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GEPSUS: Simulation-Based Decision Making System for Air Pollution Accidents

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We describe a GIS-based real-time system for emergency response and management of air pollution accidents in an urban area. The system architecture emphasises the integration of meteorological, chemical and GIS data, dispersion modeling, decision-making and geo-spatial visualization. The threat zones, unsafe areas and safe traffic routes are obtained using an improved Gaussian plume model with a decision-making module and then exported to the Google Earth browser via “kml” file format. Several simulation scenarios were conducted and verified for notable industrial sites in Montenegro using recorded meteorological data. The results demonstrate that emergency response authorities can use the proposed methodology and system as a cost effective and accurate support tool in case of industrial or deliberate air pollution incidents.

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

1 Introduction

When hazardous gases are released into the atmosphere, whether accidentally or due to a terrorist attack, emergency response authorities require quick and relevant information about the area(s) likely to be affected and anticipated injuries or mortalities. The process is time-critical because of the decision-making loop. This is especially so for urban areas where the population density compounds the potential magnitude of the consequences and complicates evacuation of both the injured and unaffected populace (Pontigia et al., 2010, Abbaspoura and Mansourib, 2005).

Hence there is a pressing need for emergency responders and other civil protection stakeholders to have access to a support system for hazardous gas releases, which will be based on the latest information and communication technologies (ICT). Current air pollutant modeling software applications such as MET, ALOHA, BREEZE, TRACE, SAMS etc. can be applied but provide only a partial solution (Baumann-Stanzer and Stenzel, 2010). 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 atmospheric conditions and source strength (De Amicis et al., 2009). In addition, they do not support automatic data importing, incorporation of weather forecasts and, most importantly, decision-making required for a successful response.

A useful system for management and control of accidental/deliberate releases of hazardous gases should at least be real-time with the possibility to integrate several subsystems to enhance response accuracy; a) Geographical Information System (GIS), b) system for measurement and monitoring of chemical parameters, c) system for hydrometeorological monitoring and forecasts, d) system for modeling gas dispersion, e) local sensor networks, and e) system for planning emergency responses forces (De Amicis et al., 2009). For many years such

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subsystem integration was a problem due to technological limitations in ensuring rapid and multifaceted data flow and complex modeling computations in real-time.

The GEPSUS (**G**eographical information processing for **E**nvironmental **P**ollution-related **S**ecurity within **U**rban **S**cale environments) project, funded by the NATO programme Science for Peace, presents one attempt in this direction to provide emergency responders with an integrated system for control and management of hazardous gases accidents, especially in urban areas. It integrates automatic data importing with GIS-based hazardous gas dispersion, simulation and decision-making.

In the present paper, emphasis is placed on accidents caused by industrial and transport facilities, which can be considered as emission point sources. During simulations, the real-time weather conditions are considered such as wind speed and direction as well as atmospheric stability. Decision making is made based on the calculation of threat zones, unsafe area and safe traffic routes. For system validation, Montenegro was selected, specifically several hazardous industrial objects. The same approach can be extended to other hazard sources such as transportation (train derailments, etc), large storage tanks, pipes etc., with small modifications in the dispersion model.

2 System architecture

The structure of the GEPSUS system is shown in Fig. 1. The GEPSUS computing facility is the core of the system, which communicates with inputs and generates the outputs. There are four major automatic 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 installations. The HMZCG collects automated current weather data and produces forecasts for a national network of weather stations in Montenegro and through the weather forecast models that are part of the European Community and international weather forecast networks. In addition, HMZCG has its own simulation and modeling capabilities including a High Performance Computing (HPC) Centre for generating forecasts for Montenegro every 3 hours at 1 km resolution. The CETI monitors actual air pollution conditions using a network of automatic telemetric stations measuring the concentration of main gases over Montenegrin cities. The REA provides updated geographical information about geospatial information taken from terrain and cadastral surveys and stored on public servers. GEPSUS communicates with HMZGC, CETI and REA over internet-supported protocol or leased lines. The GSN consists of mobile telemetric stations installed around critical installations. Primarily they measure the wind speed and direction as well as ambient temperature, and transmits data through a GSM network directly to the GEPSUS centre. In future these stations will be equipped with chemical sensors for early warning. HMZCG and CETI provide data on a 10 minute basis, while the GSN has 1 minute averages. GEO data

