Environmental Modelling in Urban Areas with GIS

L. Matejicek

L. Benesova

J. Tonika

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L. Matějíček, L. Benešová, J. Tonika
Institute for Environmental Studies, Charles University, Prague, 128 01, Czech Republic
(lmatejic@mbox.cesnet.cz)

Abstract: More accurate spatio-temporal predictions of urban environment are needed as a basis for assessing exposures as a part of environmental studies, and to inform urban protection policy and management. This paper is focused on modelling in the GIS to estimate air, water and soil pollution in urban areas. The basic environmental components are complemented by bio-monitoring, waste management and noise exposure. The models, which use data from long-time monitoring, are developed using correlation, regression and factor analysis; simulation of dynamic relation and spatio-temporal phenomena. Integration of a wide range of relatively independent factors enables more complex analysis of environment in urban areas. GIS, which can integrate a wide range of spatial and temporal data, is used for data management, input and output of data, visualization and development of programming modules that extend GIS with other statistical analysis and dynamic modelling. The analysis and models were built in ArcGIS with ArcObjects. In spite of the fact that the models are calibrated and tested by application in the urban areas of Prague, the structure of the GIS project is applicable on other similar areas. The fundamental part of the environmental models is focused on modelling of surface-water quality, soil pollution and their relation to human activities and air pollution. The models use data measured during decades, which are collected from manually and automatic pollution monitoring networks. The map layers are divided into a few classes that represent basic maps of urban areas in the scale 1:500, thematic maps, aerial photographs, monitoring networks, and outputs of environmental models. The spatio-temporal analysis and dynamic environmental models are accessible through the user interface of the GIS project.

Keywords: dynamic modelling; GIS; simulation; urban environment

1. INTRODUCTION

Environmental protection of urban areas includes a wide variety of techniques in order to determine individual factors of pollution and stress of the urban environment. Within these fields, monitoring and environmental modelling have been created with a few aims: to estimate short term and long term changes, to develop models that can simulate a real environmental situation, and to aid the decision making process. In the past, air quality, surface-water, groundwater, soil pollution, noise, waste management and landscape protection were mostly monitored in the local urban scale of some larger cities. Nowadays, environmental protection on a global world scale becomes necessary. Considering to the price of monitoring systems, for the present, areas with higher concentration of inhabitants and industry represent main focus of environmental authorities and agencies. The wide range of data is collected to estimate and identify various sources of pollution and stress. Air pollution, emissions and deposition are monitored with automatic and manual-operated stations. Water quality and soil pollution, usually measured in longer time periods, are evaluated in chemical laboratories. Noise, waste management and landscape protection complement all the information about life conditions.

Due to the increasingly more powerful desktop computing systems with constantly improving graphic capabilities and modest financial cost to individuals and agencies, the collected data are processed and analyse in the frame of computer information systems. Considering to the nature of collected measurements, the research requires spatio-temporal data management. The increase in computing power and graphics is facilitating the advance of geographic information systems-GIS, which can effectively satisfy these tasks. Capabilities of the GIS include mainly management of spatial data in the form of map layers, which can visualize real objects by vector and raster data formats together with graphs and multimedia presentations. Data analysis and modelling in the frame of the GIS represent one of the next steps. Now the GIS itself still concerned rather on digital mapping becomes more open to other data analysis and partially to dynamic modelling. Some finite difference models and predictions can be solved with GIS capabilities, but extensions are necessary to achieve more complex simulation.

2. ENVIRONMENTAL ANALYSIS OF URBAN AREAS IN GIS

A number of definitions describes capabilities of the GIS to solve a wide range of environmental problems, which are related to urban areas. Burrough [1998] defines the GIS as a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes. This definition is an example of the general description of the GIS. Some definitions, which are used by ESRI (Environmental Systems Research Institute, Inc.), are more deterministic. Mostly, they accent spatial data models, which are used in ARC/INFO or in the ArcGIS's geodatabase. The basic structure of the project in the GIS, which is focused on data analysis of environmental problems, is illustrated in figure 1.

