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Changes of microbiological parameters of water in domestic distribution system in terms of water supply safety

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ABSTRACT

The aim of the study was to determine the probability of exceeding the normative values of microbiological parameters in tap water intended for human consumption depending on the operating time of the installation. Based on the results of microbiological testing of water, models of microorganism growth were developed and the times of the installation operating until exceeding the normative values for selected parameters were determined. The installation operating times were used in life data analysis, which made it possible to examine the probability of water supply with appropriate microbiological parameters. For individual measurement cycles, the time of exceeding the normative parametric value of the total number of microorganisms value at a temperature of 22°C parameters was obtained in the range of 9.38–34.85 h, while for exceeding the normative parametric value of the total number of microorganisms value at a temperature 37°C parameter was obtained in the range of 29.69–48.00 h. The probability of human consumption of water that does not meet microbiological criteria increases with the duration of its stay in the domestic distribution system. Exceeding the normative parametric value of the total number of microorganisms at 22°C may occur after 11.73–41.90 h of installation operation depending on the adopted probability level (10%–99%), while exceeding the normative parametric value for the total number of microorganisms at 37°C may occur after 29.63–81.24 h. Test results can be used for identifying hazards as part of the analysis and risk assessment of domestic distribution systems.

Keywords: Domestic distribution risk assessment; Water quality; Water supply safety

1. Introduction

Tap water installations as the last element of the water distribution system must also fulfill the tasks set for the water supply system, that is, supplying water of the right quality (according to the WHO water quality standards [1]), in the right quantity, at the required pressure, at any time (according to the needs of consumers) [2]. Water supply companies strive to ensure the reliability and safety of water supply to consumers through the proper operation of the water supply system [2]. The technical condition of the tap water installation has a direct impact on the quality of the water supplied [3–7]. In case of the poor condition of the installation (corrosion, deposits, and improper installation materials) negative changes in water quality may be observed [3,6–8]. Due to the fact that water supply companies are not owners of the domestic tap water installations, they cannot improve their technical condition and therefore often cannot ensure the supply of water of adequate

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quality. Among other things, this problem was noticed during work on the new European Council directive on the quality of water intended for human consumption [9]. The new Directive uses the standards of European Norm EN 15975-2 [10] concerning security of drinking water supply and the World Health Organization Guidelines for Drinking Water Quality [1] leading to the preparation of "Water Safety Plan". It introduces a complete risk-based approach to water safety throughout the supply chain, from water intake through the distribution system until the tap. One of the components of this approach is "domestic distribution risk assessment", as the last element of the water supply system. In case of a negative impact of the installation on the quality of the water supplied, the result of the analysis would recommend taking steps to improve the technical condition of the installation, for example, by flushing or replacing it. In addition, the issues of hygiene requirements for materials used for the construction of new tap water installations or renovation of existing ones were raised [9].

One of the many threats to the health of water consumers is microbiological contamination [11–15]. Standards regarding the value of parameters of microbiological indicators of water delivered to consumers are diverse around the world [16,18–21]. The most common indicator parameters are coliforms, the total number of microorganisms at 22°C, the total number of microorganisms at 37°C, *Clostridium perfringens*, *Enterococci*, *Pseudomonas aeruginosa* [16,17]. In this research, during the microbiological testing of water, an increase in microbiological parameters was found, among others: increase of the total number of microorganisms at 22°C and the total number of microorganisms at 37°C. In the Directive of the European Council 98/83 /EC of 3 November 1998 on the quality of water intended for human consumption, for water at the consumer's tap point, for the total number of microorganisms at 22°C no limit values were specified, but only in a descriptive way – "without any incorrect changes". The testing of the total number of microorganisms at 37°C is not required [18]. Similar provisions appear in the new directive [9], which is currently working on. In Poland, these issues are regulated by the Regulation of the Minister of Health of December 7, 2017 regarding the quality of water intended for human consumption. For the parameter of the total number of microorganisms at the temperature of 22°C, the value was described descriptively as "without any incorrect changes", with the addition that the value of this parameter in the water entering the network should not exceed 100 cfu/1 mL and in the consumer's tap 200 cfu/1 mL. The testing of the total number of microorganisms at 37°C is not required for water entering the water supply network [19]. In the regulations of the American agency EPA, it is recommended that the total number of bacteria tested at 37°C should not exceed 500 cfu/1 mL [20]. The World Health Organization defines the importance of indicators for the total number of heterotrophic bacteria present in tap water as a useful indicator of undesirable changes in the distribution system, such as increasing biofilm activity, prolonging water stagnation, or loss of system tightness [21].

Reliability engineering is a field of science that studies reliability, maintainability, and availability of products [22,23]. It is based on the "life data analysis" of the product. The life data can be lifetimes of products, for example, the time the product operated successfully or before it failed [22]. It can be measured in any metric with which the life of a product can be measured. Reliability engineering mainly refers to research on inanimate objects, such as equipment, components, and systems [27]. However, the concept of life data analysis can be applied in other areas like aviation, power systems, water supply systems [24–29]. The paper presents the use of life data analysis for a product, which is water from a domestic distribution system intended for human consumption. Life data is the operating time of the domestic distribution system providing water of adequate quality in terms of microbiological parameters before it fails.

The purpose of the work was to determine the probability of exceeding the normative parametric value of microbiological parameters in water from a domestic distribution system, intended for human consumption depending on the operating time of the installation. For this purpose, based on the results of the microbiological testing of water, the models for the growth of microorganisms were developed and the operating times of the installation until the normative parametric value were exceeded, were determined. Based on the results obtained, it was possible to carry out life data analysis, which made it possible to examine the probability of supplying water with appropriate microbiological parameters, determine the probability of exceeding these parameters and the mean life. These studies present a new approach in analyzing the reliability and safety of water supply, touching the subject of changes in water quality within tap water installations. Test results can be used for identifying hazards as part of the analysis and risk assessment of domestic distribution systems.