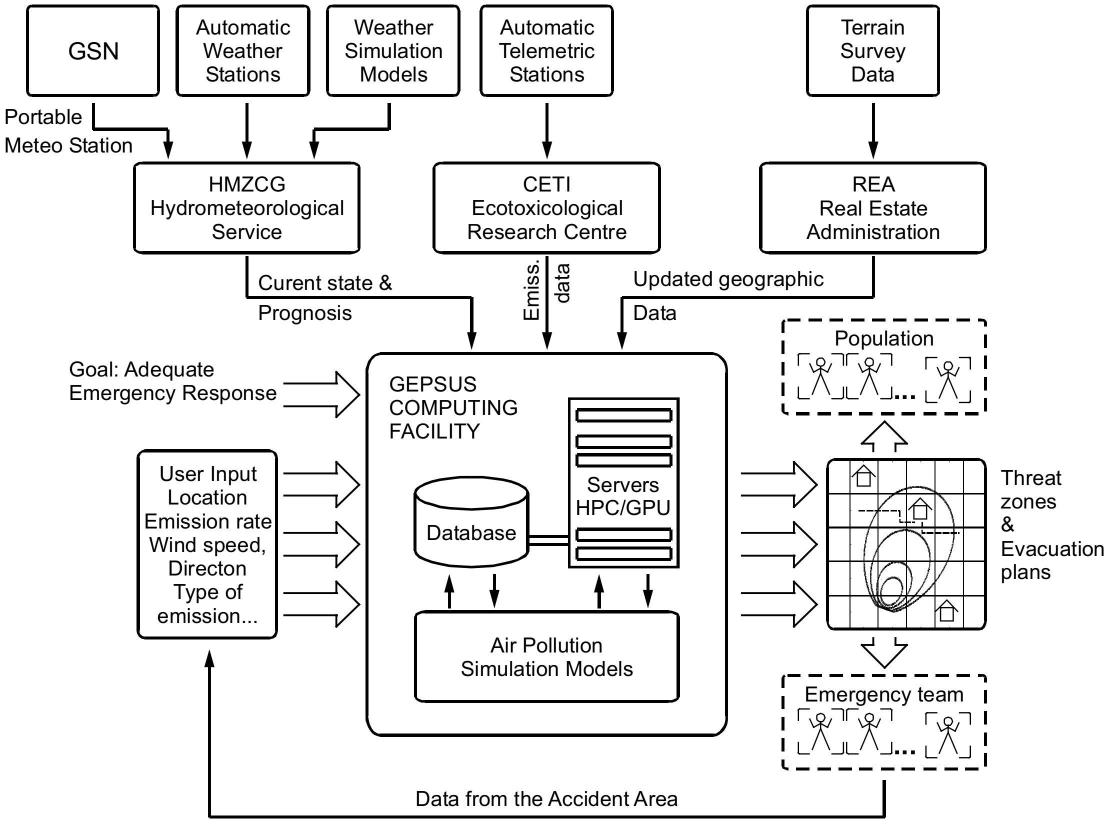

Figure 1: Architecture of the GEPSUS system

are updated on monthly scale or following important changes in geospatial information and hosts data about strategic buildings and areas such as hospitals, schools and public event areas with potentially high attendance (sports stadium, etc.).

The wind conditions (speed and direction) and their forecasts are considered as primary automatic data because the orientation and geometry of a release plume depends predominantly on them. The HMZCG provides wind conditions at a large scale, eg. for a city or region, while spot wind conditions are traced by local stations within the GSN which sends information in predefined formats readable by the GEPSUS application.

In addition to automatic inputs there are several manual inputs, usually entered by an operator or emergency expert. They provide more information about pollutant source(s) and atmospheric conditions as well the definition of the Levels of Concern (LOCs) – threshold levels of concentration in μg/m^3 or ppm. In future these inputs will also be automated. Source data includes accident location (latitude and longitude), description of the pollutant, type of gas and its characteristics, source type (point, line, area, tank or pipe) and its geometry (dimensions), emission rate, source height above aground, release duration, etc. Ground roughness, cloud cover, stability class, inversions, humidity and other parameters are weather conditions that are set manually. LOCs define the threat zones associated for each gas and they are usually standardized such as for 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 levels are 0.3 ppm, 3 ppm and 25 ppm, respectively. Here, other accurate information about an incident can be involved, provided by air pollution experts or rescue crew in the field, who can enter input parameters manually via mobile handheld devices. Fig. 1 does not explicitly show the Emergency room with appropriate servers and equipment where input data are handled and dispersion modeling and decision-making are performed.

3 Modeling and visualization

The dispersion modeling is performed in MATLAB starting from generalized Gaussian plume equation (Chitumalla et al., 2008):

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

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

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 $\sigma_y[m]$, $\sigma_z[m]$ and effective stack height H[m], which is a sum of actual stack height h^s[m] and plume rise Δh[m], $H=hs+\Delta h$. The ST is a summation term related to the inversion from mixing height z_i, while k is a 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 process.
- Wind blows in x direction which 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 towards several approximations, e.g. Pasquill's categories.
- The source emits Chemicals of Concern (COC) at a point in space x = y = 0 and z = H, where H is the effective height 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 wind speed 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 the x axis.

Retaining some of the above assumptions, the GEPSUS approach modifies Equation (1) with respect to two main elements:

1) Considering plume rise, Δh is spatially dependant and,
2) Replacing σ_y, σ_z with effective values $\sigma_{y_{eff}}$ and $\sigma_{z_{eff}}$.

