

Initial Assessment of Changes in Water Quality in the Wrocław City Moat Reservoirs

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ABSTRACT

The aim of the research was to initially assess the changes in the physicochemical composition of water in the reservoirs of the city moat (Wrocław) in the context of the analysis of the type of pollutants flowing into the inner-city water reservoirs and in relation to the impact of air quality directly in the vicinity of the reservoirs. As an element of the urban landscape, the inner-city water reservoirs play an important role in improving the local climatic conditions, increasing the biodiversity of the landscape, and eliminating the negative impact of urban heat islands. The measurement campaign was conducted for 11 months. The following parameters were determined in the analyzed water samples: turbidity, pH, electrolytic conductivity, as well as concentrations of nitrogen forms (ammonium nitrogen, nitrite nitrogen, and nitrate nitrogen), total phosphorus and sulfates. Additionally, the air quality parameters in the direct location of the reservoirs were analyzed, including: concentrations of nitrogen oxides, nitrogen dioxide, sulfur dioxide, humidity level and selected meteorological data, i.e. daily precipitation and average daily air temperature. The average concentrations of nitrogenous forms in the waters of the downtown water reservoir were as follows: ammonium nitrogen $0.155 \text{ mg} \cdot \text{dm}^{-3}$, nitrite nitrogen $0.084 \text{ mg} \cdot \text{dm}^{-3}$, and nitrate nitrogen $1.15 \text{ mg} \cdot \text{dm}^{-3}$. The sulfate concentrations showed greater variability $67.805\text{--}180.973 \text{ mg} \cdot \text{dm}^{-3}$. On the basis of the conducted observations and analyses, a statistically significant relationship was found between the quality parameters of water in municipal water reservoirs and external factors such as air quality, and in particular the correlation of air humidity with the concentration of nitrite and nitrate ions in the water. The conducted research confirms the influence of air quality on the levels of pollutants in the waters collected in the urban water reservoir.

Keywords: urban water reservoirs; physicochemical composition of water; ammonium nitrogen; total phosphorus; city moat.

INTRODUCTION

Inner-city water reservoirs are an important element of the urban landscape, which is part of the blue-green infrastructure of cities. They improve the city microclimate by increasing humidity, eliminate high temperature fluctuations by shifting locally occurring heat islands, and increase the biodiversity of the urban landscape, providing a place to live for many organisms [Hassall, 2014; Céréghino et al., 2008]. They are appreciated by residents for their aesthetic and recreational values, as one of the most frequently chosen places to relax in the city, being an element of multi-functional and attractive public spaces

[Lee, Maheswaran, 2011; Hill et al., 2017]. Their main task is, first of all, local water retention, and thus preventing droughts and floods [Hill et al., 2017; Jurczak et al., 2018]. The insufficient share of blue-green infrastructure in the urban ecosystem contributes to the difficulties in adapting the urban tissue to the progressing climate change [Gorgoń, Gocko-Gomola, 2016].

City water reservoirs are characterized by a variable height of the water level, a short retention time and a significant inflow of anthropogenic pollutants [Hassall, 2014; Jurczak et al., 2018; Zimmermann et al., 2003; Selmi et al., 2016]. Due to the shallow depth and short water retention time in the reservoir, there is no stratification that could

positively affect the quality of the ecosystem [Kinuma et al., 2016]. Due to the significant increase in surface sealing within the catchment area of urban water reservoirs, it causes changes in the dynamics of water flow and degradation of the water cycle. The level of soil sealing around city reservoirs, reaching 70% may cause rainwater infiltration dysfunction and evapotranspiration disorders, which in turn adversely affects the microclimate of the area and increases the risk of flooding, reducing the retention capacity of reservoirs [Gorgoń, Gocko-Gomoła, 2016]. The most common pollutants in surface runoff from urbanized areas are suspensions, organic matter, specific microorganisms and nutrients, the concentrations of which can reach significant values [Nguyen et al., 2017].

One of the effects of the inflow of pollutants to such reservoirs is eutrophication, leading to further degradation of water quality, disruption of the ecological balance and impoverishment of aesthetic values, and thus also recreational ones [Hassall, 2014; Jurczak et al., 2018; Nguyen et al., 2019]. The eutrophication process leads to the depletion of the oxygen content in the water of the reservoir, which in turn leads to the process of anaerobic decomposition of organic matter on the bottom and intensively multiplying blue-green algae. During summer and spring water blooms, the blue-green algae cover large areas of open reservoirs, preventing the inflow of sunlight for the rest of the flora in the reservoir [Kuśnierz, Łomotowski, 2015]. The excess of dead organic matter causes the formation of a thick layer of bottom silt that shallows the reservoir, but also causes elution of phosphorus from sediments (internal loading phenomena). Numerous studies show that it is this process that is most responsible for the negative effects of eutrophication [Augustyniak et al., 2017; Søndergaard et al., 2001; Kinuma et al., 2016].

