

Processing of Environmental Data for Air Dispersion Numerical Models and Aerodynamic Research in Wind Tunnels

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Abstract: Air dispersion modelling can be performed by a number of computer programs that are available as open-source software or as commercial software tools. Recent computer programs require a wide range of input information about pollution sources, meteorological conditions and complex terrain properties. In aerodynamic research in wind tunnels, detailed information about complex terrain is required for production of plastic models with computer numerical control machine tools or 3D printers. Thus, a complex information system has been developed to manage environmental data, provide pre-processing and post-processing steps, visualize simulation outputs and manage data exchange. The information system is implemented in GIS. In a case study, modelling of dust transport over a selected surface mining area, and its digital terrain model for aerodynamic research are presented, together with visualization of numerical simulations and captured scenes by two-dimensional optical fibre laser Doppler anemometry. The final stage of this project deals with integration of a wide range of spatio-temporal data extended by satellite images and aerial photographs, surface measurements by GPS and 3D surface scanners, and altimetry data in the 5m x 5m spatial grid from a new digital terrain model of the Czech Republic. Simulation results enable prediction of air pollution above the area of interest in the surface coal mine and its neighbouring residential sites. The described case study can be used in decision-making processes for reducing the environmental impacts of the coal mining industry.

Keywords: Air dispersion modelling; GIS; wind tunnel; surface mine.

1. INTRODUCTION

Assessment of the public health impact of air pollution exposure depends on estimates of air pollutant concentrations. Estimates can be derived either by measurements or by modelling and are often a combination of the two, where model predictions are used to provide data for areas where monitoring data are lacking. The model predictions are based on various approaches. The interpolation techniques and regression-based methods for mapping air pollution are used in the environment of industrial and urban areas on local scales, but a sufficient amount of monitoring data is required for validation and testing (Briggs et al., 2000). Numerical modelling by the Navier-Stokes equations is a more theoretically demanding approach, which can describe the flow over complex terrain with different wind directions and predict dispersion of pollution particles (Badr and Harison, 2005; Jung et al., 2003). The accuracy of the numerical models essentially depends on accurate data for the advection velocity field. Thus, many model applications were restricted to flat terrain and never tested in complex terrain and the advection velocity field data were replaced by meteorologically measured data or simplified flow profiles. An alternative approach to numerical modelling by air dispersion models is aerodynamic research, which uses wind tunnels to study the effects of air moving past models of surface industrial sites and their neighbouring areas (Ahmad et al., 2005).

2. PROCESSING OF ENVIRONMENTAL DATA

The integration of input/output model data is seen as a central task for pre-processing and post-processing of air-dispersion numerical models and aerodynamic research in wind tunnels. The basic schema of data flows is given in Fig. 1. The inputs into the pre-processing phase represent topographic data for construction of the digital terrain model, air pollution sources for creation of map layers with point, line and area sources of pollution, regular sampling of air pollution at selected sites for validation of model predictions, meteorological data for creation datasets with wind speed and direction and other data, such as temperature, humidity, precipitation and solar. After the pre-processing stage, the created spatio-temporal datasets are integrated in the GIS project and the GIS tools are used for data management of the geodatabase, which can be complemented by other data, such as satellite and aerial images, thematic maps and historical records. The paper is focused on three ways of prediction: by spatial modelling, by air-dispersion numerical models and by aerodynamic research in wind tunnels. Spatial modelling deals with deterministic and geostatistical interpolation methods, probability mapping and geographically weighted regression (GWR). The interpolation and probability mapping are based on point samples. They are used for continuous surface layers that predict the values of air pollutant concentrations for every location in the area of interest. The probability maps can assess the probability that a critical concentration threshold value has been exceeded. GWR is used to provide a local model by fitting regression equations containing the dependent variable, concentration of air pollutant, and explanatory variables, such as potential sites of pollutant emissions, local wind speed and surface temperature.

The numerical models based on the Navier-Stokes equations and other mathematical expressions are solved by standalone software tools. Additional procedures are needed to export data to the required data inputs of various numerical models. The initial tests were performed with Gaussian plume air-dispersion models, such as AERMOD, ISCST3 and ISC-PRIME. The numerical models utilized data from the digital elevation model (DEM), extended by simplified 3D buildings, datasets containing air pollution sources and sampling points/receptors, as well as records of meteorological data. The output datasets are extracted and imported into GIS by other software tools and GIS functions. These air-dispersion numerical models employ hourly meteorological data records to define the conditions for plume rise, transport, diffusion and deposition. The concentration or deposition values are estimated for each hour of input meteorology. The model outputs, user-selected, short-term averages of the concentrations at each receptor location, are exported into GIS for analysis and visualization, together with the existing spatial data.

