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Evaluation of turbidity impact on the microbiological quality of water with usage of Bayes' theorem

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ABSTRACT

Water treatment technologies applied today guarantee feeding the water supply network with water of quality which meets all requirements imposed on water intended for human consumption. However, at the stage of distribution, the phenomenon of microbiological water contamination is encountered and drinking of such water may pose a threat to health of the consumers. Therefore, the World Health Organisation recommends application of management of water supply systems according to the recommended procedures of the water safety plan. It covers identification of threats as well as risk assessment and management in the entire chain of supply from source to the consumer's tap. Water quality monitoring and testing constitute the corpus of operational actions allowing to control the safety of water supplies. Essential elements of this control are microbiological parameters, because this contamination may in a short time lead to a potential threat to health and even life of the consumers. For this reason, flexible rules and procedures of water quality monitoring are sought that will ensure safety of water supplies and will not generate significant service costs. In this paper, an attempt is made to assess the microbiological threat based on the results of turbidity tests using the Bayes' theorem on the example of water supply system providing water to the inhabitants of the Silesian agglomeration.

Keywords: Turbidity; Microbiological contamination; Risk assessment; Bayes' theorem; Water safety plans

1. Introduction

Many entities take part in the supply of safe water to the consumer, including: water suppliers, inspection and local authorities. Loss of safety is interpreted as the possibility of occurrence of an adverse event which may result in real threat to the human health and even life of the consumer. Analysis of operation of the water supply systems (WSS) exactly in the aspect of consumer's health, takes into account primarily its resistance to threats [1–6]. Intensive development of highly effective water treatment technologies allowed producing water of high quality, regardless of the dynamics of changes in the environment affecting raw water quality. The use of processes, such as coagulation, filtration, oxidation including ozonation, sorption on activated carbon or membrane filtration and disinfection using chlorine and UV, allows to produce and pump into the water distribution subsystem water that is microbiologically and chemically stable [7–18]. Currently, there are numerous research works conducted in the world aiming to improve the effectiveness of applied water treatment methods, while optimising the generated costs at the same time. The WSS operating issue, in particular in the scope of managing the work of vast distribution subsystems, is the common phenomenon of secondary water contamination. It may be caused by oversized pipes of the water supply network, resulting in decrease of the flow rate and water stagnation, increase of its temperature, translating into deterioration of

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the quality of tap water. Moreover, sudden pressure changes, poor technical condition of the distribution subsystem, corrosion, sediments as well as biofilm result in the change of the water quality in the water supply network [19–29].

Secondary water contamination results in exceeding the permissible concentration of physiochemical parameters that may affect health due to accumulation in human body. One of the examples is the build-up of lead in soft tissues, internal organs and bones. Lead or other heavy metals may be accumulated in the body for a longer period, causing long-term negative health effects. On the other hand, the microbiological water contamination may cause an acute reaction of the body, resulting in digestive system diseases [30]. The subject matter literature provides numerous examples of water-related diseases. EPA (Environmental Protection Agency) and the WBDOSS (Waterborne Disease ad Outbreak Surveillance System) expressly indicate in their reports that in the United States, in 2005–2006, in 14 states there were 20 disease cases confirmed to have their source in potable water. Of those, 12 were caused by bacteria, 3 by viruses, 2 by protozoa and just one by both bacteria and viruses. The probable cause for other disease was noroviruses [31]. These contaminations were the cause of illness of 612 people, as a result of which four deaths were recorded. Moreover according to CDC report for 2011–2012 [32], 431 cases of diseases were diagnosed, with 102 persons hospitalised and 14 dead. These diseases also had their source in water originating from collective supply systems.

Microbiological contamination of WSS may be caused by ineffective raw water treatment, injection of contaminated water to its distribution subsystem and by an effect of its secondary contamination [1,21,25,26,30,33]. The loss of microbiological water safety is a large threat to consumers. This is why the priority task for operators of such WSS is to identify the reasons behind microbiological contamination and undertake the fastest possibly actions to ensure microbiological water safety. Using effective water treatment and distribution technologies, as well as programs of water quality monitoring in the entire chain of supply from the catchment area to the consumer's tap influence improvement of public health. WHO guidelines [34] and revision of the Directive [35] introduce an option to build the system of monitoring the water quality based on risk analysis. This approach is compliant with Water Safety Plans or HACCP system. Such approach to management of water supply to the consumer poses a challenge to the world of science which is development of water microbiological contamination risk analysis methods based on alternative parameters of water quality allowing to undertake more effective actions that minimise the results of water contamination.

