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PARTICULATE MATTER AIR POLLUTION IN AN URBAN AREA. A CASE STUDY

Many European agglomerations suffer from high concentrations of particulate matter (PM), which is now one of the most detrimental pollutants characterizing the urban atmospheric environment. This paper addresses the problem of PM_{10} pollution in the Warsaw metropolitan area, including very harmful fine fractions ($PM_{2.5}$), and also some heavy metals. The analysis of air quality in the Warsaw agglomeration discussed in this study is based on results from computer modeling presented elsewhere, and refers to emission and meteorological data for the year 2012. The range of emissions considered in this analysis includes the main sectors of municipal activity: energy generation, industry, urban transport, residential sector. The trans-boundary inflow of the main pollutants coming from distant sources is also taken into account. The regional scale computer model CALPUFF was used to assess the annual mean concentrations of major pollutants in the urban area. The results show the regions where the air quality limits are exceeded and indicate the dominant sources of emission which are responsible for these violations (source apportionment). These are the key data required to implement efficient regulatory actions.

Keywords: *urban air quality, particulate matter, violation of concentration limit, source apportionment*

1. Particulate matter in the atmosphere of an urban environment

The problem of high concentrations of particulate matter is one of the most adverse health impacts in European cities. According to the latest WHO report [30], air quality

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in the majority of urban agglomerations – especially in low- and middle-income countries – do not meet the appropriate air quality guidelines [7, 8]. Moreover, ambient air pollution is continuing to rise at an alarming rate.

Air pollutants, and particulate matter in particular, are emitted into the atmosphere from many categories of sources and have various environmental impacts, including hazardous effects on human health. The greatest environmental risk to health (strokes, heart disease, lung cancer, chronic and acute respiratory diseases including asthma) is caused by small and fine fractions of particulate matter [7, 16]. As stated in a recent WHO report [30], high concentrations of air pollution of this type cause more than 3 million premature deaths worldwide each year.

Issues regarding particulate matter mainly relate to PM_{10} and $PM_{2.5}$ (fine fraction). Note that the index corresponds to the aerodynamic diameter. They are emitted into the atmosphere in similar proportions by the following sectors: energy generation, industry, transport, communal and household usage. The most harmful, the fine fraction ($PM_{2.5}$), also contains atmospheric aerosols (SO_4^{2-} and NO_3^- in our case) and heavy metals, such as lead (Pb), nickel (Ni), cadmium (Cd), arsenic (As) and mercury (Hg), which get into the atmosphere as particulate matters and aerosols [7, 11]. They are mainly emitted as a result of various industrial activities and the combustion of coal. Although their concentration levels are low, they contribute to the deposition and build-up of heavy metal contaminants in soils, sediments and organisms.

In an analysis of particulate matter pollution, it is common to make a distinction between primary and secondary pollution [11, 12]. The former (carbonaceous, heavy metals and other minerals) is directly emitted by their sources or re-suspended due to road traffic, while the second is created by chemical processes in the atmosphere (e.g. aerosols). Thus, the description of emission types and the resulting concentration maps are based on the following main components (respectively for PM_{10} and $PM_{2.5}$):

- PPM_{10} – particulate matter (diameter ≤ 10 μm, primary emission),
- $PPM_{10\_}r$ – re-suspended particulate matter PM_{10},
- $PPM_{2.5}$ – particulate matter (diameter ≤ 2.5 μm; primary emission),
- $PPM_{2.5\_}r$ – re-suspended particulate matter $PM_{2.5}$,
- SO_2 and NO_x – sulfur and nitrogen oxides (primary emission),
- SO_4^{2-} and NO_3^- – sulfate and nitric ions in aerosols (secondary pollutants),
- PM_{10} ($PPM_{10} + PPM_{10\_}r + SO_4^{2-} + NO_3^-$) – total PM_{10} concentration,
- $PM_{2.5}$ ($PPM_{2.5} + PPM_{2.5\_}r + SO_4^{2-} + NO_3^-$) – total $PM_{2.5}$ concentration.

