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Examining pollution emissions in relation to atmospheric conditions: a case study on air-quality management in Kraków

Abstract: This article presents the topic of atmospheric pollution. The authors have presented the most important national air-quality regulations. They have identified measurement stations in Kraków (Poland), collected data from them and conducted their analysis. The aim of the article is to present the research results on developing a statistical model for estimating air pollution in Kraków depending on the changing weather conditions during the year. The authors used the mathematical modelling method to prepare the air-pollution model. The article presents collected data showing the situation prior to the introduction of a number of environmental regulations in the city of Kraków.

The paper is based on meteorological data in the form of daily average values of air temperature, wind speed, air humidity, pressure and precipitation. Emission data included the average daily concentrations of the selected air pollutants, including sulfur dioxide (SO_2), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), nitrogen oxide (NO), carbon monoxide (CO), ozone (O_3) and particulate matter PM10 and PM2.5.

The results of the study indicate that the three most significant factors influencing the level of air pollution (appearing as explanatory changes in the models for each of the pollutants listed) are the

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value of ambient air temperature (a destimulant, except for ozone), wind speed (a destimulant) and the concentration of each pollutant on the previous day (a stimulant). The article concludes with a summary and conclusions.

Keywords: mathematic model, air pollution, PM10, carbon monoxide (CO), sulphur dioxide (SO_2)

Introduction

Urbanization and the development of transport has lead to noticeable effects such as air pollution, which, in this era of increasing globalization and civilization, is one of the most important concepts in environmental protection and human life hygiene. There are many examples in literature of atmospheric air analysis (Hławiczka et al. 2016; Janota et al. 2015; Wierzbińska et al. 2023; Borowiadk et al. 2023).

Poland, being one of the main European coal producers, exceeds the permissible levels of air pollution due to the widespread use of this fuel in outdated domestic coal-fired boilers causing the phenomena of so-called low emissions (Kleczkowski 2019; Mirowski and Orzechowska 2015). The biggest problem concerns the high emissions of PM10 and PM2.5, the levels of which, despite the legal regulations introduced, still exceed the permissible values, sometimes by several times. One of the main reasons for this type of pollution is the high level of energy poverty in comparison to other European countries, leading to the use of the cheapest low-quality fuels.

In Poland, there is national environmental monitoring covering the whole country, with a particular focus on places where permissible pollution levels are frequently exceeded. The levels of individual pollutants in the air are assessed on the basis of continuous automatic measurements. The study and assessment of air quality in Poland are conducted on the basis of the legal framework contained in Art. 85–95 of the Act of 27 April 2001 – Environmental Protection Law (Chancellery of the Polish Parliament 2001) transposing the requirements of Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (Council of the European Union European Parliament 2008) and Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 on arsenic, cadmium, nickel, mercury and polycyclic aromatic hydrocarbons in ambient air (Council of the European Union European Parliament 2004) and Commission Directive (EU) 2015/1480 of 28 August 2015 amending certain Annexes to the European Parliament Directives. These regulations, together with the regulations of the Minister of the Environment, the regulation of the Minister of the Environment of 8 June 2018 on assessing levels of substances in the air, the Ministry of Climate and Environment 2020 and the Journal of Polish Laws 2021, define the air-monitoring system in the country, the scope and method of testing its quality, determine the minimum number of stations and the methods and criteria for assessment.

Measurement stations monitoring the level of air pollution are located in Polish cities. Almost 300 measurement stations are located throughout Poland, of which the cities with the largest number of measurement stations are Warsaw and Kraków. In the Małopolska voivodship, there are thirty stations, of which eight are located in the city of Kraków. Measurement data at the stations is collected either automatically or manually. Automatic air monitoring involves the use of a number of gas analyzers that are selective for a given type of pollution. The tests consist of atmospheric air being fed into the devices, which is then analyzed by analytical methods for the presence and concentration of relevant pollutants. The measurement of gaseous samples is performed continuously and, as the direct analysis takes place in the equipment, it is possible to obtain measurement results in real time. Manual measurements, on the other hand, are conducted using aspirators, in which the pollutants are extracted from the air using filters or scrubbers that absorb specific substances. Subsequently, the collected samples are transported to the laboratory and analyzed using appropriate analytical techniques. The waiting time for the results of manual measurements is significantly extended. Environmental monitoring is used to determine the current state of the environment and to collect ecological information and it also forms the basis for verifying the effectiveness and efficiency of implemented air protection programs and solutions to environmental protection and shaping problems. Supervision over the collection of data from measurement stations located throughout the country is exercised by the Environmental Protection Inspectorate.

