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COMPARATIVE ANALYSIS OF PM10 CONCENTRATIONS IN A LARGE AND A SMALL URBAN AREA

This paper aims to analyse the concentrations of PM10 measured in Kraków and Starachowice. The choice of these areas enabled a comparison of PM10 concentrations between Kraków, where an anti-smog resolution is in force, and Starachowice, where no such regulations apply. Although numerous studies investigated particulate matter pollution, there remains a gap concerning field-based research presenting real-time PM10 concentrations. This article addresses this gap by presenting real-time measurements of PM10 concentrations in the investigated regions. Measurements were taken using the Steinberg Systems SBS air quality sensor. Measurements were conducted in the evenings, with wind speeds below 5 m/s, at temperatures of approximately −10, 0, and 10 °C. The collected results were presented by maps of the spatial distribution of PM10. Subsequently, results were analysed using statistical methods. The study enabled visualization of PM10 concentrations within the research areas and identification of zones with higher pollution levels. At comparable temperatures, the highest PM10 values were observed in the Wierzbnik district of Starachowice. A strong negative correlation between PM concentrations and temperature was found in Wierzbnik and Kraków, whereas Orłowo did not show this trend, likely due to post-snowfall conditions.

1. INTRODUCTION

Air pollution is a significant issue affecting numerous cities across Poland. The World Bank Group's data reveals that Poland accounts for 36 of the 50 most polluted cities in the European Union [1]. High concentrations of air pollutants can result in a spectrum of health effects, ranging from mild symptoms to more severe conditions in individuals [2, 3].

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WHO estimates that particulate matter (PM) air pollution contributes to approximately 4.2 million premature deaths each year, making it one of the leading causes of mortality worldwide [4]. However, PM air pollution does not only affect humans. It can also cause harm to wildlife, vegetation, and even historical monuments [5–7].

Particulate matter concentration in the air is susceptible to seasonal variation [8]. The highest concentration values occur during the autumn-winter season. High concentrations of PM during the heating season are primarily associated with increased demand for heat as temperatures drop. The analysis of PM10 composition conducted in Kraków by the AGH University of Science and Technology demonstrated that during winter periods, the predominant sources of PM10 are coal combustion and secondary inorganic aerosols [9]. However, the reason for this is not only the emission of pollutants associated with the combustion of solid fuels but also the meteorological conditions [10].

Variables such as atmospheric turbulence, meteorological and topographic conditions, as well as the type of emission source and the dynamic elevation of the pollution plume, significantly influence the dispersion of particulate pollutants in the atmosphere [11]. This phenomenon is characterized by an increase in air temperature with altitude and can be divided into two types: surface-based and elevated inversions. Atmospheric factors affecting the concentration of suspended particulate matter also include solar radiation, air temperature, humidity, precipitation, and wind speed [12, 13].

The concentration of PM in the air is the subject of much scientific research. Studies mainly rely on the analysis of measurements taken by the Chief Inspectorate of Environmental Protection, stationary PM meters, or conducting computer simulations. On the other hand, there is a notable gap in the scientific literature regarding field-based research that presents actual, real concentrations of PM2.5 and PM10 within the studied regions. The research conducted within the framework of the project aimed to address this gap by illustrating the real-time concentrations of PM10 in the areas under investigation, located in Kraków and Starachowice.

The choice of these specific research areas enabled a comparative analysis of the instantaneous PM10 concentrations between a large urban area, Kraków, where an anti-smog resolution has been implemented, and a smaller urban area, Starachowice, where such legislative measures have not been enacted. Regulations of this type are introduced by the Regional Assembly pursuant to Article 96 of the Environmental Protection Law of 27 April 2001 [14]. In Kraków, such a resolution has been in force since 1 September 2019 [15]. It imposes a complete ban on the use of coal and wood in boilers, furnaces, and fireplaces within the city

Therefore, the primary aim of this paper was to analyse the concentrations of PM10 measured in Kraków and Starachowice. The research results were presented through spatial distribution maps of PM concentrations. Subsequently, a statistical analysis of the obtained results was conducted, along with a discussion of the findings.

2. GENERAL CHARACTERISTICS OF THE RESEARCH AREAS

Kraków is situated almost at the centre of the Małopolskie Voivodeship and serves as its capital. The city has a population of 803,282 and covers an area of 327 km^2, making it the second-largest city in Poland in terms of population and area [16]. The spatial structure of Kraków consists of several distinct elements, including the historic city centre, residential single-family housing areas, multi-family housing estates, and industrial zones.

Kraków lies at the intersection of five physio-geographic macroregions, which encompass the Kraków Gate, the Sandomierz Basin, the Nida Basin, the Western Beskids Foothills, and the Kraków-Częstochowa Upland. The Vistula River constitutes the main hydrographic axis of the city. The landscape of Kraków is significantly diverse, encompassing flat plains on one side and hilly areas with isolated hills on the other. The city's terrain ranges in elevation from 187 meters in the low-lying areas to 368 meters in the southern outskirts. This varied topography influences the modification of climatic features compared to its surrounding areas, resulting in unfavourable microclimatic conditions such as higher temperature amplitudes, lower wind speeds, decreased precipitation, and frequent fogs and mists [17, 18].

