Modelling and Simulation of Accidental Air Pollutant Dispersion in Urban Areas – an Approach Suitable for Developing Countries

Živorad Kovačević, Radovan Stojanović, Gojko Nikolić
Faculty of Electrical Engineering in Podgorica
University of Montenegro,
Podgorica, Montenegro
stox@ac.me, Zika12@gmail.com,

Abstract— **In this paper an idea of using commercial, low cost software for simulation of air pollution dispersion over complex terrain is presented. The modified Gaussian equation is used as well as custom design software pre-processor, needed to prepare elevation image. The case study with terrain map of city Podgorica, Montenegro, with elevation and embedded urban area is presented. The simulation system, named Z-plume is very suitable for developing countries since request low cost and widely available, GIS software as Global Mapper and mathematical tool as MATLAB. The approach is mainly based on the research and technical results from NATO GEPSUS project [1].**

Keywords – air pollution, hazardous gases, software simulation, Gaussian equation, GEPSUS

I. Introduction

When hazardous gases are released into the atmosphere, whether accidentally or due to terrorist attacks, emergency response authorities and other responsible bodies require quick and relevant information about affected populations and infrastructure. The process is time-critical, especially in urban areas, because of population density and consequences of a delayed response.

The Great Smog of ’52, The Seveso Disaster’76, Island Nuclear Explosion’79, The Bhopal Disaster’84, The Three Mile, The Kuwait Oil Fires’91, The Chernobyl Nuclear Explosion’86, Phillips Disaster’89 are only few of the examples of man-caused disasters that resulted in uncontrolled emission of pollutants and losses in lives and properties [2]. Hence, there is a pressing need from emergency responders and other civil protection stakeholders to have access, inter alia, to support systems for modeling, simulation and visualization of hazardous gas releases through space and time. Such systems should include all available emerging technologies including various hardware and software tools.

Recently, numerous air pollutant modeling software have been developed such as ALOHA, MEMPLEX, Breeze, SAFER, SAM, and TRACE that can integrate in themselves different dispersion models like SCREEN3, AERSCREEN, AERMOD, ISC3, CALPUFF, ROADS, HISPLIT, DEGADIS, SLAB and others. However, these pollutant modeling software provide only a partial solution. They predominantly model off-line gas dispersion over simple terrain (2D space). The graphical presentation of calculated threat zones (plumes) are mainly static and do not consider real-time changes of atmosphere (weather) and source (strength, type etc.). Also, the complex terrain, elevation and urban infrastructure are not taken in consideration.

The idea of modeling gas dispersion is almost 100 years old. The main objective was to assess the spread of toxic chemicals discharged on battlefields. The purpose was extended to dispersion of hazardous gases in industrial areas. In the beginning, the calculation was done manually, using simple tables and graphs. Today, computer packages and powerful processors are employed. There are a number of different types of models for modeling gas dispersion. The selection of the appropriate one depends on the specific application, space and atmospheric conditions and problem dimension as well of the available input and output parameters and calculation speed.

Generally, the dispersion models can be divided into two groups: physical models and mathematical models. Physical models simulate real phenomena in significantly reduced conditions like in the laboratory (such as models of wind tunnels, etc). They discover mechanisms of dispersion and provide validation data obtained by mathematical models. Mathematical models are a set of analytical numerical algorithms that describe the physical and chemical aspects of the problem and can be further divided into deterministic models and statistical models. Diffusion of gas pollutants can be numerically simulated, within deterministic approach, using Eulerian, Langrangian and Gaussian models. Eulerian and Langrangian models track the movement of a large number of particles of pollutants from their initial location [3]. Eulerian reference system is fixed (relative to the ground) while Langrangian tracks the movement of the wind. Gaussian models are a combination of Eulerian and Langangian. The Gaussian model is perhaps the oldest (circa 1936) and perhaps the most commonly used model type [4]. It assumes that the air pollutant dispersion has a Gaussian distribution, meaning that the pollutant distribution has a normal probability distribution. Gaussian models are most often used for predicting the dispersion of continuous, buoyant air pollution plumes

