Spatial Modelling of Air Pollution in Urban Areas with GIS: A Case Study on Integrated Database Development

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Abstract: A wide range of data collected by monitoring systems and by mathematical and physical modelling can be managed in the frame of spatial models developed in the GIS. In addition to data management and standard environmental analysis of air pollution, data from remote sensing (aerial and satellite images) can extend all the data sets. In spite of that simulation of air pollutant distribution is carried out by standalone computer systems, the spatial database in the frame of the GIS is used to support decision-making processes in a more efficient way. Mostly, data are included in the map layers as attributes. Other map layers are carried out by the methods of spatial interpolation, raster algebra and case oriented analysis. A series of extensions is built in the GIS to adapt its functionality. As examples, the spatial models of the flat urban area and the street canyon with extensive traffic polluted with NOx are constructed. Different scales of the spatial models require variant methods of construction, data management and spatial data sources. The measurement of NO_x and O_3 by the automatic monitoring system and data from the differential absorption LIDAR are used for investigation of air pollution. Spatial data contain digital maps of both the areas complemented by digital elevation models. Environmental analyses represent spatial interpolations of air pollution that are displayed in horizontal and vertical plains. Case oriented analyses are mostly focused on risk assessment methods. Finally, the LIDAR monitoring results and the results obtained by modelling and spatial analyses are discussed in the context of environmental management of the urban areas. The spatial models and their extensions are developed in the frame of the ESRI's ArcGIS and ArcView programming tools. Aerial and satellite images preprocessed by the ERDAS Imagine represent areas of Prague.

Keywords: spatial modelling; GIS; air pollution; Lidar

1. INTRODUCTION

The recent development of spatial data management in the frame of geographic information systems (GISs) has created the new era of environmental modelling. More powerful computers have made running air quality models at global and locale spatial scales possible. In order to understand the function of more complex models, the modelling system should consist of other subsystems (point and area sources of pollution, spatial description of terrain elevations, meteorological data, air quality monitoring networks). Obviously, the use of the GIS has become essential in providing boundary conditions to the air quality models. Certainly, the use of the GIS in air pollution modelling can be extended moreover to processing the surface data. Many models have been coupled with the GIS in the past decade to simulate various environmental processes as described in the book written by Longley et al. [2001]. Due to the four-dimensional nature of distribution of atmospheric pollutants, the concept of the GIS should be extended to include temporal variations of three-dimensional spatial data. Considering to a huge volume of numerical calculations, two-dimensional interpolations into the horizontal layers are used to interpolate three-dimensional atmospheric data onto a model grid system. The interpolations, integrations of land cover surface data and the GIS analyses focused on small scale spatial models carried out in the kilometer grid are discussed by Lee in the book published by Goodchild [1996]. In case of large scale air quality modelling, more detailed spatial data are needed to include the impact of buildings and other man-made barriers on distribution of air pollutants, [Janour, 1999; Civis 2001]. Apart from this approach, the statistical theory is also used to indicate spatio-temporal interactions as described by Briggs et al. [2000].

2. METHODS OF INTEGRATION AIR QUALITY MODELS INTO THE GIS

A few scenarios can be established to integrate air quality models into the GIS. The basic level is represented by the standalone software application for simulation of air quality models (ISCST3, ISC-PRIME), which is accompanied by data inputs and outputs. All data can be used independently by other software systems (GIS, RDBMS, Surfer, WWW-presentations). The individual programs form heterogeneous data structures that require the transport of data into various data formats. Figure 1 illustrates an example of steps carried out during the simulation of air quality models.

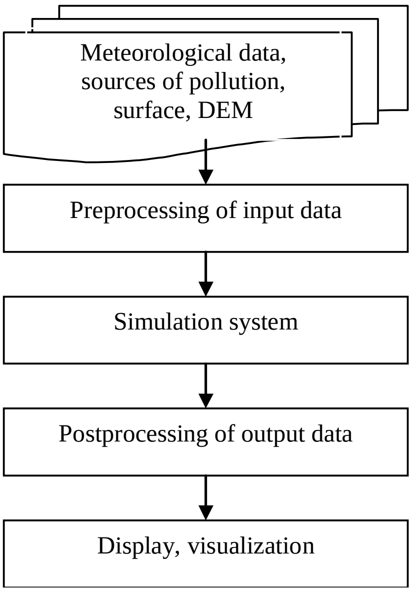

Figure 1. The standalone simulation of air quality models, which is extended by preprocessing and postprocessing software systems.

