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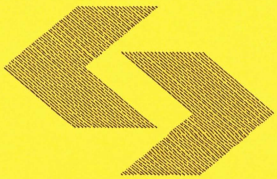
P. Holnicki, A Kałuszko

Instytut Badań Systemowych
Polska Akademia Nauk

Systems Research Institute
Polish Academy of Sciences



POLSKA AKADEMIA NAUK

Instytut Badań Systemowych

ul. Newelska 6

01-447 Warszawa

tel.: (+48) (22) 3810100

fax: (+48) (22) 3810105

Kierownik Zakładu zgłaszający pracę:
Prof. dr hab. inż. Zbigniew Nahorski

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URBAN SCALE PARTICULAR MATTER AIR POLLUTION IN WARSAW

Piotr Holnicki[1], Andrzej Kałuszko[1]

[1)] Systems Research Institute of the Polish Academy of Sciences,

01-447 Warsaw, Newelska 6

Abstract

Management of ambient air quality requires linking the various categories of the input data (emission data and meteorological data) and analytical description of pollutant transport processes. The purpose of the mathematical model is to provide a quantitative assessment of the individual processes intensity and their results in the form of pollution concentration maps. These data are in turn the basis for evaluation of the resulting environmental risk and for supporting planning decisions. Particular matter, PM_{10} and $PM_{2.5}$, are typical polluting compounds which characterize the urban atmospheric environment. The paper presents selected results of computer simulation of PM dispersion processes to get the final concentration maps. Calculations were carried out for the Warsaw area, on the actual emission and meteorological data set for the year 2012. The basic forecasting tool is the regional CALPUFF model, which was used to link the emission sources with the distributions of the annual mean concentrations. The resulting concentration maps of the main PM fractions indicate the areas, where the air quality standards are violated and remedial procedures are required.

1. Decision support in air quality management

Systems for assessing ambient air quality are among the most complex structures, and are based on computer models of the pollutant dispersion (Bucholz et al. 2013; Calori et al. 2006; Jacobson 2005; Russel and Denis 2000; Sportisse 2007). Their construction and operation principle combines knowledge from different fields of science, such as physics (transport and transformations of pollutants in the atmosphere), chemistry (chemical reactions between the polluting components), economics (cost analysis, selection of "clean " technologies), health care (pollution impact on health and life expectancy), biology (impact on environment) and computer science (computer model implementation). The mathematical description of pollution dispersion processes is mostly based on the system of advection-diffusion equations, describing their transport in the wind field, turbulent diffusion, chemical transformations, dry deposition of pollutants and their scavenging by precipitation. These models are used to support decisions at various levels, in management of

environmental quality (Mediavilla-Sahagún and ApSimon 2006; Carnevale et al. 2012; Oxley et al. 2009; Sax and Isakov 2003).

The complexity of the models simulating processes in environmental systems is very large. This applies in particular to so-called IAM (*Integrated Assessment Models*) (compare ApSimon at al. 2002; Buchholz et al. 2013; Carnevale et al. 2012; Mediavilla-Sahagún and ApSimon 2006) more and more widely used in decision support processes. Such a system allows to include additional conditions and restrictions such as technological, economic, environmental or demographic ones, and to search for optimal strategies to meet environmental standards. An exemplary block diagram of such a system is shown in Figure 1. Since the pollution transport model is usually the central module of this system, the generated air quality forecasts and related regulatory decisions should take into account quite a large range of uncertainty (ApSimon et al. 2002; Holnicki et al. 2010; Maxim and van der Sluijs 2011; Moore and Londergan 2001). The sources of this uncertainty lie both in the model itself (simplifications of the mathematical description, skipping or parameterization of certain processes), the numerical

implementation (finite dimensional approximation of continuous processes, discretization of time-space area, description of chemical processes, parameterization of turbulent diffusion) and first of all in the input data, on which the model works.