To implement any strategy for reducing emissions, a decision maker must know the spatial distribution of PM concentrations, as well as the areas where the air quality standards are violated. Other key information relates to source apportionment, especially in the areas where the concentration limits are exceeded. The above data can be

obtained by computer modeling techniques, commonly used for analyzing the dispersion processes of air pollution.

2. Computer models in air quality assessment and control

Systems for assessing ambient air quality are complex structures based on computer models of pollutant dispersion [3, 5, 25, 28]. The mathematical description of pollution dispersion processes is mostly based on a system of advection-diffusion equations, representing transport in the wind field, turbulent diffusion, chemical transformations, dry deposition of pollutants and their scavenging by precipitation. These models are often used to support decisions at various levels in the management of environmental quality [4, 24, 26].

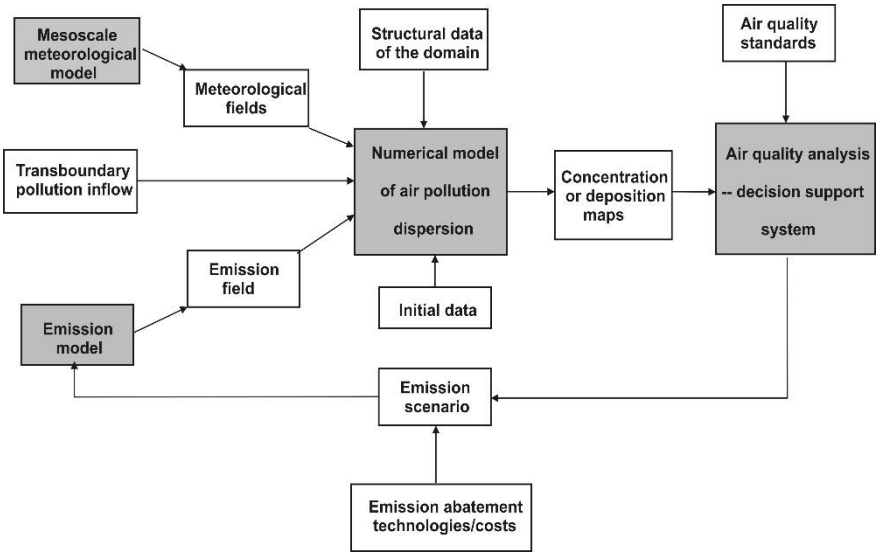

Fig. 1. Block diagram of the decision-making system

The results from modeling can be directly used for supporting decisions in air quality control or can be built into so-called integrated assessment models (IAM) [1, 3, 4, 19], which are being more and more widely used in decision support processes. Such a system allows us to include additional conditions and restrictions, e.g. technological, economic, environmental or demographic, and to search for optimal strategies to meet environmental standards. An example block diagram of such a decision support process is shown in Fig. 1. The model of pollution transport is usually the central module of such a system. Thus, the generated air quality forecasts and related regulatory decisions

should take into account quite a large range of uncertainty related to the complexity of the pollution dispersion model [1, 18, 23]. The sources of this uncertainty lie both in the model itself, the numerical implementation and above all in the input data, based on which the model works [13].

The aim of the model of air quality, which is the central component of the system shown in Fig. 1, is to implement the link between emissions, atmospheric conditions and the resulting pollution concentrations. The main datasets are: emission data, meteorological forecasts, boundary and initial conditions for the concentrations of pollutants, orographic/topographic characteristics of the domain (location, land cover, road network, etc.).

Regulatory decisions can utilize the available measurement values [10], but a model of air pollution provides a decision maker with additional information: a map of the concentration fields of air pollution (even where no measurements exist), which indicates where the pollution limits are exceeded and infers the sources of these violations [12, 14].

