Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.26426

199 (2020) 499–511
September

Use of water turbidity as an identifier of microbiological contamination in the risk assessment of water consumer health

Izabela Zimoch[a,*], Jarosław Paciej[b]

[a]*Silesian University of Technology, Faculty of Energy and Environmental Engineering, Institute of Water and Wastewater Engineering, Konarskiego St. 18, 44-100 Gliwice, Poland, Tel. (032) 237-28-84, 237-27-27; email: izabela.zimoch@polsl.pl (I. Zimoch)*
[b]*Silesian Waterworks PLC, Wojewodzka St. 19, 40-026 Katowice, Poland, Tel. +48 32 603 88 61; email: jarek.paciej@gmail.com (J. Paciej)*

Received 15 December 2019; Accepted 9 August 2020

ABSTRACT

Laboratory tests of water in the water supply system (WSS) are the basic component of water quality control. One of the key parts of that control should be the analysis of the dynamics of changes when it is transported to the consumer. This is due to the dynamically changing local hydraulic conditions in distribution systems, resulting in exposure to secondary water contamination. The phenomenon results in loss of microbiological water safety and drinking such water poses a potential threat to its consumers' health. The paper presents a procedure for assessing the risk of losing microbiological safety of water quality, taking into account the size of the population threatened with waterborne diseases. In the proposed analytical method, turbidity is used as an identifier of water microbial contamination. The areas of different risk categories (acceptable, controlled and not acceptable) are determined based on defined three range turbidity levels. The proposed procedures for estimating the turbidity limit value allow using online monitoring of turbidity in WSS for spatial interpretation of the health risk of the water consumer. Based on the research carried out with the use of analytical procedures in the GIS system, a risk map is developed taking into account the degree of population exposure to microbiological water stability loss. The risk map also includes the identification of critical areas of secondary microbial contamination of drinking water. The proposed risk assessment method is an innovative tool in the decision support system to make rational operational decisions as an effective safety barrier in risk management.

Keywords: Turbidity; Water distribution subsystem (WDS); Secondary microbiological water contamination; Quantitative microbial risk assessment (QMRA); Risk analysis; Risk maps

1. Introduction

The project of revising the directive on the quality of water intended for human consumption Drinking Water Directive (DWD) introduces the obligatory assessment of risk in the water supply. Its proposals go beyond the obligations effective so far, which defined merely requirements for the quality only of the water flowing out of the consumer's tap. The provisions of the DWD in question impose on the member states and managers of the water supply process new tasks, related for instance with water safety, the necessity to inform the society about the quality of supplied water and risks and the obligation to minimize potential risks by introducing a risk management system. The direction of the above changes as well as the experience of many countries where the use of water supply system (WSSs) is based on risk management [1–8] emphasizes the magnitude of cooperation between water quality

* Corresponding author.

Presented at the 14th Conference on Microcontaminants in Human Environment, 4–6 September 2019, Czestochowa, Poland

1944-3994/1944-3986

monitoring and continued risk analysis. Much evidence gathered over several dozen years indicates that the system including continued risk assessment and risk management, being preventive in nature, brings more benefits for public health than the system of water quality supervision, used in many countries, including Poland, in which system repair action is taken only after a threat to human health occurs. The above facts confirm that an integrated system of water quality control and risk analysis, as a cohesive and synchronized system for WSS management, allows the introduction of preventive actions limiting the consequences of potentially harmful events. The provision of effective resistance to threats generated in the entire water supply chain is the basic part of the analysis of WSS analysis as regards the consumer's safety [3,9–11].

The conducted literature review [12–19] indicates that currently one of the biggest problems with WSS use is secondary water contamination. The issue is particularly important for users of extensive water distribution subsystems (WDS). Secondary water contamination occurs due to a range of factors, such as lower water flow speeds resulting from lower water demand in the system. As a result of the use of oversized extensive waterworks systems, there are areas of critical water stagnation in WSSs, which are a source of microbiological threats. Moreover, the deterioration in the quality of transported water is related to fluctuating pressure, poor technical and sanitary conditions of the infrastructure of WDS parts, corrosion or biofilm [15,16,19–21]. The secondary water contamination is linked with both microbiological and physicochemical water quality. In the cases of ineffective removal of natural organic matter (NOM), which is the precursor of disinfection by-products in water delivered to consumers, it is crucial to ensure proper management of the disinfection process using chlorine to protect drinking water against the creation of high centration of trihalomethanes (THMs). Low water velocity in the pipe network, high concentration of NOM in water, as well as water high temperature and extending transport time of water to the consumer due to oversized WSS, is the most significant operational factors responsible for the dangerous events, which lead to the creation of THMs. Therefore, it is very important to control the level of free residual chlorine concentration to keep a balance between microbiological and chemical stability in drinking water. This approach in risk management of WSS operation guarantees a high level of water consumer safety [22]. The effects of secondary water contamination are a high concentration of parametric physicochemical and microbiological indicators that can cause adverse health effects and even pose a threat to the consumer's life. The issue of microbiological contamination of water is of particular importance due to the fact that the results of this threat can cause an immediate acute reaction of the body, manifesting in the development of digestive tract diseases [1,10,23,24]. Therefore, an application of risk analysis methods for the loss of microbiological safety of water intended for human consumption is extremely important. The crucial issue is the fact that such an assessment model should allow for simple, quick to obtain results and would be economically possible to implement in WSS management on a large scale. Such a method of estimating microbiological contamination should ensure the necessary prevention and rapid reaction capabilities means to deal with any random hazards occurrence. This approach to risk management can be a useful tool to provide effective operational action, that is, increasing the dose of chlorine in water disinfection, chlorination of water in the water pipe network. For over 10 y, the World Health Organization has been recommending the quantitative microbial risk assessment (QMRA) to be applied in water safety management as a tool in water safety plans [25]. QMRA is a probabilistic method and it is the main method used to estimate the microbiological risk of infection from exposure to microorganisms present in water intended for human consumption. It is a formal four-step risk assessment process including (i) problem formulation as a hazard identification to determine the pathogens and human health outcomes of concern; (ii) exposure assessment, which provides information on the frequency and magnitude of drinking water consumer exposure to specific pathogens; (iii) health effects assessment evaluates dose-response; (iv) risk characterization. Based on this method, the information on exposure (step ii) and the health effects assessment (step iii) are combined to assess a quantitative measure of risk. QMRA is effective, and time-consuming risk management approach introduced above. Despite this, Netherland and Australia are the world's leading countries where QMRA-based regulation has helped in decision-making in drinking water safety management [26,27].

It results from the reports of the Centres of Disease Control and Prevention [28,29] that the number of waterborne epidemics in years 2013–2014 increased by 31% in relation to 2011–2012 as a result of which the incidence rate increased by 133% from 432 to 1,006 (Fig. 1). In the years 2013–2014, the pathogen in 208 cases was bacteria (49%), in 32 – viruses, in 11 – protozoa, in 6 – chemical compounds. The epidemics resulted in the hospitalization of over 124 people, 13 out of whom died [28]. Whereas in the years 2011–2012, 102 persons out of 431 cases were hospitalized, 14 of them dying [29]. Bacterial contamination of water (accounting for 62%) caused mainly by *Legionella* spp. were the main cause of the waterborne epidemics in the years 2011–2012 (Fig. 1).

The identification of waterborne diseases and analysis of their causes conducted in the USA showed that, on average, 89% epidemics foci had their source in the municipal WSSs (93.7% in years 2011–2012, 84% in years 2013–2014), resulting in more than doubled incidence rates in 2013–2014 (Table 1). The share of the municipal systems operating based on both surface and ground waters in the number of waterborne epidemics foci in years 2013–2014 was the same (33.3%), in the years 2013–2014, however, the incidence count increased eight times and was 795 persons. More than 36% of all outbreaks in 2011–2014 led to 1,170 cases of acute gastrointestinal illness, of which 79% were water-related diseases (71.5% in 2011–2012 and 85.7% in 2013–2014). On the other hand, respiratory system diseases accounted for 61% of all epidemics, but the number of people with water-related diseases was only 121, which was on average 19% of the total number of cases (25.8% in 2011–2012 and 12.9% in the years 2013–2014) [28,29].