In Poland, Kraków is one of the areas with the highest levels of air pollution, especially in the autumn-winter season. The main sources of air pollution are solid fossil fuels used in households (especially in municipalities located near Kraków), public buildings, local heating plants and power stations. The share of emissions from household heating in the concentration of pollutants in the region is as follows: 55% of all 10 µm particulate matter (PM10), 50% of all 2.5 µm particulate matter (PM2.5) and 71% of benzo(a)pyrene.

The aim of this paper is to build a statistical model to predict the amount of air pollution in Kraków (Poland) depending on the weather conditions occurring on consecutive days of the year.

There are a number of methods for predicting ambient air quality and assessing the state it is in (Foszcz et al. 2021). One of these methods is the use of mathematical modelling of the propagation of air pollutants. Air-pollutant propagation models can be divided into deterministic models, based on the application of the continuity equations of mass, motion and momentum (accounting for convection and diffusion), and empirical (stochastic) models (Tumidajski et al. 2009). Both static and deterministic models have a number of advantages and disadvantages. With static models, we usually have low hardware requirements, predictions can be made quickly, they assume invariability of emissions over a certain time scale, require long series of pollutant emission measurements, and give a prediction of concentrations only for emission measurement points. Deterministic models predict concentrations for the entire calculation area; they can also be used to predict concentrations where there are no emission measurements; it is possible to study the impact of individual emitters. Among the deterministic models, a distinction can be made between volume models (Euler models), in which the diffusion members of the deterministic models are neglected (Juda and Chróściel 1974; Markiewicz 2004; Finzi and Tebaldi 1982). This was also the approach taken by the authors of this article.

1. Materials and methods

The basis for this study was meteorological data presented in the form of daily mean values of: air temperature (T – measured in °C), wind speed (V – measured in km/h), air relative humidity (W – measured in %), atmospheric pressure (P – measured in hPa) and precipitation (O – measured in mm). Emission data was comprised of the daily average values of concentrations of selected air pollutants: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), nitrogen oxide (NO), carbon monoxide (CO), ozone (O_3), particulate matter PM10 and particulate matter PM2.5. The emission value of pollutants is understood as the amount of pollutants introduced into the atmosphere per unit of time. The collected meteorological data was dependent upon the availability of measurements at the measuring stations, as not every station monitors all the above-mentioned parameters in detail. For nitrogen oxides NOxand for measurements of particulate matter, i.e. PM10 and PM2.5, measurement data was collected from three research stations located on the territory of the city placed in particular city districts, namely Kraków Kurdwanów, Kraków Nowa Huta and Kraków Aleja Krasińskiego; values from these three stations were averaged. With regard to sulfur dioxide and carbon monoxide pollution, data was collected from the Kraków Nowa Huta and Kraków Aleja Krasińskiego stations. The average values of the parameters from these two stations were examined. Concentrations of ozone were monitored at one of the mentioned stations, namely Kraków Kurdwanów. It should be noted that the location of the measuring stations from which the measurements of pollutant concentrations are obtained is of crucial importance. It is on the location of the measuring station that the amount of pollution occurring in a given area depends. The Kraków Kurdwanów measuring station is located on the outskirts of the city, where urban transport and passenger car traffic are mainly responsible for the formation of pollution. Kraków Aleja Krasińskiego is a station located in the central part of the city where there is a high level of traffic and industrial centers. The measurement station of Kraków Nowa Huta is located in the industrial part of the city and the largest plant is the Sendzimir Steelworks in Kraków, which has so far been the main emitter of pollutants to the atmosphere in this area (in 2020, the plant authorities decided to permanently shut down the blast furnace). Thus, for pollutants that are the average of two or three meteorological stations, the location of these stations should be taken into account.

For O_3 pollution, the data were collected directly from the Kraków Kurdwanów station. The amount of recorded pollutants at a research station depends on the shape of the terrain on which the research station is located. If the terrain is flat, the pollutants have a greater opportunity to move, whereas if the terrain is located in a basin, which is the location of the city of Kraków, the opportunity for the pollutants to move offsite is significantly impeded.