The problem with water quality concerning small inner-city reservoirs is related primarily to their location and the free inflow of traffic pollution, as well as frequent inflows from sewage pipes [Kuoppamäki et al., 2014; Barańkiewicz et al., 2014]. Their location in the very center of the city, with high traffic, exhaust emissions and low air quality, is not without significance [Zimmermann et al., 2003; Selmi et al., 2016; Jasiński et al., 2021]. One of the main sources of metallic pollutants in urban waters is dry and wet deposition, which in the case of stagnant waters with limited exchange capacity causes

the accumulation of heavy metals that pose a threat to the organisms of the entire ecosystem [Bhat et al., 2012]. The condition of the water is also negatively affected by the lack of species-rich macrophyte habitats, which integrate the nature of the reservoirs in terms of chemical, physical and biological properties, provide food for many species of native fauna, drive the dynamics of nutrients, prevent elution from sediments and enrich the water with oxygen through photosynthesis [Ciecierska, Kolada, 2014]. The pollution washed away by torrential rains from the surface of roads, parking lots and roofs, as well as sewage entering as a result of leaks in sewage systems cause contamination of both surface and underground waters. Contaminated waters are a potential source of danger to human health through accidental skin contact or inhalation routes [Wijesiri et al., 2018]. A direct threat to humans and animals are the toxins secreted by cyanobacteria that cause blooms of eutrophicated waters [Whiteside, Herndon, 2019].

In order to limit the inflow of pollutants to the reservoirs, intermediate solutions are used, such as buffer zones, preliminary tanks (intended for sedimentation), but these are methods used to improve water quality in large (extra-urban) water reservoirs where the allocation of additional space is not a problem, unlike urban reservoirs very often located in city centers or densely built-up areas [Jurczak et al., 2018; Pokorny, Hauser, 2002; Rosinska et al., 2017; Peretyatko et al., 2012]. Revitalization treatments (often necessary) are not carried out due to the high cost of their implementation, low, temporary and limited effectiveness as well as due to the constant influx of pollutants [Hassall, 2014; Céréghino et al., 2008; Jurczak et al., 2018; Pokorny, Hauser, 2002].

The main purpose of the research was i) preliminary assessment of changes in the physico-chemical composition of water in the reservoirs of the city moat in the context of the type of pollutants flowing into the inner-city water reservoir as well as in relation to the air quality in the immediate vicinity of the reservoir and ii) identification of the type and sources of pollution.

MATERIALS AND METHODS

The research on the quality of water in city reservoirs was carried out over a period of 11



Figure 1. City moat reservoirs in the center of Wrocław

months in 3 reservoirs constituting the remains of the city moat (the remains of the fortification of the city of Wrocław 51°06'36"N 17°01'20"E).

The measuring points are located in close proximity to roads with heavy traffic, while ensuring the largest possible surface runoff (Fig. 1). Each time (1 month apart), a water sample in the amount of 1.5L was taken into sealed polyethylene containers. In the water samples, the parameters of pollutants were determined as listed in Table 1. The data on air quality in the immediate vicinity of the reservoirs were also analyzed, with particular emphasis on the concentrations of nitrogen oxides, nitrogen dioxide and sulfur dioxide as well as selected meteorological data: temperature, precipitation and relative air humidity [GIOŚ, 2019–2020; IMGW-PIB, 2019–2020].

The results were statistically processed by determining statistically significant differences based on the non-parametric Kruskal-Wallis test for independent variables. The Kruskal-Wallis test is equivalent to the one-way analysis of variance. It allows for the determination of statistically significant differences between individual observation points and the measured parameter [Knapp, 2018]. Statistical analysis was performed with the use of StatSoft software, Statistica ver.13.0.

RESULTS AND DISCUSSION

The city moat reservoirs from which the samples were taken were located in the very center of the city, right next to the main streets, and also in the area surrounded by urban greenery (city park).

