Capacity of surface water to reduce air multi-pollution in urbanized areas (the City of Krakow, southern Poland)

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Abstract: The study analyzes changes in the physico-chemical parameters in a 400 cm^2 artificial water reservoir with distilled water, exposed to a 2-week (±2 days) period of atmospheric conditions in Krakow. After nearly 500 days, dry and wet deposition caused a shift from neutral to acidic pH levels (7.30–5.12, averaging 6.22 pH) and an average electric conductivity of 19.5 μS/cm (1.6–143.0 μS/cm). The study investigated chemical and biological pollutants, including pollen and fungal spores. Three distinct air quality periods were identified: (1) characterized by vehicle and combustion-related pollutants (Oct-Jan), (2) a transitional phase with increased biological particles (Feb-May), and (3) dominated by pollen and fungal spores (Jun-Sep). Despite peak air pollution in the warmest months, air temperature showed an inverse relationship with pollutant concentration, possibly due to decreased air humidity. Precipitation positively impacted air quality. The artificial reservoir received a total of 0.7 kg of air pollutants (723.6 mg/m^2 of surface water table). This corresponds to an annual load of 0.5 kg (551.4 mg) and a daily load of 1.51 mg. The reservoir's pollutant capture capacity was estimated at 28% ±21% (mean±SD), with a critical value of 12%. The study evaluated Krakow's surface water reservoirs' capacity to mitigate air pollution, indicating potential benefits for urban air quality.

Keywords: air multi-pollution, environmental quality, urbanized area, water reservoirs, surface water, aerobiological monitoring, the City of Krakow

INTRODUCTION

From a chemical point of view, sources of air pollution in Krakow are considered to be mainly emissions from vehicles and thermal emissions from building roofs. The recipients are humans, other organisms, and various components of the environment, including surface waters (Shao et al. 2006, Yunus et al. 2012, Gautam & Bolia 2020, Manisalidis et al. 2020, Thakur et al. 2020, Xu et al. 2022).

Krakow air quality has changed over time in comparison to the global and European contexts. For several days in December 2021, the city topped the major city Air Quality Index (AQI) list, ranking it as one of the most polluted cities in the world. The following month (January 2022), the city fell back to 31st on the list. Krakow and other Polish cities (Warszawa, Wrocław, and Poznań) usually top the list, along with others in India, Bangladesh, and Pakistan (Rogala 2022). Krakow's position on the list of European "polluters" has also changes steadily. According to Airly (2022), in terms of PM10 (particulate matter) concentrations suspended in the air exceeding the standard established by the World Health Organization ($PM10_{24h}$ 45 μg/m^3), Krakow ranked 7th in March 2022 (36.8 μg/m^3; 82% of the standard). Data were averaged across all measuring stations in each city.

So, what is air pollution? In winter, it is associated with the occurrence of smog and volatile compounds in polluted post-industrial areas, while in spring, summer, and autumn, natural airborne particles prevail, including pollen and fungal spore allergens. According to the World Health Organization (WHO), "Air pollution is the contamination of the indoor or outdoor environment by chemical, physical, or biological agents that alter the natural properties of the atmosphere". Generally, air pollutants can include "any substance that adversely affects humans and other living organisms or material goods" (Kleczkowski 2020). This paper adopts this definition of air pollutants since in some European countries biological agents, pollen grains, and fungal spores are considered air pollutants similar to anthropogenic particles suspended in the air (PM10; PM2.5), causing health problems at different levels (see CEN 2019).

It should be noted that air quality in Krakow is generally improving. According to the analysis of the AGH University report for the year 2020 (the corresponding year of the conducted research), the change in the average concentration of PM10 dust is higher in Krakow than in the entire province excluding Krakow. While the decrease (calculated during heating seasons) in Krakow is 45.42%, in Lesser Poland it is much lower – 28.73%. A similar trend is observed for PM2.5 dust – a decrease of 43.76% in Krakow, compared to 32.15% in the entire province excluding Krakow (Kleczkowski & Kotarba 2020). However, when analyzing the phenomenon of environmental pollution in Krakow, it should be noted that pollution in the city covers all environmental components: surface water (Aleksander-Kwaterczak & Plenzer 2019), groundwater (Kleczkowski et al. 2009), soil (Wardas & Pawlikowski 2008, Pierri 2020), bottom sediments (Wardas et al. 1996, Rzętała 2014), and atmospheric air (Traczyk & Gruszecka-Kosowska 2020, Nazar & Niedoszytko 2022). The aim of the study was to determine the interaction between surface water and air quality by distinguishing the types of air pollutants (chemical and biological) in different atmospheric conditions. Measurements were taken at research stations, usually every 2 weeks, over a period of 1.5 years. By examining the open water reservoirs in cities, we can verify whether their presence contributes to the city's ability to clean itself. Based on Greaver et al. (2012), we assumed that air pollution particles trapped on water surfaces are effectively removed from the air. Particles caught by other elements (such as wet leaves or asphalt) are blown away when the gripping surface is dry and are thus carried away again by the wind. Therefore, the following research hypothesis was formed: Due to the properties of the surface of water to capture and retain air pollutants, the air quality in urbanized areas is directly proportional to the total area of surface water reservoirs. Thus, urbanized areas with more reservoirs will be cleaner in terms of air pollution than similar areas with fewer reservoirs.

METHODS

The study was conducted in Krakow over a period of 1.5 years, from December 2, 2019, to March 24, 2021. Monitoring of the observed process, including the measurement of different variables at different locations, was performed. Measurements were taken at four sites: [1] an experimental surface water reservoir at AGH University (Fig. 1), which we used to measure physical data on the mass of air pollution particles captured by water exposed to the atmosphere, [2] the Śniadecki building roof at the Krakow Center at Jagiellonian University Medical College, where aerobiological monitoring was performed and the concentration of pollen and fungal spores in the air were observed, [3A] the weather station at the AGH University, at which meteorological data were measured; and [3B] a chemical air quality monitoring station (Polish General Inspectorate of Environmental Protection – GIOŚ), at which the concentrations of chemical particles in the air were recorded.

