Modeling of the Air-Pollution Emergency Situations Control and Geographical Information Processing for Rescue Decision Making

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Abstract
GEPSUS, decision support system for handling hazardous air pollutant releases was developed based on a Gaussian simulation model of air pollution dispersion using MATLAB. For the Gaussian model the following assumptions apply: a) the smokestack emission is constant and continuous, b) flat homogeneous terrain, and c) the wind speed is constant. It is assumed that in the main wind direction, x, advection dominates over diffusion and dispersion. A detailed outline of the system integration is provided, which includes aspects of hydro-meteorological data, eco-toxicological data, Geographical Information Systems (GIS), user input, and system output including a description of threat zones and evacuation plans using a geo-browser. The Gaussian air-pollution dispersion simulation model is linked to the GIS by generating the output in KML file format. Several simulation scenarios were considered using meteorological data sets of wind speed, wind direction and ambient temperature. The developed simulation model and decision support system is intended to facilitate rapid emergency response for both deliberate and accidental air pollution releases. System dynamics model is developed to address the crisis mitigation issues.

Keywords: simulation model, air pollution, decision support system, emergency response

1 Introduction

An emergency situation involving air pollution is time-critical because of the rapid changes in meteorological conditions and need to integrate such information in a decision-making response loop. In urban areas the population density compounds the potential magnitude of the consequences and complicates evacuation of both the injured and unaffected residents (Pontigia et al., 2010; Abbaspoura and Mansourib, 2005). In order to develop a decision support system for the management of emergency situations at a national level, several state agencies are usually involved, to provide proper data input to the system and then provide an adequate response. The goal of the described research is part of a project known as GEPSUS (GEPSUS, 2011; Geographical Information Processing for Environmental Pollution-Related Security within Urban Scale Environments) to develop an integrated system for environmental pollution-related disaster management based on a fusion of geographical information processing, computer modelling and simulation, and credible decision-making for

Montenegro. The system could be applied to other urban areas but with modifications needed to the local data inputs. Technical approaches to emergency response will increasingly rely on improved and sophisticated communication technology. By the application of system approach and system dynamics model the inclusion of the rescue team workforce engagement is considered.

2 GEPSUS system structure description

The structure of the GEPSUS system is displayed in Figure 1 and consists of three major automatic inputs from: a) Hydrological and Meteorological Service of Montenegro (HMZCG), which provides current data and forecasts, b) Center for Ecotoxicological Research of Montenegro (CETI), which provides data on toxic emissions, and c) Real Estate Administration of Montenegro (REA), which provides geospatial information. The data includes a) HMZCG: automatic weather stations and weather simulation models based on data gathered from the weather centers in ECMWF, Reading, UK, and AVN GFS, Washington, USA, b) CETI: automatic telemetric stations positioned at strategic points in Montenegro. Several mobile stations are also available, and c) REA has terrain survey data as well as cadastral surveys.

HMZCG and CETI data input is provided at 1 minute intervals, while the geospatial input is updated on a monthly basis or only for important changes. The HMZCG has its own simulation and modeling capabilities including a High Performance Computing (HPC) centre, which enables HMZCG to generate weather forecasts for Montenegro every 3 hours at a resolution of 1 km on their developed software simulation models. In order to run the forecast models, the HMZCG determines the initial and end conditions as well as other parameters obtained from weather centers in Washington and Reading. Information obtained from the REA includes data on strategic buildings and areas, such as hospitals, schools, public event areas and other sites where large concentrations of people may be anticipated. This is important for adequate decision-making in the case of an emergency event where decision makers must examine the severity of the accident, identify populated areas at risk, and announce appropriate evacuation/escape routes.

Another input to the GEPSUS system is from mobile sensor platforms, or from qualified individuals in the field such as rescue crews who can provide accurate observations. This includes a description of the pollutant, visual information from the release site such as the dimension of the source (e.g. tank with toxic liquid), location (preferably using a GPS device), chemical emission rate, weather condition parameters, release parameters, and threat zones determination.