On the other side, a number of computer programs has been developed to integrated particular functions of the GIS, air quality modelling and graphic systems. Mostly, they are determined to carry out specific calculation without links to other software applications. The GIS based software applications are mostly based on spatial software libraries. The missing functions (air quality modelling, visualisation tools) can be complemented or shared through the dynamic–link libraries. The integrated emission evaluation systems, which offer alternative ways of using the emission models together with selected functionality of the GISs, are described by Rebolj [1999]. A number of software applications is focused on design of relational databases and their interconnection together with standard air quality modelling systems. The structure of the programs developed with spatial software libraries shows figure 2.

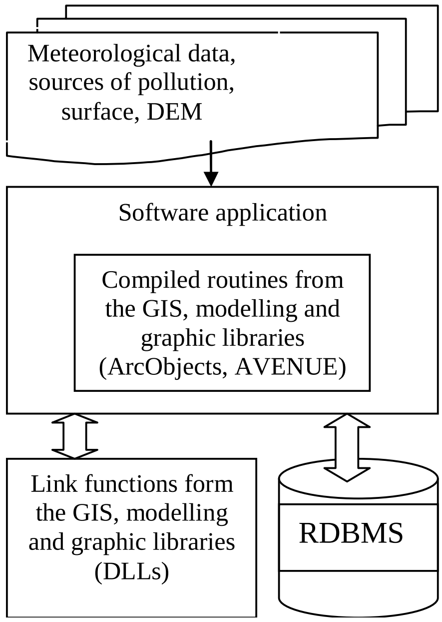

Figure 2. The standalone software application for integrated evaluation of air quality.

2.1 GIS data management and functionality

Considering to the both described scenarios of integration, the scope and scale of urban areas problems make the GIS a powerful tool for management of spatial and temporal data, complex analyses and visualization, [Matejicek, 2002]. Due to the ability to manage a number of spatial and temporal data formats, data structures created in the frame of the GISs open the ways to building air quality information systems that synthesize geospatial and temporal air quality data to support spatio-temporal analysis and dynamic modelling. There is also a growing amount of the digital maps in the GIS community, which are used to support decision-making processes of the urban authorities (data sets for land cover and climatic variables, digital elevation models, which are extended by blocks of buildings and trees, air pollution sources and monitoring networks, soil and hydrologic properties, road and railway networks). While much progress has been made with the mapping of environmental data and the creation of national, regional and local data sets, many challenges remain. For example, air quality models are not used to be included into the GIS. As standalone software applications, they use various data formats, which can usually operate independently with their own GIS database. Similarly, air quality management agencies are creating GIS data sets to support their operations without any data standards that can support spatio-temporal analysis and dynamic modelling. The common theme among these challenges is the need for integration of different spatial and air quality data, integration of data and modelling, integration across spatial scales. The requirements for the integrated spatial modelling of air quality in the frame of the GIS represent a common geospatial coordinate system, vector themes (points, lines and areas) for description of surface objects (buildings, bridges, vegetation) supported by raster and TIN surface data (digital elevation models), vector themes for representation of air pollution inputs (local point, line and area sources of pollution, long-distance transport of air pollution). The key parts of the projects represent data of air quality measured by monitoring networks, terrain measurements (LIDAR) and simulation results of air quality models.