To effectively monitor air quality and the potential of open reservoirs to catch pollution particles, an artificial reservoir was installed at AGH University to simulate the behavior of natural and/or anthropogenic reservoirs. An artificial reservoir was built on the roof of a representative – building at AGH University, located in the city center (Mickiewicz Avenue), at a height of about 10 meters. The station was out of the rainfall shadow, meaning that the measuring station was exposed to full atmospheric conditions, including precipitation. There were no higher elements nearby (buildings or trees) that could limit wet deposition. This is important because wet deposition is currently acknowledged in the literature as a major deposition pathway (Wu et al. 2018, Jain et al. 2000). The artificial reservoir was covered with a metal grill to protect it from birds. The grill's material was inert to atmospheric precipitation (Bablik 1950) and therefore could not influence the test results. The reservoir consisted of 20 cylinders made of LDPE material, each with a gripping area of 19.625 cm^2 (5 cm wheel diameter) and a height of 12 cm (Fig. 1). The total gripping area was approximately 400 cm^2 (392.5 cm^2). Each cylinder was filled with 50 mL of distilled water and then exposed to real weather conditions in the urbanized area. In natural reservoirs, other factors influence the mechanisms of chemical reactions (resulting from the biological and chemical composition of water), which makes it difficult to analyze individual processes. The use of distilled water allowed for the monitoring of selected physicochemical changes caused exclusively by air particles. However, the mechanism of capturing air particles is the same.

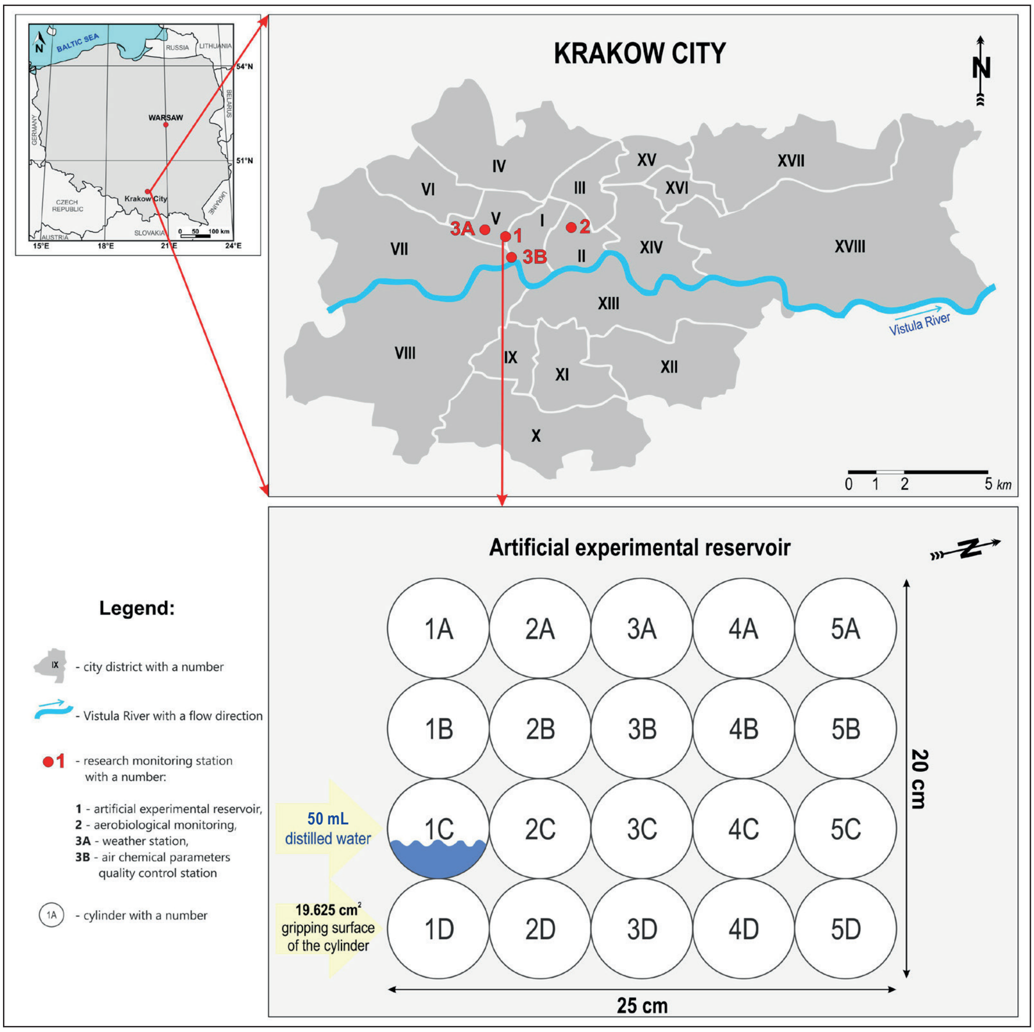

Fig. 1. *Location of research field, including four monitoring stations along with a scheme of an artificial water reservoir*

The exposure period of the artificial reservoir was intended to last two weeks, but due to COVID-19 related lockdowns, the measurement periods changed significantly for several series. Out of 31 measurement series, two lasted one week (1st and 15th) and three (7th, 9th, and 13th) lasted 44, 54, and 27 days, respectively. The time extension was enforced by the inability to access the building on which the measurement station was built. The remaining 26 measurement series each lasted 2 weeks ±2 days.

After exposure *in situ* (or after thawing the sample in the Hydrodynamic Laboratory at AGH University), the pH value and electric conductivity of the water were measured using WTW MultiLine IDS field meter. Then, after preparing and weighing the filters, a peristaltic pump was used to filter the water samples through a mixed cellulose esters (MCE) membrane filter with a porosity of 0.45 μm. After the filter was dried at 100°C, it was weighed to identify residual solids in the sample (Fig. 2). The mass of particles on the filter is equivalent to the amount of air particles caught on the water's surface in the artificial reservoir.