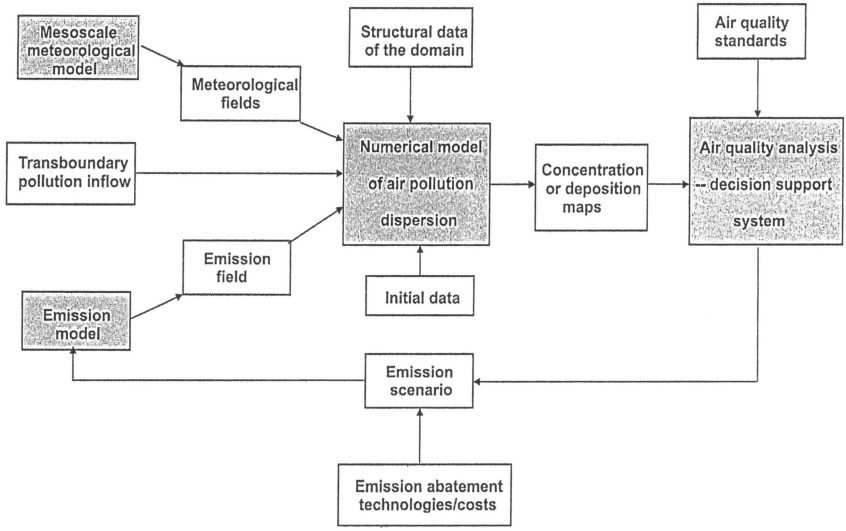

Fig. 1. Block diagram of IAM system

The problem of high particulate matter concentrations is considered to be one of the most adverse health impact in European cities. Particular matter issues mainly relate to PM_{10} and $PM_{2.5}$ (fine fraction), respectively to the aerodynamic diameter. Air quality assessment and the required regulatory decisions can be based on available measurement values and on the modeling results. General

PM monitoring strategy and the respective limit PM values are set in the Air Quality Directive (EC 2008). Monitoring network provides routine observations at some locations (ETC/ACM 2013), using automatic or manual measurements. Air pollution modeling provides a decision maker with additional information: mapping air pollution concentration fields (even where no measurements exist), indicate where the pollution limits are exceeded and asses the source apportionment for these exceedances, forecasting future air pollutions, understanding the air pollution phenomenology.

2. Air pollution dispersion model

The aim of an air quality model is to implement the link between emissions, atmospheric conditions and the resulting pollution concentrations. Thus, the main datasets are: emission data, meteorological forecast, boundary and initial conditions for the modeling process, aerological/topographic characteristic of the area (location, land cover, road network, etc.). The total emission field of big cities is usually characterized by the concentration of a large number of emission sources with very diversified technological

characteristics. In the case of particular matter analysis, description of emission field and the resulting concentration maps consists of the following main components (respectively for PM_{10} and $PM_{2.5}$):

- primary particulate matter (carbonaceous and other mineral species),
- secondary particulate matter (re-suspended due to the road traffic),
- aerosols (mainly sulfur aerosol, $SO_4^=$ and nitric aerosol NO_3^-), which arethe secondary pollutions of sulfur and nitrogen oxides emissions,
- heavy metals which mainly constitute the fine fraction of the former three,
- trans-boundary inflow of PM's and the related components.

Air pollutants, and particular matter in particular, are emitted to the atmosphere from many categories of sources and have a different environmental impact, including hazardous human health effects. For the typical polluting compounds of urban atmospheric environment,

relying mainly on the work of Juda-Rezler (2000) and EEA (2012), the list below shows the main risks associated with related emissions:

- Particulate matter (PM_{10} and $PM_{2.5}$) is emitted into the atmosphere in similar proportions by the sectors of energy generation, industry, transport, communal and household usage. They adversely affect human health, but also vegetation, soil, water, materials and limit visibility. They penetrate the human body, usually by inhalation or indirectly through the digestive system. Studies have shown that fine particulate matters cause very serious health consequences: worsening of asthma, cough, difficulty in breathing, chronic bronchitis, shortness of breath, pneumoconiosis, premature mortality.

- Sulfur dioxide (SO_2) and nitrogen oxides (NOx) – are precursors of the atmospheric aerosols: sulfate aerosol – ($SO_4^{=}$) and nitric aerosol – (NO_3^{-}). They get into the atmosphere mainly from combustion processes of fossil fuels. Sulfur dioxide is a toxic compound for all living organisms, and at the same time has a corrosive effect on materials

(metals, building materials). In the case of the human body it causes inflammation of the upper respiratory tract, conjunctivitis, disorders of taste and smell, irritation of mucous membrane, cardiovascular disease. Nitrogen oxides consist of nitrogen dioxide (NO_2) and nitrogen monoxide (NO). They have a negative impact on animal organisms (including humans) causing conjunctivitis, inflammation and ulceration of the mouth, respiratory tract infections, changes in the image of the lungs, drop in blood pressure, negative impact on reproduction. These compounds are precursors of tropospheric ozone (O_3), which also has a very negative influence on the environment.

