Raport Badawczy

Research Report

RB/5/2014

Supporting management of air quality in an urban area

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

Warszawa 2014

SUPPORTING MANAGEMENT OF AIR QUALITY IN AN URBAN AREA

Piotr Holnicki[1], Andrzej Kałuszko[1],

[1)] Instytut Badań Systemowych Polskiej Akademii Nauk,

01-447 Warszawa, Newelska 6

Ambient air quality management requires linking the various categories of input data (emission data and meteorological data) and analytical (mathematical) description of pollutants 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. Due to high complexity of the system, its forecasts contain a fairly wide range of uncertainty, which should be taken into consideration in the decisions taken. The paper presents selected results of computer simulation of pollution transport processes and the final air quality maps for the typical polluting compounds which characterize the urban atmospheric environment. Calculations were carried out on the actual emission and meteorological dataset from 2012 for Warsaw. The basic forecasting tool is the regional CALPUFF model, which was used to link the emission sources with the distributions of the annual mean concentration values. The resulting concentration maps of most dangerous pollutants show the areas, where thresholds of air quality standards are exceeded and remedial procedures are required.

1. Decision support in air quality management

Systems for assessing ambient air quality are among the most complex structures, based on computer models of the pollutants 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 the control and 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 systemsis 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 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). 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, description of turbulent diffusion) and first of all in the input data, on which the model works.

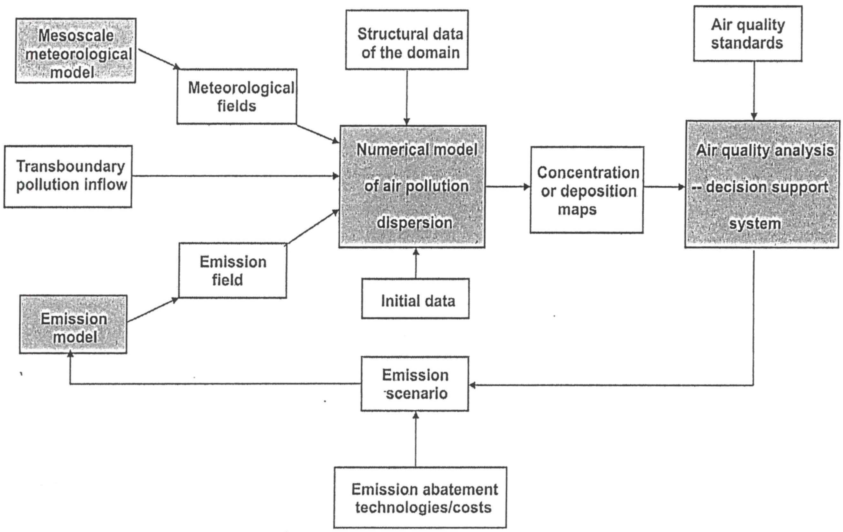

Fig. 1. Block diagram of IAM system

The total emission field of big cities is usually characterized by the concentration of a large number of emission sources with very different characteristics. These sources not only differ in technological parameters (such as the emitter height, diameter, velocity and temperature of the waste gases), but also in composition of emitted pollutants, the emissions intensity of the individual compounds, the uncertainty range of emission data and the negative impact on environment. For typical atmospheric pollution in urban areas, relying mainly on the work of Juda-Rezler (2000), below is the list of the main risks associated with related emissions.

- Sulfur dioxide (SO_2) – gets to the atmosphere by burning fossil fuels. It 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 (NOx), consisting of the nitrogen dioxide (NO_2) and nitrogen monoxide (NO), are also formed as a result of combustion processes. They have 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.

- Ozone (O_3) is one of the strongest oxidants and in the case of human being can cause coughing, symptoms of asthma, pneumonia or lung damage, eye irritation, increase of susceptibility to infections.
- Particulate matters (PM_{10} and $PM_{2.5}$ mainly) are 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.

- Atmospheric aerosols are airborne particles matters of 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 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 as lead – Pb, nickel – Ni, cadmium – Cd, mercury – Hg) get to the atmosphere as particulate matters and aerosols. 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, 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 lymphoid 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 kidney diseases, chronic pulmonary diseases, liver and testicles damage. It adversely affects the immune, nervous and hematopoietic systems. Mercury is emitted into the atmosphere from fuel combustion (power generation, metallurgy), mining industry and pesticides. For humans, mercury is highly toxic. This can result in the weakening of the heartbeat, disorders of the respiratory system, central nervous system paralysis.