3.1 Calculation of plume rise and effective dispersion coefficients

Two categories of smokestack plumes tend to occur: the vertical plume and bent-over plume (Fig 2). They form depending on several parameters such as: stability classes, wind speed,

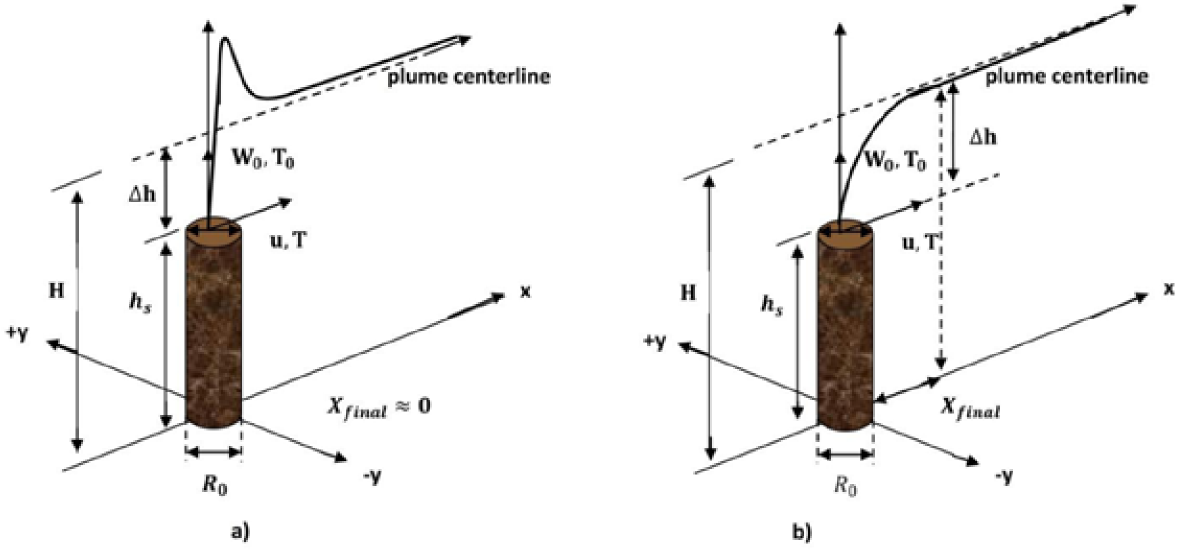

Figure 2: Direct plume (a) and bent-over plume (b).

exit speed of the gas, buoyancy flux parameter, etc. For example, in Pasquill 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.

The calculation of plume rise is based on a modified Briggs algorithm (Beychok, 2005) where Δh is calculated for two segments, before X_{final} - the point of maximum plume rise, and after X_{final}. Generally, Δh is a complex function and depends of numerous input parameters.

$$\Delta \mathrm{h} = \mathrm{f}(\mathrm{x}, X_{final}, \mathrm{T}, \mathrm{To}, \mathrm{u}, \mathrm{wo}, \mathrm{g}, \mathrm{Ro}, \frac{\Delta\theta}{\Delta T}, Stability\ Classes) \quad (3)$$

where:

x: downwind distance from plume source [m]

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

u: wind speed at actual stack height [m/s]

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

T_0: pollutant temperature at the source output [K]

T: ambient temperature [K]

W_0: pollutant exit speed at stack exit [m/s]

R_0: diameter of the stack [m]

g: gravitational acceleration [9,81m/s^2]

ΔΘ/ΔT: coefficient in [K/m] which depends on stability classes

The effective values $\sigma_{y_{eff}}$ and $\sigma_{z_{eff}}$ are calculated from dispersion coefficients σ_y and σ_z, taking into consideration the above parameters:

$$\sigma_{y_{eff}}, \ \sigma_{z_{eff}} = f(x, X_{final}, T, To, u, wo, g, Ro, \sigma_y\ \sigma_z\ ,\ Terrain\ Type) \quad (4)$$

where σ_y and σ_z are determined from Pasqual-Gifford dispersion coefficients (Briggs, 1965).

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

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

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

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

3.2 Visualization and interfacing to GIS

The overall program for calculation of pollutant concentration according to Equations (1) to (5) was developed in MATLAB and has an algorithmic structure, as given in Fig. 3. The function accepts input parameters and produces mid-term output in the form of a 3D concentration matrix *C'*(x,y,0) and the final output in the form of a set of contour matrices *Coi*(x,y), i = 1,2..n. In fact *Coi*(x,y) presents threat zones and is obtained as:

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

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

In order to be displayed by a GIS, the obtained threat zones need to be transferred into format readable by a Geo Browser. In GEPSUS, Google Earth (Tiwary and Colls, 2009) is used because of its wide availability, good graphical interface and possibility to run even on PDA devices. The "kml" file format is used as an interface between MATLAB and Google Earth (http://www.google.com/earth, Accesed, January 12, 2012). It is an open standard officially named the OpenGIS RKML Encoding Standard (OGC KML) (Google Earth, 2012) and is maintained by the Open Geospatial Consortium, Inc. (OGC). In addition the kml format can be read by a majority of GIS browsers. When kml files are produced from the application, such as MATLAB custom code, the format should be checked for errors with the XML validator against the kml schema. Before generating kml, the contour graphs (given in meters) should be transferred in latitude-longitude coordinates taking into account source position and then rotated wind angle. As a wind reference angle, north (N) is considered (). Coordinate transformation, rotation and kml forming are also implemented in MATLAB according to the algorithmic flow given in Fig. 3 (right-side).

