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GIS-BASED SYSTEM FOR AIR-POLLUTION MANAGEMENT[1]

Abstract: Paper describes the GIS-based real-time system for emergency management and control in the case of air pollution accidents in urban areas. The system architecture is presented with emphasis on integration of meteorological, chemical and GIS data, dispersion modeling, decision making and GIS visualization. The threat zones and unsafe areas are obtained using improved Gaussian plume model with decision making module and then exported to Google Earth browser via „KML" file format. The real scenario is conducted and verified using environmentally critical industrial object Thermo Electric Plant Pljevlja in Montenegro under real weather conditions. The testing results show that emergency responders can use proposed methodology and system as a cost effective and accuracy supporting tool in case of air pollution accidents.

Key words: *hazardous gas releases, air-pollution simulation, emergency, GIS*

1. INTRODUCTION

When hazardous gases are released into the atmosphere, accidentally or due to a terrorist attack, the emergency responders need to have early and true information

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about the maximum outline of the area affected and all consequences to be expected. The process is time-critical because many lives depend on how quickly and accurately the decisions will be taken. Especially, in the urban areas where the presence of high population density multiplies the magnitude of the consequences and complicates the problem of evacuation [1], [2].

Therefore, there is a raised need from emergency responders and other civil protection stakeholders to use a support system for hazardous gas releases, which will be based on modern information and communication technologies (ICT). Current software applications MET, ALOHA, BREEZE, TRACE, SAMS etc. only partially solve the problem [3]. They are off-line and predominantly model the pollutant dispersion in 2D or 3D space displaying the concentration profiles (plumes) over digital maps. The plumes are static and do not consider the dynamics of the process, primarily the changes in the weather conditions and source strength [4]. Additionally, they do not support an automatic data importing, weather prognosis and especially decision making which is in many cases the cause of failure in response.

An useful system for management and control of accidental releases of hazardous gases should be at least real-time with possibility to integrate several subsystems of which depends the accuracy of reaction: a) Geographical Information System (GIS); b) System for measurement and monitoring chemical parameters; c) System for hydro meteorological monitoring and prognosis; d) System for modeling of gas dispersion; e) Local sensor networks and e) System for planning emergency response [4]. For many years the integration was a problem due to the technologically inability in ensuring high data flow and complex computation in real-time.

The GEPSUS (Geographical information processing for Environmental Pollution-related Security within Urban Scale environments) project presents one trial in this direction, aiming to provide emergency responders with an integrated system for control and management of hazardous gases accidents, especially in urban areas. It integrates the automatic data importing with GIS-based simulation of dispersion and decision making.

2. SYSTEM ARCHITECTURE

The structure of the GEPSUS system is shown in Fig. 1. It consists of GEPSUS computing facility and data inputs from: a) Hydrological and Meteorological Service of Montenegro (HMZCG); b) Centre for Ecotoxicological Research of Montenegro (CETI); c) Real Estate Administration of Montenegro (REA) and d) GEPSUS Sensor Networks (GSN) installed around critical object. HMZCG provides current weather situation and prognosis for places of interests. It is done automatically through the network of weather stations installed over Montenegro and through the weather prognosis models which are part of EU and worldwide weather prognosis network. CETI monitors the actual situation of air pollution using a network of automatic telemetric stations which measure the concentration of main gases over Montenegrin cities. REA provides updated geographical information about the geospatial data of Montenegro. The geospatial information are taken from the ter-