3. The assumptions for the assessment of air quality in Warsaw

The following analysis of PM pollution in the Warsaw agglomeration is based on the results of the modeling presented elsewhere [14, 15]. The regional scale modeling system CALPUFF/CALMET [27] was used for simulating pollutant dispersion processes. It is a Gaussian, non-steady-state puff model that takes into account the basic atmospheric processes (transport in the wind field, chemical transformations, dry and wet deposition, formation of aerosols).

CALPUFF has been used in a number of studies, to investigate gas dispersion in urban domains [9, 15] or to simulate an episode of particle pollution [2, 15]. Validation studies have shown strong correlations with field measurements [14, 15]. The linear structure of the model allows us to easily carry out source apportionment when analyzing the PM concentration at some specified receptor site.

Using the results from modeling [15], below we analyze the distributions of the annual mean PM_{10} and $PM_{2.5}$ concentrations of the primary and secondary pollutants (as described in Section 1) for the year 2012 data, including heavy metals: Ni, Cd, Pb, As, Hg. The numerical simulation was performed for the study area (Fig. 2), discretized using a uniform 0.5×0.5 km grid. This resolution was applied for emission and meteorological input data, as well as for the resulting pollution maps. The calculated annual mean concentrations were recorded at 2248 fictitious receptor points located within the administrative boundaries of Warsaw. Each receptor point is located in the center of the corresponding square in the grid. The three receptors specified in Fig. 2 represent characteristic urban sites: a crossroad (A), the urban central district (B), and a residential

district (C). For these three receptors, a detailed description of the results of source apportionment for PM pollution is given in the sequel.

