



Dispersion modeling in assessing air quality of industrial projects under Indian regulatory regime

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Abstract

Environmental impact assessment (EIA) studies conducted over the years as a part of obtaining environmental clearance in accordance with Indian regulation have been given significant attention towards carrying out Gaussian dispersion modeling for predicting the ground level concentration (GLC) of pollutants, especially for SO₂. Making any adhoc decision towards recommending flue gas desulfurization (FGD) system in Indian fossil fuel combustion operations is not realistic considering the usage of fuel with low sulfur content. Thus a predictive modeling is imperative prior to making any conclusive decision. In the light of this finding, dispersion modeling has been accorded in Indian environmental regulations. This article aims at providing approaches to ascertain pollution potential for proposed power plant operation either alone or in presence of other industrial operations under different conditions. In order to assess the performance of the computational work four different cases were analyzed based on worst scenario. Results obtained through predictions were compared with National Ambient Air Quality Standards (NAAQS) of India. One specific case found to overshoot the ambient air quality adversely in respect of SO₂ and was therefore, suggested to install a FGD system with at least 80 % SO₂ removal efficiency. With this recommendation, the cumulative prediction yielded a very conservative resultant value of 24 hourly maximum GLC of SO₂ as against a value that exceeded well above the stipulated value without considering the FGD system. The computational algorithm developed can therefore, be gainfully utilized for the purpose of EIA analysis in Indian condition.

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1. Introduction

Power is one of the most important components of our modern technological society. In fact, generation of power in India has been given top priority in national planning process. Fossil fuel power generation is continuing to expand in India with the growth of population and industrialization. Intrinsically, power generation from fossil fuels is a process of combustion of fuels that produces air pollutants, mainly, particulate matter (PM), SO₂ and NO_x. Degradation of surrounding ambient air quality would be significant at times, if adequate measures are not being taken prior to commissioning of the plant. Burning of coal constitutes more than 70% power generation in India. Combustion of fossil fuel thus would generate air pollutants considerably. As a result, it is mandatory to assess the pollution potential of a major power project so that counter measures may be undertaken to curb its adverse impact on the surrounding air quality. To address this issue, Ministry of Environment and

Forests (MoEF), Government of India decided to put forward dispersion model for assessing the emission of air pollutants from multiple point sources. The main objectives of this dispersion model were to provide an insight to atmospheric contamination process, to promote understanding on pollution dispersion mechanism, to suggest rational approaches to translate complex physical phenomena governing pollution dispersion processes in appropriate mathematical formulation amenable to numerical solution and finally the development of a computational tool in the form of a software for serving the designers in evaluating the effect of power plant operations on the ambient air quality in terms of concentration level of various pollutants.

Literature revealed that accurate prediction of GLC of air pollutants emitted from a point source into the atmosphere in industrial applications is necessary so as to meet the requirements of governmental regulations. The GLC of the emitted pollutants are generally estimated from the statistical distributions of the concentration fields using widely accepted "Gaussian distribution" with varied success. Some of these investigations are reviewed here for our better understanding. The impact of emission of NO_x from automobiles to the air quality in Singapore was analyzed [1] using AIRVIRO, a regional scale dispersion model developed by the Swedish Meteorological and Hydrological Institute. A new method was used by first modeling only the impact of point and area sources and then overlaying the traffic impact on air quality at different locations. The proposed approach predicted reasonably well with the variations in NO_x concentration as a function of traffic and meteorological conditions. The quantification of model uncertainty was reported by Dabberdt and Miller [2] through the use of ensemble simulations. Dispersion modeling was illustrated as an emergency-response measure using an actual event that involved the accidental release of oleum. Both surface footprints of mass concentration and the associated probability distributions at individual receptors were reported to provide valuable quantitative indicators of the range of expected concentrations and their associated uncertainty. Jiang et al. [3] described an approach to assess air quality assessment of a power plant in the Hongkong–Shenzhen area over coastal complex terrain. They had analyzed regulatory models and an atmospheric dispersion modeling system. The latter consists of a three-dimensional non-hydrostatic planet boundary layer (PBL) numerical model and a puff diffusion model, and was employed to simulate sea–land breeze circulation and ground-level concentrations (GLC) from an elevated source over the coastal complex terrain. The study suggested the potential of the mesoscale atmospheric dispersion modeling system for air quality assessment in complex terrain. Two dispersion modeling was studied by Borrego et al. [4] for the assessment of air pollution in Lisbon city at local scale through. They had described the Transport Emission Model for Line Sources (TREM) and the Local Scale Dispersion Model (VADIS). The main objective of this study was to analyze the performance of the models from the standpoint of the new European Legislation. The models were applied to the Lisbon downtown area and results of CO concentrations were analyzed. Demonstrated were the conditions for yielding satisfactory performance to calculate the flow and dispersion around obstacles under variable wind conditions that could provide information to be used by policy makers for assessment of the ambient air quality. Furthermore, a comparison between simulated and measured data using criteria stipulated by the European legislation was elucidated. The Industrial Source Complex Short Term (ISCST-3) model was used by Rama Krishna et al. [5] for assessing the ambient air quality stemming from the emissions of SO_2 from an industrial complex, located at Jeedimetla in the outskirts of Hyderabad city, India. The spatial distribution of SO_2 concentrations over the study area during the summer and winter months indicated that the levels of SO_2 were within the limits stipulated in the National Ambient Air Quality Standards except near the industrial area. The model-predicted concentrations were in good agreement with observed values that resulted in satisfactory performance of the model. Holmes and Morawska [6] reviewed the application of atmospheric models for particle dispersion. The different types of dispersion models available were outlined and the suitability of the different approaches to dispersion modelling within different environments was assessed. Finally, several major commercial and non-commercial particle dispersion packages were reviewed based on their advantages and limitations of use. Baroutian et al. [7] investigated identifying the origin of PM10 in the atmosphere of Kerman on the dispersion conditions for these particles, the variations of the mass concentration and size distribution. The main objective was focused on the local environmental impact of Kerman Cement Plant. Furthermore, PM10 concentration was predicted by using Gaussian plume model for continuous point source emission. The model predicted values were reported to be in good agreement with the measured data. Liu et al. [8] proposed a geo-informatics augmented framework of environmental modelling and information sharing for supporting effective urban air pollution control and management. This framework was outlined in terms of its key