Since the atmospheric processes affecting air pollution dispersion are fast and dynamic, direct data input to the GEPSUS system is provided via mobile handheld devices. Figure 1 does not explicitly show the Command Room where the full-scale emergency response will be prepared and issued. The Command Room is designed to hold appropriate display equipment to provide immediate and up-dated geospatial awareness to execute response and/or evacuation plans based on the developed simulation models and relevant communicated observer inputs (Kljajić et al., 2000; Škraba et al., 2003, Škraba et al., 2007).

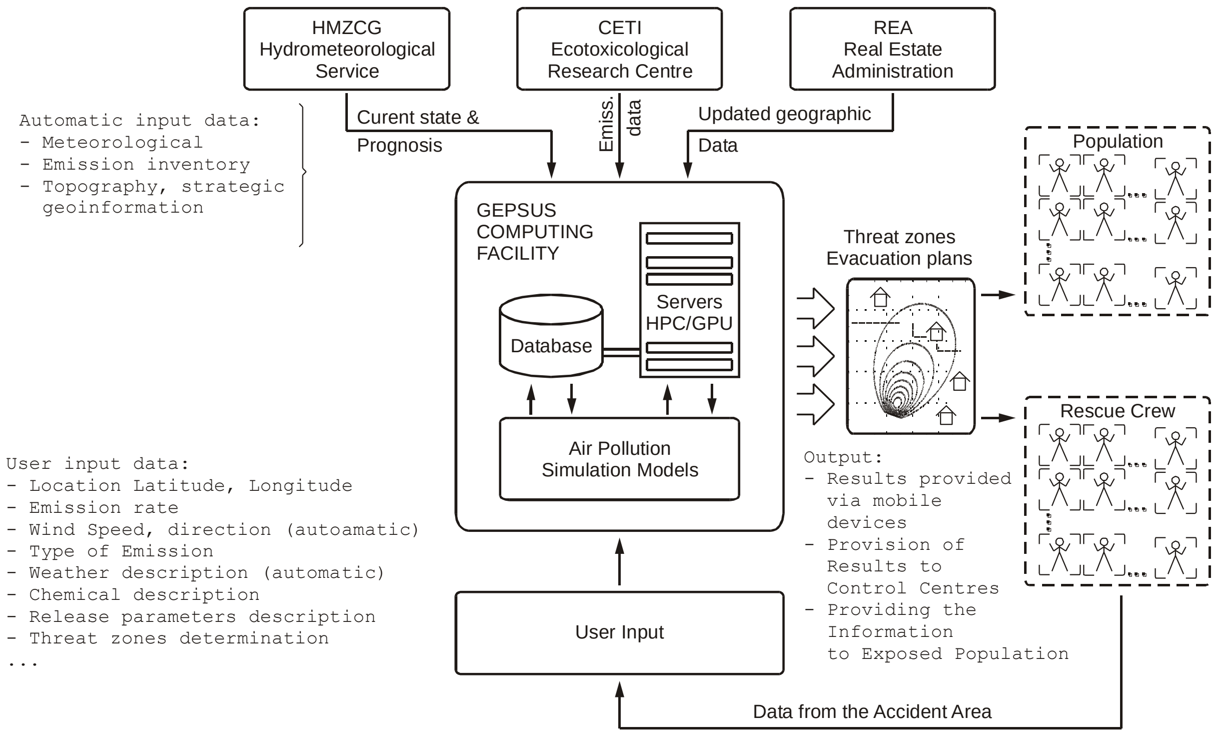

Figure 1: Structure of the GEPSUS system based on air pollution simulation models and data from several information sources

