

Three-dimensional visualization of harmful gas diffusion in an urban area

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Abstract. This paper simulated a harmful gas diffusion in an urban area. Based on the Gaussian Plume Model, the simulation was performed in the 3D virtual environment of the Digital Earth Scientific Platform, which was established by the Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences (CAS). This paper calculated the spread distance of harmful gas in every direction and the concentration of a certain point near to the accident point. The spread range of the gas with same concentration could be drawn in the scene and the 3D range affected by the gas diffusion accident also could be performed as well. The result showed that combining the Gaussian Plume Model with GIS technology we can show the affected range clearly in the scene by using curved surface with different color and transparency, which was much better than the common two-dimensional visualization. Besides, this paper also discussed the way to count the number of people who might be affected by the harmful gas, trying to make sense in emergency evacuation and city planning.

1. Introduction

With the development of chemical industry, the security of harmful chemical material has attracted more and more attentions. Air pollution models find their greatest application in the implementation of air quality monitoring and environmental protection. Based on analytical formulas of plume distribution, the Gaussian Plume Model (GPM) is a widely used air dispersion model for the estimation of ground level pollutant concentration arising from smokestack emissions[1].

As a powerful data management and spatial analysis tool, the Geographic Information System (GIS) can help a lot when simulating gas diffusion. Combining GIS and GPM, we can draw the diffusion area on the digital map and do some diagnosis and prognosis of gas diffusion efficiently. A lot of work has been done base on GIS and GPM[2,3,4]. However, the two-dimensional Geographic Information System (2DGIS) can't show us the height information so we can't see how high the harmful gas will disperse and how wide the harmful gas will affect in the 3D world. Comparing with 2DGIS, the Digital Earth System seems to be more vivid and closer to the real world, while researches on visualization of gas diffusion based on a Digital Earth System are really rare. It will be significant to simulate the harmful gas diffusion and to do some spatial analysis in a Digital Earth System.

Established by the Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences (CAS), the Digital Earth Scientific Platform (DESP) is an immersive computing environment with rich functionalities featuring interactive operation, coordinated work mode, data services and representation capability of earth spatial information simulation. Based on DESP and GPM, the simulation of harmful gas diffusion and overlay analysis are performed in this paper. The

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basic equations and diffusion parameters for the GPM are presented firstly, followed by the methods for visualization of gas diffusion in the 3D virtual environment. Then the simulation and analysis results in the DESP are developed, and finally we get some conclusions and extensions.

2. The Gaussian Plume Model

2.1. Symbols used

Table 1. Symbol used in the GPM.

Symbol	Discription	Symbol	Discription
$\pi=3.14$ (-)	mathematical constant	σ_y (m)	crosswind diffusion parameter
C (mg/m ³)	downwind concentration	σ_z (m)	vertical diffusion parameter
Q_m (mg/s)	gas source emission rate	x (m)	downwind distance from source
u (m/s)	mean horizontal wind speed	y (m)	horizontal distance from plume centre
H (m)	effective height of plume	z (m)	height above the surface

2.2. Equations and diffusion parameters

The Gaussian Plume Model is simple and flexible enough to visualize gas diffusion and it provides a reliable framework for the correlation of field diffusion trials[5]. The GPM is formulated as[6]

$$C(x, y, z, H) = \frac{Q_m}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left[\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right] \right] \quad (1)$$

This equation computes the atmospheric concentration at a given point (x, y, z) downwind from the gas source location. The values of Q_m , u can be set according to the situation of gas diffusion accident. H is equal to the sum of the physical stack height H_0 and the plume rise ΔH which depends on different environmental conditions (temperature, air stability *et al.*)[7][8].

The diffusion parameters (σ_y and σ_z) depend upon many factors such as downwind distance(x), atmospheric stability, ground roughness and so on. The atmospheric stability and classes can be picked using the rules presented by Pasquill stability classification scheme [9].

The ground roughness (Z_0) can be classified by the rules in table 2[10].When the ground roughness is less than or equal to 0.1 ($Z_0 \leq 0.1$) the diffusion parameters can be computed by the Briggs' formulae [2]. While $Z_0 > 0.1$ the diffusion parameters should be modified to make them work well [10].

Table 2. Ground roughness classification scheme.

Ground type	Z_0 (m)
Grasslands, open county	0.1
Crops	0.1-0.3
Village, sparse woods	0.1-3
Sparse and low buildings(small city)	1-4
Clustered and high buildings(metropolis)	4

3. Methods for Visualization

3.1. Coordinate transformation

Some different coordinate systems will be used while simulating the gas diffusion.

- *The GPM Coordinate System.* All calculation related to the Gaussian Plume Model will be executed in the GPM Coordinate System. It is defined like this: the origin is the gas source on the ground, the X axis points to the mean horizontal wind direction, the Y axis is vertical to the X axis and the Z axis is up to the ground.

