

SAFETY ANALYSIS OF TAP WATER BIOSTABILITY

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Abstract

The work concerns the analysis and assessment of the risk of biological stability of water. The consequence of the lack of water stability is an increased susceptibility of the distribution system to secondary microbial contamination of water and thus a threat to the health of consumers. The value of risk function is a measure of the loss of safety of water supply. The health of water consumers is a priority. From the point of view of the required quality of water intended for human consumption, the value of the risk function is related to failure to meet certain water quality parameters that may adversely affect physico-chemical parameters and the bacteriological quality of the water reaching the consumers. The paper presents the method of analysing and evaluating the risk of loss of biostability of tap water. The analysis was based on the operating data obtained from the water treatment plant.

Streszczenie

Praca dotyczy analizy i oceny ryzyka braku stabilności biologicznej wody. Skutkami braku stabilności wody jest zwiększona podatność w systemie dystrybucji na wtórne skażenie mikrobiologiczne wody, a więc zagrożenie zdrowia konsumentów. Wartość funkcji ryzyka jest miarą utraty bezpieczeństwa dostaw wody. Priorytetem jest bezpieczeństwo zdrowotne konsumentów wody. Z punktu widzenia wymaganej jakości wody przeznaczonej do spożycia przez ludzi wartość funkcji ryzyka związana jest z niedotrzymaniem określanych parametrów jakości wody, które mogą mieć negatywny wpływ na parametry fizyko-chemiczne i jakość bakteriologiczną wody docierającej do konsumenta. W pracy przedstawiono metodę analizy i oceny ryzyka utraty biostabilności wody wodociągowej. Analiza została wykonana na podstawie uzyskanych danych eksploatacyjnych ze stacji uzdatniania wody.

Keywords: Biofilm; Biological stability of water; Risk; Water supply system; Water quality assessment.

1. INTRODUCTION

The primary and basic subject which the concept of water safety concerns is the consumer. A measure of safety in relation to water consumers is risk, defined as the probability of undesirable event occurrence (cause), whose consequence may be a real threat to the lives or health of water consumers (effect).

When analysing the functioning of the water distribution subsystem (WDS) in terms of the protection of water consumers mainly the resistance of system to various types of threats (undesirable events) that may occur in the subsystem is taken into account [1–4]. The consequence of these events may be break in water supply (e.g. due to the failure of mains) or the so called secondary water pollution in the water supply network. Hydraulic conditions in the WDS influence changes in the physicochemical and bacteriological water composition. The important problem that arises in many urban water supply systems is also the significant pipes oversizing which results in a decrease in the flow velocity of water and, consequently, in unfavourable flow conditions that cause deterioration of water quality in the water supply network.

Types of the secondary water contamination in the water supply system are [4–6]: chemical contamination (most often corrosion products of iron and steel) and microbiological contamination. The main factors causing the secondary water contamination in the water supply network include, among others, type of material from which the pipes are made, significant changes in flow velocity, low flow velocity, rapid pressure changes resulting in local negative pressure, poor technical and sanitary conditions, corrosion caused by water aggression, improper choice of treatment resulting in water stability in the network, the residue of large doses of unused disinfectant in the water supply network, the presence of biochemical processes in the network, repairs of the network, exchange of pipelines and fittings, direct connection of household and industrial equipment to the network [5–7].

The main objective of the paper is to present a methodology for analysing and assessing the risk of biological stability in terms of the water consumers safety.

2. RESEARCH METHODOLOGY

2.1. Water biostability

In water distribution systems more than 95% of the

microorganisms is on the internal surfaces of water pipes in the form of biofilm. Biofilm is a group of microorganisms that are linked by trophic dependence from autotrophic and heterotrophic bacteria and fungal toxins and their parallel developing consumers, such as flagellates, ciliates, and creepers [8–10]. Bio-stable water is considered to be non-microbial and does not sustain the growth of microorganisms in the water supply network. The epidemiological risk caused by the presence of biological membrane in the water supply network is related both to the quality and type of water taken by the water treatment plants and to the efficiency of treatment and disinfection processes [11–14].