An alternative approach to numerical modelling is represented by aerodynamic research that uses wind tunnels to study the effects of air moving past models of a surface. The size of our model on a scale of about 1:9,000 is 1.5 m x 1.5 m. The measurements are visualised by two-dimensional optical fibre Laser Doppler Anemometry (LDA). After capturing the scenes, the experimental data are imported into the computer system for other processing (Bodnar et al., 2013). The plastic models are produced using computer numerical control (CNC) machine tools. The data inputs are derived from DEMs created in GIS. The DEMs are based on a large data set of points (1,500 x 1,500 points for the 1.5 m x 1.5 m model).

The inputs into the post-processing phase represent continuous surface layers from spatial modelling, user-selected short-term averages of concentrations at each receptor location from numerical models and captured images of flow fields from aerodynamic research in wind tunnels. The post-processing phase employs import of simulation results into the GIS project to integrate new datasets together with existing data in the geodatabase. The spatio-temporal analysis and visualization are used to create thematic maps of environmental impacts for decision-making processes, linked projects that are focused on health protection and information in the public domain.

The described data flows were used for the research project dealing with dust transport over surface mining areas. It is focused on the environmental impacts from coal mining in the northwest part of the Czech Republic. The aim of the project is to eliminate dominant sources of dust pollution that reduce air quality and affect humans and nature in and around mining areas. It also proposes sustainable development of mining activities, which would play a positive role in the economic development of the region. The proposed integrated spatio-temporal modelling project in GIS environment facilitates more comprehensive risk assessment.