2. Materials and methods

2.1. Experimental methods

The tests were carried out on water samples from the research installation supplied with tap water shown in Fig. 1. The installation is made of polyvinyl chloride (PVC) pipes with a diameter of 25 and 32 mm. It consists of three main parts: tap water connection, circulation circuit, and water drainage from the installation. A ball valve and a water meter are mounted on the water supply pipe. Then, the water is directed to a closed circuit of 7 m length equipped with a circulating pump, a circulating water meter, drain, and vent lines, and a point for disinfectant dosing. There is a sampling point on the drain pipe. Before the series of tests, the installation was one-time disinfected with 15% sodium hypochlorite solution. The disinfectant solution was injected into the research installation in the amount that allowed to obtain the concentration of free chlorine at the level of about 50 g Cl_2/m^3 of water (350 g NaClO/m^3). Then, the circulating pump was started, and the water with the disinfectant circulated in a closed circuit for 12 h, then stagnated for 12 h. After this time, the system was discharged and rinsed with tap water until reaching the level of 0.2 mg Cl_2/L of free chlorine in it. The control analysis of the total number of bacteria and the presence of *E. coli* which showed no signs of microbial contamination, allowed us to conclude that the installation was properly disinfected before starting the tests. The water in the installation comes from the collective water supply

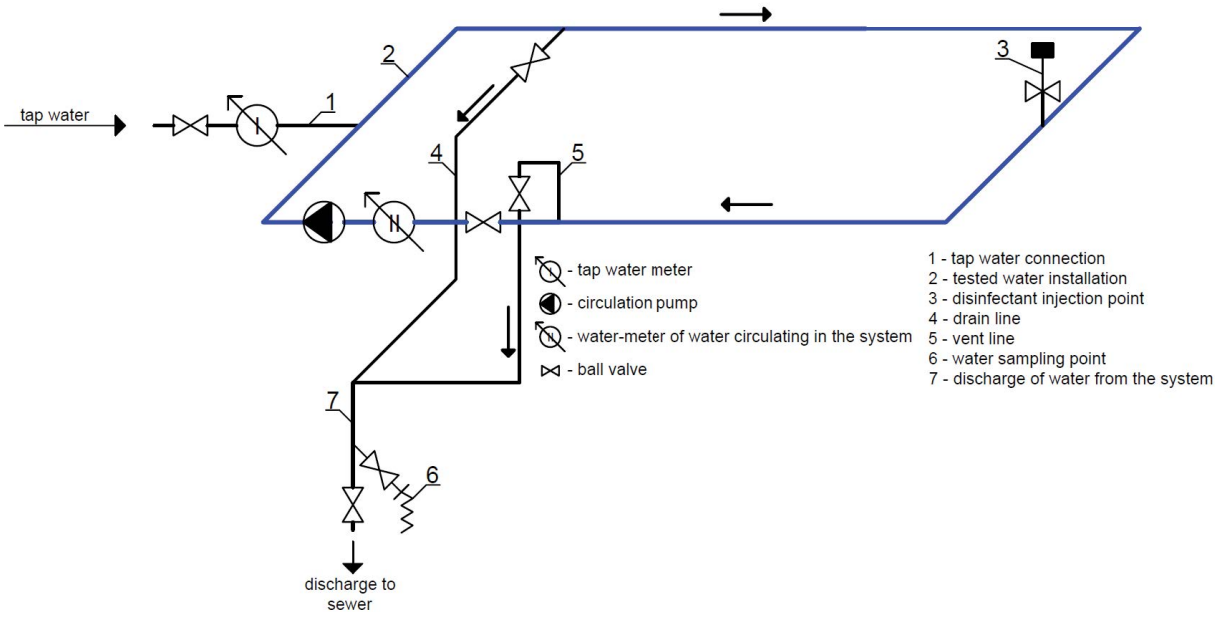

Fig. 1. Scheme of the research installation.

system (CWSS). It is surface water treated in the processes of coagulation, filtration, ozonation, sorption on activated carbon, disinfection, which met the quality requirements for water intended for human consumption.

The research installation is a continuation of the tap water installation of the public facility building in which it is located. It was built with the use of materials and diameters typical for tap water installations. The pressure in the research installation was the same as in the tap water installation of the building. By using a circulation pump with a capacity of Q = 0.65 L/s, the flow velocity in the circulation circuit was kept at about 1 m/s, in accordance with the design guidelines for tap water installations.

Tap water installations are characterized by pauses in water consumption (especially in public facilities). During such a pause, depending on the type of installation, water may be stagnated in the pipes or circulate in a closed circuit.

There were 18 measuring cycles carried out. Each of them lasted 48 h and three water samples were taken from the installation at 0, 24, and 48 h of its operation, which simulated pauses in water consumption from the installation. During the test cycle, the water in the installation circulated in a closed circuit. After the completed measuring cycle, the entire volume of water in the installation was changed and a new cycle started.

Table 1 presents selected physicochemical parameters of inlet and outlet water from the research installation. Changes in these parameters are described in detail in Papciak et al. [30].

2.2. Water microbiological testing

The samples were subjected to microbiological analysis for the total number of microorganisms at 22°C and the total number of microorganisms at 37°C, the number of *Escherichia coli*, *P. aeruginosa*, and ATP measurement, using current testing procedures (Table 2). In addition, the temperature of the water entering and leaving the installation was measured. The results obtained were characterized by means of the minimum, maximum, average values, and standard deviation values.

2.3. Reliability life data analysis

Reliability life data analysis refers to the study and modeling of operational data of tested objects such as systems, machines, or individual components. Life data can be the lifetimes of objects such as the time the product operated successfully or the time the product operated before it failed. It can be measured in hours, kilometers, cycles-to-failure, or any other metric with which the life of an object can be measured. The subsequent analysis and prediction are described as life data analysis. It includes the estimation of life characteristics of the object such as reliability, probability of failure at a specific time, the mean life, and the failure rate [22].

The life data for this analysis is the operating time of the tap water installation, from the beginning of the research cycle until the normative parametric values for indicators of the total number of microorganisms at 22°C and the total number of microorganisms at 37°C, are exceeded. This time is called time-to-failure (TTF). After exceeding the normative parametric values, water from the domestic distribution system is not fit for human consumption, posing a microbiological threat to health and life. The stages of data analysis are shown in Fig. 2.

2.3.1. Part A: statistical analysis of measurement results

The results of microbiological tests have been subjected to preliminary statistical processing in order to eliminate measurement errors that may significantly affect the correct fitting of mathematical models. For this purpose, the values

Table 1
Values of selected physicochemical parameters of inlet and outlet water from experimental installation and water pumped into the CWSS

Parameter	Water pumped into CWSS	Inlet/outlet 0 h				Outlet 24 h				Outlet 48 h			
	Mean	Minimum	Maximum	Mean	σ	Minimum	Maximum	Mean	σ	Minimum	Maximum	Mean	σ
Temperature, °C		14.60	20.30	18.01	1.73	21.0	23.90	22.5	0.86	19.00	24.0	22.02	1.45
Dissolved oxygen, mg O_2/L	–	12.56	16.30	14.32	1.13	5.83	10.25	9.25	1.23	6.14	10.43	9.05	1.20
pH	7.59	7.01	7.69	7.54	0.17	7.17	7.74	7.60	0.14	7.38	7.72	7.60	0.11
Conductivity, μs/cm	564	383	506	429	35.31	475	662	543	53.07	378	533	448	44.34
Turbidity, NTU	<0.20	0.31	2.25	0.81	0.57	0.37	5.36	1.84	1.19	0.44	2.87	1.84	0.69
Oxidisability, mg O_2/L	1.05	0.30	1.50	0.99	0.32	0.20	1.70	1.06	0.33	0.10	1.80	1.23	0.36
TOC, mg C/L	2.16	0.98	2.05	1.50	0.30	1.99	5.00	2.44	0.86	1.68	4.09	3.26	0.64
UV absorbance	2.06	1.48	2.76	2.15	0.35	2.42	3.70	2.89	0.36	1.74	4.94	3.25	0.87
Ammonium nitrogen, mg N–NH_4^+/L	0.09	0.00	0.07	0.008	0.016	0.00	0.05	0.011	0.014	0.00	0.04	0.009	0.011
Nitrite nitrogen, mg N–NO_2^-/L	<0.015	0.00	0.004	0.001	0.001	0.001	0.004	0.002	0.001	0.000	0.003	0.002	0.001
Nitrate nitrogen, mg N–NO_3^-/L	0.87	0.60	1.40	0.99	0.27	0.30	1.70	0.83	0.36	0.30	1.80	0.89	0.39
Phosphates, mg PO_4^{3-}/L	0.027	0.010	0.080	0.036	0.021	0.010	0.050	0.028	0.013	0.010	0.090	0.031	0.019
Total chlorine, mg Cl_2/L	–	0.010	0.210	0.103	0.068	0.01	0.070	0.025	0.017	0	0.080	0.025	0.02
Free chlorine, mg Cl_2/L	–	0.010	0.080	0.033	0.021	0.000	0.040	0.012	0.011	0.000	0.020	0.007	0.006