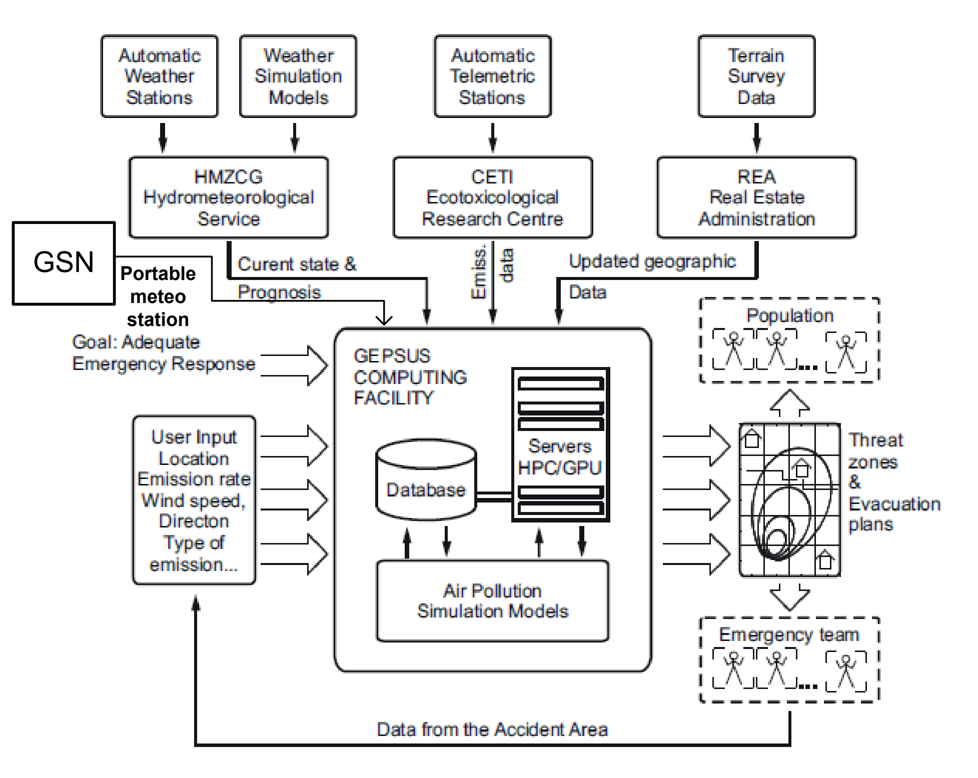

Figure 1: Architecture of the GEPSUS system

rain survey as well as from the cadastral survey and stored on public servers. With HMZGC, CETI and REA GEPSUS communicates over Internet supported protocol or over leased lines. GSN consists of mobile telemetric stations installed around critical objects. Primarily they measure the wind speed and direction as well as ambient temperature, sending information via GSM network directly to GEPSUS centre.

The wind condition (speed and direction) and its prognosis are considered as main automatic data, because the orientation and geometry of the plume dominantly depends on them. HMZCG gives wind conditions on large scale, e. g. for one city or region, while in-spot wind conditions are traced by local stations within GSN.

In addition to automatic inputs there are several manually inputs, usually entered by operator or emergency expert. They give more information about pollutant source and atmospheric conditions as well as define the Levels of Concern (LOCs) – thresholds levels of concentration in ug/m^3 or ppm. Source data include the place of accident (latitudes and longitudes), description of the pollutant, type of the gas and its characteristics, type of the source (point, line, area, tank, pipe) and its geometry (dimensions), emission rate, source height above a ground, release duration and so on. Ground roughness, cloud cover, stability class, inversions and humidity are weather conditions which are set manually. LOCs define the threat zones, associated for each gas and they are usually standardized like the Emergency Response Planning Guidelines (ERPGs) or Acute Exposure Guideline Levels (AEGLs). As an example, for sulfur dioxide (SO_2) the ERPG-1, ERPG-2 and ERPG-3 have values 0.3 ppm, 3 ppm and 25 ppm respectively. Here, the other accurate information about the incident can be involved, provided by air pollution experts or rescue crew on the field which can enter the input parameters manually, via mobile handheld devices.