The goal of water safety plans (WSP) is widely understood protection of raw water against contamination, water treatment for the purpose of removal of the contamination and venture of actions in the water distribution subsystems for protection against secondary contamination. More and more countries employ the management of WSS based exactly on WSP. Water supply safety management is used in Canada [36], Germany [37], Portugal [38] or Iceland [39]. One of the WSP elements based on risk management may be dedicated to DSS (decision support system) using online measurements (e.g. turbidity, chlorine concentration, water flow), which aid the assessment of microbiological water safety. Results of these measurements allow making a quick decision regarding the correction of operational parameters of water treatment or need of water chlorination in the distribution subsystem. On-line monitoring of water quality together with risk analysis model, for example, risk matrix, event tree or conditional probability may pose the basis to development of algorithms that support decision making in WSP procedures. The reviewed literature confirms usage of analytical methods based on Bayes' theorem to perform water quality evaluation [40–45]. Analytical methods based on Bayes' theorem are applied to manage risk in WSS, to predict results of extreme events related to consumer heath safety [46–49], as well as being used in analysis systems in real time [50]. These methods are also used in analyses of contamination level in underground water resources [51].

The goal of this work is to use the Bayes' theorem to assess the microbiological water safety based on designated parametric value of turbidity. The presence of at least one of the following colony forming unit was assumed for the condition of microbiological contamination: *Escherichia coli*, enterococci and coliform bacteria. Choice of these indicative parameters was based on applicable provisions of the regulations of the Minister of Health in Poland [52].

2. Material and method

2.1. Study area

The data from 2016, obtained from water quality monitoring performed in the scope of internal control by the facility administrators and by the local competent body of State Sanitary Inspection (SSI) for the Silesian Voivodeship, were subject to analysis. It is the unit of the territorial self-government and the unit of administrative division of Poland with surface of 12,333.09 km^2, resided by ca. 4.6 million people. Silesian Voivodeship has the highest number of cities with 100 thousand citizens in Poland. In this region, in 2016, the collective water supply was implemented by 796 operators of local WSS and the Silesian Waterworks PLC (SWPLC) one of the largest water companies in Europe [51,52]. Operators of most of local WSS manage only the water distribution subsystem, while SWPLC takes water from surface and underground sources. Those water sources are located on the outskirts of the Silesian Voivodeship, several dozen kilometres from endpoint of water supply. Next, SWPLC operates highly efficient technological water treatment systems covering processes of coagulation, filtration, ozonation, sorption on activated carbon and disinfection with chlorine compounds.

The ongoing sanitary supervision of water quality in Silesian Voivodeship is conducted by 20 State District Sanitary Inspectors (SDSI) and Silesian State Voivodeship Sanitary Inspector. For the purposes of assessment of microbiological water safety, the voivodeship was divided according to the competence of the local SSI (Table 1).

2.2. Research model

In the research model of evaluation of microbiological quality condition, water turbidity and microbiological water quality were assumed as independent variables. The Bayes'

Table 1
Characteristics of the local SDSI in the Silesian Voivodeship

No.	State District Sanitary Inspectors	Number of residents	Area in km²	Number of WSS
1	SDSI in Bielsko-Biała	303,000	582.16	54
2	SDSI in Bytom	379,000	751.73	30
3	SDSI in Chorzow	159,000	46.82	1
4	SDSI in Cieszyn	245,000	730.2	42
5	SDSI in Częstochowa	404,000	1,679.1	62
6	SDSI in Dabrowa Gornicza	204,000	555.83	39
7	SDSI in Gliwice	464,000	877.67	31
8	SDSI in Jaworzno	93,000	152.2	4
9	SDSI in Katowice	455,000	255.79	5
10	SDSI in Kłobuck	84,000	889.15	30
11	SDSI in Lubliniec	72,000	822.13	32
12	SDSI in Myszkow	69,000	478.62	33
13	SDSI in Raciborz	162,000	543.98	19
14	SDSI in Ruda Śląska	161,000	77.59	1
15	SDSI in Rybnik	303,000	437.53	19
16	SDSI in Sosnowiec	207,000	91.26	2
17	SDSI in Tychy	338,000	943.29	36
18	SDSI in Wodzisław Slaski	229,000	372.36	16
19	SDSI in Zawiercie	122,000	1,003.27	60
20	SDSI in Żywiec	85,000	1,039.96	280

theorem was applied in the proposed methodology of assessment of microbiological water quality. The Bayes' conditional probability of event *A* under the condition of occurring of event *B* is determined by the following formula:

$$P(A|B) = \frac{P(B|A)}{P(B)} P(A) \tag{1}$$

where $P(A|B)$ is a conditional probability (Bayes' law): the likelihood of event *A* given event *B* is true; $P(B|A)$ is a conditional probability: the likelihood of event *B* given event *A* is true; P(*A*), P(*B*) are probability of *A* and *B*, respectively.

