The effect of the mixing of water from different sources in the water supply system on tap water quality – a full-scale technical investigation case study

A. Szuster-Janiaczyk and J. Bylka

ABSTRACT

The paper presents a detailed analysis of the quality of water pumped into a network and sampled from 39 monitoring points located on the network. A difference in the quality of water sampled from two different sources was demonstrated, as well as the impact of the mixing of the two waters in the water distribution system (WDS) on tap water quality. A mathematical model was used to identify the zones of water mixing and the areas of unfavourable hydraulic conditions (low flow rates and long retention times).

Key words | chemical and biological stability of water, corrosive properties, hydraulic conditions in the water supply network, mixing of waters in the water distribution system, water quality

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INTRODUCTION

The chemical and biological stability of water and its corrosive properties depend on the processes conducted in water treatment plants and have a critical impact on the quality of water during its distribution. Furthermore, taking into account the impact of the construction materials of which water distribution systems (WDS) are built (type, quality and age), the hydraulic conditions (flow direction and velocity, retention time, pressure stability and the presence of mixing zones), as well as measures protecting the network against external impacts, we will get a complete overview of how complex the subject is. One of important factors influencing the quality of water in distribution systems is the chemical and biological stability of water supplied to the network. In a situation of the mixing of water from two different sources, changing the water supply source or a change of the treated water parameters, e.g., as a result of modernization of the water treatment plant, maintenance of the water parameters' stability becomes even more challenging (Montiel *et al.* 2002; Ainsworth 2004; Taylor *et al.* 2006; Liu *et al.* 2010; Bray *et al.* 2011; Szuster-Janiaczyk *et al.* 2012; Chen *et al.* 2013; Puleo *et al.* 2014; Pieper *et al.* 2017). Therefore, each water supply system should also be analyzed in such terms.

The aim of this study is to show the effect of the mixing of water from different sources on its quality in monitoring points located in a network. Some hydraulic parameters (the age of water and velocity) were taken into consideration in interpretation of the results of the research.

Study area

The study described herein was carried out on a technical scale on a water supply system servicing approximately 315,000 inhabitants. The source waters which enter the network are surface waters coming from three water intakes, treated in two different water treatment plants (ZUW I and ZUW II). In ZUW I, water from two independent surface water intakes (U-1 and U-2) undergoes treatment processes. Initially, the treatment process takes place in two separate technological process lines: A (ozonation, volumetric coagulation, sedimentation, filtration) and B

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(ozonation, coagulation, filtration). After the filtration process, water from both lines, A and B, goes to a shared pumping station where mixing takes place. From the pumping station building, water is delivered to intermediate ozonation tanks and, subsequently, onto carbon filters. After passing through carbon filters, treated water enters clean water reservoirs. In the supply pipeline, feeding the reservoir, chlorine solution, as a chlorine water, is added for disinfection purposes. From the reservoirs, water is pumped into the network via two separate water mains: MI and MII, in the northern direction. ZUW II plant is supplied with water from the U-3 surface water intake. Treated water from ZUW II goes to the analyzed network by the MIII water main (Figures 1 and 2). First of all, the water is de-aerated in primary water tanks, where coarse suspended solids are also removed. From the tanks, water flows by way of gravity to the filter building which houses contact filters. If necessary, water coagulation using aluminium sulphate can be performed in the filter area. After filtration, water goes to clean water reservoirs, where it is disinfected using chlorine gas. Water from the reservoirs is pumped, via second-stage pumping stations, into a reinforced concrete water main and flowing by way of gravity covers a distance of approximately 32 km to the pumping station. Water treatment processes are presented in Table 1.