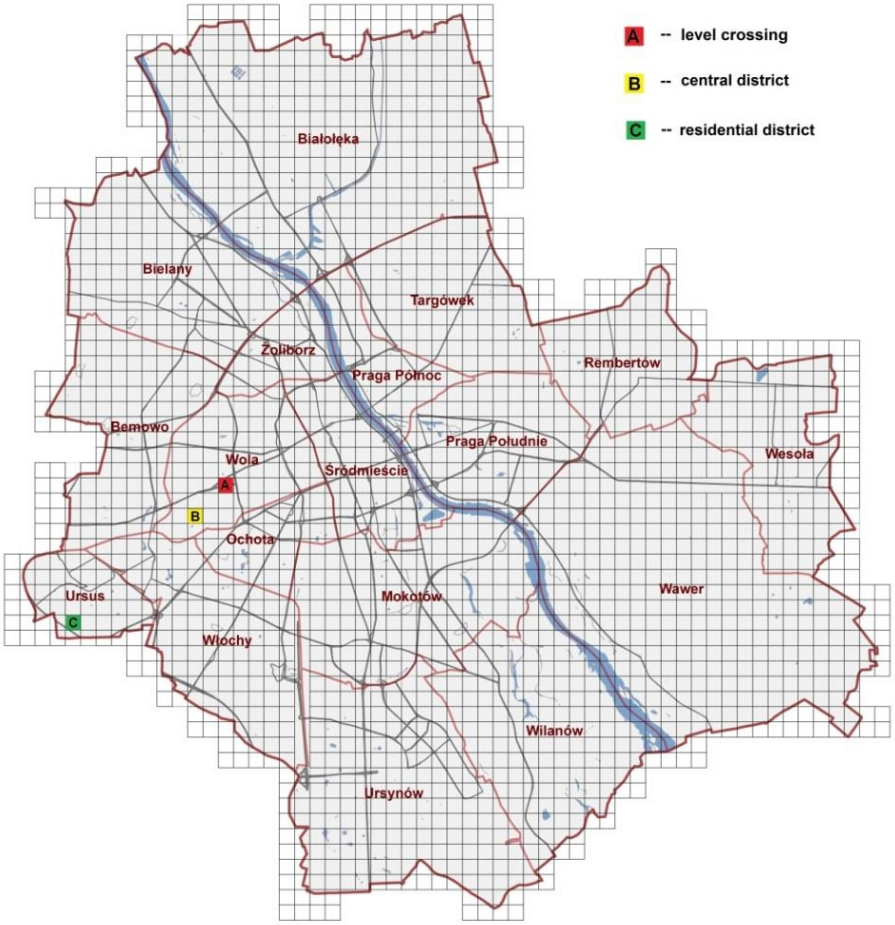

Fig. 2. Warsaw area under study and the spatial resolution

The total emission field in Warsaw was divided into 5 categories of sources that differ in their main emission parameters [14, 15]. These categories are: high-standing point sources (I), which mainly represent power/heating plants and all are characterized by high stacks (mainly 100–300 m); their location is defined by the latitude and longitude of the stack, low-standing point sources (other industrial and local heating sources) (II), location defined by their latitude and longitude, area sources (residential sectors or somewhat dispersed industrial sources) (III), the source is described by the coordinates of the corresponding square (0.5×0.5 km) in the grid and surface emissions from this

square, line sources (e.g. urban road network) (IV), each source is described by the coordinates of the related grid square (0.5×0.5 km) and the emissions from this square, (V) agricultural sources, mainly located in the vicinity of Warsaw and represented by aggregated (5×5 km) surface emissions.

At the regional scale, modeling both the formation of secondary pollutants and trans-boundary transport is critical [11, 15]. The final concentration maps of particulate matter, presented in this study, also include the trans-boundary inflow of pollutants from other sources, located outside the analyzed urban area. This import also includes aerosol formation which is a time-consuming process, and the share of distant sources is much greater than that coming from the local sources [15]. These data, based on [8] and the results from simulation using the European scale model EMEP [10], are included in the boundary conditions for the CALPUFF model and generate the background for pollution coming from the local sources.

Emissions and meteorological data for the CALPUFF simulations are entered with 1 h time steps, and the model generates the concentrations at receptor points with the same temporal resolution. On this basis, one can calculate the average values over a specified period of time. The results discussed in the next section relate to the annual mean PM concentrations, which are compared with the EU limits. This comparison shows where air quality standards are violated and appropriate control procedures are necessary.

Due to the large number of emission sources (about 20 000) and the number of receptor points (2248), the calculations need a lot of computer time. On the other hand, the linear structure of the model allows us to implement parallel computation, and facilitates source apportionment, an important piece of information when a strategy for emission abatement is to be considered.

4. Air quality assessment – selected results

The air quality maps presented below demonstrate whether the annual average concentrations of particulate matter, PM_{10}, $PM_{2.5}$, and certain heavy metals satisfy air quality standards. According to the *Air Quality Directive* [12], the yearly average concentration shall not exceed 40 $\mu g/m^3$ for PM_{10} and 25 $\mu g/m^3$ for $PM_{2.5}$. The first limit (for PM_{10}) came into force in January 2005. According to the regulations of the Ministry of the Environment [20], in 2012 the limit for the yearly mean concentration of $PM_{2.5}$ was increased to 27 $\mu g/m^3$, and the threshold of 25 $\mu g/m^3$ was to be achieved in 2015.

As seen from Fig. 3 (ArcGIS software), the above standards are violated for both PM fractions in some regions of the city, and the maximum values reach about 150% of the limit. For PM_{10}, the area where the threshold is exceeded is large and includes the city center (mainly the left bank of the Vistula River), as well as some residential areas located in the

S-W of the city. Since PM_{10} pollution is strongly related to traffic, the highest concentrations are seen in the central districts and also in the vicinity of the main arterial streets.

