Development of Simulation System for Air-Pollution Emergency Management

Radovan Stojanović*, Andrej Škraba†, Neđeljko Lekić*, Raffaele de Amicis‡
Giuseppe Conti‡, Doron Elhanani§ Simon Berkowitz¶ and Matevž Bren‖
*University of Montenegro, Faculty of Electrical Engineering
Đorđa Vašingtona bb., 81000 Podgorica, Montenegro, Email: {stox, nedjo}@ac.me
†University of Maribor, Faculty of Organizational Sciences
Kidričeva cesta 55a, SI-4000 Kranj, Slovenia, Email: andrej.skraba@fov.uni-mb.si
‡Fondazione GraphiTech, Via alla Cascata, 56/c, 38123 Povo (TN), Italy
Email: {raffaele.de.amicis, giuseppe.conti}@graphitech.it
§EMESCO, 11, Ha-avoda St. POB 142, Rosh Ha-ayin, 48017, Israel, Email: edn5@012.net.il
¶Hebrew University of Jerusalem, Arid Ecosystems Research Center, Inst. Earth Sciences
Givat Ram, Jerusalem, 91904, Israel, Email: berkowi@vms.huji.ac.il
‖University of Maribor, Faculty of Criminal Justice and Security
Kotnikova 8, SI-1000 Ljubljana, Slovenia, Email: matevz.bren@fvv.uni-mb.si

***Abstract*—Paper describes the development of the system for emergency management and control in the case of air pollution accidents. The detailed scheme of system integration is provided which includes aspects of hydro-meteorological data, eco-toxicological data, Geographical Information Systems (GIS), user input and system output which includes description of threat zones and evacuation plans. The Gaussian air-pollution dispersion simulation model has been implemented and connected to the GIS by generating the output in kml file format. Several simulation scenarios were conducted which were based on the real meteorological data of the wind speed, wind direction and ambient temperature. Developed simulation model which was integrated with GIS provided proper spatial visualization of hypothetical crisis situation. Important aspect addressed by the test solution is availability of the simulation results to the emergency response team as well as the public.**

***Index Terms*—simulation, air-pollution dispersion, emergency, GIS**

I. Introduction

In order to develop the system for management and control of incident air pollution events, several key subsystems should be integrated which are: a) Geographical Information System (GIS), b) System for monitoring the contamination in the case of accident, c) hydro meteorological monitoring and prognosis system, d) Simulation system for air pollution dispersion and e) Emergency service system. Simulation of air pollution dispersion is inevitably complex and was for many years primarily accessible only to the researches. Besides, the computer technology was not sufficiently developed to run these models on an ordinary personal computer. However, the estimation of the air pollution spread could only be properly estimated by the application of simulation models. These models have recently become more user-friendly and applicable [1], however more complex models are not jet in the form of user-friendly networked programs. It is of prime importance, that such models are available for the cases of emergency situation with the state of the art input-output, user-friendly networked interface. Present paper describes development of GEPSUS system which adresess Geographical information processing for Environmental Pollution-related Security within Urban Scale environments.

II. Description of System Structure

The structure of the GEPSUS system is shown in Fig. 1. System input consist of three major automatic inputs from: a) Hydrological and Meteorological Service of Montenegro (HMZCG) which provides current state of weather and prognosis, b) Centre for Ecotoxicological Research of Montenegro (CETI) which provides the data on the toxic emissions and c) Real Estate Administration of Montenegro (REA) which provides updated geographical information about the geospatial information of Montenegro. Basic data sources for each of organizations are: a) HMZCG: i.) automatic weather stations and ii) weather simulation models, which are based on the weather data gathered from the weather centres in ECMWF Reading UK and AVN GFS Washington USA, b) CETI gets the data from the automatic telemetric stations which are positioned on strategic points in Montenegro. Besides mentioned, several mobile stations are available and c) REA gets the geospatial information from the terrain survey data as well as from the cadastral survey. The basic input for the GEPSUS system which is automatic are therefore the information about the weather condition which includes the weather prognosis with the special emphasis on the wind condition and prognosis. Here we should mention the different aspects of the data sampling for each of the stated automatic input. HMZCG and CETI input should be provided on the one minute (60s) scale while the GEO input should be updated on the monthly scale or only at the important changes in the geospatial information. HMZCG has its own simulation and modeling capabilities including High Performance Computing