- Polycyclic aromatic hydrocarbons (PAH) are a group of organic compounds containing two or more benzene rings. They get to the atmosphere mainly as a result of incomplete burning of fossil fuels (mostly coal). They are highly toxic to humans and animals, and get to the organism through the respiratory or digestive tract. The biggest danger to the health associated with PAH concerns its mutagenic and carcinogenic effects (lung cancer). Studies have shown a particularly strong correlation between the incidence of cancer with the concentration of B[a]P (benzo-alpha-pyrene) belonging to the group of PAHs.

2. Assumptions for the calculation of air quality in Warsaw

The presented below results concern the forecast of air pollution in the Warsaw agglomeration, wherein for the simulation of pollutant dispersion processes CALPUFF v.5 (Scire et al. 2000) model was used. It is a Gaussian puff model taking into account the basic atmospheric processes (transport in the wind field, chemical transformations, dry and wet deposition, formation of aerosols).

Meteorological fields are generated by CALMET cooperating module, taking into account, among other factors, the impact of terrain orography and aerodynamic roughness of the ground.

Distributions of the annual average concentrations for the year 2012 data of the following primary and secondary pollutants (according to the categories of emission sources) were analyzed:

SO_2 – sulfur dioxide,

SO_4 – sulfate aerosol (secondary pollution),

NO_x – nitrogen oxides,

HNO_3 – nitric acid (secondary pollution),

NO_3 – nitrate aerosol (secondary pollution),

NH3 – ammonia,

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

PPM_{10}-R – re-suspended particulate matter PM_{10} (secondary emission),

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

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

$PPM_{2.5}$-R – re-suspended particulate matter $PM_{2.5}$ (secondary emission),

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

CO – carbon monoxide,

C_6H_6 – benzene,

B[a]P – benzo-alpha-pyrene,

Ni – nickel,

Cd – cadmium,

Pb – lead,

As – arsenic,

Hg – mercury.

In the case of large urban agglomerations or industrial regions, the emission field is usually characterized by concentration of a huge number of emission sources in a relatively small area, and with the great diversity of their parameters. Sources differ in technological characteristics (e.g., spatial description, stack height, temperature and velocity of exhaust gases), emission rate and its distribution in time, composition of the emitted pollutants, as well as uncertainty regarding the scope of the emission intensity. If the analysis results are to be representative, this diversity should be included in the input data.

Computational area was discretized by the uniform square grid 0.5 km x 0.5 km. In this grid, basic input data were introduced to the model and the results of computer simulation were recorded. The calculated annual mean concentrations of the concerned pollutants were recorded in 2248 receptor points located within the administrative boundaries of Warsaw (compare Fig. 2). Each receptor was located in the center of the corresponding discretization square.

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: the point sources with high stacks (energy sector), other point sources (industry), linear sources (transport), area sources (residential sector) and agricultural production sources (mainly on the outskirts of the city). Location of each point source in the domain is identified by its geographical coordinates. Area and linear (mobile) sources are represented as elementary, spatial discretization element with the uniformly averaged surface emission.

For calculations presented in this study, in the entire urban emission field within and in the immediate vicinity of Warsaw, the assumed five categories of emission sources (including the number of emission sources in each category) are as follows:

- 20 high point sources (power generation sector). Location by latitude and longitude, geometric parameters and the emission of the source are taken into account. The description is relatively accurate, because the combustion process, its parameters as well as fuel parameters are well defined and stable,
- 3880 low point sources (other industrial sources). Location by latitude and longitude, geometric parameters and the emission of the source are taken into account. Increased uncertainty in

the characterization of the emission parameters due to less accurate (sometimes very inaccurate) description of the technological characteristics and fuel parameters,

- 6962 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,
- 7285 line sources (urban road network). Source 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. Large uncertainty, emission data are estimated on the basis of various parameters (emission depends on traffic intensity, fuel quality, and on the technological characteristics and age of cars as well).

- 256 agricultural sources, mainly located in the vicinity of Warsaw. They are represented by the aggregated (5 km x 5 km) surface sources.