Pollen samples were collected in Krakow using the volumetric method according to the recommendations of the European Aerobiology Society (Galán et al. 2014), European Standard (CEN, 2019), and the procedures for Polish aerobiological stations (Stach & Kasprzyk 2005). The concentration of grass pollen and fungal spores in the air was determined using a Lanzoni VPPS 2000 sampler that was placed at a standard height of 20 m above ground level (220 m above sea level) (Galan 1998) on the roof of the Collegium Sniadecki building at the city center. The volumetric sampler operated continuously throughout the entire year, collecting air samples, including pollen material and fungal spores, on Melinex tape on a rotating drum. Air was drawn in at a constant rate of 10 L/min. The samples were examined using a light microscope at 400× magnification. Pollen grains were counted along four longitudinal lines (recommended by the European Aerobiology Society). The concentration of biological particles (pollen grains or fungal spores per unit/m^3 of air/24 h) was calculated for the average mass using unit weight (pollen particle = 3.5×10^{-3} g and fungus spore = 0.04 g) (Pal & Poka 1973, Money 2016, Frka et al. 2022). The daily meteorological data were kindly provided by the METEO Service of the Environmental Physics Group in the Faculty of Physics and Applied Computer Science at AGH University. The data used were air temperature, precipitation, dew point, air pressure, and relative humidity. The weather station is at a similar altitude (10 m) to the artificial reservoir and is about 750 m away from the experimental reservoir.

Chemical particles in the atmospheric air in Krakow were obtained from GIOŚ on Krasiński Avenue (international code: PL0012A). The data used concerned SO_2, NO_2, NO_x, NO, CO, CO(8 h), C_6H_6, PM2.5, and PM10, as well as substances in PM10, including As, Cd, Pb, Ni, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, benzo(j)fluoranthene, dibenzo(a,h)anthracene, benzo(k)fluoranthene,

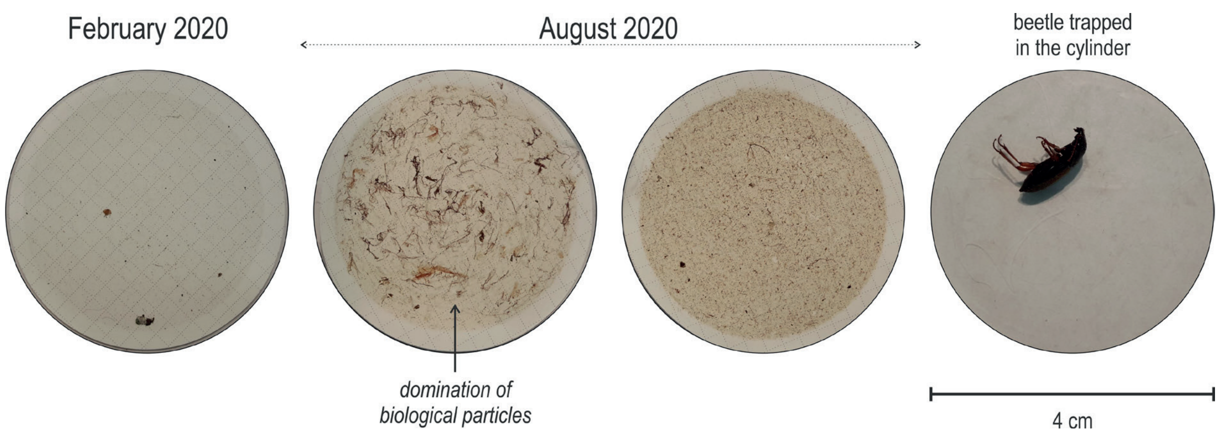

Fig. 2. *Filters after filtering the water from the cylinder of the experimental reservoir (photo D. Pierri)*

benzo(a)anthracene, benzo(b)fluoranthene, and benzene. (Note: NO_x is the sum of all nitrogen oxides in the air, not just NO and NO_2). The methodology for measuring substances in the air is specified in the EU directive (2008/50/EC), regulations of the Minister of the Environment (Rozporządzenie 2010, 2020, 2021), and Polish standards (PKN 2004, CEN 2012, 2014). Chemical results obtained from GIOŚ were verified by the National Reference and Calibration Laboratory for ambient air quality (QA/QC system) in accordance with EU Directive 2008/50/EC on ambient air quality and cleaner air for Europe (Directive 2008/50/EC). The measuring station is 800 m away from the artificial reservoir.

The data obtained from the research stations (Table S1 attached to the article as a supplementary file in online version) were statistically analyzed using linear models in the lme4 package (version 1.1.30) for R (version 4.2.1). We used the total mass of particles in air (in milligrams per cubic meter) as the dependent variable. We created one model for each of the variables of interest: air temperature, precipitation, dew point, air pressure, and humidity. All continuous variables were transformed and/or scaled to obtain a normal distribution. We considered any factor significant for which a statistic was above two. The results of the linear models are shown in Table 1. The correlations between all variables are presented in Figure 6 (p. 200).

RESULTS AND DISCUSSION

Air quality studies conducted in Krakow (Obtułowicz et al. 1996, Bokwa 2008, Szulecka et al. 2017, Pierri 2020, Traczyk & Gruszecka-Kosowska 2020, Zaręba & Danek 2022) have shown that the levels of particulate matter (chemical and biological) present in the air significantly impact the quality of surface water. In addition, the air in urbanized spaces is strongly differentiated in volume (Frka et al. 2022), not only regionally, but also on a small experimental scale, according to our results (Table S1).

The mechanism of air pollution in Krakow

When a stable atmosphere and air stagnation occur in depressions such as river valleys, extremely adverse conditions associated with smog, and in a broader sense, air pollution arise. One such area is the city of Krakow in southern Poland, which is located in a depression through which the longest Polish river, the Vistula, flows. In this case, cold air is collected in the valley and begins to invert. The presence of rivers or other reservoirs promotes fog formation, further maintaining and exacerbating this air stagnation. During the day, solar radiation that passes unhindered through the atmosphere under high pressure conditions is reflected by the overlying fog layer. Thus, the earth's surface warming associated with high-pressure areas does not occur. As a result, there is further cooling at night due to the heat release of infrared radiation. Furthermore, the same process that radiates heat is partially absorbed by daytime fog (Kleczkowski 2020). In Poland, nocturnal radiation reversal occurs 60–70% of the year. The quantity of days with surface inversion may exceed 20% in winter and several percent in summer. Typically, upper inversions occur 20–30% of the days of the year; however, in winter, they occur at a rate of often more than 50%. Upper inversions occur hundreds of meters (up to 1000 m) above the ground, and inversion thickness is usually tens to hundreds of meters (Wielgosiński & Zarzycki 2018, Kleczkowski 2020).