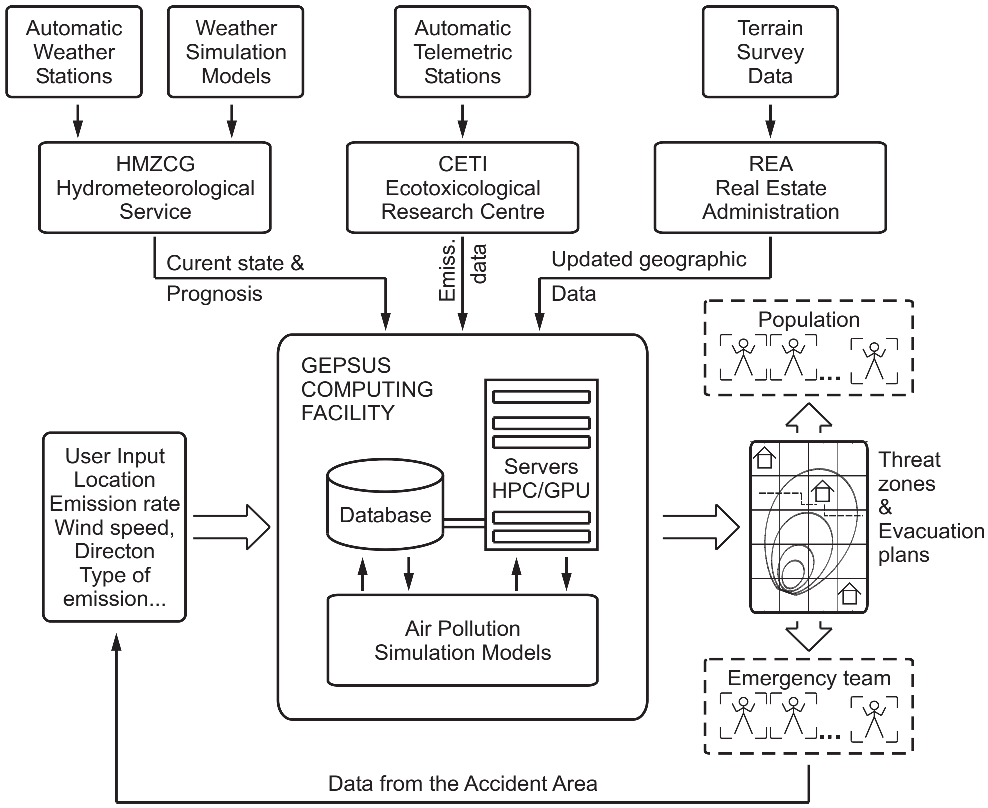

Fig. 1. Structure of the system for air-pollution management and control

(HPC) centre which enables HMZCG to generate weather prognosis for the territory of Montenegro every 3 hours for the resolution of 1km on their own developed software simulation models based on the data from weather centers in Washington-USA and Reading-UK. Important information from REA is the strategic geospatial information which includes the data on the strategic buildings and areas, such as hospitals, schools, public event areas and other where the large concentration of people is anticipated. Another input to the GEPSUS system is user input, which provides the description of the pollutant, such as, location Latitude and Longitude, chemical emission rate, special weather condition parameters, which could not be provided by the automatic input, type of emission, release parameters and thread zones determination. User input should address the data, which could not be reliably acquired by some automatic methods; here the visual information from site is important such as dimension of the source (e.g. tank with toxic liquid) or the type of the chemical in question (from the tank specification). The user input is provided from the experts for the air pollution emergency management as well as the rescue crew which is on the field and provides accurate information about the incident. Since the processes in the field of incident air pollution dispersion are fast, the direct input to the GEPSUS system will be provided via mobile handheld devices. Figure 1 does not explicitly show the Emergency room where the emergency situation management will be performed. Here the appropriate display equipment will be employed to provide proper geospatial awareness to the decision makers which execute the evacuation plans based on the developed simulation models [2].

