# Developing a GIS based Plume Rose for Industrial Chemical Incident Preparedness and Response

Abhik Kumar Das, Subhrajit Debnath, Jai Asundi
Center for Study of Science, Technology and Policy,
Dr. Raja Ramanna Complex,Raj Bhavan Circle,
High Grounds, Bangalore - 560001, India
{abhik, subhrajit.debnath, asundi}@cstep.in

***Abstract*— The variable nature of wind speed and direction affects the critical zones of chemical incidents (spills and effluents). We describe a method to develop a GIS based "plume rose" using its corresponding wind rose to map the areas that might be affected by a chemical release incident. The plume rose can thus be used in the preparation and response phases of emergency management for an industrial chemical incident. In this study we examine an industrial region in Bangalore, India and show that seasonal variation in winds significantly change the nature (size and direction) of the plume rose. The annual plume rose is coarse and inadequate for effective planning and response for this location. Thus the GIS based monthly plume-rose is more effective for planning and response management.**

***Keywords-plume rose, GIS, chemical incident, preparedness & response***

## I. INTRODUCTION

The Bhopal (India) gas disaster in 1984 [1], the Jilin (China) chemical plant explosion in 2005 [2] and the Jaipur (India) oil fire in 2009 [3] clearly demonstrate the impact of industrial accidents on populations that reside in areas adjacent to such installations. Many industrial facilities earlier built on the outskirts of urban areas are now surrounded by residential areas that have grown around them. This situation demands strategic planning in preparing for the impact of accidents/incidents on the neighbouring populations [4].

In a chemical emission incident, chemical agents from a localized source are dispersed into the environment [5]. Understanding the direction and the extent of dispersion of a hazardous substance is essential for an effective disaster management response [6, 7]. A dispersion model that uses the advection-diffusion process is typically used to estimate the extent of spread of chemicals in the environment [5]. Dispersion depends on the wind speed and direction and the nature of the terrain. Mitigation, preparedness and response phases of disaster management are a challenge given the stochastic nature of wind. A 'wind rose' [8] for a location provides us information on the wind speed, direction and the frequency of wind velocity in a particular direction. In this paper we describe a method to use this wind rose information to create an equivalent "plume rose" – which describes the extent of chemical dispersion in the environment along with its relative probability in a particular direction. The plume rose chart developed is Geographic Information System (GIS) based. The plume rose can thus be used for effective disaster management planning through mitigation and preparedness policies – be it through the construction of redundant assets, to the execution of evacuation drills for effective response at the time of the incident. In incidents where real-time sensing/dispersion data are unavailable, the plume rose chart can be used for effective response activities – such as determining the areas where populations must be warned as well as evacuated.

In this paper we describe a method to develop a GIS based plume rose based on a corresponding wind rose. We use this method to plot the annual as well as monthly plume roses for a specific industrial location in Bangalore, India. Section II shows the analytical description of chemical plume and the GIS based plume rose is described in section III. Section IV discusses the use of GIS based plume rose in preparedness and response considering the study area at Bangalore, India.

## II. CHEMICAL PLUME

A computational model is used to estimate the behavior of agents in a chemical release. The computational model relies on plume modeling where the plume propagation includes two processes: advection and diffusion. The 'Advection' indicates the plume particle is shifted from one position to another by airflow while the 'Diffusion' indicates that there will be a net flow of agents from a high concentration region to a region of low concentration. The "advection-diffusion" equation can be written as [12-14],

$$\left[-u\frac{\partial}{\partial x}+\frac{\partial}{\partial y}\left\{K_y\frac{\partial}{\partial y}\right\}+\frac{\partial}{\partial z}\left\{K_z\frac{\partial}{\partial z}\right\}\right]F(x,y,z;t)=\frac{\partial}{\partial t}F(x,y,z;t) \qquad (1)$$

where $F(x,y,z;t)$ is the concentration at the point $(x,y,z)$ at time $t$. Here $u$ is the air velocity, and transport process is due to air in $x$-direction which is an advection process. The effect of turbulent 'diffusion' is in the direction of $y$ and $z$ where the exchange of plume-particle with the surrounding air-parcels occurs. Here $K_y$ and $K_z$ are the "eddy diffusivity" [19] in $y$ and $z$ direction respectively, which represents the intensity of the turbulent motions and varies with stability. For a steady state solution of the equation we consider for a time t > $T$,

$$\frac{\partial}{\partial t}F(x,y,z;t)\rightarrow 0 \,. \qquad (2)$$

We consider $\int_0^T F(x,y,z;t)dt = C(x,y,z)$, hence the time integrated solution of the advection-diffusion equation can be written as [15, 16],