Table 2
Analytical methods and procedures used in research

Parameter	Analytical method/Standard
Total number of bacteria at 37°C (mesophilic bacteria), cfu/mL	HPC method using R2A Agar (CM0906) manufactured by Oxoid Thermo Scientific (UK) (incubation 7 d) and A Agar (P-0231) manufactured by BTL Sp. z o.o. Zakład Enzymów i Peptonów (Poland) (incubation 2 d)
Total number of bacteria at 22°C (psychrophilic bacteria), cfu/mL	HPC method using R2A Agar (CM0906) manufactured by Oxoid Thermo Scientific (UK) (incubation 7 d) and A Agar (P-0231) manufactured by BTL Sp. z o.o. Zakład Enzymów i Peptonów (Poland) (incubation 3 d)
Escherichia coli, cfu/100 mL	Membrane filtration procedure using Chromocult® Coliform Agar (MERCK, Poland)
Pseudomonas aeruginosa, cfu/100 mL	Membrane filtration procedure using KING B Agar (MERCK, Poland)
ATP, RLU	Luminometric method with a LuminUltra Photonmaster Luminometer, by LuminUltra Technologies Ltd., Canada. BacTiter-Glo™ microbial cell viability assay by Promega Poland

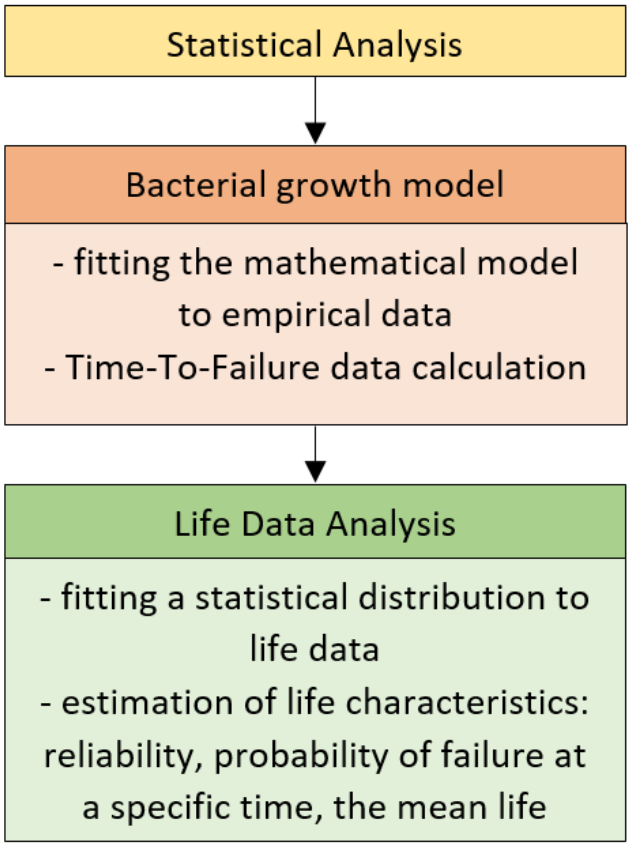

Fig. 2. Stages of data analysis.

intervals were determined for the results in each group of measurements, that is, 0, 24, and 48 h, which were included in further analyses. The lower values of the ranges were determined as the difference of the mean value and two standard deviations, while the upper values of the range as their sum. This assumption results from the standard deviation properties, where with a deviation from the mean value of two standard deviations in the range <–2σ, 2σ> is 95.4% of all observations of the studied population assuming normal distribution [31].

2.3.2. Part B: microorganism growth model

Due to the fact that the tests were performed in 48 h cycles and the results have an increasing tendency, it can be assumed that they included the phase of growth of microorganisms [32–37]. Literature studies indicate that the growth phase of the microorganism population can be described using mathematical models of linear, logistic, exponential, and Gompertz [36,37]. This stage of analysis is aimed at fitting the mathematical model for the increase in the total number of microorganisms at 22°C and 37°C in water from the research installation as a function of time. For this purpose, the Reliasoft Weibull ++ software was used [22]. The analysis of fitting test results to selected models, that is, the linear model (1), exponential model (2), and Gompertz model (3), according to Eq. [22], was performed:

$$y = a \cdot t + b \tag{1}$$

$$y = a^{t} \tag{2}$$

$$y = a \cdot \exp\left[-\exp\left(b - c \cdot t\right)\right] \tag{3}$$

where t is the time of the installation operating, a, b, and c are the mathematical parameters of selected models.

Model fitting is based on the ranking created by the program based on the result of the sum of the squared estimate of errors (SSE). The SSE values are obtained by first calculating the distance (the error) vertically from each data point to its corresponding value on the fitted model. The error value is squared, and then all the squared values are added up. The highest rank is given to the best-fitted model with the lowest SSE value [22]. A detailed description of the method is presented in the work [22].

2.3.3. Part C: life data model

Based on the results obtained in the previous section, the operating time of the tap water installation was determined from the beginning of the test cycle until the normative parameters were exceeded. For this, the operating time of the installation was read from the graph of the microbial

growth models based on the point of intersection of the model with the line parallel to the *x*-axis, which determines the normative value of a given parameter. In this way, the input data to life data model – TTF were obtained. The next thing is to fit a statistical distribution (model) to collected life data.

Model fitting was carried out using the Reliasoft Weibull ++ software. The fitting of the statistical distribution is based on rank, which results are composed of the factors: the Kolmogorov–Smirnov (K–S) test and the normalized correlation coefficient (Rho) test [22]. For each of these tests, a weighting factor is assigned, which is used to determine the final ranking [22]. Due to the fact that the tested models are not linear, the correlation coefficient is not a recommended tool for testing the fit of the theoretical model to TTF data. It is better to test such non-linear relations with the goodness of fit test, for example, the K–S test [22,31]. For the purposes of the study, the authors determined the weights of the individual components that make up the final fit ranking, where 80% is the K–S test rank and 20% is the Rho rank.