The calculations take also into account the aggregated impact of the agricultural sector sources, mostly located in the vicinity of Warsaw, in a strip about 10 km width. Presented final concentration maps of the basic pollutants include also trans-boundary inflow of pollutants from other sources, located outside the analyzed area. These data, based on the simulation results from the European scale model EMEP (EMEP/EEA Technical Report 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.

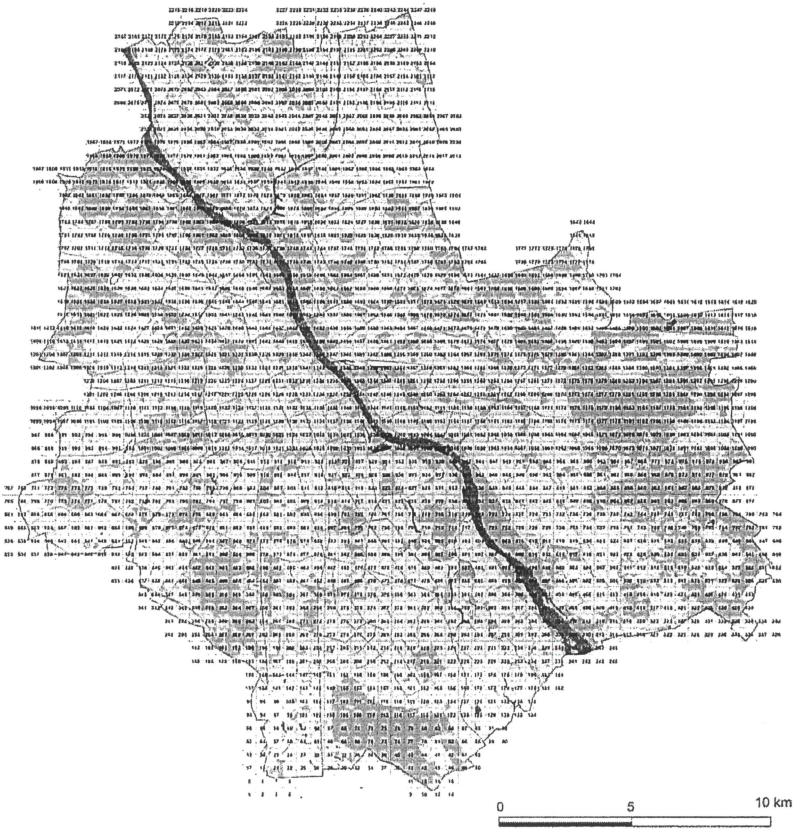

Fig. 2. The modeled area of Warsaw agglomeration

Emission and meteorological data for the CALPUFF model calculations 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 presented in the next section relate to the annual mean concentrations, which can be the basis for the assessment of air quality by their comparison with threshold values.

Due to the large number of sources (approximately 20 000) and receptors (2248), the calculations performed by CALPUFF model are very labor intensive. On the other hand, the linear structure of the model allows performing parallel computation. The results presented in Section 3 were obtained using a parallel implementation of the calculation.

3. Selected results of calculation

For obtaining the following graphical visualization of the results, the ArcMap software was used. Figures 3–4 show the distribution maps of the annual average concentrations of selected pollutants, based on the value in the receptors, projected by the model. The maps shown in Figure 3 refer to the concentrations of PM_{10} and NOx, which are typical transport pollutants. This sector has a dominant share in the formation of this type pollution, and is responsible for exceeding of the admissible concentration levels in areas with heavy traffic as well.

In Poland, in accordance with the standards adopted by the Ministry of Environment, the annual average concentration admissible levels are: PM10 – 40 $\mu g/m^3$ and NOx – 30 $\mu g/m^3$. Both maps presented in Figure 3 show the exceedance of the critical concentration level in the central districts of Warsaw (mainly the left bank of the river), as well as in the neighborhoods of the main roads. The impact of urban transport is particularly evident in the case of NOx pollution, where the share of mobile (linear) sources is dominant. In the case of particulate matters, also heavily dependent on transport sector (it applies mainly to PM_{10} and much less to $PM_{2.5}$), considerable is also the share of so-called "low emission" sources, i.e. local point and surface sources. This explains the high concentrations of PM_{10} in the western districts of Warsaw, including the region of Wlochy and Ursus.