The measured data on the volume of air pollutants is publicly available in Poland and posted on the portal of the Chief Inspectorate for Environmental Protection (GIOŚ 2023). Air-quality monitoring within the framework of the State Environmental Monitoring is coordinated in accordance with the Act of 10 July 1991 on Environmental Protection Inspection (Chancellery of the Polish Parliament 1991) by the Chief Inspector of Environmental Protection.

The task set for this publication was to build a mathematical model showing the dependence of these pollutants on the prevailing meteorological conditions. The data on meteorological conditions in the analyzed period were taken from the OGIMET database, which provides information on current and archival weather conditions worldwide (OGIMET 2023). The information used for the purposes of this article refers to the city of Kraków.

In order to illustrate the situation in the city of Kraków before the introduction of various forms of air quality support in the city, in particular the introduction of environmental regulations, measurement data for 2016 was collected. The chosen year was a period in which the concentrations of individual air pollutants in the city of Kraków reached the upper limits of the pollution standards or exceeded them. Therefore, the authors chose this period as it enables the exposure of the influence of individual meteorological/weather parameters on the concentrations of the analyzed pollutants.

The year was a leap year, so a period covering 366 days was analyzed. The following meteorological/weather parameters were analyzed as part of this study:

- value of the air temperature (T – measured at °C),
- wind speed (V – measured in km/h),
- humidity level (W – measured in %),
- the pressure value (P – measured at hPa),
- the amount of precipitation (O – measured in mm).

Multivariate regression analysis was used to investigate the relationship between pollutant concentrations and quantities relating to meteorological conditions. Its aim was to quantify the relationship between multiple independent variables (explanatory – X) and the dependent variable (explained – Y). In building models, the principle followed was that, in order to best represent reality, it is necessary to introduce as many independent variables as possible and to collect as much quantitative explanatory data as possible. Care was taken to include variables in the model that are highly correlated with the dependent variable, to reflect the relationships in the data well, while minimizing the correlations between them to avoid the undue influence of multiple collinearity.

The linear multiple regression model is written with the equation:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \ldots + b_i X_i + \varepsilon \tag{1}$$

where:

b_i – model parameters (regression coefficients) describing the impact of the *i*-th variable,
ε – random component (S_e).

As a rule, in a multiple regression model, the number of observations n should be many times the number of estimated parameters $n > i+1$. None of the independent variables can be a linear combination of the other independent variables, i.e. a lack of collinearity between the independent variables is necessary. Negative values of the regression coefficients indicate that the independent variable is a destimulant for the dependent variable, and positive values indicate that it is a stimulant. The interpretation of the coefficients is as follows: the *i*-th, partial regression coefficient describes by how much, on average, the value of variable Y changes when the *i*-th value of variable X increases by a unit at fixed values of the other independent variables. Parameters b_i of the model are estimated using the method of least squares so that the sum of the squares of the observed residuals from the regression hyperplane is the smallest. The multiple correlation coefficient, R, is a measure of the interdependence between one variable and the other variables taken together. To determine the validity of the estimated equation, model verification is required, which is based on checking that the following model assumptions are met:

- significance of linear regression,
- significance of partial regression coefficients,
- no collinearity (redundancy) between independent variables,
- the variance of the random component (residual) is the same for all observations,
- no autocorrelation of residuals,
- normality of the distribution of the residuals,
- the random component (residual ε) has an expected value of 0.

The significance of a multiple regression is verified using an F-test and the probability level p should be less than the adopted significance level α. R2 indicates how much of the variation in a given variable is explained by the other variables.

The multivariate regression analysis performed in this study will allow us to answer the question of which quantities (parameters) best describe the amount of air pollution Y under study. The present study investigated the dependence of pollution on weather parameters, i.e. values of air temperature, wind speed, air humidity, pressure and precipitation values occurring on the current day (t) and on pollution concentrations from the preceding day (t–1) (St – measured in $\mu g/m^3$). The dependent variables are the pollution concentration parameters from the current day. The statistical package of the Statistica 13 program was used to build the model.

2. Results and discussion

As a result of the statistical analysis, the regression equations were obtained describing the values of the individual analyzed air pollutants, depending on the atmospheric conditions. When developing pollution models, a complete analysis of their correctness was conducted, thus eliminating those not meeting the requirements of the adopted method. For this reason, some of the independent variables were excluded. The models with a sufficiently high coefficient of determination R2 were assumed as correct. The significance of the regression equation and coefficients has been confirmed for all the developed models.