Table 1. Determined parameters of pollutants

Parameter	Determination method
Nitrate nitrogen (mg N _{NO3} ·dm ³)	Spectrophotometric method: PN-82C-04576/08 Polski Komitet Normalizacyjny 1982
Ammonium nitrogen (mg N _{NH4} ·dm ³)	Spectrophotometric method: PN-ISO 7150:2002 Polski Komitet Normalizacyjny 2002
Nitrite nitrogen (mg N _{NO2} ·dm ³)	Spectrophotometric method: PN-EN 26777:1999 Polski Komitet Normalizacyjny 1999
Total phosphorus (mg P·dm ³)	Spectrophotometric method: PN-EN ISO 6878/1:2006 Polski Komitet Normalizacyjny 2005
Sulfates (mg SO ₄ ·dm ³)	Weight method: PN-ISO 9280:2002 Polski Komitet Normalizacyjny 2002
pH	Potentiometric method: PN-90/C-04540.01 Polski Komitet Normalizacyjny 1990
Electrolytic conductivity μS·cm ⁻¹	Conductometric method: PN-EN 27888:1999 Polski Komitet Normalizacyjny 1999
Turbidity (NTU)	Nephelometric method: PN-EN ISO 7027-1:2016-09 Polski Komitet Normalizacyjny 2003
Mean temperature (°C)	Instytut Meteorologii i Gospodarki Wodnej (IMGW-PIB)
Precipitation (15 days, mm)	
Relative air humidity (%)	
NO ₂ in air (μg/m ³)	Główny Inspektorat Ochrony Środowiska (GIOŚ)
NO in air (μg/m ³)	
SO ₂ in air (μg/m ³)	

The pH, electrolytic conductivity and turbidity in the analyzed water reservoirs showed little variability during the research, and their changes were not related to the location of the reservoirs (Table 2). The performed statistical analysis for independent samples (test power $H = 5$ and probability $p = 0.841-0.9112$) did not show statistically significant differences between the analyzed qualitative parameters and measurement points, despite the specific location of the city moat reservoirs. The analysis showed statistically significant differences for the sampling dates (Fig. 2, 3).

The average concentration of nitrogen compounds in the water samples taken from the municipal moat reservoirs for the analyzed forms of ammonium, nitrate and nitrite nitrogen was $0.155 \text{ mgN}_{\text{NH}_4} \cdot \text{dm}^{-3}$, $1.149 \text{ mgN}_{\text{NO}_3} \cdot \text{dm}^{-3}$, and $0.084 \text{ mgN}_{\text{NO}_2} \cdot \text{dm}^{-3}$, respectively. In the case of nitrates and nitrites, the highest concentrations were observed in reservoir 1 (measurement points 1 and

2). The lowest values of nitrate (NO_3^-) and nitrite (NO_2^-) nitrogen were observed in the spring and summer months (Fig. 2), the highest at the turn of the winter months (January, February) and early autumn (Fig. 3). These nitrogen forms were strongly correlated with the air temperature measured on the sampling day (Table 3). The concentrations of ammonium nitrogen remained constant throughout most of the research period, showing greater variability of values in the spring and summer months (Fig. 4). The mean concentration of total phosphorus in the observed period was $0.797 \text{ mgP} \cdot \text{dm}^{-3}$ (Table 2).

The highest values were observed in reservoirs in the immediate vicinity of roads (Fig. 5). The highest changes in the values were observed for total phosphorus in the summer months (July–August) (Fig. 5).

The sulfate concentrations were within a wide range of $67.805-180.973 \text{ mgSO}_4 \cdot \text{dm}^{-3}$, and their