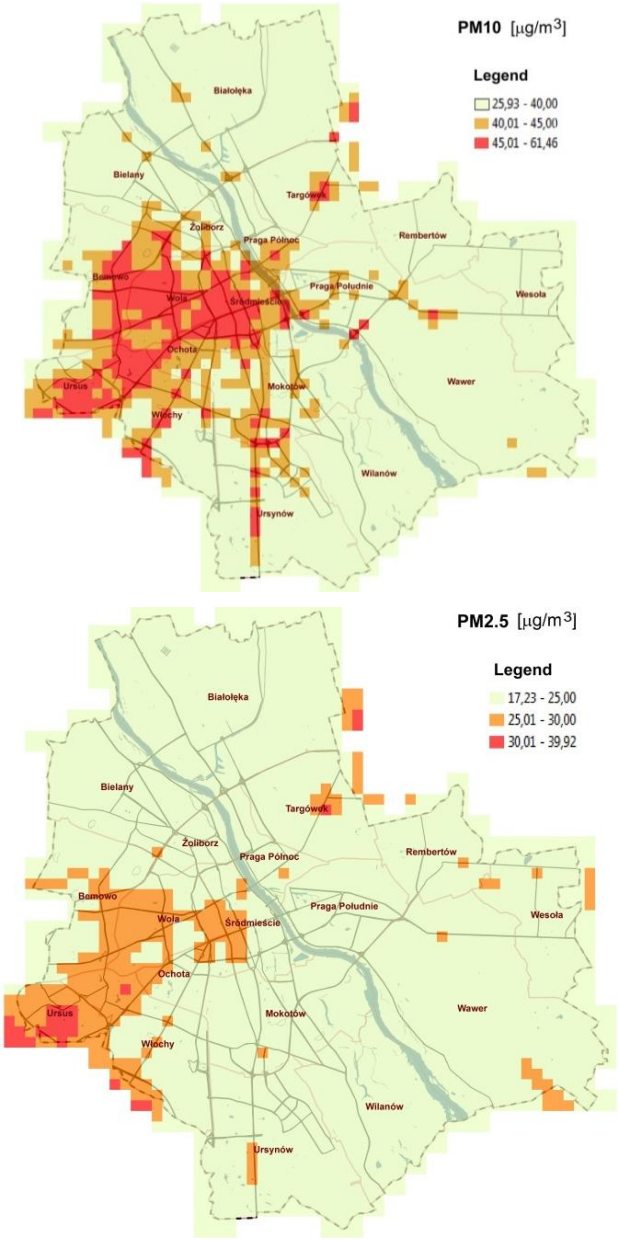

Fig. 3. Maps indicating the violation of the concentration limits for PM_{10} (40 µg/m^3) and $PM_{2.5}$ (25 µg/m^3)

Concentrations of $PM_{2.5}$ also violate the 25 $\mu g/m^3$ limit (and even the less restrictive limit of 27 $\mu g/m^3$ which was set in 2012). The area in which this threshold is exceeded is smaller compared to that of PM_{10}, and also the area where the highest concentrations are reached is limited. However, the more harmful effects on health of fine PM fractions must be remembered [7, 30]. The most hazardous area is again the S-W periphery, where the residential districts of Ursus and Włochy are located.

In the case of fine particulate matter, the contribution of traffic related sources is less apparent (see Fig. 5 below for details). On the other hand, the impact of local area sources of residential heating, as well as trans-boundary inflow from some distant sources, is more significant. However, the long-term effect of PM atmospheric transport, due to the relatively low deposition rate, is a major source of the fine fractions. Moreover, these fractions contain aerosols, which are formed in the atmosphere as secondary pollutants, mainly via chemical transformations.

The official air quality standards for heavy metals are presented in Table 1. The second column gives the limits of the yearly average concentrations, which were obligatory in 2012, according to [21]. The third column shows the target thresholds [12], which have been in force since 1st January 2013, as accepted by the Polish Ministry of the Environment [22]. Since no EU limit/target has been set for Hg concentrations, the limit set in [21] has been adopted.

Table 1. Limits and target values
for the annual average concentrations of heavy metals

Pollutant	PL limit (2012) [Environ. Model. Soft.,]	EU/PL target (since 2013) [ng/m^3]
Arsenic, 6 ng/m^3	10	6
Cadmium, 5 ng/m^3	10	5
Lead, 500 ng/m^3	500	500
Nickel, 20 ng/m^3	25	20
Mercury	40	

Results from simulations show that the maximum yearly concentrations for all the above heav metals are definitely below the EU [10] thresholds. To illustrate the spatial distributions of key heavy metals in Warsaw, Figure 4 shows two example maps, for Pb and Ni, respectively. The concentrations of these metals are relatively high, but the maximum values in both cases are definitely below the limits shown in Table 1.