Starachowice is a city located in the northern part of the Świętokrzyskie Voivodeship in Poland, situated at the foothills of the Świętokrzyskie Mountains. It is surrounded by forest complexes, remnants of the Świętokrzyskie Primeval Forest. The city has a population of 43,883 and covers an area of 32 km^2 [19]. The city is divided into 18 districts, featuring a mix of residential, industrial, post-industrial, recreational, and agricultural areas. The northern part is highly industrialized with dense residential areas and services, while the southern part is mainly residential with single- and multi-family housing.

According to the physical-geographic classification, Starachowice is located in the region of the Kielce Upland. The Kamienna River flows through the city, cutting across its upland terrain and serving as the main hydrographic axis. The terrain features a parallel and alternating arrangement of hills and valleys, distributed in an east-west direction. The differences in altitude range from 200 to 298.8 m, where there is a hill formed because of mining activity. The maximum elevations of the natural terrain reach up to 270 m.

3. MEASUREMENT RANGE

The research was done in three distinct territories, providing a diverse range of research conditions. These areas are:

• Kraków Old Town – the historic district of Kraków, frequently visited by tourists from all over the world. It hosts numerous universities, administration offices, and historical monuments. The district is characterized by multi-family buildings in the form of tenements. The research zone is bounded to the south by Św. Idziego Street and Podzamcze Street, and on the remaining sides by Planty Park. A total of 45 measurement points were located in the study area.

- Wierzbnik district in Starachowice – the historical part of Starachowice, which until 1939 constituted a separate city. Its central part is the market square, near the Church of the Holy Trinity. The research area is characterized by single-family and multi-family housing in the form of tenements. Some buildings were constructed at the beginning of the 20th century, while the rest were built later. The area under study is bounded to the south by a railway line, while the eastern and northern borders are formed by the busy Armii Krajowej Avenue. In this area, 38 measurement points have been located.
- Orłowo district in Starachowice – a part of the city characterized by single-family housing. Houses began to be built here in the 1920s. The southern boundary of the study area is formed by a railway line, and the northern boundary by a forest. The eastern boundary is limited by Stroma Street and the western boundary by Pogodna Street. A total of 48 measurement points were located in the study area.

4. CHARACTERISTICS OF AIR QUALITY IN THE STUDIED AREAS

Currently, Kraków has eight air quality monitoring stations integrated into the State Environmental Monitoring system. Depending on the station's location, research is conducted with attention to various sources of pollutant emissions. In 2023, none of the stations recorded an exceedance of the annual limit value for PM10 and PM2.5 concentrations in the air [20]. Additionally, there were no exceedances recorded for the allowed number of days with daily PM10 concentrations surpassing the limit value. The highest average annual PM2.5 and PM10 concentrations were recorded in the measurement station located on Krasiński Avenue. The annual average concentration of PM10 in Kraków, calculated based on data from monitoring stations, was 24.9 $\mu g/m^3$. For PM2.5, this value was 17.1 $\mu g/m^3$. The maximum daily value of PM10 was 264.0 $\mu g/m^3$, while for PM2.5 it was 135.5 $\mu g/m^3$. Analysing the above measurement results, stations in the city centre, near main streets, exhibit increased concentrations of PM2.5 and PM10 in the air. The current air quality in Kraków is significantly better than in previous years, mainly thanks to the implementation of the so-called anti-smog resolution. Currently, nearly all buildings in the city are heated without the use of solid fuels. Over 45 thousand boilers have been replaced with eco-friendly heat sources, and around 80 buildings are heated with gas. At present, a considerable share of PM concentrations is due to inflow emissions [21]. This notable contribution arises from the combustion of solid fuels in adjacent municipalities and Kraków's geographical positioning. Analysing the measurement data from 2018 to 2023, a significant improvement in air quality is evident (Fig. 1). A downward trend in concentrations of PM2.5 and PM10 is observable, along with a sudden drop in the centre of Kraków in 2020.