Table 2. Basic characteristic values of the tested parameters

Measurement point	pH	Conductivity	Turbidity	NO_3^-	NO_2^-	NH_4^+	P_{og}	SO_4
	-	$\mu\text{s cm}^{-1}$	NTU	$\text{mgN}_{\text{NO}_3} \cdot \text{dm}^{-3}$	$\text{mgN}_{\text{NO}_2} \cdot \text{dm}^{-3}$	$\text{mgN}_{\text{NH}_4} \cdot \text{dm}^{-3}$	$\text{mgP} \cdot \text{dm}^{-3}$	$\text{mgSO}_4 \cdot \text{dm}^{-3}$
-	Mean							
1	7.23	1035	4.466	1.544	0.105	0.181	1.140	72.609
2	7.43	1023	6.055	1.233	0.084	0.140	0.753	67.805
3	7.31	1020	4.366	1.029	0.077	0.140	1.004	85.418
4	7.26	1027	3.962	1.073	0.079	0.159	0.854	111.404
5	7.31	1024	3.560	1.034	0.080	0.171	0.541	82.565
6	7.41	1029	3.236	0.984	0.077	0.139	0.493	180.973
-	Min.							
1	6.43	868	2.700	0.450	0.030	0.009	0.163	0.823
2	6.07	857	2.000	0.350	0.020	0.001	0.115	2.468
3	6.28	903	0.900	0.050	0.007	0.001	0.005	1.646
4	6.32	902	1.400	0.000	0.009	0.001	0.281	4.114
5	6.47	909	1.000	0.050	0.008	0.004	0.135	3.291
6	6.24	928	1.000	0.110	0.004	0.003	0.074	0.823
-	Max.							
1	8.00	1238	8.000	2.548	0.241	0.285	3.568	169.497
2	8.07	1231	15.000	2.187	0.139	0.290	1.300	155.509
3	8.10	1229	10.010	1.945	0.120	0.350	3.800	189.244
4	8.10	1197	7.720	2.202	0.135	0.370	5.500	211.460
5	8.10	1208	6.760	2.449	0.146	0.410	4.177	203.232
6	8.23	1142	6.460	2.244	0.147	0.370	1.390	638.493
-	Standard deviation							
1	0.53	124.360	1.711	0.675	0.038	0.108	0.915	65.109
2	0.64	105.867	3.803	0.680	0.035	0.099	0.308	52.831
3	0.59	101.302	3.089	0.729	0.035	0.099	1.123	57.008
4	0.62	90.398	1.955	0.719	0.038	0.106	1.558	77.129
5	0.54	90.371	1.952	0.888	0.043	0.111	1.178	76.880
6	0.67	75.003	1.452	0.814	0.040	0.113	0.355	195.575

highest values were observed for samples collected in the reservoir 3 (measuring points 5–6). The highest concentration values were observed in August (Fig. 6), the lowest in April and June.

Simultaneously with the analysis of the physicochemical composition of water samples, the air quality parameters obtained from measuring devices located in the immediate vicinity of the

reservoirs and selected meteorological data were given [GIOŚ, 2019–2020; IMGW-PIB, 2019–2020]. The results of the correlation of selected air quality parameters and the physicochemical composition of water samples are summarized in Table 3. The analyzed forms of nitrogen and the concentration of sulfates in water showed medium and strong correlation with the content of