3. Modeling and visualization

The dispersion modeling is performed in MATLAB starting from generalized Gaussian plume equation [5]:

$$C(x,y,z) = \frac{Q}{2\pi u \delta_y \delta_z} e^{-\frac{y^2}{2\delta_y^2}} \left(e^{-\frac{(z-H)^2}{2\delta_z^2}} + e^{-\frac{(z+H)^2}{2\delta_z^2}} \right) + ST \quad (1)$$

$$ST = \sum_{n=1}^{k} e^{-\frac{(z+H-2nz_i)^2}{2\delta_z^2}} + e^{-\frac{(z+H+2nz_i)^2}{2\delta_z^2}} e^{-\frac{(z-H-2nz_i)^2}{2\delta_z^2}} + e^{-\frac{(z-H+2nz_i)^2}{2\delta_z^2}} \quad (2)$$

in which the concentration of pollutant $C\,(x, y, z)[g/m^3]$ in point $x[m]$,$y[m]$,$z[m]$ depends on mass emission rate $Q[g/s]$, wind speed $u[m/s]$, dispersion coefficients $\sigma_y[m]\cdot\sigma_z[m]$ and effective stack high $H[m]$ which is a sum of actual stack high $h^s[m]$ and plume rise $\Delta h[m]$, $H=h^s + \Delta h$. The ST is a summation term related to the inversion from mixing height z_i, while k is summation limit for multiple reflection, usually ≤ 4.

The above equation is used to model the plume impacts from point sources, flare releases, and volume releases, and gives satisfactory results under several assumptions/approximations: Steady state; wind blows in x direction and is constant in both, speed and direction; transport with the mean wind is much greater than turbulent transport in the x direction; source emission rate is constant; dispersion coefficients are constant in time and have space dependence toward several approximations, e. g. Pasquill's categories; the source emits Chemicals of Concern (COC) at point in space $x=y=0$ and $z=H$, where H is the effective size of the stack; the COC are inert, non decaying and non reactive; there is no barrier to plume migration; mass is conserved across the plume cross section; mass within a plume follows a gaussian distribution in both, the crosswind (y direction) and vertical (z direction); it is assumed that exit gas temperature is higher than the ambient temperature and varies in the range of 120–260 C°; the extent to which the moving speed of wind at the point of gas release must be from 6–30 m/s; The effective stack high H is spatially constant, therefore plume rise has a constant value along x axes.

The GEPSUS approach modifies Equation (1) in two main elements:

1) Considering plume rise Δh spatially depended and

2) Replacing $\sigma_y \cdot \sigma_z$ with effective values $\sigma_{y_{eff}}$ and $\sigma_{z_{eff}}$.

Two categories of smokestack plumes are observed, often present in practice, vertical plume and bent over plume, Fig 2. Which of the two forms will occur depends on several parameters such as: stability classes, wind speed, exit speed of the gas, buoyancy flux parameter etc. For example, in stability classes A to D when the intensity of wind is significant the bent over plume will be dominant, while the vertical form will be present in stable conditions, E or F.

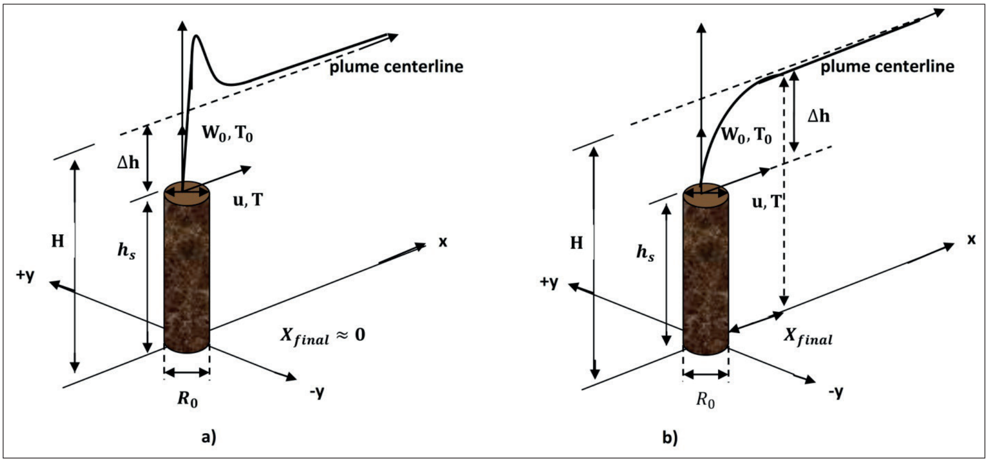

Figure 2: Direct plume (a) and bent over plume (b).