Figure 4 in turn shows the same type of maps with the distributions of both sulfur dioxide (SO_2) and benzo-alpha-pyrene (B[a]P) concentrations. Sulfur dioxide was until recently one of the main components of air pollution in Poland, due to the big share of coal and lignite based power plants. Results obtained in the present study show a significant reduction in the share of high point sources, such as energy plants, in comparison with similar results for the year 2005 (compare e.g. papers Holnicki et al. (2010) and Holnicki and Nahorski (2013)). The substantial reduction of SO_2 emission follows from the significant modernization of technological equipment and new desulfurization installations in this sector in the recent years. On the other hand, due to the simultaneous increase of the traffic intensity (which also emits SO_2) in Warsaw agglomeration, the respective concentration maps also show a correlation between SO_2 pollution and the course of the main streets, with a substantial impact of low emission sources as well. However, the annual average SO_2 concentrations in the whole city do not exceed the admissible level, which in this case is 20 $\mu g/m^3$.

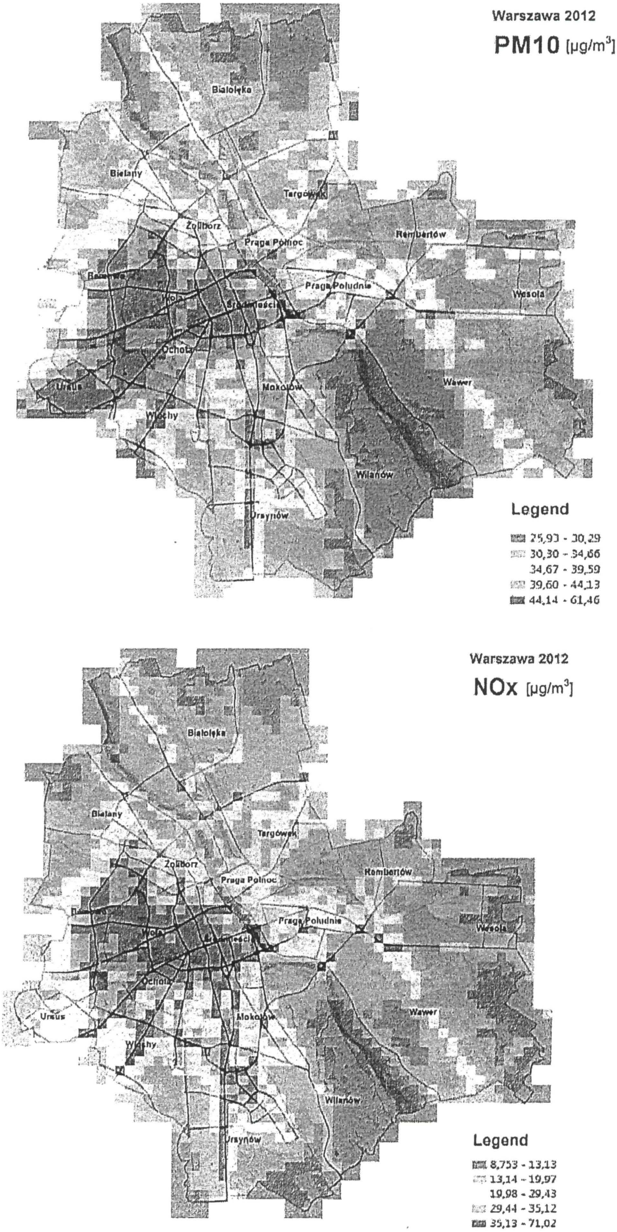

Fig. 3. Distributions of PM_{10} and nitrogen dioxides concentrations

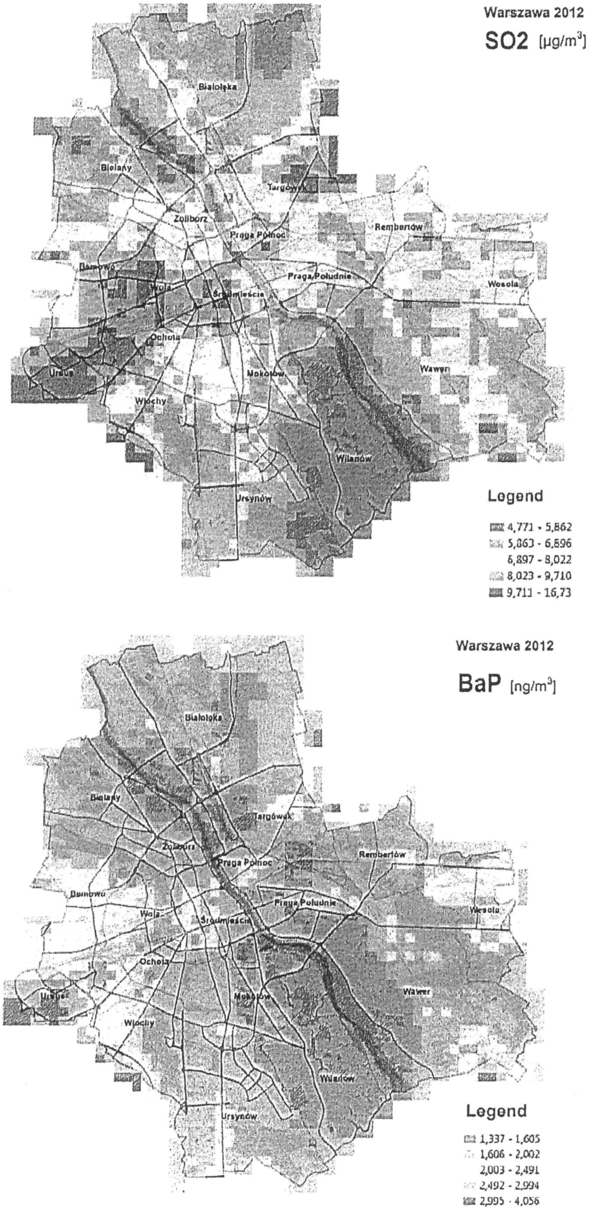

Fig. 4. Distributions of sulfur dioxide and B[a]P concentrations

The last of the maps, presented in Figure 4, shows the concentration distribution of benzo-alpha-pyrene ($C_{20}H_{12}$). This pollutant belongs to the group of aromatic hydrocarbons, which are formed mainly in the processes of the "low combustion" (combustion at low temperatures and often incomplete one) and primarily originate