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Research Article

FACTORS AFFECTING WATER QUALITY IN A WATER SUPPLY NETWORK

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ABSTRACT
An effect of factors determining water quality in the water supply network in Kraków is assessed. The data collected over a four-year research period included quality parameters of water taken from the water distribution system in the period between 1 January 2011 and 31 December 2014. In the analysis the supply zones of four municipal water treatment plants in Krakow were considered. The selection of 29 water sampling points within the supply area allowed comparing water quality with respect to operational and technological aspects. Factor analysis enabled 4 components explaining correlations between tap water quality variables to be distinguished. It follows from the research performed that the obtained factors applied to 77% of overall water variability. The highest share was assigned to factor 1 that explained 32% of the chemical composition of water under consideration and was correlated with calcium, conductance, nitrates (V), magnesium and to a moderate extent with ∑ THM (with negative sign).

Keywords: factor analysis, secondary contamination of water, water supply network, water quality

INTRODUCTION

In water distribution systems both physicochemical and microbiological indices can change. There are a lot of factors that have an effect on secondary contamination of water that can be supplied to consumers. The type and intensity of processes occurring within water supply systems decide on the form of contamination (suspended, colloidal or dissolved). However, the type of concentration of contaminants penetrating into water depend on the amount and chemical composition of deposits in a water supply system, the number and kind of microorganisms living in biofilms, microbial metabolic pathways, biochemical processes and stability of flowing water [Kowal and Świderska-Bróż 2009, Pierścieniak 2009].

Chemical and microbiological stability of water in distribution systems is affected by the raw water quality [Jachimowski 2016] and reliability of treatment processes. Therefore, the main problem of all water supply systems is the loss of water stability during the transmission from water treatment plant to customer [Łomotowski 2007, Kowal and Świderska-Bróż 2009].

Water is considered as chemically stable when it does not cause the precipitation of deposits, mainly calcium carbonate ($CaCO_3$) [Świderska-Bróż and Wolska 2006, Biłozor et al. 2010]. The main indicators of contamination for chemically unstable water in the water distribution system are total iron and related turbidity, colour and the use of free chlorine [Świderska-Bróż i Wolska 2005]. However, biologically stable water does not support microbial growth. This is connected with the lack of organic and inorganic nutrients enabling microbial growth [Świderska-Bróż 2003, Świderska-Bróż and Wolska 2006, Kowal and Świderska-Bróż 2009, Biłozor et al. 2010].

Secondary bacterial growth in the water supply system imposes high doses of disinfection agents to be used to inhibit microbial growth. This is why the kind and concentration of disinfectant used depend on the number of microorganisms and their resistance to a specified agent, pipeline material and deposits that use disinfectant [Kowal, Świderska-Bróż 2009]. Water supply tubing is an ideal habitat both for heterotrophic and autotrophic bacteria. However, the development of biofilm depends on the quality of water flowing through the pipe network. The presence of assimilable organic carbon in water is a factor limiting the growth of heterotrophic microorganisms [Łomotowski 2007].

During the transmission of water in water supply networks a deterioration of its taste and odour and increased colour and turbidity indices are often observed. There is also a risk of an increase in the number of indicator bacteria. In addition, in water disinfected with chlorine or chlorine dioxide the amount of disinfection by-products increases. Also, iron and manganese concentrations increase and water pH, hardness and alkalinity change [Łomotowski 2007, Bergel et al. 2013].

The aim of this paper is to determine an effect of some factors on water quality in the distribution system of the Water Treatment Plants at the Municipal Water Supply and Sewerage Plant in Kraków.

Application of factor analysis to identify the origin of chemical composition of water intended for human consumption is presented. This is a complex problem as water production is based on 4 water treatment plants (Raba, Rudawa, Dłubnia and Bielany) that use surface waters as a source of drinking water, except for one deep water intake. The analysis made in the years 2011 to 2014 pertained to selected physicochemical parameters determined in selected points of the water supply network.

SECONDARY CONTAMINATION OF WATER IN DISTRIBUTION SYSTEM

The cause of deteriorating water quality may be sediments which build up on the inside of pipelines. The research performed has shown that iron sediments may occur inside water supply pipelines at iron concentration of 0.05 $mg \cdot dm^{-3}$. This leads to an increase in iron concentration despite of good water chemical composition when pumping water into the network. This is caused by picking off sediments due to changes in water flow direction or rate in water distribution network and iron penetration into water by its dissolution. It has been demonstrated that in the latter case an appropriate oxygenation can inhibit the diffusion of Fe(II) from the sediment into tap water [Weber 2010].