The obtained results have shown that the developed regression models are correct because:

1. All explanatory variables were correctly included in linear regression models due to the fact that the Student's test *p value* for these variables is lower than the significance level of 0.05;
2. The F-test *P-value* calculated for linear regression models is lower than the significance level of 0.05.

In addition, all formal requirements for the classical linear regression model were met:

1. The explanatory variables are exogenous, which means that the values of the random component are not a function of the variables explaining the linear regression model;
2. There is a linear relationship between the explanatory variables and the explained variables;
3. The number of n observations is greater than the number of structural parameters of the regression equation;
4. The explanatory variables are non-random;
5. The expected value of the random component is zero;
6. The vector of the random component is homoscedastic, meaning that the variance of the random component is the same for all observations, as confirmed by the White test;
7. The distribution that the values of the random component have is similar to a normal distribution N (0, σ), as indicated by the Shapiro-Wilk statistical test;
8. The values of the random component are independent, i.e. there is no autocorrelation (covariance is zero), as confirmed by the Durbin-Watson statistical test.

The fulfillment of these assumptions allows us to analyze the obtained results of the estimation of parameters of the linear regression model, which are presented in the form of equations. The obtained regression equations are presented in Table 1. The values of the multiple correlation coefficients R and the obtained values of the coefficients of determination R2 are also presented.

Table 1. Regression equations describing the relationship between the concentration of selected air pollutants and meteorological elements, 2016.

Tabela 1. Równania regresji opisujące związek pomiędzy stężeniem wybranych zanieczyszczeń powietrza a elementami meteorologicznymi, 2016 rok

	Type of pollutant	Regression equation	R2 [%]
1	SO_2	$StSO_{2B} = -0{,}2169T - 0{,}0327W - 0{,}1169V + 0{,}0511P + 0{,}571StSO_{2P} - 43{,}3148$	74
2	NO_x	$StNO_{xB} = -2{,}0381T - 3{,}2627V + 0{,}5245P + 0{,}3579StNO_{xP} - 404{,}68101$	44
3	CO	$StCO_B = -18{,}2012T - 20{,}7091V + 4{,}1545P + 0{,}3751StCO_P - 3383{,}0976$	65
4	PM10	$StPM10_B = -1{,}9068T - 2{,}0879V + 0{,}3172StPM10_P + 72{,}4825$	62
5	PM2,5	$StPM2{,}5_B = -1{,}5472T - 1{,}6215V + 0{,}3055StPM2{,}5_P + 54{,}4807$	66
6	O_3	$StO_{3B} = 47{,}4683T + 0{,}5781W - 0{,}4789V + 0{,}4812StO_{3P} + 0{,}4004$	71

Source: own elaboration.

Explanations for regression equations:

1. $StSO_{2B}$ – concentration of SO_2 pollution on the current day [μg/m^3],
   $StSO_{2P}$ – concentration of SO_2 pollution on the day before [μg/m^3].
2. $StNO_{xB}$ – concentration of NO_x pollution on the current day [μg/m^3],
   $StNO_{xP}$ – concentration of NO_x pollution on the day before [μg/m^3].
3. $StCO_B$ – concentration of CO pollution on the current day [μg/m^3],
   $StCO_P$ – concentration of CO pollution on the day before [μg/m^3].
4. $StPM10_B$ – concentration of PM10 pollution on the current day [μg/m^3],
   $St\ PM10_P$ – concentration of PM10 pollution on the day before [μg/m^3].
5. $StPM2{,}5_B$ – concentration of PM2, pollution on the current day [μg/m^3],
   $StPM2{,}5_P$ – concentration of PM2,5 pollution on the day before [μg/m^3].
6. StO_{3B} – concentration of O_3 pollution on the current day [μg/m^3],
   StO_{3P} – concentration of O_3 pollution on the day before [μg/m^3].

Other parameters of the equation:

T – air temperature of the current day [°C],
V – wind speed of the current day [km/h],
W – relative air humidity of the current day [%],
P – atmospheric pressure of the current day [hPa].

Analyzing the results obtained, we can conclude that the greatest influence on the development of sulfur dioxide (SO_2) concentrations is exerted by parameters such as:

- ambient air temperature – negative impact – negative impact (a destimulant),
- relative air humidity (a destimulant),
- wind speed (a destimulant),
- atmospheric pressure – positive impact (a stimulant),
- concentration of SO_2 pollution on the day before (a stimulant).