from local area and point sources, using obsolete equipment. These compounds are also emitted in large quantities especially when burning different types of waste, packaging, plastics. Since B[a]P is very dangerous for human health and has carcinogenic and mutagenic effects (compare Juda-Rezler 2000), the average annual admissible concentration level for this compound is very low and has value of 1 ng/m^3. As can be seen from the map in Figure 4, this level is exceeded in all of Warsaw, with the highest values (exceedance about 3-4 times) observed on the outskirts of the city, especially in the western districts (again Ursus, Wlochy).

Confirmation of the above remarks give Figures 5-6, which show the percentage contribution of each emission category to the total concentration value of the four presented pollutants. These graphs concern receptor point No. 672, which is located in the area of the intersection of al. Jerozolimskie street with Lopuszanska street. The share of each category of sources is very diverse, depending on the type of pollutant. In the case of NO_x pollution the dominant share has the transport pollution (89%), with a small contribution of the local surface sources. In the case of PM_{10} the share of transport sources is 47%, but the impact of the area sources and the inflow of pollutants from outside of the area are also significant (location of the spot is close to the city border). This explains the higher "fuzziness" of dust (particulate matter) pollution in this region (compared with NO_x), to be also seen on the maps shown in Figure 3.

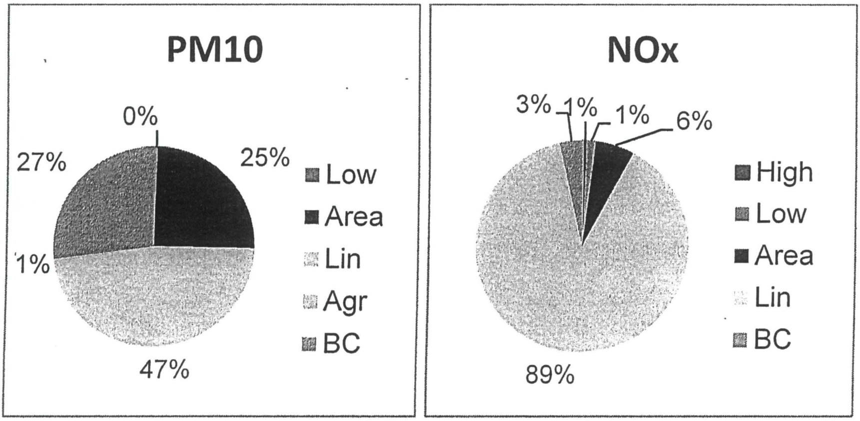

Fig. 5. The relative contribution of emission source categories for PM_{10} and NO_x (receptor no. 672)