The quality of the treated water depends, to a large extent, on factors related to technical condition and the age of the water supply network [Gamrot et. al. 2001, Bergel 2012]. Pipe age that decides on failure rate is of special importance. A long period of use significantly accelerates the wear of pipe materials [Bergel et. al. 2013]. This increases the risk of water supply system failure [Tchórzowska-Cieślak 2010, Kwietniewski 2011, Rak and Tchórzowska-Cieślak 2013]. Hydraulic conditions in the water supply network (flow velocity, water pressure and too long water age as well as water supply outages have an important effect on the quality of water delivered to consumers [Świderska-Bróż and Wolska 2006].

One of the factors causing the deterioration of water supplied to customers is corrosion processes in outdoor and indoor water pipes. Corrosion is enhanced by the presence of aggressive carbon dioxide in water that deteriorates the passive films (oxide coatings). Corrosion rate is affected not only by water pipeline materials but also by physicochemical composition of water. The effect of corrosion is the deterioration of water supply network materials and enrichment of water delivered to customers with dissolved forms of metals. Therefore, the quality of water delivered to consumers depends primarily on processes that occur in the water distribution system. The water corrosivity index plays an important role in these processes [Januszewska et al. 2011].

Biofilms may be formed on the inner walls of water supply pipelines. They may increase the risk of microbiological contamination of water. As follows from the research carried out, the strongest water quality changes related to corrosion and biofilms will occur in indoor water supply systems of small diameter pipes.

In the water disinfection process chlorine water or chlorine dioxide solutions are used. Some water supply plants use sodium hypochlorite.

The process of disinfectant decay in water involves two stages. The first stage occurs directly after the disinfectant is put into water and lasts from a few minutes to several hours depending on water composition and temperature. The rate of disinfectant decay is affected by its relations with organic and mineral compounds susceptible to oxidation [Łomotowski 2007]. At the second stage the rate of chlorine decay in water is characterized by a first-order reaction (first-order kinetics) [Haas and Karra 1984, Kiéné and Lévi 1998].

The key task of collective water supply systems is to provide inhabitants with healthy water [Act of 7 June 2001]. However, this objective is not always achieved. This is observed in deteriorating water quality in distribution systems for many years. There are various causes of secondary contamination of water delivered to customers. They may occur individually or coexist and interact, thus deteriorating the quality of water transferred in distribution systems. The thorough analysis allowed identification of the crucial factors involved. When classifying them the full range of causes of secondary contamination in the network was considered and the factors of especially strong influence on water quality (according to its severity) were highlighted [Kwietniewski et. al. 2012]. When considering the above assumptions the following division has been proposed, as presented in Table 1.

The factors listed above do not always affect individually the quality of water transferred in the network. A single factor may often cause changes in water quality in various areas of influence [Kwietniewski et. al. 2012].

However, Bergel and other researchers divide the factors affecting tap water quality into two categories: external and internal ones. The external ones include water contamination during failures and its resolving, expanding the pipelines and operation and repairs. The inner ones include sediment accumulation in pipes, sediment loosening, pipe corrosion, chemical reactions in water, microbial growth on pipe walls and biological contamination (the so called biofilm) [Świderska-Bróż and Wolska 2007, Bergel et. al. 2009].

RESEARCH METHODOLOGY

The object of this study was to perform statistical analysis of laboratory water test results in the distribution network in Kraków. The determination of tap water physicochemical parameters was carried out in the years 2011 – 2014. Test samples were taken at a specified point of the network on average every three months every year (Table 2). The mean values were computed from the results obtained over an 8-year period. The results of determination were made available from the Central Laboratory of the MPWiK S.A. of Kraków [Central Laboratory MPWiK S.A. 2015], and selected indices were determined according to the research method register [Central Laboratory MPWIK S.A. 2013].

The samples of treated water for laboratory testing were taken at points located in various Kraków districts. There were primarily public facilities such as schools, kindergartens, shops, petrol stations and offices.

The basic statistical parameters, i.e. mean, minimum and maximum values, standard deviation and coefficient of variation were calculated for selected tap water quality parameters.