Based on the conducted studies, it was found that the intensity of microorganisms growth in the water supply network is mainly determined by the presence of organic compounds, in particular biodegradable dissolved organic carbon (BDOC) and assimilable organic carbon (AOC). The values of these parameters indicate the content of nutrients that can be easily assimilated by water-borne microorganisms. The AOC concentration in the water entering the network is usually 0.1–9% of dissolved organic carbon (DOC) and about 15–25% of biodegradable dissolved organic carbon (BDOC) [5]. The conventional water purification system based on coagulation, sedimentation, filtration and disinfection eliminates the AOC fraction in less than 30% and total organic carbon (TOC) in 22%, while the system extended with an additional biofiltration by activated carbon deposit removes these fractions up to 60 and even 74% [15–20].

For the risk analysis and assessment, the following threshold values for the biological stability parameters of water were adopted: $BDOC < 0.25 \text{ gC/m}^3$, $\sum N_{\text{inorganic}} < 0.2 \text{ gN/m}^3$, $PO_4^{3-} < 0.03 \text{ gPO}_4^{3-}/\text{m}^3$, according to the methodology described by Wolska [5].

2.2. Method of risk analysis and assessment of lack of water biological stability in the water supply network

The risk of failure of not meeting certain (required) water quality parameters in the water supply network that may adversely affect the physicochemical parameters and the bacteriological quality of the water reaching the consumer is a measure of lack of biostability [22]. The purpose of risk analysis is to determine risk value using the appropriate method. The value of the risk of biological instability of water in the water supply network describes the so-called risk

function $f(r)$, defined as the expected value of losses under certain system operating conditions that influence the system's vulnerability (resistance) to threat [3, 23]. In the risk analysis, the priority is to identify potential threats. Risk assessment is a comparison of the obtained risk value with the assumed criteria values.

For the analysis of the risk of loss of water biological stability, the following risk definition was adopted:

$$r = E(C \geq C_{gr}) \tag{1}$$

where $E(C \geq C_{gr})$ – the expected value of losses C greater than the accepted limit losses C_{gr} .

and:

$$C_{gr} = f(S_1, S_2, S_3) \tag{2}$$

where S_1 is the criterion corresponding to the content of BDOC, gC/m^3 , S_2 is the criterion corresponding to inorganic content $\sum N_{inorganic}$, gN/m^3 , S_3 is the criterion corresponding to PO_4^{3-} , gPO_4^{3-}/m^3 .

The limit values were proposed for the probability of exceeding the parameters BDOC, $\sum N_{inorganic}$ and PO_4^{3-} based on the criteria contained in the work [5]. The following threshold values for the biological sta-

bility parameters were adopted for the risk analysis and assessment: $BDOC < 0.25 gC/m^3$, $\sum N_{inorganic} < 0.2 gN/m^3$, $PO_4^{3-} < 0.03 gPO_4^{3-}/m^3$.

Assuming that P_S is the probability of not exceeding the water quality parameters (BDOC, $\sum N_{inorganic}$ and PO_4^{3-}), P_i is the probability of not exceeding the water quality parameters (BDOC, $\sum N_{inorganic}$ and PO_4^{3-}) in a given water sample, P_p is the probability of exceeding the water quality parameters (BDOC, $\sum N_{inorganic}$ and PO_4^{3-}) and P_{pi} is the probability of exceeding the water quality parameters (BDOC, $\sum N_{inorganic}$ and PO_4^{3-}) in a given water sample.

where:

$$P_S = \sum_{i \in E^+} P_i \tag{4}$$

$$P_i = \prod_{j=1}^M P_{i0} \cdot (1 - P_{i0}) \tag{5}$$

$$P_p = \sum_{i \in E^-} P_{pi} \tag{6}$$

Table 1 presents the criteria for the probability of exceeding BDOC, $\sum N_{inorganic}$ and PO_4^{3-} parameters,

Table 1.