In the case of nitrogen oxides and carbon monoxide, the relevant parameters are:

- ambient air temperatures (a destimulant),
- wind speed (a destimulant),
- atmospheric pressure (a stimulant),
- concentration of the relevant oxides on the day before (a stimulant).

The parameters were not significantly affected by humidity in this case.

In the case of particulate pollutants, i.e. PM10 as well as PM2.5, the relevant parameters are:

- ambient air temperatures (a destimulant),
- wind speed (a destimulant),
- concentration of relevant dust on the previous day (stimulant).

For O_3, the relevant parameters are:

- ambient air temperatures (a stimulant),
- relative air humidity (a stimulant),
- wind speed (a destimulant),
- concentration of O_3 pollution on the previous day (a stimulant).

The three most significant recurring factors in each of the pollutants listed are the ambient air -temperature value, the wind speed and the concentration of each pollutant on the previous day.

Based on the analysis of the residuals and the correlation and determination coefficient, it can be assumed that the fit of the model to the empirical data is very good. The highest value of the coefficient of determination was obtained in the case of sulfur dioxide pollution and it was 74%, which means that it explains 74% of the variation in SO_2 concentration from the current day. However, the lowest value of the coefficient of determination was obtained for NO_x pollution and this was 44%, which means that it explains only 44% of the variation in NO_x concentration from the current day.

In the case of sulfur dioxide pollution, a spike in atmospheric sulfur dioxide concentration values during the autumn-winter period was perceived, so an additional analysis was conducted covering the period from 22 September to 21 December 2016, when increased sulfur dioxide concentration values occurred. In this case, the regression equation took the following form:

$$StSO_{2B} = -0{,}26034T - 0{,}1083V + 0{,}0795P + 0{,}4319StSO_{2P} - 74{,}4334 \quad (2)$$

The coefficients for the temperature, wind speed, atmospheric pressure, and SO_2 concentrations from the day before are close to the coefficients in Equation no. 1 (year-round). In the autumn, the humidity parameter was not as significant as during the whole year period. The determination factor dropped to 63%.

In addition, exceedances of air-quality limit values were also examined. The permissible levels of pollutants are presented in Table 2. The permissible level is the determined level of substances in the air, based on scientific knowledge, in order to avoid, prevent or reduce harmful effects on human health or on the environment. It should be reached within a specified period of time and should not be exceeded afterwards.

In the analyzed year, air-quality limit values (the permissible concentrations of pollutants, mainly particulate matter) in Kraków were significantly exceeded. In the case of the analyzed monitoring stations, the highest level of PM10 concentration in 2016 was observed on January 23 and amounted to 307.33 $\mu g/m^3$. The highest levels of PM10 were observed in the end of December and lasted until mid-February, i.e. the winter period of the year.

In order to be in a better position to monitor the state of the air, the Air Quality Index was introduced by Environmental Protection Agencies, for which ranges of air pollutant values have been set to classify the state of air quality. The scale is defined from a level of 0 to 300+, with a range of 0–50 indicating that air quality is considered satisfactory and that air pollution poses little or no risk. A value of 300+, on the other hand, is known as a health alert, where anyone can experience more serious health effects. Figure 1 illustrates the Air Quality Index recorded worldwide in January 2016.

Table 2. Permissible concentration of pollutants

Tabela 2. Dopuszczalne wartości stężenia zanieczyszczeń

	Name of the substance	Measurement averaging period	Limit level for substances in the air [µg/m^3]	Permissible frequency of exceedance of the limit value in a calendar year
1	Nitrogen oxides	calendar year	30[e]	–
2	Sulphur dioxide	one hour	350[c]	24 times
		twenty-four hours	125[c]	3 times
		year calendar year and winter season (period from 1 X to 31 March)	20[e]	–
3	Particulate matter PM2,5g	calendar year	25[c,j]	–
		calendar year	20[c,k]	–
4	Particulate matter PM10h	twenty-four hours	50[c]	35 times
		calendar year	40[c]	–
5	Carbon monoxide	eight hoursi	10,000[c,i]	–

c – limit value for the protection of human healthe – limit value for the protection of plantsg – concentration of particulate matter with an aerodynamic diameter of up to 2.5 µm (PM2,5) measured by fractional weighing or by methods recognized as equivalent.

i – maximum eight-hour average, from among the running averages, calculated hourly from the eight one-hour averages over the twenty-four-hour period. Each eight-hour average so calculated is assigned to the day on which it ends. The first calculation period for any twenty-four-hour period is the period from 1,700 on the previous day to 100 on that day; the last calculation period for any twenty-four-hour period is the period from 1,600 to 2,400 on that day CET.

j – limit value for PM2,5 to be attained by 1 January 2015 (phase I).

k – limit value for PM2,5 to be attained by 1 January 2020 (phase II).