Wind currents through urban areas differ from wind currents over open or sparsely populated areas. The drag of the buildings increases the total friction of air against the ground, reducing the average air velocity. Previous research in Krakow has shown that turbulence persists in so-called rough layers (i.e., soil layers) at the urban and regional levels (Kleczkowski 2020). Turbulence is the highest especially in the lowest part of the boundary layer, the part that is in direct contact with the ground and buildings. In this layer, the horizontal wind speed is heterogeneous because it is affected by individual objects and their groups, causing turbulence in the airflow. The depth of the rough layer depends on the average height of the building, which is typically two to five times the average height (Szulecka et al. 2017, Kleczkowski 2020). On the street scale, direct interactions occur between pollution sources and their recipients.

Research periods

Changes in air quality characteristics that affected the amount of pollutants captured by surface water in reservoirs in urbanized areas were observed over three periods (Fig. 3), which were selected based on the statistical pollen calendar for Lesser Poland in Region II:

1) October 1 to January 31, when chemical pollutants in the air are mainly from vehicle exhaust and combustion products in heating furnaces. Pollen does not occur or is negligible.
2) February 1 to May 31, when a period of pollination begins, particularly for trees, which results in the presence of biological particles in the air. Particles of chemical pollution are still present in atmospheric air.
3) June 1 to September 30, when the pollination of herbaceous plants and grasses predominates, and many fungi release spores. Pollen concentration is highest this time of year.

Period No. 1, October 1 to January 31, was characterized by average daily temperature rising to +3.7°C. This period accumulated the least rainfall; the average daily precipitation was 0.59 mm. Despite this, Period No. 1 experienced the highest daily relative air humidity (75.9 g/m^3). Moreover, air pressure achieved an average of 84 hPa, which was the highest recorded among the periods.

Period No. 2, February 1 to May 31, was characterized by its average daily temperature's increasing to +5.8°C. This period's average daily precipitation was 1.03 mm. The relative air humidity was 56.9 g/m^3. The air pressure was, on average, 61 hPa.

Period No. 3, June 1 to September 30, was characterized by an increase of +19.1°C in the average daily temperature. The summer months in warm temperate climates are statistically the rainiest, and the average daily precipitation during period No. 3 was 1.86 mm. The relative air humidity was 61.2 g/m^3. Moreover, the pressure averaged 76 hPa.

The division of the observation year into three periods was a direct result of analyzing what types of pollution in what volumes are present in Krakow's air. For example, the coldest period No. 1, was characterized by having the most particles contained in the air. Using the example of:

[chemical compounds] : [pollen] : [fungal spores]

period 1's ratio was 9 : 0 : 1, period 2's was 3 : 1 : 1, and period 3's (the warmest) was 0 : 1 : 4.

It should be noted all chemical compounds, including those resulting from anthropopressure, that entered the air during research periods were considered chemical particles. Biological particles included pollen and fungal spores.

The mass of pollutants contained in the air

The main parameter that was measured in terms of the artificial reservoir was the total mass of the particles caught by the distilled water exposed to atmospheric conditions. The measurement of dry mass, according to the adopted definition of air pollution, indicates the amount of chemical and biological particles contained in the air. Each period was characterized by a different average daily mass. Period No. 1 had the lowest average of 0.88 mg per day. Periods Nos. 2 and 3 presented similar results. Period No. 2, including spring, averaged 2.33 mg per day, and period No. 3, including summer, averaged 2.16 mg per day.

After discarding measurement series that were either longer or shorter than 2 weeks ±2 days, a maximum mass of 83.2 mg was reached in the 10th series, which ran from May 8 to May 22, 2020, in period No. 2. The average weight was 22.25 mg.

In Period No. 1, the total mass of pollutants in the air per day was 2.23 mg/m^3 and the total mass of pollutants over the entire study was 354.94 mg/m^3. Period 2's daily total mass of airborne pollutants was 4.68 mg/m^3 and total amount was 982.14 mg/m^3. Period No. 3 had a daily pollutant concentration of 43.39 mg/m^3 and a total concentration of 4773.40 mg/m^3. It should be noted that periods Nos. 1, 2, and 3 comprised 159, 210, and 110 measurement days respectively.

All chemicals SO_2, NO_2, NO_x, NO, CO, CO(8h), C_6H_6, PM2.5, PM10, and substances in PM10, including As, Cd, Pb, Ni, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, benzo(j)fluoranthene, dibenzo(a,h)anthracene, benzo(k)fluoranthene, benzo(a)anthracene, benzo(b)fluoranthene, and benzene except As and Ni exhibited the same trend: the highest concentrations occurred in period No. 1, and the lowest were measured in period No. 3. As and Ni were most concentrated in period No. 2.