- Atmospheric aerosols ($SO_4^=$ and NO_3^- in our case) are airborne particles of the solid phase, gas or liquid. The water in the particles forms a thin spray coating or covering insoluble material or forms aqueous solution, together with dissolved chemicals in it. Most aerosols are a two- or three-phase mixture. Aerosols affect many atmospheric phenomena, such as the formation of clouds and precipitation, scattering and

absorption of solar radiation. They are the direct cause of many diseases, acting negatively on the eyes, skin and respiratory system.

- Heavy metals (such lead – Pb, nickel – Ni, cadmium – Cd, arsenic – As, mercury – Hg), get into the atmosphere as particulate matters and aerosols. They are common air pollutants, mainly emitted as a result of various industrial activities and combustion of coal. Although the atmospheric levels are low, they contribute to the deposition and build-up of heavy metal contents in soils, sediments and organisms. Their sources are: energy generation, industry (metallurgy, mining, chemical industry), construction sector, public utilities sector, transportation. Lead is particularly toxic to humans and animals; it accumulates in bones, kidneys, skin and breast milk. Due to the possibility of damage to the nervous system, it is particularly dangerous for children. Tests on animals have shown carcinogenic effects of lead. The main source of nickel is the combustion of solid fuels, especially coal, the burning of oil and waste, and steel production and galvanization

processes. In the air, the metal is in the form of sulfates, sulfides and oxides of nickel. Absorption into the human body takes place primarily via the respiratory system. Nickel tends to accumulate in the lung and lymph tissues. Cadmium gets in the atmosphere as a result of metallurgical processes, combustion of fossil fuels and waste, production of phosphate fertilizers. It is one of the most dangerous pollutants for human and animal organisms, where it can get in through respiratory routes or digestive tract. It accumulates mainly in kidneys, liver, and bones and causes the kidney diseases, chronic pulmonary diseases, liver and testicle damage. It adversely affects the immune, nervous and hematopoietic systems. Arsenic and the related chemical compounds are very dangerous for humans and animals. It is released into the atmosphere from both natural and anthropogenic sources. Most man-made emissions are released from metal smelters and the combustion of fuels. Pesticides used to be an important source but their importance declined as a result of restrictions in various countries. The oral uptake of As, through food and

drinking water, is generally the most important route of exposure. Arsenic exposure is associated with increased risk of skin and lung cancer. The non-cancerous effects of inhaling air with high As levels include increased mortality from cardiovascular diseases, neuropathy and gangrene of the extremities. Mercury is emitted into the atmosphere from combustion of coal and other fossil fuels. Other sources include metal production, cement production, waste disposal and cremation. In addition, gold production makes a significant contribution to global air emissions of Hg. It can damage the liver, the kidneys and the digestive and respiratory systems. It can also cause brain and neurological damage and impair growth. Unborn children are the most vulnerable population group.

3. Assumptions for the calculation of air quality in Warsaw

The results presented below concern the analysis of particulate matter (PM) air pollution in the Warsaw agglomeration. Regional scale model CALPUFF v.5 (Scire et al. 2000) was used for simulation

of 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). Meteorological fields used for simulations are preprocessed by CALMET cooperating module, which includes, among the other factors, the impact of terrain orography, land cover and aerodynamic roughness of the ground.

CALPUFF has been used in a number of studies, to investigate gas dispersion in urban domain (Elbir 2003), to simulate a particle pollution episode (Barna and Gimson 2002). Validation studies have shown good correlation with field measurements, also recently in (Holnicki and Nahorski 2013). Linear structure of the model allows easily assess the source apportionment when analyzing PM concentration at some specified receptor site.

Emission field in urban agglomerations is usually composed of a large number of emission sources, with the great diversity of their emission parameters. Sources differ in technological characteristics (e.g., spatial description, stack height and diameter, temperature and velocity of the exhaust gases), emission volume and its distribution in

time, the composition of the emitted compounds, as well as the uncertainty regarding the scope of the emission intensity. If the results of the analysis are to be representative and effectively used for decision support, this diversity should be included in the input data.

In an analysis of particular matter pollution, it is common to make a distinction between primary and secondary pollution (ETC/ACM 2013). The former one is directly emitted by sources while the second is produced in atmospheric chemical processes. In this study, we analyze distributions of the annual average PM concentrations for the year 2012 data of the following primary and secondary pollutants (according to the categories of emission sources characterized below):

PPM_{10} – particulate matter; diameter $\leq 10 \mu m$ (primary emission),

PPM_{10}_r – re-suspended PM_{10} (secondary emission),

$PM_{10} = PPM_{10} + PPM_{10}\_r + SO_4^{=} + NO_3^{-}$ – total PM_{10} concentration,

$PPM_{2.5}$ – particulate matter; diameter $\leq 2.5 \mu m$ (primary emission),

$PPM_{2.5}\_r$ – re-suspended $PM_{2.5}$ (secondary emission),

$PM_{2.5} = PPM_{2.5} + PPM_{2.5}\_r + SO_4^{=} + NO_3^{-}$ – total $PM_{2.5}$ concentration,

$SO_4^=$ and NO_3^- – sulfate and nitric aerosols (from local and regional sources)

heavy metals (Ni, Cd, Pb, As, Hg).