2.2 GIS data models

Nowadays, all the mentioned properties can accomplish a few of the GISs. In the presented study, the ArcGIS distributed by the Environmental Systems Research Institute (ESRI) has been used for the proposed operations. The ArcGIS, a descendant of the widely used ArcInfo, can manage spatial data in a few levels as shapefiles, coverages and geodatabases. Moreover the expansion of the ArcGIS functionality by the COM technology, the Visual Basic is the standard interface language, just as Microsoft uses the Visual Basic as the interface language for other software applications. The ArcGIS can be customized for particular applications of the GIS using specially designed data models. Currently, a number of data models have been published in hydrology [Maidment, 2002], biodiversity, forestry, etc. Air quality modelling can be accomplished by exchanging data between ArcGIS and the independent air quality simulation system, by constructing a simulation tools attached to a project in the ArcGIS, or by customizing the behavior of the ArcGIS objects. The choice depends on the model complexity and calculation requirements in the frame of the various ArcGIS levels. All data are stored in the relational database, which can be represented on the basic level by the personal geodatabase (Microsoft Access), or by the RDBMS (Oracle, Microsoft SQL Server). So, the data transfer among other standalone software applications can be realized directly through the implemented database connections. In case of the ArcGIS's geodatabase, all the data are loaded into the relational database, so that the geospatial coordinate data of the GIS data layers are stored in the relational data tables. Since the relational database supports relationships between its tables, feature-to-feature spatial connections can be set up among the GIS data layers together with linking and joining of external data tables.

2.3 SPATIAL MODELS FOR AIR QUALITY ASSESSMENT EXTENDED BY THE LIDAR MEASUREMENTS

The data required for spatial models to serve air quality modelling can be grouped into a few classes. Figure 3 shows spatial data included into map layers in the frame of a GIS project.

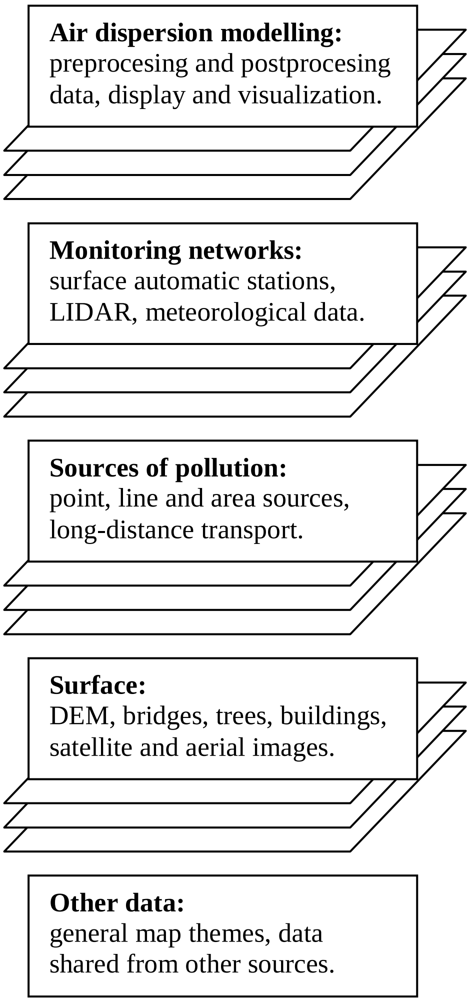

Figure 3. Data included into GIS map layers.

It is impossible to completely enumerate all the spatial and non-spatial data needed, since the more that is known, the better. However, the accuracy of the model results does not depend on the data alone. Choice of the appropriate modelling tools and their setting represents other key parts of air quality modelling. So, if the models do not require or are not capable of evaluating some detailed information, there is little benefit in putting that data in a GIS project. To examine the functionality of the spatial modelling system, the Industrial Source Complex-Short Term (ISCST3), its version with Plume Rise Enhancements (ISC-PRIME), and the AMS/EPA Regulatory Models (AERMOD/AERMOD-PRIME) have been included into the projects. The ISC-AERMOD View with its preprocessing and postprocessing modules has been used as the unified interface of the air dispersion models.

The spatial surface data (digital elevation model-DEM, buildings) make up the input into the preprocessing modules (Import of the Digital terrain data in ISC-AERMOD, Building Profile Input Program-BPIP). Other surface data (bridges, trees, satellite and aerial images) complement spatial information for display and visualization. The layers with sources of pollution contain (in addition to the coordinates and shapes) the attributes, which describe emission properties. The surface data and data about sources of pollution have to be transferred into appropriate input formats to run the air quality dispersion models. The primary storage in the GIS spatial database serves furthermore for spatial analysis, display and visualization. Likewise the previous data, meteorological data are also preprocessed from the database storage into the input formats for air quality dispersion modelling. The map layers, which represent monitoring networks and LIDAR measurements, serve for a comparison of the measured data with the predicted air pollution data calculated by the models.