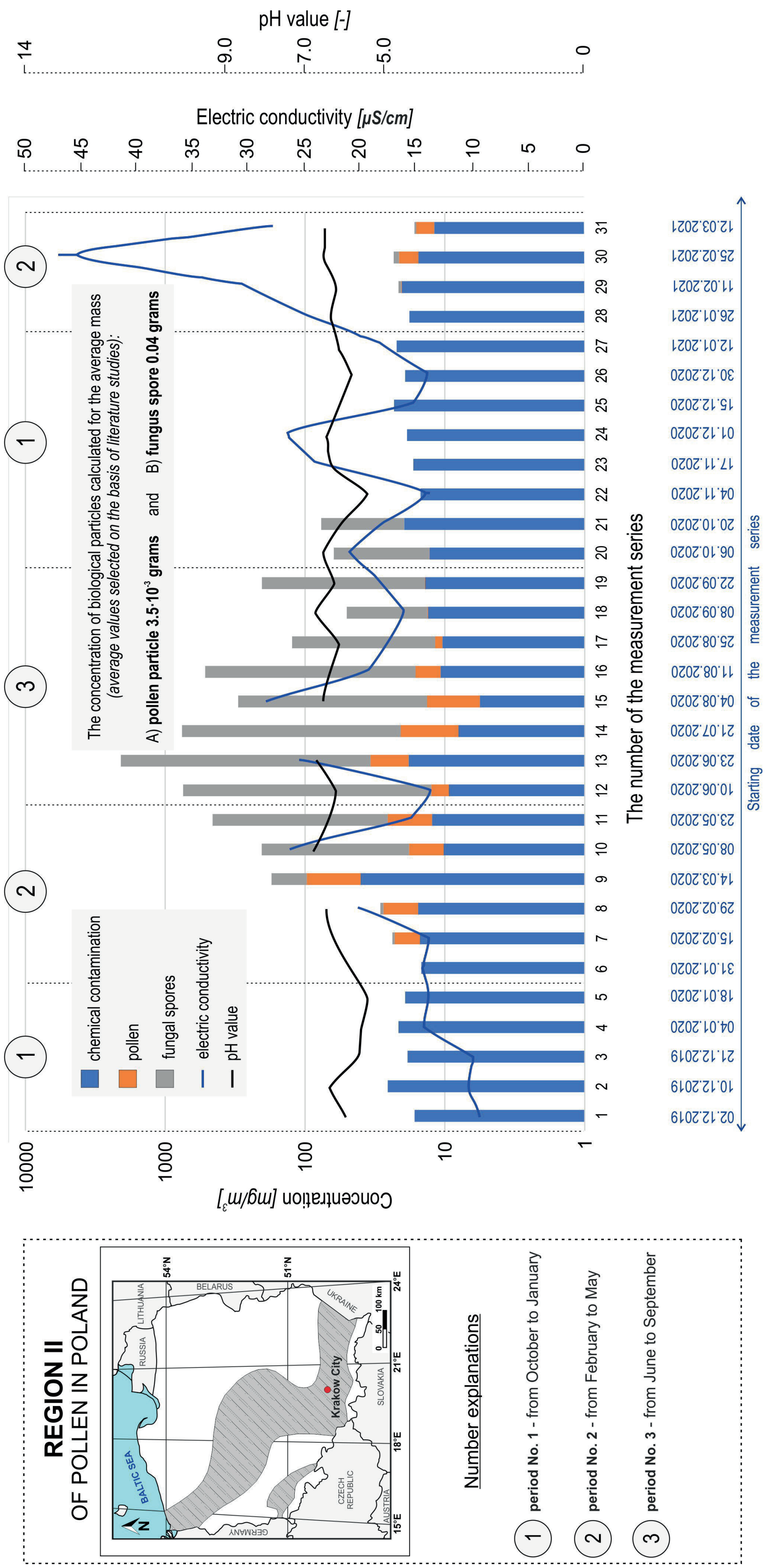

Fig. 3. *Composition of air polluting particles in Krakow, broken down into types (average weight of pollen particles and fungal spores based on literature review, including Money 2016 and Pal & Poka 1973)*

Therefore, it is conjectured that chemical pollutants may be primarily associated with combustion in homes and vehicle exhaust fumes on cold days. On warm and hot days, home heating systems are turned off, and some car users switch to bicycles and scooters.

Biological particles showed a reverse trend: the highest and lowest concentrations occurred in periods Nos. 3 and 1 respectively. Pollen and fungal spores dominate the air on the warmest days, but during the cold months, this phenomenon does not occur. Moreover, the mass of fungal spores, is on average, an order of magnitude greater than that of pollen.

Period No. 2 is therefore a transitional phase in which the volume of chemical pollutants decreases and the amount of biological particles increases.

Physicochemical parameters

In the artificial water reservoir's total research area of about 400 cm^2, the water's electric conductivity (EC) varied 90 times, from 1.6 to 143 µS/cm, after exposure to external conditions. Such significant differences may be caused by the presence of, for example, the salt crystals used to maintain the streets in Krakow in winter, which rises into the air as a result of turbulent air movements in the rough layer. These assumptions were based on the proximity of Mickiewicz Avenue and the extensive use of road salt in Krakow. In all measurement series, the pH varied by 2.2 between 5.12 and 7.30 (Fig. 4). In this layer, the horizontal wind speed is heterogeneous. Chemical pollution is also related to the exhaust fumes emitted by vehicles which degrade the quality of life of Krakow residents (Gawryluk et al. 2023).

Prior studies have shown no correlation between changes in pH and the EC of water in an artificial reservoir exposed to atmospheric air. However, a linear trend (R^2 = 36%) shows that as chemical and biological particles settle on the water's surface, the acidity of the pH decreases (Fig. 5).

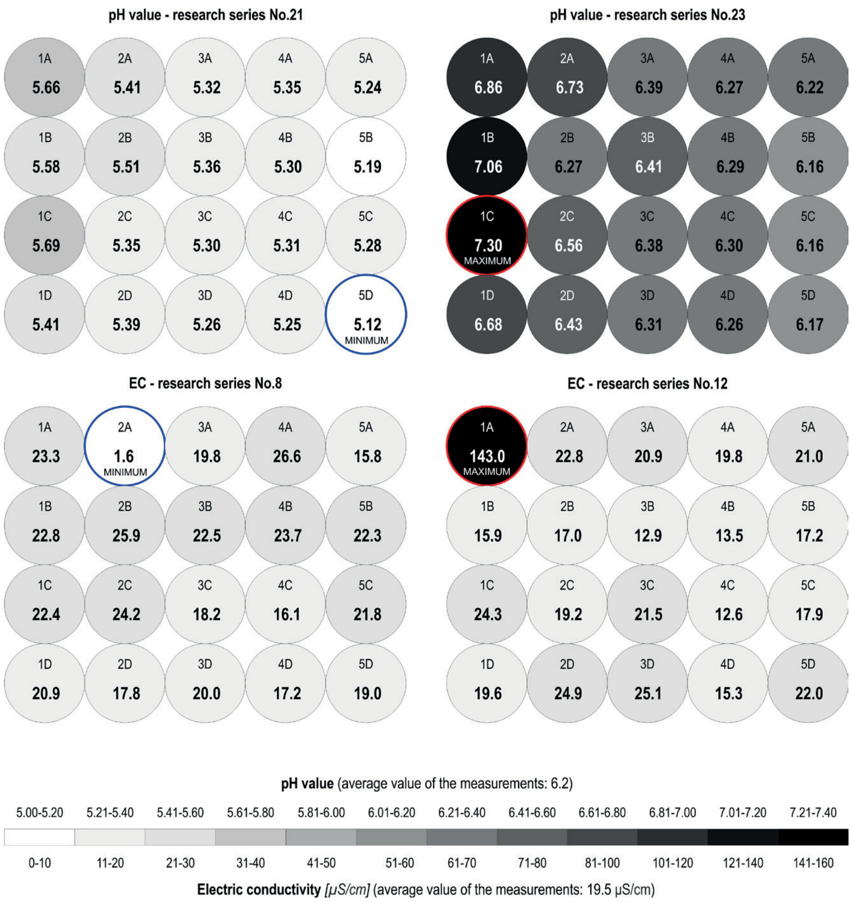

***Fig. 4.** Results of electric conductivity and pH measurements in the waters of an artificial reservoir (in selected test series with measurement minima and maxima)*