3 System Dynamics Representation of the System for Crisis Mitigation

The main purpose of the system developed within our research framework is to perform and support a process of complex decision-making concerning rescue in the case of air pollution in urban area. Figure 2 represents the control system where the desired i.e. reference value of consequences is set to minimal and should be obtained by the introducing of an acceptable strategy. The Decision Group should provide a proper strategy which is the Reference input to the system in the form of different scenarios. Parameter Estimation and Parameter Boundaries are in the domain of the Decision Group, which should provide proper model parameters. Here the analysis of historical data serves as the initial estimation of Parameter values as well as Boundaries. By setting the Simulation scenarios, the Optimization Algorithm is applied (A) as well as Hybrid model of complex system which incorporates technical as well as System Dynamics simulation. Simulation System Output is compared to Real System Output. The discrepancy between Simulation System Output as well as Simulation Scenario Results influence the Decision Group members, who consider the set of possible solutions. Based on the mentioned two feedback loops, Real System Control is performed by implementation of selected Scenario (C) on the Real System influencing the Rescue System Configuration and management. It has to be mentioned that a complete understanding of the system by the Decision Group is a prerequisite for successful implementation and application of the developed methodology.

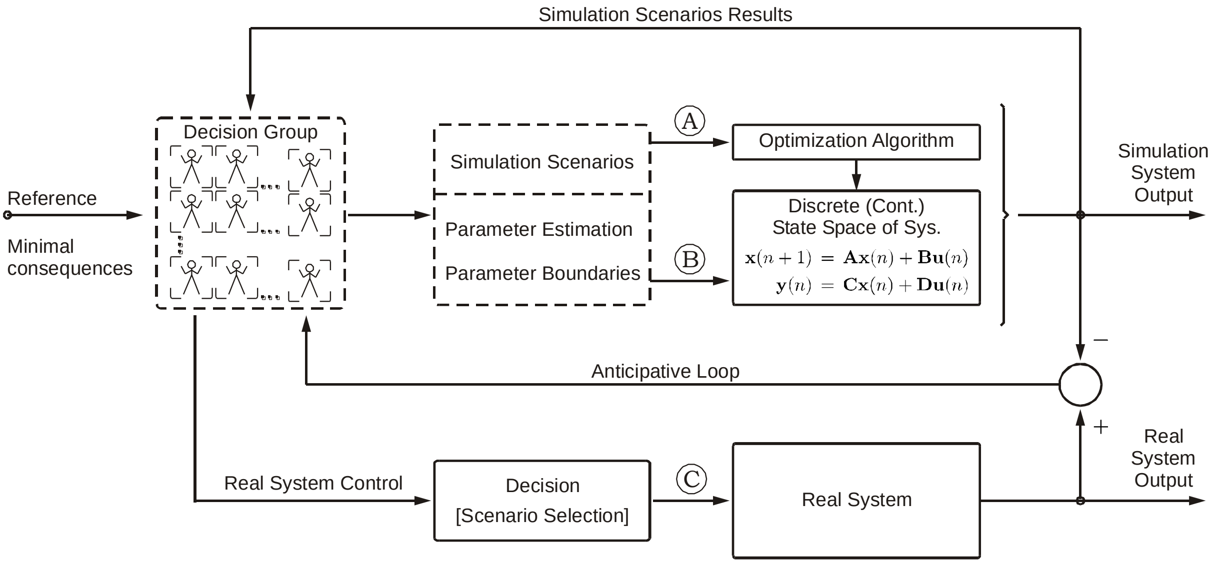

Figure 2: Structure of the emergency control system

In the development of the simulation model, which forms part of the control system, the methodology of SD was applied (Bajracharya et al., 2001; Trost, 2002; Mayo et al., 2001) in order to provide an easy-to-understand structure of the system considered by the Decision Group. The developed simulation model incorporates the flows of personnel through various ranks, displaying the dynamic response of the system

According to Figure 3 the extent of the pollution increases by the Spreading pollution. On the other hand, the Extent of the pollution decreases by the pollution mitigation. The rescue system has a goal to keep the Desired extent of pollution to the minimal possible value. The difference between Extent of the pollution and Desired extent of the pollution positively influences the Desired Mitigation efforts. The Desired mitigation efforts determine the extent of the Desired Workforce needed to mitigate the pollution. By the spread of the pollution the important system perception delay is included. If the Desired mitigation increases, the Desired Workforce increases above the level that would otherwise have been. Desired Workforce is dependent on the workforce's Efficiency. If the Efficiency of the rescuers were higher, the number of Desired Workforce would be less than in the case of lower efficiency. If the number of Desired Workforce increases, the Recruitment rate would increase above the level that would otherwise have been. Increase of Reicruitment increases the level of Workforce. If the level of Workforce increases, the extent of Pollution mitigation would increase above the level that would otherwise have been. This is influenced by Efficiency; if the Efficiency increases, the rate of Pollution mitigation also increases. If the extent of Pollution mitigation increases, the Extent of the pollution decreases below the level that would otherwise have been. The structure described represents the negative feedback loop where the reference point is the Desired extent of pollution which is null.