In WSS, two states of microbiological quality of water can be distinguished:

1. State one (S1) is the state of microbiological water quality compliant with parametric value defined in applicable legislative requirements [52],
2. State two (S2) is the state of microbiological contamination defined by the presence of at least one colony forming unit of the following microorganisms: *Escherichia coli*, enterococci and coliform bacteria.

The choice of these parameters was based on the provisions of the Polish regulation of the Minister of Health [52]. In Poland, the official control authority issuing the administrative decision ordering both shutdown of water supply to the consumers and immediate disinfection of pipe network in case of identification of presence of at least one of these microbiological parameters. In such situations, it is impossible to perform a full identification of causes of microbiological contamination and assess the real health risk of the water consumer. Repeated incidental exceedance of indicator parameters which are coliform bacteria does not pose a risk to expose the population to the potential health effects. On the other hand, the administrative effect of the decision of shutdown of water supply is the costs of alternative water supply. Abovementioned decision also results in decrease of consumer's trust in the health safety of water and quality of services provided by the water supply companies.

Key elements in proposed methodology of estimating the microbiological safety of water are as follows:

Step 1: Divide the study area into separate *i*th zones according to defined criteria, for example: division based on water supply zones, or based on the administrative division of the official control by the State Sanitary Inspectorate authorities or any controlling authority;
Step 2: Determination of the limit values (LV) for the water turbidity as a threshold value specifying the state of microbiological safety of water (S1);
Step 3: To determine the Bayes' conditional probability of occurrence of the state of microbiologically clean water for the turbidity value below LV for each separated *i*th study areas;
Step 4: Determination of the acceptable level of turbidity as the global decision variable (DV).

Essential step of the developed assessment methodology is to indicate the LV for the water turbidity as a threshold value specifying the state of microbiological safety of water (S1). In order to determine the LV of the water turbidity, a set of random variables from a given research period was evaluated for conformity of turbidity distribution in the population with normal distribution using the Kolmogorov–Smirnov (K–S) test (level of significance $\alpha = 0.01$) and χ^2 (level of significance $\alpha = 0.05$). In case of adopting the hypothesis H_0 about conformity of turbidity distribution with normal distribution, the limit value of water turbidity LV is defined with the mean μ and/or sum of the mean and standard deviation $\mu + \delta$. In case of rejection of the hypothesis H_0, the LV value of turbidity is defined based on median Me or third quartile Q3.

In the following step of the research procedure for the separated *i*th study areas, we determine the Bayes' conditional probability of occurrence of the state of microbiologically clean water for the turbidity value below LV according to the formula:

$$P(M_{S1}|T_j)_i = \frac{P(T_j|M_{S1})_i P(M_{S1})_i}{P(T_j)_i} \tag{2}$$

where $P(T_j|M_{S1})_i$ is the probability of occurrence of water of turbidity T_j lower than the limit value (T_j < LV) for the state one of the microbiologically clean water (S1), for *i*th study area; $P(T_j)_i$ is the probability of occurrence of water turbidity T_j lower than limit value in the entire set of random variable, for *i*th study area; $P(M_{S1})_i$ is the probability of occurrence of state one of the microbiologically clean water (S1), for *i*th study area.

In the research procedure, the probability of occurrence of turbidity lower than the limit value (T_j < LV) for state S1 is determined by the relationship:

$$P\left(T_j \middle| M_{S1}\right)_i = \frac{\left|T_j \cap M_{s1}\right|_i}{\left|M_{S1,i}\right|} \quad (3)$$

where $T_j \cap M_{S1}$ is the set of random variables for the water turbidity lower than the limit value LV and microbiologically clean one, for ith area of research; $M_{S1,i}$ is number of water samples for which the state S1 of microbiological water quality was detected, for ith study area; $|A|$ is the cardinality of a set A, number of elements in set A.

On the other hand, in the ith study area the probability value $P(T_j)_i$ of occurrence of water turbidity lower than limit value (T_j < LV) in the entire set of data is defined by the formula:

$$P\left(T_j\right)_i = \frac{T_{j,i}}{T_i} \quad (4)$$

where $T_{j,i}$ is size of the set of random variables in ith study area, for water samples of turbidity lower than the limit value; T_i is number of water samples in ith study area in which the turbidity was tested.