4 Decision making

The determination of air pollution spread in urban areas is not the only content of the GEPSUS system. As was mentioned earlier, the important issue for emergency response authorities is decision-making. Usually, an individual or group must take decisions but, in many cases, techniques can help him to do so faster and with an increased capability of being more accurate (OpenGL, 2012). In this project phase two algorithms for supporting decision-making are considered:

1. Determination of an unsafe area and,
2. Proposing a safe traffic route between two points.

The unsafe area (UA) is associated with an unsafe perimeter and unsafe arc that are related to each threat zone. Three main parameters should be considered (Fig. 4 a): initial perimeter (P), initial angle (IA), perimeter span (PS) and angle span (AS). P is associated with each threat zone and presents the distance between source of emission and farthest point in the observed zone. PS is an extension of P produced by changing input parameters, wind speed, source strength, stability classes etc. AS is predominantly a function of wind direction (WD), while IA is associated with actual WD. As seen in Fig. 4a, the selected threat zone can rotate and translate from *(IA - AS)*^{O} to *(IA + AS)*^{O} and from *0 to P + PS*. As example is presented in Fig. 4a for IA = 270° and AS = 90°, P about 8 km and PS about 1 km. The emergency response group should evacuate people from unsafe areas without losing precious time. Using current parameters and weather forecasts, it is important to predict PS and AS as precisely as possible and for such purposes special algorithms and expert modules are used (Škraba et al., 2003). As an example, AS is determined from the standard deviation of WD.

As shown the UA overlaps the critical infrastructure such as roads, schools, student hostels and hospitals that are within the plume hazard area, as example 3 critical objects are covered by UA in Fig. 4a. The attributes of critical infrastructure are determined from emergency data base as well as evacuation instructions and plans. The GEPSUS system uses the records of emergency data base.

The second case concerns taking the shortest safe path in urban traffic. Namely, when an accident happens at some location the traffic needs to be redirected through the safe area. Here GEPSUS developed an algorithm for dynamic routing according to the criteria of the shortest path and safest area, based on an acceptable level of pollutant concentration. The