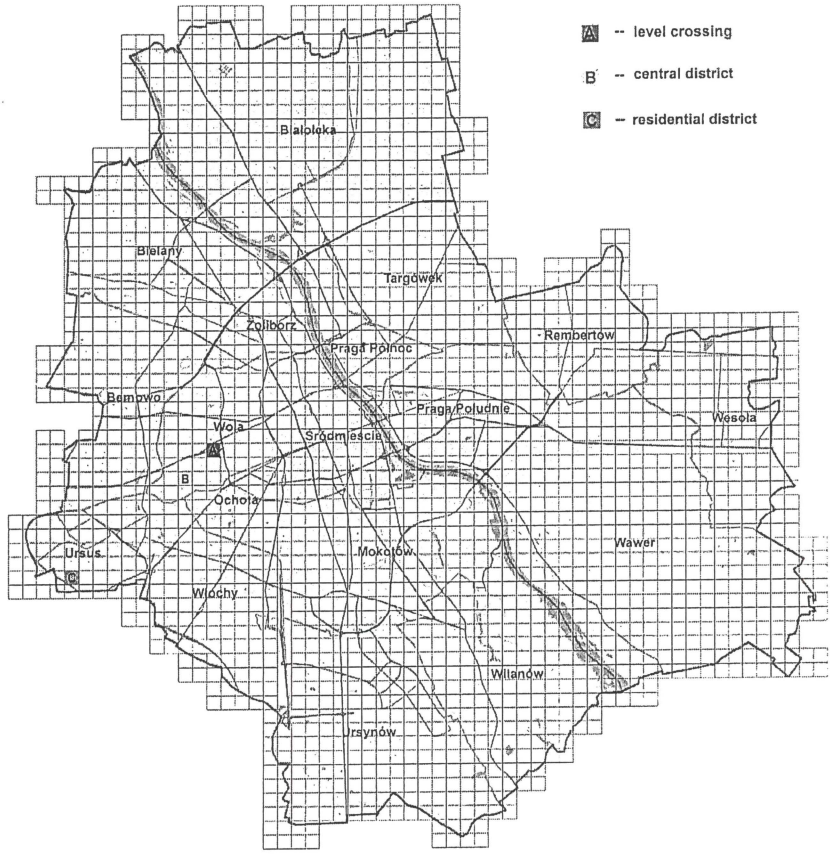

Fig. 2. The study area of Warsaw agglomeration and the receptor elements

Depending on the spatial scale considered, PM concentrations are highly sensitive to emissions and their spatio-temporal variability (ETC/ACM 2013). Thus, emissions are still one of the main sources of uncertainty in PM modeling (compare Holnicki et al. 2010).

The numerical simulations were performed on the study area discretized by the uniform square grid 0.5 km x 0.5 km. In this grid, the basic emission and meteorological input data were defined as well as the results of computer simulation were recorded. The calculated annual mean concentrations of the concerned pollutants were recorded at 2248 fictitious receptor points located within the administrative boundaries of Warsaw (compare Fig. 2). Each receptor point is located in the center of the corresponding discretization square. Three specified in Fig. 2 receptors – denoted A, B and C – represent characteristic urban sites: crossroad, urban central sector and residential district, respectively. For these three receptors, a detailed analysis of the source apportionment for PM pollution (which depend on the type of receptor site), is discussed in the sequel.

The total emission field for Warsaw area was divided into 5 categories of sources that differ among other factors in: geometry of

the source, technological parameters, composition of emitted pollutants, emission intensity with regard to its variation in time, the level of uncertainty of the emission data. In the model simulations the following categories of emission sources were considered: (I) the point sources with high stacks (energy sector), (II) the other point sources (industry), (III) linear sources (transport), (IV) area sources (residential sector) and (V) agricultural production sources (mainly on the outskirts of the city). The location of each point source in the domain is identified by its geographical coordinates. Area, linear (mobile) and agricultural sources are represented as elementary, spatial discretization elements with the uniformly averaged surface emission.