Lead is a typical pollutant related to emissions from the transportation sector. High concentrations are usually associated with regions of high traffic intensity. According to Pb emission data [29], a small share of old vehicles still use leaded gasoline. The map in Fig. 4 (top) shows the relatively high Pb concentrations in the central districts, and also in the vicinity of the main arterial streets. Generally, the central and S-W districts

are again relatively more polluted, but the maximum concentrations do not exceed 50 ng/m^3, which is 10% of the limit (Table 1).

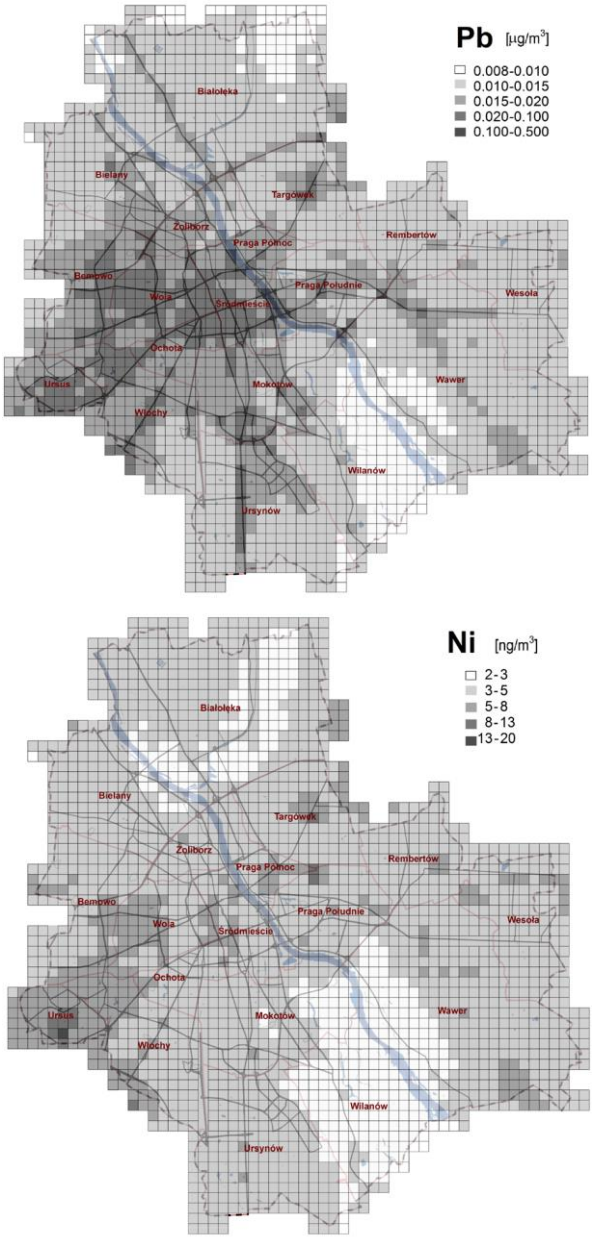

Fig. 4. The concentrations of Pb – top (limit 0.5 µg/m^3) and Ni – bottom (limit 20 ng/m^3) do not exceed the quality standards