The K–S statistical test is about testing the null and alternative hypotheses such as:

- H0: the distribution represents the data,
- H1: the distribution does not represent the data.

The K–S test statistic (*D*) is the maximum difference between the observed and predicted probability [22]:

$$D = \max_{1<i<N} \left| \breve{Q}_i - Q_i \right| \tag{4}$$

where Q_i is the observed probability; $\breve{Q}_i$ is the predicted probability based on the fitted distribution; *N* is the number of observations.

Then, the *D* statistic is compared with the D_{crit} for the K–S test for different distributions at a given significance level. The Weibull ++ calculates the value of AVGOF – the critical probability at which we cannot reject H0. The lower the probability, the better the distribution is fitted, and the higher the ranking obtained described by the $RANK_{AVGOF}$ parameter [22].

The result of the second test is represented by the AVPLOT value determined according to Eq. (5). The lower the AVPLOT value, the higher the ranking obtained described by the $RANK_{AVPLOT}$ parameter [22]:

$$\text{AVPLOT} = 100 \cdot \frac{1}{N} \sum_{i=1}^{N} \left| \breve{Q}_i - Q_i \right| \tag{5}$$

The final result of the model fitting is described by the DESV parameter, based on which the final ranking is created. The lower the DESV value, the higher the final ranking obtained. The DESV value is determined according to Eq. (6) [22]:

$$\text{DESV} = \left(\text{RANK}_{\text{AVGOF}} \cdot 80 \right) + \left(\text{RANK}_{\text{AVPLOT}} \cdot 20 \right) \tag{6}$$

More information on creating a ranking of the fit of probabilistic models is included in the work [22].

For the collected data, an analysis of the fitting of selected statistical models: exponential (7), normal (8), and two-parameter Weibull distribution (9), which are described by the density function equations –*f*(*t*), was performed [22]:

$$f(t) = \lambda \cdot e^{-\lambda \cdot (t-\gamma)} \tag{7}$$

$$f(t) = \frac{1}{\sigma \sqrt{2 \cdot \pi}} \cdot \exp\left(\frac{-(t-\mu)^2}{2 \cdot \sigma^2} \right) \tag{8}$$

$$f(t) = \frac{\beta}{\eta} \cdot \left(\frac{t}{\eta} \right)^{\beta-1} \cdot e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{9}$$

where *t* is the time of the installation operation, λ is the exponential distribution parameter, σ, μ are the normal distribution parameters: the standard deviation and the expected value, β, η are the Weibull distribution parameters: shape parameter and scale parameter.

Then, based on the obtained model, the life characteristics such as reliability, probability of failure at a specific time, the mean life, were determined. One of the most important functions in life data analysis is a function of reliability. The reliability function gives the probability of success of a unit operating for a given time duration [22]. Since the cumulative distribution function (cdf) is the integral of the probability density function (pdf) of the fitted model and defines the probability of failure by a certain time, we could consider this the unreliability function (10) [22]. Subtracting this probability from 1 will give us the reliability function (11) [22]. The mean life function provides a measure of the average time of operation to failure and is given by (12) [22]:

$$F(t) = \int_0^t f(t) dt \tag{10}$$

$$R(t) = 1 - F(t) \tag{11}$$

$$\overline{T} = \int_0^{\infty} t \cdot f(t) dt \tag{12}$$

where *t* is the time of the installation operation, *f*(*t*) is the probability density function of the fitted model, *F*(*t*) is the unreliability function, *R*(*t*) is the reliability function, $\overline{T}$ is the mean life function.

The Weibull ++ software estimates the parameters of fitted distributions using the least-squares method (rank regression). The method of least squares requires that a straight line be fitted to a set of data points, such that the sum of the squares of the distance of the points to the fitted line is minimized. This methodology can be applied to distributions with cumulative density function equations that can be linearized [22].

Additionally, the confidence bounds on the obtained reliability functions at the 95.0% level of confidence were calculated using the Weibull ++ software. The bounds are calculated with the use of the inverse Fisher information matrix which gives the variance-covariance matrix and provides the information on variance of the estimated parameters [22]. A detailed description of the Fisher Matrix Bounds method is presented in the papers [38,39].

On the basis of the obtained results, the characteristic operating times of the installation were determined with the probability of exceeding the normative parameters at levels 10%, 25%, 50%, 75%, and 99%. This time can be read from the graph of the reliability function.

3. Results

3.1. Water microbiological quality assessment

As a result of water circulation in the installation during the tests, its microbiological quality changed. An increase in the values of such parameters as the total number of microorganisms at 22°C, the total number of microorganisms at 37°C, ATP was observed and the presence of *E. coli* was noted. *P. aeruginosa* was not detected in the tested samples of water coming from the installation. The results of microbiological tests are presented in Table 3. The variability of bacterial growth in individual 18 test cycles is presented in Figs. 3a, b, 4a, and b. The deterioration of the microbiological quality of tap water together with the time spent in the installation may indicate the development of biofilm on the surface of the installation material. The biofilm formed on the internal surfaces of installation was a source of microbial contamination that affects the deterioration of water organoleptic parameters [7].

Selected physicochemical parameters of water were tested (Table 1). One of them was the water temperature which stimulates the development of microorganisms. For the water flowing into the installation, its value varied between 14.6°C–20.3°C. However, after passing through the installation, the water temperature increased to a maximum of 24°C, which results from the lack of thermal insulation of the installation. A strong positive correlation was found between the total number of psychrophilic bacteria and temperature (r = 0.90102) [40]. The mean value of the turbidity of the inlet water was 0.81 NTU and for the outlet, water was 1.84 NTU. This difference indicates that the water has lost physical stability as a result of contact with the installation [41]. The content of total and free chlorine in the water supplied to the research installation was very low, which is the result of water treatment technology which involves disinfecting it with ozone, and chlorine is added only to maintain the required sanitary condition. Such low chlorine concentration value could also be caused by its consumption during the transport of water through the water supply system and the tap water installation in the building to the research installation (oxidation of organic matter and accumulated sediments, corrosion products, etc.). The concentration of total and free chlorine in the outlet water, compared to the inlet water, decreased after 48 h of the installation operation to the following values: 0.025 and 0.007 mg Cl_2/L. Chlorine is a disinfectant and guarantees the microbiological safety of water, which in this case was clearly violated. In Poland, the required concentration of free chlorine in the water supplied to the water supply network should be between 0.2 and 0.5 g Cl_2/m^3, and at the ends of the network (the taps), it should not be less than 0.05 g Cl_2/m^3. Gillespie et al. [42] proved that water distribution systems with a free chlorine concentration below 0.5 mg Cl_2/L were associated with higher concentrations of bacterial cells. Francisque et al. [34] showed that the number of heterotrophic bacteria was much higher in the samples with chlorine content <0.3 mg Cl_2/L.