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z}\left[\exp\left\{-\frac{(z-h)^2}{2\sigma_z^2}\right\} + \exp\left\{-\frac{(z+h)^2}{2\sigma_z^2}\right\}\right]\exp\left\{-\frac{y^2}{2\sigma_y^2}\right\} \quad (3)$$

Where $C$ is the concentration, $Q$ is the emission rate of the pollutant from the source, $u$ is the wind speed which defines the $x$ direction. $y$ is the horizontal distance perpendicular to the wind direction, $z$ is the vertical direction, $h$ is the effective height of the plume. Here $\sigma_y$ and $\sigma_z$ can be defined as $\sigma_y^2 = \frac{2K_y x}{u}$ and $\sigma_z^2 = \frac{2K_z x}{u}$. Here σ in $y$ and $z$ direction are functions of $x$ and can be represented empirically as,

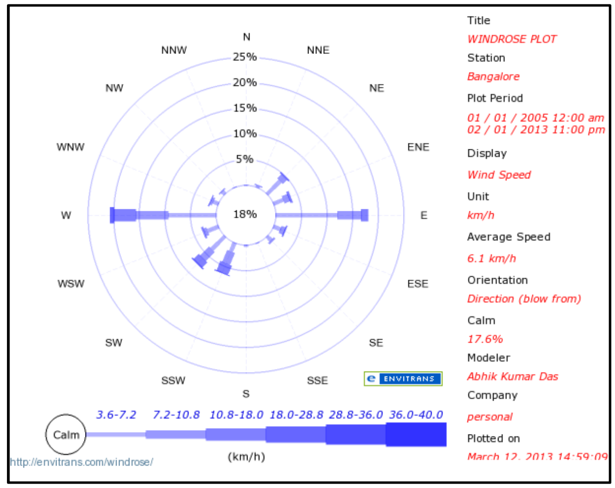
$$\sigma_z(\mathrm{x}) = a x^b \quad (4)$$

$$\sigma_y(\mathrm{x}) = 465.11628 \tan\{0.017453293(\mathrm{c} - \mathrm{d}\log \mathrm{x})\}$$

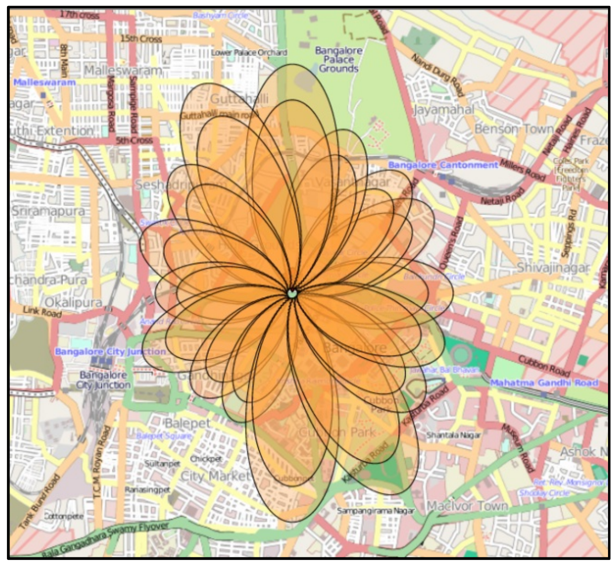
where $a$, $b$, $c$ and $d$ are the empirical coefficients known as Pasquill-Gifford coefficients [17] which depend on environmental stability. Wind direction and speed are major variables in the plume propagation model. These variables are dependent on time and the topology of the location.