III. Modelling of Air-Pollution Dispersion

There are several approaches to model air-pollution dispersion: Gauss model (Plume, Puff) [3], [4], regression models, box model, multiple cell model and other new approaches, e.g. [5]). For the purpose of the proof of the concept the Gaussian model was implemented in MATLAB® [6]. Gaussian model has several assumptions: a) the smokestack emission is constant and continuous b) terrain which is observed is flat, c) the wind speed is constant. Here, one considers, that in 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:

$$\frac{\mathrm{d}c(t)}{\mathrm{d}t} = K\frac{\partial^2 c}{\partial x^2} \tag{1}$$

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

$$c = \frac{Q}{\sqrt{4\,K\,t}}\, e^{\frac{-x^2}{4\,K\,t}} \tag{2}$$

where Q represents the emission strength (measured for example in units of $\frac{\mathrm{kg}}{\mathrm{s}}$). Gaussian model also considers constant diffusivities in horizontal (y) and vertical (z) direction. Here, rather idealized conditions are assumed in order to derive the mathematical model of the process. If diffusion in horizontal direction is neglected the following differential equation is obtained which describers the dispersion process:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial y} D_y \frac{\partial c}{\partial y} + \frac{\partial}{\partial z} D_z \frac{\partial c}{\partial z} - v \frac{\partial c}{\partial x} - \lambda c \tag{3}$$

where D_y and D_z represent the diffusivity in y and z direction and λ represents the decay rate of the process. The steady state equation of observed diffusion process:

$$\frac{\partial c}{\partial x} = \frac{\partial}{\partial y} \frac{D_y}{v} \frac{\partial c}{\partial y} + \frac{\partial}{\partial z} \frac{D_z}{v} \frac{\partial c}{\partial z} - \frac{\lambda}{v} c \tag{4}$$

Solution of the system yields:

$$c(x,y,z) = \frac{Mv}{4\pi x \sqrt{D_x D_y}} e^{-\frac{v}{4x}\left(\frac{y^2}{D_y} + \frac{z^2}{D_z}\right) - \frac{\lambda}{v} x} \tag{5}$$

Eq. 5 represents the steady state solution for a constant source in 3D. The product $Q = Mv$ represents the emission rate in unit $[\frac{\text{mass}}{\text{time}}]$. Since the different heights of the plume should be considered, Eq. 5 could be modified for a source at height H. If one considers the three dimensional instantaneous puff situation where time is considered the solution becomes:

$$c(x,y,z,t) = \frac{Q}{\sqrt{2\pi\sigma^2}^{\,3}} \; e^{-\frac{-r^2}{2\sigma^2}} \tag{6}$$

where σ is standard deviation of the puff concentration at any particular time t and $r^2 = (x - v\,t)^2 + y^2 + z^2$. The rate at which the buoyant plume enters ambient air is proportional to the plume area and the plume velocity relative to the surrounding air. Buoyancy flux which determines the driving force is expressed as:

$$F_b = w_0 R_0^2 \frac{g}{T_{p0}} \left(T_{p0} - T_{a0}\right) \tag{7}$$

where w_0 is the initial plume speed, R_0 the stack radius, T_{p0} the initial plume temperature (K) and T_{a0} the ambient temperature at stack height. By application of the Briggs equations for the curved motion over plume the effective plume stack could be determined.