In Europe, the European Centre for Disease Prevention and Control (ECDPC) records the foci and counts of waterborne diseases. Although these data, prepared for 30 countries, do not fully reflect the reality (many cases of diseases are

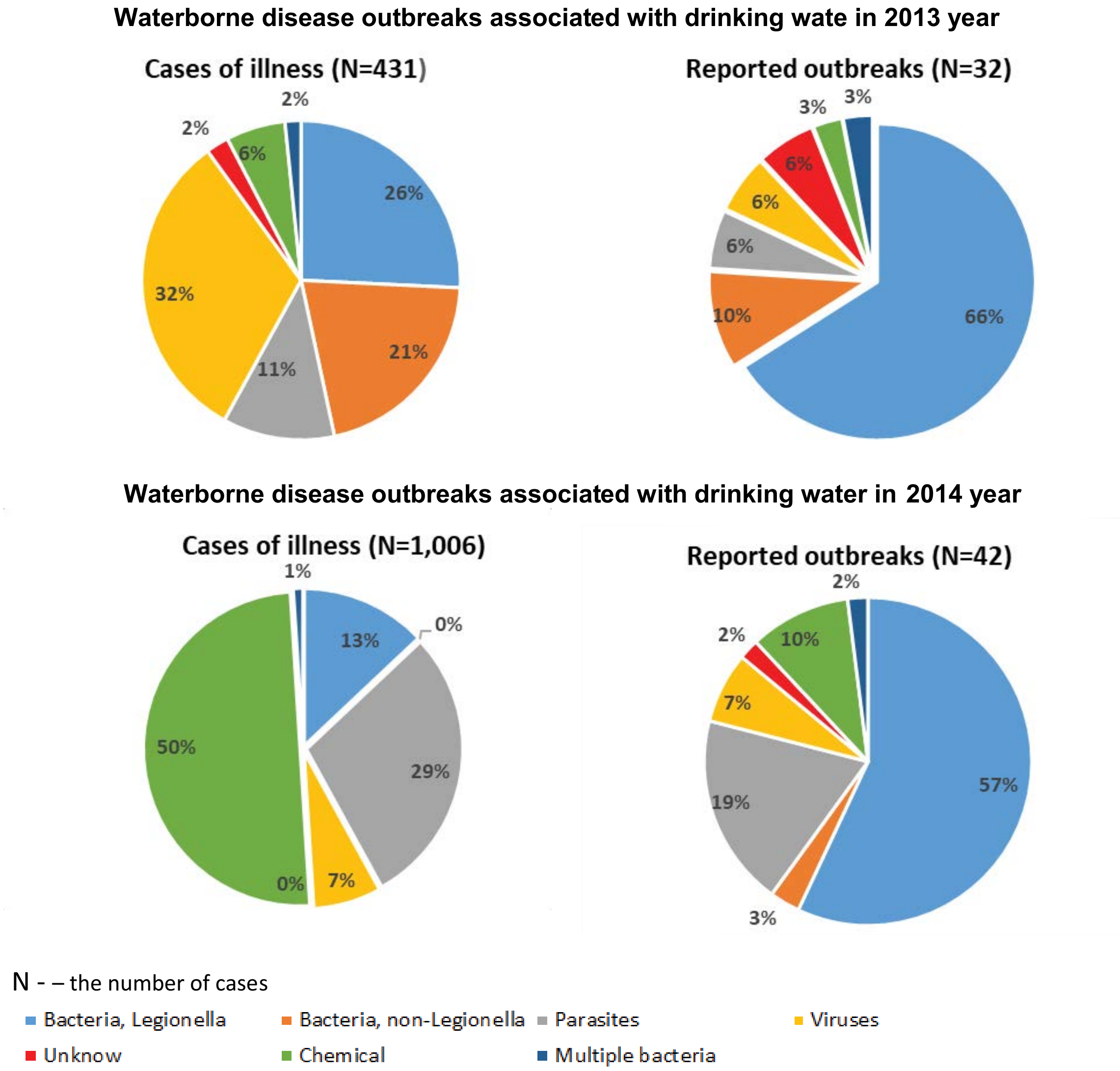

Fig. 1. A reported number of cases of waterborne disease in the USA, data from 2013–2014 [28].

not reported), the data collected by ECDPC allow assessing certain tendencies. According to data for years 2013–2017 [30–33], the annual number of cases of diseases transmitted in water increased by 15%. The greatest threat for health is infections caused by *Cryptosporidium*, *Shigella*, *Campylobacter*, *Escherichia coli* and *Legionella* bacteria (Fig. 2) a major source of which is contaminated water.

Waterborne diseases, as an acute reaction of the body, are caused by the microbiological contamination of water. The state of loss of water microbiological safety in the WSS may be a result of pumping in improperly treated or contaminated water batches as a consequence of the treatment subsystem failure as well as of its secondary contamination or terrorist attack. The occurrence of such a situation in combination with the characteristics of the vast infrastructure the water distribution subsystem is required taking efficient and quick corrective measures by the operators. A high level of safety of microbiological water supply to the consumers is ensured by the implementation of the WSS operation procedures concerning risk management based on the Water Safety Plan the purpose of which is the creation of effective protective barriers to minimize the risk [34]. In the case of microbiological water contamination, such a barrier can be water quality monitoring, including real-time control of substitute parameters (e.g., measurement of turbidity, free chlorine concentration, flow speed and direction).

Rich literature sources [35–42] prove that turbidity measured online as an identifier of microbiological contamination can be an effective, quick water contamination risk control parameter, allowing for immediate commencement of rational preventive activities upon threat identification should a potential for microbiological contamination arise. New risk management methods [40] use the Bayesian probability to assess the microbiological safety of water based on the measurement of turbidity of water intended for human consumption. The results of the presented research indicate that turbidity can be used as a replacement parameter to analyze the risk of water-borne diseases.

Table 1
Characteristics of the reasons and effects of waterborne diseases in years 2011–2014, developed based on [28,29]

Characteristic	Category	Period			
		2011–2012		2013–2014	
		Outbreaks *N* = 32 (%)	Cases *N* = 431 (%)	Outbreaks *N* = 42	Cases *N* = 1,006
Water system	Community	25 (78.1)	184 (42.7)	30 (72)	759 (75.4)
	Non-community	5 (15.6)	222 (51.5)	5 (12)	115 (11.4)
	Individual	–	–	3 (7)	124 (12.3)
	Unknown	–	–	3 (7)	6 (0.6)
	Bottled	2 (6.3)	25 (5.8)	1 (2)	2 (0.2)
Water sources	Ground water	11 (34.4)	261 (60.6)	14 (33.3)	157 (15.6)
	Surface water	18 (56.3)	120 (27.8)	14 (33.3)	795 (79)
	Unknown	1 (3.1)	22 (5.1)	12 (28.6)	39 (3.9)
	Mixed	2 (6.3)	28 (6.5)	1 (2.4)	12 (1.2)
	Unreported	–	–	1 (2.4)	3 (0.3)
Predominant illness	ARI*	21 (65.6)	111 (25.8)	24 (57.1)	130 (12.9)
	AGI*	10 (31.3)	308 (71.5)	17 (40.5)	862 (85.7)
	Other	1 (3.1)	12 (2.8)	1 (2.4)	14 (1.4)

ARI – acute respiratory illness; AGI – acute gastrointestinal illness; *N* – number of cases, (%) –percentage for each category.