To identify processes deciding on the chemistry of water taken and treated by the ZUW factor analysis, principal component method was used. This technique allows the variability of all water parameters under examination to be analysed simultaneously, and various sources of tap water contamination to be extracted as factors. Another possibility is to determine the percentage share of theses sources in forming water chemical composition [Modelska and Burzyński 2007].

Table 1. Factors causing secondary contamination in water supply networks

Factor classes	Examples of factors
Water-related factors	• Effectiveness of water treatment processes in water supply systems • Disinfection by-products • Lack of water biostability and consequential microbial growth • Lack of water biostability and resulting corrosivity and sediment accumulation
Factors connected with hydraulic conditions in the network	• Water flow velocity • Water ceasing to flow and stagnation in the network • Pressure variations
Operational factors	• Pipe age • Presence of sediments • Incrustation in pipelines • Network failure rate • Operational negligence
Factors related to pipe material and tightness	• Types of pipe material, sealing and protective coatings
Factors related to network structure	• Network spatial layout • Fire fighting requirements

Source: based on [Kwietniewski et. al. 2012]

Table 2. Water sampling points in the municipal water supply network in Kraków in the years 2011–2014

Item	Sampling point	Supply area	Item	Sampling point	Supply area
1	ul. Zarzecze 106 – fire department	ZUW Rudawa	16	ul. Kutrzeby 4 – NZOZ Kraków Południe (Central Laboratory)	ZUW Raba
2	ds. Sosnowa 8 – Sera and Vaccines Manufacturing Company		17	ul. Kosiarzy 1 – MPWiK – Sewage Treatment Plant	
3	ul. Stawowa 179 – school		18	Rynek Podgórski 1 – Kraków City Council	
4	ul. Tokarskiego 1 – DS "Akropol" (dormitory)		19	ul. Komandosów 1 – SM Podwawelska	
5	ul. Nałkowskiego 1 – health care centre		20	ul. Stoczniowców 7 – health care centre	
6	ul. Łokietka 177 – Energoprzem		21	ul. Kantorowicka 77 – bakery	ZUWDłubnia
7	ul. Poronińska 7 – Samorządowe Przedszkole nr 145	ZUW Raba	22	os. Złotej Jesieni 1 – WSS im. L. Rydygiera	
8	ul. Chałubińskiego 21 – sklep ogólnospożywczy „Olimp"		23	os. Górali 5 – Dom Kultury	
9	ul. Stojałowskiego 1 – petrol station		24	os. Na Skarpie 8 – szkoła	
10	ul. Cechowa 57 – school		25	ul. Mirowska 278 – RZGW	ZUW Bielany
11	ul. Babińskiego 29 – Krakowski Szpital Neuropsychiatryczny		26	ul. Astronautów 5 – sklep	
12	ul. Spółdzielców 3, Spółdzielnia Mieszkaniowa na Kozłówce,		27	ul. Kamedulska 70 – health care centre	
13	ul. Bieżanowska 40 – kindergarten		28	Tyniec, ul. Bolesława Śmiałego 7	
14	ul. Brożka 3 – M.P.K.		29	Las Wolski – ZOO	
15	ul. Gronostajowa 3 – kampus UJ				

The principal component analysis was used also to examine the water produced by 4 water treatment plants (Raba, Rudawa, Dłubnia and Bielany) that employ a highly advanced treatment technology [Adamczyk and Jachimowski 2014]. This is why only these parameters that had sufficient representations and showed diversification were used.

RESULTS AND DISCUSSION

The most important cause of secondary contamination of water introduced into the distribution network from the treatment plant is the lack of its biological and chemical stability. However, there are conditions enhancing bacterial growth and sedimentation dissolution in stable drinking water.

The following physicochemical indices were determined in tap water: free chlorine, colour, turbidity, pH, conductivity, iron, aluminium, sodium, ammonium ion, potassium, magnesium, calcium, ∑ chlorates(V) and chlorates(III), fluorides, chlorides, nitrates(III), nitrates(V), phosphates(V), sulphates(VI), copper, total organic carbon (TOC), ∑THM (total trihalomethanes). For the above parameters the most important factors responsible for water quality changes in the distribution system are presented in (Fig. 1). It follows from the correlation matrix of factor loadings that the examined waters from Rudawa, Dobczyce Reservoir, Dłubnia and Sanka differ in the number and share of extracted factors (Table 3).