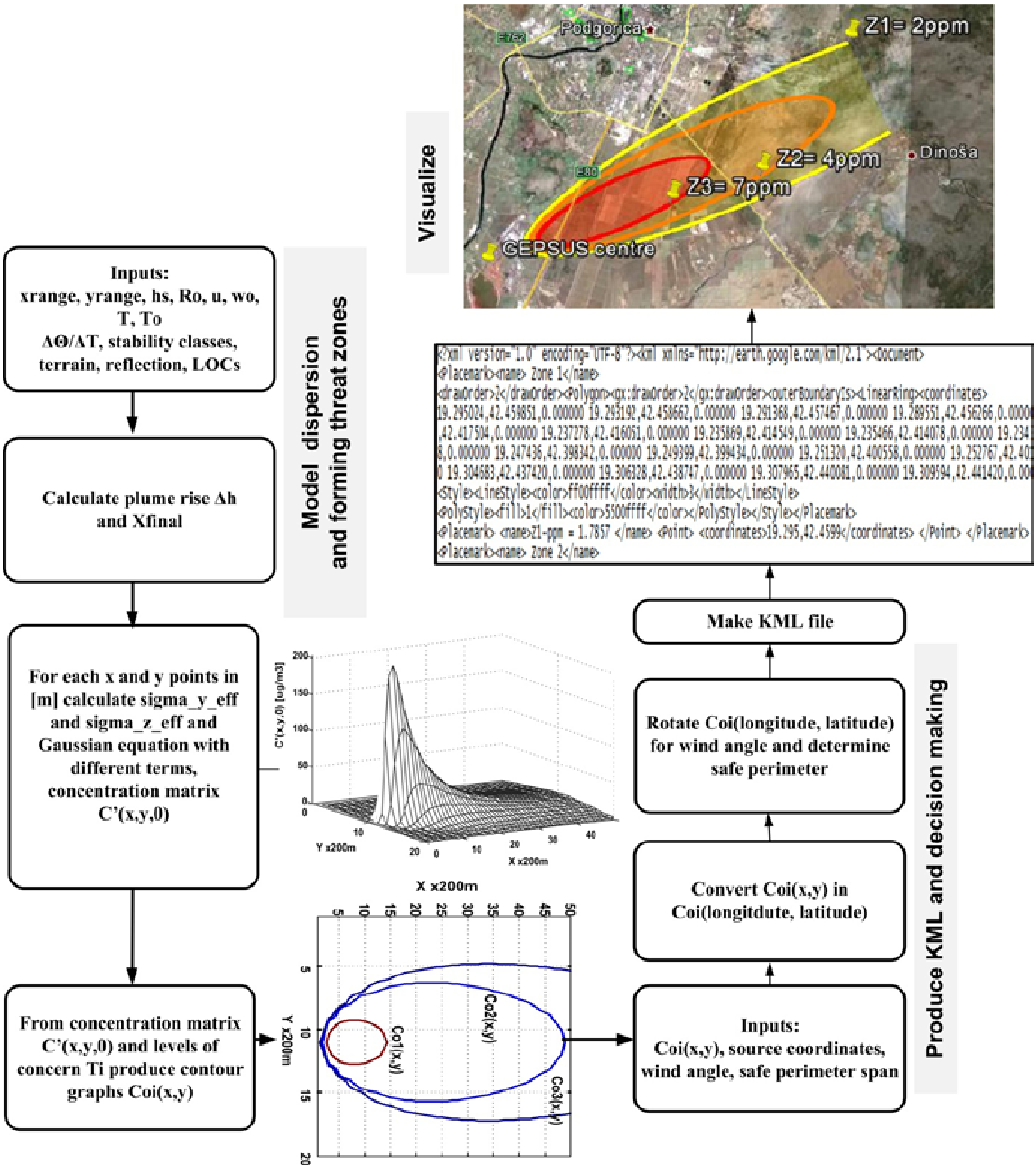

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Figure 3: Algorithmic structure of GEPSUS code for modeling and visualization; left side dispersion modeling, right side KML forming with decision-making functions.

algorithm searches for the shortest path between points A and B, Fig. 4b. Concentration thresholds determine the threat zone to be avoided and includes the following steps:

1. Select concentration limit and determine the threat zone
2. Get intersections (nodes) and roads (edges) of the observed area representing possible evacuation routes
3. Remove all nodes and edges inside the polluted area
4. Remove all edges intersecting the polluted area

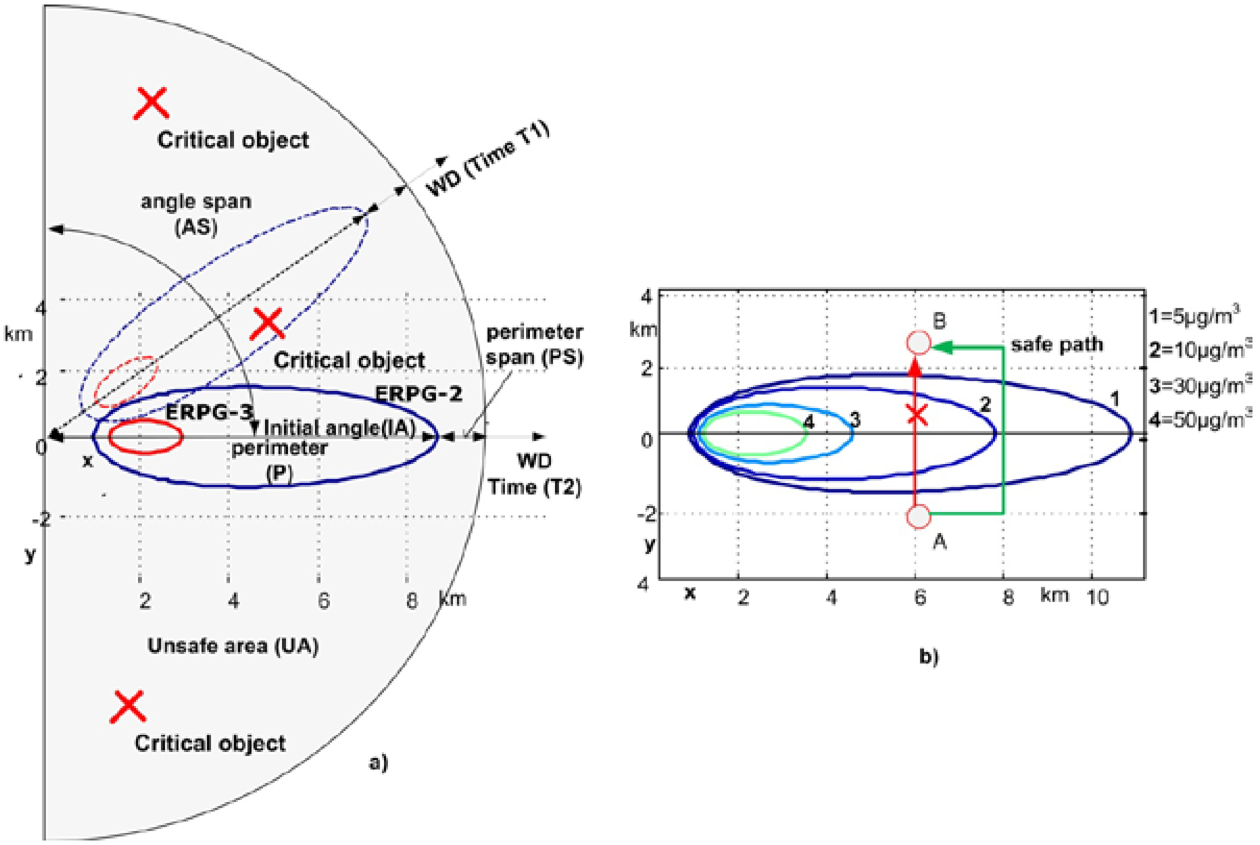

Figure 4: Decision making algorith: a) calculation of unsafe area, b) shortest safe path.