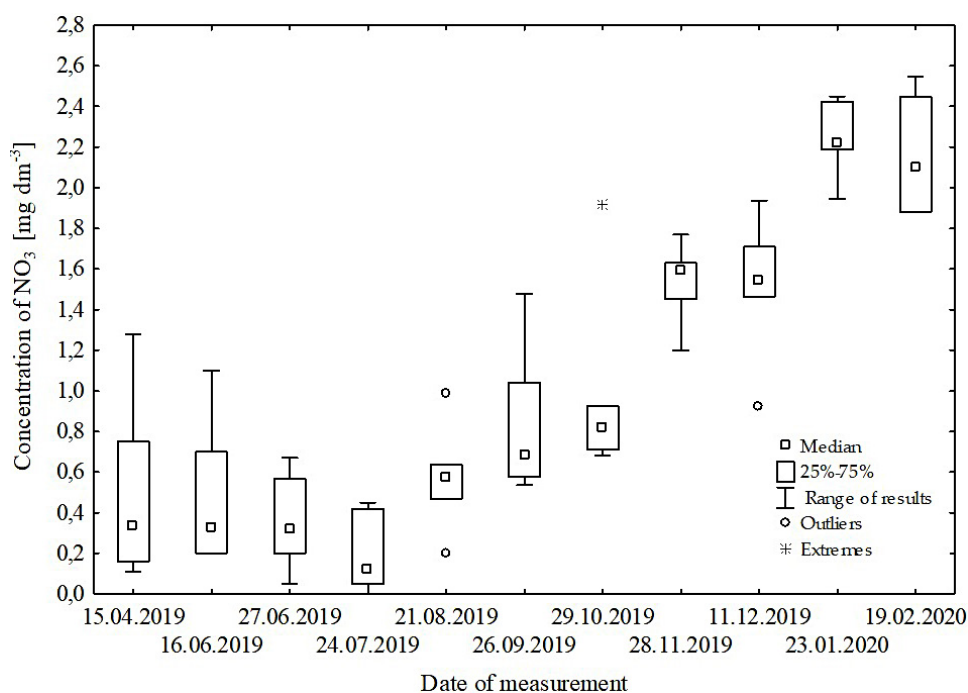


Figure 2. Concentrations of nitrate nitrogen (NO₃) in urban reservoirs

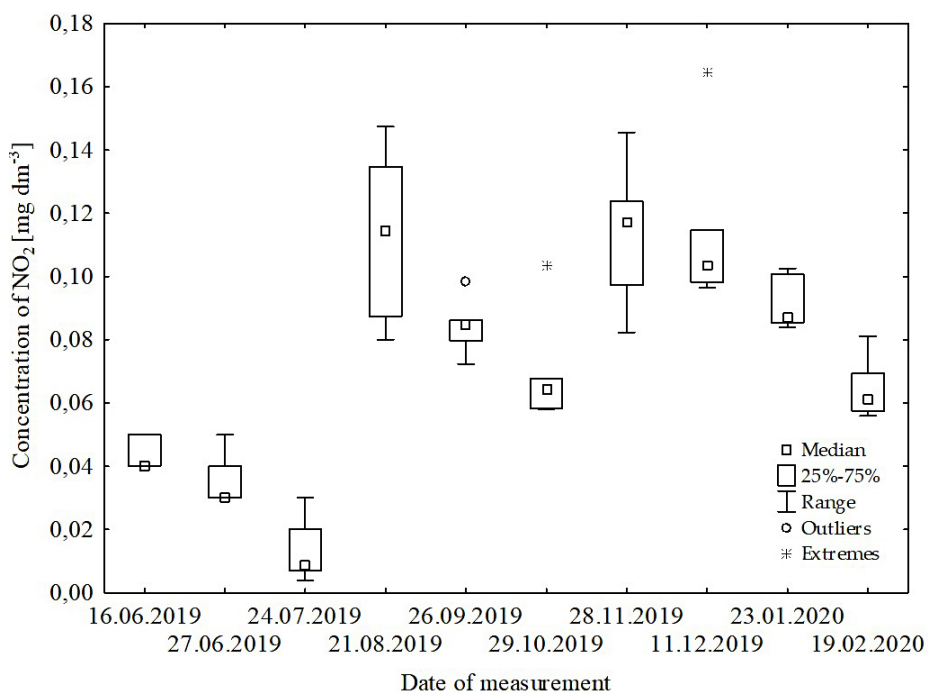


Figure 3. Concentrations of nitrite nitrogen (NO₂) in urban reservoirs

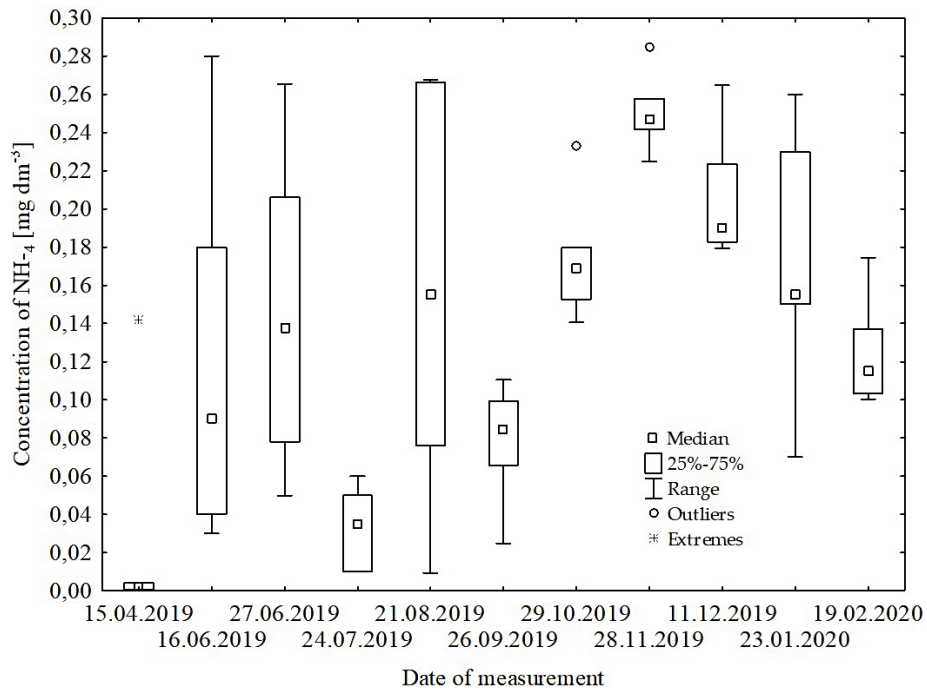


Figure 4. Concentrations of ammonium nitrogen (NH₄) in urban reservoirs

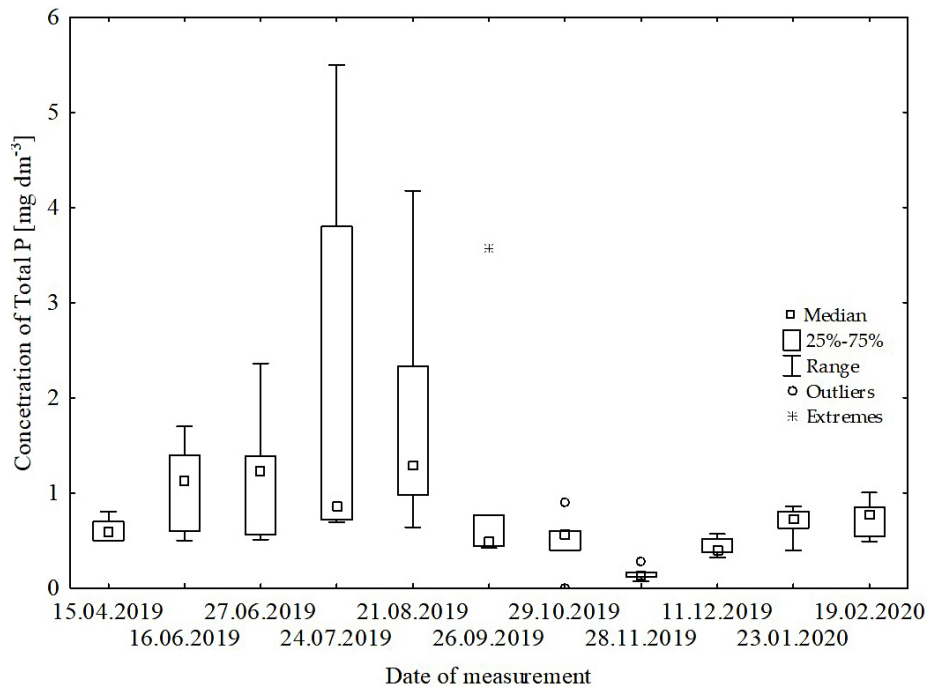


Figure 5. Concentrations of total phosphorus (P_{tot}) in urban reservoirs

nitrogen oxide and dioxide in the air, while no statistically significant correlation with the amount of precipitation was found. The content of nitrate and nitrite nitrogen was also strongly correlated with the relative air humidity (Table 3), which indicates the influence of external factors on the water quality in inner-city reservoirs. [Hassall, 2014; Céréghino et al., 2008; Revitt et al., 2014;

Kuoppamäki et al., 2014; Zimmermann et al., 2003]. The content of total phosphorus was characterized by high variability in the research period, but no statistically significant relationships with the observed air quality parameters were found.

The conducted research confirmed that the quality of surface waters depends on air quality. This fact is also confirmed in other studies