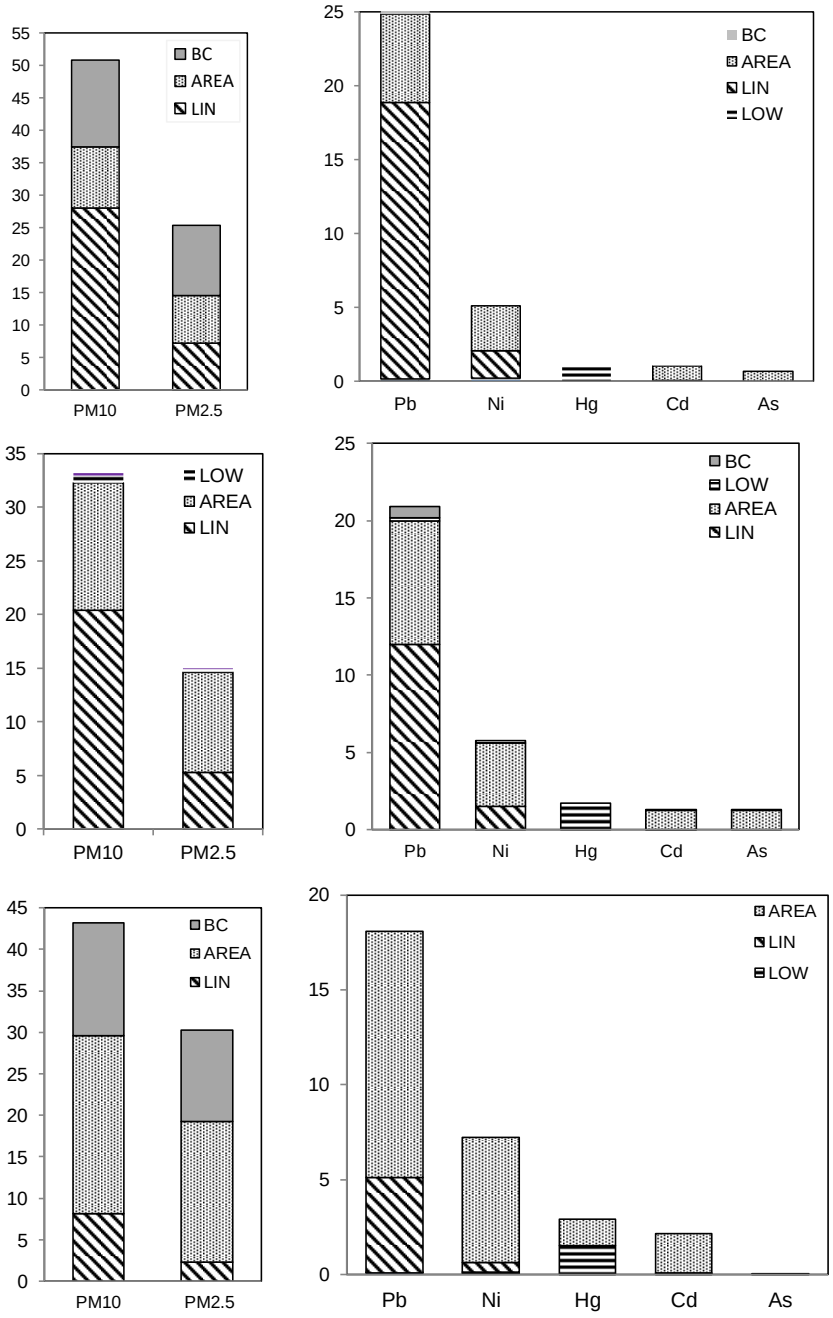

Fig. 5. Concentrations and source apportionment for PM_{10} and $PM_{2.5}$ (μg/m^3, left column) and heavy metals (ng/m^3, right column) at 3 types of the receptor sites (Fig. 1) A – crossroad (top), B – central district (middle), C – residential area (bottom)

The spatial distribution of nickel (Fig. 4, bottom) is more homogeneous, with somewhat higher values in the S-W and central districts. The Ni concentration map also shows low pollution levels, below 5 ng/m^3 in the majority of the city, while the 3–4 isolated sites with concentrations of about 10 ng/m^3 are related to local industrial activity. In this case, the maximum concentrations do not exceed 50% of the limit, according to the (EU 2013) standard.