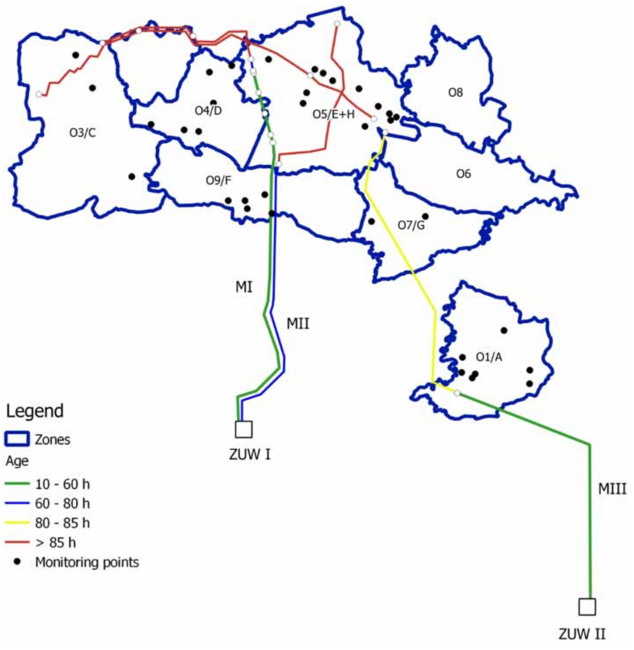

Figure 1 | The studied area with water quality monitoring points and estimated times of water retention in water mains.

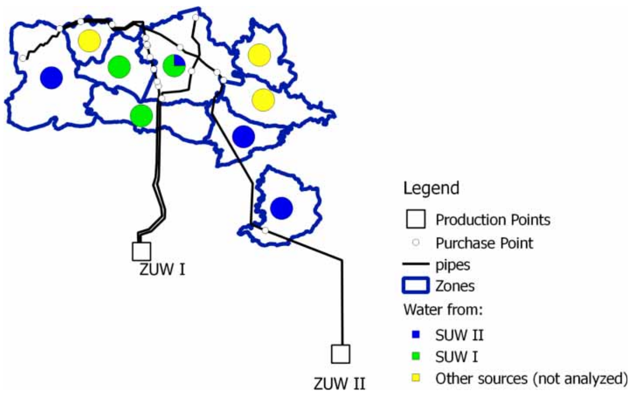

Figure 2 | Areas supplied with water.

Water mains are made of steel, grey or ductile cast iron, reinforced concrete (iron concrete), polyethylene, glass fibre reinforced epoxy resin (GFK), ductile iron with cement lining and steel pipes with three-coating polyethylene coating outside and cement lining inside. The diameters of the water mains mentioned above range from Ø400 mm to Ø1,600 mm.

The studied area is supplied with water from the water mains using 18 connection points. The total length of the water mains and distribution pipelines is 1461 km. The network is built of many types of materials (mainly steel, PE, cast iron and PVC) which differ in terms of age structure (from 3 to over 40 years). The area where the mixing of waters coming from two different sources takes place is situated in the strict centre of an urban agglomeration

Table 1 | Water treatment processes in water treatment plants ZUW I and ZUW II

ZUW I		
Technological line I	**Technological line II**	**ZUW II**
Initial oxidation	Initial oxidation	De-aeration of water
Volumetric coagulation	Coagulation	Filtration
Sedimentation	Filtration	Coagulation
Filtration		Disinfection
Intermediate oxidation		
Filtration		
Disinfection		

(Figure 2). Two pressure zones are found in that area: (I) with a pressure range of 0.4–0.5 MPa covering the whole area of the city and (II) with a pressure range of 0.7–1.0 MPa, covering high-rise buildings (with more than five storeys) in Śródmiescie district. In the urban area, a ring-type network is operated, with a diameter range ∅600–250 mm and a ring and branch distribution network with a diameter range of ∅100 (PE ∅90)–∅200 mm. According to the data based on the hydraulic model (integrated with GIS environment) of the distribution network, the water mixing zone is an area with the most favourable hydraulic conditions in terms of maintenance of appropriate water quality (optimum flow velocities and age of water), versus other parts of the studied area.

Figures 1 and 2 present the area where the investigation was carried out, with administrative district boundaries and points of monitoring network water quality. Moreover, the maps also show calculated (using the Epanet hydraulic model) times of water retention in the network and areas supplied with water from a specific source (ZUW I or ZUW II) or where mixing of waters from ZUW I and ZUW II takes place.