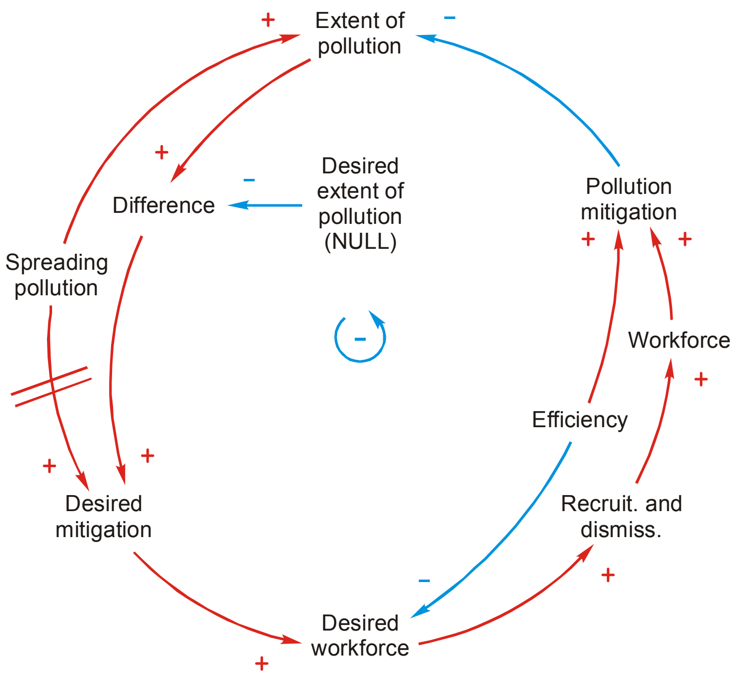

Figure 3: Causal Loop Diagram of Pollution, Workforce and Pollution Mitigation

Figure 4 Figure 2 shows the structure of the model for the problem of air-pollution mitigation by the SD methodology.