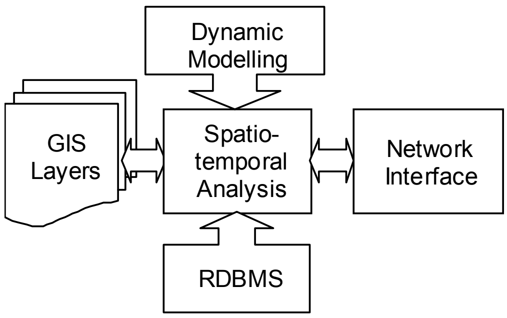

Figure 1. Environmental Analysis in the GIS

All the data are stored in a database, which is managed by a relational database management system-RDBMS. The GIS contains a huge range of spatial analyses and temporal comparisons, which allow carrying out and display of output data in the GIS's layers. A part of data and analyses can be shared through a network connection that offers sharing data by GIS browsers. A major part of the GIS project represents dynamic modelling, which is developed to make predictions and optimisation. Whereas the GIS can produce spatial and temporal analysis, implementation of dynamic modelling and predictions requires new hardware and software capabilities of computer systems. Besides of the computer power, other numerical algorithms for simulation of dynamic phenomena have to be developed.

2.1 Simulation of Dynamic Models in the Frame of the GIS

Environmental modelling has been growing up separately for a long time, so simulation systems of environmental models differ in data structures, functions and methods for sharing spatial information. Also the structure of each group of environmental models is subordinated to the purpose of their field of a study. All these factors represent obstacles for building common data structures and functions. Generally, a few levels of model integration exist in the GIS. The lowest level is represented by moving data files or sharing database. The obstacles with a data exchange can be overcome by rewriting environmental models into a form in which they can directly use data from GIS data structures. There is no need to carry out new mathematical models. The basic laws governing the motion of pollution in air, surface water and groundwater have been elucidated in the intervening years. The key is to isolate the principal phenomena and to implement complex spatio-temporal data structures. Since the scope of environmental modelling is very broad, the main goal is to generalize and simplify the effects of individual interactions, which are caused by many random and uncertain elements.

The description of environmental dynamic phenomena can be carried out by a few ways. The algebraic equations with time-dependent variables are used to describe changes of separated processes, which can be presented by vector and raster data structures. The vectors are in the GIS represented by points, lines and polygons. Spatial data structures describe their location, shape and topology. The raster structures form regular grids. Further more, both data structures can link data, which represent their attributes (estimation or prediction of air pollution, water contamination, noise level etc.). The attribute data managed by algebraic expressions can be derived from ordinary or partial differential equations. The dynamic models described by ordinary differential equations form mostly the lumped models. The changes of state variables are separated into discrete space that is bounded by vector data. The partial differential equations represent continuous space modelling. The solution can be one, two or three dimensional, depending on how many dimensions are used to describe environmental phenomena. Maidment and others in their contributions in Goodchild et al. [1996] describe lumped and distributed models, which are used for modelling of flow and transport processes. The lumped models are described by ordinary differential equations whose dependent variables are a function of a single variable, which is time. By contrast, distributed models, which operate over a continuous space, are based on partial differential equations. Their dependent variables are a function of time and one or more space variables. The distinction between discrete and continuous modelling from the GIS perspective is illustrated in figure 2.

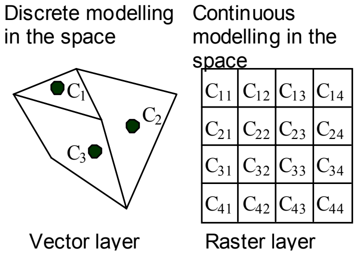

Figure 2. GIS layers for discrete and continuous modelling

The lumped model can be described as an accumulation of matter or energy in the stocks by ordinary differential equation:

$$\frac{dS}{dt} = \sum \text{inflow} - \text{outflow} \qquad (1)$$

where S is the amount of the matter or energy stored in a particular object. The inflows and outflows cause the change of the amount of the mater or energy. They are functions of time, space and other factors. The variable S in the equation (1) represents the state variable. Instead of state variables, normalized variables (density, concentration or intensity) are used to make presentation of environmental models. In figure 2, the amount of pollution is divided by a volume or mass, which enables to compare concentrations of pollution in the neighbour areas.