Summary of the criteria for probability of exceeding the parameters BDOC, $\sum N_{inorganic}$ and PO_4^{3-}

Explanations	PBDOC	$P\sum N_{inorganic}$	PPO_4^{3-}	E(C)
Tolerable risk (R_T) $\rightarrow C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC < 0.25 gC/m^3) \wedge (S_2 = \sum N_{inorganic} < 0.2 gN/m^3) \wedge (S_3 = PO_4^{3-} < 0.03 gPO_4^{3-}/m^3)$				
R_T	0.417	0.841	0.99	0.34719
Controlled risk (R_{CI}) $\rightarrow C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC < 0.25 gC/m^3) \wedge (S_2 = \sum N_{inorganic} < 0.2 gN/m^3) \wedge (S_3 = PO_4^{3-} \geq 0.03 gPO_4^{3-}/m^3)$				
R_{CI}	0.417	0.841	0.01	0.00350
Controlled risk (R_{CII}) $\rightarrow C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC < 0.25 gC/m^3) \wedge (S_2 = \sum N_{inorganic} \geq 0.2 gN/m^3) \wedge (S_3 = PO_4^{3-} < 0.03 gPO_4^{3-}/m^3)$				
R_{CII}	0.417	0.159	0.99	0.06564
Controlled risk (R_{CIII}) $\rightarrow C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC \geq 0.25 gC/m^3) \wedge (S_2 = \sum N_{inorganic} < 0.2 gN/m^3) \wedge (S_3 = PO_4^{3-} < 0.03 gPO_4^{3-}/m^3)$				
R_{CIII}	0.583	0.841	0.99	0.48540
			$\sum R_{CI-III}$	0.55454
Controlled risk (R_{CIV}) $\rightarrow C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC \geq 0.25 gC/m^3) \wedge (S_2 = \sum N_{inorganic} \geq 0.2 gN/m^3) \wedge (S_3 = PO_4^{3-} < 0.03 gPO_4^{3-}/m^3)$				
R_{CIV}	0.583	0.159	0.99	0.09177
Controlled risk (R_{CV}) $\rightarrow C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC \geq 0.25 gC/m^3) \wedge (S_2 = \sum N_{inorganic} < 0.2 gN/m^3) \wedge (S_3 = PO_4^{3-} \geq 0.03 gPO_4^{3-}/m^3)$				
R_{CV}	0.583	0.841	0.01	0.00490
Controlled risk (R_{CVI}) $\rightarrow C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC < 0.25 gC/m^3) \wedge (S_2 = \sum N_{inorganic} \geq 0.2 gN/m^3) \wedge (S_3 = PO_4^{3-} \geq 0.03 gPO_4^{3-}/m^3)$				
R_{CVI}	0.417	0.159	0.01	0.00066
			$\sum R_{CIV-VI}$	0.09734
Unacceptable risk (R_{una}) $\rightarrow C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC \geq 0.25 gC/m^3) \wedge (S_2 = \sum N_{inorganic} \geq 0.2 gN/m^3) \wedge (S_3 = PO_4^{3-} \geq 0.03 gPO_4^{3-}/m^3)$				
R_{una}	0.583	0.159	0.01	0.00093

based on the formulas 4-6 and the work [5].

In addition, the controlled risk should be adopted if one of the six criteria is met. For risk analysis, the following values of limit losses $E(C < C_{gr})$, related to maintaining the biological stability of tap water, were assumed:

- tolerable risk (R_T) – water is biologically stable with the criteria presented in Table 1. The expected value $E(C < C_{gr})$ is expressed by the probability $P_{RT} = 0.34719$,
- controlled risk (R_C) – there are premises for maintaining the biological stability of water if the parameters shown in Table 1 are maintained. The expected value $E(C < C_{gr})$ with the probability for conditions I-III is $P_{RCI-III} = 0.55454$, for the rest conditions $P_{RCIV-VI} = 0.09734$,
- unacceptable risk (R_{una}) – water is biologically unstable at the parameters shown in Table 1. The expected value $E(C < C_{gr})$ with the probability $P_{una} = 0.00093$.