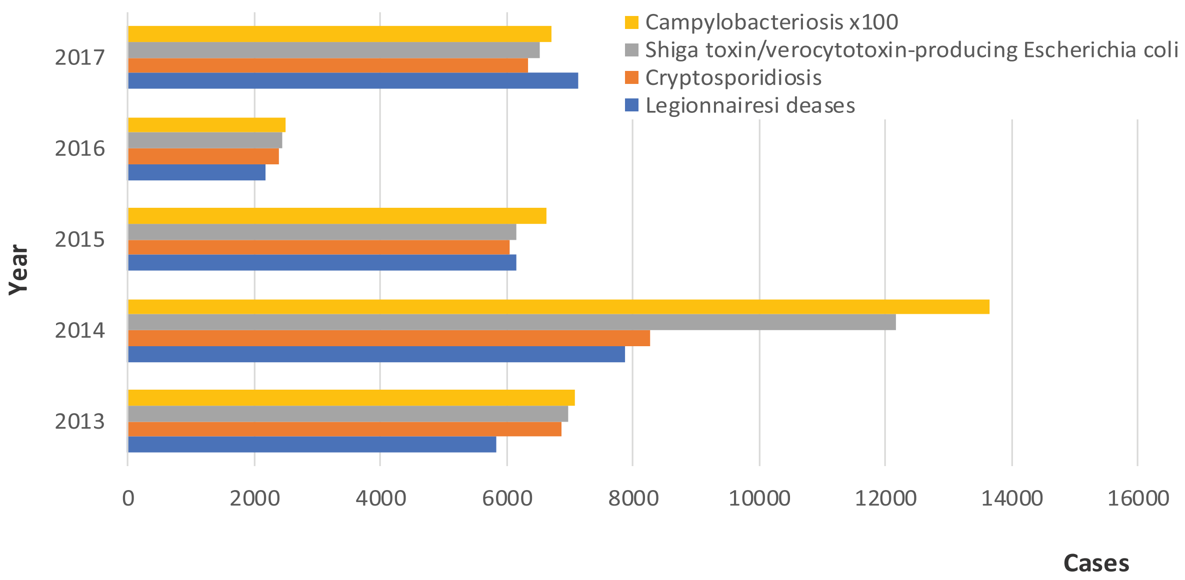

Fig. 2. Number of epidemiology disease cases by year for different bacteria in the European Union in the period 2013–2017 [30–33].

The objective of this paper is the presentation of results of the spatial analysis of water consumer health risk as a result of microbiological contamination of water, with the identification of critical areas. Furthermore, the article presents the evaluation of the potential use of turbidity as an identifier of water microbiological contamination in the procedures of waterborne disease onset risk analysis.

2. Research area

The subject of the study is one of the largest water system complexes in Europe, which is a collective WSS of the Silesian Agglomeration located in southern Poland (Fig. 3). This system spans over the total area of 12,333 km^2, supplying water to nearly 4.5 million residents of the Silesian Voivodeship. The administrative division of the voivodeship includes 17 districts and 19 cities with district rights.

Drinking water is supplied to the residents of the Silesian region by 798 WSSs (Table 2). Supply of water to the residents of the central part of the Silesian Agglomeration, to ca. 800 thousand residents living in large municipal and industrial centers, (e.g., Katowice, Chorzów, Ruda Śląska – Świętochłowice, Siemianowice Śląskie, Mysłowice), is performed by one big

Table 2
Characteristics of the local SDSI in the Silesian Voivodeship – period 2017–2017

No. of SDSI	State District Sanitary Inspectors	Number of residents	Area in km^2	Number of WSS
1	SDSI Bielsku-Białej	303,000	582.16	54
2	SDSI Bytomiu	379,000	751.73	30
3	SDSI Chorzowie	159,000	46.82	1
4	SDSI Cieszynie	245,000	730.2	42
5	SDSI Częstochowie	404,000	1,679.1	62
6	SDSI Dąbrowie Górniczej	204,000	555.83	39
7	SDSI Gliwicach	464,000	877.67	31
8	SDSI Jaworznie	93,000	152.2	4
9	SDSI Katowicach	455,000	255.79	5
10	SDSI Kłobucku	84,000	889.15	30
11	SDSI Lublińcu	72,000	822.13	32
12	SDSI Myszkowie	69,000	478.62	33
13	SDSI Raciborzu	162,000	543.98	19
14	SDSI Rudzie Śląskiej	161,000	77.59	1
15	SDSI Rybniku	303,000	437.53	19
16	SDSI Sosnowcu	207,000	91.26	2
17	SDSI Tychach	338,000	943.29	36
18	SDSI Wodzisławiu Śląskim	229,000	372.36	16
19	SDSI Zawiercie	122,000	1,003.27	60
20	SDSI Żywcu	85,000	1,039.96	280
Total		4,538,000	12,330.64	796

water supply company. This company manages 11 Water Treatment Stations the production of which is based on 87% on the surface water resources. The current daily water production is 381.5 thousand m^3, which accounts for only 45.5% of the available production capacity. The water production subsystem uses high-performance process lines guaranteeing high water treatment effects. 876.2 km of water pipe networks are used to transport the produced water, mostly high diameter pipes – 1,800–500 mm, characterized by significant material diversification. Next, water is distributed to the residents by the local water supply enterprises. A separate water supply structure is found in the north-eastern area of the voivodeship where nearly 92% of WSSs have a daily capacity ranging from 5 to 1,000 m^3/d.

In the Silesian Voivodeship, the authority supervising water quality in the scope of public health are the

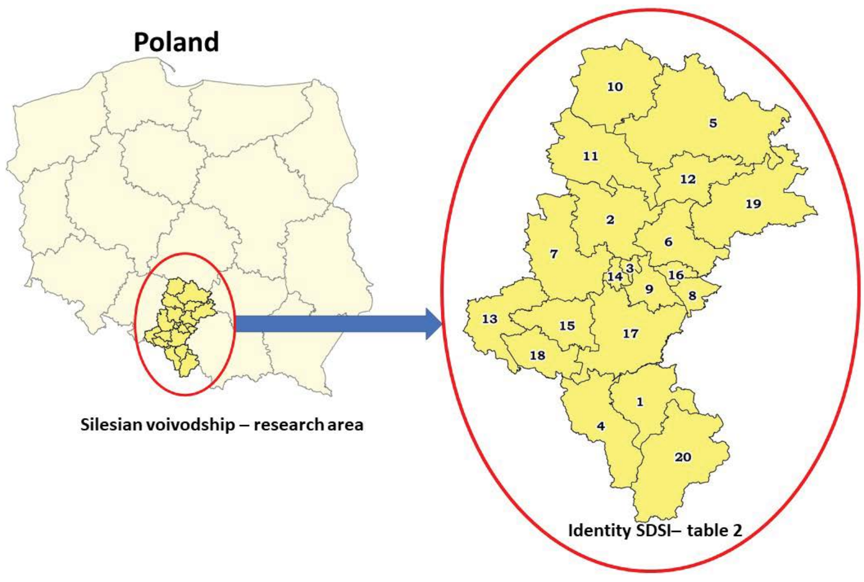

Fig. 3. Research area - Silesian Voivodeship, southern Poland (State District Sanitary Inspectors).

bodies of the State Sanitary Inspection, composed of 20 State District Sanitary Inspectors (SDSI) and the Silesian District Voivodeship Sanitary Inspector (Fig. 3). For the purpose of assessment of the water microbiological safety in the Silesian Voivodeship, a territorial division based on the venues of the SDSIs (Table 2) and water quality data for the period 2016–2017 [43,44] were used in the conducted risk analyses.

3. Research method

The estimation method of the health risk for the water consumer resulting from water microbiological contamination is based on two defined water quality states. The water quality states refer to the presence of potential microbiological contaminations in water:

- S_1 – the first water microbiological safety state in which the water quality at the given control point is compliant with the legal requirements imposed on water intended for human consumption;
- S_2 – state of loss of microbiological safety of water, determined by the presence of at least one colony-forming unit of the following microorganisms: *Escherichia coli*, *Enterococci*, *Clostridium perfringens* and coliform bacteria (according to the test of water microbiological quality conducted with a frequency not lower than defined in the monitoring program according to Table 1 of Annex II, part B of DWD [45]).

In the research method procedure, the above microorganisms were adopted as an indicator parameter as their presence might be a sign of improper operation of the water treatment plant, leakage in the distribution system, failure of elements of both the water treatment plant and water pipe network. Moreover, these indicators are also used as a measure of the presence of other pathogens in the water. Additionally, the selection of these parameters was based on the European and Polish legal regulations [45–47]. If the presence of at least one of these microorganisms is found in the tested water sample, the water supply company is obliged in Poland to inform about the incident the competent water quality control authority, to determine the cause as well as prepare and take corrective measures. As a result of the applied research procedures, the information on the microbiological quality of water is obtained only after 24 h. Due to this fact, these indicators cannot be the operating parameter in risk management. Therefore, the proposed research methodology suggests the application of turbidity as a substitute indicator of the potential microbiological contamination of water supplied to the consumers.