Table 3. Rotated component matrix – tap water

Index	Component			
	1	2	3	4
Conductivity	0.955			
Calcium	0.949			
Nitrates	0.896			
Magnesium	0.825			
∑THM	-0.746			
Turbidity		0.939		
Colour		0.888		
Iron		0.877		
Sodium			0.826	
TOC			0.805	
Aluminium			-0.756	
Free chlorine				0.790
Ammonium ion				0.714
Percent contribution in variability	32	20	16	9

Source: own research based on the MPWiK results

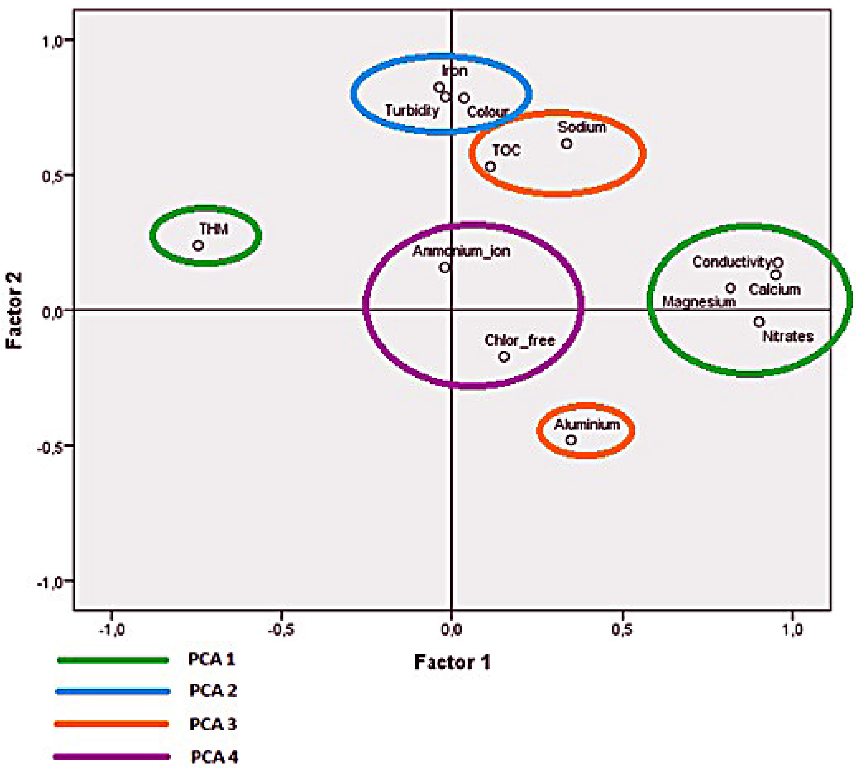

Fig. 1. Plot of factor loadings for tap waters in the years 2011–2014

Source: own research based on the MPWiK results

The analysis of waters coming from 4 main supply areas of the city of Kraków enabled 4 factors that explain 77% of its chemical composition to be isolated. Based on factor loadings of water withdrawn at specified points of the water supply network factor 1 that explains 32% of water chemical composition was isolated. During the analysis it was highly correlated with the following indices: calcium, conductivity, nitrates(V), magnesium and moderately with ∑THM (with negative sign). These indices have the largest contribution in multi-feature differentiation of tap water quality. The values of factor loadings indicate that water that contained a relatively large amount of nitrates(V) had both higher conductivity and total hardness (sum of Ca^{2+} and Mg^{2+}ions). However, soft waters of the lowest conductivity among all examined samples had a relatively high concentration of disinfection by-products, i.e. ∑THM. These waters were produced at the ZUW Raba where gaseous chlorine is used.

Factor 2 that explains 20% variability of chemical composition is characterised by a strong correlation with turbidity, colour and iron. This indicates that the number of colour units increased with increasing iron concentration. Iron cause water to turn a reddish brown colour and give water an unpleasant taste and odour and stimulates bacterial growth. In addition, the presence of iron compounds in drinking water causes turbidity that enhances microbial growth.

Factor 3 representing 16% of variability is strongly correlated with sodium, total organic carbon and aluminium (minus sign). This indicates that the use of aluminium coagulants promotes removal of organic substances from water of lower sodium ion concentrations.

For Factor 4 that explains 9% of water chemical composition, there is a strong relationship with free chlorine and a moderate with ammonium nitrogen. The content of ammonium nitrogen is an important factor from the chlorine disinfection efficiency, as it forms chloramines in reaction with chlorine.

The principal component analysis carried out forms a general assessment model for water quality in the water supply system of the city of Kraków. This consists in determining quite new variables (principal components) to explain chemical composition variations for the examined water. Each of isolated factors has been represented as a linear combination of the original variables.

