quality of pipeline repairing, active role of leaks, and pressure management [30]. On the basis of above assumptions, it is possible to effectively delineate critical areas requiring, introduction of repair actions, under Water Safety Plans procedures. Those actions led not only to reduce water losses but also guarantee increase effectiveness of water quality monitoring according to rules of minimizing hazard of secondary microbiological water contamination. The prevalence of secondary microbiological contamination of water and the actions taken by water supply companies implementing Water Safety Plans indicate that there is a necessity to develop simple and effective analytical tools identifying potentially hazardous events of loss of safety of water during its transport to the consumer. Development of such methods would be an important tool supporting risk management in WSS, in accordance with requirements of the new Drinking water directive 2020/2184 [31]. Procedures and results of the analysis of effects of the water age transported to the consumer and the age of pipelines on the loss of microbiological stability of water, presented in this paper, are a scientific method for identification of hazardous events being one of key elements of the assessment of risk of secondary microbiological contamination of water.

2. Materials and methods

2.1. Subject of research – Silesian Water Supply System

The study focuses on the water supply system supplying water to the inhabitants of the Silesian and Lesser Poland Voivodeships located in southern Poland. The system relies on surface water resources in its production in 87%. Other 13% of water demand of this WSS is an abstraction from underground water resources. According to the data from 2018, the average daily water production is approximately 350,000 m^3, which is merely 45% of the available production capacity. Water production subsystem (WPS) is built of 10 Water Treatment Plants taking water from independent underground water and surface water intakes. This WPS provide strong guarantee of continued supply of water to the inhabitants of the Silesian and Lesser Poland Voivodeships. WPS uses highly efficient production processes guaranteeing strong effect of water treatment. Treated water supplies water distribution subsystem (WDS) using an extensive water pipeline network 876.2 km long characterised by high diversity of materials and pipe age (Table 1). For over 134 y this WDS have been delivering water to Silesian inhabitants. Despite systematic modernisations, steel pipelines still dominate the WDS (nearly 50% of the pipeline). Water intended for human consumption is transport via the main network, mostly with cross-sections of high diameters between Ø500 and Ø1800 mm (Table 2.) The DWS is located in strongly developing urbanised area in southern Poland. An intensive exploitation of coal deposits significantly shapes the operating conditions of the water pipe network. Every year, there are over 350 failures of the water pipe network, which directly translates into a relatively high failure rate at an average level of 0.403 fail./(km × a). The most prone to failure element of the WDS are steel pipes, for which the average failure rate is 0.53 fail./(km × a). This is greater than the average failure rate of the whole WDS by over 32%. The highest failure rate at the level of 2.39 fail./(km × a) occurs in steel pipes with Ø500 mm diameter, which is nearly 6 times higher than the average failure rate of the whole WDS. The average age of the steel pipes with the diameter with Ø500 is over 54 y and is 14% greater than the average age of the steel pipes building WDS in the Silesian agglomeration. The pipes with Ø1,000 in the steel water distribution network have the lowest failure rate, which is hardly 0.069 fail./(km × a). This may result from fact that the average age of these pipes (43 y) is 10% lower than the average age of steel pipes and as much as 21% less than the average age of steel pipes with diameter of Ø500 mm with the biggest failure rate in Silesian WDS.

A major part of the WDS consists of 9 complexes of network equalising-emergency tanks with the total capacity of 363,800 m^3 and 5 network pump stations. The main water recipients are regional water supply and sewage system companies, which in turn provide water directly to consumers via their local networks. Such expansive and complex water supply infrastructure leads to a risk of hazardous events generating secondary contamination of water, including the loss of its microbiological stability [32].