In the developed research method, use of specific turbidity value thresholds was proposed for the purpose of determination of the areas exposed to loss of water microbiological safety as well as to develop a risk map, that is, a spatial interpretation of the critical areas sensitive to microbiological contamination of water poisoning a major hazard to the consumer health.

The developed study method consists of three inherently related stages including (Fig. 4):

- determination of the probability of occurrence of state S_2 of water quality for the adopted limit value (LV) of turbidity – stage 1,

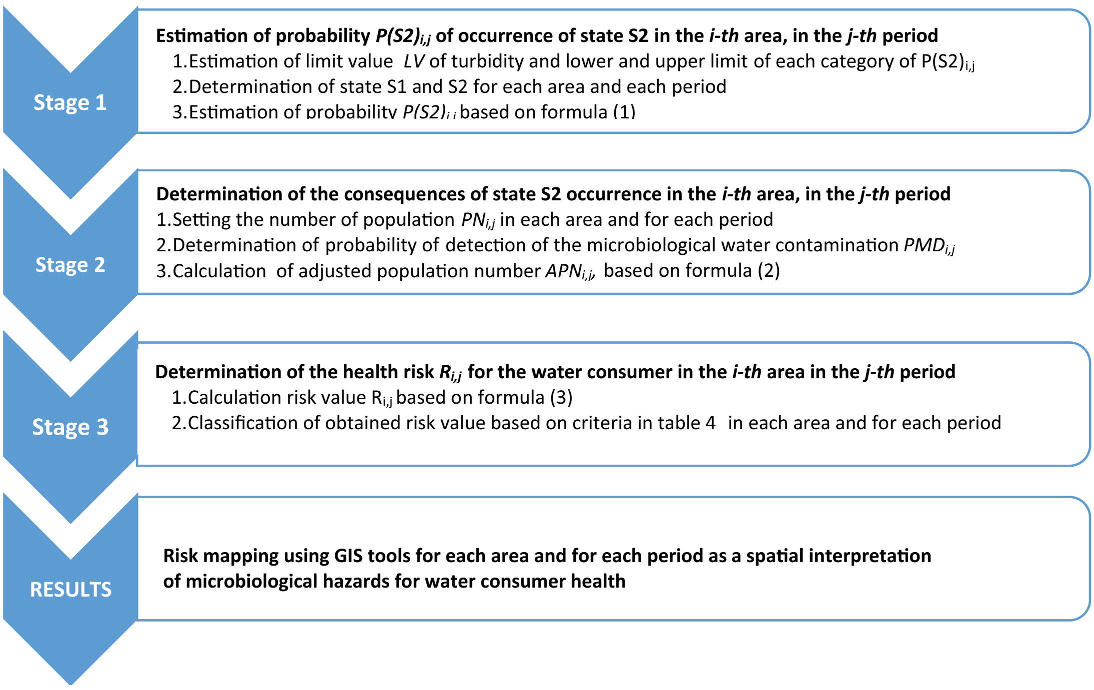

Fig. 4. Algorithm for estimating the health risk of a water consumer as a result of microbiological water contamination based on turbidity as an identifier.

- determination of the consequences of the occurrence of the water microbiological contamination, defined by the size of the population potentially exposed to waterborne gastrointestinal diseases – stage 2;
- occurrence of health risk for the water consumer as a result of the loss of microbiological quality of water – stage 3.

In the first step of the analysis (stage 1), the LV is determined for water turbidity as the threshold value of the operating indicator determining the microbiological water safety state. Because turbidity changes in a wide range in drinking water due to secondary water contamination, the new DWD [45] proposes 0.5 NTU value as a control parameter in the monitoring system, to control both microbiological stability of water and risk management of operation WSS. Therefore, the LV should be determined based on water quality data from online monitoring and it should be less than 0.5 NTU. Determination of the turbidity threshold values is based on the research methodology on a statistical analysis of water quality datasets including turbidity and indicative microbiological parameters. The set of water turbidity values must be assessed in terms of conformity of the distribution of the random variable with the normal distribution. To assess goodness of fit of distribution of this set with the normal distribution, the Kolmogorov–Smirnov test (K–S) and χ^2 test were applied (level of significance $\alpha = 0.01$ for K–S test and $\alpha = 0.05$ for and χ^2). If the goodness of fit of the analyzed distribution with the normal distribution is confirmed, the LV is determined by the mean value of the random variable, whereas if the variable distribution differs from the normal distribution, the LV is determined by a median. The determined LV value allows to determine the occurrence probability $P(S_2)_{i,j}$ of state S_2 of loss water microbiological safety in the given i-th study area in the j-th study period, according to the following equation:

$$P(S_2)_{i,j} = \frac{L\left(T_{\mathrm{LV}} \cap M_{S_2}\right)_{i,j}}{L(T \cap M)_{i,j}} \tag{1}$$

where $L\left(T_{\mathrm{LV}} \cap M_{S_2}\right)_{i,j}$ is the number of water samples in which microbiological safety state S_2 and turbidity value exceeding the LV were found in the i-th study area, in the i-th study period, $L(T \cap M)_{i,j}$ is the number of water samples in which both turbidity and at least one of the adopted microbiological indicators in the i-th study area, in the j-th study period were tested.

This probability is determined based on data collected in archival monitoring databases containing information on both laboratory tests of microbiological parameters and water turbidity. Probability $P(S_2)_{i,j}$ characterizes the possibility of occurrence of random hazardous events, defined by water microbial contamination, through the use of deviations from the obtained LV of turbidity of water during its transport to consumer tap.

Another variable of the water consumer health risk is the determination of the value of adjusted population number ($\mathrm{APN}_{i,j}$), defined as the size of the population potentially exposed to waterborne diseases of the gastrointestinal system in the i-th study area in the j-th study period caused by *Cryptosporidium*, *Campylobacter* and *Rotaviruses*. The variable is defined by the following equation:

$$\mathrm{APN}_{i,j} = \mathrm{PN}_{i,j} \cdot \mathrm{PMD}_{i,j} \cdot \sum_{k=1}^{3} \left[P\left(\mathrm{DE}_{i,j}\right)_k \cdot P(S_2)_{i,j} \right] \tag{2}$$

where $\mathrm{PN}_{i,j}$ is the population number in the i-th study area in the j-th study period, $\mathrm{PMD}_{i,j}$ is the probability of detection of the microbiological contamination in the i-th study area in the j-th study period, calculated based on:

- $\mathrm{PMD}_{i,j} = NM_{i,j}/N_j$ in which: $NM_{i,j}$ – days number of laboratory test of microbiological parameters in the monitoring process in the i-th study area in the j-th study period;
- $P(\mathrm{DE}_{i,j})_k$ – the probability of diarrhea as a result of microbiological contamination of water, accordingly for *Cryptosporidium* – 6.7×10^{-4}; *Campylobacter* 2.2×10^{-4}; *Rotaviruses* 1.2×10^{-3} [48];
- $P(S_2)_{i,j}$ – the probability of occurrence of the microbiological contamination in the i-th study area in the j-th study period, defined by Eq. (1).

Based on the research procedure, stage 3 involves the determination of the health risk $R_{i,j}$ for the water consumer as a result of microbiological contamination of water in the i-th study area in the j-th study period, according to the following Eq. (3):

Table 3
Two-parameter matrix of consumer health risk assessment

Probability $P(S_2)_{i,j}$		Consequence $\mathrm{APN}_{i,j}$		$\mathrm{APN}_{i,j} \le \mu^a$	$\mu < \mathrm{APN}_{i,j} \le \mu + \delta^a$	$\mathrm{APN}_{i,j} > \mu + \delta^a$
				$\mathrm{APN}_{i,j} \le \mathrm{Me}^b$	$\mathrm{Me} < \mathrm{APN}_{i,j} \le Q_3^b$	$\mathrm{APN}_{i,j} > Q_3^b$
				Weight $W(\mathrm{APN}_{i,j})$		
				1	2	3
$P(S_2)_{i,j} \le \mu^a$	$P(S_2)_{i,j} \le \mathrm{Me}^b$	Weight	1	1	2	3
$\mu < P(S_2)_{i,j} \le \mu + \delta^a$	$\mathrm{Me} < P(S_2)_{i,j} \le Q_3^b$	$W(P(S_2)_{i,j})$	2	2	4	6
$P(S_2)_{i,j} > \mu + \delta^a$	$P(S_2)_{i,j} > Q_3^b$		3	3	6	9

[a]thresholds of random variable values if the zero hypothesis H_0 is true;
[b]thresholds of random variable values if the zero hypothesis H_0 is rejected.