The calculation of plume rise is based on modified Briggs algorithm [6] where Δh is calculated for two segments, before x_{final} – the point of maximum plume rise, and after x_{final}. Generally seen, Δh is a complex function and depends of numerous input parameters.

$$\Delta h = f\left(x, Xfinal, T, To, u, wo, g, Ro, \frac{\Delta\theta}{\Delta T}, stability\ Classes\right) \quad (3)$$

where are:

x: downwind distance from plume source [m];

X_{final}: downwind distance from plume source to point of maximum plume rise [m]

u: wind speed at actual stack height $\left[\frac{m}{s}\right]$

A, B, C, D, E or F: stability classes

T_0: pollutants temperature at the source output [K]

T: ambiental temperature [K]

W_0: pollutant exit speed at stack exit $\left[\frac{m}{s}\right]$

R_0: diameter of the stack [m]

g: gravitational acceleration $\left[9.81\, m/_{s^2}\right]$

$\frac{\Delta\theta}{\Delta T}$: coefficient in $\frac{K}{m}$, which depends on stability classes.
The Δh is calculated using a set of equations. For such purposes a special MATLAB function is developed.
The effective values $\sigma_{y_{eff}}$ and $\sigma_{z_{eff}}$ are callculated from dispersion coeeficiants σ_y and σ_z taking in consideration the above paramaters:

$$\sigma_{y_{eff}}, \sigma_1(z_1 eff\,) = f(x, Xfinal, T, To, u, wo, g, R, \sigma_1 z\,, \quad terrain\,type) \quad (4)$$

where σ_y and σ_z are determined from Pasqual-Gifford dispersion coefficients [7]. The calculation is done by set of equations.

Considering the explained modifications the concetration $C\,(x, y, z)$ from Equation (1) takes an analytical expression $C'(x, y, z)$, which is consider as a basic equation in GEPSUS calculations for case of industrial point sources:

$$C'(x,y,z) = \frac{Q}{2\pi u \delta_{y_{eff}} \delta_{z_{eff}}} e^{-\frac{y^2}{2\delta_{y_{eff}}^2}} \left(e^{-\frac{(z-(h_s+\Delta h))^2}{2\delta_{z_{eff}}^2}} + e^{-\frac{(z+(h_s+\Delta h))^2}{2\delta_{z_{eff}}^2}} \right) \ldots$$

$$\ldots + TS(\Delta h, \sigma_{y_{eff}}, \sigma_{z_{eff}}) \quad (5)$$

Usually sumation term *TS* is neglected and concentration is observed at ground level (z=0).

3. 1. Visualisation and interfacing to GIS

The overall program for callculation of polutant concetration according to Equations (1) to (5) is developed in MATLAB with the following algorithmic steps, Fig. 3:

1. The function accept input parameters and produce 3D matrix $C'(x, y, 0)$.
2. From $C'(x, y, 0)$ a set of contour matrixs $Coi\,(x, y)$ are produced. In fact $Coi\,(x, y)$ present threat zones and is obtained as:

$$Coi(x,y) = \begin{cases} 1 \; for\; C'(x,y,0) = Ti \\ 0 \; elsewhere \end{cases} \quad (6)$$

where *Ti* is *LOC* for observed gas in $\frac{\mu g}{m^3}$ or ppms.