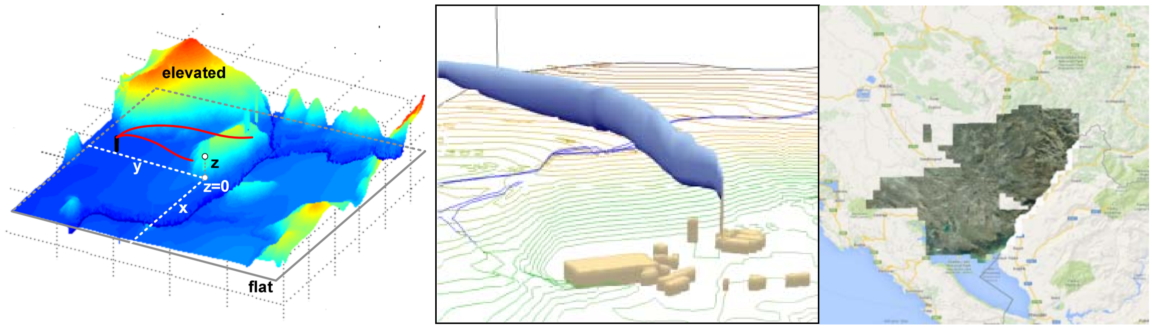

Figure 1. Complex terrain, elevation map, elevation map + urban architecture, LIDAR data

originating from ground-level or elevated sources. Gaussian models may also be used for predicting the dispersion of non-continuous air pollution plumes (called puff models).

II. Z –PLUME APPROACH

Although the derivation of the Gaussian Plume model assumes ideal conditions such as an infinite, flat, homogeneous area, the Gaussian plume model can be used to predict concentrations at receptors in complex, elevated terrain, Fig. 1 (left). Complexity should include elevation or urban infrastructure, Fig. 1 (middle panel), or both Fig. 1 (right). There are several ways to account for these effects. The models SCREEN3 and ISC3 are both similar in their approach to terrain modelling. The approach used in AERMOD is more sophisticated. In all these models, the vertical distribution function is affected. The CALPUFF model allows the mechanism for lateral deflection of the plume due to terrain. GEPSUS modified this approach from ISC3.

Generally seen the Gaussian dispersion equation can be expressed as:

$$C(x,y,z)=A\cdot V\cdot H \quad (1)$$

Where:

$$A=(Q*CORR*K)/(2\pi u\delta_y\delta_z) \quad (2)$$

$$H= e^{-\frac{y^2}{2\delta_y^2}} \quad (3)$$

$$V=\left(e^{-\frac{(z-H)^2}{2\delta_z^2}}+e^{-\frac{(z+H)^2}{2\delta_z^2}}\right) \quad (4)$$

$$CORR=(400-(z-Hef))/400 \quad (5)$$

For $z>H_{ef}$; CORR=1 for $z<=H_{ef}$;

$$Hef=z_0-(1-f_t)*(z-z_s)=H+d_h-(1-f_t)*(z-z_s) \quad (6)$$

For f_t=0.5, for stability categories A-D and f_t=0, for stability categories E, F.

and:

- Q - pollutant emission rate,
- K - units scaling coefficient,
- X - downwind distance from source centre to receptor measured along plume axe,
- Y - lateral distance from plume axe to receptor,
- Z - attitude in receptor position,
- z_s - attitude of the stack base,
- δ_y, δ_z - dispersion coefficients along x and z axis,
- H - stack high,
- d_h - plume rise,
- f_t - terrain adjustment factor.

The above terms are derived from a modified Gaussian equation taking in account complex terrain adjustments according to the ISC3 model [5,6]. As seen, V and CORR are the terms which depend on z.

III. RESULTS - EXAMPLE OF Z-PLUME APPROACH

In order to improve the Z-plume model the precise elevation of the terrain including urban area features (buildings, streets etc.) has been considered (Fig. 2), detail of city Podgorica in Montenegro. In addition to the characteristics of source, the following GIS attributes are used as a system input: Elevations for each point (Z), Projections, North-West corner of terrain area (Long, Lat), North-West corner of considered urban area (Long, Lat), Pixel Spacing-X (meters), Pixel Spacing-Y (meters), X size of terrain area (meters), Y size of terrain area (meters), X size of urban area (meters), Y size of urban area (meters).