Methodology

This paper presents an analysis of the quality of water supplied to the network from two water treatment plants (ZUW) covering a period of 5 years. In total, 82 treated water samples were subjected to physicochemical analyses (ZUW I: $n = 17$, ZUW II: $n = 65$) – Table 1, and 45 samples were subjected to microbiological analyses (ZUW I: $n = 1$, ZUW II: $n = 44$) in the range of 35 water quality parameters. The water supplied to the investigated water distribution system was evaluated in terms of corrosive properties, and chemical and biological stability. The evaluation of corrosive properties, chemical stability and the tendency to form protective coatings on pipeline surfaces was carried out by the Ryzner Index (RI), the Langelier Index (LI), Larson–Skold indexes (LSI_1) and (LSI_2) and the German guideline DVGW (W216). The assessment of water susceptibility to destabilization during mixing was carried out for waters from two sources (ZUW I and ZUW II) which blend together in the area indicated in Figure 2. Additionally, the waters were analyzed for stability during transport in the water distribution system. Out of 11 parameters specified in the guideline, seven (temperature, dissolved oxygen (DO), pH, chlorides, sulphates, nitrates and phosphates) are analyzed in this paper due to limited data availability.

Additionally, 2,065 water samples from monitoring the quality of water in the distribution system were analyzed (Figure 1). The analyses were conducted for a period of 9 years at varying time intervals (depending on the work executed at the time on the network and in the water treatment plant). The first series of data covered a period of 4 years and included 874 quality analyses of water samples from a number of randomly selected monitoring points, evenly distributed across the network, evaluating four water quality parameters (colour, turbidity, iron and manganese content). The second series of data, initiated at the time of commissioning the operation of a system for dosing corrosion inhibitors into the water, covered the next 5 years and included 1,191 analyses of water from 39 monitoring points in the range of 15 water quality parameters: colour, turbidity, pH, iron, manganese, total phosphorus, orthophosphates, free chlorine, conductivity, ammonium ion, total alkalinity, total hardness, dissolved oxygen, total bacterial count in 1 ml incubated at 37 °C, 48 h, total bacterial count in 1 ml, at 22 °C, 72 h. The applied analytical methods, regardless of where the analyses were performed, were consistent with the current guidelines set out in the applicable regulations of the Polish Minister of Health (Regulation of the Polish Minister of Health of 13 November 2015) implementing Directive 98/83/EC. Table 2 describes the schedule of the water sample collection programme in the conducted research.

The results of the water quality examinations were processed using the STATISTICA and Excel software. As part of the statistical analysis, the distribution type was identified for each parameter, using Fisher's exact test, Student's t-test and the Kolmogorov–Smirnov test. The critical significance level p was set at 0.05. The following descriptive statistics were also determined: maximum and minimum values, arithmetic means, median values, standard deviations, upper and lower quartiles and the standard error. In the case of selected water quality parameters, correlations of two characteristics were examined using Spearman's non-parametric rank-order correlation test for values which differed significantly from the normal distribution and Pearson's product–moment correlation test for values demonstrating distribution consistent

Table 2 | Water quality monitoring programme in research area

Total research period: 9 years			
Treated water			
Research period[a]		5 years	
Quantity of samples	ZUW I	$n = 17$ (ZUW I) physicochemical analysis	$n = 1$ (ZUW I) microbiological analysis
	ZUW II	$n = 65$ (ZUW II) physicochemical analysis	$n = 44$ (ZUW II) microbiological analysis
Scope of the research		temperature, colour, turbidity, pH, conductivity, alkalinity, hardness, dry residue, iron, manganese, ammonium ion, nitrates, nitrites, sulphates, chlorides, free and aggressive CO_2, calcium, magnesium, permanganate index, lead, copper, oxygen, free chlorine, orthophosphates, general phosphorus, THM, acidity, sodium, potassium, DOC	total bacterial count in 1 ml, at 22 °C, 72 h, total bacterial count in 1 ml incubated at 37 °C
Water from network (39 monitoring points located as shown in Figure 1)			
Research period[a]		4 years	5 years
Quantity of samples		$n = 874$	$n = 1{,}191$
Scope of the research		turbidity, colour, iron, manganese	colour, turbidity, pH, iron, manganese, total phosphorus, orthophosphates, free chlorine, conductivity, ammonium ion, total alkalinity, total hardness, dissolved oxygen, total bacterial count in 1 ml incubated at 37 °C, 48 h, total bacterial count in 1 ml, at 22 °C, 72 h

[a] Analysis of treated water and water from the network started at the same time.

with normal distribution. In order to define the correlation structure between variables for selected water quality parameters, multiple regression analysis was carried out.

Retention times and water mixing zones were determined using a hydraulic model of the water supply network prepared in the Epanet application.

RESULTS

Quality of treated water supplied to the investigated water distribution system

Waters from the two sources supplied to the water distribution system were characterized by low average colour and turbidity values.