The probability of occurrence of state one S1 of microbiologically clean water $P(M_{S1})$ for the ith study area is determined by the following relationship:

$$P\left(M_{S1}\right)_i = \frac{M_{S1,i}}{M_i} \quad (5)$$

where $M_{S1,i}$ is defined above, M_i is number of water samples in which at least one microbiological parameter was tested for the ith study area.

Next, in order to determine the global decision variable DV for the entire study area the designated Bayes' probabilities set of data is used. For this set of data, the study of the distribution of the random variable is performed. The global decision variable DV is the basis to make a decision on the necessity to perform a microbiological test in the ith study area or to resign from it based on turbidity.

The Kolmogorov–Smirnov (K–S) test and χ^2 (level of significance $\alpha = 0.01$ for K–S test and $\alpha = 0.05$ for χ^2) is used to evaluate the conformity of distribution of the set of Bayes' probabilities random variables for state S1 of microbiological water quality for turbidity value lower than LV with normal distribution. If the data are normally distributed, the decisive variable DV shall be defined by an average value. In case of rejection of the null hypothesis, the value of DV, the median Me is determined. Designating the global value of DV allows defining the procedures of assessment of microbiological water quality based on online monitoring of turbidity in tap water as below:

Case 1: Water turbidity in the ith study area meets the requirement T_j < LV and Bayes' conditional probability of occurrence of the state of microbiologically clean water is higher than DV, then the operator may make the decision to resign from microbiological test of the water sample,

Case 2: Water turbidity in the ith study area is lower than LV and the Bayes' conditional probability meets the relationship $P(M_{S1} | T_j)_i \leq$ DV, in that case the operator should perform the microbiological tests of water quality for the purpose of minimisation of health threats for the water consumer.

3. Results and discussion

The set of turbidity (random variable) was subjected to statistical analysis (Table 2). As part of the statistical analysis of the set of random variables, an empiric cumulative distribution function of turbidity was determined (Fig. 1).

The verified set of turbidity, according to the research methodology, was subject to assessment of conformity of turbidity distribution with normal distribution by means of standard conformity Kolmogorov–Smirnov tests and χ^2. The results of tests ($p < \alpha$) for the adopted significance levels showed non-conformity of turbidity distribution with the normal distribution. Therefore, two limit values LV, defined both by median Me and by third quartile Q3, were adopted for the purpose of further analysis. On the basis of the LV value, the Bayes' conditional probability was determined for occurrence of the state S1 of microbiologically quality for the particular functioning areas of the State District Sanitary Inspectors in the Silesian Voivodeship (Table 3). Basic descriptive statistics was determined for the obtained set of random variables (Table 4).

Table 2
Basic descriptive statistics of water turbidity in the year 2016

N	9,988
Mean	0.39
Min	0.02
Max	7.7
Standard deviation	0.48
Q1	0.12
Me	0.27
Q3	0.5

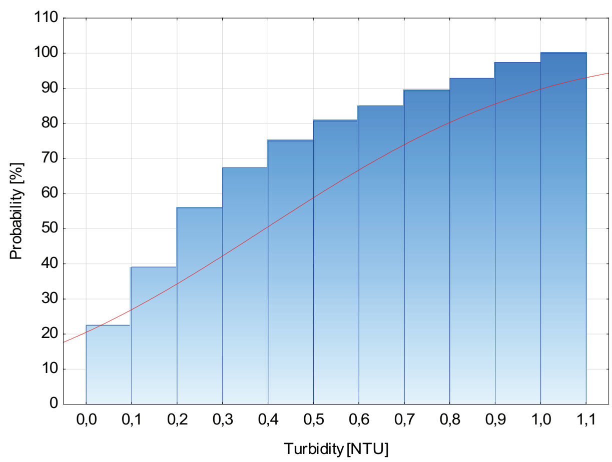

Fig. 1. Empiric cumulative distribution function of turbidity.

The conducted analysis showed clearly that the probability P(M_{S1} | T_j)$_i$ in the particular *i*th study areas is higher for the limit turbidity value determined by way of the median, that is, 0.27 [NTU]. For the limit value of the median, the highest values of the probability were observed for the areas of operation of the State District Sanitary Inspectorates in Bielsko-Biała and in Rybnik, and the lowest value – for the State District Sanitary Inspectorate in Kłobuck. Whereas, for the limit LV determined by Q3, the highest values of the analysed probability were observed for the area of the State District Sanitary Inspectorate in Chorzów and in Rybnik, and the lowest value for the State District Sanitary Inspectorate in Kłobuck. The conducted analysis confirmed the assumption that for lower limit values of turbidity as a substitute parameter of microbiological safety assessment, the probability of occurrence of the first state (S1), that is, microbiological water quality conformity with the governing legislative requirements, increases.