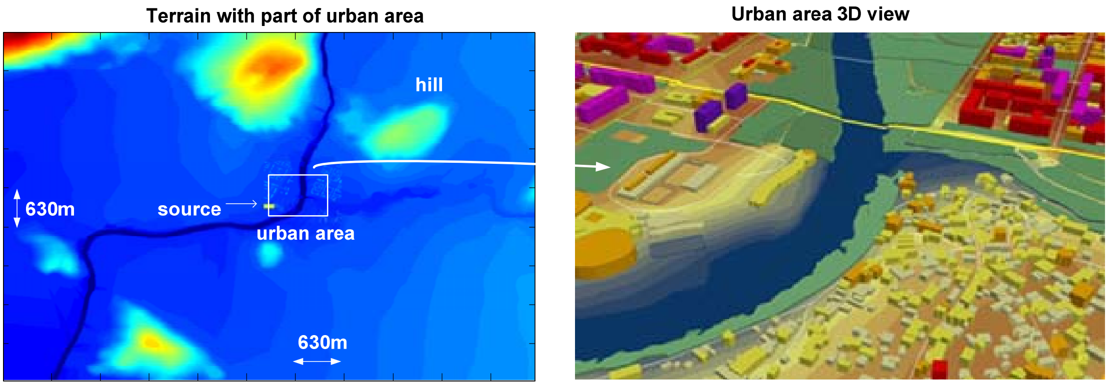

Figure 2. Terrain map of Podgorica with elevation (left) and embedded urban area (right)

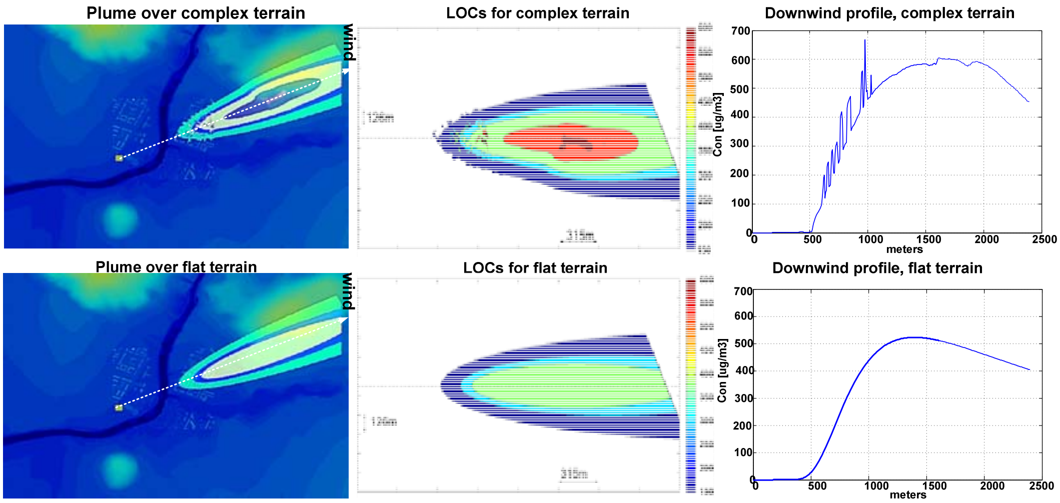

Figure 3. Comparison of air pollution dispersion in case of complex and flat terrains. Effects obtained by improved Z-Plume software version

The analysis of dispersion effects over complex and flat terrain have been performed using the Equation 1, of course, after implementing a test software in MATLAB. Fig. 2 shows some of the results. Sub-figures in the left column present different geometrical shapes of Level of Concerns (LOCs) for flat and elevated terrain. This is more clearly represented in the sub-figures, middle column. When complex terrain is considered, five levels of LOCs are detected. The LOCs for flat terrain shows only LOC1 to LOC3 (blue, light blue and light green colours). Sub-figures in the right column represent downwind profiles for complex and flat terrain.