The entire urban emission field used in this study is wider than that shown in Fig. 2 (which shows the receptor field), and also includes the main sources in the immediate vicinity of Warsaw. The neighboring stripe of about 20 km width is also considered. Thus, the total number of sources in the particular emission categories is as follows: (I) 24 high point sources which mainly represent power and heat generation plants and all are characterized by high stacks (mainly

100-300 m). Location by latitude and longitude, the geometric and emission parameters of the source are taken into account. The emission characteristics are relatively accurate, because the combustion process, as well as fuel parameters are well defined and stable; (II) 3880 low point sources (other industrial and local heating sources). Location by latitude and longitude, geometric parameters and the emission of the source are taken into account. Increased uncertainty of the emission parameters due to less accurate (sometimes very imprecise) description of the technological characteristics and fuel parameters, (III) abut 7000 area sources (residential sector or distributed industrial sources). Source described by the coordinates of the corresponding discretization square (0.5 km x 0.5 km) and surface emissions from this square. High uncertainty – emission data are estimated on the basis of the fuel consumption of different types, (IV) above 7000 line sources (urban road network). Each source is described by the coordinates of the corresponding discretization square (0.5 km x 0.5 km) and represented by the area emissions from this square. High uncertainty, emission data is estimated on the basis of traffic parameters (traffic intensity,

fuel composition and quality, the technological characteristics and age of cars as well), (V) 256 agricultural sources, mainly located in the vicinity of Warsaw. They are represented by the aggregated (5 km x 5 km) surface emissions.

At the regional scale modeling, the secondary pollutant formation and transboundary transport are critical (ETC/ACM 2013). The final concentration maps of particular matter, presented in this study, also include transboundary inflow of pollutants from other sources, located outside the analyzed urban (receptor) area. The import also includes the aerosol formation which is the time-consuming process, and the share of distant sources is much greater than that coming from local sources. These data, based on (EEA 2014) and the simulation results from the European scale model EMEP (EMEP/EEA 2013), is introduced as the boundary conditions for the model CALPUFF. As a consequence, it generates the background for pollution coming from the local sources.

Emission and meteorological data for the CALPUFF model simulations are entered with 1-hour time step, and with the same temporal resolution the model generates the concentrations at receptor

points. 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 (including heavy metals), which can be compared with the threshold values. The comparison shows where air pollution limits are violated and the respective controlling actions are necessary.

Due to the large number of emission sources (approximately 20 000) and the number of receptor points (2248), the calculations performed by the CALPUFF model are very labor intensive. On the other hand, the linear structure of the model allows to implement parallel computation, and this approach was used to obtain results presented in Section 4. Moreover, parallelization facilitates assessment of source apportionment, which is an important piece of information when emission abatement strategy is to be considered.

4. Air quality assessment – selected results

Air quality maps presented below demonstrate how the annual average concentrations of particular matter, PM_{10}, $PM_{2.5}$, and some basic heavy metals satisfy air quality standards. Due to Air Quality

Directive 21/05/2008 (EU 2008), which is also adopted by the Polish Ministry of the Environment, 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 value (for PM_{10}) is entered into force in January 2005. Due to the regulations of the Ministry of the Environment (2008) – the limit value for $PM_{2.5}$ yearly mean concentration in 2012 can be increased to 27 $\mu g/m^3$, and the threshold 25 $\mu g/m^3$ is to be reached in 2015.

The maps shown in Figure 3 refer to the concentrations of PM_{10} and $PM_{2.5}$ and indicate the regions of the city, where the air quality limits are violated.