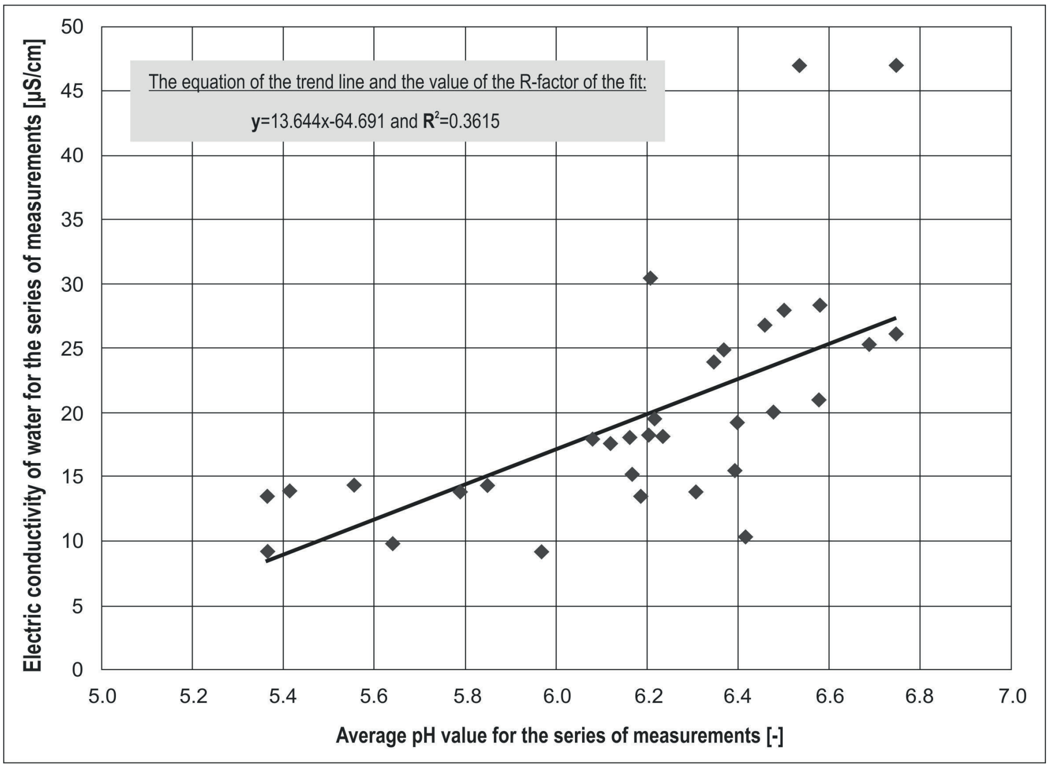

Fig. 5. *Relationship between pH and electric conductivity [µS/cm] of water in an artificial experimental reservoir*

Statistical analysis

Although the maximum concentrations of all air pollutants (chemical and biological) in Krakow are highest in the warmest months of June – September (period No. 3), the linear model shows that the air temperature is inversely proportional to the average concentration of pollutants (see Table 1). The higher the air temperature, the lower the concentration of pollutants (using the adopted definition).

Table 1
Results of statistical analysis of atmospheric factors

Characteristics	Statistics			
	Estimate	Standard Error	*t* value	*p* value
Intercept	0.08	0.04	1.98	0.05
Air temperature	−0.03	0.01	−5.97	0.0001
Intercept	0.02	0.06	0.36	0.72
Precipitation	−0.06	0.02	−2.15	0.04
Intercept	0.08	0.06	1.33	0.19
Air pressure	0.01	0.06	0.09	0.93
Intercept	0.08	0.05	1.59	0.12
Humidity	0.02	0.05	3.51	0.001

This finding may be true because the air humidity decreases with increasing temperatures. In fact, the results of the linear humidity model show that the higher the humidity value, the higher the concentration of pollutants in the air. This can be explained by the fact that, at high air humidity, pollutants suspended in space on water molecules have a limited possibility of falling to the earth's surface. With an increase in temperature, humidity decreases (water evaporation), thereby explaining the absence of pollutants in warmer periods (see the correlation results in Figure 6). However, the finding may also be related to the composition of the studied pollutants: in summer, much less pollen is suspended in the air, and many more gaseous pollutants are present than were monitored in this work. Moreover, pollen concentration increases on short rainy days but decreases over continuous rainy days, especially in the case of tree and shrub pollen (Bishan et al. 2020). In Krakow, the daily pollen concentrations are influenced by meteorological elements up to seven days past, among which temperature and relative humidity prevail (Myszkowska & Majewska 2014).

