Integration of Environmental Models Based on Fluid Mechanics in GIS

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Abstract: An exploration of dust dispersion over the surface of coal mines requires more complex modelling tools in order to estimate dust emission and dust transport. Thus, spatial data and data originating from a numerical simulation are integrated into a GIS environment. The Reynolds averaged Navier-Stokes equations for incompressible flows with turbulent algebraic extensions are used for dispersion modelling of the wind flows and dust transport. In addition to spatial data management, the GIS is used for the creation of a digital terrain model originating from surface laser scanning, GPS measurements, a geodetic survey and existing data sources. This more precise mapping of the surface is required in order to estimate the wind flows over a temporary coal storage site and adjacent slopes. The flow patterns are displayed together with aerial images in the GIS for assessment of potential erosion fields over the stockpiles, and for an evaluation of environmental impacts. Integration of modelling in the GIS is carried out for testing of various environmental scenarios, including man-made barriers as well as different wind flow conditions.

Keywords: Dispersion modelling; Dust emission; Surface laser scanning; GIS.

1. INTRODUCTION

Environmental modelling covers a wide range of principles describing the motion of matter or energy in dependence on spatial scales, time scales and other attributes [Parker et al., 2002]. Nowadays, various software tools have been developed to solve environmental models based on spatial modelling or dynamic modelling, but they rely on different data structures and functionality. Spatial modelling, traditionally represented by geographic information systems (GISs), is focused on spatial relationships [Zeiler, 1999]. Dynamic modelling, based on the numerical solution of algebraic or differential equations [Jørgensen et al., 2001], is represented by models implemented in a number of simulation packages or standalone applications. This creates barriers in the linking of spatial models and dynamic models. In general, there are two ways in which to overcome these difficulties in environmental modelling.

First, from the spatial modelling point of view, existing GISs can be extended by data structures and numerical methods that can assist in solving dynamic models. The strategies can range from simple pre- and postprocessor linkage through shared data files to building dynamic models as fully functional extensions by using programming development tools in the GIS environment [Maidment, 1996].
Second, in the case of dynamic modelling, there are case oriented extensions for the display of simulation outputs. However, the data structures are dedicated for the calculation of numerical models [Littlefield, 2004]. In spite of the fact that the graphic user interface allows the models to be created as a work flow by stringing individual processes together, and running each model via its dialog box or the command line [Dabney, 2003], the interconnection with the original spatial environment is quite limited.

In order to demonstrate the integration of environmental models based on dispersion modelling, processes of dust emission and dust transport over a selected surface mining area are solved in the framework of the GIS project. Spatial data are used for a more accurate numerical simulation of wind flows over the temporary coal storage site and surrounding neighbourhoods. After simulation, the results are displayed together with map layers.

2. SPATIAL INFORMATION SYSTEM

The purpose of the selected spatial information system, namely ESRI’s ArcGIS, is to provide a spatial framework for dispersion modelling. In addition to spatial data management, advanced spatial analysis is used to create the digital terrain model (DTM), to provide pre-processing and post-processing for numerical simulation, to interpolate output variables in the frame of thematic map layers, and to create virtual scenes for visualization. For these reasons, a new object-oriented data model is developed in the framework of the ESRI geodatabase [Maguire, 2005] that can characterize features and their relationship in a more natural way. Features represented by vectors, rasters, TINs or other user defined structures are stored and centrally managed in one database together with the defined spatial relationship. The main spatial data sources originate from the Landsat 7, aerial images, surface laser scanning, GPS measurements, a geodetic survey and existing digital thematic map layers.

2.1 Spatial data from passive remote sensors

The satellite scene from the Landsat 7 Enhanced Thematic Mapper (ETM+) is used for giving an overview of the whole mining area, and for the mapping of land degradation features related to soil erosion [Metternicht, 1998]. A true colour composite and pseudo colour composites combining the bands 1-7 at a resolution of 30 meters support display of the coal mine and its surroundings. The aerial images at a resolution of 0.5 meters are draped on the DTM to display the surface of the local areas of interest, the temporary storage site and the nearby residential zone.

2.2 Surface laser scanning and GPS mapping

In order to provide more accurate simulation of wind flows over the potential emission sources, surface laser scanning was chosen for acquisition of the DTM in the area of the temporary coal storage site and its neighbouring slopes. This represents the most important parts that influence dust transport by wind flows drifting from the mining areas to the residential zones. Multiple scans from different locations are provided to obtain complete data sources from shielded parts of the terrain. Finally, the clouds of points are georeferenced in the framework of the GIS project together with satellite images and aerial images. In spite of the fact that airborne laser scanning is becoming the standard technique for acquisition of digital elevation models [Vosselman, 2005], surface scanning can capture spatial points from shielded areas. But, more data processing is needed to filter redundant points or incorrect points caused by vegetation interference and reflection of the mining equipment. A set of spatial points and lines is collected by GPS for mapping slopes and surface objects (excavators, conveyors, sorting places, man-made barriers, pylons). The accuracy of the GPS measurements is improved during the post-processing phase by data from the nearest reference stations in the territory of the Czech Republic. Thus, more
precise mapping is provided for the creation of the DTM that represents an input into the numerical modelling. Finally, the DTM together with thematic map layers complement visualization of the dust dispersion based on numerical simulation.