## III. PLUME ROSE USING WIND ROSE

Wind rose of a location provides the information about the percentage of time during which the wind remained in a particular wind-speed range and in a particular direction. The variable nature of the wind direction and wind speed can be represented by a wind rose. The information regarding the direction, speed and the frequency of the wind flow can be used to produce an equivalent plume rose of an industrial zone. As shown in Figure 1, the wind rose is used to create the equivalent plume rose of a location. The plume configuration in the plume rose represents the region where the chemical agent concentration is more than the permissible limit after 30 minutes. The initial concentration (or the source rate) can be determined by performing a vulnerability analysis or risk analysis of the industrial location. To create the equivalent plume rose, the value of wind speed used for calculation is the maximum value of the wind-speed in that particular direction. This is used (instead of the average value) so as to estimate the maximum extent of the plume area. From the plume rose, we observe that some plumes are more likely (than others) for the given frequency distribution of wind direction obtained from the wind rose.




(a)




(b)

Fig 1(a) represents the wind rose of Bangalore, India and (b) represents the equivalent plume rose after one hour

## IV. PRE-DISASTER PLANNING USING PLUME ROSE

Pre-disaster planning consists of activities such as disaster mitigation and disaster preparedness. Disaster mitigation focuses on the hazards that causes the disaster and tries to eliminate or drastically reduce its direct effects. Preparedness focuses on plans to respond to a disaster threat or occurrence[9]. The vulnerability analysis or risk assessment for an area, people and property due to a chemical disaster or the probability of its occurrence can be undertaken using the plume-rose. The probabilistic form of the plume rose becomes a forerunner for evolving appropriate preventive measures and mitigation strategies. Preparedness and mitigation plans, therefore, will have to be evolved and its implementation should be monitored locally at the industrial zone to reduce the impact of the chemical disasters. While evolving such area specific preparedness and mitigation plans, wind rose specific plume will essentially identify the areas that might be most affected and hence define the mitigation strategies as well as the target areas for preparedness measures.

Preparedness considers an estimation of emergency needs in a particular area and identifies the resources required to meet these needs. It involves preparation of well-designed plans to structure the entire post-disaster response, and familiarizing the stakeholders, particularly the communities through training, drills and simulation exercises. Mitigation distinguishes actions that have a long-term impact from those that are more closely associated with preparedness which involve immediate response and short-term recovery from a specific disaster. It must be recognized that the boundaries are not absolute. The pre-disaster planning can be done using the development of local warning and community evacuation plans through community education, evolving local response structures and administrative preparedness by way of stockpiling of supplies, developing emergency plans for rescue and relief. The application of plume rose in pre-disaster planning identifies the areas where the effects of the chemical disaster have high probability. Since the nature of wind direction and speed have a monthly variation, it is interesting to note that the high probability areas for chemical dispersion are different for different months.

The three major plumes of the plume rose show the possible zones of industrial disaster, where the probability of the presence of chemical agents is maximum and creates the critical zones for pre-planning activities of a chemical disaster. These critical zones are time dependent and depend on the wind distribution of the particular location as shown in Table I. The varying nature of the critical zones implies subjective pre-planning of evacuation zones, safe-routes and resource mobilization. For example, the critical zones in January and September (see Table I) are completely non-overlapping and are in opposite directions. Hence the preparation for as well as response for chemical disasters for the months of January and September will be very different. This fact poses a significant challenge to the civil security administration that will need situational awareness at the time of the emergency situation.

During a chemical disaster, a computation based dispersion model may be used to estimate the plume extent to find the possible critical zones. In case of non-availability of computational resources the plume rose model can also be used to identify the possible critical zones of rescue operations provided the conditions used as assumptions are reasonably accurate. The plume rose can thus help identify the possible safe and unsafe zones and help plotting of safe routes for evacuation and rescue.

## V. Conclusion

In this paper we introduce the concept of a “plume rose” which is GIS based and computed using a steady-state dispersion model and data from the wind rose for that location. Based on available wind (rose) data, the plume rose is plotted for an industrial location in Bangalore, India. We compute and plot the annual as well as monthly plume rose charts for this location. It may be observed that seasonal variation in winds significantly change the nature (size and direction) of the plume rose. Based on the charts, we observe that the annual plume rose is coarse and inadequate for effective planning and response for this location. The monthly plume rose charts on the other hand capture some seasonal variations in wind velocity and direction, making them useful for mitigation and preparedness planning. Monthly plume rose charts can also be used for response activities in the absence of real-time sensor or computational outputs. We conclude that the annual plume rose alone may be inadequate for effective planning and response management activities and that monthly plume rose charts are useful and might be necessary in certain situations.