3. The „KML” file format is used as an interface betwen MATLAB and Google Earth. It is an open standard officially named the OpenGIS RKML Encoding Standard (OGC KML) [8, 9]. Before generatting KML the contour graphs given in meters should be transfered to latitude-longitude coordinates taking into an account source possition and then rotated wind angle. As wind reference angle the North (N) is considered (0°). Coordinate transforation, rotation and KML composition are also implemented in MATLAB.KML file beside threat zones consists and description unsafety area that will be detailed described in the next section.
4. At the end the KML file is displayed by Google Earth Browser

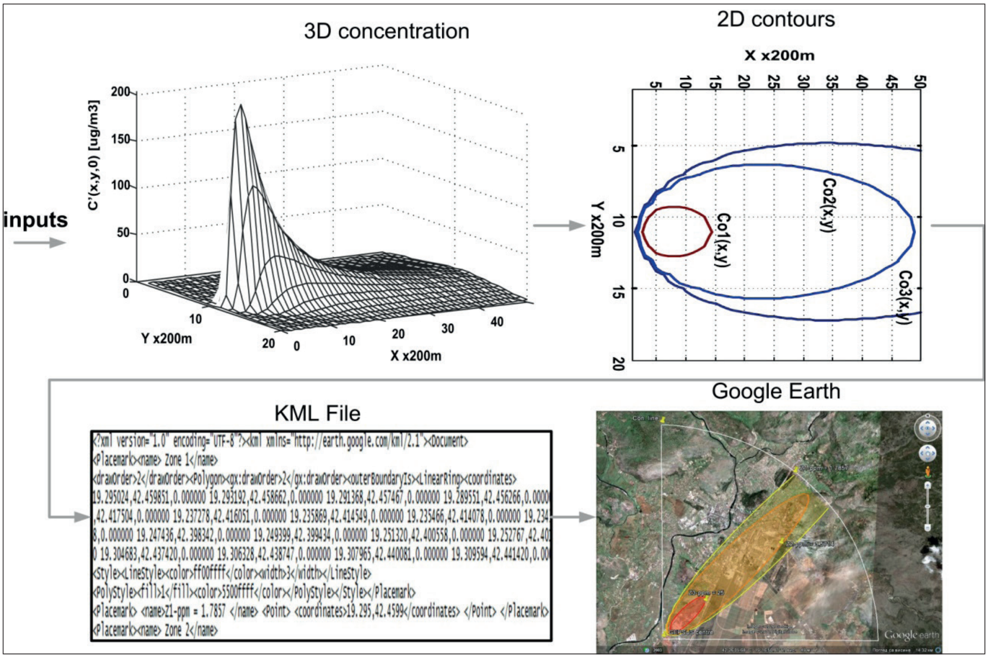

Figure 3: Algorithmic structure of GEPSUS code for modeling, KML composition and visualization.

5. DECISION MAKING

The determination of the pollution spread in the urban area is not only content of GEPSUS system. Usually, the man takes the decisions, but in many cases, techniques can help him to do it easier and more accurate [10]. In this project phase one algorithm for supporting decision making are considered named „determination of unsafe area”.