Some of the main causes of secondary water contamination include: an oversized distribution network, low water flow rates in pipelines (even 0.01 m/s), abrupt

Table 1
Material and age structure of pipelines, status as at 2018 [32]

Material	Length		Age (y)	
	km	%	range of variation	average
Glass reinforced plastic	0.3	0.03	3	2
Polyethylene	102.3	11.68	2–54	9
Steel	***432.2***	***49.33***	10–114	48
Steel with cement lining	171.0	19.52	3–30	21
Steel with polyurethane coating	1.0	0.11	3–26	19
Steel with PE-LD sleeve	14.5	1.65	4–17	9
Reinforced concrete	38.8	4.43	44–62	45
Grey cast iron	32.6	3.72	13–134	79
Spheroidal graphite iron	81.5	9.30	2–13	16
Sum	***876.2***	***100.00***	***2–134***	***37.56***

Table 2
Characteristic of pipeline failure rate for different pipe diameters, status as at 2018 [32]

Diameter		mm	200	250	315	350	400	450	500	600	700
Length		km	20.0	7.2	31.2	8.7	44.6	12.4	100.1	126.7	3.0
λ		fail./(km × a)	0.340	0.278	0.06	–	0.470	0.081	1.019	0.497	–
λ_{st}		fail./(km × a)	1.462	–	–	–	0.779	–	2.39	0.633	–
PA* < 10	percentage	%	0	–	0	–	0.5	100	0.1	3.1	0
10 ≤ PA* < 40		%	1	–	29.3	–	20.4	0	44.6	24.9	24.3
PA* ≥ 40		%	99	–	70.7	–	79.1	0	55.3	72.0	75.7
Diameter		***mm***	***800***	***900***	***1,000***	***1,100***	***1,200***	***1,400***	***1,500***	***1,600***	***Sum/Full***
Length		km	94.2	7.1	127.1	4.7	82.6	95.4	38.4	72.8	876.2
λ		fail./(km × a)	0.350	0.424	0.330	0.856	0.157	0.388	0.442	0.069	0.403
λ_{st}		fail./(km × a)	0.517	0.424	0.336	0.856	0.160	0.407	–	0.069	0.538
PA* < 10		%	6.9	0	92.0	0	1.7	0	–	0	20.1
10 ≤ PA* < 40		%	34.1	0.1	8.0	0	32.3	59.0	–	98.5	37.4
PA* ≥ 40		%	59.0	99.9	0	100.0	66.0	41.0	–	1.5	42.5

λ – failure rate for all pipes; λ_{st} – failure rate for steel pipe, PA – pipe age in years changes in volumetric flow caused by failures, and regulations in the network. Such conditions often lead to formation of critical zones where the hydraulic conditions of WSS operation cause water stagnation with all effects of potential microbiological contamination of water.

In the conducted studies, an analysis was performed which preliminary identified a threat of loss to water biological stability in relation to the age of water and age of WSS pipeline network. To that end, water age was determined on the basis of conducted hydraulic simulations of conditions of use of water pipeline network with a calibrated mathematical model for WSS of the Silesian Voivodeship. The hydraulic model was developed in the EPANET 2.0 software. Hydraulic models are defined by linear and non-linear algebraic equations, similar to equations describing current and voltage in electric networks and resulting from I and II of Kirchhoff's law [33,34].

In mathematical terms, the hydraulic model of WSS network is a function of types of models: junction and sections. Junction models are created using mass conservation law (continuity of flow), which lead to the following expression of mass balance at every nods [33,34]:

$$\forall n \in N: \sum_{l \in L_{n+}; l \neq l_{d_n}} Q_l(t) - \sum_{l \in L_{n-}; l \neq l_{p_n}} Q_l(t) = Q_{l_{p_n}}(t) - Q_{l_{d_n}}(t) \quad (1)$$

where n – junction node of hydraulic model, N – number of all nodes, l – separate pipe, L – number of all pipes in model, +/– – inflow and outflow index respectively, t – time [s], $Q_{l_{p_n}}$ – water demand in n-th node, (m^3/s), $Q_{l_{d_n}}$ – inflow to n-th node, $Q_l(t)$ – water inflow/outflow to the start and end nodes of pipe l, respectively.

On the other hand, junction models are created using law of energy conservation in form of Bernoulli equation:

$$\frac{p_i}{\gamma_w} + z_i + \frac{v_i^2}{2g} = \frac{p_j}{\gamma_w} + z_j + \frac{v_j^2}{2g} + \sum h \quad (2)$$

where p_i, p_j – pressure in i-th and j-th nodes, respectively; γ_w – water specific weight (N/m^3); z_i, z_j – elevation of nodes i and j; v_i, v_j – water velocity in cross section at the start and end of l-th pipe (m/s); g – acceleration of gravity (m/s^2); Σh – headloss (m).