In the case of SO_2 pollution, the shares of five considered categories of sources can be seen, with the dominant impact of the surface emission (proximity to Wlochy and Ursus). At the same time, compared with the corresponding results for the year 2005 (Holnicki et al. 2010; Holnicki and Nahorski 2013), the share of high emitters is a much smaller (as mentioned above). The exceedance of permissible B[a]P concentration level is mainly due to the high emission from the area sources in the region (the residential sector). Significant is also the influx of pollutants from the outside, which represents approximately 70% of the concentration permissible level for this compound.

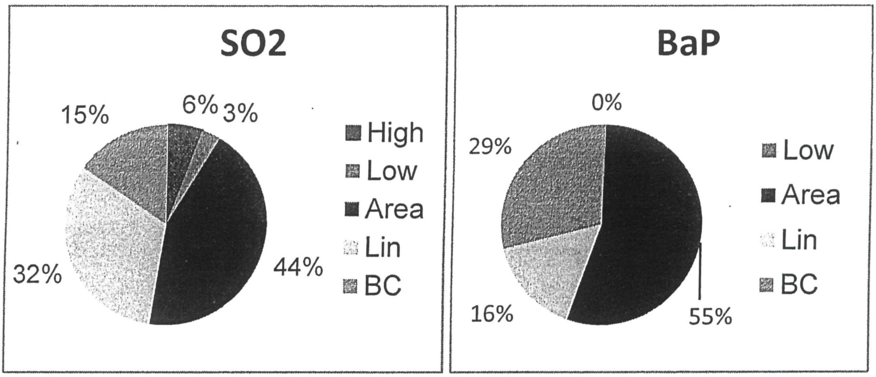

Fig. 6. The relative contribution of emission source categories for SO_2 and B[a]P (receptor no. 672)

4. Summary

The study analyses the possible applications of computer simulation methods in forecasting of air pollution dispersion and assessment of negative environmental impact. In case of urban agglomerations – due to high concentration of a huge number of emission sources and, on the other hand, high population density – the problem of air quality is very severe. High exposure to dangerous pollutants, which often exceed the admissible standards, can lead to adverse health 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, transformations and the resulting environmental impact were analyzed by the regional scale, Gaussian puff model CALPUFF (Scire et al. 2000). All active emission sources were taken into consideration in the modeling process, which included about 20 major polluting compounds, characteristic for urban atmospheric environment. Due to the limited volume of this presentation, only selected results have been shown. They illustrate the methodology of investigation used in computer simulation of air pollution dispersion as well as in assessment of key emission sources which are responsible for violation of air quality standards.

General deterioration of air quality in Warsaw relates mainly to activity of the mobile sources of urban transport system. The influence of this category of emission sources is dominating, first of all, in NOx pollution, which violates the admissible concentration level (30 $\mu g/m^3$) in a substantial part of central districts. Exceedance of the concentration limits is also apparent in vicinity of the main and transit roads (compare Fig. 3). The car traffic contributes also highly to particulate matter pollution (PM_{10} and $PM_{2.5}$), but in this case the impact of the local area and point sources is more important. The area where PM_{10} concentration limit (40 $\mu g/m^3$) is violated is large and also includes central and western districts (Fig. 3). This situation results from very intensive traffic (including transit traffic) in central part of the city. New circle roads (being now under construction) and displacement of the transit and heavy truck transport outside the central districts should gradually improve the situation.

The annual mean sulfur dioxide concentrations are below admissible level (20 $\mu g/m^3$) in all receptor points (compare Fig. 4). When comparing to the results for the year 2005 (Holnicki et al. 2010; Holnicki and Nahorski 2013), substantially lower in present pollution is the share of high point sources of the energy sector (EC Żerań, EC Siekierki, EC Kawęczyn), which is the result of technological modernization of these plants during the last years. On the other hand, one can see increasing contribution of other emission categories, which mainly relates to linear sources of the transport system (see Fig. 6).