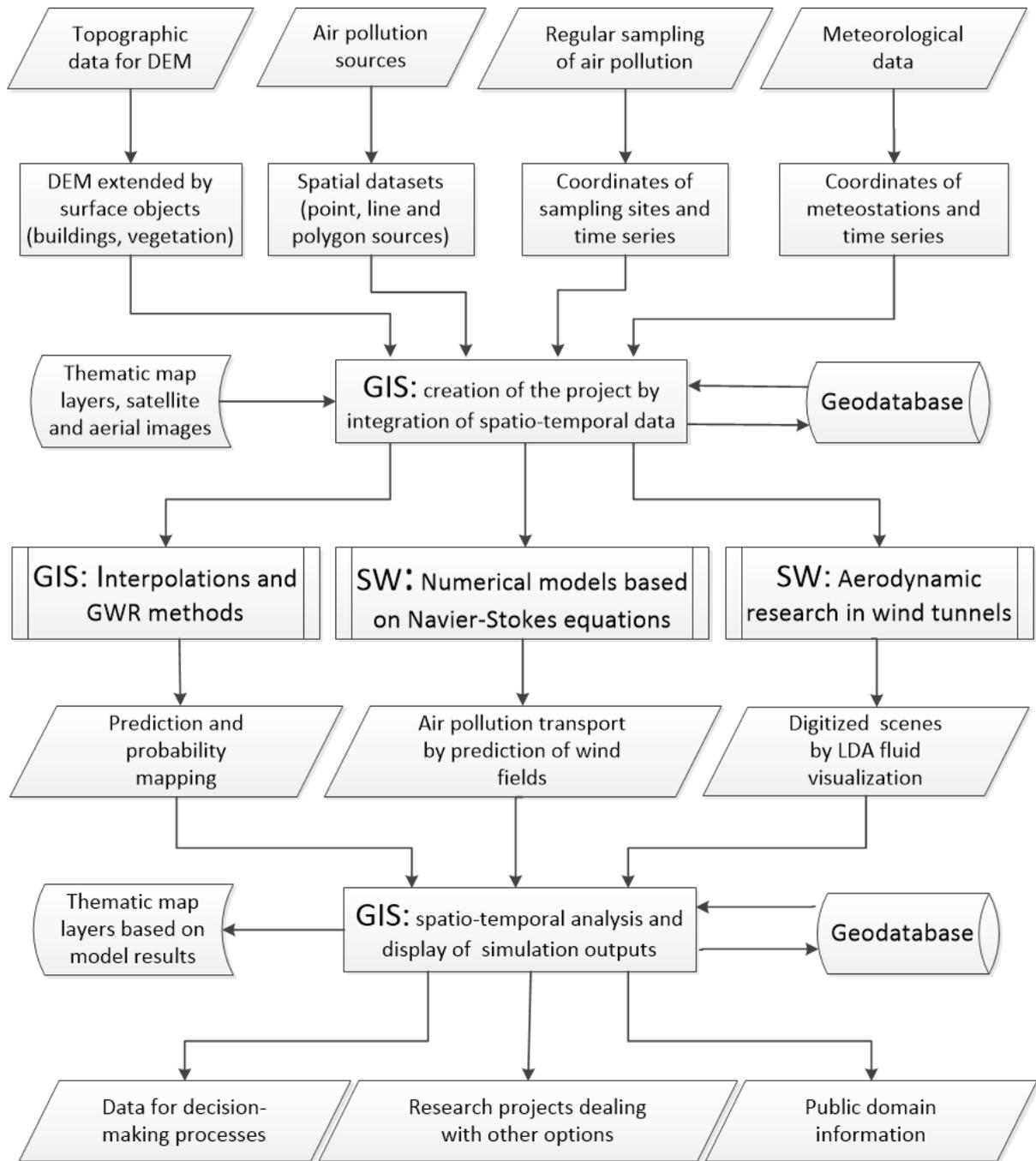


Figure 1. Data flows in the processing of environmental data for spatial modelling, air-dispersion numerical models and aerodynamic research in wind tunnels designated for decision-making processes, linked projects that are focused on health protection and information in the public domain.

3. A CASE STUDY: DUST TRANSPORT OVER A SURFACE MINING AREA

The described case study demonstrates the use of data flows in the processing of environmental data for spatial modelling, air-dispersion numerical models, and aerodynamic research in wind tunnels. The area of interest is a surface coal mine in the northern part of the Czech Republic, Fig. 2. The dust emissions from mining activities represent dominant sources of air pollution. The geostatistical techniques, numerical models and aerodynamic research in the wind tunnel are used for prediction of air pollution dispersion.



Figure 2. The area of interest: the surface coal mine in the northern part of the Czech Republic (from Landsat 8, captured in May 2013).

The DEM is based on the Digital Terrain Model of the Czech Republic of the 4th generation (DMR 4G, heights in discrete points in a regular grid of 5 m x 5 m) and 3D contour lines. The changes in terrain heights in the 2010-2014 period are illustrated in Fig. 3. The 3D view shows the DEM for a stage of mining in 2010, and the DEM for a proposed stage of mining in 2014. The changes in terrain heights in the 2010-2014 period are indicated by light and grey pixels in Fig. 3 in the bottom part of the 3D view. The surface sources of air pollution include coal extractions, loading and unloading, road transport and coal-handling plants. Their locations and shapes are estimated by terrain mapping with GPS. Air pollution by PM₁₀ is sampled by monitoring stations located at the nearest residential sites. Monitoring stations are also used for measuring wind speed and direction.

The air dispersion numerical model employs information about air pollution sources and meteorological conditions to predict how PM₁₀ moves through the atmosphere above the surface area of interest. The Industrial Source Complex Short-Term model (ISCST3) together with Plume Rise Model Enhancements (ISC-PRIME) and digital terrain models are used to provide predictions based on advanced meteorological turbulence calculations that are influenced by local terrain effects.

The modelling tools employ hourly meteorological data records to define the conditions for plume rise, transport, diffusion and deposition. The concentration or deposition values are estimated for each hour of input meteorology. The model outputs for one year, user-selected short-term averages of concentrations at each receptor location in the regular grid, are given in Fig. 4. The isolines of PM₁₀ concentrations are complemented by the DEM layer, which is attached to the stage of mining in 2010. Other features represent monitoring stations that are used for validation of model predictions. The aerodynamic research uses wind tunnels to study the effects of air moving past the models of a surface coal mine and its neighbouring areas. The model on a scale of 1:9 000 has a size of 1.5 m x 1.5 m. Production of the plastic model is made with the computer numerical control (CNC) machine tools. The datasets for production were derived from DEMs created with GIS. The actual DEMs are based on large data sets of points (1,500 x 1,500 points for the 1.5 m x 1.5 m model). A model for visualisation by two-

dimensional optical fibre Laser Doppler Anemometry (LDA) is in Fig. 5. After capturing the scenes, the experimental data are imported into the computer system for other processing. The final stage of the described case study deals with integration of a wide range of spatio-temporal data in the GIS environment. The GIS tools manage data from remote sensing (LANDSAT and aerial images), surface measurements (GPS data), existing thematic map layers, altimetry datasets (DMR 4G, 3D contour lines), regular sampling of PM₁₀ and meteorological data.