According to the idea of the puff dispersion in the downwind direction in continuous manner the following equation describes the concentration as the function of the (x, y, z) coordinates:

$$c(x,y,z) = \frac{Q}{2\pi v \sigma_y \sigma_z} e^{\frac{-y^2}{2\sigma_y^2}\left(e^{\frac{-(z-H)^2}{2\sigma_z^2}}\right)} \tag{8}$$

where σ_y and σ_z describe the width of the concentration distribution. Here it is assumed, that the majority of the dispersion moves in the downwind i.e. x direction. If one considers, that there is no absorption from the ground, the mirroring effect takes place. The upward dispersion occurs in this case, contributing to the atmospheric pollutant concentration. In this case, one has to add an mirror source, which equals in magnitude to the actual source however, at the coordinate location of H, i.e. $2H$ below the abscise. Therefore the equation where the reflection from the ground is considered is stated as:

$$c(x,y,z) = \frac{Q}{2\pi v \sigma_y \sigma_z} e^{\frac{-y^2}{2\sigma_y^2}\left(e^{\frac{-(z-H)^2}{2\sigma_z^2}} + e^{\frac{-(z+H)^2}{2\sigma_z^2}}\right)} \tag{9}$$

where the additional exponential term accounts for the additional contribution from the mirror source. Besides the reflection from the ground there is a common situation of the reflection from the inversion. In the case of the incident pollution this is important since the concentrations could significantly increase on the account of the inversion reflection. Diffusion equation is therefore expanded with the effect of the reflection from the inversion; here the height is considered as $(2H_i - H)$:

$$c(x,y,z) = \frac{Q}{2\pi v \sigma_y \sigma_z} e^{\frac{-y^2}{2\sigma_y^2}} \; \Psi^* \tag{10}$$

where Ψ^* represents the following exponential terms:

$$\Psi^* = e^{\frac{-(z-H)^2}{2\sigma_z^2}} + e^{\frac{-(z+H)^2}{2\sigma_z^2}} + \tag{11}$$

$$+ e^{\frac{-(z-2H_i+H)^2}{2\sigma_z^2}} + e^{\frac{-(z+2H_i-H)^2}{2\sigma_z^2}} + e^{\frac{-(z-2H_i-H)^2}{2\sigma_z^2}}$$

where H_i 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 inversion 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 [7].In developed models the traditional classification of common atmospheric conditions by Pasquill-Gifford classification which is shown in Tab. I was applied. The Pasquill curves give the values for the pair of dispersion coefficients depending on atmospheric conditions. For approximate calculation the following equations were used:

$$\sigma_y = a\,x^{0.894} \tag{12}$$

$$\sigma_z = c\,x^d + f \tag{13}$$

TABLE I
PASQUILL GIFFORD EMPIRICAL STABILITY CLASSES

v	Day (solar radiation)			Night (cloud.)	
[m/s]	strong	moderate	slight	$> \frac{4}{8}$	$\leq \frac{4}{8}$
< 2	**A**	**A – B**	**B**	**E**	**F**
$2 - 3$	**A – B**	**B**	**C**	**E**	**F**
$3 - 5$	**B**	**B – C**	**C**	**D**	**E**
$5 - 6$	**C**	**C – D**	**D**	**D**	**D**
> 6	**C**	**D**	**D**	**D**	**D**

where a, c, d and f are constants which were in our case modeled by the means of the empirical lookup table with x in kilometres and σ values obtained in meters. At the modeling of dispersion the lookup table was applied for σ_y, σ_z.

A. Existing Air-Pollution Simulation Systems

In order to provide the proper simulation capabilities other existing simulation systems are considered [8]. One of the important systems is ALOHA [1] which is one of the computer programs designed especially for use by people responding to chemical releases, as well as for emergency planning and training developed by U.S. Environmental Protection Agency, National Oceanic and Atmospheric Administration. Another system which has been considered to be included into the GEPSUS system is CALPUFF [9]. While ALOHA considers the air pollution accidents in smaller scope, the CALPUFF considers models for assessing long range transport of pollutants and their impact on the environment. On the other hand, it should be mentioned, that these systems are subjected further development and validation [10].