## Acknowledgment

This manuscript has benefited from discussions with a number of researchers at CSTEP. The authors would like to thank Dr. V. S. Arunachalam and Dr. Anshu Bharadwaj for their encouragement, advice, comments and suggestions during the course of this study. This work was supported by grants from DRDO and IDRC.

## References

[1] M. Iasija, “Industrial Disasters: A case study of Bhopal Gas Leak Disaster” ( http://www.preservearticles.com/201101143273/case-study-of-bhopal-gas-leak-disaster.html)

[2] Fu W, Fu H, Skøtt K, Yang M (2007): Modeling the Spill in the Songhua River after the Explosion in the Petrochemical Plant in Jilin. Env Sci Pollut Res, DOI: http://dx.doi.org/10.1065/espr2007.11.457

[3] M. Gridhar, Jaipur Fire and its Environmental effects, 12th ESRI India User Conference 2011

[4] Cutter, Susan LL. Hazards Vulnerability and Environmental Justice. Routledge, 2012.

[5] Pontiggia, M., et al. "Hazardous gas dispersion: a CFD model accounting for atmospheric stability classes." Journal of hazardous materials 171.1 (2009): 739-747.

[6] N. Narang, O. Hoysala, S. Arlekar, A. Chadgar, and J. Asundi, “Developing gis tools for planning, mitigation and preparedness for large scale emergencies & disasters,” Int. J. System of Systems Engineering, 3(2), 2012

[7] Narang N.,Das, A., Arlekar, S.,Asundi, J., ‘Using GIS to reassess urban plans based on changing industrial emissions’, *in Proceedings of 2012 IEEE International Conference on Electronics Computer Technology (ICECT 2012)*, Kanyakumari, India, Vol 2, Pg 60-64, April, 2012

[8] Wind Rose, India Meteorology Department, [Online]. Available: http://www.imdagrimet.gov.in/node/381

[9] Shukla, Moumita Mookerjee and Asundi, Jai, Considering emergency and disaster management systems from a software architecture perspective”, Int. J. of System of Systems Engineering, Volume 3, Number 2, August 2012 , pp. 129-141(13)

[10] C. Ghenai and C. Lin, “Dispersion modeling of pm10 released during decontamination activities,” Journal of hazardous materials, vol. 132, no. 1, pp. 58–67, 2006.

[11] S. Straja, “The importance of the pollutant dispersion along the nominal wind direction,” Atmospheric Environment, vol. 28, no. 2, pp. 371–374, 1994.

[12] O. Sutton, “A theory of eddy diffusion in the atmosphere,” Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, vol. 135, no. 826, pp. 143–165, 1932.