Source: Own elaboration based on (Journal of Polish Laws. 2021).

Conclusions

The results of the regression analysis have shown that meteorological conditions have a significant influence on the formation of air-pollutant concentrations. A significant variation in the nature of the relationship between the magnitude of concentrations of the analyzed pollutants and meteorological conditions was obtained. The relationship between air temperature, the occurrence of windy days and the concentrations of individual pollutants are evident. High wind speeds cause dilution and, possibly, a shifting of pollutant layers.

It was also observed that the change in the occurrence of pollutants in the air was influenced by the season of the year. Over-normative concentrations of air pollutants were recorded at

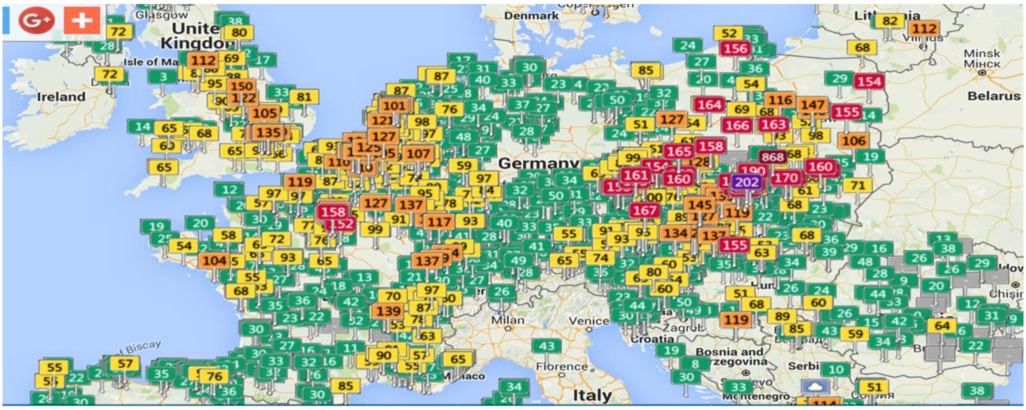

Fig. 1. Air Pollution in the World: Real-time Air Quality Index Visual Map (19.01.2016,15:55)

Rys. 1. Zanieczyszczenie powietrza na świecie: Mapa Indeksu Jakości Powietrza w czasie rzeczywistym (19.01.2016, 15:55)

measurement stations in Kraków during the studied period. Exceedances of emission standards occurred mainly on windless winter days.

The results obtained in the form of regression equations can be used to forecast the level of air pollution in Kraków on subsequent days on the basis of the forecast atmospheric conditions. More precise results are possible if this analysis is extended over a number of years, which will be the subject of further research.

This will allow the city authorities to take warning and preventive measures. The prepared models can be used in practice to forecast (based on meteorological forecasts) air pollution, including in other cities of a similar nature. Activities related to the development of research conducted in the direction of better identification of the main factors that have a negative impact on the aero sanitary situation of cities will pay off in the improvement of people's living conditions.

Statistical models make it possible to conclude that, given an unchanging synoptic situation characterized by low average temperatures and windless weather, exceedances of pollutant concentration limits can be expected. The developed mathematical models describe the relationship between pollutant concentrations and meteorological parameters to a more or less precise degree. An increase in the precision of the results of the multiple regression analysis would be possible by using databases with a larger number of records and extending them by additional years of observations. The highest level of precision was obtained for pollutants related to the occurrence of sulfur dioxide, as evidenced by the calculated values of the R2 determination coefficients. In the case of the model for nitrogen oxide pollution, further research is needed to take into account other independent variables that have not yet been considered.

Mathematical models can form the basis for the construction of local environmental protection programs and serve as tools for improving air quality, mainly in large urban agglomerations.

The air pollution situation in Kraków was so serious that the authorities began to introduce resolutions to improve the city's air quality and measures to improve the health and quality of the life of its residents. Following the introduction of a number of environmental regulations and, above all, the introduction of the so-called Anti-Smog Resolution, the use of coal and wood in boilers, cookers and fireplaces were completely banned in Kraków from 1 September 2019 (Anti-Smog Resolution 2016). Although local decision-makers have taken numerous measures in Kraków to improve air quality, emission problems persist.