TABLE I. NUMERICAL OUTPUT OF GEPSUS SYSTEM AS AREA FOR PARTICULAR LOC AREA

LOC	Flat terrain, area affected [m^2]	Complex terrain, area affected [m^2]
LOC1	0	11790
LOC2	0	164320
LOC3	361620	309700
LOC4	169640	141260
LOC5	354310	324550

Then the overlapped terrain is examined in term of areas in square matters affected by denoted levels of concern. The differences can be seen in Table 1 and Table 2 which show numerical output of Z-plume system for LOC1-LOC5 where the affected area in m2 is reported for flat terrain as well as complex terrain. When, in the model, flat terrain is considered, the area affected for LOC1 and LOC2 is 0 m2 while when the developed model for complex terrain is used, this area is rather significant for LOC1, 11,790 m2 and LOC2 164,320 m2. The LOC3 area when the model for flat terrain is used is 361,620 m2 and is larger than in the case where complex terrain model is used, 309,700 m2, due to undetected LOC1 and LOC2 areas. LOC4 (red) and LOC5 (cafe) also differ mainly due to different accuracy of the applied models.

TABLE II. NUMERICAL OUTPUT OF GEPSUS SYSTEM AS AREA FOR LOC WHEN ONLY URBAN AREA IS CONSIDERED

LOC	Flat terrain, urban area affected [m^2]	Complex terrain, urban area affected [m^2]
LOC1	0	516
LOC2	0	1310
LOC3	11748	20559
LOC4	19805	20321
LOC5	59217	57471

Table 2 shows the size of urban area affected. Here the urban area territory 1000 m x 1000 m is considered. In the urban area, which is of the greatest concern due to the exposed population, the area of LOC1 and LOC2 is reported as 0 m^2. When the complex terrain model is used, the area of LOC1 is given as 516 m^2 and the area of LOC2 as 1310 m^2. The area of LOC3 is also given as larger in the case of complex terrain model indicating a larger area exposed to the LOC3 levels. LOC4 and LOC5 in this case also differ mainly due to the different accuracy of the applied models.

The results of Z-plume model (LOCs) could be exported in KML format and integrated in any GIS browser, like Google Earth, using an approach described in [7]. Fig. 4 shows the example of dispersion in urban area and influence of a hill.

Figure 4. Z-plume model exported in KML and its visualization over Google Earth

IV. SOFTWARE PREPROCESSOR FOR Z-PLUME MODEL

In order to adopt Z-plume for stand-alone application, several modifications should be performed. They are related to importing images of elevation terrain using the designed software preprocessor. Fig. 5 shows the preprocessor tasks needed to prepare elevation image. The final aim was to compose elevation matrix of terrain including urban architecture in the form XYZ, where Z is elevation in meters and XY projections. For pre-processing a MATLAB based GUI is used.

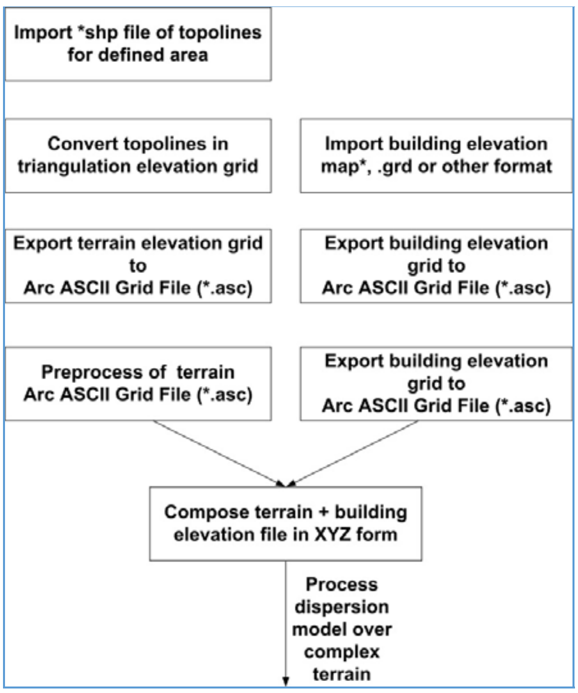

Figure 5. Preprocessing algorithm for composing complex terrain in XYZ form

V. CONCLUSIONS

The modified Gaussian equation can be used for air pollution dispersion over complex terrain are presented. Software preprocessor based on widely available low costs software can be composed to prepare elevation image. The case study with terrain map of city Podgorica, Montenegro, with elevation and embedded urban area is presented. It is obviously that such system is suitable for developing countries, like Western Balkan Region, especially Bosnia and Herzegovina with many examples of complex terrains.

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