To determine the total number of bacteria, the most commonly used are breeding methods (HPC plate test), luminometric determination of the ATP amount [43], and direct counting of bacteria with the use of fluorochromes [5]. Determination of the number of microorganisms by culture methods was carried out on two types of agar. R2A agar stimulated the growth of a much larger number of microorganisms compared to agar A (incubation time 2 and 3 d) and the results obtained for both media differed by two orders of

Table 3
Water microbiological test results

Measurement time	Parameter	Total number of bacteria at 37°C – Agar A	Total number of bacteria at 37°C – Agar R	Total number of bacteria at 22°C – Agar A	Total number of bacteria at 22°C – Agar R	ATP	*Escherichia coli*	*Pseudomonas aeruginosa*
		cfu/mL	cfu/mL	cfu/mL	cfu/mL	RLU	cfu/100 mL	cfu/100 mL
0	Minimum	2	1,080	3	60	5,100	0	0
	Maximum	77	2,530	133	5,240	52,238	0	0
	Mean	30	1,041	33	2,076	16,111	0	0
	σ	20	706	32	1,571	11,232	0	0
24	Minimum	30	1,800	40	2,600	12,501	0	0
	Maximum	795	28,750	1,300	40,000	75,745	3	0
	Mean	214	15,608	318	26,841	35,077	0	0
	σ	178	7,563	304	10,047	13,984	1	0
48	Minimum	65	10,000	155	22,000	14,335	0	0
	Maximum	1,400	63,000	3,800	168,500	85,232	7	0
	Mean	540	31,247	1,302	59,986	46,670	1	0
	σ	380	13,549	888	36,540	20,280	2	0

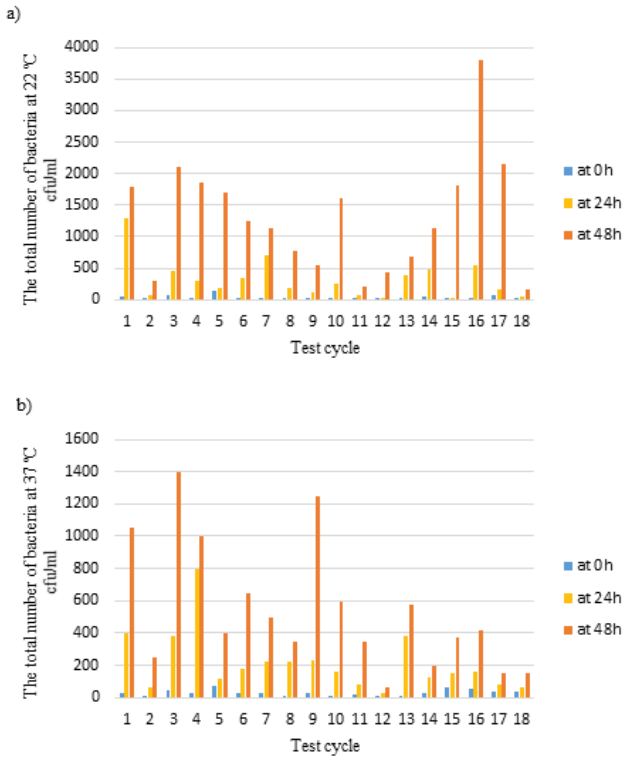

Fig. 3. Total number of microorganisms value in individual 18 test cycles at a temperature of (a) 22°C and (b) 37°C – Agar A.

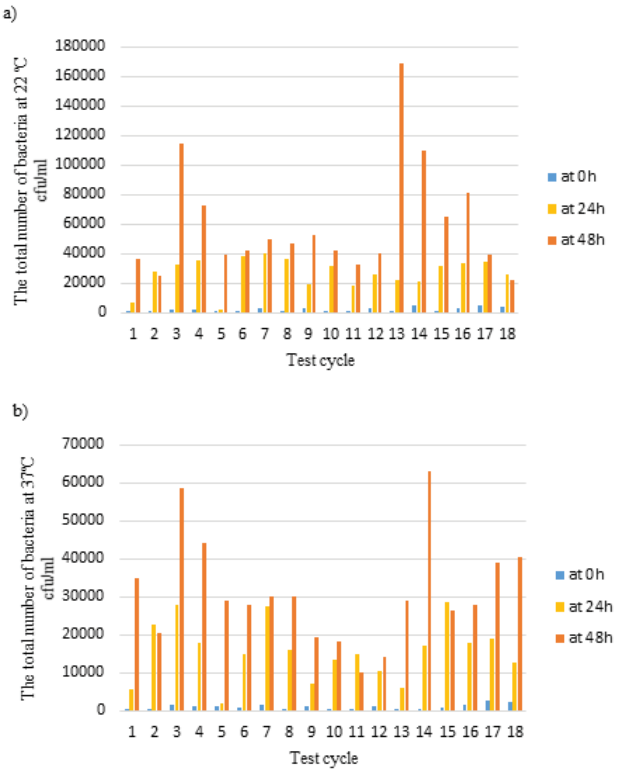

Fig. 4. Total number of microorganisms value in individual 18 test cycles at a temperature of (a) 22°C and (b) 37°C – Agar R.

magnitude. In the case of R2A agar, both the composition of the medium and the incubation time of 7 d, were different. For damaged and stressed microorganisms, a longer incubation time could provide better conditions for their growth. Measurements made by culture methods and luminometric measurement of ATP cannot be compared with each other in terms of the number of microorganisms, due to the differences in the forms determined (cells, colonies, ATP, live particles, and dead particles) [44].

For further analysis, the results of measurements of the total number of microorganisms at 22°C and the total number of microorganisms at 37°C determined with the HPC method using A Agar (P-0231) (reference method [19]), for which the normative values were exceeded, were used.

3.2. Reliability life data analysis

A preliminary statistical analysis was carried out to eliminate measuring errors. Value ranges in each measurement group were determined, that is, measurements after 0, 24, and 48 h for both analyzed parameters. For both parameters, 3 out of 18 measurement cycles were rejected, the results of which were outside the range <–2σ, 2σ>. Other data were entered into the Reliasoft Weibull ++ software to fit the model of microorganism growth in water from the research installation. For the purposes of the analysis, the fitting of the linear, exponential, and Gompertz models was compared to the results of tests on the total number of microorganisms at 22°C and 37°C. Table 4 presents the mathematical model fitting ranking based on the sum of SSE value. For the growth of microorganisms at 22°C for 15 measuring cycles, the Gompertz model obtained the highest ranking in 10 cases, the exponential model in three cases, and the linear model in two cases. For the growth of microorganisms at 37°C for 15 measuring cycles, the Gompertz model obtained the highest ranking in nine cases, the exponential model in five cases, and the linear model in one case. The best fit of the microorganism growth model in the case of psychrophilic bacteria was obtained for cycles 7 and 13, in the case of mesophilic bacteria for cycles 7, 8, 12, 13, 14, and 17, where the lowest SSE values were obtained. For further analysis, the results of the measuring cycles described with the Gompertz model which in both cases was fitted the largest number of times were taken into account. Parameters of equations describing individual measuring cycles are presented in Table 5.