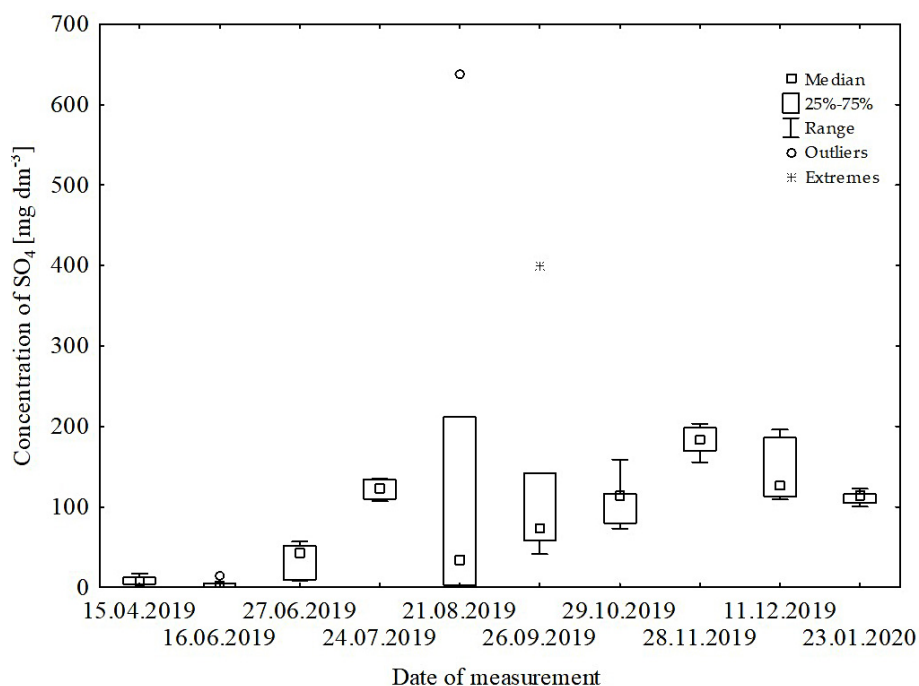


Figure 6. Concentrations of sulfates (SO₄⁻) in urban reservoirs

Table 3. Correlation matrix

Specification	pH	Cond.	Turb.	NO ₃	NO ₂	NH ₄	P _{tot}	SO ₄	NO ₂ /Air	NO ₃ /Air	SO ₂ /Air	Mean temp.	15 days precipitation	Air humidity
pH	1	0.211	-0.1271	0.4263	0.0532	0.1789	-0.086	-0.1273	0.3872	0.3558	0.3954	-0.6393	0.3154	0.0053
	p=---	p=.133	p=.369	p=.002	p=.708	p=.204	p=.544	p=.369	p=.005	p=.010	p=.004	p=.000	p=.023	p=.970
Cond.	0.211	1	0.4643	-0.0782	0.3115	0.1892	0.1283	0.1677	0.0064	0.0151	0.1115	0.0571	-0.3996	-0.0201
	p=.133	p=---	p=.001	p=.582	p=.025	p=.179	p=.365	p=.235	p=.964	p=.915	p=.431	p=.687	p=.003	p=.887
Turb.	-0.1271	0.4643	1	-0.4519	-0.3255	-0.4161	0.3863	-0.1566	-0.4033	-0.4848	-0.3521	0.5368	-0.3444	-0.2472
	p=.369	p=.001	p=---	p=.001	p=.019	p=.002	p=.005	p=.267	p=.003	p=.000	p=.010	p=.000	p=.012	p=.077
NO ₃	0.4263	-0.0782	-0.4519	1	0.6091	0.462	-0.3327	0.0808	0.7044	0.7663	0.5609	-0.7906	0.2364	0.5213
	p=.002	p=.582	p=.001	p=---	p=.000	p=.001	p=.016	p=.569	p=.000	p=.000	p=.000	p=.000	p=.092	p=.000
NO ₂	0.0532	0.3115	-0.3255	0.6091	1	0.6121	-0.2345	0.4283	0.5225	0.6486	0.4935	-0.5135	-0.3101	0.5533
	p=.708	p=.025	p=.019	p=.000	p=---	p=.000	p=.094	p=.002	p=.000	p=.000	p=.000	p=.000	p=.025	p=.000
NH ₄	0.1789	0.1892	-0.4161	0.462	0.6121	1	-0.2252	0.2625	0.2575	0.3743	0.3165	-0.3953	0.0543	0.1057
	p=.204	p=.179	p=.002	p=.001	p=.000	p=---	p=.108	p=.060	p=.065	p=.006	p=.022	p=.004	p=.702	p=.456
P _{tot}	-0.086	0.1283	0.3863	-0.3327	-0.2345	-0.2252	1	-0.2129	-0.3386	-0.4133	-0.3119	0.4339	-0.2817	-0.2141
	p=.544	p=.365	p=.005	p=.016	p=.094	p=.108	p=---	p=.130	p=.014	p=.002	p=.024	p=.001	p=.043	p=.128
SO ₄	-0.1273	0.1677	-0.1566	0.0808	0.4283	0.2625	-0.2129	1	0.2539	0.2721	0.1669	-0.0854	-0.1211	0.3368
	p=.369	p=.235	p=.267	p=.569	p=.002	p=.060	p=.130	p=---	p=.069	p=.051	p=.237	p=.547	p=.393	p=.015
NO ₂ /Air	0.3872	0.0064	-0.4033	0.7044	0.5225	0.2575	-0.3386	0.2539	1	0.9545	0.8985	-0.7591	0.1664	0.6309
	p=.005	p=.964	p=.003	p=.000	p=.000	p=.065	p=.014	p=.069	p=---	p=.000	p=.000	p=.000	p=.238	p=.000
NO ₃ /Air	0.3558	0.0151	-0.4848	0.7663	0.6486	0.3743	-0.4133	0.2721	0.9545	1	0.8139	-0.8367	0.2169	0.7419
	p=.010	p=.915	p=.000	p=.000	p=.000	p=.006	p=.002	p=.051	p=.000	p=---	p=.000	p=.000	p=.122	p=.000
SO ₂ /Air	0.3954	0.1115	-0.3521	0.5609	0.4935	0.3165	-0.3119	0.1669	0.8985	0.8139	1	-0.6226	-0.0458	0.2886
	p=.004	p=.431	p=.010	p=.000	p=.000	p=.022	p=.024	p=.237	p=.000	p=.000	p=---	p=.000	p=.747	p=.038
Mean temperature	-0.6393	0.0571	0.5368	-0.7906	-0.5135	-0.3953	0.4339	-0.0854	-0.7591	-0.8367	-0.6226	1	-0.3673	-0.5704
	p=.000	p=.687	p=.000	p=.000	p=.000	p=.004	p=.001	p=.547	p=.000	p=.000	p=.000	p=---	p=.007	p=.000
15 days precipitation	0.3154	-0.3996	-0.3444	0.2364	-0.3101	0.0543	-0.2817	-0.1211	0.1664	0.2169	-0.0458	-0.3673	1	0.1424
	p=.023	p=.003	p=.012	p=.092	p=.025	p=.702	p=.043	p=.393	p=.238	p=.122	p=.747	p=.007	p=---	p=.314
Air humidity	0.0053	-0.0201	-0.2472	0.5213	0.5533	0.1057	-0.2141	0.3368	0.6309	0.7419	0.2886	-0.5704	0.1424	1
	p=.970	p=.887	p=.077	p=.000	p=.000	p=.456	p=.128	p=.015	p=.000	p=.000	p=.038	p=.000	p=.314	p=---