The mentioned air quality models are steady-state Gaussian plume models used to assess pollutant concentrations from a wide variety of sources mostly associated with an industrial complex. The steady state values of variables are transferred and incorporated into the GIS database, which can be handy to manage data time series. To accommodate large data and many variables such as air quality data, climatic data, properties of sources of pollution, the data repository containing all types of time series data for all features and for all times is proposed. So, time series information can be depicted in 3-D space. The three coordinate axes mark space (S-identification code of a spatial future), time (T-discrete time) and variable being measured (V- identification code of a variable). The data value indexed by the space, the time and the variable can be defined as D(S,T,V). Thus, each stored value is represented by a point in three-dimensional space with its corresponding coordinates, figure 4. In order to extract time series, the space and variable coordinate have to be specified in a query. The result is represented by selected records that match up to the condition in a query. Due to spatial properties of the GIS, space coordinates can be derived from a spatial query in the frame of GIS functionality. The associations between data repository and spatial objects in the ArcGIS geodatabase are specified by relationships, which are stored into the relationship classes.

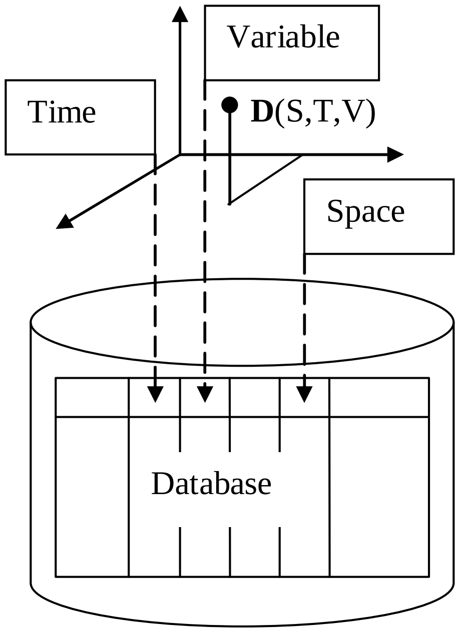

Figure 4. Data repository with 3-D space indexes.

4. CASE STUDIES OF THE URBAN AREAS

The various data sets (digital maps, aerial and satellite images, spatio-temporal data in the 3-D database, data outputs from simulation systems) have been linked together to make up projects for different spatial scales. The GIS, originally design to display 2-D digital maps, has been extended into 3-D mapping and data management in the frame of the ArcGIS. As examples, two urban areas of Prague have been used to demonstrate abilities of the spatial modelling.

4.1 Spatial modelling of the flat urban area

The inputs of spatial data represent digital elevation model, which can be used for air pollution modelling, and aerial or satellite images, which can serve for classification of the surface into classes to set the surface graininess and temperature. The sources of air pollution are mapped into a few categories according to a volume of pollution. Their locations and shapes (in case of the line and area sources) together with the attributes are stored in separate themes. Influential sources of pollution among others are represented by NOx (mostly traffic-related air pollution mapped as the line sources) and SO_2 (mostly stationary air pollution registered as the point sources). In addition to data from automatic monitoring system, the LIDAR [Zelinger, 2003], has been used to complete the data sets. The map composition, which contains the aerial images complemented by the layers with sources of air pollution and 3-D LIDAR data (O_3 concentration labelled by the elevation), is illustrated in figure 5.