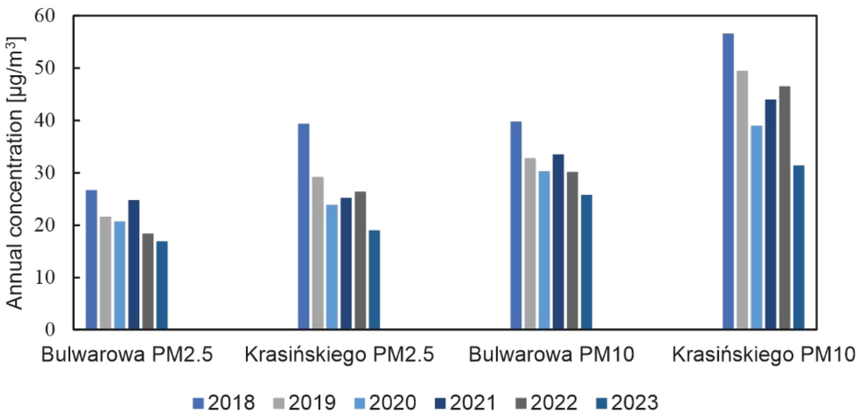

Fig. 1. Annual average concentrations of PM2.5 and PM10 recorded at selected monitoring stations in Kraków from 2018 to 2023 (based on: © Główny Inspektorat Ochrony Środowiska)

Since 2012, there has been one air pollution monitoring station operating within Starachowice, integrated into the State Environmental Monitoring system. It is located at Złota Street. The station measures PM2.5 and PM10 concentrations, as well as the concentrations of arsenic, cadmium, nickel, and benzo(a)pyrene in PM10. PM2.5 and PM10 measurements are conducted continuously, averaging over one hour. In 2023, the annual average concentration of PM10 was 19.7 µg/m^3, which is well below the permissible limit of 40 µg/m^3 [20].

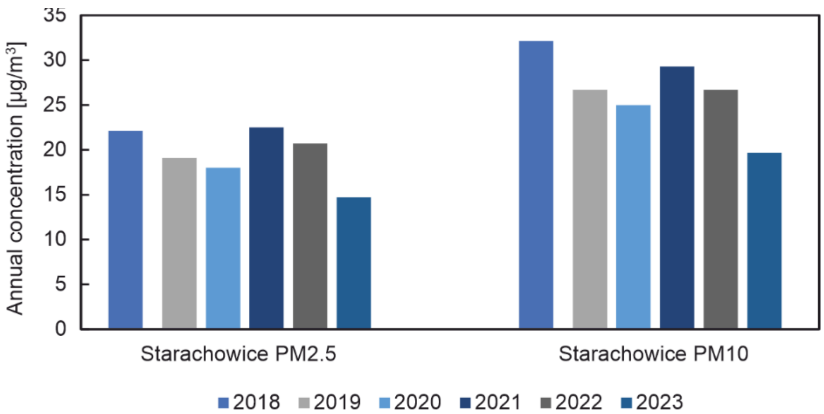

Fig. 2. Annual average concentrations of PM2.5 and PM10 recorded at the monitoring station in Starachowice from 2018 to 2023 (based on: ©Główny Inspektorat Ochrony Środowiska)

Analysing the results averaged over one day, the permissible PM10 concentration was exceeded 6 times. The maximum daily value of PM10 was 108.3 µg/m^3, while the maximum hourly value measured was 350.8 µg/m^3. The annual average concentration of PM2.5

was 14.7 μg/m^3, which is also below the permissible value. However, the maximum observed hourly value was 244.7 μg/m^3. Analysing the annual average concentrations of PM2.5 and PM10 from 2018 to 2023, a decreasing trend is observed (Fig. 2). The highest values observed during this period were in 2018. However, they didn't exceed the limit values for annual concentration.

5. RESEARCH METHOD

The research was conducted from January to the end of March 2024. It was planned for the measurements to be taken in the evening hours, with weak wind conditions not exceeding 5 m/s. Additionally, three different temperature scenarios were planned as part of the measurements. The first scenario involved taking measurements at approximately –10 °C, the second at around 0 °C, and the third at about 10 °C. Measurements were taken using the Steinberg Systems SBS air quality sensor. This device measures PM concentration using the laser method. The collected results were presented in maps. The created maps show the spatial distribution of the measured concentrations of PM10 within the studied areas. Subsequently, results were analysed using statistical methods. The first step in the statistical analysis was to present the basic descriptive statistical parameters. Then, statistical tests were conducted to determine significant differences between the examined groups within a single research site and across different locations. The last step undertaken to perform statistical analysis of the measurements was to check correlation coefficients to conduct the analysis and test the hypotheses. The RStudio software version 2024.04.01 was used. The final part of this paper was dedicated to discussing the results of the conducted research. During the discussion, factors contributing to the occurrence of the investigated PM concentrations were taken into consideration.

6. RESULTS AND STATISTICAL ANALYSIS

6.1. MAPS OF SPATIAL DISTRIBUTION

The results of PM10 concentration measurements are presented in maps of spatial distribution. Due to prevailing meteorological conditions, the measurements planned for the first scenario were conducted only in the Old Town of Kraków (Fig. 3). In the second scenario, measurements were carried out in all designated research areas, including the Old Town of Kraków (Fig. 4), as well as the Wierzbnik (Fig. 5) and Orłowo (Fig. 6) districts in Starachowice. Similarly, measurements conducted at a temperature of 10 °C included the Old Town of Kraków (Fig. 7) and the Wierzbnik (Fig. 8) and Orłowo (Fig. 9) districts of Starachowice.