AN ASSESSMENT OF WATER QUALITY IN A WATER SUPPLY NETWORK

The water quality indices at selected points of the water supply network that correspond to a specified plant were evaluated. Monitoring covered the period between 2011 and 2014. The values of microbiological and physicochemical parameters were compared with guidelines contained in the Regulation of the Minister of Health on quality requirements for water intended for human consumption [Regulation of the Minister of Health of 13 November 2015].

When assessing the quality of water taken into the water supply network of the city of Kraków it should be concluded that monthly means of analysed physicochemical indices in the period under investigation meet the requirements of national [Regulation of the Minister of Health of 13 November 2015] and European standards [EU Directive 98/83/EC of 3 November 1998]. It follows from the conducted research that the water produced at the ZUW Raba was of the best quality – the lowest values of physicochemical indices compared to those of other plants [Adamczyk and Jachimowski 2012].

The maximum values of tap water quality indices are presented in Table 4.

In water intended for consumption the values of microbiological indices , i.e. group of coliform bacteria, *Escherichia coli*, Enterococcus and *Clostridium perfringens* should be 0 cfu in 100 ml of

Table 4. An assessment of water quality in the municipal water supply network in Kraków in the years 2011–2014

Index	Unit	TLV	Max	Number of exceedings	Location of exceedings
Coliform bacteria	cfu/ml	0	0	0	No
Escherichia coli	cfu/ml	0	0	0	No
Enterococcus (Enterococcus feacalis)	cfu/ml	0	0	0	No
Clostridium perfringens (including spores)	cfu/ml	0	0	0	No
Total number of microorganisms at 22°C after 72h	cfu/ml	100	370	5	Tokarskiego 1, Cechowa 57,Gronostajowa 3, Kutrzeby 4, Kosiarzy 1, Bolesława Śmiałego 7, Las Wolski – ZOO
Free chlorine	$mg·dm^{-3}$	0.3	0.5	3	Babińskiego 29, Kamedulska 70, Las Wolski – ZOO
Colour	$mgPt·dm^{-3}$	15	16	1	Mirowska 278
Turbidity	NTU	1	2.9	6	Cechowa 57, Mirowska 278, Kamedulska 70
Odour			acceptable		No
Taste			acceptable		No
pH		9.5	8.11	0	No
Specific conductivity at 25°C	$µS·cm^{-1}$	2500	765	0	No
Iron	$mg·dm^{-3}$	0.2	0.49	7	Kutrzeby 4, Mirowska 278, Las Wolski – ZOO
Aluminium	$mg·dm^{-3}$	0.2	0.117	0	No
Sodium	$mg·dm^{-3}$	200	42.6	0	No
Ammonia	$mg·dm^{-3}$	0.5	0.39	0	No
Potassium	$mg·dm^{-3}$		5.9		No
Magnesium	$mg·dm^{-3}$	125	18	0	No
Calcium	$mg·dm^{-3}$		135		No
Σ chlorates and chlorites	$mg·dm^{-3}$	0.7	0.66	0	No
Fluorides	$mg·dm^{-3}$	1.5	0.29	0	No
Chlorides	$mg·dm^{-3}$	250	78	0	No
Nitrates (III)	$mg·dm^{-3}$	0.5	0.2	0	No
Nitrates (V)	$mg·dm^{-3}$	50	26.2	0	No
Phosphates (V)	$mg·dm^{-3}$		0.84		No
Sulphates (VI)	$mg·dm^{-3}$	250	109	0	No
Copper	$mg·dm^{-3}$	2	0.02	0	No
TOC	$mg·dm^{-3}$	5	4.57	0	No
Σ THM	$µg·dm^{-3}$	100	48.6	0	No

Source: own research based on the MPWiK results examined water. The related requirements stipulated in the regulation were met. The total number of microorganisms at 22°C after 72h should not exceed 100 cfu per 100 ml of water. These requirements have not been met at eight points of the water supply network, namely: Tokarskiego 1 (22 July 2014 – 130 cfu/ml), Cechowa 57 (3 October 2012 – 134 cfu/ml), Gronostajowa 3 (17 June 2014 – 104 cfu/ml), Kutrzeby 4 (31 August 2011 – 370 cfu/100 ml), Kosiarzy 1 (31 August 2011 – 110 cfu/100 ml), Stoczniowców 7 (19 August 2014 – 180 cfu/ml), Tyniec – Bolesława Śmiałego 7 (24 April 2013 – 112 cfu/100 ml) and Las Wolski – ZOO (24 April 2013 – 121 cfu100 ml).