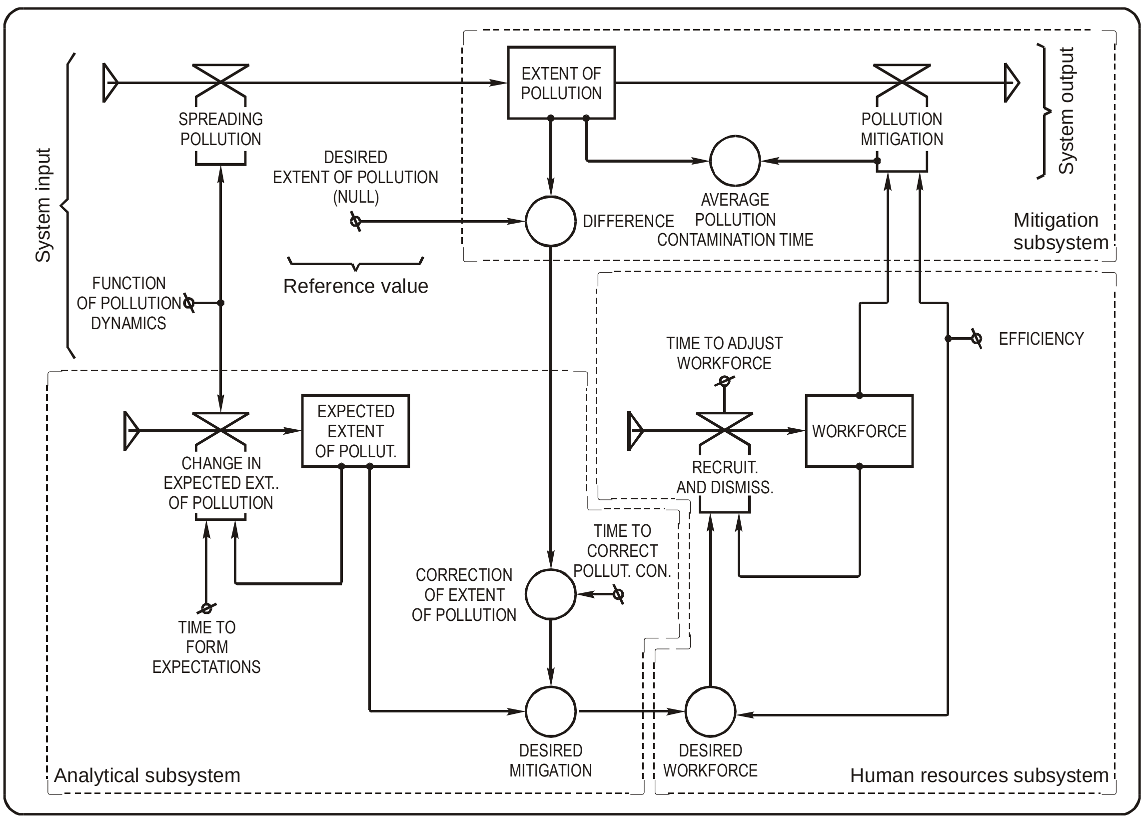

Figure 4: System dynamics model of the rescue team Workforce

4 Air pollution dispersion modelling

There are several approaches to the description of the air pollution dispersion process: Lagrangian model, Box model, Eulerian model, Dense gas model and other new approaches (Grašič, 2008; Osalu et al. 2009). To demonstrate system functionality, the Gaussian Dispersion model was applied, which is built on the Gaussian probability distribution of the wind vector that determines the pollutant concentration (Holzberger, 2007; Tiwary, 2010). Modeling pollution dispersion using a Gaussian model involves an instantaneous release, i.e. pollutant puff from a point source which then moves in the downwind (x) direction. By moving along in the downwind direction the puff expands in volume, incorporating air from around it and reducing its concentration. Assumptions of the Gaussian model are that the point source emission rate is constant and continuous, flat terrain, t and that the wind speed is constant. Iin the main wind direction (x), advection dominates over diffusion and dispersion.

The initial concept for deriving the Gaussian dispersion model is the solution of the transport equation, which accounts only for diffusion and determines how concentration changes with time:

$$\frac{d\,c}{dt} = K\frac{\partial^2 c}{\partial x^2} \tag{1}$$

where c is the concentration of pollutant and K is diffusion coefficient. Equation 1 has an analytic solution:

$$c = \frac{Q}{\sqrt{(4Kt)}}e^{(\frac{-x^2}{4Kt})} \tag{2}$$

where Q represents the emission strength (measured for example in units of $\frac{kg}{s}$). If one neglects the diffusion in horizontal direction the following differential equation is obtained for three dimensional case:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial y}D_y\frac{\partial c}{\partial y} + \frac{\partial}{\partial z}D_z\frac{\partial c}{\partial z} - v\frac{\partial c}{\partial x} - \lambda c$$

where D_y and D_z represent the diffusivity in y and z direction and λ represents the decay rate of the process.

The diffusion equation solution could be expanded with the effect of the reflection from the inversion; here the height is considered as ($2H_i$-H):

$$c(x,y,z)=\frac{Q}{2\pi v\sigma_y\sigma_z}e^{\frac{-y^2}{2\sigma_y^2}\left(e^{\frac{-(z-H)^2}{2\sigma_z^2}}+e^{\frac{-(z+H)^2}{2\sigma_z^2}}+e^{\frac{-(z-2H_i+H)^2}{2\sigma_z^2}}+e^{\frac{-(z+2H_i-H)^2}{2\sigma_z^2}}+e^{\frac{-(z-2H_i-H)^2}{2\sigma_z^2}}\right)} \tag{3}$$

where Hi is the height of the inversion or the top of the atmospheric boundary layer. The exponential terms represent various effects of reflection from the ground and inversions as well as the direct effect. Applying the principle of superposition, the expressions could be combined for several sources. The values of σ_y and σ_z depend on the state of the atmosphere where the empirical approach is usually considered (Turner, 1970).