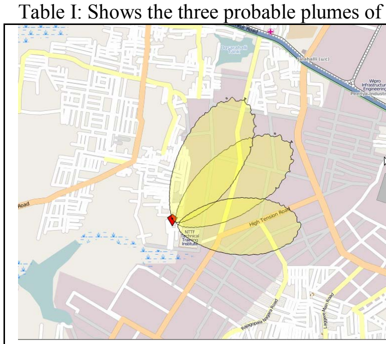
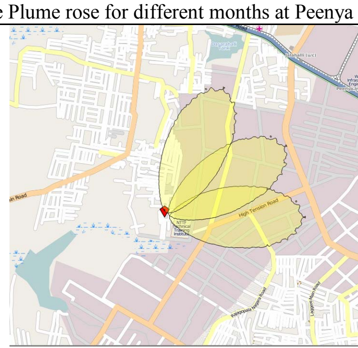
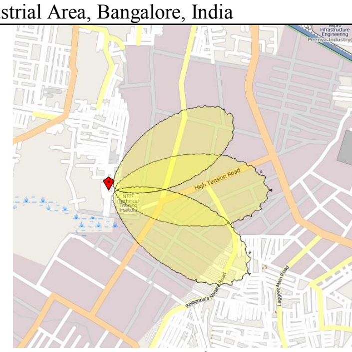
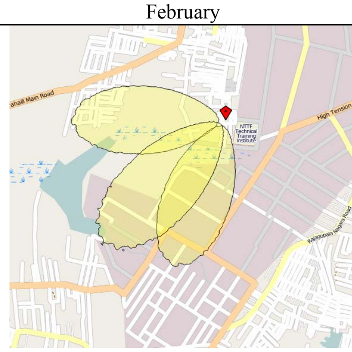
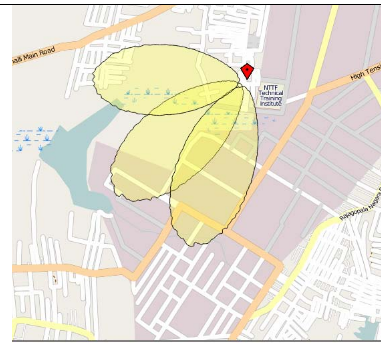
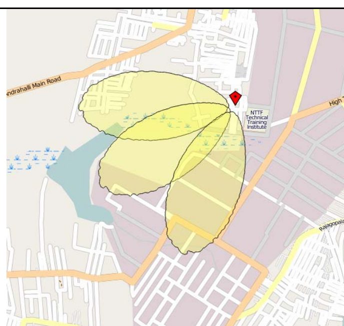
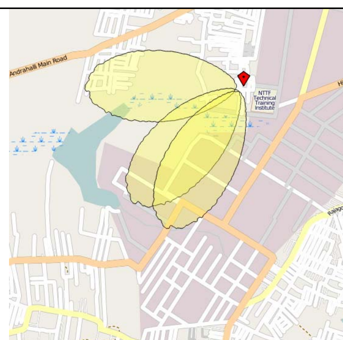
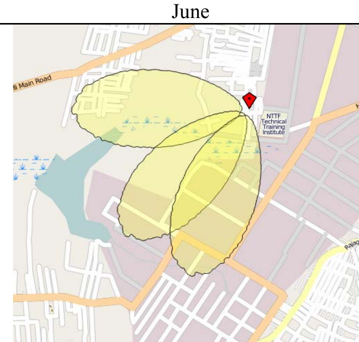
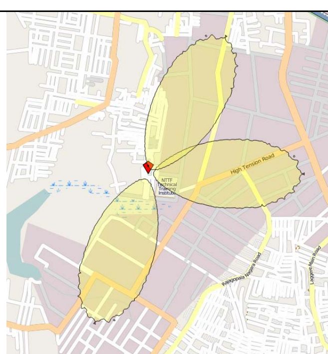
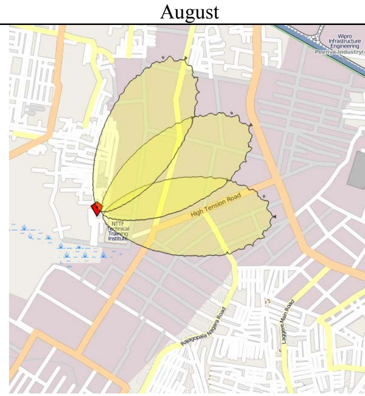
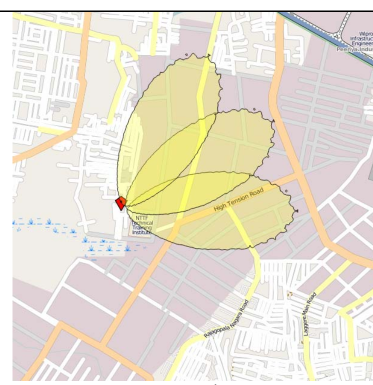
[13] Sykes, R.I.; Lewellen, W.S.; Parker, S.F. “Gaussian plume model of atmospheric dispersion based on second-order closure”, J. Appl. Meteorol; Journal Vol.25:3, 1986

[14] A. E. S. Green, R. P. Singhal & R. Venkateswar, “Analytic Extensions of the Gaussian Plume Model”, Journal of the Air Pollution Control Association, Vol.30:7, 1980

[15] G. A. Davidson, “A Modified Power Law Representation of the Pasquill-Gifford Dispersion Coefficients”, Journal of the Air & Waste Management Association

[16] Inglesby, Thomas V. "Progress in disaster planning and preparedness since 2001." *JAMA: The Journal of the American Medical Association* 306.12 (2011): 1372-1373.


Table I: Shows the three probable plumes of the Plume rose for different months at Peenya Industrial Area, Bangalore, India

| | | |
|---|---|---|
| <br>January | <br>February | <br>March |
| <br>April | <br>May | <br>June |
| <br>July | <br>August | <br>September |
| <br>October | <br>November | <br>December |