If water is contains chlorine compounds exceeding the applicable standard, free chlorine should be kept at a level of 0.3 mg·dm^{-3}. The maximum permissible chlorine concentration in water was exceeded at: Babińskiego St. 29 (4 April 2012 – 0.50 mg·dm^{-3}), Kamedulska 70 (1 March 2011 – 0.44 mg·dm^{-3}) and Las Wolski – ZOO (13 February 2012 – 0.38 mg·dm^{-3}).

Water colour should be acceptable for consumers and show no abnormal changes. According to the regulation of the Minister of Health of 2007, the permissible value was set at 15 mgPt·dm^{-3}. This limit has been exceeded only once – on 7 June 2011 at Mirowska St. 278 and was 16 mgPt·dm^{-3}.

According to legal regulations drinking water turbidity must be acceptable for consumers, and should show no abnormal changes and not exceed 1 NTU. This limit was exceeded once in water withdrawn at Cechowa 57 (31 July 2012 – 1.1 NTU), 5 times at Mirowska 278 (1 March 2011 – 1.5 NTU; 7 June 2011 – 2.9 NTU; 13 February 2012 – 1.5 NTU; 9 May 2012 – 1.2 NTU; 22 April 2014 – 2 NTU) and twice at Kamedulska 70 (7 June 2011 – 1.26 NTU; 22 April 2014 – 1.5 NTU).

Odour and taste of water intended for consumption by humans were acceptable for consumers and did not exceed permissible standards.

The examined water had pH ranging from 6.5 to 9.5, i.e. compliant with the quality requirements. The highest pH of 8.11 was recorded in water taken at Stoczniowców St. on 19 November 2014.

According to standards, conductivity of clean water should be lower than 2500 µS·cm^{-1}. At sampling points this parameter did not exceed permissible values. The highest conductivity of 765 µSm·dm^{-3} was observed on 3 April 2012 at Tokarskiego St. 1.

Iron concentration should be kept at a level of 0.2 mg·dm^{-3}. An increased content of this element was found 8 times: one at Kutrzeby 4 (31 August 2011 – 0.303 mg·dm^{-3}), 5 times at Mirowska 278 (1 March 2011 – 0.490 mg·dm^{-3}; 7 June 2011 – 0.382 mg·dm^{-3}; 13 February 2012 – 0.479 mg·dm^{-3}; 9 May 2012 – 0.204 mg·dm^{-3}; 22 April 2014 – 0.308 mg·dm^{-3}) and twice at Las Wolski – ZOO (9 May 2012 – 0.219 mg·dm^{-3}; 16 January 2013 – 0.228 mg·dm^{-3}).

Other parameter, namely aluminium, sodium, ammonium nitrogen, potassium, magnesium, calcium, Σ chlorates(V) and chlorates(III), fluorides, chlorides, nitrates(III), nitrates(V), sulphates(VI), copper, TOC and ΣTHM did not exceed permissible values stipulated in standards.

CONCLUSIONS

1. A plurality of factors determining drinking water quality causes that the quality is a function of many parameters that have a different and variable contribution in the final microbiological and physicochemical composition. The factors associated with water, hydraulic conditions in the network, pipe material and sealing and network structure play an important role.
2. Factor analysis enabled 4 components explaining a relationship between tap water quality indices to be distinguished. The obtained factors applied to 78% of total water variability. The highest share was assigned to factor 1 that explained in 32% the chemical composition of water under consideration and was correlated with calcium, conductance, nitrates(V), magnesium and to a moderate extent with ∑ THM (with negative sign).
3. Within the ZUW Dłubnia drinking water supply area an increase of ∑THM concentration with increasing distance from the plant was observed. It follows from the analysis carried out that water disinfection by-products (∑ THM) did not exceed permissible limits.
4. An increase in iron concentration at specified points of the network may indicate corrosion of pipelines.
5. Secondary contamination of water in the water supply system occurred most often at the ZUW Bielany supply area at the following locations: Mirowska 278, Kamedulska 70 and ZOO – Las Wolski. This water was of poorest quality, but in any case still remained healthy. It follows from the conducted research that the pipe material has a stronger effect on water quality than the distance from the water treatment plant.

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