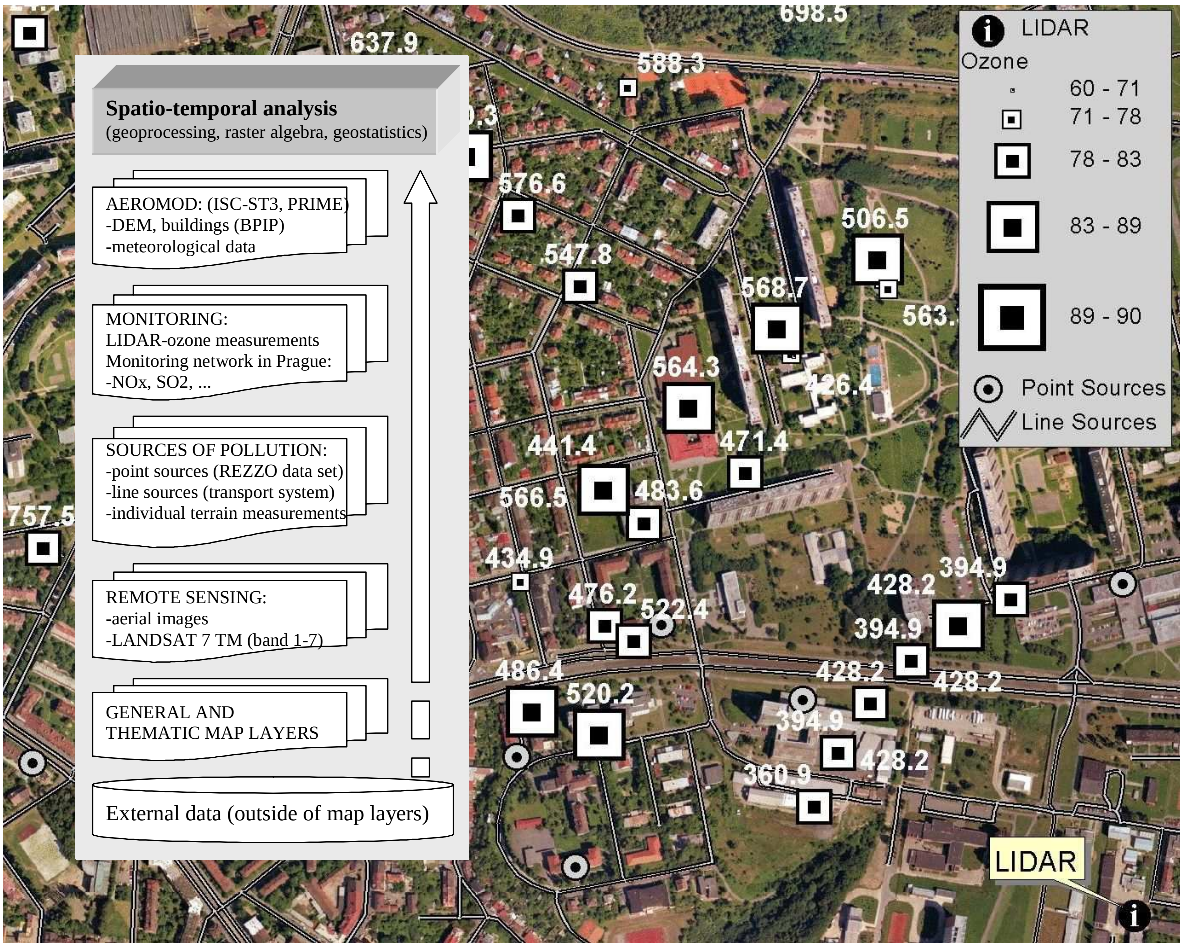

Figure 5. Map layers of the flat urban area.