References

Anti-Smog Resolution 2016. [Online] https://powietrze.malopolska.pl/antysmogowa/ [Accessed: 2023-03--10].

Borowiak et al. 2023 – Borowiak, K., Budka, A. and Lisiak-Zielińska, M. 2023. Air Pollution in Summer and Winter – Real Threat (*Zanieczyszczenia powietrza latem i zimą – realne zagrożenie*). *Ciepłownictwo, Ogrzewnictwo, Wentylacja* 54(2), pp. 21–26 (*in Polish*).

Chancellery of the Polish Parliament 1991. Act of 20 July 1991 on Environmental Protection Inspection. (*Ustawa z dnia 20 lipca 1991 r. o Inspekcji Ochrony Środowiska*) (*in Polish*).

Chancellery of the Polish Parliament 2001. Act of 27 April 2001. Environmental Protection Law (*Ustawa z dnia 27 kwietnia 2001 r . Prawo ochrony środowiska*) (*Dz.U. 2001 nr 62 poz. 627*) (*in Polish*).

Council of the European Union European Parliament 2004. *Dyrektywa Parlamentu Europejskiego i Rady 2004/107/WE z dnia 15 grudnia 2004 r. w sprawie arsenu, kadmu, niklu, rtęci i wielopierścieniowych węglowodorów aromatycznych w otaczającym powietrzu 1882* [Online] http://eur-lex.europa.eu/legal-content/PL/TXT/?uri=OJ:L:2005:023:TOC [Accessed: 2023-03-10].

Council of the European Union European Parliament 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (*Dyrektywa Parlametu Europejskiego i Rady Europy 2008/50/WE z dnia 21 maja 2008 r. w sprawie jakości powietrza i czystszego powietrza dla Europy*). Dziennik Urzędowy UE, L 152, 0001–0044 (*in Polish*).

Finzi, G. and Tebaldi, G. 1982. A mathematical model for air pollution forecast and alarm in an urban area. *Atmospheric Environment* 16(9), pp. 2055–2059, DOI: 10.1016/0004-6981(82)90276-1.

Foszcz et al. 2021 – Foszcz, D., Niedoba, T. and Siewior, J. 2021. Models of air pollution propagation in the selected region of katowice. *Atmosphere* 12(6), DOI: doi.org/10.3390/atmos12060695.

GIOŚ 2023. Chief Inspectorate for Environmental Protection (*Główny Inspektorat Ochrony Środowiska*). [Online] https://powietrze.gios.gov.pl/pjp/home [Accessed: 2023-04-11] (*in Polish*).

Hławiczka et al. 2016 – Hławiczka, S., Cenowski, M. and Fudała, J. 2016 Parameterization of episodes of high concentrations of air pollutants using PM10 as an example (*Parametryzacja epizodów wysokich stężeń zanieczyszczeń powietrza na przykładzie pyłu PM10*). [In:] Powietrze Atmosferyczne Jakość – Zagrożenia – Ochrona Collective work edited by Kazimierz Gaia and Józef Kuropk Oficyna Wydawnicza Politechniki Wrocławskiej (*in Polish*).

Janota et al. 2015 – Janota, D., Czech, R. and Czech, P. 2015. Analysis of atmospheric air pollution with nitrogen oxides on the example of selected Silesian cities (*Analiza zanieczyszczenia powietrza atmosferycznego tlenkami azotu na przykładzie wybranych śląskich miast*). *Logistyka* 4, pp. 3795–3812, CD2 (*in Polish*).

Journal of Polish Laws 2021. Notice from the Minister for Climate and the Environment of 12 April 2021 on the announcement of the consolidated text of the Regulation of the Minister for the Environment on levels of certain substances in the air (*Obwieszczenie Ministra Klimatu i Środowiska z dnia 12 kwietnia 2021 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Środowiska w sprawie poziomów niektórych substancji w powietrzu)* (Dz.U. 2021, poz. 845) (*in Polish*).

Juda, J. and Chróściel, S. 1974. Ambient air protection. (*Ochrona powietrza atmosferycznego)*. Pp. 303––335, Warszawa: Wydawnictwo Naukowo-Techniczne (*in Polish*).