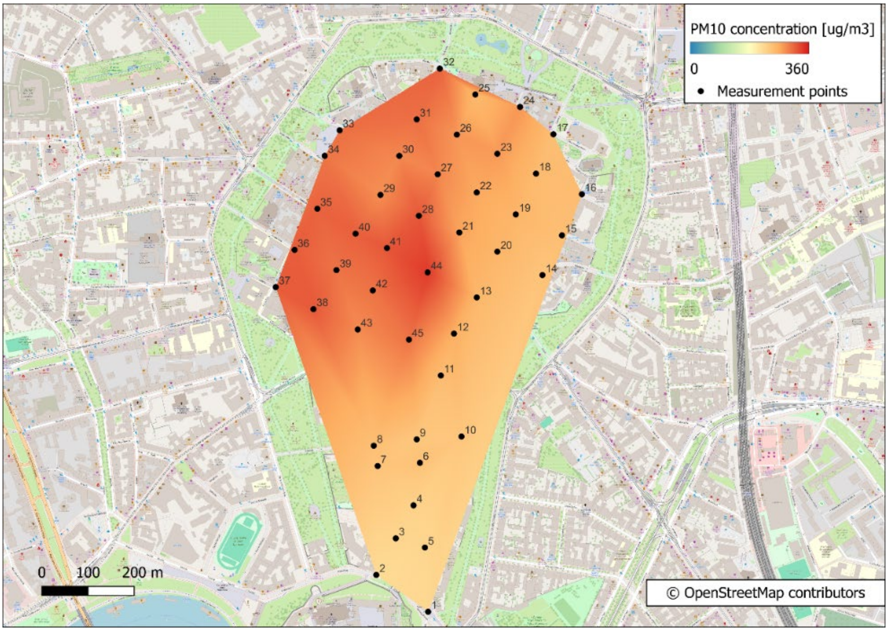

Fig. 3. Map of the spatial distribution of PM10 concentrations based on measurements taken in the Old Town district in Kraków under conditions assumed in the first scenario

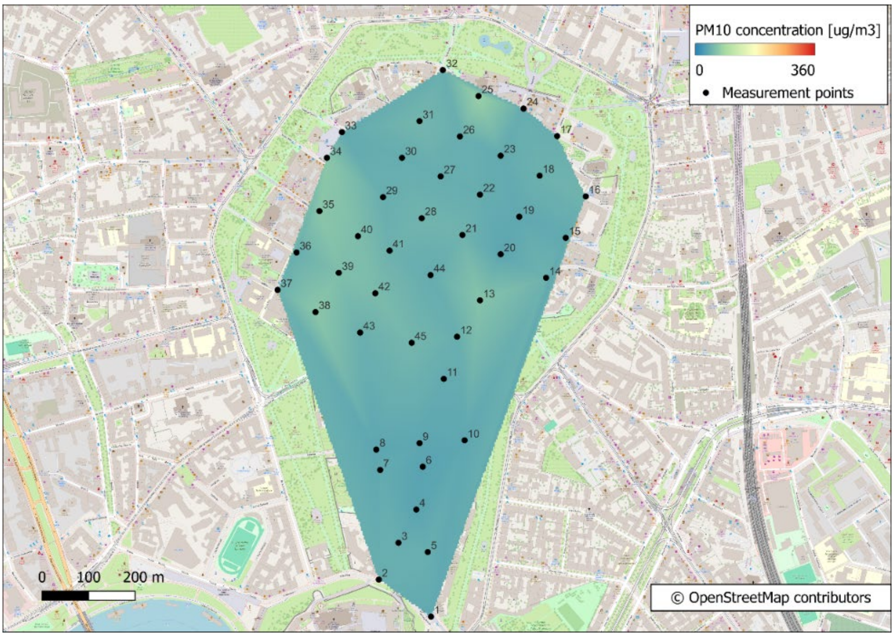

Fig. 4. Map of the spatial distribution of PM10 concentrations based on measurements taken in the Old Town district in Kraków under conditions assumed in the second scenario