The parameters defining the tolerable risk area indicate that the parameters of water provide the required biological stability in the water supply network (acceptable safety level (SLT)), whereas the controlled risk means that the water quality parameters indicate the possibility of changes in the chemical stability of water in the water supply network (safety level which requires control and reduction of (SL_C)). The unacceptable risk means the occurrence of such water quality parameters that cause biological instability of water in the water supply network, which may result in the secondary contamination (unacceptable safety level (SL_{UNA})).

3. ANALYSIS OF THE SELECTED WATER DISTRIBUTION SYSTEM

3.1. Characteristics of the research object

The analysis of the underground water treatment system is performed for the city of 80 thousand inhabitants. Water devices for the water intake are SI pumps consisting of 5 drilling wells ($Q_{\max} 183 \text{ m}^3/\text{h}$) and SII consisting of 22 drilling wells ($Q_{\max} = 715 \text{ m}^3/\text{h}$). The designed maximum capacity of the water treatment plant (WTP) is $715 \text{ m}^3/\text{h}$. The annual average, for example in 2012/2013, was about $265 \text{ m}^3/\text{h}$.

The treated water is discharged from the clean water tank to the two water mains through 3 pumps. Two of them have a capacity of $440 \text{ m}^3/\text{h}$ and the third one the capacity of $280 \text{ m}^3/\text{h}$. Their lifting capacity is 58 m. The city's water supply network consists of the 16.8 km main network, 176.6 km of the distributional network. The household connections network consists of 3958 connections and has length of 98.40 km. Approximately 42.70% of the entire water supply network is made of pipes less than 20 years old but more than 11 years old. 90.2 km of the network is made of materials less than 10 years old.

The intake water does not meet sanitary requirements in terms of turbidity, colour, permanganate index, ammonium, iron and manganese. The physicochemical composition of the intake water indicates that there may be difficulties in its treatment. The physical and chemical parameters of the intake water were presented in Table 2.

The intake water is directed to the collection well (stop time 2-4 hours, depending on the current water

Table 2.
The physical and chemical parameters of the intake water

Parameter	Turbidity	Colour Hazen	Permanganate index	Ammonium ion	Iron	Manganese	TOC	Total hardness	Sulfates
Value	8-14 NTU	40-100	11.0-18.1 mg O ₂ /dm ³	1.2-1.98 mg NH ⁴⁺ /dm ³	14.0-44.0 mg Fe/dm ³	0.74-2.58 mg Mn/dm ³	14-20 mg C/dm ³	4.0-9.4 mval/dm ³	60-240 mg SO ₄ ²⁻ /dm ³

Table 3.
The physicochemical parameters were determined according to the applicable research procedures

Parameter	Research procedures	Guidelines of procedure
ammonium nitrogen	direct nesslerization method	PN-C-04576-4:1994P
nitric nitrogen (III)	colorimetric method with 4-diazobenzenesulfonic acid	PN-EN26777:1999
nitrate nitrogen (V)	colorimetric method with sodium salicylate	PN/C-04576.08
phosphates	spectrometric method with ammonium molybdate	PN-EN ISO 6878
TOC	TOC analyzer Sievers 5310	C/PN - EN 1484:1999
BDOC	the modified Kaplan and Newbold method	[21]

production). Then the water is directed to the oxygenation cascade. Just beneath the cascade lies the dosage of chemical oxidant – potassium permanganate and coagulant PAX-18. The next step in water treatment are vertical coagulatory and sedimentation chambers with a contact time of 6-8 hours. The water after the chambers, which is directed to the horizontal settlers, is dosed with calcium milk to raise the pH. The settling time in the settlers is several hours. The next step is the filtration of water in the filters at a rate of 1.5–3 m/h and the final step – disinfection with sodium hypochlorite.