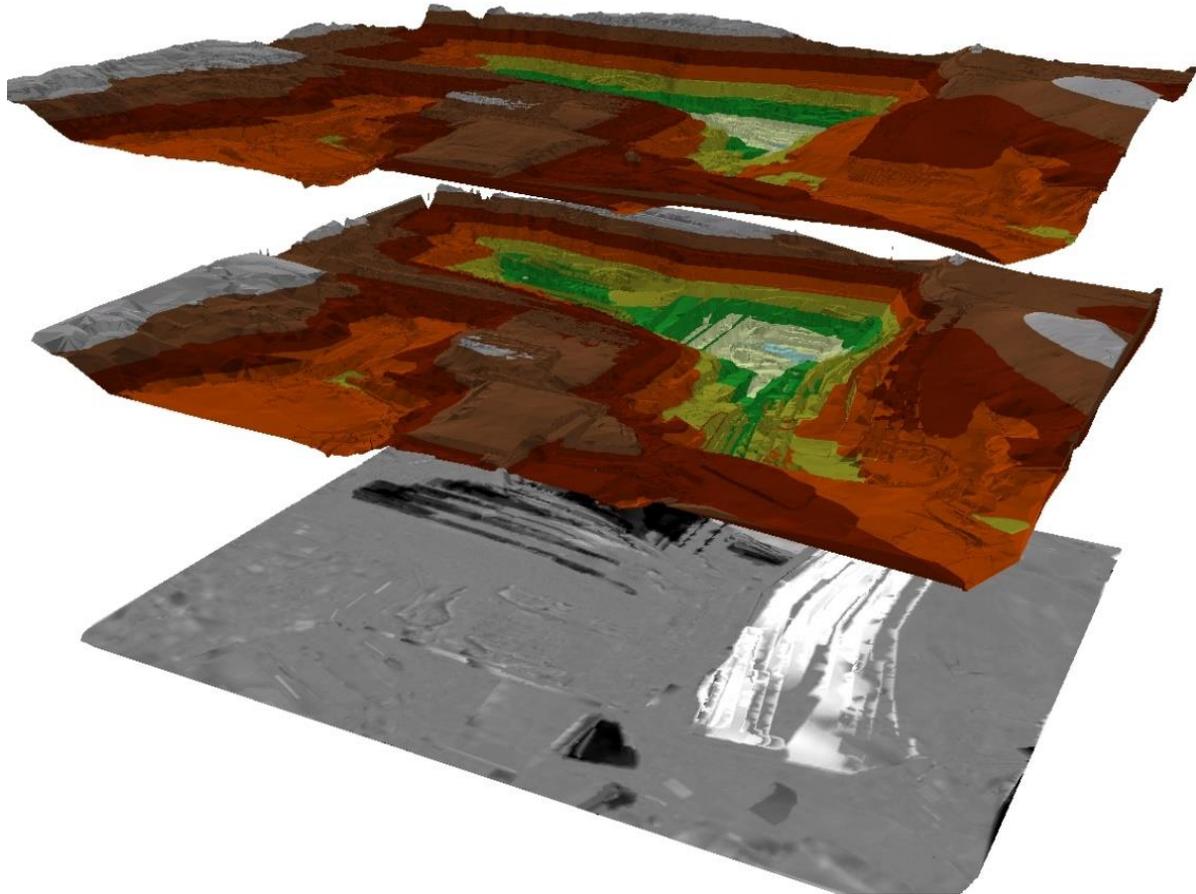


Figure 3. The DEM for the stage of mining in 2010 and the DEM for a proposed stage of mining in 2014, the changes in terrain heights in the 2010-2014 period are indicated by light pixels (decrease in elevations by extraction) and by grey pixels (increase in elevations by accumulation) at the bottom part of the 3D view.