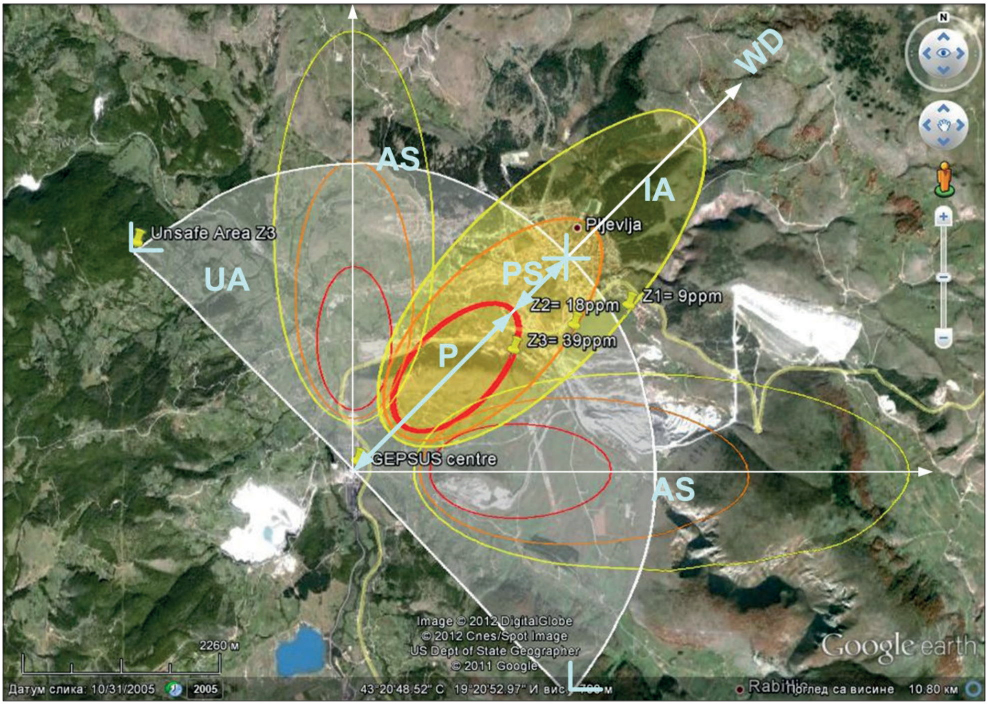

Figure 4: Examples of decision making algorithms, unsafe area shaded white.

The unsafe area is associated to unsafe parameter and unsafe arc which are related to each threat zone. In their construction three main parameters should be considered, Fig. 4: initial perimeter (P), initial angle (IA), perimeter span (PS) and angle span (AS). P is associated to each threat zone and presents the distance between source of emission and top point of observed zone. PS is an increment of P produced by changing of input parameters, wind speed, source strength, stability classes etc. AS is dominantly function of wind direction (WD), while IA is associated to the actual wind direction. As seen, in Fig. 4, the selected threat zone can rotate and translate from IA-AS to IA + AS and from 0 to P + PS. As example in Fig. 4 the IA=225° and AS=90°, P about 8 km and PS about 1 km. The emergency responders should to evacuate people from unsafe areas (UA), not to waist precious time. Using current parameters and weather prognosis it is important to predict PS and AS as precisely as possible and for such purpose special algorithms and expert modules are used [11]. As an example, AS is determined from standard deviation of WD.

6. RESULTS AND VALIDATION

In order to verify the developed dispersion model as well as proposed decision making techniques, the real industrial source in North Montenegro is observed. The Thermo Electric Plant Pljevlja (TEPP) has an installed power of 218 MW and is one of the biggest polluters in Montenegro. Due to lack of filters the harmful gases are released directly into the atmosphere, among other Sulfur Dioxide SO_2.

As a case study, a day when accidental situation happened has been selected, 12. 6. 2011. Because of specific weather conditions the plume was spread over the city and CETI station suited at city center measured increased concentration of SO_2 near alarm value of 110 μg/m^3. At the same time, 9:00, the GEPSUS center, received by automatic link the source parameters from Command Room of TEPP and weather conditions from HMZCG, Table 1, Scenario 1-SC1. The simulation model was started showing a plume spreading and increased zone of SO_2 over the city area. The simulation of initial situation is displayed in Fig. 5. RED zone, Fig. 5d), is associated to 110 μg/m^3, Montenegrin alarm threshold, ORANGE to 50 μg/m^3, EU threshold and YELLOW 25 μg/m^3, half of EU standard. The WHITE line borders unsafe area.

Table 1: Input data for TEPP during accidental situation.