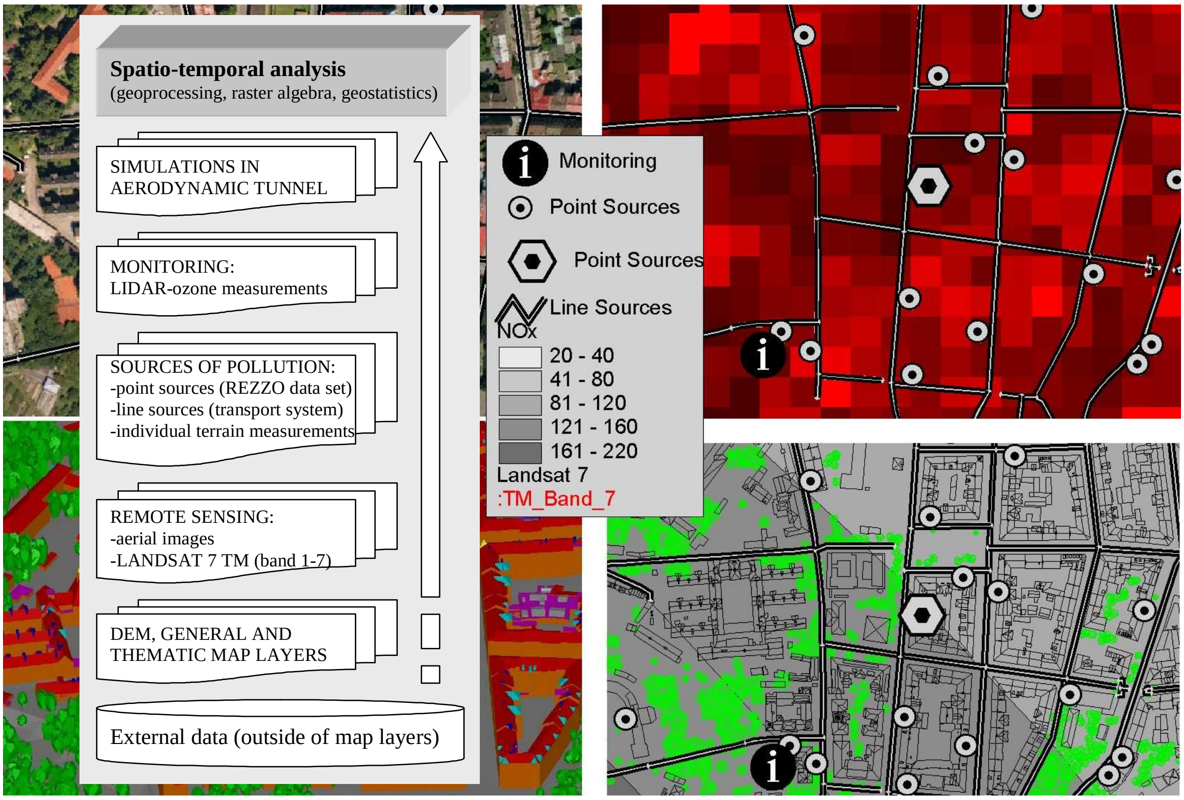

Figure 6. Map layers of the street canyons.

4.2 Spatial modelling of the street canyons

The streets surrounded by high buildings in the urban areas polluted with the traffic-related sources are spatially modelled as the street canyons. Accumulation of air pollution (mostly from cars) results in high concentrations of organic and inorganic compounds in the street canyons. Distribution and local accumulation of pollutants can be solved by mathematical and physical modelling. In the first stage, the digital terrain model complemented by buildings and other terrain objects is needed to support air quality modelling. Consequently, complex analysis of all spatio-temporal data has to be carried out. Spatial modelling in the frame of the GIS can help to accomplish nearly all these tasks. To demonstrate GIS suitability, a case study of spatial modelling of air quality in urban streets illustrates figure 6. Map compositions contain various sets of themes. The first part shows the aerial images of the studied local area complemented by the layers with sources of air pollution and one point of the monitoring network. Other map compositions contain the same area complemented by the satellite image from Landsat 7 (the 7th band, which refers to temperature of the surface), the digital terrain model with buildings and trees, and a sample of the spatial interpolation of air pollution in the area. Again in additions to standard analysis, the LIDAR system and the results of physical modelling in the scaled down models (simulations in wind tunnels) can be used to complete the data sets.

5. CONCLUSIONS

Spatial modelling of air quality in this paper is mainly focused on integration of a wide range of data in the frame of the GIS spatial database. This way of data management and analysis is also promoted by the LIDAR data, which represent measurements of compounds above the surface located by 3-D coordinates. Despite of complex spatial data management, analysis and visualization, modelling of air pollution has to be solved independently in the frame of standalone computer systems (mathematical modelling or physical scaled models). So, the GISs serve as the data stores, which can manage all the data together with model outputs to carry out risk assessment analysis and map compositions. The spatial modelling of street canyons in the frame of the larger urban area complemented by the 3-D LIDAR measurements requires more detailed three dimensional mapping that can generate extensive volume of data. So, the spatial modelling of air pollution extended by air dispersion models under the united interface can be used in case of the adequate hardware, software and data support.

6. ACKNOWLEDGEMENTS

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