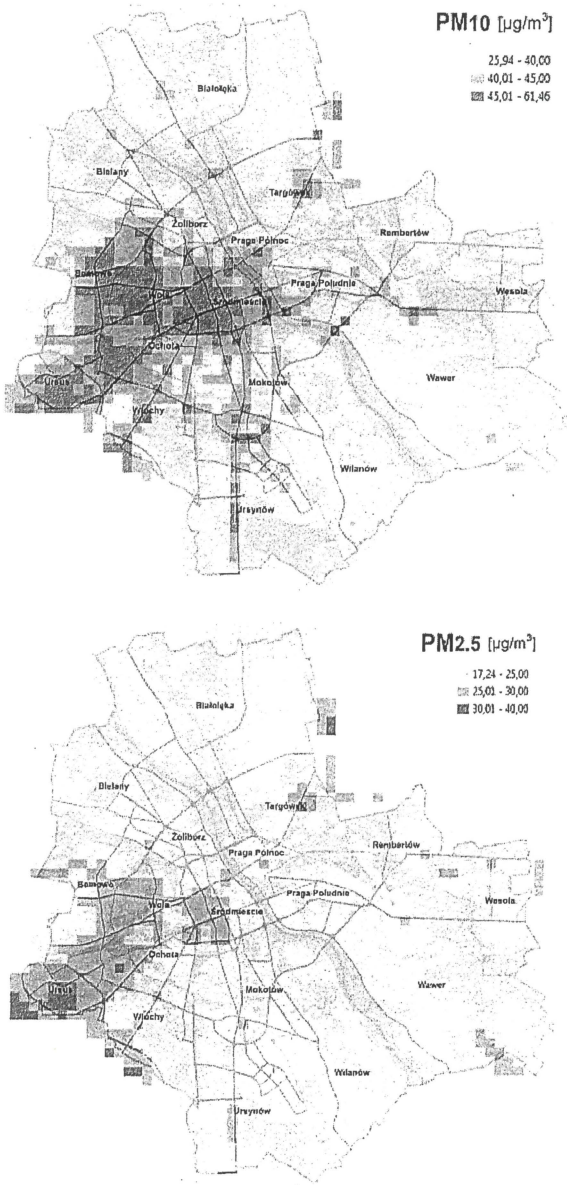

Fig. 3. The maps of violation of concentration limits for PM_{10} (40 $\mu g/m^3$) – top and $PM_{2.5}$ (25 $\mu g/m^3$) – bottom.

The ArcGIS software was used to obtain this visualization. As seen from Fig. 3, 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 required threshold is exceeded is large and includes central region Warsaw (mainly the left bank of the Vistula river), as well as some residential districts, located in S-W part of the city. Since PM_{10} pollution is strongly related to the traffic intensity, the high concentrations are seen in central districts, and also in the vicinity of the main arterial streets.

Concentrations of $PM_{2.5}$ also violate the admissible threshold 25 $\mu g/m^3$ (or even the less restrictive level 27 $\mu g/m^3$ which is set for 2012). The area of this exceedance is smaller compared to that of PM_{10}, and also the area where the highest concentrations are reached is limited, but the more harmful health effects of fine PM fractions must be remembered. The hazardous area is again S-W, peripheral part of the city, where the residential districts Ursus and Wlochy are located.

In the case of fine particular matter, the contribution of traffic related source is less apparent (see results below for details). On the other hand, the more significant is the impact of the local area sources of the residential heating as well as transboundary inflow from some distant sources. The long range transport processes comprise mainly the fine fractions, due to relatively low deposition velocity. Moreover, these fractions contain aerosols which are formed in the atmosphere as the secondary pollutants, mainly in chemical and physical transformation processes of the primary emissions from distant sources.

The official air quality standards for heavy metals are presented in Table 1. The first column of Table 1 gives the limit values of the yearly average concentrations for heavy metals, which were obligatory in 2012, according to the Ministry of the Environment (2010). The second column shows the target thresholds (EU 2008), which are in force since 1 January 2013, accepted by the Polish Ministry of the Environment (2012). Since no EU target or limit has been set for Hg concentrations in the air, the threshold value set in the Ministry of the Environment (2010) is adopted.