Some listed items are used for development of inputs in the air dispersion models (DEMs, locations and properties of air pollution sources and meteorological data) and aerodynamic research in the wind tunnel (digital datasets of DEMs for models made by CNC machine tools). The simulation outputs from modelling systems are used as data inputs for spatial analysis and visualization. An example of GIS outputs shows layer datasets of isolines with PM₁₀ concentrations in the receptor grid, the DEM, monitoring stations, and location of sources of air pollution PM₁₀ in Fig. 6. Visualization of these layer datasets in a 3D view is depicted in Fig. 7. The GIS environment offers a wide range of spatio-temporal analyses and ways to share datasets with other case-oriented software tools for air-dispersion modelling and aerodynamic research in wind tunnels. The results of the described case study facilitate prediction of air pollution by PM₁₀, and optionally other pollutants, above the area of interest in the surface coal mine and its neighbouring residential areas. Combined research by numerical modelling and aerodynamic research can explore the influence of terrain changes caused by mining activities on wind flows and air pollution dispersion. This can be used in decision-making processes related to reducing the environmental impacts of coal mining in the northwest part of the country. The described case study enables simulation of appropriate manmade barriers and different flow conditions to test the most suitable solution for reducing the environmental impacts of mining activities.

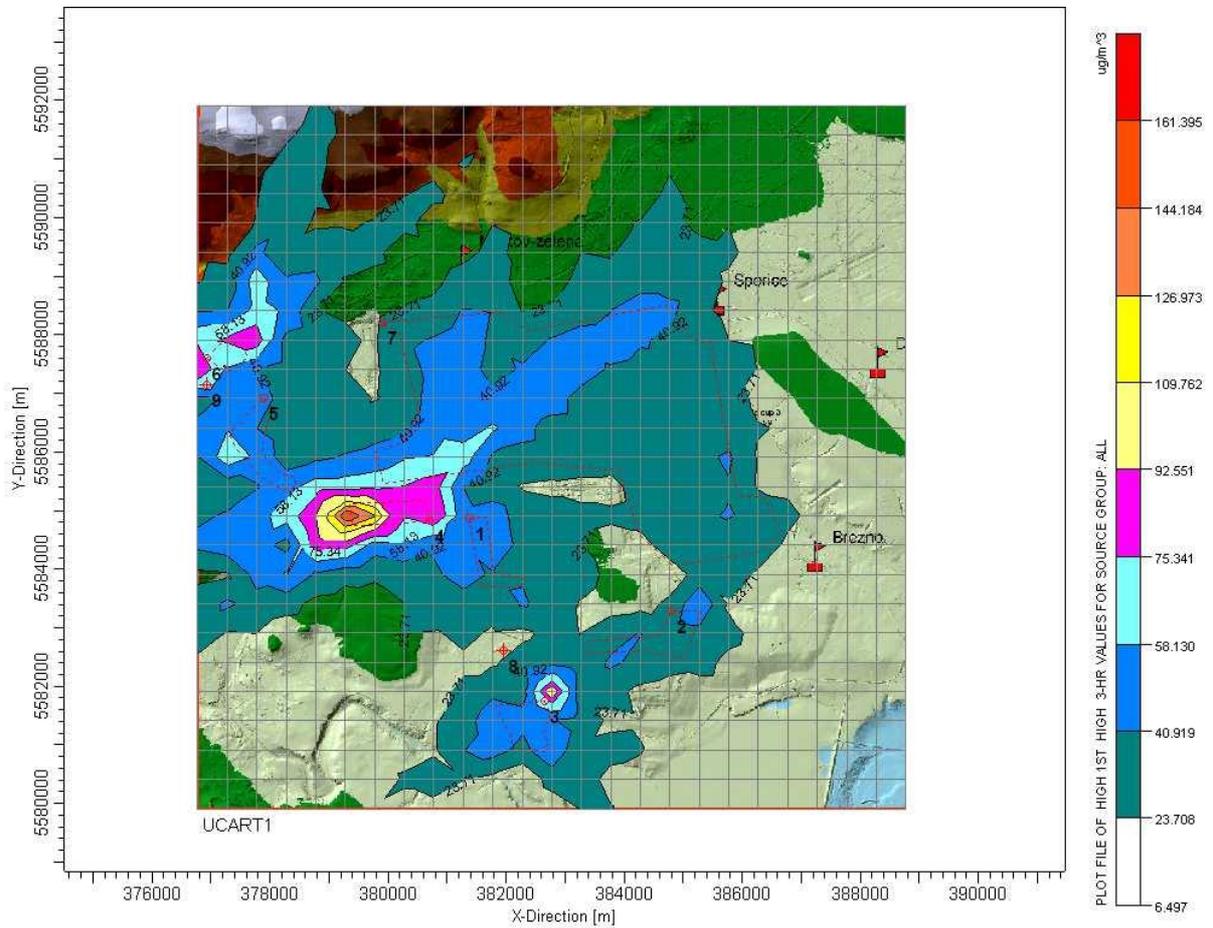


Figure 4. The model outputs for a period of one year: user-selected short-term averages of concentrations at each receptor location in the regular grid. The isolines of PM₁₀ concentrations are complemented by the DEM layer and by other features, such as monitoring stations and a receptor grid.



Figure 5. Aerodynamic research: a model for visualization of flow fields in the wind tunnel by two-dimensional optical fibre Laser Doppler Anemometry.

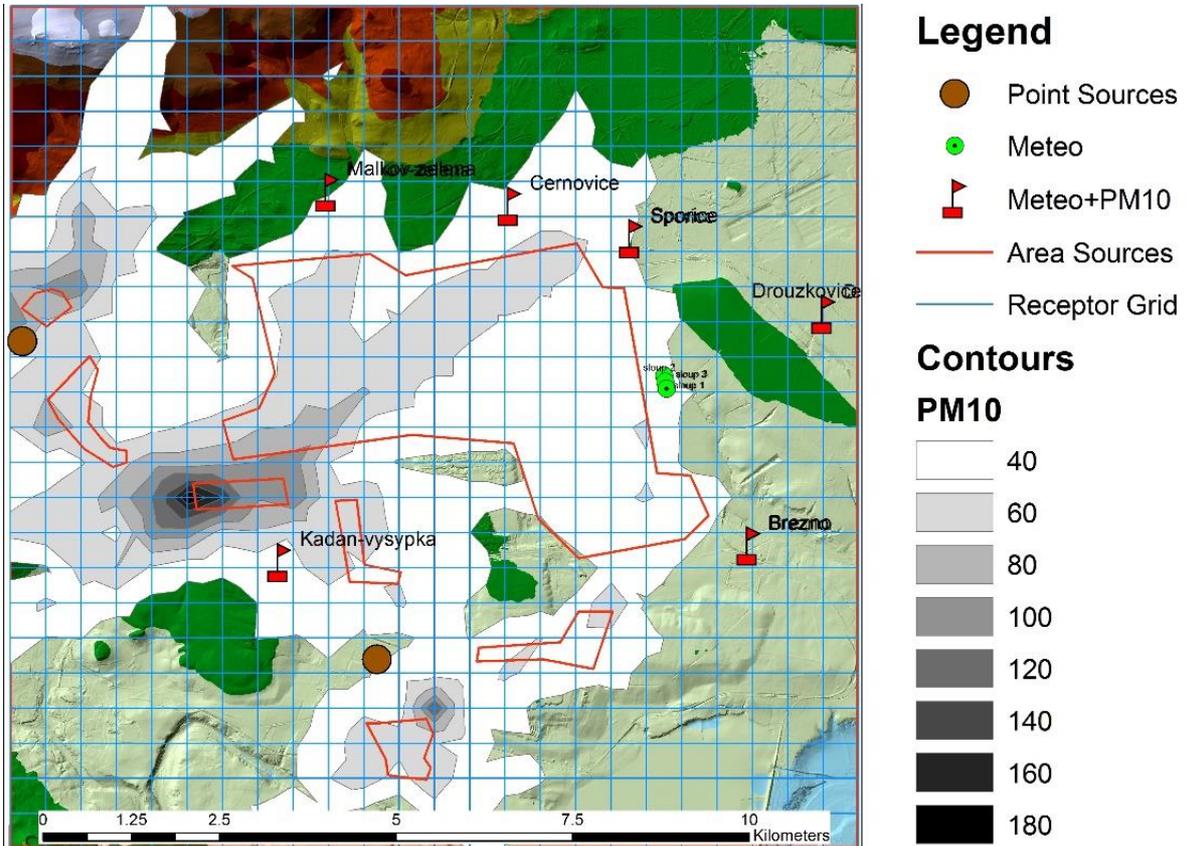


Figure 6. An example of GIS outputs: layer datasets of isolines with PM₁₀ concentration in the receptor grid, the DEM, monitoring stations, and locations of sources of air pollution PM₁₀.