In the next step of the analysis, the Bayes' conditional probability set, which was obtained for the particular *i*th study areas, was subject to analysis of conformity with normal distribution for which obtained results of K–S and χ^2 tests showed non-conformity with the normal distribution. Therefore, the decision variable DV is defined by median value. Figs. 2 and 3 present the spatial distribution of the obtained results of the microbiological water quality analysis in WSS of the Silesian Voivodeship. Based on different adopted limit values of turbidity LV, there for two study areas were differences identified in the scope of the process of making a safe decision regarding the possibility of resigning of the making of the microbiological water quality test. For the State District Sanitary Inspectorate in Bielsko-Biała and in Sosnowiec, the relation between the Bayes' conditional probability P(M_{S1} | T_j)$_i$ and the value of the decision variable DV for LV < 0.27 NTU was the basis to make the decision on the possibility to resign from performance of the microbiological water quality test. Whereas, for LV defined at the level of 0.5 NTU, the obtained value P(M_{S1} | T_j)$_i$ has not been a basis to make such decision. These two cases confirm validity of application of the lower limit water turbidity value for assessment of microbiological water quality.

Table 3
Bayes' conditional probability for occurrence of the state S1 of microbiological quality in the Silesian Voivodeship of the year 2016

No.	State District Sanitary Inspectors	Probability $P(M_{S1} \mid T_j)_i$ for accepted limited value of turbidity	
		$T_j < 0.27$ NTU	$T_j < 0.5$ NTU
1	SDSI in Bielsko-Biała	0.997	0.940
2	SDSI in Bytom	0.942	0.938
3	SDSI in Chorzow	0.988	0.987
4	SDSI in Cieszyn	0.948	0.941
5	SDSI in Częstochowa	0.963	0.811
6	SDSI in Dabrowa Gornicza	0.948	0.914
7	SDSI in Gliwice	0.980	0.959
8	SDSI in Jaworzno	0.972	0.968
9	SDSI in Katowice	0.932	0.927
10	SDSI in Kłobuck	0.691	0.377
11	SDSI in Lubliniec	0.979	0.975
12	SDSI in Myszkow	0.939	0.922
13	SDSI in Raciborz	0.979	0.977
14	SDSI in Ruda Śląska	0.968	0.956
15	SDSI in Rybnik	0.996	0.985
16	SDSI in Sosnowiec	0.973	0.863
17	SDSI in Tychy	0.979	0.977
18	SDSI in Wodzisław Slaski	0.965	0.960
19	SDSI in Zawiercie	0.977	0.976
20	SDSI in Żywiec	0.969	0.961
21	WSS of Silesian Voivodeship – in total	0.969	0.944

Table 4
Descriptive statistics of conditional probability $P(M_{S1} \mid T_j)_i$ for the limit values of turbidity LV in the Silesian Voivodeship of 2016 year

LV NTU	N	Probability $P(M_{S1} \mid T_j)_i$ for T_j < LV						
		Mean	Min	Max	Standard deviation	Q1	M_e	Q3
0.27	20	0.954	0.691	0.997	0.063	0.948	0.970	0.979
0.5	20	0.917	0.377	0.987	0.131	0.927	0.958	0.975

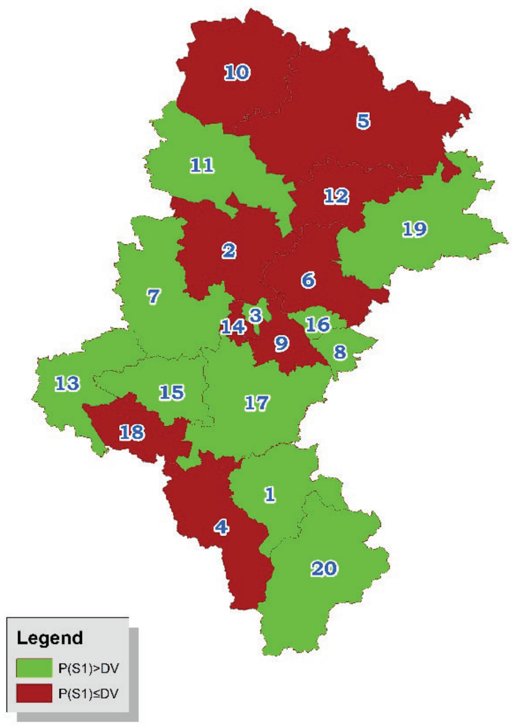

Fig. 2. Spatial distribution of the microbiological water quality in WSS of the Silesian Voivodeship for turbidity limit value of 0.27 NTU.