3.2. Methodology of determination of physicochemical parameters of the treated water

Samples of water were taken twice a month from November 2015 to November 2016. The treated water was taken from the clean water tank prior to the final disinfection process. The modified Kaplan and Newbold method was used to determine the BDOC content by using for this purpose colonized by autochthonous bacteria bioreactor with granular activated carbon.

The physicochemical parameters were determined according to the applicable research procedures presented in Table 3.

3.3. Risk analysis and assessment

The existing water treatment station very effectively removes iron and manganese. In the treated water there are traces of these impurities. On the other hand, the colour parameter is maintained at 10-15 Hazen, with an acceptable Hazen value of 15. In the discussed example the colour was affected by organic substances - the content of TOC in the treated water was 7–12 mg C/dm³, exceeding the value recommended by the WHO – 5 mg C/dm³. Other parameters of the treated water are as follows: BDOC 2.27–11.20 g/m³, $\Sigma N_{inorganic}$ 0.16–1.20 g/m³ and PO₄³⁻ 0–0.007 g/m³. The detailed analysis of BDOC, $N_{inorganic}$ and PO₄³⁻ parameters was performed to analyse the risk of lack of biological stability.

Figure 1 shows the parameters of the treated water and the safety criteria established in Table 1.

All tested samples are in the range of controlled risk (R_C).

Of the 22 tested water samples 21 corresponds to variant IV of controlled risk (R_C):

$$IV. C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC \geq 0.25 \text{ gC/m}^3) \wedge$$

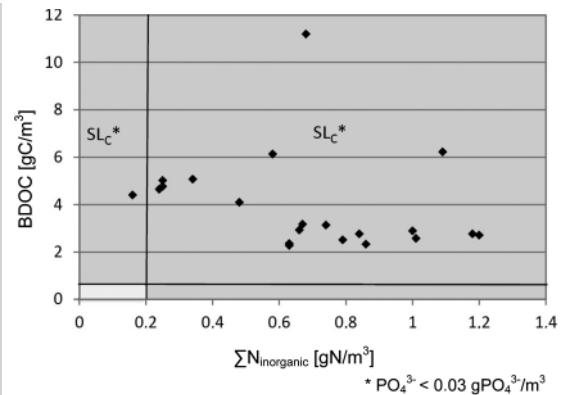


Figure 1. Criteria for determining the individual safety levels taking into account the parameters of the treated water

$$(S_2 = \Sigma N_{inorganic} \geq 0.2 \text{ gN/m}^3) \wedge (S_3 = PO_4^{3-} < 0.03 \text{ gPO}_4^{3-}/\text{m}^3)$$

One sample of water corresponds to variant III of controlled risk (R_C):

$$III. C_{gr} = f(S_1, S_2, S_3) = (S_1 = BDOC \geq 0.25 \text{ gC/m}^3) \wedge (S_2 = \Sigma N_{inorganic} < 0.2 \text{ gN/m}^3) \wedge (S_3 = PO_4^{3-} < 0.03 \text{ gPO}_4^{3-}/\text{m}^3)$$

The controlled risk level (R_C) means that the nature of the water samples determined by BDOC, $\Sigma N_{inorganic}$ and PO₄³⁻ corresponds to a safety level that requires control and reduction (SL_C).

4. CONCLUSIONS

Conventional water purification processes i.e. coagulation, sedimentation, filtration and disinfection do not provide effective elimination of biogenic substances and, in particular, BDOC and inorganic nitrogen. Because of the insufficient degree of nutrient removal it is necessary to include to conventional water treatment systems the additional unit processes or to optimize the existing ones. For the considered technological variant the treated water corresponds to a safety level which requires control and reduction (SL_C) to a level where there are the premises of maintaining the biological water stability. In case of the tolerable risk, the further monitoring and the maintenance of the current level of drinking water quality are recommended. The controlled risk indicates the need for correction in the water treatment process. In case of receiving the unacceptable level of risk, it is recommended to supplement the technological process, e.g. by using the biofiltration process.

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