The average concentration of iron as well as manganese were below the maximum acceptable limits for water. Both waters exhibited low mineralization (as evidenced by average conductivity and dry residue values), low alkalinity and low total hardness. The water from ZUW I was slightly acidic (average $pH = 6.9$), while the water from ZUW II was alkaline (average $pH = 7.21$). The average, maximum and minimum values of such water parameters as pH, conductivity, permanganate index, total organic carbon (TOC), ammonium ions, nitrate nitrogen, nitrite nitrogen, chlorides, sulphates, trihalomethanes (THMs) and heavy metals were within the ranges specified in the Regulation of the Polish Minister of Health of 13 November 2015.

The results of the physicochemical analysis of treated water from ZUW I and ZUW II (min–max range and the average value) are presented in Table 3.

Water supplied to the investigated water distribution system from both water treatment plants was characterized by high microbiological purity. None of the analyzed water samples was found to have excessive values of the parameters specified in the Regulation of the Polish Minister of Health of 13 November 2015, including total bacterial count in 1 ml incubated at 37 °C for 48 hours, total bacterial count in 1 ml incubated at 22 °C for 72 hours, total

Table 3 | The results of the physicochemical analysis of treated water supplied to the network

Parameter	Denomination	TLV	ZUW I ($n = 17$) mean/min–max	ZUW II ($n = 65$) mean/min–max
Temperature	°C	–	23*	11.3/0–22.5
Turbidity	NTU	1	0.2/0–1.7	0.4/0–2
Colour	mgPt/l	15	1.9/0–7	4.2/0.1–19.0
pH	pH	6.5–9.5	6.9/6.5–7.38	7.2/6.7–7.7
Conductivity	μS/cm	2,500	181/156–197	161/117–198
Alkalinity	mmolH$^+$/l	–	0.9*	1.2/0.6–1.7
Hardness	mgCaCO$_3$	60–500	91.3/71–104	86.5/58–165
Dissolved oxygen	mgO$_2$/l	–	n.a.	10.01/10.00–10.02
Permanganate index	mgO$_2$/l	5	0.45*	1.66/0.72–3.0
TOC	mgC/l	5	1.29*	2.21/2.14–2.27
Ammonium ions	mgNH$_4$/l	0.5	0.11/0.02–0.219	0.04/0.00–0.68
Nitrate nitrogen	mgNO$_3$/l	50	4.7/2.8–7.6	4.93/0.02–9.74
Nitrite nitrogen	mgNO$_2$/l	0.5	0.082/0.0001–0.31	0.0009/0–0.019
Free carbon dioxide	mgCO$_2$/l	–	12.1*	7.7/6.2–11.0
Aggressive carbon dioxide	mgCO$_2$/l	–	23.6*	4.95/2.2–6.4
Iron	mgFe/l	0.2	0.11/0.03–0.82	0.04/0.0–0.34
Manganese	mgMn/l	0.05	0.020/0.002–0.062	0.012/0.000–0.051
Calcium	mgCa/l	–	23.6*	29.0/20.8–40.5
Magnesium	mgMg/l	up to 30–125	2.92*	8.15/3.3–21.6
Sulphates	mgSO$_4$/l	250	25.5/0–44.0	24.1/14.0–48.0
Chlorides	mgCl/l	250	11.5/10.0–15.0	9.8/6.5–15.0
Total THMs	μg/l	100	1.3*	9.1/6.4–12.8
Lead	mgPb/l	0.025	0.0006*	0.002/0.0001–0.0038
Copper	mgCu/l	0.002	0.0017*	0.002/0.001–0.003
Free chlorine	mgCl$_2$/l	0.1–0.3	0.26/0.00–0.58	0.26/0.00–0.80
Orthophosphate dissolved	mgPO$_4$/l	–	n.a.	n.a.
Dry residual		–	113.3/105–128	90.5/61.0–108.0
Total phosphorus	mgP/l	–	n.a.	0.11/0.04–0.23
Sodium	mgNa/l	200	n.a.	7.0/6.0–8.1
Potassium	mgK/l	–	n.a.	3.0/2.5–3.3
DOC	mgC/l	–	n.a.	0.99/0.94–1.03

*Single measured value, n.a. – not available.

coliforms in 100 ml incubated at 37 °C for 24 hours and total thermo-tolerant coliforms in 100 ml incubated at 44 °C for 24 hours.