Parameter	SC1	SC2	SC3
Gas	SO_2	SO_2	SO_2
Emision rate Q[g/s]	918	918	918
Actual stack high hs [m]	250	250	250
Stack diameter Ro [m]	7.5	7.5	7.5
Ambiente temp. T (K)	286.6	298.5	290
Gas temp. on exit T (K)	413	413	413
Wind speed at ref. point ur (m/s)	1	3.2	2
Wind direction (deg)	225	18	315
Speed of polutant on exit wo (m/s)	6.3	6.3	6.3
Stability class	B	B	B
Terrain	Urban	Urban	Urban
Reflection	From ground	From ground	From ground
Source location (lat, lon)	43.334269,19.327522	43.334269,19.327522	43.334269,19.327522
Perimeter span PS [m]	1000	1000	1000
Angle span AS [deg]	90	90	90
Critical LOC [μg/m3]	110	110	110

At the same time the span perimeter SP and span angle SA for unsafe area are defined by emergency experts for purpose of evacuation (WHITE shaded region

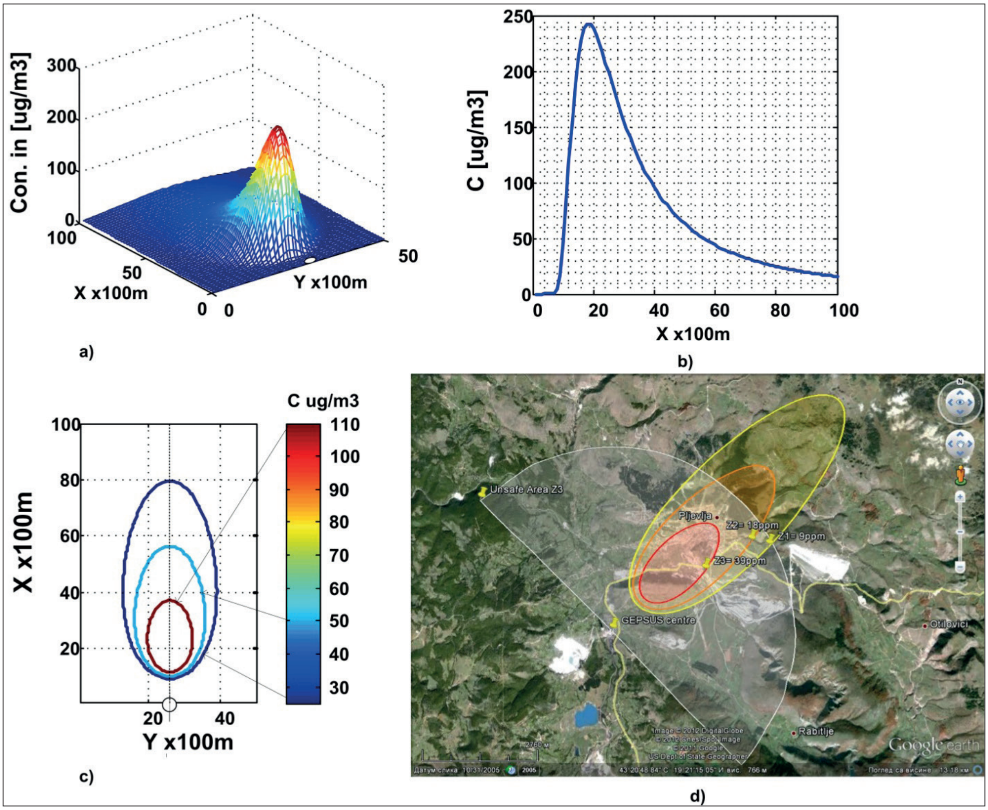

Figure 5: Simulation of scenario SC 1. a) 3D concentration plot on ground level, b) downwind profile, c) threat zones for 25 μg/m3, 50 μg/m3 and 110 μg/m3, d) threat zones plot over Google Earth with AS=90° and PS 1 km. Plume rise Δh=681 m, Xfinal=1110 m, speed on top of stack u=1.6207 m/s.