In the results presented above, very significant is high concentration of B[a]P. The values shown in Fig. 4 violate throughout the city the concentration standard (1 ng/m3) assumed by the Polish Ministry of Environment. As follows from Fig. 6, in this case dominates the contribution of the area sources of the residential sector. Responsible for this situation are mainly local sources connected with a number of small dwelling-houses with local, coal-based heating/cooking installations (often obsolete). Moreover, as a fuel are often used garbage, domestic wastes, plastic materials which emit a substantial amount of B[a]P. Besides, high concentrations of this pollutant strongly depend on the trans-boundary inflow (29% share of the boundary conditions, as shown in Fig. 6), mainly in the peripheral districts. Similar situation concerning violation of B[a]P critical levels is a more general problem, observed in many other Polish cities.

Acknowledgements

The emission data used in the calculation was developed by EKOMETRIA company, under the leadership of Wojciech Trapp, M. Sc., whom the authors want to thank for his help.

Bibliography

ApSimon H.M., Warren R.F. Kayin S. (2002) Addressing uncertainty in environmental modeling: a case study of integrated assessment of strategies to combat long-range transboundary air pollution. *Atmospheric Environment*, 36, 5417 – 5426.

Buchholz, S., Krein, A., Junk, J., Heinemann, G., Hoffmann, L. (2013) Simulation of Urban-Scale Air Pollution Patterns in Luxembourg: Contributing Sources and Emission Scenarios. *Environmental Modeling and Assessment*, 18, 271– 283.

Carnevale, C., Finzi, G., Pisoni, E., Volta, M., Guariso, G., Gianfreda, R., Maffeis, G., Thunis, P., White, L., Triacchini, G. (2012) An integrated assessment tool to define effective air quality policies at regional scale. *Environmental Modelling & Software*, 38, 306 – 315.

Calori, G., Clemente, M., De Maria, R., Finardi, S., Lollobrigida, F., Tinarelli, G. (2006) Air quality integrated modelling in Turin urban area. *Environmental Modelling & Software*, 21, 468 – 476.

Holnicki P., Nahorski Z., Tainio M. (2010) Uncertainty in air quality forecasts caused by emission uncertainty. Proceedings of *HARMO 13th Conference on Harmonisation within Atmospheric Dispersion Modelling*, pp. 119 – 123, Paris, 2010.

Holnicki, P., Nahorski Z. (2013) Air quality modeling in Warsaw Metropolitan Area. *Journal of Theoretical and Applied Computer Science*, 7, 56 – 69.

Jacobson M.Z. (2005) *Fundamentals of Atmospheric Modeling*. Cambridge University Press, Cambridge, U.K.

Juda-Rezler K. (2000) *Environmental Impact of Air Pollution* (in Polish). Warsaw University of Technology Publishers, Warsaw 2000.

Malherbe, L., Ung, A., Colette, A., Derby, E. (2011) *Formulation and quantification of uncertainties in air quality mapping.* ETC/ACM Technical Paper 2011/9.

Maxim, L., van der Sluijs J. (2011) Quality in environmental science for policy: Assessing uncertainty as a component of policy analysis. *Environmental Science & Policy* 14, 482– 492.

Mediavilla-Sahagún, A., ApSimon, H.M. (2006) Urban scale integrated assessment for London: Which emission reduction strategies are more effective in attaining prescribed PM10 air quality standards by 2005? *Environmental Modelling & Software*, 21, 501– 513.

Moore G.E., Londergan R.J. (2001) Sampled Monte Carlo uncertainty analysis for photochemical grid models. *Atmospheric Environment*, 35, 4863 – 4876.

Oxley, T., Valiantis, M., Elshkaki, A., ApSimon, H.M. (2009) Background, Road and Urban Transport modeling of Air quality Limit values (The BRUTAL model). *Environmental Modelling & Software*, 24, 1036–1050.

Russel A., Dennis D. (2000) NASTRO critical review of photochemical models and modeling. *Atmospheric Environment*, 34, 2283 – 2324.

Sax T., Isakov V. (2003) A case study for assessing uncertainty in local-scale regulatory air quality modeling applications. *Atmospheric Environment*, 37, 2003, 3481 – 3489.

Scire J.S., Strimaitis D.G., Yamartino R.J. (2000) *A User's Guide for the CALPUFF Dispersion Model*. Earth Technology Inc.,

Sportisse B. (2007) A review of current issues in air pollution modeling and simulation. Computational Geosciences, 11, 2007, 159 – 181.

EMEP/EEA Air Pollutant Emission inventory Guidebook (2013). EEA Technical Report, No 12/2-13. European Environmental Agency 2013.