The distributed models can be assembled with a few basic phenomena: diffusion, advection, chemical reaction and source description. The fundamental two-dimensional system can be described by a partial differential equation:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial c}{\partial y}\right) + K_x\frac{\partial c}{\partial x} + K_y\frac{\partial c}{\partial y} + f^{ch}(t,x,y) + f^{s}(t,x,y) \qquad (2)$$

where c is a concentration, D and K_x, K_y represent diffusion and advection constants. f^{ch} is the term, which contains all the physical or chemical transformation. f^s describes the spatio-temporal input and output of pollution. The equation (2) is formed to describe the diffusion, advection and other interactions in two dimensions. The equation (2) can be extended to three dimensions. The more the dimensions, the more complex the system, which causes lager amount of calculations. From the GIS perspective, the two dimensions enable to use directly grid formats, which can be included into the map layers. Certainly, the data can be transformed to the grid layers from one or three dimensions. The basic arrangement of a two dimensional regular grid of concentrations is in figure 2. All the data represent attributes of individual cells. The deduced mathematical expressions have to be transformed to the numerical models that provide approximate solutions. The first order approximation for lumped models (1) can be described be the following formula:

$$S_{k+1} = S_k + \Delta t \sum \text{inflow} - \text{outflow} \qquad (3)$$

where S_k is the sequence of the amounts and Δt is the time step. The calculation is carried out step by step from the initial time ($k = 0$) to the final time ($k = n$) in the isolate time points, which are separated by intervals Δt on the time axis. In practice, numerical solutions are used to be calculated with more complex formulas, which enable a higher accuracy. Similarly, the formula for approximate calculation of continuous models (2) can be in the form:

$$\begin{aligned} c_{i,j,k+1} = {} & \tau\left[D\frac{c_{i-1,j,k} + c_{i,j-1,k} - 4c_{i,j,k} + c_{i+1,j,k} + c_{i,j+1,k}}{h^2}\right] + \\ & + \tau\left[K_x\frac{c_{i+1,j,k} - c_{i,j,k}}{h} + K_y\frac{c_{i,j+1,k} - c_{i,j,k}}{h}\right] + \\ & + \tau\left[f^{ch}_{i,j,k}(t_k) + f^{s}_{i,j,k}(t_k)\right] \end{aligned} \qquad (4)$$

where $c_{i,j,k}$ is the concentration in the cell of the grid, which is in the i^{th} row, the j^{th} column and the k^{th} grid in the frame of the time sequence. τ represents the time step. h is the distance of the centres of the cells in the grid. The time sequence is similar to the sequence of the individual state variables in the lumped models. Compare to continuous models, mostly, the lumped models require less calculations. In case of the formula (4), more precise techniques are used to minimize numerical errors. The demonstrated numerical solutions of dynamic models focused on the urban environment can be implemented in the GIS. Some GISs, like for example the ESRI's ArcGIS, contains classes of objects that are used to manage data, automate setting of parameters and running functions. Moreover, the programming tools can be used to develop numerical calculation. Besides the described way of calculation of the dynamic models in the frame of the GIS, the GIS programming libraries can be used to develop standalone modules. This is one of the most efficient ways, which offers the direct solution of dynamic models inside programming modules supported by GIS functions.

3. THE GIS BASED MONITORING AND MODELLING TOOLS

The synthesis of GIS and dynamic modelling is realized by programming modules inside the GIS. The structure of the integrated system is in figure 3. Map layers are complemented with attribute tables, which contain the experimental data and model outputs. Other data in external tables can be joined to attribute tables. Spatial analysis and a part of environmental analysis can be performed by built-in GIS's tools. The environmental modelling and analysis is developed with programming tools. GISs offer programming support on various levels. Due to a high amount of numeric calculations, the efficient programming systems are needed. Among various tools, the COM technology in the frame of ArcGIS is used to build simulation modules. Another way represents sharing data between GIS and a standalone simulation system. The database and the data files are used to realize the connection.