[Zimmermann et al., 2003]. Atmospheric precipitation and the associated air humidity wash out different kinds of pollutants and then deposit them

in the reservoirs. Another path of pollutants movement is their initial assimilation by plants (e.g. tree leaves), i.e. wet and dry deposition [Zimmermann

et al., 2003; Selmi et al., 2016], and then, together with the falling matter, feeding the tanks in the autumn and winter period [Hassall, 2014; Céréghino et al., 2008; Jurczak et al., 2018].

Statistically significant differences were indicated between the content of nitrogen forms in water samples and the date of the observation. It was directly related to the air temperature (Table 3). The changes in nitrogen concentrations in water samples are related to the temperature-dependent ammonification and denitrification processes [Jørgensen, 1989; Rysgaard et al., 1996]. The flow of pollutants from sediments towards the water depths (internal loading) is also intensified by anoxic conditions and the phenomenon of eutrophication [Pokorny, Hauser, 2002; Rosinska et al., 2017; Jørgensen, 1989]. The constant inflow of organic matter, the inflow of organic nitrogen to the reservoirs of the city moat intensifies this phenomenon, simultaneously supplying the water with nitrogen compounds [Rysgaard et al., 1996; Beutel, 2016; Augustyniak et al., 2017; Søndergaard et al., 2001]. Internal loading causing a flux of compounds between the sediment and the water in the reservoir also explains significant fluctuations in total phosphorus concentrations in the analyzed reservoirs of the city moat [Augustyniak et al., 2017; Søndergaard, Jensen, Jeppesen, 2001]. Internal loading occurs most intensively under anaerobic conditions caused by eutrophication; however, this phenomenon is also observed under aerobic conditions [Augustyniak et al., 2017; Søndergaard et al., 2001]. Stratification in shallow inner-city reservoirs does not occur; however, observations confirm that the main mechanism driving the internal loading phenomenon in this case are spring and summer algae blooms (Fig. 2, 5) [Rosinska et al., 2017; Augustyniak et al., 2017; Søndergaard et al., 2001]. This is also confirmed by the correlation of total phosphorus concentrations in water with air temperature (Table 3).

CONCLUSIONS

On the basis of the observations and the analyses performed, the following conclusions were formulated:

1. The physicochemical composition of water in downtown water reservoirs shows high variability during the season with the temperature

above 15°C. In the period with lower temperature, the physicochemical composition of water was more stable.

2. Changes in the content of nitrogenous forms and the content of total phosphorus were caused by the internal loading phenomenon dependent on temperature, oxygen conditions in the tank and the flow of organic matter.

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