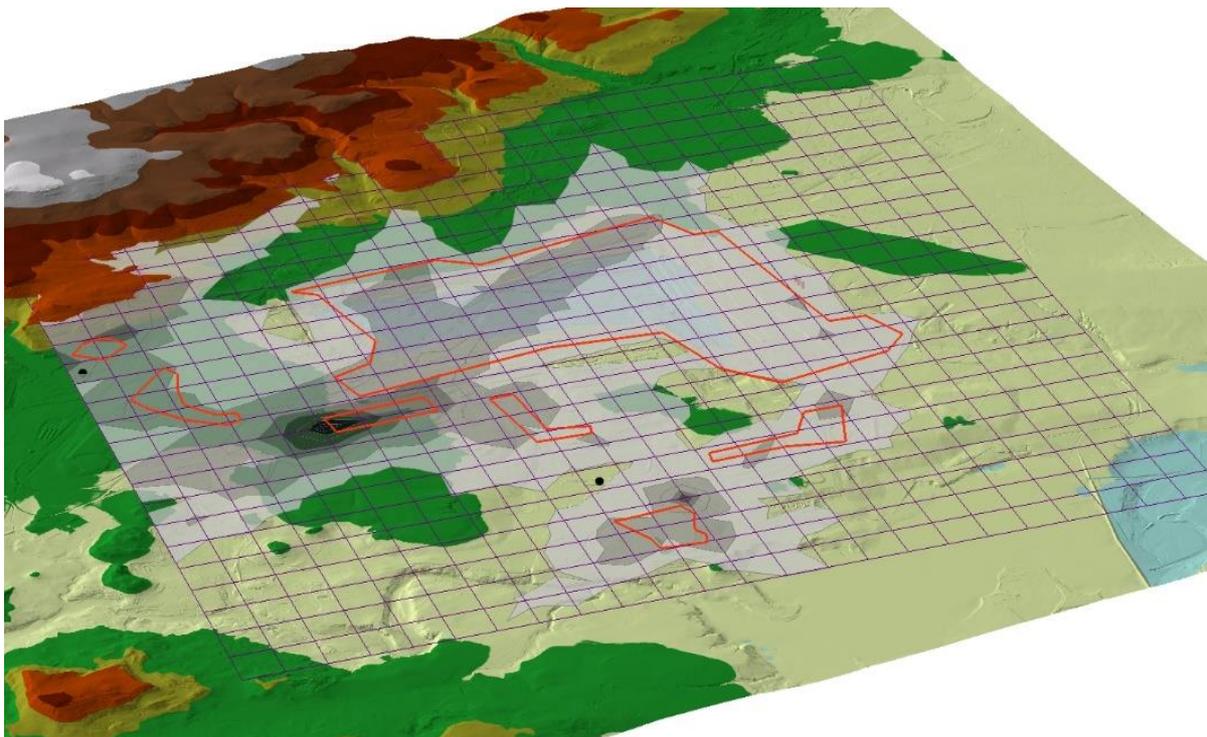


Figure 7. An example of GIS visualization in a 3D view: layer datasets of isolines with PM₁₀ concentrations in the receptor grid, the DEM, monitoring stations, and location of sources of air pollution PM₁₀.

4. CONCLUSIONS AND RECOMMENDATIONS

New approaches have appeared during the last few decades, opening the way to some new aspects of research in numerical modelling and visualization in the GIS environment (Zeiler, 2010), which documents a number of studies (Matejicek, 2010). At the present time, GIS can be used to perform nearly all the tasks focused on spatio-temporal modelling and visualization of air pollution phenomena. For time-consuming numerical simulations, it is necessary to couple GIS with advanced software tools designed for high performance in dynamic modelling. However, with the increasing power of GIS tools, this relationship needs to be reconsidered.

The attached case study demonstrates selected steps in processing of environmental data for air dispersion numerical models and aerodynamic research in wind tunnels. It is focused on exploration of the dust transport over a surface area, which represents an integrated research of a few departments dealing with GIS, air dispersion numerical models and aerodynamic research in wind tunnels. The achieved results based on processing of environmental data benefit all participating research groups.

The described data flows in the processing of environmental data for spatial modelling, air-dispersion numerical models and aerodynamic research in wind tunnels can be used for a number of similar projects in this area of interest, and applied in decision-making processes for health protection and information in the public domain.

5. ACKNOWLEDGMENTS

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