5. Construct a directed graph from remaining nodes and edges where the weight of the edges represents the distance between two nodes
6. Apply the Dijkstra algorithm (Kurashiki et al., 2005; Cormen et al., 2001) to solve the shortest path problem
7. Save shortest route in the kml format

Fig. 4b represents an example of the shortest path (green line) between points A and B. The concentration limit that should be escaped is zone “2” with concentration of 10 μg/m^3 and more.

5 Results and validation

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

As a case study, a day when an accident occurred at TEEP has been selected. Because of specific weather conditions, the plume spread over the city, and the CETI station situated in the city center measured increased concentrations of SO_2 near the alarm value of 110 μg/m^3, the level at or above which the general population could experience life-threatening health effects. At the same time, 09:00, the GEPSUS center, received by automatic link the source parameters from the TEPP Command Room and weather conditions from the 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 the initial situation is displayed in Fig. 5. The RED zone (Fig. 5d) is associated with 110 μg/m^3, (the Montenegrin alarm threshold), ORANGE 26-50 μg/m^3 (European Union threshold) and YELLOW 25 μg/m^3. The WHITE line border unsafe area was obtained by perimeter and angle spans.

In parallel the span perimeter SP and span angle SA for unsafe areas are defined by emergency experts for the purpose of evacuation (WHITE line around the RED zone) (Fig. 6). Simultaneously, taking into account weather forecasts from the HMZCG, SC2 is considered for the next 3 hours, until 12:00. SC2 shows that wind speed and direction will change as well as temperature (Table 1, SC2). The unsafe area under SC2 shifts to the region around the Thermo Plant, with low population density but measures of protection need to be taken in area SC2. At 12:00 the actual weather conditions are taken, Table 1, SC3, shows the difference in wind speed and direction as obtained by forecasts and actual data. However, with a good delineation of the unsafe area, the actual threat zone (RED in SC3) still overlaps with the unsafe area SC2 (See marker Unsafe Area Z3(SC3&SC2), Fig. 6).

Table 1: Input data for TEPP during an accident, June 12, 2011

Parameter	SC1	SC2	SC3
Gas	SO_2	SO_2	SO_2
Emision rate Q[g/s]	918	918	918
Actual stack height hs [m]	250	250	250
Stack diameter Ro [m]	7.5	7.5	7.5
Ambient temp. T (K)	286.6	298.5	290
Gas temp on exit T(K)	413	413	413
Wind speed at ref point u_r (m/s)	1	3.2	2
Wind direction (deg)	225	18	315
Speed of pollutant on exit (m/s)	6.3	6.3	6.3
Pasquill 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/m^3]	110	110	110