Figs. 5 and 6 show models for the growth of microorganisms at 22°C and 37°C in water from the research installation. The horizontal lines indicate the normative values for the parameters of the total number of microorganisms at 22°C–200 cfu/mL [19] and for the total number of microorganisms at 37°C–500 cfu/mL [20]. The intersection points of each of the microorganism growth models and horizontal straight lines determine the time from the beginning of the measurement cycle to the moment when the normative values are exceeded. This time is called TTF, which will be used for reliable life data analysis. The accurate values of the TTF parameter for each test cycle are presented in Table 6. For the total number of microorganisms at 22°C, the normative

Table 4
Microorganism growth model fit rank

(a) For the total number of microorganisms at 22°C						
Test cycle	Model			Model		
	Linear	Expotential	Gompertz	Linear	Expotential	Gompertz
	SSE value			Rank		
2	3,750.000	1,951.191	99.957	3	2	1
3	271,362.667	8,412.920	5,775.968	3	2	1
4	269,240.166	82,686.494	1,232,160.167	2	1	3
6	54,150.000	164,456.729	399.887	2	3	1
7	8,664.000	626,295.719	0.013	2	3	1
8	28,704.167	116,076.633	25.010	2	3	1
9	17,173.500	0.804	189,649.585	2	1	3
10	200,568.167	309,843.510	2,521,028.983	1	2	3
11	840.166	3,490.784	27,416.790	1	2	3
12	23,688.166	10,683.850	4,294.058	3	2	1
13	2,320.666	621,316.204	0.013	2	3	1
14	7,993.500	145,421.925	1,934.683	2	3	1
15	515,094.000	635,607.487	1,438.661	2	3	1
17	608,016.666	362,658.035	105,734.138	3	2	1
18	1,014.000	120.105	197.908	3	1	2
(b) For the total number of microorganisms at 37°C						
Test cycle	Model			Model		
	Linear	Expotential	Gompertz	Linear	Expotential	Gompertz
	SSE value			Rank		
1	12,696.000	161,327.848	503,316.590	1	2	3
2	2,816.666	631.668	99.986	3	2	1
6	17,066.666	4,087.246	261,465.700	2	1	3
7	1,204.166	22,439.914	0.011	2	3	1
8	1,066.666	53,461.328	0.013	2	3	1
9	112,888.166	3,136.653	1,089.007	3	2	1
10	12,788.166	49,273.868	15.299	2	3	1
11	6,337.500	8.756	375.548	3	1	2
12	28.166	64.445	0.012	2	3	1
13	5,890.666	616,043.411	0.014	2	3	1
14	150.000	2,891.521	0.014	2	3	1
15	2,604.166	0.007	207.884	3	1	2
16	3,952.666	114.625	130.876	3	1	2
17	32.666	171.320	0.013	2	3	1
18	816.666	284.578	338.716	3	1	2

values were exceeded 10 times, while for the total number of microorganisms at 37°C only 4 times, which is presented in Figs. 5 and 6.

Then the statistical distribution was fitted to the operating times of the installation – TTF. The exponential, normal and Weibull distribution, were analyzed. Table 7 presents the ranking of statistical distribution fitting to previously obtained life data. For TTF of the first analyzed parameter exceeded (the total number of microorganisms at 22°C) the highest fitting ranking was obtained by the Weibull distribution, while for the second parameter, that is, the total number of microorganisms at 37°C, the highest-ranking was obtained by the exponential distribution. The exponential distribution cumulative at $t = 0$ tends to infinity, which makes it impossible to use it, assuming that at 0 h of installation operation its reliability is 100%. Therefore, the normal distribution was adopted to describe the life data model, which was ranked second in the ranking.

Life data models and their characteristics are presented in Table 8. Figs. 7 and 8 present a reliability function graph illustrating the likelihood of delivering water that meets microbiological standards. For the obtained

Table 5
Gompertz model parameters

(a) For the total number of microorganisms growth at 22°C				(b) For the total number of microorganisms growth at 37°C			
Measurement cycle	Gompertz model $y = a \cdot \exp[-\exp(b-c \cdot t)]$			Measurement cycle	Gompertz model $y = a \cdot \exp[-\exp(b-c \cdot t)]$		
	a	b	c		a	b	c
2	364.5069	8.00E-06	0.9181	2	302.2488	4.00E-06	0.9166
3	2,528.2440	1.07E-07	0.9113	7	822.4464	3.04E-02	0.9602
6	1,461.3500	2.00E-06	0.9119	8	379.8281	2.63E-02	0.9241
7	1,249.7575	2.16E-02	0.9243	9	1,537.278	2.67E-08	0.9118
8	896.1711	4.27E-08	0.9064	10	1,177.495	3.20E-03	0.9569
12	504.4154	2.00E-06	0.9198	12	192.9906	4.14E-02	0.9779
13	723.8913	4.14E-03	0.9115	13	600.3284	3.33E-03	0.8991
14	1,231.0614	1.80E-05	0.9029	14	239.133	1.25E-01	0.9502
15	4,694.0038	4.86E-09	0.9395	17	378.4867	8.98E-02	0.9803
17	2,439.2892	5.25E-07	0.9170	–	–	–	–

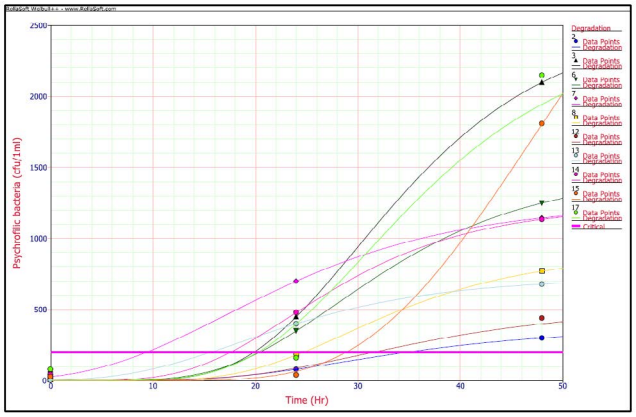

Fig. 5. Total number of microorganisms at 22°C growth models.