When considering air pollution modeling, several model packages (Mazzola, 1995) are available. ALOHA, for example, is a computer program designed especially for use by people responding to chemical releases, as well as for emergency planning and training (U.S. Environmental Protection Agency, National Oceanic and Atmospheric Administration, 2007). ALOHA has therefore been considered for use in the GEPSUS system as the one of the modeling support modules.

5 Application of the simulation model with observed data

In order to test the technical part of the GEPSUS system, the air pollution models were developed using MATLAB and were assessed against actual data from the field. MATLAB has been applied in other air pollution modeling tasks due to its practical application value (Fatehifar 2006). Data for the city of Podgorica was provided by the HMZCG (Hidrometeorološki zavod Crne Gore, 2011) (Figure 2). Cardinal data for the developed model are wind direction, wind speed and ambient temperature. In the left panel the past and present data are shown, while in the right panel the forecast data are shown.

For our three scenarios, the air pollution accident/incident occurs at 09:00 and the data from the HMZCG (HMZCG, 2011) are acquired and entered into the model. The forecasted values for 12:00 can then also be entered.

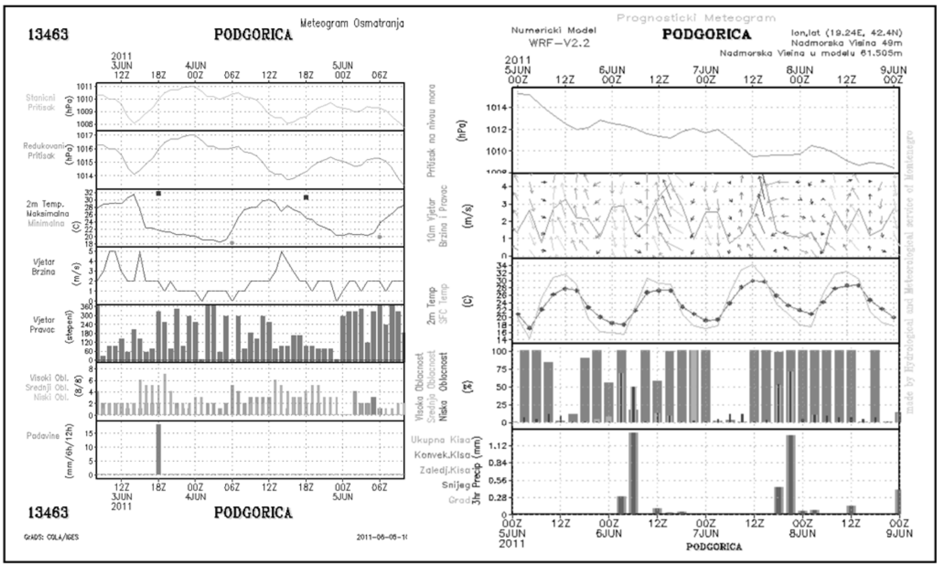

Figure 5: Meteorological data for the city of Podgorica with current weather condition parameters showing pressure, reduced pressure, 2 m temperature, wind speed, wind direction, cloud cover, precipitation (left panel), and forecast data (right panel) obtained from a numerical model of the HMZCG.

Parameters were prepared for the three different simulation scenarios and are shown in Table 1. Here we consider the start time as 09:00. At that time Scenario 1 is performed based on the real time data. In parallel, Scenario 2 is performed, which is based on the parameter values from the forecast for 12:00. Therefore at 09:00 one could have simulation results based on current values of parameters and the forecast parameters. After the actual data for 12:00 are available, a validation scenario is performed, i.e. Scenario 3, as shown in Table 1. Here W. stands for Weather conditions from A-F according to the Pasquill atmospheric stability classes.