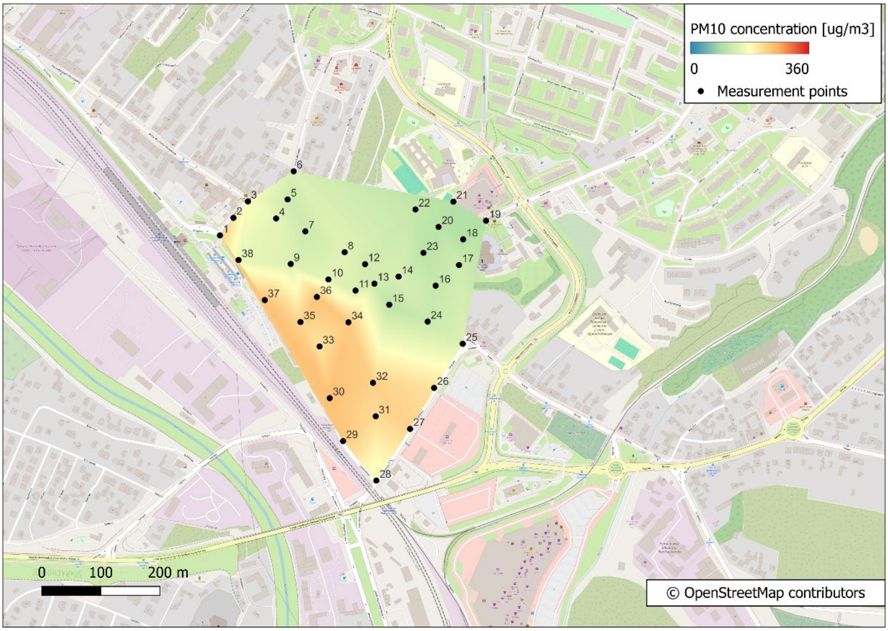

Fig. 5. Map of the spatial distribution of PM10 concentrations based on measurements taken in the Wierzbnik district in Starachowice under conditions assumed in the second scenario

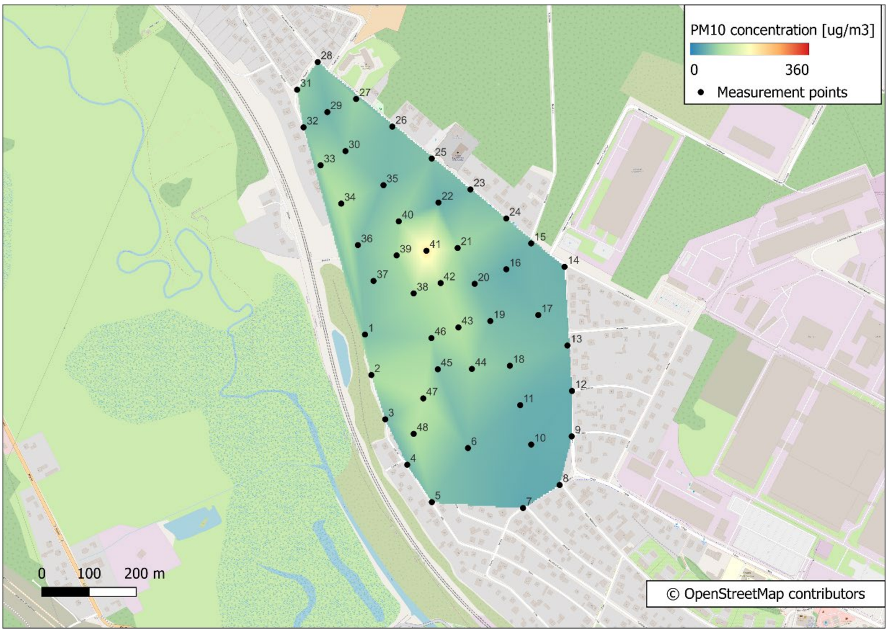

Fig. 6. Map of the spatial distribution of PM10 concentrations based on measurements taken in the Orłowo district in Starachowice under conditions assumed in the second scenario

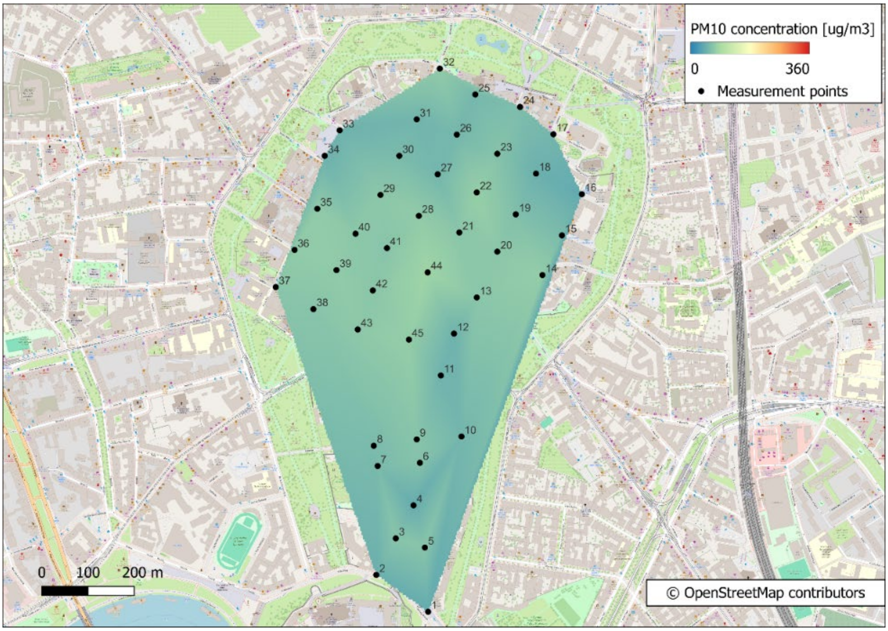

Fig. 7. Map of the spatial distribution of PM10 concentrations based on measurements taken in the Old Town district in Kraków under conditions assumed in the third scenario