IV. Test Case Example

For the purpose of the test case, the location of the emission was determined which is the plume at location of the Thermal Power Plant (TPP) Pljevlja, Lat.: 43.333494, Lon.: 19.327311. The location is picked arbitrarily and all of the simulation scenarios are hypothetical in order to test the concept of GEPSUS system. The GIS representation of the data has a significant importance for the decision makers, response crew as well as the population in order to increase geospatial awareness [11]. The parameters which were prepared for three different simulation scenarios are shown in Tab. II. The parameter values are approximate used for the performance of test scenarios however, data on the weather conditions are taken from the HMZCG [12]. For the test case we consider, that the present time is 9:00h. At that time, the Scenario $SC1$ is performed based on the real time data. At the same time, the Scenario $SC2$ is performed, which is based on the parameter values from the prognosis for 12:00h from the simulation run of WRF-V2.2 model with horizontal resolution of approx. 6km on the GFS (Global Forecast System) data [12]. Therefore at 9:00h one could have the simulation results based on current values of parameters and the prognosis parameters. After the real data for 12:00h were available, the validation scenario was performed; Scenario $SC3$, which parameter values are shown in the last column of Tab. II. Results of the simulation for the Scenario $SC3$ in the form of 2-D graph are shown in Fig. 2. Here we have x and y distance and the concentration levels on the ground level, $z = 0$. One could observe the concentration on the scale $\times 10^{-4}$. Scenario $SC3$ represents the results based on the real data gathered at 12:00h. Fig. 3 shows the concentration in $3D$ where the distribution of the concentration is represented. The results are shown for the ground level $z = 0$. Results of the previously described simulation runs were put into the GIS system from the MATLAB by the kml format [13]. KML is an open standard officially named the

TABLE II
PARAMETER VALUES FOR $SC1$, $SC2$ AND $SC3$

Parameter	SC1	SC2	SC3
Emission rate $Q[\frac{\text{g}}{\text{s}}]$	942	942	942
Height H [m]	250	250	250
Wind welocity $[\frac{\text{m}}{\text{s}}]$	1	3.8	2
Wind direction $^\circ$	225	18	315
z [m]	0	0	0
Stack x [m]	50	50	50
Stack y [m]	200	200	200
x max [m]	5000	5000	5000
y max [m]	2000	2000	2000
Weather condition [A-F]	'A'	'A'	'A'
Temperatre $T[^\circ\text{C}]$	13.6	25.5	17.0
Real time of sim. run	9h	9h	12h

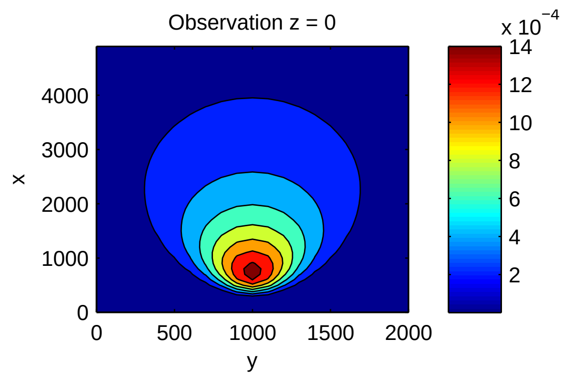

Fig. 2. Concentration of the ground level $z = 0$ for the Scenario $SC3$

OpenGIS® KML Encoding Standard (OGC KML) [14]. It is maintained by the Open Geospatial Consortium, Inc. (OGC [15]). In our case the standard xml structure has been produced by the developed system. The kml format is the format which could be read by majority of GIS browsers. In our case we have prepared the kml files for the Google Earth [16]. 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. The results of the simulation runs put on the Google Earth GIS are shown in Fig. 4. Here the three simulation runs at TPP Pljevlja were considered at the location: Lat.: 43.333494, Lon.: 19.327311. The part $SC1$ represents the Scenario $SC1$. Here the concentrations of the hypothetical pollutant on 11^{th} June 2011 at 9:00 h are shown; these are results of the first simulation run based on the field data. The simulation run is based on the real data on wind direction which is 225°, wind speed of $1\frac{\text{m}}{\text{s}}$ and ambient temperature 13.6°C. Part B represents Scenario $SC2$, where the anticipated concentrations of pollutant on 11^{th} June 2011 at 12:00h were considered,