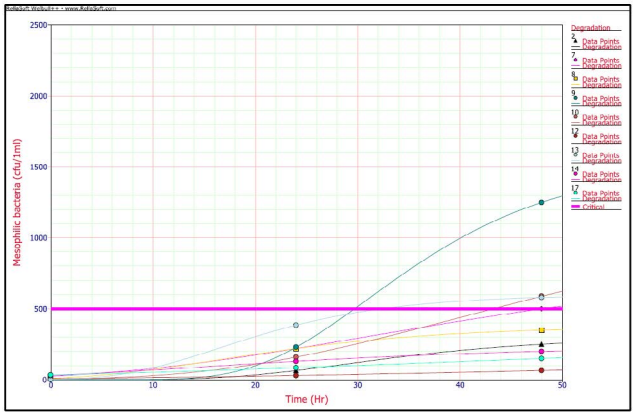

Fig. 6. Total number of microorganisms at 37°C growth models.

reliability functions the confidence bounds at the 95.0% level of confidence were calculated.

On the basis of the obtained results, the installation operation time was determined depending on the probability of exceeding the normative parameters assumed at the levels of 10%, 25%, 50%, 75%, and 99% (Table 9). Reliability function values lie between calculated confidence bounds with a probability of 95.0%.

4. Discussion

Microbiological tests of water from a tap water installation indicate a deterioration in its quality. An increase in the following parameters was observed: the total number of microorganisms at 22°C, the total number of microorganisms at 37°C, ATP, and the presence of *E. coli* bacteria were also noted. The microbiological parameters covered by the normative values are the total number of microorganisms at 22°C, the total number of microorganisms at 37°C, *E. coli* bacteria. Exceeding the normative parametric values for the total number of microorganisms at 22°C and the total number of microorganisms at 37°C was observed for the tested samples. Deterioration of the microbiological quality of tap water may indicate the development of biofilm. Its presence on the internal surfaces of the installation is a source of microbiological contamination [7]. The speed of biofilm formation is determined by many factors, among others, the type of surface of the analyzed materials and their chemical composition, the presence of disinfectants, the availability of nutrients such as organic compounds, nitrogen, or phosphorus [7]. The tap water supplying the research installation is chemically unstable water with a tendency to dissolve sediments [7]. The low content of chlorine in the water supplied to the research installation was observed which creates good conditions for the development of microorganisms. Contact of water with the inner surface of water pipes can lead to aging of pipes material, leaching of chemical compounds. Phosphorus or carbon, which are nutrients for microorganisms, during the contact of installation materials with water, may leach into it in the form of microbiologically available phosphorus (MAP) [5] or available organic carbon (AOC) [44] accelerating biofilm formation. The results of physicochemical tests indicate an increase in the content of nutrients after the contact of tap water with the installation material, which creates conditions for the development of biofilm. In addition, an increase in water temperature in the installation

Table 6
Time-to-failure values

(a) For the total number of microorganisms at 22°C		(b) For the total number of microorganisms at 37°C	
Measurement cycle	Time (h)	Measurement cycle	Time (h)
2	34.85	7	48.00
3	19.86	9	29.69
6	20.42	10	43.24
7	9.38	13	32.35
8	24.69	–	–
12	31.58	–	–
13	15.65	–	–
14	17.58	–	–
15	28.87	–	–
17	20.26	–	–

Table 7
Statistical distribution fitting rank

(a) For TTF of the total number of microorganisms at 22°C parameter exceeded						
Distribution	AVGOF	AVPLOT	$RANK_{AVGOF}$	$RANK_{AVPLOT}$	DESV	RANK
Expotential	50.2850254	12.10604	3	3	300	3
Normal	1.569967669	4.054823	2	1	180	2
Weibull	0.627626299	4.114421	1	2	120	1
(b) For TTF of the total number of microorganisms at 37°C parameter exceeded						
Distribution	AVGOF	AVPLOT	$RANK_{AVGOF}$	$RANK_{AVPLOT}$	DESV	RANK
Expotential	0.000000631	7.090204	1	3	140	1
Normal	0.00000098	5.659405	2	1	180	2
Weibull	0.00000749	5.978499	3	2	280	3

was noticed, which also impacted the development of microorganisms.

The aim of the study was to examine the probability of exceeding the normative parametric values of microbiological parameters in water intended for human consumption depending on the operating time of the installation. For this purpose, life data analysis was carried out. The first stage was determining the TTF value, that is, the time of the installation's operation until the normative values were exceeded, on the basis of the microorganism growth model based on empirical data.

The data on the basis of which the models of microorganism growth were developed included the measurement of the total number of microorganisms in the time interval 0–48 h. The shape of the obtained models illustrates the growth of microorganisms characteristic for the first and second growth phases in accordance with the microbial growth curve presented in the literature [35,36]. In the first hours of the installation operation, a slight growth of microorganisms were observed, and the shape of the model takes the appearance of a straight line parallel to the x-axis. This illustrates the adaptive phase. For the growth model of psychrophilic bacteria, it was observed that the time of duration of the adaptation phase varied from 0 to 14 h, and for the mesophilic bacteria growth model from 0 to 10 h. After the adaptation phase, an intensive increase in the number of microorganisms was observed, which in the literature is referred to as the exponential growth phase [35,36]. On the presented models, especially for cycle 7 and 13 in the case of psychrophilic bacteria and 7, 8, 12, 13, 14, and 17 in the case of mesophilic bacteria for which the lowest SSE values were obtained, it was observed that this phase lasted up to about 48 h of the installation operation. In the following hours of the installation operation, a gradual flattening of the curve is observed on the presented models, which suggests the beginning of the third growth phase of microorganisms, the so-called stationary phase, where the number of new cells forming and the number of cells dying becomes equal [32–37]. The last phase of microbial growth according to the microbial growth curve presented in the literature is the so-called death phase characterized by a decrease in the number of microorganisms [35,36]. The presented growth models are similar to the microorganism growth models presented in the works [32–37], referring with their shape to the microorganism growth curve presented in the literature [35,36].

The normative values of the total number of microorganisms at 22°C and 37°C parameters in water intended for human consumption were determined on the basis of a

Table 8
Life data model parameters

(a) For TTF of the total number of microorganisms at 22°C parameter exceeded	
Statistical distribution	Weibull
β	2.968611
η	25.047835
pdf	$f(t)=\frac{2.968611}{25.047835}\cdot\left(\frac{t}{25.047835}\right)^{2.968611-1}\cdot e^{-\left(\frac{t}{25.047835}\right)^{2.968611}}$
cdf	$F(t)=1-e^{-\left(\frac{t}{25.047835}\right)^{2.968611}}$
Reliability function	$R(t)=e^{-\left(\frac{t}{25.047835}\right)^{2.968611}}$
Mean life	22.36 h
(b) For TTF of the total number of microorganisms at 37°C parameter exceeded	
Statistical distribution	Normal
μ	38.320001
σ	9.919419
pdf	$f(t)=\frac{1}{\sigma\sqrt{2\cdot\pi}}\cdot\exp\left(\frac{-(t-38.320001)^2}{2\cdot 9.919419^2}\right)$
cdf	$F(t)=1-\int_0^{\infty}\frac{1}{\sigma\sqrt{2\cdot\pi}}\cdot\exp\left(\frac{-(t-38.320001)^2}{2\cdot 9.919419^2}\right)dx$
Reliability function	$R(t)=\int_0^{\infty}\frac{1}{\sigma\sqrt{2\cdot\pi}}\cdot\exp\left(\frac{-(t-38.320001)^2}{2\cdot 9.919419^2}\right)dx$
Mean life	38.32 h