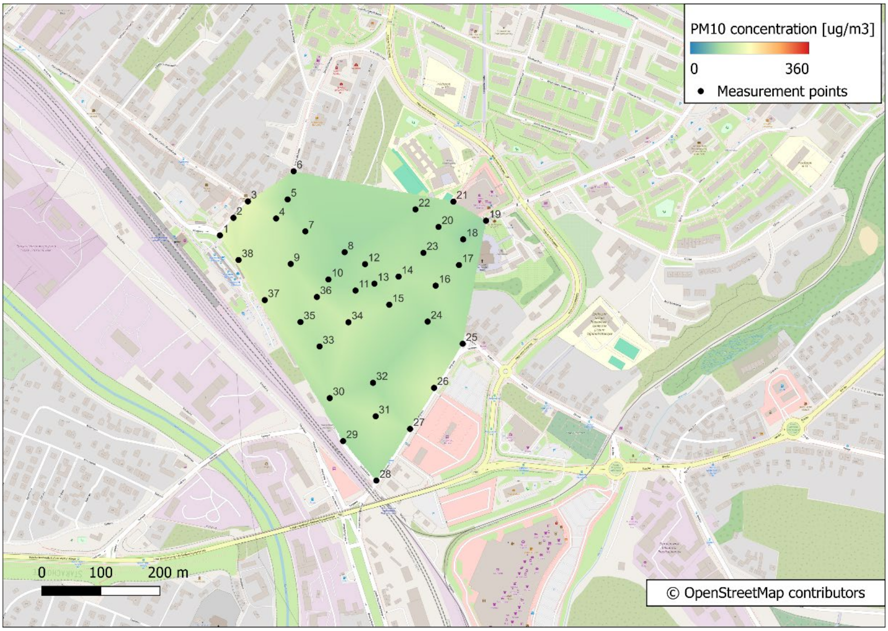

Fig. 8. Map of the spatial distribution of PM10 concentrations based on measurements taken in the Wierzbnik district in Starachowice under conditions assumed in the third scenario

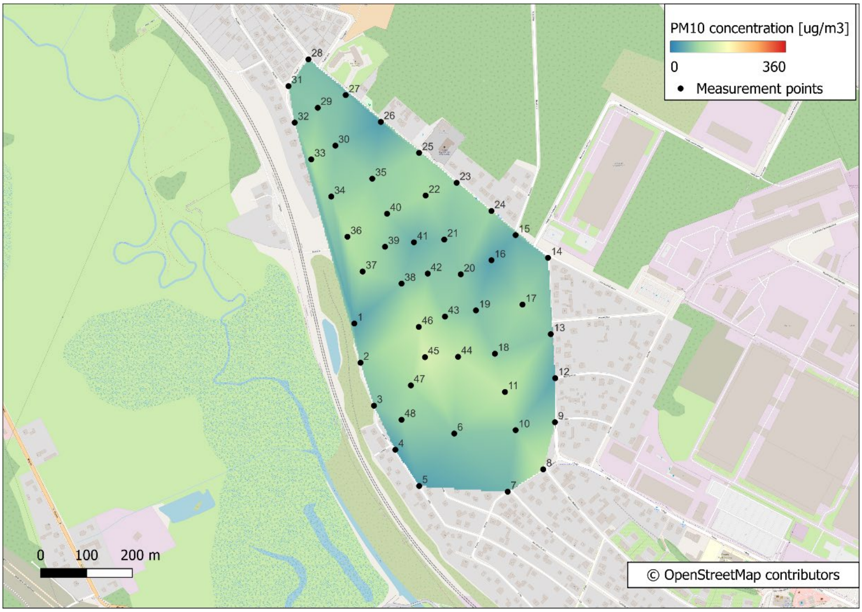

Fig. 9. Map of the spatial distribution of PM10 concentrations based on measurements taken in the Orłowo district in Starachowice under conditions assumed in the third scenario

6.2. DESCRIPTIVE STATISTICS. DIFFERENCES BETWEEN PERFORMED MEASUREMENTS

Basic descriptive statistical parameters (the mean, median, standard deviation, maximum and minimum values, as well as skewness and kurtosis) are presented in Table 1. The analysis was conducted separately for each measurement series, depending on the measurement location and weather conditions.