Table 4 shows the chemical stability and corrosivity indexes for analyzed waters. It follows that treated waters from both water treatment plants were corrosive and chemically unstable.

The data in Table 5 indicate that, due to temperature, pH and sulphate concentrations (only in water of ZUW I), both waters should be classified as water of variable quality over time, which may interfere with the formation of the protective layer on the surfaces of pipe materials in the network. Additionally in the case of waters that are mixed in the network, it may lead to destabilization of water quality

Table 4 | Summary of chemical stability and corrosivity indicators of treated water

				Larson–Skold indexes	
Water treatment plant	**Ranges of results**	**Langelier Index (LI)**	**Ryzner Index (RI)**	**LI_1**	**LI_2**
ZUW I ($n = 1$)	min–max (mean)	−1.90* (–)	10.69* (–)	0.94* (–)	0.31* (–)
ZUW II ($n = 48$)	min–max (mean)	−2.27–−0.54 (−1.36)	8.79–11.29 (9.93)	0.15–0.69 (0.29)	0.15–0.53 (0.23)

*Single calculated value.

Table 5 | Data summary for the analysis of water stability in accordance with DVGW W216

		Variability range of the analyzed parameter for individual water sources – (min–max)	
Parameter	**Denomination**	**ZUW I**	**ZUW II**
Temperature	°C	23*	0–22.5
Dissolved oxygen	mgO_2/l	–	10.00–10.02
pH	–	6.5–7.4	6.7–7.7
Mineral acidity to pH = 4.3 ($Ks_{4.3}$)	mmol/l	–	–
Chlorides	$mgCl^-/l$	10.0–15.0	6.5–15.0
Sulphates	$mgSO_4^{2-}/l$	0–44	14–48
Nitrate nitrogen	$mgNO_3^-/l$	2.8–7.6	0.02–9.7
Phosphates	$mgPO_4^{3-}/l$	–	0.07–0.31
DOC	mg/l	–	–
$[c(Cl^-) + 2(SO_4^{2-})]/Ks_{4.3}$	–	–	–
$0.5\{[c(Na^+) + c(K^+)]/[c(Ca^{2+}) + c(Mg^{2+})]\}$	–	–	–

Grey background colour means parameters that may indicate instability of the water during its distribution in the water distribution system.
*Single measured value.
– Not analyzed.

and scale structure (W216, DVGW). The lack of chemical and biological water stability was an important cause of the intensification of the processes of secondary water contamination, which had already occurred in water mains – for ZUW II, a high correlation ($r = 0.58$, $p = 0.00$, $n = 65$) between iron concentration and distance was stated, and for ZUW I water colour increased as a function of distance ($r = 0.69$; $p = 0.00$; $n = 17$).

Quality of water sampled from the water distribution system

Table 6 presents data from the analysis of water samples from the water distribution system collected during the first series of tests. It shows that out of all four analyzed parameters (colour, turbidity, iron and manganese concentration), only the minimum values meet the acceptable limits specified in the Regulation of the Polish Minister of Health of 13 November 2015, while average and maximum values exceed the acceptable limits as much as 150 times, as in the case of maximum turbidity. The results of analysis

Table 6 | The results of the physicochemical analysis of water from the water distribution system – the first data series from the entire area under investigation

Parameter	**Denomination**	**TLV**	**value ($n = 874$) mean/min–max**
Turbidity	NTU	1	5.54/0.00–150
Colour	mgPt/l	15	27.3/5–200
Iron	mgFe/l	0.2	0.74/0.00–10
Manganese	mgMn/l	0.05	0.24/0.01–2.36

of water samples from the second series of tests are presented in Table 7 and in Figures 3–8. The data clearly show that the analyzed water is of much better quality compared with the water from the first series of tests, with regard to parameters evaluated in both measurements, such as iron, manganese, colour and turbidity. Of crucial significance for this finding is the fact that the second series of analyses was initiated at the time of commissioning the process of the dosing into the water of phosphate corrosion inhibitors, which in general have a masking effect on iron and manganese ions and, consequently, improve the organoleptic properties of water.