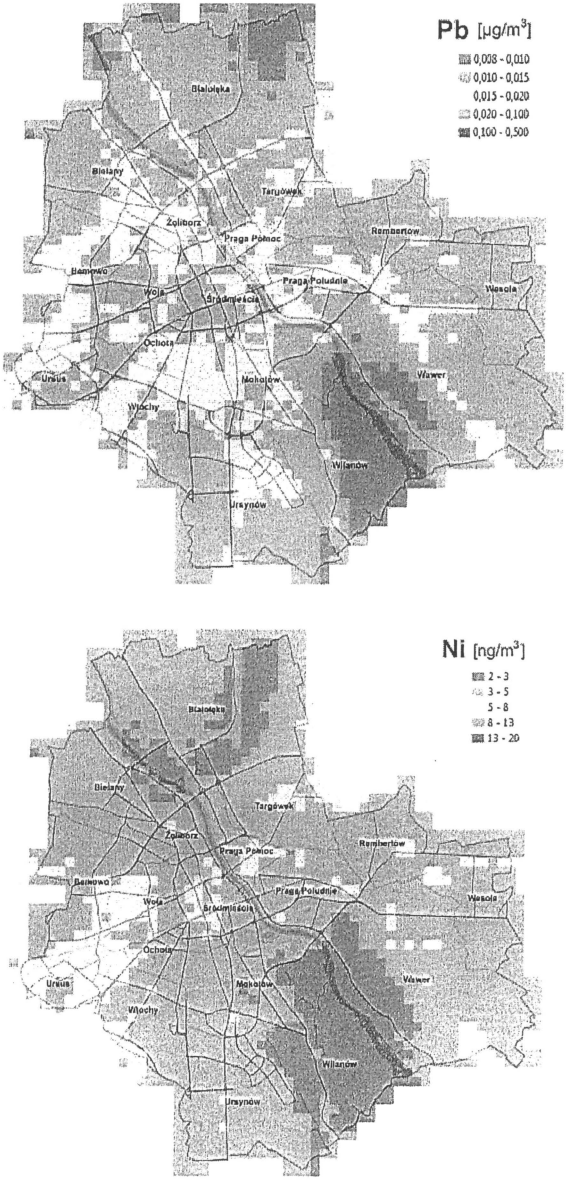

Fig. 4. The concentrations of Pb – top (critical level 0,5 µg/m^3) and Ni – bottom (critical level 20 ng/m^3) do not exceed the quality standards

Table 1. Air quality limits (2012) and target values (since 2013) for heavy metals annual average concentrations

Pollutant	(PL) limit value (2012)	(EU) / (PL) target value (since 2013)
Arsenic 6 ng/m^3	10 ng/m^3	6 ng/m^3
Cadmium 5 ng/m^3	10 ng/m^3	5 ng/m^3
Lead 500 ng/m^3	500 ng/m^3	500 ng/m^3
Nickel 20 ng/m^3	25 ng/m^3	20 ng/m^3
Mercury	40 ng/m^3	

Simulation results show that the maximum year average concentrations for all the above heavy metals are definitely below the EU (2013) threshold values. To illustrate the spatial distribution of key heavy metals in Warsaw, Figure 4 shows two exemplary maps, for Pb and Ni, respectively. The concentrations of these two compounds are relatively high, but the maximum values in both cases are definitely below the limit values shown in Table 1.

Lead is a typical pollutant related to the emission of the mobile sources of transportation sector. The high concentration sites are usually correlated with the main arterial streets or other regions of high traffic intensity. The map in Figure 4 (top) shows the relatively high Pb concentrations in the central districts, and also in the vicinity of the

main arterial streets. Generally, central and S-W districts of the city are again relatively more polluted. However, the maximum concentrations do not exceed 100 ng/m^3, which is about 20% of the limit value (compare Table 1).

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

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

The basic question, when one considers emission abatement policy, is which the emission sources mainly contribute to the receptor's pollution. Source apportionment answers this question in a quantitative form. Figure 5 shows contribution of the basic emission categories to PM pollutions, registered at 3 selected receptor points: A, B and C, as shown in Fig. 2. These receptors represent different, characteristic sites of the city: crossroad with a traffic dominating impact, urban central district, and a typical residential area in a peripheral district.

The share of emission categories in polluting receptor point strongly depends on the character of the site. In the case of PM_{10}, the impact of the mobile sources is dominating at receptor A (crossroad), is also remarkable at the center (B), and is small at the residential part (C), where the contribution of area sources significantly increases. The contribution of the linear sources is much smaller for $PM_{2.5}$. In this case the fine PM fractions, coming from the local heating, become the main contributor, especially in the residential area. The share of the transboundary inflow is also remarkable (it mainly consists of fine particulates, including aerosols).