Table 1

Basic descriptive statistics of the studied PM10 concentrations concerning different temperature scenarios and measurement locations

T [°C]	Site	Mean [μg/m³]	Std. dev. [μg/m³]	Med. [μg/m³]	Min. [μg/m³]	Max. [μg/m³]	Skewness	Kurtosis
10	Kraków – Old Town	61.23	10.79	64.4	40.1	82.1	–0.26	1.97
	Starachowice – Wierzbnik	107.3	20.47	99.45	80.1	158.5	0.88	2.92
	Starachowice – Orłowo	72.03	24.54	69.65	28.3	141.3	0.44	3.44
0	Kraków – Old Town	47.03	10.07	44.1	33.4	78.8	1.29	4.27
	Starachowice – Wierzbnik	166	51.09	145.8	101.5	249.5	0.43	1.64
	Starachowice – Orłowo	69.31	28.02	62.6	39.6	208.5	2.69	13.7
–10	Kraków – Old Town	277	32.88	275.6	220.3	339.5	0.02	1.78

Std. dev. – standard deviation, Med. – median, Min – minimum, Max. – maximum.

In the Old Town district of Kraków, at 10 °C, the average PM10 concentration was recorded at 61.23 μg/m^3. Meanwhile, in the districts of Wierzbnik and Orłowo in Starachowice, these values were 107.3 μg/m^3 and 72.03 μg/m^3, respectively. Kraków exhibits a smaller standard deviation of 10.79 μg/m^3 compared to Wierzbnik's 20.47 μg/m^3 and Orłowo's 24.54 μg/m^3. The maximum observed value was recorded in Wierzbnik, and it was 158.50 μg/m^3. The skewness values suggest that the distribution in Kraków is slightly negative, while the distributions in Orłowo and Wierzbnik are positively skewed.

At 0 °C, the average concentration of PM10 in the Old Town district in Kraków was equal to 47.03 μg/m^3. Higher values were observed in Starachowice in Wierzbnik district at 166.00 μg/m^3 and Orłowo district at 69.31 μg/m^3. Measurements conducted in Wierzbnik indeed showed a significantly larger standard deviation of 51.09 μg/m^3 compared to those in Kraków and Orłowo. In Wierzbnik, the highest recorded PM10 concentration for 0 °C was also observed, reaching 249.50 μg/m^3.

At –10 °C, measurements conducted in Kraków showed a significant increase in the average concentration of PM10, reaching 277 μg/m^3. The standard deviation for PM10 was 32.88 μg/m^3, and the maximum observed value was 339.50 μg/m^3. The skewness for PM10 was low, indicating a symmetrical distribution.

The next stage of the statistical analysis involved examination of the differences between the performed measurements and comparing the levels within one location across different temperature conditions. The differences in measurements taken in Starachowice were tested using the Wilcoxon test. In the case of measurements taken in Kraków, the Dunn test was performed. The results of these tests are summarized in Table 2. Significant differences were observed in all tests except one. No significant variation in PM10 concentrations was found in the Orłowo district of Starachowice between 0 °C and 10 °C.

Table 2

Differences in concentrations of PM10 within the same locations at different temperatures

Temperature [°C]	Kraków – Old Town	Starachowice – Wierzbnik		Starachowice – Orłowo	
	p-value	Wilcoxon *W*-value	*p*-value	Wilcoxon *W*-value	*p*-value
–10 and 0	0.0	–	–	–	–
0 and 10	< 0.01	703.0	< 0.01	511.5	0.43
–10 and 10	< 0.01	–	–	–	–

The next step of the analysis examined differences in PM10 concentrations between locations using Dunn's test. A significant difference at 0 °C was found only between Kraków – Old Town and Starachowice – Orłowo ($p < 0.01$).

6.3. CORRELATIONS

Based on the previously conducted statistical analysis, it was decided to perform correlation tests. Spearman's rank correlation coefficient was used for this purpose. The first hypothesis tested in the correlation study was that the concentration of PM10 increases as temperature decreases. The second hypothesis tested was an increase in PM10 concentration in the Wierzbnik district with decreasing elevation. The results of testing this hypothesis are presented in Table 3.

Table 3

Correlation coefficient between PM10 concentration and air temperature

Tested hypothesis	Research site	Correlation coefficient	*p*-Value
PM10 increases as temperature decreases	Kraków – Old Town	–0.548	< 0.01
	Starachowice – Wierzbnik	–0.654	< 0.01
	Starachowice – Orłowo	0.132	0.20
PM10 increases as terrain elevation decreases	Starachowice – Wierzbnik at 0 °C at 10 °C	 –0.902 –0.513	< 0.01

The calculated coefficients indicate that for measurements taken in the Old Town district in Kraków and the Wierzbnik district in Starachowice, there is a strong negative correlation between temperature and PM concentrations, which is statistically significant. This means that as the temperature decreases, the concentration of PM10 increases. In the case of measurements taken in the Orłowo district in Starachowice, the results are different. There is a positive correlation between temperature and PM10. However, the *p*-value indicates that the correlation coefficients for Orłowo are not statistically significant. Additionally, in the Wierzbnik district, a strong negative correlation is found between terrain elevation and PM concentrations, with statistical significance across all analysed cases.