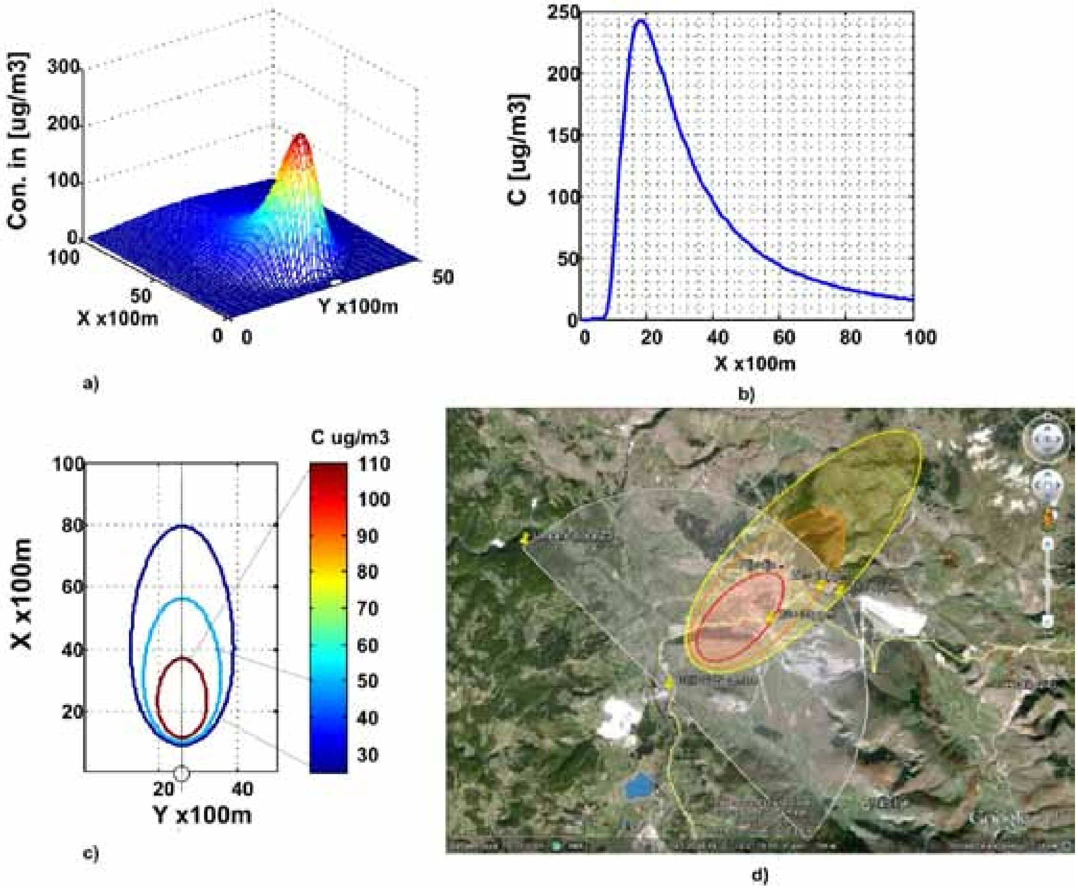

Figure 5: Simulation of scenario SC1: a) 3D concentration plot on ground level, b) downwind profile, c) threat zones for 25 µg/m^3, 50 µg/m^3 and 110 µg/m^3, d) threat zones plot over Google Earth with AS = 90° and PS 1 km. Plume rise (Δh) = 681 m, Xfinal = 1110 m, speed on top of stack u = 1.6 m/s

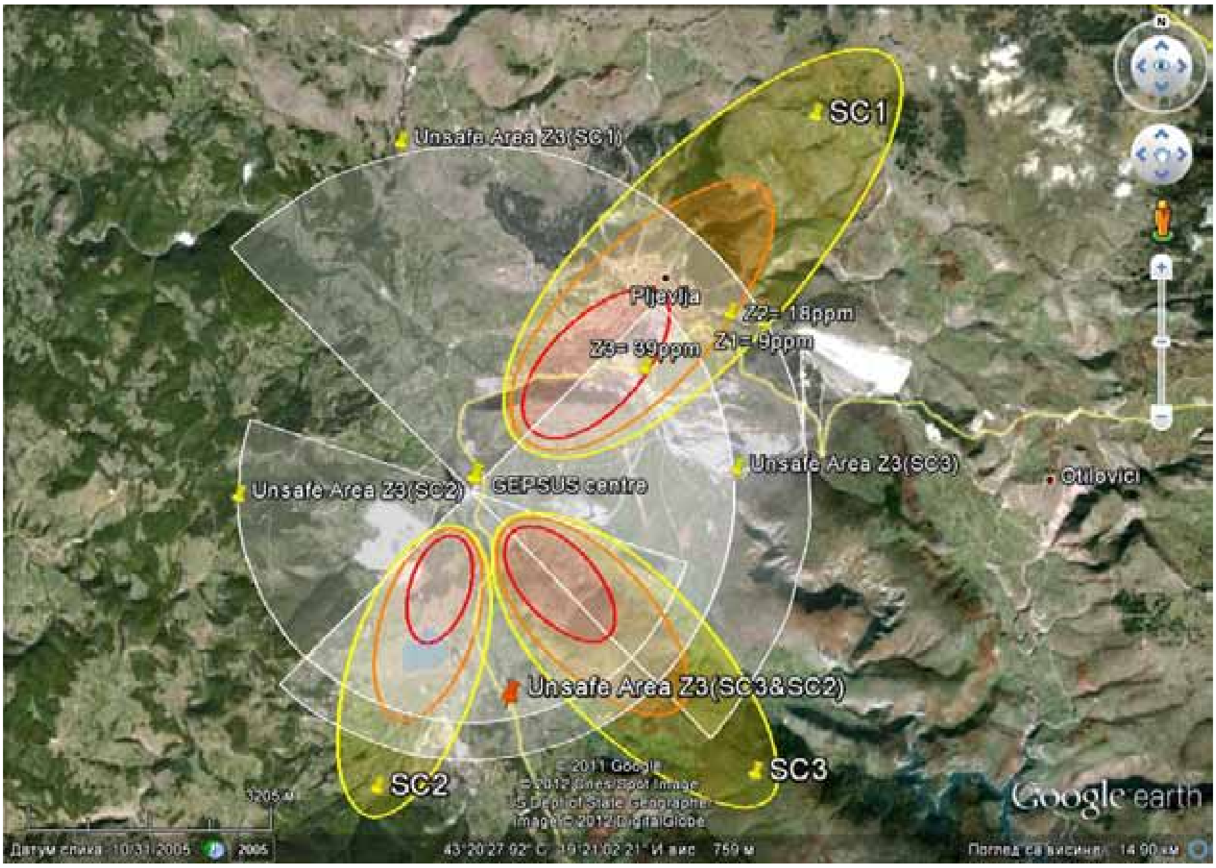

Figure 6: Scenarios SC1, SC2 and SC3 together with unsafe areas

Table 2: Parameters for the release accident at KAP

Parameter	Type/value
Gas	SO2
Emision rate Q [g/s]	200
Actual stack height hs [m]	62
Stack diameter Ro [m]	2.1
Ambient temp. T (K)	301.5
Gas temp on exit T(K)	498
Wind speed at ref point (m/s)	2
Wind direction (deg)	210
Speed of pollutant on exit (m/s)	42.3
Pasquill stability class	B
Terrain	urban
Reflection	from ground
Source location (lat., long.)	42.389000, 19.218797
Critical LOC [μg/m^3]	50