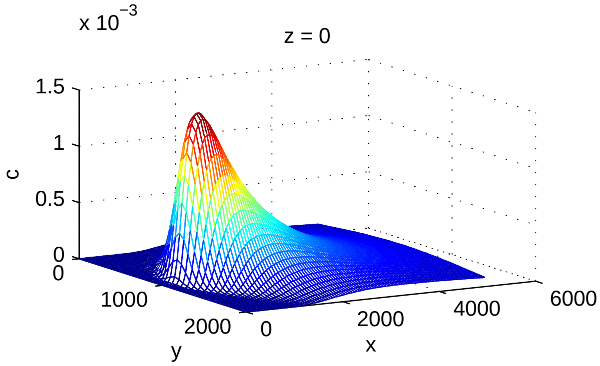

Fig. 3. Concentration of the ground level $z = 0$ for the Scenario $SC3$ in 3D

based on the prognosis of wind direction which was $18°$, wind speed of $3.8\frac{\mathrm{m}}{\mathrm{s}}$ and temperature of $25.5°\mathrm{C}$. Scenario $SC3$ results are represented by $SC3$ mark where the concentrations of the pollutant on 11^{th} June 2011 at 12:00h are considered, based on the real data on wind direction $315°$, wind speed of $2\frac{\mathrm{m}}{\mathrm{s}}$ and temperature $17°\mathrm{C}$. One could observe change in the direction of air pollutant spread which occurred in the period of three hours. Actual wind change was from $225°$ ($SC1$) at 9:00h to $315°$ at 12:00h ($SC3$). The predicted wind direction ($SC2$) was $18°$. Due to the larger predicted wind speed of meteorological prognosis, one could observe larger expected perimeter in the predicted run $SC2$.

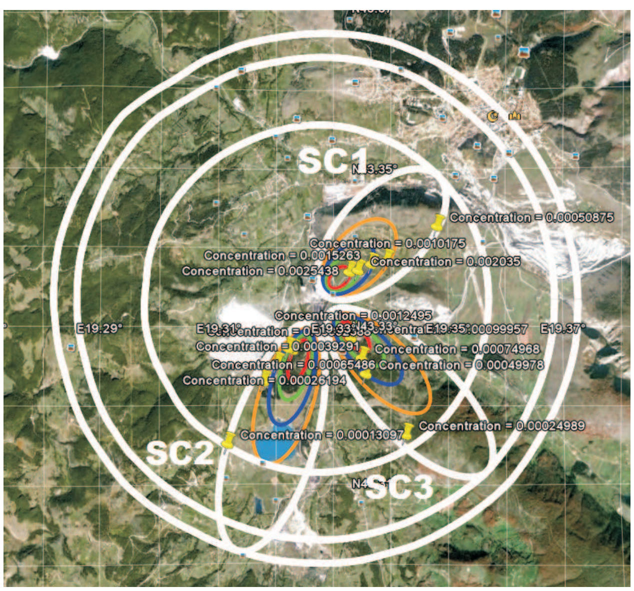

Fig. 4. Threat zones at the level $z = 0$ for the Scenarios $SC1$, $SC2$ and $SC3$

V. Conclusion

Development of system for management and control of emergency pollution in the case of incidents is a complex process. Data from several institutions have to be integrated in order to provide the working system. Besides, since the process occurs in atmosphere the system models are nonlinear and the solutions should thoroughly be tested. Applied Gaussian model proved to be sufficient for the test of the concept. MATLAB has been applied as the tool for rapid development of the system. The important aspect at the development is GIS representation which was sucessfully provided by the application of the Google Earth component. In this manner the results of the simulation run could be widely distributed to the response team and population. Three different scenarios showed the potential usage of the system. Since the processes of air pollution dispersion are fast, the final system should incorporate near real time data. Major topic at the development of the system are air-pollution dispersion models, which should be validated and tested. Such system should include properly trained operators, since the processes considered are complex and should carefully be described in order to gain proper results and conduct proper response actions.

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