Parameter	Scenario 1 (09:00)	Scenario 2 (12:00)	Scenario 3 (12:00)
Emission rate Q [g/s]	76.3	76.3	76.3
Height H [m]	37	37	37
Wind velocity [m/s]	2	3.2	2
Wind direction [deg]	180	135	270
z [m]	0	0	0
Stack x [m]	100	100	100
Stack y [m]	200	200	200
x max [m]	1000	1000	1000
y max [m]	400	400	400
W. condition [A-F]	'A'	'A'	'A'
T [C]	28.5	28	28.7
Real time of simulation execution	5.6.2011 9:00	5.6.2011 9:00	5.6.2011 12:00

Table 1: Parameters for three different scenarios based on actual data (Scenarios 1 and 3) and forecasted data (Scenario 2).

Results of the simulation for the first run are shown in Figure 6. Here x and y display distances while concentrations are represented on the z axis

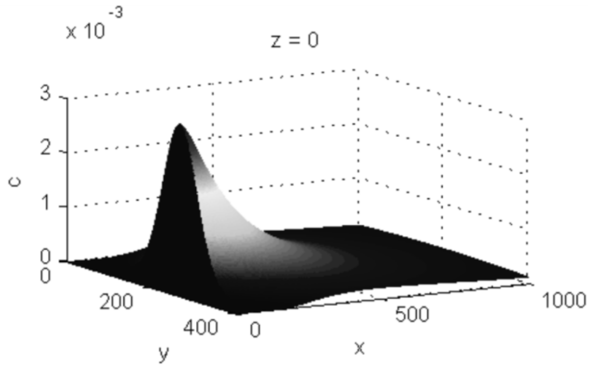

Figure 6: Concentration graph for Scenario 1.

As the HMZCG (HMZCG, 2011) provides the forecast for the next three hours, we conduct the simulation on the basis of the forecast data and obtain the predicted output anticipated for 12:00 (top panel of Figure 7). Here one notes the concentration, which is less than $2x10^{-3}$, primarily a result of the increased wind speed parameter from the forecast data. The third scenario is validation scenario; here the real data at 12:00 are taken and can be compared with the concentration level, which exceeds $2x10^{-3}$, as shown in the bottom panel of Figure 7. For these three cases we do not address the type of pollutant and its chemical characteristic; only the concentration of the hypothetical pollutant is considered. In all cases the *z* coordinate is set to 0.

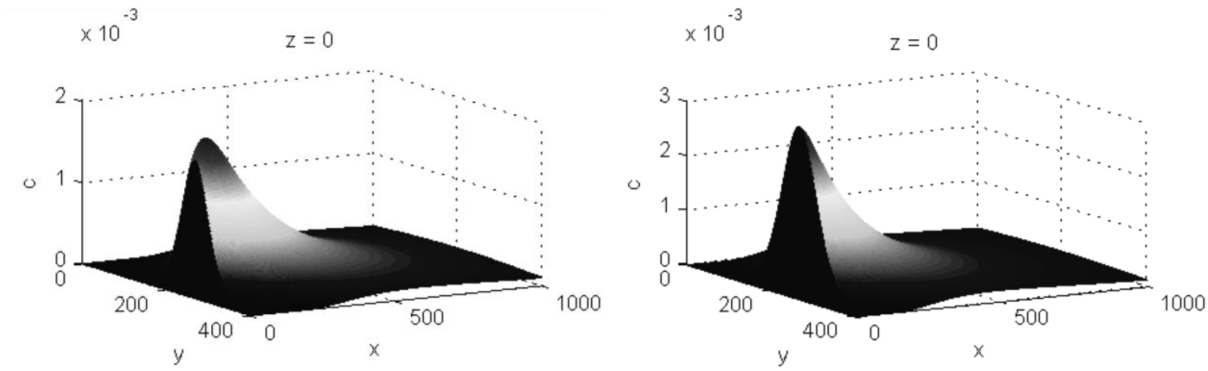

Figure 7: Concentration graphs for the 12:00 simulation based on the forecast (top) and on real data (bottom).