Table 4
Risk classification of population exposure level to loss of microbiological water safety

Risk category	Risk value $R_{i,j}$
Tolerated risk	1–2
Controlled risk	3–4
Not acceptable	6–9

$$R_{i,j} = W\left(P\left(S_2\right)_{i,j}\right)\cdot W\left(\text{APN}_{i,j}\right) \quad (3)$$

where $W(P(S_2)_{i,j})$ is the weight of probability of occurrence of state S_2 for the turbidity value exceeding LV in the *i*-th study area in the *j*-th study period (Table 3), $W(\text{APN}_{i,j})$ is the weight for the APN potentially exposed to waterborne diseases of the gastrointestinal tract (Table 3).

In the research method, for the three-level scale of risk variables, the determination of their weights is based on the LVs of the probability of occurrence of state S_2 for the turbidity value exceeding the LV and APN. For this purpose, hypothesis H_0 regarding the conformity of the empirical distribution of risk variables with the normal distribution is verified. To assess goodness of fit of the distribution of random variables set $P(S_2)_{i,j}$ and $\text{APN}_{i,j}$ with the normal distribution, the K–S and χ^2 tests are applied for the significance levels $\alpha = 0.01$ for the K–S test and $\alpha = 0.05$ for the χ^2 test, respectively. If the goodness of fit of the analyzed distribution with the normal distribution is confirmed, the random variable thresholds are defined by the mean (m) and sums of the mean and standard deviation (m + d), whereas if the zero hypothesis H_0 is rejected, the value thresholds of variables are set using the median (Me) and the third quartile (Q_3). The determined LVs of the variability intervals allow assigning weights to the variables in three intervals (Table 3). The mathematical interpretation of risk as a function of the probability of adverse events and their effects expressed by weights of these variables allows us determining the numerical values of risks in the matrix method according to Eq. (3). These values are the basis for assignment of the *i*-th study area to the given risk category in its three-level scale: tolerated, controlled and not acceptable (Table 4).

Determination the risk value allows to define the procedures of assessment of microbiological water quality based on constant on-line monitoring of water turbidity of pipe water, as specified below:

- tolerated risk – the operator may make the decision to resign from the performance of the microbiological test of the water sample;
- controlled risk – the operator should decide on performing microbiological tests of the water sample at the list at the control site to confirm microbiological contamination;
- not acceptable risk – the operator must perform microbiological tests in the entire supply zone, inspect the managed WSS and notify the services responsible for crisis management.

4. Results and discussion

In the first step of the research procedure, the statistical analysis of the drinking water turbidity dataset was carried out. This set was created and verified based on the data obtained during the official and internal controls conducted in the years 2016–2017 (Table 5).

The minimum turbidity value 0.01 NTU was found in the functioning area of SDSI in Rybnik in 2016, whereas the maximum value of 11.7 NTU was found in the functioning area of SDSI in Bytom in 2017. In the years 2016–2017, only 2.5% of all samples (524 observations) were recorded as characterized by turbidity exceeding the normative value of 1 NTU. The average turbidity in that set of variables was 2.67 (Table 5). The obtained, verified turbidity set, according to the researcher's methodology, was assessed in terms of conformity of the random variable distribution with the normal distribution. The results of K–S and χ^2 tests for the significance levels $\alpha = 0.01$ for the K–S test and $\alpha = 0.05$ for the χ^2 test do not show the goodness of fit of the empirical distribution and normal distribution. Thus, the value LV in the further research procedure was determined using the median and third quartile (Q_3). Obtained value 0.26 NTU is in accordance with the proposal of the new DWD as a control parameter in procedures of risk management. Table 6 presents the characteristic of free chlorine concentration for each of the 20 study areas. The maximum chlorine concentration (2.0 mg/dm^3) was observed in the functioning area of SDSI in Rybnik in 2016. In the study period, the mean free chlorine concentration change from 0 mg/dm^3 (in SDSI in Lublińcu and SDSI in Myszkowie) to 0.2 mg/dm^3 (in SDSI in Kłobucku).

Table 5
Descriptive statistics of turbidity (T) of water intended for consumption in the Silesian Voivodeship with data of events number with microbiological water contamination in 2016–2017

Turbidity range (NTU)	NMC	NT	Mean	Minimum	Maximum	Q_1	Median	Q_3	Standard deviation
Whole dataset	324	21,199	0.40	0.01	11.7	0.17	0.26	0.50	0.51
$T \leq 0.26$	139	10,600	0.16	0.01	0.26	0.1	0.17	0.2	0.05
$0.26 < T \leq 0.5$	71	5,477	0.36	0.26	0.5	0.3	0.36	0.42	0.06
$0.5 < T \leq 1$	84	5,122	0.93	0.51	11.7	0.61	0.74	0.91	0.84
$T > 1$	29	524	2.67	1	11.7	1.4	2	3.1	1.82

NMC – number of events with microbiological water contamination; NT – number of data for a different range of turbidity.

Table 6
The free chlorine concentration in each study areas in 2016–2017

No. of SDSI	Free chlorine concentration for differ ranges of turbidity, (mg/dm^3)															
	2016								2017							
	$T \leq 0.26$ NTU		$0.26 < T \leq 0.5$ NTU		$0.5 < T \leq 0.1$ NTU		$T > 1$ NTU		$T \leq 0.26$ NTU		$0.26 < T \leq 0.5$ NTU		$0.5 < T \leq 0.1$ NTU		$T > 1$ NTU	
	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean
1	0.85	0.17	0.59	0.14	0.76	0.13	0	0	0.66	0.23	0.74	0.17	0.78	0.14	–	–
2	0.40	0.07	0.50	0.07	0.22	0.02	0.16	0.01	0.49	0.06	0.41	0.06	0.26	0.04	0.15	0.02
3	0.29	0.03	0.20	0.03	0.09	0.02	0	0	0.48	0.05	0.39	0.06	0.18	0.03	0	0
4	1.30	0.11	0.72	0.05	0.68	0.07	0.30	0.07	1.00	0.11	1.00	0.07	1.00	0.07	0.04	0
5	0.10	0.06	0.12	0.02	0.21	0.02	0.10	0.04	0.20	0.03	0.10	0.01	0.24	0.02	0	0
6	0.68	0.09	0.65	0.10	0.14	0.04	0.03	0.01	0.84	0.13	1.01	0.13	0.60	0.06	0	0
7	0.30	0.04	0.32	0.02	0.33	0.04	0.50	0.11	1.00	0.03	0.33	0.04	0.30	0.04	0	0
8	0.48	0.14	0.80	0.06	0.23	0.02	0.80	0.09	0.42	0.12	0.42	0.06	0.25	0.03	0.10	0.04
9	0.52	0.09	0.31	0.07	0.43	0.08	0.08	0.05	0.52	0.13	0.44	0.11	0.36	0.09	0.18	0.06
10	0.12	0.07	2.0	0.20	0.30	0.09	–	–	0.24	0.07	0.15	0.06	0.18	0.04	–	–
11	0	0	0	0	0	0	–	–	0.11	0.01	0	0	0.10	0.03	–	–
12	0.13	0.06	0.06	0.03	0	0	–	–	0.12	0.04	–	–	0.03	0.03	–	–
13	0.40	0.03	0.21	0.04	0.13	0.02	0.03	0.01	0.27	0.01	0.23	0.03	0.13	0.03	0.23	0.04
14	0.38	0.09	0.45	0.09	0.22	0.08	0.08	0.08	0.37	0.13	0.58	0.12	0.43	0.11	0.12	0.08
15	0.54	0.08	0.46	0.09	0.29	0.05	0.14	0.07	0.37	0.10	3.0	0.18	0.20	0.06	0.10	0.05
16	0.48	0.08	0.30	0.07	0.18	0.07	0.06	0.02	1.7	0.11	0.42	0.07	0.30	0.08	0.20	0.04
17	0.80	0.10	0.57	0.07	0.54	0.09	0.57	0.19	0.50	0.10	0.81	0.14	0.28	0.09	0	0
18	0.42	0.12	0.44	0.10	0.25	0.07	0.15	0.15	0.38	0.11	0.36	0.07	0.19	0.05	–	–
19	1.5	0.16	0.13	0.12	0.26	0.14	0.27	0.17	1.60	0.23	0.22	0.11	0.10	0.06	0.09	0.09
20	0.30	0.13	0.31	0.12	0.33	0.11	0.22	0.07	0.40	0.13	0.31	0.12	0.35	0.15	0.34	0.16