DISCUSSION AND CONCLUSION

The analysis of water corrosiveness and stability carried out on the basis of the stability indexes has shown that both waters pumped into the network were under-saturated with respect to $CaCO_3$ and had aggressive properties (contained aggressive CO_2). The analysis of water stability with reference to guideline W216 (DVGW) has demonstrated that due to temperature and pH values, the formation of the protective coating on water pipelines may be disturbed in the area of the mixing of the two types of water. Additionally, the water supplied from ZUW I had a distorting process of forming a protective coating by reason of variable sulphate concentrations. Based on the conducted analysis it can be concluded that measures should be implemented with regard to water treatment technologies in both treatment plants in order to minimize the degree of fluctuation of the problematic parameters.

On the basis of literature data (van der Kooij 1992; Sathasivan *et al.* 1997; Volk & LeChevallier 1999; Lehtola *et al.* 2001, 2004), selected indicators of stability of the water supplied to the investigated water distribution system were defined: AOC as 9% of TOC and BDOC as 21% of DOC. Taking into account only the analysis of assimilable organic carbon – AOC (116 μg/l for ZUW I and 193–204 μg/l for ZUW II) and biodegradable dissolved organic carbon – BDOC (unknown for ZUW I and 0.20–0.22 mg/l for ZUW II), neither the water from ZUW I nor from ZUW II is biologically stable. The impact of water stability on its quality in the investigated water distribution system is evident in the fact that the samples of water from areas supplied by ZUW II (with the highest values of biogenic indicators), in the circumstances where there is no effective water disinfection (0–0.06 $mgCl_2/l$, median 0.00 $mgCl_2/l$), exhibited the worst microbiological parameters.

The analysis of the impact of the presence of mixing zones, where waters from different sources blend, on the quality of water has shown that certain sections of the investigated water distribution system are conducive to the occurrence of water quality destabilization. A summary of average values of selected water quality parameters for areas grouped together depending on the source of water supply are presented in Table 7 and in Figures 3–8. In the case of nearly all analyzed water quality parameters, the

Table 7 | The results of analyses of water from the water supply network in areas where waters from two different sources mix together and in isolated areas – the second data series

		Source of water supply mean/min–max		
Parameter	**Denomination**	**ZUW I**	**ZUW II**	**Water mixing area ZUW I + ZUW II**
pH	pH	7.17/6.6–8.78	7.27/6.54–8.09	7.20/6.6–7.98
Conductivity	μS/cm	204/101–317	202/101–343	200/101–292
Total alkalinity	$mmolH^+/l$	1.24/0.52–2.61	1.45/0.7–2.2	1.38/0.73–2.4
Total hardness	$mgCaCO_3$	100.5/50–199	102.8/55–261	104.8/56–207
Dissolved oxygen	mgO_2/l	5.2/0–11.6	6.9/0.5–13	7.0/0–13.9
Ammonium ions	$mgNH_4/l$	0.07/0.00–0.41	0.06/0.00–0.26	0.06/0.00–0.40
Free chlorine	$mgCl_2/l$	0.01/0–0.4	0.00/0–0.06	0.03/0–0.20
Orthophosphates dissolved	$mgPO_4/l$	0.12/0.00–1.27	0.18/0.00–2.52	0.13/0.00–4.25
Total phosphorus	mgP/l	0.06/0.0–0.41	0.08/0.00–0.36	0.07/0.00–1.10

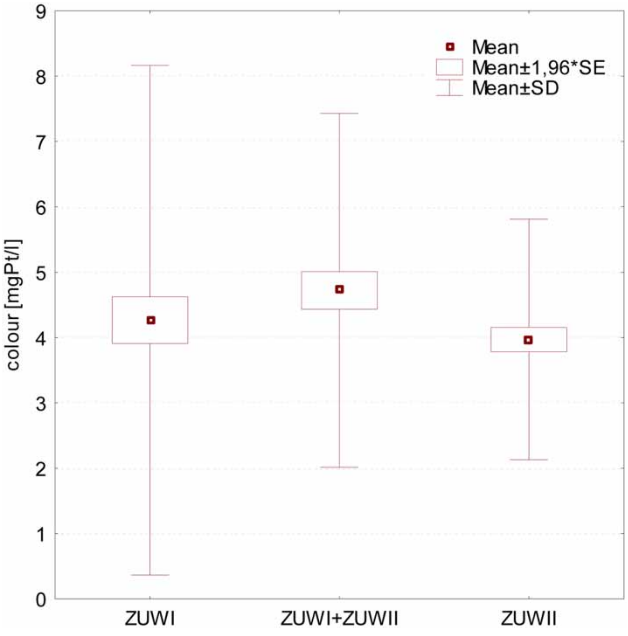

Figure 3 | Water colour.