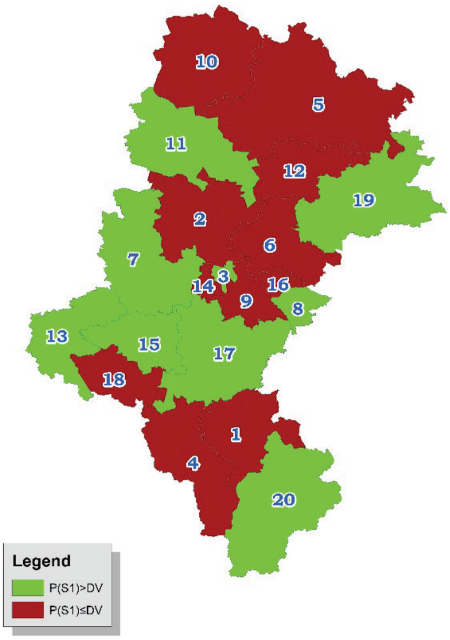

Fig. 3. Spatial distribution of the microbiological water quality in WSS of the Silesian Voivodeship for turbidity limit value of 0.5 NTU.

4. Summary and conclusions

The proposed analysed method allows for quick and effective assessment of the microbiological safety of water quality. One of the advantages of this method is the short time needed to obtain information. The test of turbidity can be performed by the sampling person at the time of water sampling. Therefore, the first information regarding microbiological water quality is obtained almost instantly. Further determination of turbidity of the same sample can be performed at a laboratory. In such case, having two random events, it is possible to estimate the microbiological water contamination based on, for instance Bayesian network. The proposed method can be a useful complement to microbiological monitoring of the tap water based on online water turbidity measurements. If the specified LV is exceeded, the operator, after obtained this information, can decide if it is necessary to carry out an additional microbiological test.

Furthermore, the operators, based on the knowledge gained while managing the WSS, can control water quality in a more effective manner. The data set obtained in the course of application of the research procedure is new information proving the effectiveness of the water treatment processes and potential changes in its distribution subsystem.

The proposed analysis methodology can be a useful tool in the risk management regarding safety of water supply to the consumer and can be fully exploited to WSS assessment and as an element of the decision-making support system.

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References

[1] N.J. Ashbolt, Microbial contamination of drinking water and human health from community water systems, Curr. Environ. Health Rep., 2 (2015) 95–106.
[2] G. Howard, S. Pedley, S. Tibatemwa, Quantitative microbial risk assessment to estimate health risk attributable to water supply: can the technique be applied in developing countries with limited data?, J. Water Health, 4 (2006) 49–65.
[3] A. Nowacka, M. Wlodarczyk-Makula, B. Tchorzewska-Cieslak, J. Rak, The ability to remove the priority PAHs from water during coagulation process including risk assessment, Desal. Wat. Treat., 57 (2016) 1297–1309.
[4] V. de Jesus Gaffney, C.M.M. Almeida, A. Rodrigues, E. Ferreira, M.J. Benoliel, V.V. Cardoso, Occurrence of pharmaceuticals in a water supply system and related human health risk assessment, Water Res., 72 (2015) 199–208.
[5] I. Zimoch, E. Łobos, Evaluation of health risk caused by chloroform in drinking water, Desal. Wat. Treat., 57 (2016) 1027–1033.
[6] E. Szymura, I. Zimoch, Operator reliability in risk assessment of industrial systems function, Przem. Chem., 93 (2014) 111–116 (in Polish).
[7] Md. Asrafuzzaman, A.N.M. Fakhruddin, Md. Alamgir Hossain, Reduction of turbidity of water using locally available natural coagulants, ISRN Microbiol., 2 (2011) 1–6.
[8] A. Bhatnagar, W. Hogland, M. Marques, M. Sillanpaa, An overview of the modification methods of activated carbon for its water treatment applications, Chem. Eng. J. (Amsterdam, Neth.), 219 (2013) 499–511.
[9] Ch. Comninellis, A. Kapalka, S. Malato, S.A. Parsons, I. Poulios, D. Mantzavinos, Perspective advanced oxidation processes for water treatment: advances and trends for R&D, J. Chem. Technol. Biotechnol., 83 (2008) 769–776.
[10] A. Hamamototo, M. Mori, A. Takahashi, M. Nakano, N. Wakikawa, M. Akutagawa, T. Ikehara, Y. Nakava, Y. Kinouchi, New water disinfection system using UVA light-emitting diodes, J. Appl. Microbiol., 103 (2007) 2291–2298.
[11] A. Ikhlaq, D.R. Brown, B. Kasprzyk-Horden, Catalytic ozonation for the removal of organic contaminants in water on alumina, Appl. Catal., B, 165 (2015) 408–418.
[12] J.C. Kruithof, R. Chr. van der Leer, W.A.M. Hijnen, Practical experiences with UV disinfection in the Netherlands, J. Water Supply: Res. Technol.-AQUA, 41 (1992) 88–94.
[13] A. Matilainen, M. Sillanpaa, Removal of natural organic matter from drinking water by advanced oxidation processes, Chemosphere, 80 (2010) 351–365.
[14] J. Nawrocki, Catalytic ozonation in water: Controversies and questions, Discussion paper, Appl. Catal., B, 142–143 (2013) 465–471.
[15] M.A. Oturan, J.J. Aaron, Advanced oxidation processes in water/wastewater treatment: principles and applications. A review, Crit. Rev. Environ. Sci. Technol., 44 (2014) 2577–2641.
[16] A.R. Ribeiro, O.C. Nunes, M.F.R. Pereira, A.M.T. Silva, An overview on the advanced oxidation processes applied for the treatment of water pollutants defined in the recently launched Directive 2013/39/EU, Environ. Int., 75 (2015) 33–51.
[17] T. Schwartz, S. Hoffmann, U. Obst, Formation of natural biofilms during chlorine dioxide and U.V. disinfection in a public drinking water distribution system, J. Appl. Microbiol., 95 (2003) 591–601.
[18] I. Zimoch, B. Kotlarczyk, A. Sołtysik, Use of prehydrolyzed coagulants for the enhancement of water treatment efficiency in the Czaniec Water Treatment Plant, Ochrona Środowiska, Environ. Protect., 29 (2007) 45–49 (in Polish).
[19] G. Liu, Y. Zhang, W.J. Knibbe, C. Feng, W. Liu, G. Medema, W. van der Meer, Potential impacts of changing supply-water quality on drinking water distribution: a review, Water Res., 116 (2017) 135–148.
[20] Lj. Zlatanovi, J.P. van der Hoek, J.H.G. Vreeburg, An experimental study on the influence of water stagnation and temperature change on water quality in a full-scale domestic drinking water system, Water Res., 123 (2017) 761–772.