- *The World Coordinate System.* This is a virtual but essential coordinate system defined in 3D engine. It is the origin of different coordinate systems. The X axis points to right, the Y axis points into the screen and the Z axis goes up to form a right hand coordinate system.
- *The GCS_WGS_1984.* It's the most commonly used globe coordinate system which describes our world by latitude, longitude and height. It's the coordinate system used in DESP as well.
- *The Local Coordinate System.* It links the GPM Coordinate System and the World Coordinate System. The origin is the same as the GPM Coordinate System, the X axis points to the east from the gas source, the Y axis points to the north and the Z axis is up to the ground.

The DESP provides some functions to transform coordinates between the world coordinate system and the GCS_WGS_1984. We can also get the transformation matrix when locating models from the local coordinate system to the DESP. As shown in figure 1, the GPM coordinate system and the local coordinate system have a rotation of θ , which is the angle between the mean horizontal wind direction and the east ($\theta \in [0, 360]$). The transformation is given by

$$\begin{bmatrix} x_L \\ y_L \\ z_L \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_G \\ y_G \\ z_G \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} x_G \\ y_G \\ z_G \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_L \\ y_L \\ z_L \end{bmatrix} \quad (3)$$

where $(x_L, y_L, z_L)^T$ is the coordinate in local coordinate system and $(x_G, y_G, z_G)^T$ is the coordinate in GPM coordinate system.

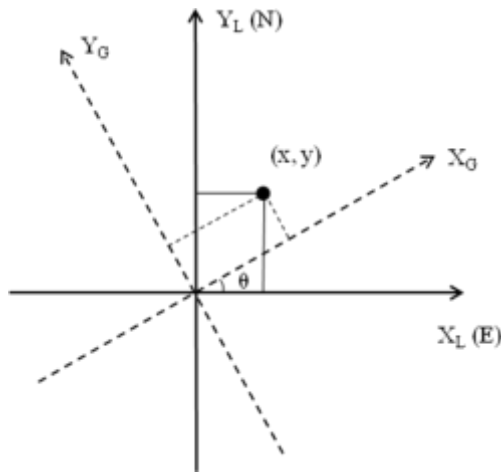


Figure 1. The GPM coordinate system (dotted line) and the local coordinate system (solid line).

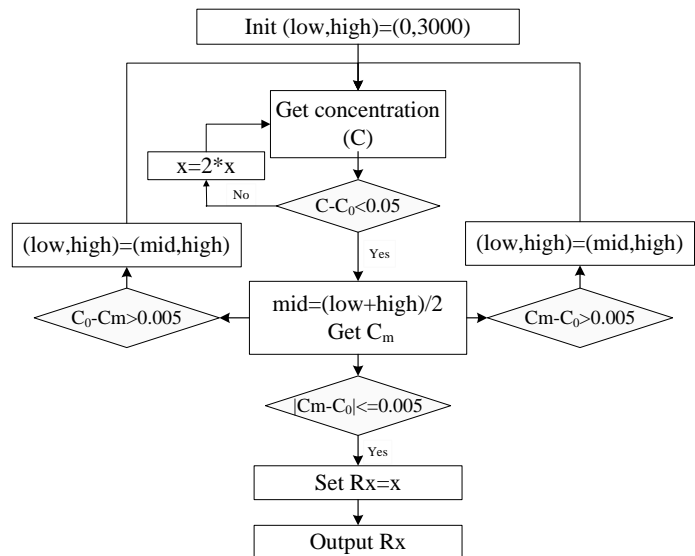


Figure 2. Compute R_x using bisection method.

3.2. Calculation of diffusion distances

When given a certain concentration (C_0), all coordinates satisfied $C = C_0$ can be calculated out by equation (1) and these coordinates will form a closed area which shows the diffusion range of harmful gas. The maximum diffusion distance in every axis is the most representative characteristics to describe the gas diffusion range. The maximum diffusion distance in the mean horizontal wind direction (R_x) can be computed using bisection method (see figure 2). Calculation process of horizontal distance from plume centre (R_y) is shown in figure 3, where N is a threshold to make sure

R_y is the maximum of all the y-coordinates when $C = C_0$, $Center$ is the x-coordinate when $y = R_y$. Calculation process of height (R_z) is similar to that of R_y .

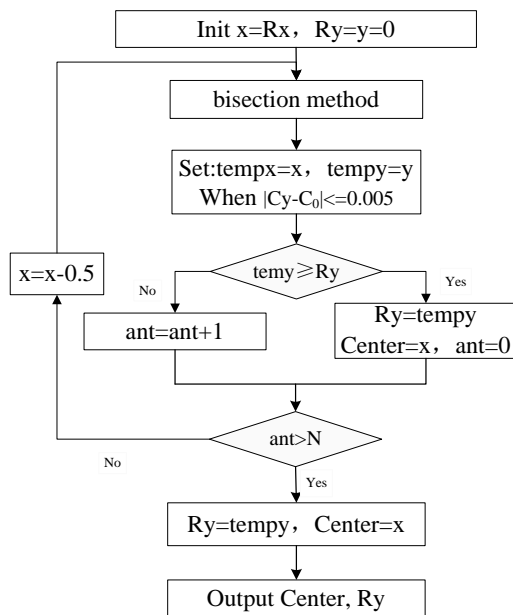


Figure 3. Algorithm of computing R_y .