EPANET software enables to model a reactions occurring in the bulk flow with n-th order kinetics [10,33], based on reaction rate formula:

$$R = K_b \cdot C^n \quad (3)$$

where K_b – a bulk reaction rate coefficient; K_b has units of concentration raised to the (1–n) power divided by time; C – reactant concentration (mg/dm^3); n – a reaction order.

In a special case of zero-order kinetic reaction (in which C = 0, K_b = 1, n = 0) formula (3) can be used to model water age, where with each unit of time the, age increases by one unit.

The EPANET software have been used to the mathematical hydraulic model for Silesian WSS. This model reflecting the structure and topology of the water pipeline network forms a simplified hydraulic graph building a numerical water pipeline network composed of 5,891 nodes and 4,425 sections. The said hydraulic model was calibrated on the basis of conditions of operation of a water pipeline network in 2017, achieving the compliance of the simulation and the actual conditions at 98.7% for the volumetric flow rate. Using the said network model, water age was determined for average conditions of WSS operation (for the average daily water demand 321,387 m^3/d and the amount of water production 351,781 m^3/d – average values for 2017) and for the simulation duration of 168 h. Considerable variability in water age transported to the recipient was noted (Table 3).

Performed study used microbiological water quality data from 6 y of water quality monitoring in Silesian Voivodeship WSS (6 y of field studies).

Collected data covering the material structure of the water pipeline network, the diameter and age of water pipes, the water age and microbiological water quality from the period of 6 y study were ordered and verified. For such ordered databases, additional characteristics were determined for individual water pipes, covering: the length of water pipe (where microbiologically water parameters exceeded the limit value in the study period), pipeline construction material, cross-section diameter, and average speed and size of water flow which were tested using a simulation of selected pipeline sections. Due to a very high amount of data, it was grouped by the type of pipeline material and the sum of events associated with loss of microbiological stability of water during the conducted study (Table 4). Analysis of collected data allowed then to conclude that loss of microbiological water stability occurs more often in pipelines made out of steel, especially for old pipelines – with average age of 75 y – where the frequency of microbiological water stability loss was the highest.

Conducted analysis indicated that during the testing period, the average water age in the system was 42.74 h (range of variability from 2.3 to 82.96 h), the median of which was Me = 42.86 h. On the other hand, the age of pipelines forming the water distribution system in the Silesian Voivodeship changed from 2 y to 134: the average pipeline age was 37.56 y and the median – 34 y.

In the conducted study, statistical calculations were done with the Analysis ToolPak analytical tool package.

2.2. Scientific model

During conducted study, all analyses of microbiological parameters of water quality were carried out by accredited

Table 3
Distribution of water age in WSSs in the Silesian Voivodeship

Water age (WA)	Percent contribution of the water pipeline network, %
WA ≤ 10 h	4
10 h < WA ≤ 24 h	24
24 h < WA ≤ 40 h	21
40 h < WA ≤ 72 h	42
72 h < WA ≤ 96 h	9
WA > 96 h	0

Table 4
Specification of characteristic parameters of pipelines

	Characteristic parameter of pipeline							
Pipeline material	Ap_{av} (y)	Qp_{av} (m^3/h)	Dp_{av} (mm)	Dp_{min} (mm)	Dp_{max} (mm)	WA_{av} (h)	Lp_{av} (m)	Number of LMS
Spheroidal graphite iron	16	173	591	400	800	44	268	31
Steel	48	499	892	300	1,600	43	269	222
PE17	9	61	367	279	558	45	145	86
Reinforced concrete	45	1,852	1,500	1,500	1,500	11	312	6