The characteristics of the concentrations of other heavy metals (As, Cd, Hg) are similar; the spatial distributions are homogeneous and the maximum values are definitely below the limits specified in Table 1. Namely, the maximum As concentration is 3 ng/m^3 (2013 limit – 6 ng/m^3), the maximum concentration of Cd is 3 ng/m^3 (2013 limit – 5 ng/m^3), and the maximum concentration of Hg is 10 ng/m^3 (2012 limit – 40 ng/m^3).

When any policy for emission abatement is considered, an important question refers to the share of the main emission sources in the pollution observed at a receptor. Source apportionment answers this question in a quantitative form. Figure 5 shows the contribution of the basic categories of emitters to PM pollution, recorded at 3 selected receptor points, as shown in Fig. 2. These receptors represent different, characteristic sites of the city: a crossroad with heavy traffic (A), the urban central district (B), and a typical residential area in a peripheral district (C).

The share of various categories of emitters in the pollution at a receptor point strongly depends on the character of the site. In the case of PM_{10}, the impact of mobile sources is dominant at receptor A (crossroad), is also significant in the city center (B), and is small in the residential district (C), where the contribution of area sources significantly increases. The contribution of line sources is much smaller for $PM_{2.5}$. In this case, the fine PM fractions from local heating are the main contributor, especially in the residential area. The share of the trans-boundary inflow is also significant (it is mainly composed of fine particulates, including aerosols).

In the group of heavy metals, source apportionment for Pb is similar to that for PM_{10} (a strong association with traffic), but the impact of the trans-boundary inflow is negligible. The last remark refers to the other heavy metals. Most of them mainly come from area sources. In the case of Ni, there is a small contribution from line sources, while Hg pollution also depends on local point sources (industry).

5. Summary

Selected results from an urban-scale analysis and an assessment of the negative environmental impact of PM pollution have been presented. In urban agglomerations, due to the high concentration of various types of sources of emission and, on the other hand, high population density – the problem of air quality is very important [30]. High exposure to particulate matter pollution, which often exceeds admissible thresholds, can lead to adverse effects such as loss of health, deterioration of professional efficiency, premature mortality.

This in turn causes a measurable economic loss at a city or regional scale. Application of appropriate computer models can indicate the most sensitive regions, where air quality standards are violated and can also show which emission sources are responsible for these violations. These are key factors for activating appropriate recovery programs.

The results presented in this study are based on a real inventory of sources of emission and meteorological dataset for the Warsaw area in the year 2012. The processes of air pollution transport and chemical transformations are simulated by the regional scale, Gaussian model CALPUFF [27]. All the active PM sources were taken into consideration in the modeling process. Due to space limitations, this paper only addresses the environmental impact of air pollution, based on earlier results from modeling [14, 15]. Moreover, source apportionment shows the main categories of emission sources which are responsible for high PM concentrations at some characteristic receptor sites.

PM related deterioration of the air quality in Warsaw is mainly due to the activity of the of urban transport system. The influence of this emission category is above all dominant in the case of PM_{10} pollution, which violates the admissible concentration level (40 $\mu g/m^3$) in a substantial part of the central and S-W districts. The concentration limits are also exceeded in the vicinity of the main and transit roads (see Fig. 3). Car traffic also contributes to $PM_{2.5}$ pollution, but in this case the impact of local area and point sources is much more important, especially in peripheral districts. This is a result of residential heating, where obsolete and inefficient coal-fired installations are often used. In the case of $PM_{2.5}$, the contribution of fine PM fractions imported via transboundary inflow is also more significant.

Heavy metals contribute to a fine fraction of particulate matter. In spite of their low atmospheric concentration, they have adverse health effects. In Warsaw, the concentrations of Pb, Ni, Cd, Hg, and As do not exceed their limits, as shown in Table 1. Generally, area sources contribute to pollution by all five of these heavy metals. Pb pollution is strongly associated with the urban transport sector. In this case, the share of line sources depends on the location of a receptor, and is the most evident in the vicinity of major crossroads (Fig. 5). Mobile sources also have some impact on Ni concentrations. On the other hand, Hg pollution is the result of certain low-standing point sources related to local industrial installations.

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