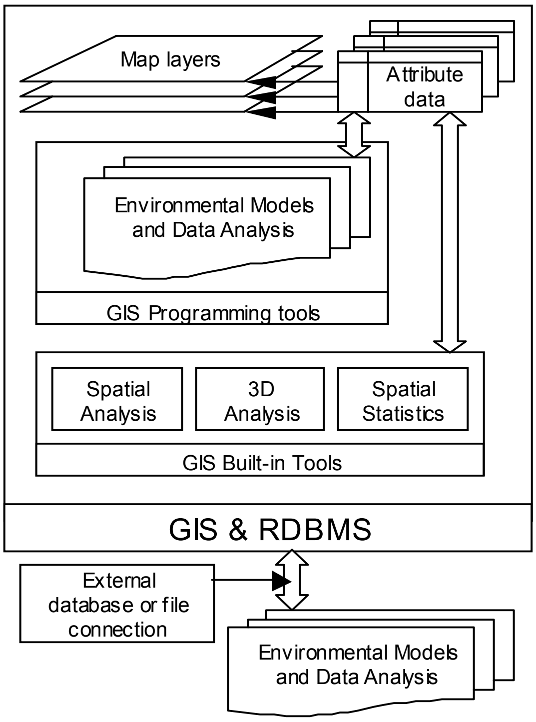

Figure 3. Environmental modelling and data analysis in the frame of the GIS

The environmental models and analysis are divided into a few classes. The individual classes are focused on the air, surface water, landscape, soil and groundwater phenomena. Each class contains its modelling and analysis tools. These data and modelling tools are complemented by other information needed for decision-making process (cadastral maps and entries, public services, etc.). The model solutions are aggregated and analysed together with the raster algebra tools in the frame of the GIS. Figure 4 illustrates a basic schema of environmental modelling and data interactions. The modelling tools, which are focused on simulation of individual phenomena (air pollution, water pollution, etc.), are closed to standalone modules. Some simulation (air and water pollution) can be carried out externally by simulation expert systems. The results are imported backward to the GIS. The modelling tools, which include raster algebra, enable complex analysis of all the particular results from individual simulations and data analyses.

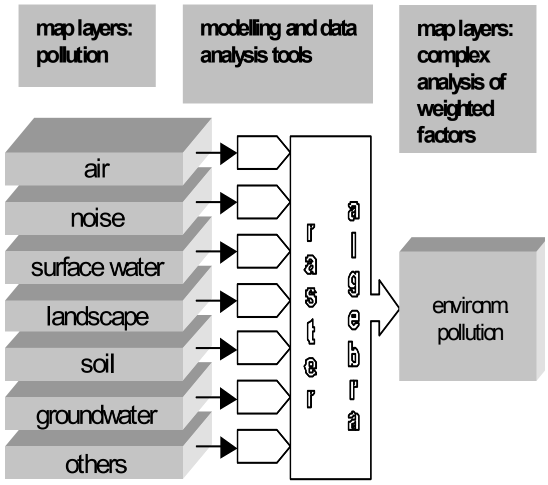

Figure 4. Data processing and aggregation

The raster algebra tools operate with cell-based modelling. Each cell of the input layer contains an attribute (concentration, amount or other factor). The attribute of the cell in the same position in the output layer is calculated by the algebraic expression from the attribute of the cells in the input layers, figure 5.