Ap_{av} – average age of pipe; Qp_{av} – average water flow in pipe, Dp_{av} – average pipe diameter;
Dp_{min} – minimal pipe diameter; Dp_{max} – maximal pipe diameter; WA_{av} – average water age;
LP_{av} –average length of pipe; LMS – loss of microbiological stability

laboratories with reference methods indicated in the Polish Regulation of the Minster of Health on the quality of water intended for human consumption [35]. The laboratory tests were first and foremost to control the dynamics of changes in water quality in an extensive water pipeline system in representative sampling points that best characterised the quality of water in the delineated water supply zone. As part of water quality control on the basis of the Regulation of the Minister of Health [35], samples were collected in over 150 sampling points located on the water pipeline network and in points where water was fed in WSS. The total number of cases of exceeded limit values found for 21 parameters in the testing period was 1803. For 19% of these cases (i.e., 345), microbiological parameters were exceeded including coliform bacteria, Escherichia coli, Enterococci and the occurrence in the quantity above of 100 CFU in 1 mL for colony count at 22°C. The above exceeded threshold values were reported in 85 sampling points of the system. For the colony count, limit values at 100 CFU/ml were assumed, which indicated an increase of microbiological contamination, which meant that the operating conditions of WSS deviated from the standard conditions. For extensive water pipeline network, such situations usually result in potential threat to the consumer's health. Those states may be caused by water stagnation, biofilm break down (as a result of abrupt change in water flow), or a low concentration of residual chlorine in water.

In the conducted studies, the loss of microbiological stability of water in individual sampling points was defined as an occurrence of exceeded limit value defined as at least 1 colony forming unit (1 CFU) of coliform bacteria, Escherichia coli and Enterococci or occurrence over 100 CFU in 1 mL for colony count 22°C. Throughout the study period, 345 cases of microbiological stability loss of water were found (Table 5).

A set of random variables covering the states of microbiological stability loss was sorted by frequency of excessive values in a given water quality sampling point in all study area and the distribution function of the number of exceeded limit values was determined (Fig. 2).

The study area was divided into 15 separated water supply zones, for which a set of random variables was created being the number stats of lost microbiological stability (NS_{LMS}) of water in the study period (Table 6).

In the next step of the research methods for the created sets of random variables of water age (WA) and pipeline age (PA), an empirical distribution function was determined (Figs. 3 and 4).

On the basis of literature data and recommendations of the Water Industry Database [13], three classes of water age were determined (Table 7). The threshold value set at 40 h, which is the water age assumed not generate hazardous events of secondary microbiological contamination under normal WSS operation conditions. On the other hand, under the Regulation of the Minister of Finance on depreciation of fixed assets and amortisation of tangible assets [36], the threshold pipeline age was determined at 40 y (Table 8) to be the optimal and recommended period

Table 5
Number of water quality states of loss of microbiological stability (LMS) in relation to the type of pipe material

Year of conducted study	Number of statuses of loss of microbiological stability (LMS)			
	Spheroidal graphite iron	Steel	PE 17	Reinforced concrete
1	6	44	17	1
2	7	47	18	1
3	4	29	11	1
4	6	42	16	1
5	5	38	15	1
6	3	22	9	1
Sum	31	222	86	6

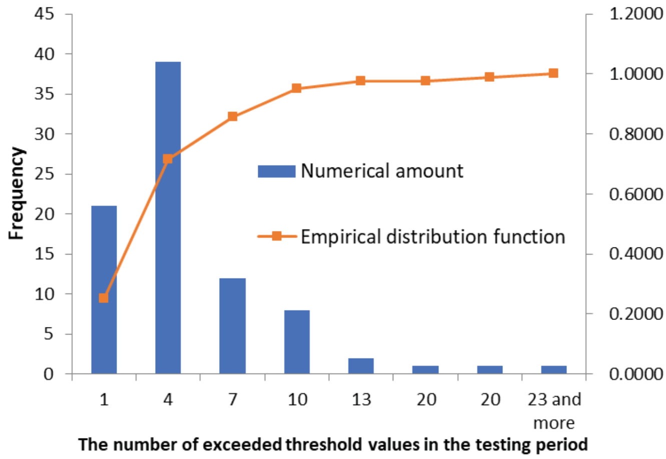

Fig. 2. Distribution function of the number of exceeded limit values in a sampling points.