Table 7
Probability of occurrence of the S_2 water quality state for turbidity in SDSI areas of the Silesian Voivodeship in the 2016–2017

No. of SDSI	$P(S_2)_{i,j}$ for turbidity T > LV					
	2016			2017		
	0.26 NTU	0.5 NTU	1 NTU	0.26 NTU	0.5 NTU	1 NTU
1	0	0	0	0.001605	0.001605	0
2	0.007919	0.004525	0.001131	0.006795	0.001133	0
3	0	0	0	0	0	0
4	0.015595	0.013645	0.003899	0.012346	0.007716	0.001543
5	0.013089	0.009162	0.003927	0.010309	0.007732	0.003866
6	0.01023	0.007673	0.002558	0.013921	0.00464	0
7	0.005902	0.003373	0.00253	0.00241	0.001606	0
8	0.01373	0.011442	0	0	0	0
9	0.014925	0.008529	0	0.002625	0	0
10	0	0	0	0.018868	0	0
11	0.022124	0.013274	0.004425	0.049242	0.037879	0.007576
12	0.021739	0.013043	0	0.014035	0.010526	0.003509
13	0.00463	0.00463	0.00463	0.026178	0.015707	0.005236
14	0.003236	0	0	0	0	0
15	0.002688	0.002688	0	0.00995	0.002488	0
16	0.00277	0	0	0.021538	0.021538	0
17	0.007874	0.003937	0	0.00624	0.00312	0
18	0.002217	0	0	0.004386	0	0
19	0.009217	0.002304	0.002304	0.019342	0.005803	0
20	0.021563	0.020216	0.006739	0.00955	0.004093	0.002729

Table 8
The $APN_{i,j}$ in SDSI areas of the Silesian Voivodeship in the 2016–2017

No. of SDSI		2016			2017		
	$PN_{i,j}$	$PMD_{i,j}$	$P(S_2)_{i,j}$	$APN_{i,j}$	$PMD_{i,j}$	$P(S_2)_{i,j}$	$APN_{i,j}$
1	303,000	0.127	0	0	0.122	0.002	0.124
2	379,000	0.107	0.008	0.672	0.107	0.007	0.578
3	159,000	0.133	0	0	0.125	0	0
4	245,000	0.119	0.016	0.953	0.095	0.012	0.598
5	404,000	0.132	0.013	1.461	0.130	0.010	1.133
6	204,000	0.130	0.010	0.569	0.118	0.014	0.702
7	464,000	0.098	0.006	0.560	0.093	0.002	0.218
8	93,000	0.053	0.014	0.142	0.052	0	0
9	455,000	0.243	0.015	3.442	0.149	0.003	0.373
10	84,000	0.148	0	0	0.132	0.019	0.437
11	72,000	0.080	0.022	0.265	0.068	0.049	0.505
12	69,000	0.075	0.022	0.235	0.061	0.014	0.123
13	162,000	0.188	0.005	0.294	0.212	0.026	1.879
14	161,000	0.130	0.003	0.142	0.128	0	0
15	303,000	0.204	0.003	0.347	0.188	0.010	1.187
16	207,000	0.143	0.003	0.172	0.159	0.022	1.484
17	338,000	0.166	0.008	0.925	0.132	0.006	0.581
18	229,000	0.127	0.002	0.135	0.126	0.004	0.264
19	122,000	0.070	0.009	0.165	0.059	0.019	0.291
20	85,000	0.029	0.022	0.110	0.029	0.010	0.049

The next stage of the analysis consisted of determination, according to Eq. (1), of the probability $P(S_2)_{i,j}$ of occurrence state S_2 of microbiological water safety loss in the given *i*-th study area for years 2016 and 2017 of conducted tests (Table 7). Additionally, for each *i*-th study area in the separated *j*-th study periods, the probability value $P(S_2)_{i,j}$ was determined for turbidity excess at the level of 0.5 and 1 NTU (Table 7).

For the study period, the highest number of water samples in which at least one microbiological parameter and turbidity were determined were collected in the functioning area of SDSI in Gliwice (1,186 samples in 2016 and 1,245 samples in 2017), whereas the lowest number of such samples were collected in the functioning area of SDSI in Kłobuck (142 samples in 2016 and 159 samples in 2017). Concurrently, most samples qualified to state S_2 for the threshold turbidity value of 0.26 NTU were found for the SDSI functioning area in Żywiec in 2016, that is, 16 samples, and in 2017 – 13 samples for the SDSI functioning area in Lubliniec. Analysis of probability $P(S_2)_{i,j}$ for the additionally adopted turbidity of 0.5 and 1 NTU showed a significantly lower level of precision in detection of the microbiological contamination of water in relation to the value LV at the level of 0.26 NTU. For the limit turbidity value at the level of 0.5 NTU, state S_2 was not found for 6 SDSI functioning areas, whereas for the LV of 1 TNU, state S_2 was not found for 14 areas. In the period of conducted study (2016–2017), the average reduction of the value $P(S_2)_{i,j}$ for turbidity 0.5 and 1 NTU was 42% (variability range from 6% for WSS Jaworzno in 2016 to 83% for WSS Kłobuck in 2017) and 75% (variability range from 57% for WSS Ruda Śląska in 2016 to 87% for WSS Bielsko-Biała in 2017), respectively. Therefore, the conducted analysis confirmed that the median value of turbidity is a good substitute parameter of indication of the secondary microbiological contamination of water in the WSS.

The next stage of the studies involved an assessment of conformity of the random variable distribution with the normal distribution for the obtain probability $P(S_2)_{i,j}$ set for the limit turbidity value of 0.26 NTU. The results of K–S and χ^2 tests for the significance levels α = 0.01 for the K–S test and α = 0.05 for the χ^2 test do not show the goodness of fit of the empirical distribution and normal distribution. Thus, the value of probability weights is defined by the median (Me = 0.0079) and the third quartile (Q_3 = 0.0140).

According to the research procedure, to determine the weights of the effects of the occurrence of secondary contamination of water supplied to the consumers of the $APN_{i,j}$ was determined according to Eq. (2) in the particular study areas (Table 8). For the analysis of $APN_{i,j}$ for individual years, the same population size was assumed for each study area due to either low value or lack of fluctuations number of inhabitants in the Silesian Voivodeship in the period 2016–2017. The highest APN (3.442) was obtained for SDSI in Katowice in 2016, which explained both the largest number of inhabitants and the highest probability of detecting microbial contamination of water. Moreover, during this period, a large number of cases of microbial water contamination were recorded here.

Subsequently, the obtained $APN_{i,j}$ set of random variables was subject to statistical analysis (Table 9) and verification of conformity of the empirical variable distribution with the normal distribution. The highest corrected value of population exposed to waterborne diseases of the gastrointestinal tract for turbidity LV equal to 0.26 NTU in 2016 was found in the area of SDSI in Katowice, whereas in 2017 – in the area of SDSI in Racibórz. The results of tests of conformity K–S and χ^2 for the adopted significance levels showed that the $APN_{i,j}$ indicator does not have a normal distribution, thus the LVs of the particular categories of effects were determined by the median value (Me) and third quartile (Q_3).

At the last stage of analysis for each *i*-th study area, the risk value in the years 2016 and 2017 was determined according to Eq. (3) and, subsequently, each study area was assigned to the relevant risk category. Using the GIS tools, the data layer of spatial boundaries of the Silesian Voivodeship SDSI functioning were combined with the determined risk values and a spatial risk interpretation for the particular research years was prepared. The final effect of the conducted tests is risk maps (Figs. 5 and 6).