[21] I. Douterelo, M. Jackson, C. Solomon, J. Boxall, Spatial and temporal analogies in microbial communities in natural drinking water biofilms, Sci. Total Environ., 581–582 (2017) 277–288.

[22] R. Renner, Pipe scales release hazardous metals into drinking water, Environ. Sci. Technol., 6 (2008) 4241.

[23] I. Zimoch, E. Łobos, The optimization of chlorine dose in water treatment process in order to reduce the formation of disinfection by-products, Desal. Wat. Treat., 52 (2014) 3719–3724.

[24] S.D. Richardson, M.J. Plewa, E.D. Wagner, R. Schoeny, D.M. DeMarini, Occurrence, genotoxicity, and carcinogenicity of regulated and emerging disinfection by-products in drinking water: a review and roadmap for research, Mutat. Res., 636 (2007) 178–242.

[25] M.J. Lehtola, I.T. Miettinena, M.M. Keinänena, T.K. Kekkia, O. Laineb, A. Hirvonenc, T. Vartiainenb, P.J. Martikainenc, Microbiology, chemistry and biofilm development in a pilot drinking water distribution system with copper and plastic pipes, Water Res., 38 (2004) 3769–3779.

[26] 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.

[27] T. Bond, J. Huang, M.R. Templeton, N. Graham, Occurrence and control of nitrogenous disinfection by-products in drinking water. A review, Water Res., 45 (2011) 4341–4354.

[28] I. Zimoch, Computer simulation as a tool assisting in the operation of water supply system, Ochrona Środowiska, Environ. Protect., 30 (2008) 31–35 (in Polish).

[29] M.S. Awopetu, A.O. Coker, J.O. Aribisala, S.O. Awopetu, Water quality in a pipe distribution network: a case study of a communal water distribution network in Ibadan, Nigeria, WIT Trans. Ecol. Environ., 171 (2013) 175–185.

[30] S.P. Luby, A.K. Halder, T.M. Huda, L. Unicomb, M.S. Islam, B.F. Arnold, R.B. Johnston, Microbiological contamination of drinking water associated with subsequent child diarrhea, Am. J. Trop. Med. Hyg., 93 (2015) 904–911.