Table 6
Specification of exceeded microbiological limit values in the water supply zones in the study period

Zone	NS_{LMS}
1	15
2	2
3	8
4	8
5	22
6	82
7	23
8	41
9	3
10	42
11	69
12	5
13	6
14	8
15	11
Total	345

of depreciation for the main and transit linear infrastructure. Therefore, the assumed threshold pipeline age is a period of use for which the hydraulic conditions of operation of water pipeline network should not generate conditions favourable for events contributing to a loss of microbiological safety of water.

3. Results and discussion

An assessment of secondary microbiological water contamination was conducted for water quality parameters in the water supplied to the inhabitants of the Silesian Voivodeship, in the period of 6 y of study. Following the adopted research procedure, empirical distribution function of the number of exceeded limit values was determined for indicators determining the microbiological contamination

Table 7
The classification of water age in procedures of identification of hazardous events concerning the loss of microbiological stability of water

Water age WA, h		
Class I	Class II	Class III
	$20 < WA \leq 40$	$WA > 40$

of water in the water pipeline network throughout the study period (Fig. 2). From the distribution function of random variable, the probability was set at 0.9524, for which the number of exceeded limit values of microbiological parameters of the quality of tap water in one point will not exceed 10. The conducted analysis allowed for determination the average frequency of the state of loss of microbiological water quality at any WDS point, being 1.76 LMS/y. The number of hazardous events of lost water microbiological stability occurring at the frequency of 1.76 LMS/y was found at 80 water quality control points, which was as much as 94% of all points where water was microbiologically contaminated in the study period.

An analysis of the distribution function of water age variability in water transported to the inhabitants of the Silesian Voivodeship (Fig. 3) showed that with the probability of 0.47, the water age does not exceed the water retention time in the distribution subsystem of 40 h, which is recommended by the Water Industry Database [13]. On the other hand, the pipe age did not exceed the depreciation period, that is, the optimal age of use being 40 y, with the probability below 0.58.

To assess the effect of the water age and the pipeline age, according to the research procedure, individually defined classes of water age WA (Table 7) and classes of pipeline age PA (Table 8) were assigned the number points where limit values of microbiological parameters were exceeded (Table 9). The conducted analysis showed that the highest number of events related to exceeding the microbiological limit values occurred when water age was above

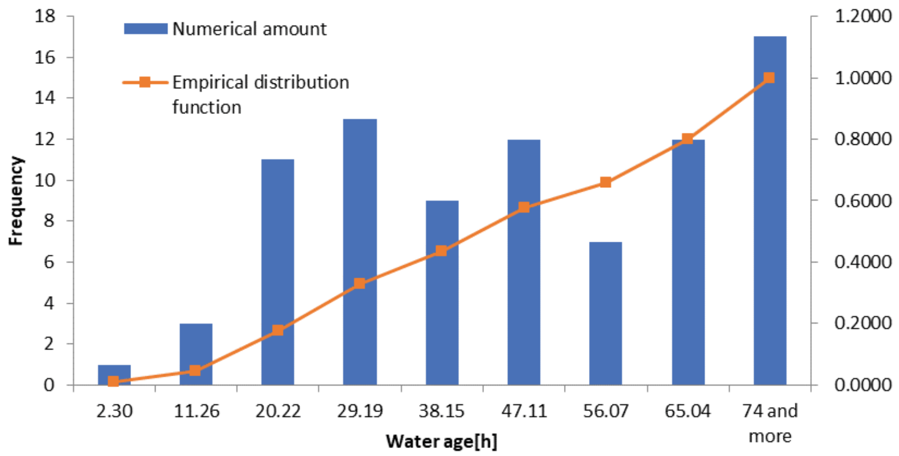

Fig. 3. Distribution function of water age variation.