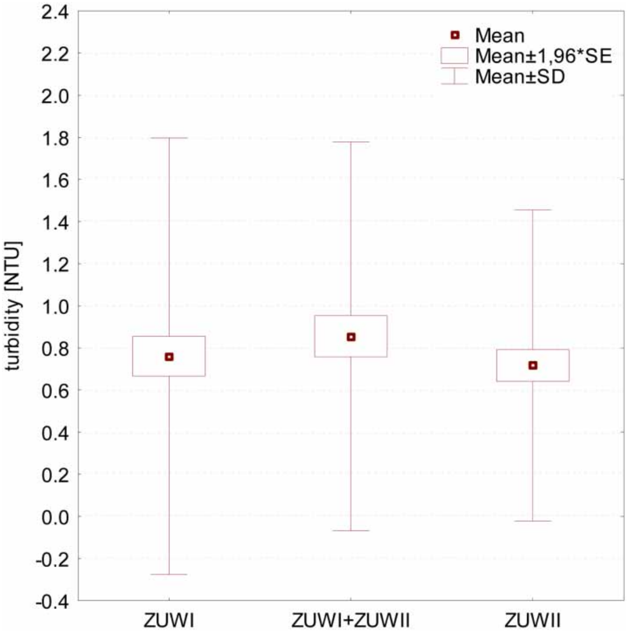

Figure 4 | Water turbidity.

average analysis results for mixed ZUW I and ZUW II waters were higher than the average results obtained in the case of water from isolated areas supplied by either ZUW I or ZUW II. Additionally, taking into consideration

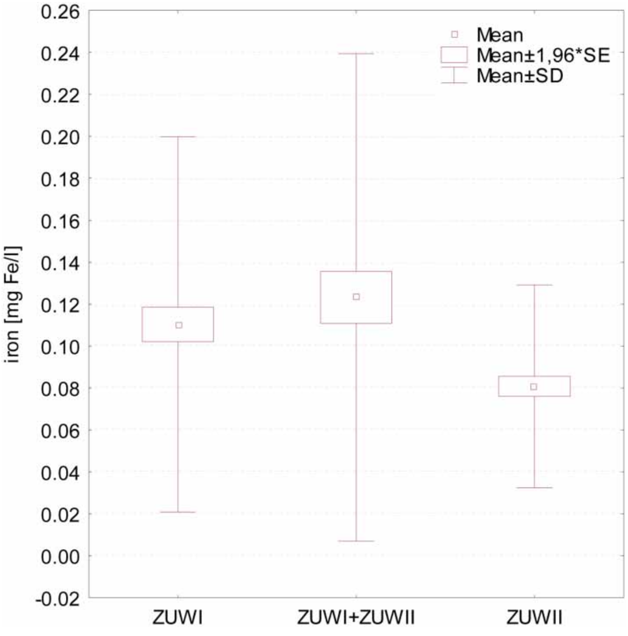

Figure 5 | Iron concentration.

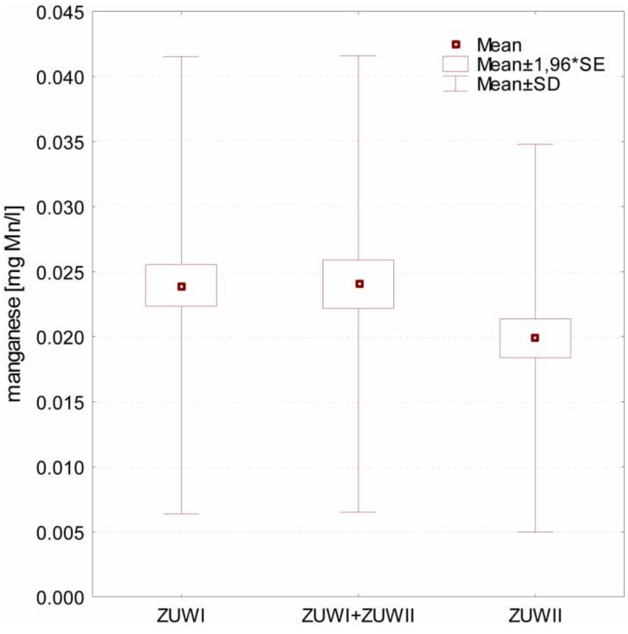

Figure 6 | Manganese concentration.