[31] J.S. Yoder, V. Roberts, G.F. Craun, L. Hicks, N.T. Alexander, V. Radke, R.L. Calderon, M.C. Hlavsa, M.J. Beach, S.L. Roy, Surveillance for waterborne disease and outbreaks associated with drinking water and water not intended for drinking — United States, 2005–2006, MMWR Surveill. Summ., 57 (2008) 39–62.

[32] D.K. Beer, J.W. Gargano, V.A. Roberts, V.R. Hill, L.E. Garrison, P.K. Kutty, E.D. Hilborn, T.J. Wade, K.A. Fullerton, J.S. Yoder, Surveillance for waterborne disease outbreaks associated with drinking water — United States, 2011–2012, MMWR Morb. Mortal. Wkly. Rep., 64 (2015) 842–848.

[33] M. Exner, A. Kramer, L. Lajoie, J. Gebel, S. Engelhart, P. Haretman, Prevention and control of health care associated waterborne infections in health care facilities, Am. J. Infect. Control, 33 (2005) 26–40.

[34] Guidelines for Drinking-Water Quality, 4th ed., WHO, 2011.

[35] Commission Directive (EU) 2015/1787 of 6 October 2015 amending Annexes II and III to Council Directive 98/83/EC on the quality of water intended for human consumption, OJ L 260, 7.10.2015, pp. 6–17.

[36] E. Perrier, M. Kot, H. Castleden, G.A. Gagnon, Drinking water safety plans: barriers and bridges for small systems in Alberta, Canada, Water Policy, 16 (2014) 1140–1154.

[37] O. Schmoll, C. Castell-Exner, I. Chorus, From international developments to local practice: Germany's evaluation and dialogue process towards Water Safety Plan implementation, Water Sci. Technol., 11 (2011) 379–387.

[38] J.M. Vieira, A strategic approach for Water Safety Plans implementation in Portugal, J. Water Health, 9 (2011) 107–116.

[39] M.J. Gunnarsdottir, S. Gardarsson, M. Elliott, G. Sigmundsdottir, J. Bartram, Benefits of Water Safety Plans: Microbiology, Compliance, and Public Health, Environ. Sci. Technol., 46 (2012) 7782–7789.

[40] J.M. Bernardo, A.F.M. Smith, Baysian Theory, Wiley, Chichester, 1993.

[41] J. Rak, Selected problems of water supply safety, Environ. Prot. Eng., 35 (2009) 29–35.

[42] N. Fenton, M. Neil, Risk Assessment and Decision Analysis with Baysian Networks, CRC Press Taylor & Francis Group, Boca Raton, 2012.

[43] B. Tchórzewska-Cieślak, Bayesian model of urban water safety management, Global NEST J., 16 (2014) 667–675.

[44] W.E. Thompson, M.D. Springer, Bayes analysis of availability for a system consisting of several independent subsystems, IEEE Trans. Reliab., 21 (1972) 212–218.

[45] R. Aspinall, An inductive modelling procedure based on Bayes' theorem for analysis of pattern in spatial data, Int. J. Geogr. Inf. Sci., 6 (1992) 105–121.

[46] B.F. Hobbs, Baysian methods for analyzing climate change and water resource uncertainties, J. Environ. Manage., 49 (1997) 53–72.

[47] K. Shihab, N. Al-Chalabi, Bayesian Methods for Assessing Water Quality, Preceding Computer Science & Information Technology, 2014, pp. 397–407.

[48] M.M. Sahoo, K.C. Patra, J.B. Swain, K.K. Khatua, Evaluation of water quality with application of Bayes' rule and entropy weight method, Eur. J. Environ. Civil Eng., 21 (1017) 730–752.

[49] M.P. Weinstein, C. Bentivegna, M.P. Bovitz, Ch.R. Harman, R.A. Hoke, U. Howson, J. Kennen, Z. Qiu, Bayesian Inference: Application to Environmental Management and Decision-making. Draft Final Report, Scientific Advisory Board (SAB), New Jersey, 2013.

[50] W.J. Dawsey, B.S. Minsker, E. Amir, Real time assessment of drinking water systems using a dynamic Bayesian network, Proc. of the 2007 World Environ. Water Resour. Congress, ed. K.C. Kabbes, ASCE, Tampa 2007, pp. 184–192.

[51] K. Ammar, M. McKee, J. Kaluarachchi, Bayesian method for groundwater quality monitoring network analysis, J. Water Res. Plan. Manage., 133 (2011) 123–135.

[52] Regulation of the Polish Minister of Health of 7 December 2017 Amending the Regulation on the Quality of Water Intended for Human Consumption, J. Laws No 2017, Item 2294. Available from: http://dziennikustaw.gov.pl/du/2017/2294/1.