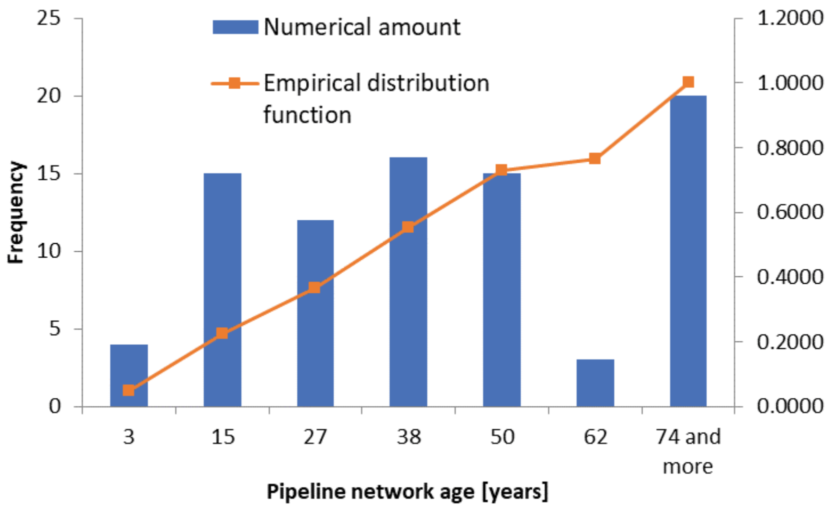

Fig. 4. Distribution function of pipeline age variation.

40 h (44 points, which is 52% of all tested points). However, the highest number of microbiologically exceeded limit values of parameters, at 38, was reported in class III of pipeline age, that is, in pipelines over the age of 40 (44% of all tested points). The number of cases of loss of microbiological quality of water for class III of water age was by 15% higher than in the cases put in category III of pipeline age.

Taking into account the simultaneous effect of two analysis factors, that is, water age WA and pipeline age PA,

Table 8
Classification of pipeline age in procedures of identification of hazardous events concerning the loss of microbiological stability of water

Pipeline network age PA, y		
Class I	Class II	Class III
0 < PA < 10	10 ≤ PA < 40	PA >= 40

Table 9
Number of monitoring points where exceeded microbiological threshold values were registered in terms of classes connected with water age and pipeline age

Analysis factor	PA(C-I) < 10 y	10 y ≤ PA(C-II) < 40 y	PA(C-III) ≥ 40 y	Total
WA(C-I) ≤ 20 h	2	1	12	15
20 h < WA(C-II) ≤ 40 h	4	8	14	26
WA(C-III) > 40 h	6	26	12	44
Total	12	35	38	85

the highest number of points being 26 (31% of all points, where the microbiological limit values were exceeded) was obtained for the water age of over 40 h (class III) and the pipe age corresponding to class II (the pipeline age between 10 and 40 y). Moreover, for the number of events where the water age exceeded the recommended values (class III) and, at the same time, the pipe age was higher than the threshold depreciation value (class III), the probability of exceeded threshold values of microbiological parameters in the testing period was 0.1412.

The conducted analysis showed that for the WSS in the Silesian Voivodeship with an extensive water pipeline network, the loss of microbiological stability of water is to a higher extent determined by water age.

4. Conclusions

The conducted studies confirmed that both water stagnation and lack of a sufficient system for modernisation of water pipeline infrastructure led to events related to loss of microbiological stability of water.

The preliminary identification of hazardous events generating microbiological threats in water supplied to the consumers living in the Silesian Voivodeship indicated that the water age exceeding 40 h and the pipeline age exceeding 40 y is favourable for the occurrence of exceeded limit values of microbiological parameters. The material used to construct the pipelines is also significant. It was found that most cases of exceeded microbiological limited values occurred in the case of pipelines made out of steel (222 events).

The proposed research method allowed to determine the average frequency of occurrence of instances where the microbiological quality of water was lost. The value may be a threshold value for making a decision on increasing the number of water quality control in monitoring points where the frequency has been exceeded. Moreover, in the decision support systems (DSS), exceeding the threshold value of frequency may be a criterion for making a decision to introduce repair actions minimising the probability of cases of lost microbiological water quality and, in turn, reducing the risk for the consumer's health.

It is also justified to include the above analysis results in modernisation plans, assuming the areas of WSS classified as category III of water age (WA) and category III of pipeline age (PA) as the decision-making criterion.

The proposed research method may be an analytical tool for developing a coherent systemic approach to secondary microbiological contamination of water. As of today, there is a shortage of such solutions in use by Polish Water Supply Companies.

Acknowledgments

This study was supported by the Ministry of Science and Higher Education of Poland within statutory funds – projects no BK-261/RIE4/2021.

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