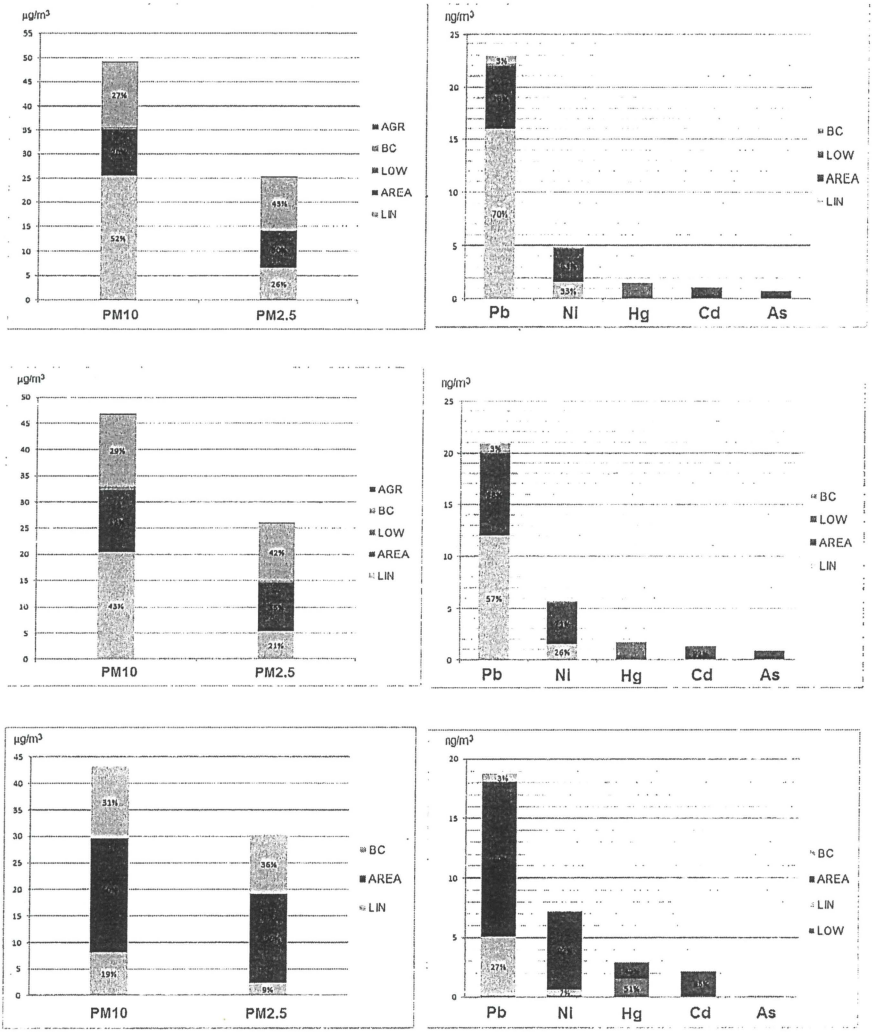

Fig. 6. Concentrations & source apportionment of PM_{10} and $PM_{2.5}$ (left) and heavy metals (right) at three types of receptor sites (Fig. 1):

- one of the main crossroads – receptor A (top),
- central district – receptor B (middle),
- residential area – receptor C (bottom).

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

4. Summary

The paper presents an urban-scale implementation of computer analysis and assessment of the negative environmental impact of PM pollution. In urban agglomerations – due to high concentration of a number of emission sources and, on the other hand, high population density – the problem of air quality is very severe. High exposure to the particular matter, which often exceeds the admissible standards, can lead to adverse effects, such as loss of health, deterioration of professional efficiency, premature mortality. This in turn causes measurable economic loss, counted in the city or regional scale. Application of the respective computer models can indicate the most

sensitive regions, where air quality standards are violated and also can show, which emission sources are responsible for these violations. Such results are the base for activating the respective recovery programs.

Results presented in this study are based on the real emission inventory and meteorological dataset for Warsaw area, for the year 2012. The processes of air pollution transport and transformations are simulated by the regional scale, Gaussian model CALPUFF (Scire et al. 2000). All the active PM sources were taken into consideration in the modeling process. Due to the volume limitations, only selected results have been shown in this study. They illustrate the methodology of investigation used in computer simulation of air pollution transport. Moreover, the source apportionment assessment shows the main categories of emission sources which are responsible for high PM concentrations at some characteristic receptor sites.

PM related deterioration of air quality in Warsaw is mainly due to the activity of the of urban transport system. The influence of this category of emission sources is dominating, first of all, in PM_{10} pollution, which violates the admissible concentration level (40

μg/m3) in a substantial part of central and S-W districts. Exceedance of the concentration limits is also apparent in the vicinity of the main and transit roads (compare Fig. 3). The car traffic also contributes to $PM_{2.5}$ pollution, but in this case the impact of the local area and point sources is much more important, mainly in peripheral districts. This is a result of the local residential heating, where often obsolete and un-efficient, coal-fired installations are used. In case of $PM_{2.5}$, the contribution of fine PM fractions, imported via the transboundary inflow, is also more significant.

Heavy metals constitute a fine fraction of particular matter. In spite of low atmospheric concentration, they have adverse health effects. In Warsaw, concentrations of heavy metals (Pb, Ni, Cd, Hg, As) don't exceed air quality limits (EU 2008), as shown in Table 1. Generally, category of the area sources contribute to all five heavy metals pollution. In case of Pb pollution, which is strongly correlated with urban transport sector, the impact of the linear sources is apparent. In this case, the share of the linear sources depends on the receptor location, and is the most evident in the vicinity of the main crossroads (compare Fig. 6). Some impact of the mobile sources is

also seen in Ni concentrations. On the other hand, Hg pollution depends on some low point sources related to local industrial installations.

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