The second simulation example concerns the shortest traffic route for the case of an uncontrolled SO_2 emission from the Aluminum Plant Podgorica (KAP) (Fig. 7), the main polluter in the region of the Montenegrin capital city, Podgorica. The concentration limit was set to the EU standard of 50 μg/m^3 (18 ppm) and because of increased SO_2 emissions (normally less than 50 g/s) and weather conditions, the RED zone spread over the city. Table 2 shows the source parameters and

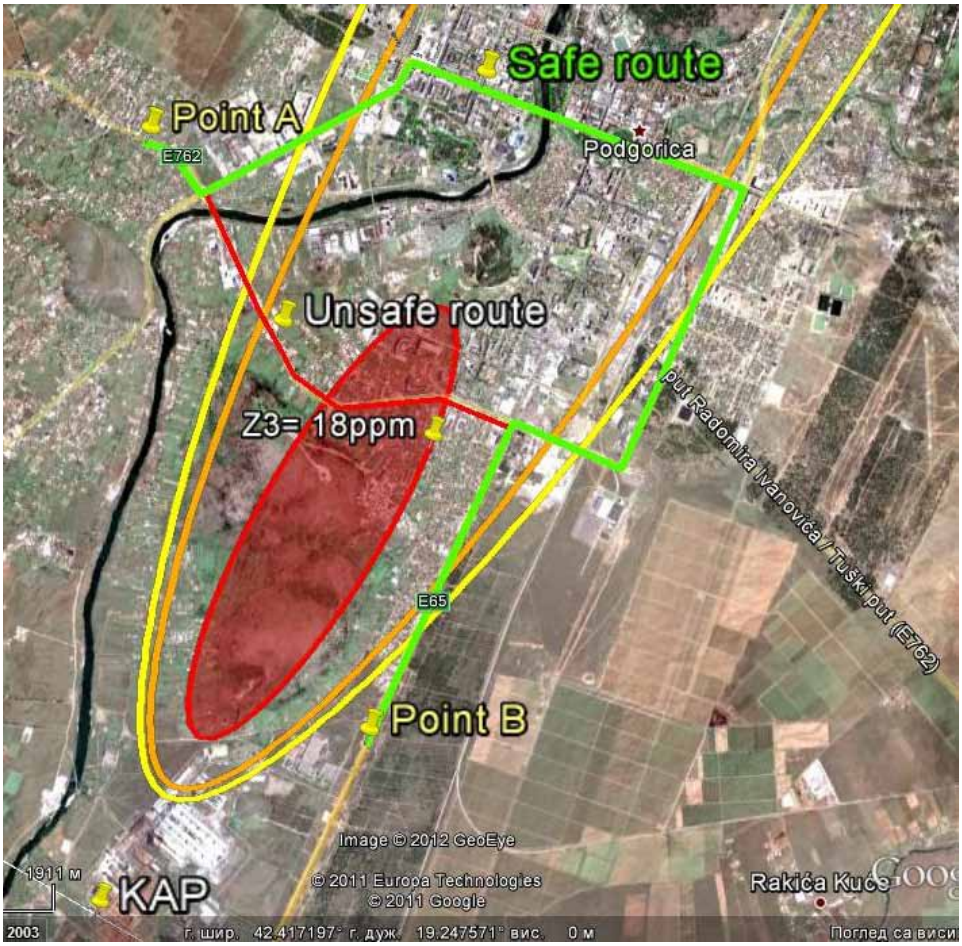

Figure 7: Shortest traffic path in case of an accident at the KAP

weather conditions. In addition to evacuation from the RED zone, the traffic through this zone must be redirected towards the shortest safe route. The driver travels from Point A (road E762) to Point B (road E65). Normally, the shortest way is going through the RED zone (red color path – Unsafe route). The GEPSUS system calculates the Safe route (green path), according to the algorithm given in Section 4, and police patrols redirect traffic on this route.

6 Conclusions

The paper elaborates upon recent developments in the GEPSUS project related to the simulation of hazardous gases releases in urban areas. The structure of the response system from aspects of data importing, modeling and simulation, decision-making, graphical visualization over Google Earth, as well as the results of testing and validation are presented. In case of an accidental or deliberate atmospheric release, the GEPSUS system is able to determine the threat zones, unsafe area and safe traffic routes for purposes of emergency responders. The system is GIS based, web-oriented and its services and outputs can be accessed by standard ICT equipment. Hazardous gas releases is an unpredictable process and thus decision-making has its own uncertainties. However, the GEPSUS tool can support improved decision-making. In future the system will be enhanced with additional features in terms of hazard sources, automated data entry, and a wide range of decision options.

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