The obtained research results confirm that the proposed method of risk estimation allows for the determination of critical areas with the highest probability of microbial contamination of drinking water. This information enables to implementation of additional safety barriers in risk management procedures reducing the health risk to water consumers. In case the online turbidity monitoring indicates the presence of controlled risk (CR) then it is necessary to test additional microbiological water parameters to confirm the occurrence of the potential hazards to consumer health. Thus, the proposed method, allows determining areas with the greatest risk to people's health due to microbial contamination of water (unlike QMRA, which concentrates on health effects assessment evaluates dose-response).

5. Conclusions

The conducted analysis demonstrated population exposure to waterborne diseases for 11 SDSI functioning areas in the Silesian Voivodeship during the study period. In both years 2016 and 2017, there were critical areas qualified as a not acceptable risk for the SDSI area in Częstochowa and Lubliniec. In 6 study areas, as a result of intensified control and implementation of corrective activities, the risk reduction was recorded in 2017, whereas in next 6

Table 9
Descriptive statistics of $APN_{i,j}$ indicator in SDSI areas of Silesian Voivodeship in the 2016–2017

Year	LV NTU	Number of data	Mean	Minimum	Maximum	Q_1	Median	Q_3	Standard deviation
2016	0.26	20	0.529	0	3.442	0.140	0.250	0.595	0.784
2017	0.26	20	0.526	0	1.879	0.123	0.405	0.624	0.525

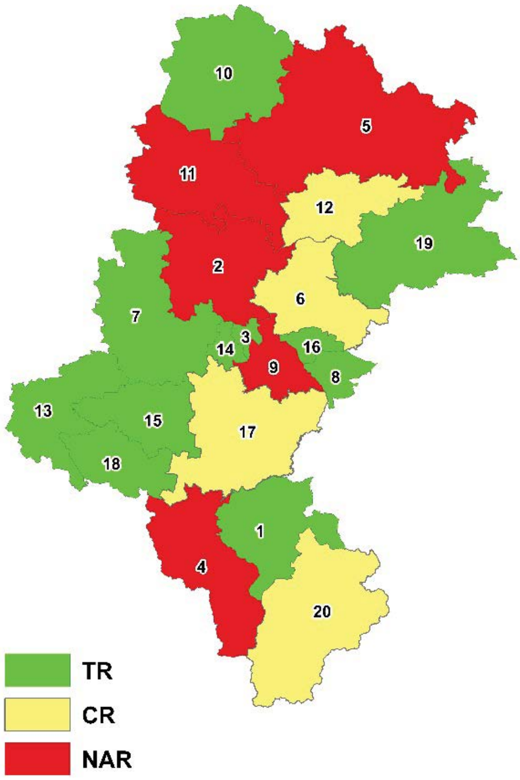

Fig. 5. Risk spatial distribution in 2016.

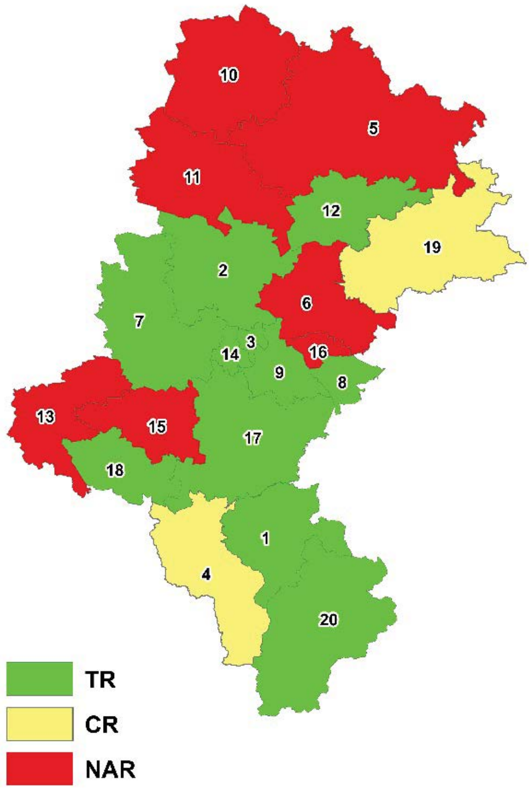

Fig. 6. Risk spatial distribution in 2017.

on the wake of random hazardous events, an increase in health risk for the water consumer resulting from secondary microbiological contamination of the pipe water was recorded too.

The novelty of the presented method is in the usage of turbidity as an identifier of potential microbiological hazards for water consumers. The conducted study showed that the application of turbidity limits values LV as a substitute parameter for spatial risk evaluation of loss of the microbiological water safety is justified. The developed method allows us to determine critical areas in which the WSS operators should implement corrective activities or verify the effectiveness of the existing safety barriers. The application of the proposed research method by the WSS as a decision support system tool for WSS safety assessment will allow us to quickly obtain information on the possible loss of water health safety. Concurrently, this tool can provide support to the water quality control and public health authority in the issue of drinking water quality assessments or estimation of the potential threat of onset of waterborne diseases, including gastrointestinal diseases, in the given area. Obtaining a spatial distribution of three risk categories as a result of the application of the proposed method allows us to take action of rational, additional safety barriers in the area of CR. However, in the areas of not acceptable risk, the obtained results may be an additional argument in undertaking long-term modernization plans. Such a detailed risk analysis with the spatial interpretation of the microbiological hazard also allows water consumers to take all precautionary measures, such as to boil water. This action successfully reduces the risk of water-borne diseases, and thus increase a sense of consumer safety and increase trust in the actions taken by water suppliers. WSS operators can use the proposed tool of risk assessment in operational management as well as to support decision-making. The developed method can complement the QMRA in WSS risk management.

Acknowledgment

This study was supported by the Ministry of Science and Higher Education of Poland within statutory funds – projects no BK-259/RIE-4/2018 and 08/040/BK-9/109.

References

[1] K.A. Reynolds, K.D. Mena, C.P. Gerba, Risk of Waterborne Illness Via Drinking Water in the United States, D.M. Whitacre, Ed., Reviews of Environmental Contamination and Toxicology, Vol. 192, Springer, New York, 2008, pp. 117–158.

[2] L.S. Mudau, M.S. Mukhola, P.R. Hunter, Systematic risk management approach of household drinking water from the source to point of use, J. Water Sanitation Hyg. Dev., 7 (2017) 290–299.

[3] A. Nowacka, M. Włodarczyk-Makuła, B. Tchórzewska-Cieślak, J. Rak, The ability to remove the priority PAHs from water during coagulation process including risk assessment, Desal. Water Treat., 57 (2016) 1297–1309.

[4] E. Szymura, I. Zimoch, Operator reliability in risk assessment of industrial systems function, Przem. Chem., 93 (2014) 111–116 (in polish).

[5] S.J.T. Pollard, J.E. Strutt, B.H. Macgillivray, P.D. Hamilton, S.E. Hrudey, Risk analysis and management in the water utility sector: a review of drivers, tools and techniques, Process Saf. Environ. Prot., 82 (2004) 453–462.

[6] M. Karamouz, S. Saadati, A. Ahmadi, Vulnerability Assessment and Risk Reduction of Water Supply Systems, Preceding of World Environmental and Water Resources Congress,