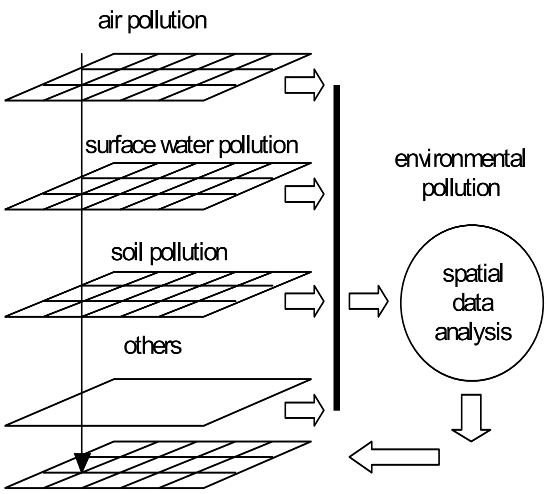

Figure 5. Spatial environmental modelling and analysis with raster algebra

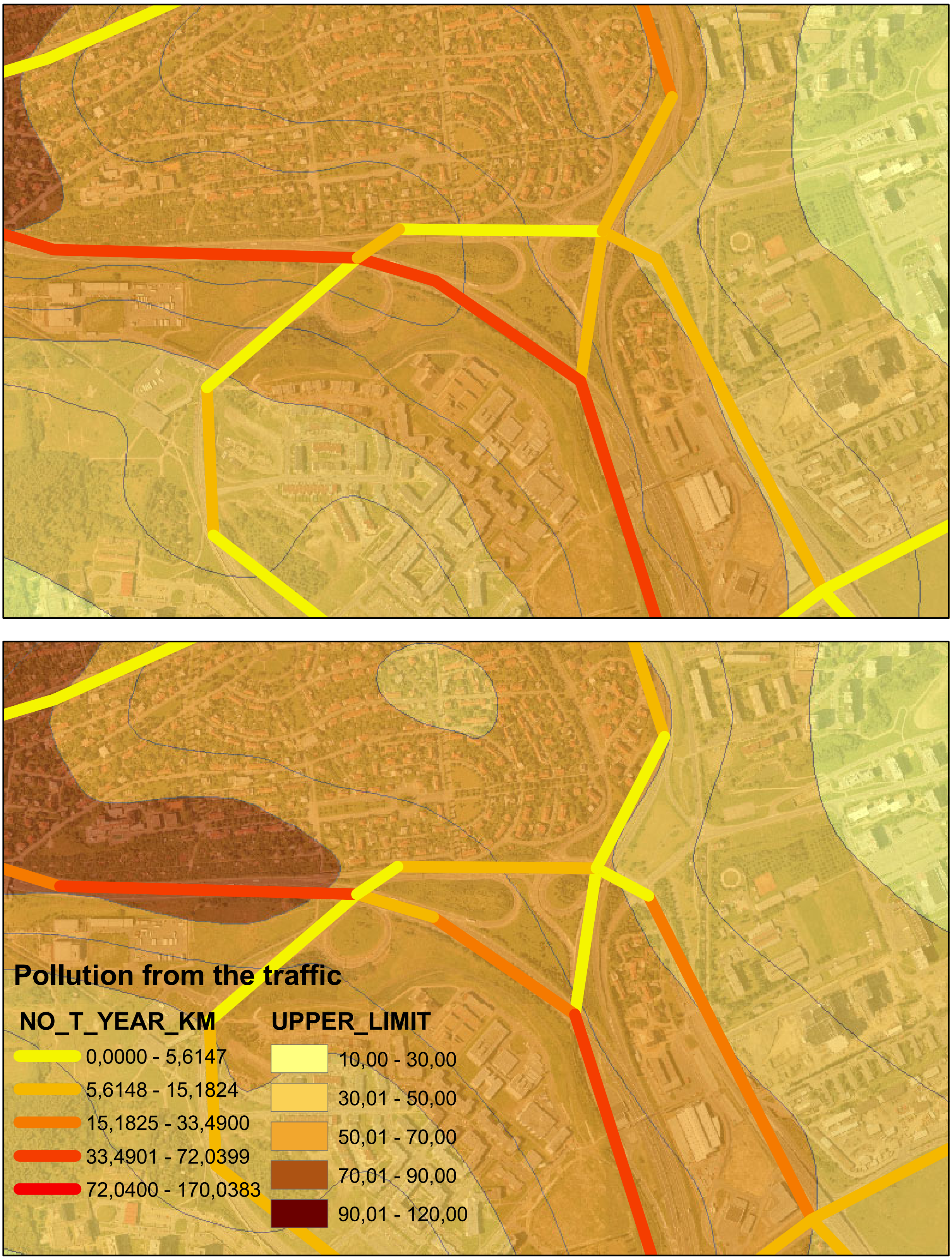

Figure 6. An example of GIS based data analysis: pollution from the traffic in 1996 (the upper part) and in 1998 (the bottom part)