Kleczkowski, P. 2019. Smog in Poland (*Smog w Polsce*). Warszawa: Wydawnictwo Naukowe PWN (*in Polish*).

Markiewicz, M.T. 2004. Basics of modeling the spread of pollutants in atmospheric air (*Podstawy modelowania rozprzestrzeniania się zanieczyszczeń w powietrzu atmosferycznym*). Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej (*in Polish*).

Ministry of Climate and Environment 2020. Regulation of the Minister of Climate and Environment of December 11, 2020 on assessing the levels of substances in the air (*Rozporządzenie Ministra Klimatu i Środowiska z dnia 11 grudnia 2020 r. w sprawie dokonywania oceny poziomów substancji w powietrzu*) (*Dz.U. 2020, poz. 2279*) (*in Polish*).

Mirowski, T. and Orzechowska, M. 2015. The use of biomass fuels in individual heating in areas threatened by low emission (*Wykorzystanie paliw biomasowych w ogrzewnictwie indywidualnym na obszarach zagrożonych niską emisją*). *Polityka Energetyczna – Energy Policy Journal* 18(4), pp. 75–88 (*in Polish*).

OGIMET 2023. Database of current and archived weather conditions *(Baza aktualnych oraz archiwalnych warunków pogodowych)* [Online] https://www.ogimet.com/home.phtml.en. 2023. [Accessed: 2023-04--11] (*in Polish*).

Tumidajski et al. 2009 – Tumidajski, T., Foszcz, D., Niedoba, T. and Siewior, J. 2009. Stochastic models of air pollution in industrial agglomerations (*Modele stochastyczne zanieczyszczeń powietrza w aglomeracjach przemysłowych*). *Rocznik Ochrona Srodowiska* 11(1), pp. 543–554 (*in Polish*).

Wierzbińska et al. 2023 – Wierzbińska, M., Kozak, J. and Zając, E. 2023. Variability of PM10 particulate matter concentrations in the area of Krościenko nad Dunajcem in the years 2018–2022 (*Zmienność stężeń pyłu zawieszonego PM10 w powietrzu na terenie Krościenka nad Dunajcem w latach 2018–2022*). *Polish Journal of Materials and Environmental Engineering* 5(25), pp. 14–22 (*in Polish*).

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Badanie emisji zanieczyszczeń w odniesieniu do warunków atmosferycznych: studium przypadku zarządzania jakością powietrza w Krakowie

Streszczenie

W artykule przedstawiono tematykę zanieczyszczenia powietrza atmosferycznego. Autorzy przedstawili najważniejsze krajowe przepisy dotyczące jakości powietrza. Zidentyfikowali stacje pomiarowe w mieście Kraków (Polska), zebrali z nich dane i przeprowadzili ich analizę. Celem artykułu jest przedstawienie wyników badań nad opracowaniem statystycznego modelu szacowania zanieczyszczenia powietrza w Krakowie w zależności od zmieniających się warunków pogodowych w ciągu roku. Do opracowania modelu zanieczyszczenia powietrza autorzy wykorzystali metodę modelowania matematycznego. W artykule zebrano dane obrazujące sytuację przed wprowadzeniem szeregu regulacji środowiskowych na terenie miasta Kraków.

Artykuł bazuje na danych meteorologicznych w postaci średnich dobowych wartości temperatury powietrza, prędkości wiatru, wilgotności powietrza, ciśnienia i opadów atmosferycznych. Dane emisyjne stanowiły średnie dobowe stężenia wybranych zanieczyszczeń powietrza, w tym: dwutlenku siarki (SO_2), ditlenku azotu (NO_2), tlenków azotu (NO_x), tlenku azotu (NO), tlenku węgla (CO), ozonu (O_3) oraz pyłu zawieszonego PM10 i PM2,5.

Wyniki badania wskazują, że trzema najistotniejszymi czynnikami wpływającymi na poziom zanieczyszczenia powietrza (pojawiającymi się jako zmiany objaśniające w modelach dla każdego z wymienionych zanieczyszczeń) są: wartość temperatury otoczenia (czynnik destymulujący, z wyjątkiem ozonu), prędkość wiatru (czynnik destymulujący) oraz stężenie każdego z zanieczyszczeń w dniu poprzednim (czynnik stymulujący).

Słowa kluczowe: model matematyczny, zanieczyszczenie powietrza, PM10, tlenek węgla (CO), ditlenek siarki (SO_2)