American Society of Civil Engineers (ASCE), Providence, 2010, pp. 4414–4426.
[7] I. Zimoch, J. Paciej, Spatial risk assessment of drinking water contamination by nitrates from agricultural areas in the Silesia province, Desal. Water Treat., 57 (2016) 1084–1097.
[8] L.W. Mays, Water Supply Systems Security, McGraw-Hill Professional Engineering, New York, 2004.
[9] S. Fortmann-Roe, R. Iwanejko, W. Wójcik, Dynamic risk assessment method – a proposal for assessing risk in water supply system, Arch. Environ. Prot., 41 (2015) 36–40.
[10] I. Zimoch, E. Łobos, Comprehensive interpretation of safety of wide water supply systems, Environ. Prot. Eng., 38 (2012) 107–117. Available at: http://epe.pwr.wroc.pl/2012/3–2012/Zimoch_3–2012.pdf
[11] K. Pietrucha-Urbanik, B. Tchórzewska-Cieślak, Approaches to failure risk analysis of the water distribution network with regard to the safety of consumers, Water, 10 (2018) 1–21.
[12] M.J. Lehtola, E. Torvinen, J. Kusnetsov, T. Pitkänen, L. Maunula, C.-H. von Bonsdorff, P.J. Martikainen, S.A. Wilks, C.W. Keevil, I.T. Miettinen, Survival of *Mycobacterium avium*, *Legionella pneumophila*, *Escherichia coli*, and caliciviruses in drinking water-associated biofilms grown under high-shear turbulent flow, Appl. Environ. Microbiol., 73 (2007) 2854–2859.
[13] A. Jachimowski, Factors affecting water quality in a water supply network, J. Ecol. Eng., 18 (2017) 110–117.
[14] Y.M. Wang, G.C. Zhu, Z.L. Yang, Analysis of water quality characteristic for water distribution systems, J. Water Reuse Desal., 9 (2019) 152–162.
[15] M.J. Lehtola, I.T. Miettinen, M.M. Keinänen, T.K. Kekki, O. Laine, A. Hirvonen, T. Vartiainen, P.J. Martikainen, Microbiology, chemistry and biofilm development in a pilot drinking water distribution system with copper and plastic pipes, Water Res., 38 (2004) 3769–3779.
[16] I. Zimoch, Assessing spatial variation of water quality in the water-pipe network by analysis of THM formation, Ochrona Środowiska, Environ. Prot., 29 (2007) 49–52 (in Polish). Available at: http://www.os.not.pl/docs/czasopismo/2007/Zimoch_4-2007.pdf
[17] R. Renner, Pipe scales release hazardous metals into drinking water, Environ. Sci. Technol., 42 (2008) 4241.
[18] H. Wang, C.R. Proctor, M.A. Edwards, M. Pryor, J.W. Santo Domingo, H. Ryu, A.K. Camper, A. Olson, A. Pruden, Microbial community response to chlorine conversion in a chloraminated drinking water distribution system, Environ. Sci. Technol., 48 (2014) 10624–10633.
[19] F. Yang, B. Shi, J. Gu, D.S. Wang, M. Yang, Morphological and physicochemical characteristics of iron corrosion scales formed under different water source histories in a drinking water distribution system, Water Res., 46 (2012) 5423–5433.
[20] M.-C. Besner, V. Gauthier, B. Barbeau, R. Millette, R. Chapleau, M. Prévost, Understanding distribution system water quality, J. Am. Water Works Assn., 93 (2001) 101–114.
[21] J. Wingender, H.-C. Flemming, Biofilms in drinking water and their role as reservoir for pathogens, Int. J. Hyg. Environ. Health, 214 (2011) 417–423.
[22] I. Zimoch, E. Bartkiewicz, Risk Analysis Associated with Secondary Water Pollution in Selected Agglomerations of the Silesian Voivodeship, 11th Conference on Interdisciplinary Problems in Environmental Protection and Engineering EKO-DOK 2019, E3S Web Conf., Polanica-Zdrój, Poland, April 8–10, 2019.
[23] https://www.vestergaard.com/global-challenges/waterborne-diseases (access17.03.2019)
[24] M. Pirsaheb, K. Sharafi, E. Ahmadi, M. Moradi, Prevalence of the waterborne diseases (diarrhea, dysentery, typhoid, and hepatitis A) in West of Iran during 5 years (2006–2010), Ann. Trop. Med. P.H., 10 (2017) 1524–1528.
[25] WHO, Quantitative Microbial Risk Assessment: Application for Water Safety Management, World Health Organization, Switzerland, 2016.
[26] F. Bichai, P.W.M.H. Smeets, Using QMRA-based regulation as a water quality management tool in the water security challenge: experience from the Netherlands and Australia, Water Res., 47 (2013) 7315–7326.
[27] M. Blokker, P. Smeets, G. Medema, QMRA in the drinking water distribution system, Procedia Eng., 89 (2014) 151–159.
[28] K.M. Benedict, H. Reses, M. Vigar, D.M. Roth, V.A. Roberts, M. Mattioli, L.A. Cooley, E.D. Hilborn, T.J. Wade, K.E. Fullerton, J.S. Yoder, V.R. Hill, Surveillance for Waterborne Disease Outbreaks Associated with Drinking Water — United States, 2013–2014, Morbidity and Mortality Weekly Report, 66 (2017) 1216–1221.
[29] K.D. Beer, J.W. Gargano, V.A. Roberts, V.R. Hill, L.E. Garrison, P.K. Kutty, E.D. Hilborn, T.J. Wade, K.E. Fullerton, J.S. Yoder, Surveillance for Waterborne Disease Outbreaks Associated with Drinking Water — United States, 2011–2012, Morbidity and Mortality Weekly Report, 64 (2015) 842–848.
[30] ECDC, Cryptosporidiosis, ECDC. Annual Epidemiological Report for 2017, European Centre for Disease Prevention and Control, Stockholm, 2019.
[31] ECDC, Legionnaires' Disease, ECDC. Annual Epidemiological Report for 2017, European Centre for Disease Prevention and Control, Stockholm, 2019.
[32] ECDC, Shiga Toxin/Verocytotoxin-Producing *Escherichia coli* (STEC/VTEC) Infection, ECDC. Annual Epidemiological Report for 2017, European Centre for Disease Prevention and Control, Stockholm, 2019.
[33] ECDC, Campylobacteriosis, ECDC. Annual Epidemiological Report for 2017, European Centre for Disease Prevention and Control, Stockholm, 2019.
[34] J.M.P. Vieira, A strategic approach for water safety plans implementation in Portugal, J. Water Health, 9 (2011) 107–116.
[35] M.J. Allen, R.W. Brecher, R. Copes, S.E. Hrudey, P. Payment, Turbidity and Microbial Risk in Drinking Water, The Minister of Health Province of British Columbia, 2008.
[36] C. Farrell, F. Hassard, B. Jefferson, T. Leziart, A. Nocker, P. Jarvis, Turbidity composition and the relationship with microbial attachment and UV inactivation efficacy, Sci. Total Environ., 624 (2018) 638–647.
[37] I. Douterelo, S. Husband, V. Loza, J. Boxall, Dynamics of biofilm regrowth in drinking water distribution systems, Appl. Environ. Microbiol., 82 (2016) 4155–4168.
[38] J. Schwartz, R. Levin, R. Goldstein, Drinking water turbidity and gastrointestinal illness in the elderly of Philadelphia, J. Epidemiol. Community Health, 54 (2000) 45–51.
[39] A.J. De Roos, P.L. Gurian, L.F. Robinson, A. Rai, I. Zakeri, M.C. Kondo, Review of epidemiological studies of drinking-water turbidity in relation to acute gastrointestinal illness, Environ. Health Perspect., 125 (2017) 086003.
[40] I. Zimoch, J. Paciej, Evaluation of turbidity impact on the microbiological quality of water with usage of Bayes' theorem, Desal. Water Treat., 134 (2018) 244–250.
[41] A.G. Mann, C.C. Tam, C.D. Higgins, L.C. Rodrigues, The association between drinking water turbidity and gastrointestinal illness: a systematic review, BMC Public Health, 256 (2007) 1–7.
[42] P. Beaudeau, A systematic review of the time series studies addressing the endemic risk of acute gastroenteritis according to drinking water operation conditions in urban areas of developed countries, Int. J. Environ. Res. Public Health, 867 (2018) 867, doi: 10.3390/ijerph15050867.
[43] www.higienawody.wsse.katowice.pl (access: 03.06.2019)
[44] SSI, Data from Silesian State Voivodeship Sanitary Inspector from 2016–2017 Years, State Sanitary Inspection, Katowice, 2019 (in Polish).
[45] Annexes to the Proposal for a Directive of the European Parliament and of the Council on the Quality of Water Intended for Human Consumption (Recast), COM (2017) 753/F1, Brussels, 2018.
[46] Council Directive 98/83/EC of 3 November 1998 on the Quality of Water Intended for Human Consumption, OJ L 330, 5.12.1998, pp. 32–54.
[47] Regulation of the Ministry of Health of 7 December 2017 on the Quality of Water Intended for Human Consumption, (J. Laws 2017, Item 2294, 2017.12.11) (in Polish).
[48] WHO, Guidelines for Drinking-Water Quality: Fourth Edition Incorporating First Addendum, World Health Organization, Switzerland, 2017, p. 132.