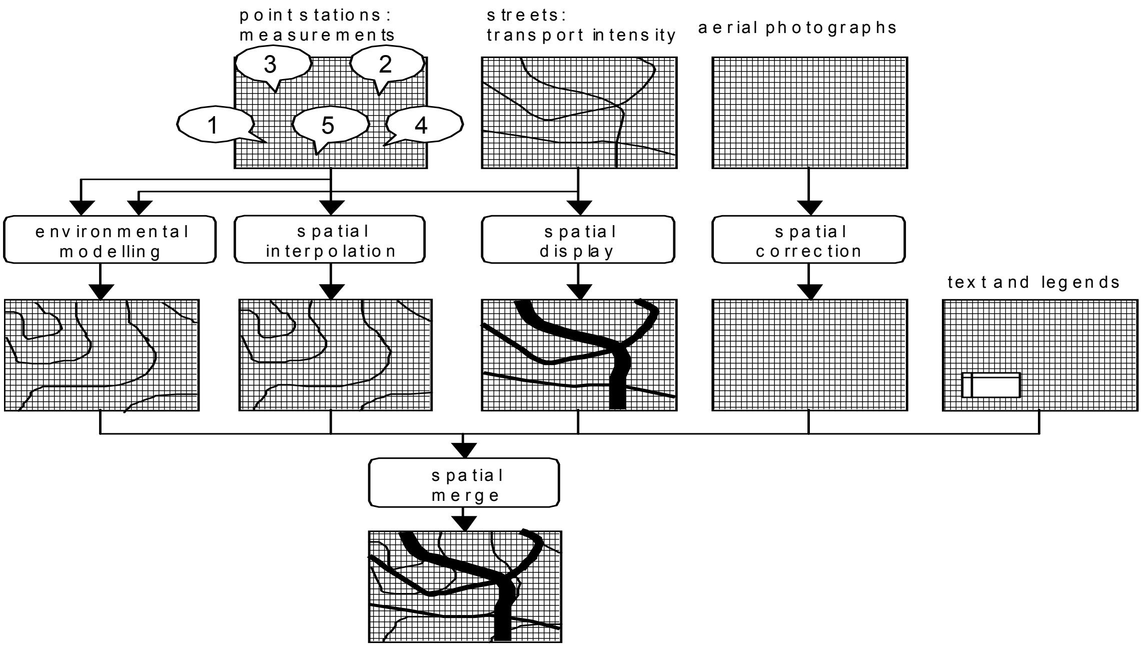

Figure 7. Diagram of spatial data analysis

As an example, data analysis of air pollution from mobile sources is illustrated in figure 6. Two frames, which are chosen from the time sequence of long-term measurements, contain layers with aerial photographs, street networks and spatial interpolations. The flows of the correspondent spatial analyses are illustrated in figure 7. The input data are formed with map layers, which contain air pollution monitoring network, street network and aerial photographs. After individual spatial analysis of each layer, the spatial merge is processed together with the results of environmental modelling. Consecutively, these particular results are combined by map algebra analysis together with the similar results from other environmental modules (water and soil pollution, etc.).

4. CONCLUSIONS

Environmental modelling in urban areas was developed to support decision-making process and to mark some common guidelines that can be used in environmental analysis and predictions. Due to the shortage of estimated data and complexity of studied phenomena, all the results of simulations have to be validated. In case of predictions, the interpretation of results should include analysis of possible errors. In spite of these critical conclusions, the presented complex analysis and environmental modelling in the frame of the GIS show new ways of assessment of the urban environment. The wide range of data, which are collected by manual and automatic processes, can be displayed, analyse and put through the environmental modelling together with their predictions.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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