Results of the previously described simulation runs were entered into the GIS system from MATLAB (MATLAB, 2011) by the KML format, an example of which is shown in Figure 8. KML is an open standard officially named the OpenGIS® KML Encoding Standard (OGC KML) (KML Reference, 2011) and maintained by the Open Geospatial Consortium, Inc. (OGC). In our case the standard XML structure can be observed. The KML format is a format that can be read by a majority of GIS browsers; we prepared the KML files for Google Earth (Google Earth, 2011; Daly, 2008). When KML files are produced from the application such as in our case from MATLAB custom code, the format should be checked for errors with the XML validator against the KML schema.

```
<?xml version="1.0" encoding="UTF-8"?>

<kml xmlns="http://www.opengis.net/kml/2.2" xmlns:gx="http://www.google.com/kml/ext/2.2"
xmlns:kml="http://www.opengis.net/kml/2.2" xmlns:atom="http://www.w3.org/2005/Atom">

<Document>

<Placemark>

<name>Center: Lat=42.4392 Lon=19.266

</name>

<Point>

<coordinates>19.266, 42.4392

</coordinates>

</Point>

</Placemark>

</Document>

</kml>
```

Figure 8: Example of KML output format for the center tick-mark at position 19.266, 42.4392.

The results of the simulation runs put on the Google Earth GIS are shown in Figure 9.

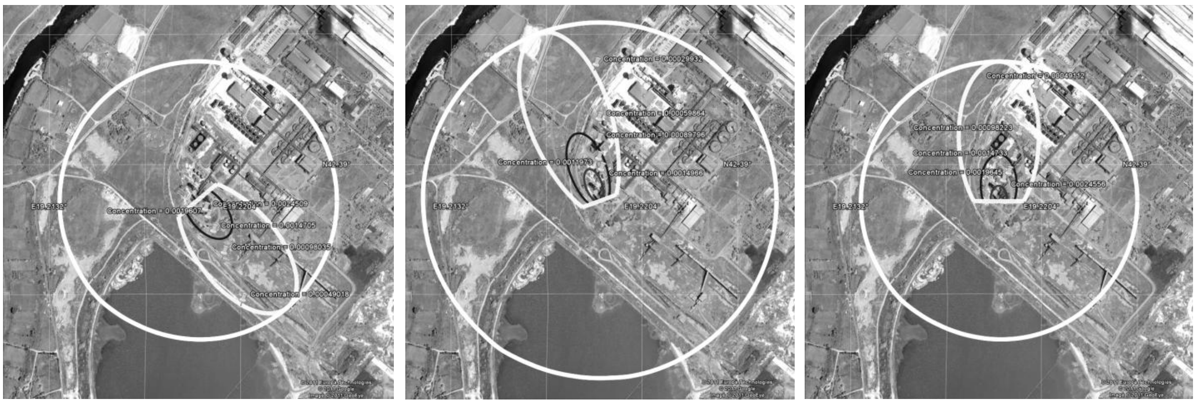

Figure 9: Example of three scenario run in GoogleEarth GIS

6 Conclusions

An overview of GEPSUS system for air pollution emergency control and decision making has been provided by the given test example. Successful intervention for air pollution accidents requires the integration of one or more governmental institutions to provide the input data to the system as well as the human resources capable of implementing a response. For the test case presented here, a Gaussian model of air pollution dispersion was adequate to present the major characteristics of a particular crisis situation.

However, there are issues of model validation (Schiffman et al., 2005; Ames et al., 2002), real-time data input and decision-making that still must be addressed. The application of Google Earth and KML as the initial GIS system contributed to the system development, since the end results of the simulation models can be observed in final form for decision-makers and emergency response teams. The developed system is at a stage where real emergency situations can be better controlled using the GEPSUS system. System dynamics model has been identified as proper for the modelling of the workforce i.e. the activity of the rescue team.

In our future work an ERMAK model will be implemented for better estimation of dispersion.

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