7. DISCUSSION ON THE RESULTS

The studies allowed for the visualization of the spatial distribution of PM10 concentrations within the research areas. It was possible to identify segments of the areas where PM concentrations reach higher values. In Kraków, higher concentrations were observed in the central and western parts of the study area, while lower levels occurred mainly in the southern and eastern outskirts. This could be associated with the direction of the prevailing wind during the measurements, as well as the building structures in the Old Town of Kraków. In this area of the city, there is dense multi-family housing, which can lead to reduced ventilation in Kraków. As a result, higher PM concentrations may occur at certain measurement points, particularly at the ends of streets.

Maps presenting the spatial distribution of PM concentrations in the Wierzbnik district in Starachowice show a trend towards higher PM concentrations in the southwest part of the studied area. The tests have shown that as the terrain elevation decreases, the concentration of particulate matter increases. Measurement points, located at a lower elevation of the terrain, are situated in the valley of the Kamienna River, which cuts through hilly terrain. Such topographic conditions can lead to the accumulation of particles in the river valley area due to limited air circulation [23]. It could also be caused by the occurrence of thermal inversion. Similarly, in Kraków, the high concentrations of PM10 in the city centre are significantly influenced by inflow emissions from heating systems in surrounding municipalities [21]. Kraków's location results in PM emitted by heating systems in adjacent municipalities being transported into the city.

The Orłowo district in Starachowice is characterized by point sources of PM emissions, as shown on the previously presented maps. Their source is the combustion of solid fuels in households. The concentration of PM in this area can vary significantly during the heating season. Additionally, lower concentrations have been observed on the outskirts of the studied area. This may be related to the lower density of buildings in these areas, as well as the fact that they border forests or meadows.

The statistical analysis showed that significant differences exist between almost all the tested samples. Only the difference analysis between PM10 concentration measurements in the Orłowo district in Starachowice at 0 °C and 10 °C did not show this. This could be because measurements at an ambient temperature of 0 °C were taken immediately after snowfall [24]. Snowfall induces the process of wet deposition, which leads to self-cleaning of the atmosphere, thereby reducing the concentrations of PM in the air.

Comparing measurements taken at the same ambient temperature, it is evident that the highest concentrations were recorded in the Wierzbnik district in Starachowice. This could be influenced by the accumulation of pollutants emitted by individual heating sources within the city. The concentrations measured in Kraków at temperatures of 0 °C and 10 °C are much lower compared to those in Wierzbnik. The lower PM concentrations in Kraków are influenced by regulations that prohibit the use of coal and wood in boilers, furnaces, and fireplaces within the city [25]. Thanks to these regulations, Kraków effectively reduces the emission of air pollutants from solid fuel combustion sources, resulting in better air quality compared to Starachowice. Even if such a solution is not feasible to implement in Starachowice due to local socio-economic reasons. The municipality should strive to support residents in replacing solid fuel boilers with more environmentally friendly options. On the other hand, measurements taken in the Orłowo district in Starachowice are an example of how burning solid fuels in households affects air quality. In the situation where the atmosphere was cleansed through wet deposition, concentrations of PM10 measured near homes heated at that time with solid fuels were significantly higher. This highlights the persistent influence of solid fuel combustion on local air pollution levels, even after natural atmospheric cleansing processes have occurred.

The conducted research allowed us to demonstrate how changes in air temperature affect the concentration of PM10. The analysis revealed a strong negative correlation between PM measurements and temperature in the Wierzbnik district in Starachowice and

Kraków. This means that as the temperature decreases, the concentration of PM10 increases. Such a relationship during the heating season is well documented in many other papers [26, 27]. Due to the previously discussed measurement conditions, such a correlation was not observed in the Orłowo district in Starachowice. However, the *p*-value obtained from these tests, conducted for the Orłowo district, indicates that the correlation coefficients are not statistically significant. It is also worth noting the sharp increase in PM concentrations in Kraków at an ambient temperature of –10 °C. Such a phenomenon may be related to a significantly higher demand for heat as temperatures drop. Another factor intensifying this could be thermal inversion or unfavourable meteorological conditions such as weak winds.

The results of this study underline the influence of local conditions on PM10 concentrations and provide a basis for further research. Future investigations are planned to extend the temporal and spatial scope of air pollution monitoring. These studies will include long-term measurements across different seasons and expansion of the research scope to incorporate PM2.5 monitoring. Additionally, the research area is planned to be expanded to include other districts of Kraków and Starachowice. Future research will also focus on evaluating the influence of meteorological conditions beyond temperature, including thermal inversion, wind speed, solar radiation, precipitation, and humidity. These efforts will provide a more comprehensive understanding of the spatial distribution of PM concentrations within the analyzed locations.

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