the fact that the operating conditions in water-mixing areas are more favourable from the point of view of water quality maintenance (higher mean flow velocities and lower retention times), the adverse effect of the mixing of water from various sources on stability-related water quality

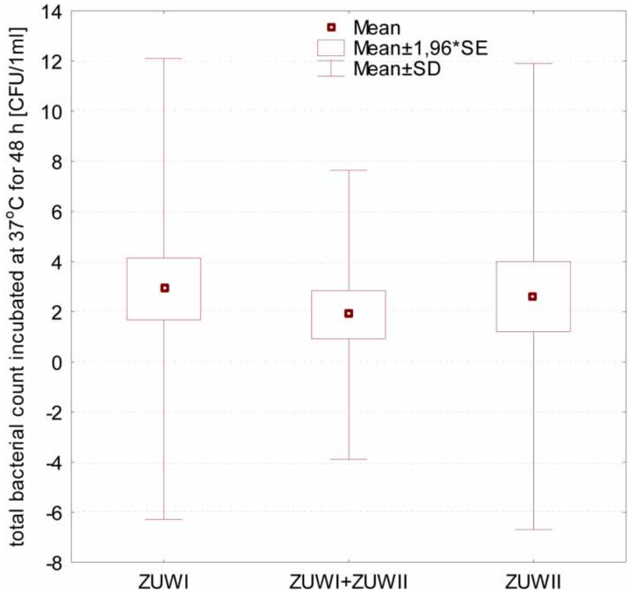

Figure 7 | Total bacterial count in 1 ml incubated at 37 °C for 48 h.

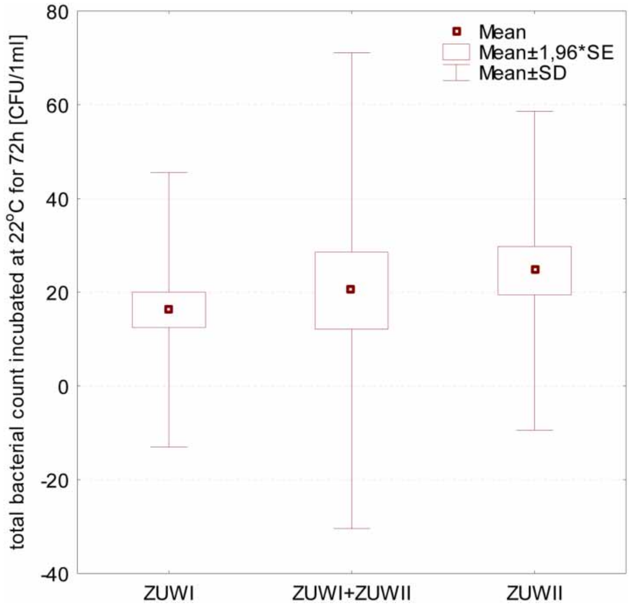

Figure 8 | Total bacterial count in 1 ml incubated at 22 °C for 72 h.

parameters in the analyzed water supply system is firmly confirmed. The only exception in the analysis concerned bacterial colonies incubated in 1 ml at 37 °C for 48 h. The average bacterial count in water samples from the mixing area was lower than in the samples from isolated areas, probably as a result of more favourable disinfection conditions in the former area and better hydraulic conditions (higher than in other areas of network flow velocities and lower age of water); velocity of water is a parameter of significance for the microbiological water quality (Manuel *et al.* 2007) and is likely to be the co-decisive factor explaining the situation described above.

Considering the obtained results, the areas in a network in which the water from different sources is mixed or the source of water supplying the network is changed should be under special supervision in view of the quality of the water. Planning such actions should be supported in advance, using all available decision-support tools such as the German DVGW guidelines (W 216 2004) and mathematical models, in which we can simulate the expected variations in mixing ratios in individual nodes of the network and try to isolate zones where water from different sources should not be mixed, due to water quality (Walski *et al.* 2007; Shang *et al.* 2008; Fisher *et al.* 2011; Grayman *et al.* 2012; Seyoum & Tanyimboh 2013; Monteiro *et al.* 2014; Szuster-Janiaczyk *et al.* 2017).

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