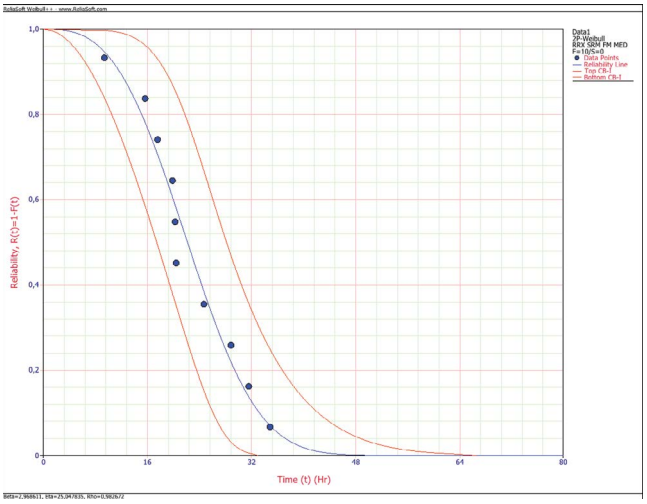

Fig. 7. Reliability function of delivering water that meets microbiological standards (for the total number of microorganisms at 22°C parameter).

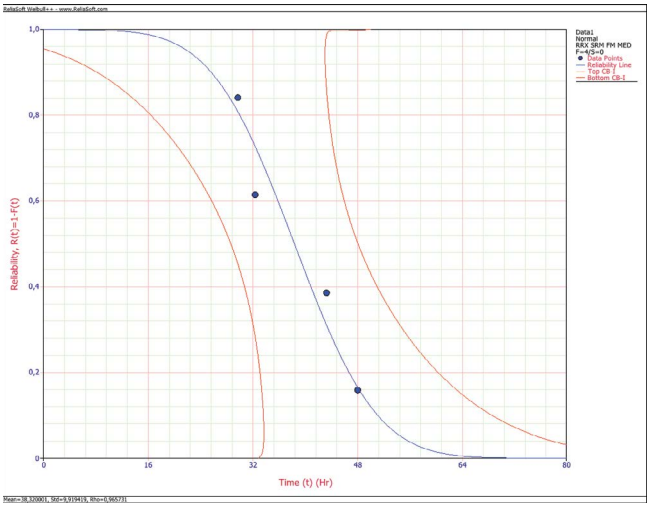

Fig. 8. Reliability function of delivering water that meets microbiological standards (for the total number of microorganisms at 37°C parameter).

Table 9
Probability of exceeding normative parameters

Probability of exceeding the normative parametric values (%)	(a) For the total number of bacteria at 22°C parameter			(b) For the total number of bacteria at 37°C parameter		
	Operation time (h)			Operation time (h)		
	Lower 95% confidence bound		Upper 95% confidence bound	Lower 95% confidence bound		Upper 95% confidence bound
10	7.32	11.73	18.81	28.87	29.63	31.64
25	11.83	16.46	22.92	29.66	31.72	37.21
50	17.41	22.14	28.14	31.41	36.37	49.60
75	22.46	27.96	34.80	34.39	44.32	70.79
99	30.74	41.90	57.10	48.24	81.24	169.16

review of international standards [16,18–20], of which the most critical values were chosen. For the parameter of the total number of microorganisms at 22°C–200 cfu/mL [19] and for the parameter of the total number of microorganisms at 37°C–500 cfu/mL [20]. For individual measurement cycles, the time of exceeding the normative parametric value of the parameters, based on the point of intersection of the microorganism growth models and the lines determining the normative value for these parameters, was obtained in the range of 9.38–34.85 h for the total number of microorganisms at a temperature of 22°C, while for exceeding the value of the parameter of the total number of microorganisms at a temperature of 37°C in the range of 29.69–48.00 h.

Based on the obtained TTF values life data analysis was carried out, thanks to which it was possible to estimate life characteristics such as reliability, probability of failure at a specific time, and the mean life for exceeding the normative parametric values of the tested parameters in water intended for human consumption. The average operating time of the installation until the normative parameters of the total number of microorganisms at 22°C exceeded was 22.36 h. The operating time of the installation until this parameter exceeded changes in the range of 11.73–41.90 h depending on the adopted probability level. The average system operation time until the normative parameters of the total number of microorganisms at 37°C were exceeded was 38.32 h. The operating time of the installation until this parameter exceeded changes in the range of 29.63–81.24 h depending on the adopted probability level. The results fit between the confidence bounds at the 95.0% level of confidence. Due to the small amount of input data, the results obtained for the upper confidence bound may better describe the real conditions. According to the upper 95% confidence bound the operating time of the installation until the total number of microorganisms at 22°C parameters is exceeded changes in the range of 18.81–57.10 h depending on the adopted probability level. The operating time of the installation until the total number of microorganisms at 37°C parameters is exceeded changes in the range of 31.64–169.19 h depending on the adopted probability level. The probability of supplying water that meets microbiological standards decreases with the duration of its stay in the domestic distribution system, while the probability of exceeding the normative parametric values increases with this time.

5. Conclusions

Tap water installations that are the last element of the water distribution system can be a source of potential threats to the quality of water intended for human consumption. This problem was raised during the work on the new European Council Directive on the quality of water intended for human consumption, where it was proposed to perform the risk assessment of domestic distribution system, and in case of negative impact on the quality of supplied water, rinsing or replacement of the installation [9].

The result of the research presents the installation operating time until the normative microbiological parameters in water intended for human consumption are exceeded depending on the adopted probability level. Consumption of water of inadequate microbiological quality carries a health risk. Potentially pathogenic and pathogenic organisms can cause many diseases: typhoid fever, salmonellosis, legionellosis, tularemia, leptospirosis, gastroenteritis, conjunctivitis, and skin infections. Infection can occur through the respiratory system, skin, or urinary tract [45]. The probability of human consumption of water that does not meet microbiological criteria increases with the duration of time spent in the domestic distribution system. The use of water from the installation can pose a risk to consumers' health, especially in case of using water after prolonged pauses in the operation of the tap water installation (e.g., from domestic installation after returning from vacation, installations in public buildings, workplaces after holiday breaks, etc.), therefore, it is recommended to replace the volume of water in the installation through the drain to the sewage system before direct consumption. Reducing the degree of impact of the tap water installation on the quality of water intended for consumption can also be achieved by periodically flushing the system or replacing installations with the poor technical condition. The presented results can be used while identifying microbiological hazards for water quality as part of the risk analysis related to the domestic distribution system,

which should be performed as a result of the provisions of the new European Council directive on the quality of water intended for human consumption.

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