3. NUMERICAL SIMULATION

A number of software packages focused on air dispersion modelling can be used for integration into the spatial information system. For example, the ISC-AERMOD with its U.S. EPA models (IS CST3, ISC-PRIME, AERMOD and AERMOD-PRIME) can assess pollution concentration and deposition from a wide variety of emission sources. In order to run the simulation, a DTM complemented by surface objects (buildings and mining equipment) and meteorological data must be imported and pre-processed by tools included in the package. Though the package includes display tools, export of the data into the GIS is needed to provide more complex spatial analysis and visualization. In the case of dust dispersion over the surface mine, pre- and postprocessor linkage through shared data files is needed to run the simulation and to import data into the GIS [Matejicek, 2008].

Another approach is represented by a standalone software application that shares data by simple pre- and postprocessor linkage through shared data files. This approach can be made more comfortable by providing direct implementation in the GIS environment. Thus, the pre- and post processing procedures can be reduced through the sharing of data in the framework of a common database. But, in cases of time consuming numerical operations, actual implementation by scripts or macros is not computationally efficient.

In the case of the presented numerical simulation focused on dust dispersion over the surface coal mine, the ESRI geodatabase is used for spatial data management and support of advanced spatial analysis. The numerical simulation of wind flow and dust transport is based on Reynolds averaged Navier-Stokes (RANS) equations for incompressible flows with turbulent closure of the model by an algebraic turbulence model [Kozel, 2007]. The numerical simulation is solved by a semi-implicit finite-difference scheme. The DTM and data from local meteorological stations are used for setting internal parameters.

4. RESULTS

This study is focused on dust emissions from the selected dominant source, the temporary coal storage site. The procedures provided in the framework of the GIS project are illustrated in Figure 1.
Figure 1. Data processing in the framework of the GIS project.

The upper part of the scheme in Figure 1 illustrates the main spatial data sources focused on the creation of the DTM (surface laser scanning, GPS and satellite/aerial images). The local meteorological stations assist in estimating the meteorological conditions (wind velocity, wind direction, temperature and atmospheric pressure) for numerical simulation of the wind fields and dust transport. After pre-processing, all the data are imported into the ArcGIS geodatabase. The final DTM complemented by the thematic layers focused on the dust concentration is shown in Figure 2. The aerial images in the background are draped on the DTM in order to provide a more realistic view of the dust transport over the surface mine and the neighbouring residential zone. The bottom layer illustrates the dust transport with the estimated predominant wind direction blowing from the west. A wind rose and histogram based on local meteorological measurements are shown in Figure 3. Thus, the predominant dust transport is in the direction of the residential zone. The grey fields indicate dust concentration levels greater than 1 µg/m$^3$. 

Figure 2. Scene with aerial images draped on the DTM, and the horizontal layers containing the dust concentrations (the bottom layer illustrates the dust dispersion from the emission source over the slope and the nearby residential zone; some of the upper layers are switched off or transparent in order to illustrate the dust concentration in the bottom layer).

Figure 3. A wind rose and histogram indicating the wind class frequency distribution (the predominant wind flows are primarily blowing from the west).
5. CONCLUSIONS

This case study focused on the integration of spatial data and the outputs/inputs of dispersion modelling demonstrates more complex tools for the risk assessment of dust transport over a surface coal mining area. Compared with some previously published dust-transport studies [Chakraborty, 2002; Lu, 2001], sharing of the spatial data based on surface laser scanning together with the wind flow fields can result in a more detailed view of the processes of wind erosion. The processes depend strongly on local wind flow characteristics that are affected by terrain geometry. In the case of this studied area and the
temporary coal storage site in particular, the prediction of the wind flows over stockpiles represents a key stage in the assessment of potential erosion that causes significant environmental impacts. Generally, use of the three-dimensional numerical simulations based on RANS equations with turbulence extensions has been tested and validated in wind tunnels for simplified surface objects [Badr, 2005]. But, the numerical simulation based on the precise DTM allows more realistic predictions of dust emission and dust transport. Integration of the dispersion modelling in the GIS environment allows more complex insights into the studied processes. Thus, other similar studies will be carried out for the testing of both man-made barriers as well as different flow conditions, in order to minimize the dust emission and deposition in the neighbouring residential zones.

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REFERENCES