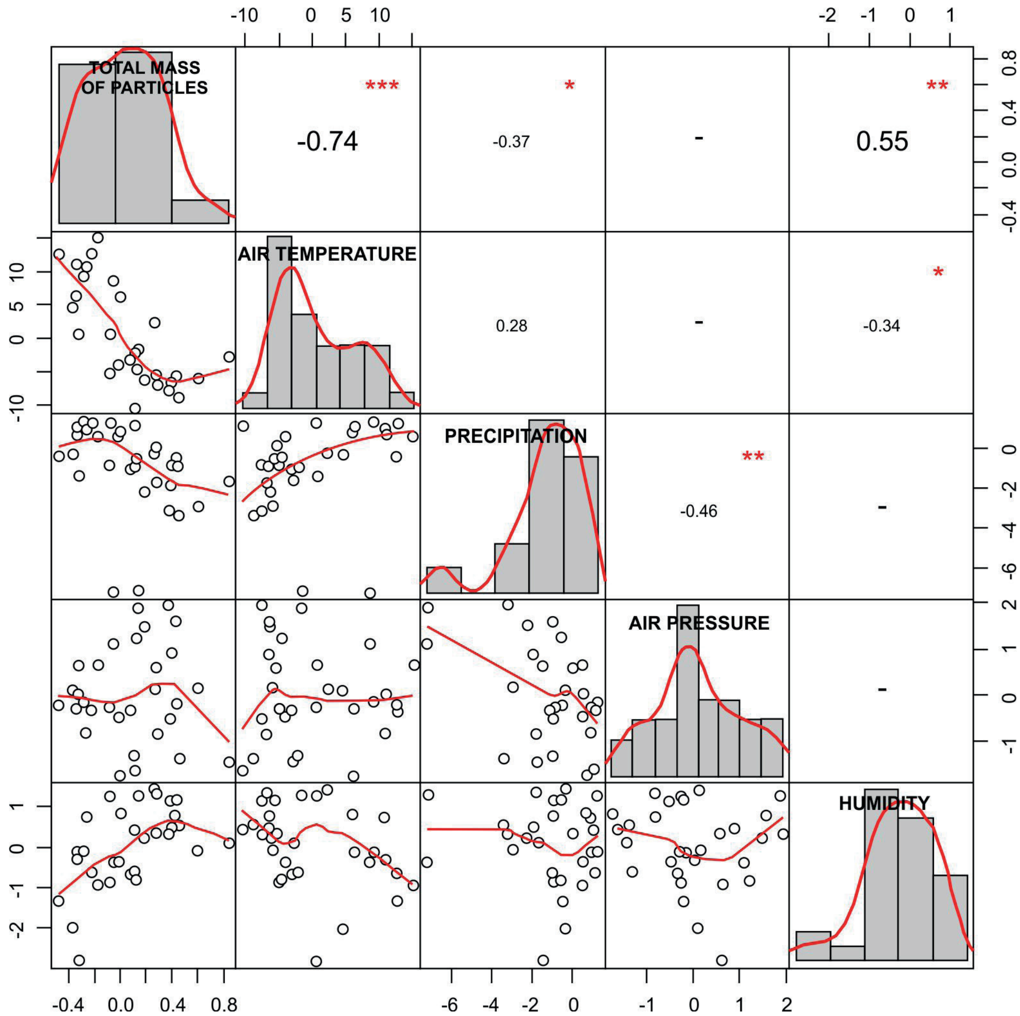

Fig. 6. *Results of statistical analysis of atmospheric factors and concentrations of pollutants in the air*

When analyzing the concentration of pollutants in the air, it should be remembered that air density (measured mainly by air humidity) decreases with increasing temperature, as our results show.

The results of the linear model show that as the amount of precipitation increases, the amount of air pollution decreases. The ratio of the amount of precipitation to the concentration of chemical particles in the air displayed a decreasing trend for all monitored components (but with a low degree of R^2 adjustment). This validates the popular phrase "Rain washes the air". Strictly speaking, individual particles present in a volume of air are trapped by raindrops (or other precipitation) and fall onto the earth's surface because of gravity. As Ritter et al. (2002a, 2002b) reported pollutants are loaded from the atmosphere into water reservoirs primarily through wet or dry deposition. Wet deposition refers to the removal of air pollutants from the air via precipitation, such as rain or snow. This is an important transport route throughout the world.

The results of the linear model show that air pressure has no effect on the presence of chemical pollutants, pollen, or fungal spores in the air.

We found that air temperature, humidity, and atmospheric pressure are correlated with the percentage of air pollution particles that can be captured by the water's surface in an open reservoir. The amount of precipitation does not seem to affect a reservoir's capacity to catch pollutants. Even so, it must be considered that precipitation is negatively correlated with air pressure and that temperature is moderately correlated with humidity.

Capacity of surface water to reduce air pollution

The artificial reservoir, which was the key element in the study, received 0.7 kg of air pollutants during the research period after conversion per square meter of research area (exactly 723.6 mg/m^2 of surface water table). This means that an annual load would weigh, on average, 0.5 kg (551.4 mg), and a daily amount, 1.51 mg.

To calculate the artificial reservoir's capacity to catch pollutants in the air in Krakow, the mass of the particles that remained in the reservoir was divided by the mass of the sum of all the chemical and biological pollutants in the same measurement series. This allowed us to assess how much air contamination was removed by the surface water, with the assumption that the quantity of contamination trapped in the solution could be compared with the quantity in the air averaged over the volume. The arithmetic mean±SD was 28% ±21%. It should be critically noted that the sum of the masses remaining on the filter divided by the sum of the masses of all impurities amounted to 12%. We assumed that the average contact time of the reservoir with contaminated air is equal to the measurement series, which is approximately 2 weeks ±2 days. Therefore, the quantity trapped over the same duration was compared to that volume of air. Early-stage research indicated that a two-week period was the shortest measurement period due to technical limitations of the measurements. The medium here is water, which is the only thing that can transport (chemical and biological) pollution particles over long distances. At the same time, the reservoir's water surface is the only thing that effectively retains these particles. A study on the effects of air pollution on water quality used emissions inventory techniques to determine that the atmospheric input of some pollutants into surface waters indicates a significant percentage of their total loading (USEPA 1977). Moiseenko et al. (2016) indicated negative consequences concerning the enrichment of surface waters by trace elements and other polluting particles that affect the quality of water as well as eutrophication, salinization, and acidification. Dry deposition refers to the removal of (1) aerosol pollutants by eddy diffusion and impact, (2) large airborne particles by gravity deposition, and (3) gaseous pollutants by direct transfer from air to water (Ritter et al. 2002a). Air pollutants can also enter surface waters indirectly, as is the case when air pollution deposited on land is transferred to the receiving water by other routes, such as stormwater runoff and inflow from tributaries. The tendency of a particular pollutant to enter a water body via wet or dry deposition or gas exchange is highly dependent on the pollutant's physical and chemical properties and current meteorological conditions (Ritter et al. 2002a, Tegart et al. 2021). It should be noted that our experiment only considered the direct deposition of pollutant particles.