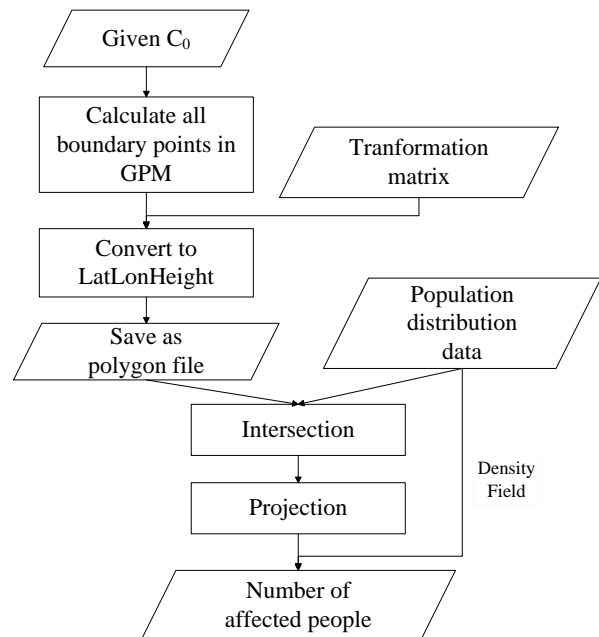


Figure 4. The pipeline of calculating affected population.

3.3. Calculation of affected people

After calculating all the coordinates satisfied $C = C_0$ we convert them to the GCS_WGS_1984 and then save them as a polygon shapefile (*.shp). Another shapefile containing population distribution information is needed to do some intersection with the diffusion polygons and it should have a coordinate system of GCS_WGS_1984 as well. Once we convert the intersection result to corresponding projection coordinate system, the total number of affected people can be given by

$$N = \sum_{i=1}^n S_i * \lambda_i \quad (4)$$

where n is the number of polygons in the intersection result, S_i and λ_i are the area and population density of the i th polygon. The pipeline is shown as figure 4.

4. Simulation in the DESP

When simulating the diffusion of harmful gas in the DESP, user should get an accident point firstly by clicking somewhere on the screen, and then set the parameters that are taken into consideration (see table 3). To get the concentration at a certain point downwind from the gas source location, just click the point in the scene and the DESP will calculate the concentration and then show it out in a textbox.

Table 3. Parameters tested in the DESP.

Parameter	Value	Parameter	Value
Emission rate	650000	Emission temperature	30.0
Stack diameter	1.5	Ambient air temperature	20.0
Emission velocity	6.0	Atmospheric stability	3.2
Wind speed	3.0	Ground roughness	B
Wind direction	30.0		

To simulate the diffusion ranges affected by different levels of harmful gas, the DESP will draw some curved surfaces with different colors and transparencies according to the diffusion distances calculated on the three axes. The more transparent surface means the lower concentration. Taking SO₂ as an example the system simulated the diffusion ranges in six levels. The affected ranges are shown as figure 5. Some other results are listed in table 4.

**Figure 5.** Diffusion ranges affected by different levels of harmful gas.**Table 4.** Calculation results in the DESP.

Concentration	R_x	R_y	R_z	Maximum height	Affected population
796	30.2895	5.7	5.7	21.4941	126
99	101.44	16.6	15.5	31.2941	901
40	184.044	30.2	22.5	38.2941	2865
6	529.175	94.2	72.5	88.2941	7795
4	656.25	117	91.3	107.094	12841
0.6	1792.97	310.7	256	271.794	40199

Here $H = 6.8m$ and $\Delta H = 9m$

From figure 5 we can see that curved surfaces with different colors and transparencies can show the diffusion range clearly. We can easily recognize which level a building belongs to, where the gas will diffuse in three-dimension and how many people may be affected. The visualization in the DESP is much more visual and easier understanding than that in a common geographic information system which can only show the affected area in a plane map.

5. Conclusion and extension

This paper stated the principles and methods of the Gaussian Plume Model, and then developed some methods how to visualize the gas diffusion in the DESP. The result showed significant advantages when simulating the harmful gas diffusion in the DESP. The proposed methods for visualization of gas diffusion provided some efficient algorithms to perform three-dimensional ranges in the DESP and extended the applications of Gaussian Plume Model to three-dimensional field. In addition, this paper introduced intersection analysis to the DESP and this method may be used by other digital earth systems as well. The simulation results of harmful gas diffusion happened in urban area can provide some important information (three-dimensional diffusion ranges, affected populations) in plant siting, city planning and emergency response.

Considering that environmental conditions vary with time and geographic position, we should improve the GPM to adapt to these changes and increase its applicability and robustness. Besides, particle system with aerodynamics should be taken into consideration to simulation the diffusion process of harmful gas. We continue to develop these extensions in the DESP to make the simulation of harmful gas more realistic and efficient.

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