around RED zone, Z3(SC1)), Fig. 6. Simultaneously, taking in account weather prognosis from HMZCG the SC2 is overseen for next 3 hours, till 12:00. SC2 shows that wind speed and direction will change as well as temperature, Table 1, SC2. Unsafe area under SC2, Z3(SC2), moves to the region around Thermo Plant, with low population density but measures of protection need to be taken in area Z3(SC2). In 12:00 the actual weather conditions are taken, Table 1, SC3, showing difference in wind speed and direction obtained by prognosis and actual ones. However, with good definition of unsafe area the actual threat zone (RED in SC3) is still overlapped by unsafe area SC2 (See marker Unsafe Area Z3(SC3&SC2), Fig. 6).

CONCLUSION

The paper elaborates recent achievement in the GEPSUS project related to the simulation of hazardous gases releases in urban areas. The structure of the responding system from aspects of data importing, modeling and simulation unit, deci-

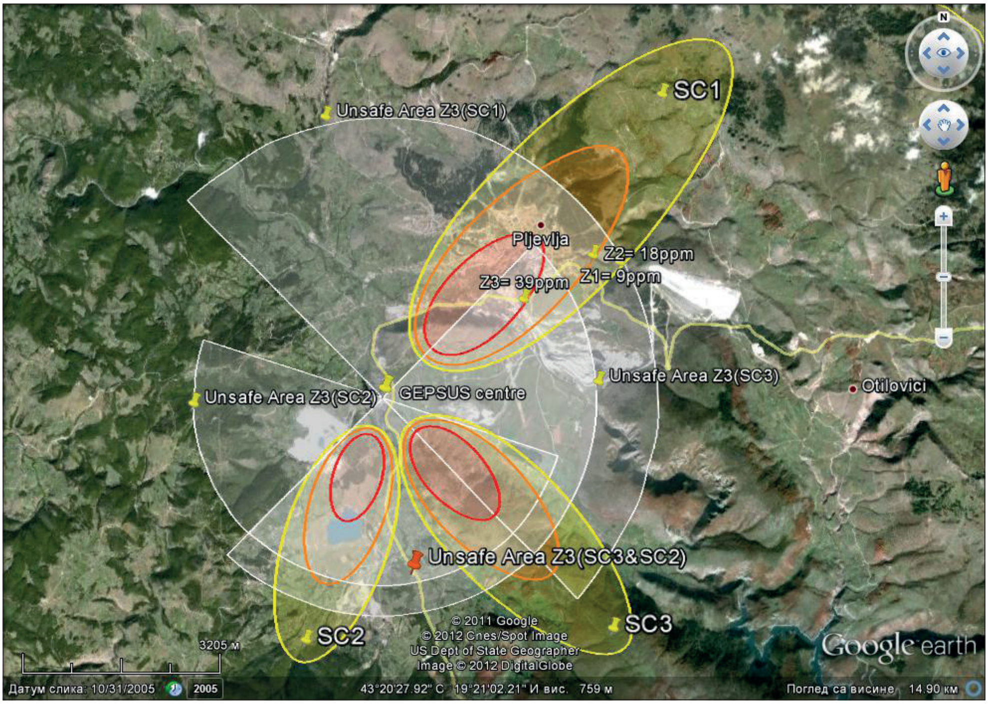

Figure 6: Scenarious SC 1, SC 2 and SC 3 together with unsafe areas.

sion making unit, graphical visualization over Google Earth as well as the results of testing and validation are presented. In case of accident, for purposes of emergency responders, the GEPSUS system is able to determine the threat zones, unsafe area and safe traffic routes. The system is GIS based, web-oriented and its services and outputs should be accessed by low cost ICT equipment that is of importance for developing countries like Montenegro. Hazardous gas releases is an unpredictable process, decision-making is uncertain. However, the GEPSUS tool can help in taking right decision. In future the system will be improved with additional features, consideration of different sources, automated data entry, and wider range of decisions.

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