The city of Krakow covers a 326.9 km^2 area. Surface flowing and stagnant waters cover 693 ha (Statistical Office in Kraków 2021), which represents 2.1% of the city area. Air pollution, including smog, was assumed to be a phenomenon comparable between cities, including those in Europe (e.g. Newcastle, Paris, and Seville). Although this study is preliminary, the authors allowed themselves to offer a significant approximation of the capture of pollutants from the air in Krakow. Over 479 days, the observations indicated that the total mass of the pollutants in the city's air was 6,110.48 mg/m^3. To maintain a high approximation to obtain illustrative results, the area of the surface water in Krakow was multiplied by the mass of the pollutants using 12 and 28% rates of pollutant capture (according to calculations for an artificial reservoir).

For a 12% capture level of multi-pollutants in the air, the surface waters in Krakow absorbed 5 Mg of load (5,081 kg). For 28% capture level increases to 12 Mg of pollutants (11,856 kg). Presenting the same result calculated for one year (365 days), this value varied from 3.9 to 9.0 Mg of pollution.

Using these values, the daily load of pollutants absorbed by Krakow's surface waters ranges from 10.6 to 24.8 kg.

It is worth mentioning that microbial bioaerosol tests were conducted two years prior to our study on Mickiewicz Avenue in Krakow (Grzyb et al. 2017). Indeed, their microbial experiment research site is about 170 m away from our artificial reservoir. The average concentration of bacteria in the alley was around 18,500 CFU/m^3. The results of an analysis of dustiness divided into day and night showed that, regardless of the measuring station and fraction (PM10 or PM4), dust concentration was higher at night. Lower concentrations of bacteria have been recorded with increasing air pollution, which means that only a fraction of bacterial cells settle on air pollution particles (chemical or biological).

The microbiological aspect of air pollution was not considered in this research because atmospheric factors affect bacterial populations. Above all, strong solar radiation causes some bacteria to die during the day because of its drying and bactericidal effects. In rural areas, atmospheric factors significantly influence bacterial concentrations (Lighthart & Shaffer 1995, Tong & Lighthart 1999). However, in large cities and urbanized areas, atmospheric factors seem to have little effect (Grzyb et al. 2017). Therefore, when assessing the impact of atmospheric air pollution on the water's surface in Krakow, a detailed analysis of bacteria counts is unnecessary.

Natural and artificial open water surface reservoirs (lakes, ponds, retention reservoirs) play many roles in cities and urban areas. The ability of surface water reservoirs to capture multi-pollutants has a direct effect on cleaning the air above the reservoir. This also means that allergy sufferers should feel relieved when biological particles, often allergenic, are caught in the immediate vicinity of the reservoir – allergen reduction or avoidance measures have been widely utilized (Kalayci et al. 2022). Immobilization of pollen is often visible in the form of a yellowish pollen slime forms on the water table (even on a puddle) (Woodfolk et al. 2015). Also, the presence of water reservoirs contributes to a local temperature drop (Gupta et al. 2018), despite the presence of an urban heat island.

All forms of open water in urbanized areas (ponds, lakes, and even fountains) improve the quality of life of the inhabitants. Reservoirs are more than just eye-catching objects. Access to green spaces and bodies of water has a positive impact on residents' mental health and promotes community cohesion and social interaction (Wood et al. 2022, Overbury et al. 2023, Utilities One 2023). The presence of open water reservoirs results in the presence of a variety of plant and animal species. Moreover, these reservoirs act as crucial habitats for various wildlife, contributing to local biodiversity conservation (Hassal 2014, Oertli & Parris 2019, Gibbons et al. 2023, Utilities One 2023).

Larger reservoirs occupy a specific area, not overgrown, i.e. not requiring mowing. Therefore, reduce the costs of maintaining urban greenery in good condition. Some reservoirs can also function as retention reservoirs, storing the surface runoff of rainwater which is abundant in concrete cities and limiting the loss of valuable water resources.

In hydrogeology, the potential for the self-purification of the environment (especially in relation to the soil and groundwater environment) is called "natural attenuation" or "internal reclamation". These methods assume the use of environmental opportunities for cleanup activities, which are often assessed by low financial outlays (McAllister & Chiang 1994, Illman & Alvarez 2009). Translating the analogy from groundwater to global air pollution, we should look for a method of self-purifying air with multi-pollution in urban areas. Accordingly, the ability of surface water reservoirs to capture biological and chemical particles can be treated as "natural attenuation" for the air.

However, the authors are aware that immobilization of pollutants in water reservoirs causes the pollution of these waters. This is not a problem for closed-circuit water (fountains, ponds) where filters and/or purifiers are installed. The aspect of water pollution in natural reservoirs should be monitored by hydrologists, especially when the reservoirs are of an infiltrating nature, since they may cause groundwater contamination.

CONCLUSION

Air pollution in cities varies greatly in terms of composition (chemical and biological) and such heterogeneous environmental components are difficult and expensive to clean. Therefore, the conclusions of this study indicate that open surface water reservoirs in urbanized zones may constitute the basis for the “natural attenuation” of air.

When analyzing the types of air pollution in the studied urbanized space, three periods were distinguished:
- period No. 1 – from October to January, when chemical pollutants are related to vehicle exhaustion and combustion products in heating furnaces and pollen does not occur;
- period No. 2 – from February to May, when chemical pollution is still present and biological particles are present;
- period No. 3 – from June to September, when biological particles dominate, especially fungal spores occurs; pollen is the most intense of the year.

The research showed that an artificial reservoir exposed to atmospheric factors (dry and wet deposition) caught 0.7 kg of multi-pollutants from the air in Krakow (per 1 m^2 of tank surface) in 479 days. Water tests showed that distilled water had gone from neutral to acidic (average 6.22 pH) with a conductivity of average 19.52 μS/cm.

Locating reservoirs in cities has a number of advantages: (1) cleaner air, (2) reduced costs of maintaining urban greenery, (3) water conservation, (4) lowering the air temperature in the immediate vicinity of the reservoir, (5) relief for allergy sufferers.

In future studies, to investigate whether reservoir size correlates with purification capacity, we plan to continue measuring air pollution levels using different sizes of artificial water reservoirs. We then wish to compare our results with those obtained in places with natural water reservoirs (i.e., lakes and ponds).

Based on the results of this research, and regardless of future findings, we conclude that the creation of artificial water reservoirs (and the preservation of natural ones) positively contributes to improving air quality. To generalize strongly, the more reservoirs in a city, the higher the quality of life of its inhabitants.

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