components and processes for instance, an integrated adaptive network of sensors for environmental monitoring; a set of distributed databases for data management; a set of intelligent models for environmental modelling; a set of efficient user interfaces for data access; and a reliable, high capacity, high performance computing and communication infrastructure for integrating and supporting other framework components and processes. Carmichael et al. [9] reported on the advances in air quality forecasting with an emphasis on data assimilation. Applications of the four-dimensional variation method (4D-Var), the ensemble Kalman filter (EnKF) approach and the computation challenges were elucidated. Elkamel et al. [10] investigated on the impact of multiple pollutants (i.e., CO, NO_x and SO₂) emitted from different sources within a given area on the ambient air quality. An interactive optimization methodology was used for allocating the number and configuration of an Air Quality Monitoring Network. A mathematical model based on the multiple cell approach was used to create monthly spatial distributions for the concentrations of the pollutants emitted from different point sources. The model was tested to refinery stacks and results indicated that three stations could provide a total coverage of more than 70%. Ainslie and Jackson [11] investigated the methods for determining the adverse effects of air emission from potential burning of isolated piles of mountain pine beetle-killed lodge pole pine in the city of Prince George, British Columbia, Canada. The CALPUFF atmospheric dispersion model was used to analyze to identify safe burning regions based on atmospheric stability and wind direction. Reportedly, model results showed that the location and extent of influence regions was sensitive to wind speed, wind direction, atmospheric stability and a threshold used to quantify excessive concentrations. Critical appraisal of the existing literature indicates that such a traditional statistical approach using the Gaussian-type dispersion model has thus far been used extensively for carrying out environmental impact assessment (EIA) studies of several industrial projects.

Attempts have been made in this article to demonstrate the features of a computational algorithm that is developed [12] based on Gaussian dispersion to assist the policy makers, planners, designers in evaluating the effect of stationary point sources as in the emissions occurring from the stack of a coal fired thermal power plant on the surrounding ambient air quality in terms of ground level concentration of pollutants, especially for SO₂. The necessities of conducting such study are to:

- Identify plausible impacts of air pollutants emitted from stationary point source from an industry on surrounding ambient air quality.
- Characterize the design modifications in achieving improved ambient air quality.
- Identify plausible site for establishment of proposed industrial activity.
- Assess the carrying capacity of a place intended for industrial activity leading to point source air emission and hence to evaluate the suitability of a site to accommodate new industries.

To characterize the fundamental features of this algorithm some case studies are described taking into consideration of few power projects and a sponge iron plant those are being planned for establishment. Though the numerical computation method developed based on Gaussian dispersion modeling for power plants and a sponge iron plant, it can also be applicable to host of other industrial operations having the potential to generate air pollutants through point stationary sources.

2. Modeling of air pollution dispersion: Indian development

Government of India has now made it mandatory for establishing new industry or for expansion project that are listed in the EIA Notification of 2006 [13] to obtain environmental clearance from the MoEF. However, a rational decision on the carrying capacity of any industrial establishment from the environmental standpoint would importantly depend on the ability to predict as also to evaluate the impacts of its operation on the surrounding environment. In India, the methods for the prediction of GLC of pollutants due to emission from industries are all adopted from the existing literature. Adaptability of such methods in Indian climatic conditions, however, needs to be ascertained carefully through extensive field observation and research works. In the light of these findings, it was felt necessary by the MoEF to develop methodology and approach that are essential for the purpose of mathematical modeling of air pollution dispersion. General guidelines for EIA studies were, therefore, put forward by the Central Pollution Control Board (CPCB) of India under the aegis of MoEF [14]. The present article takes into account all these guidelines in formulating the atmospheric pollution dispersion models under Indian condition that are discussed in the next section.

3. Guidelines of MoEF for Gaussian dispersion modeling

The guidelines for EIA studies put forward by the CPCB of India under the aegis of MoEF are discussed here in this section. The guidelines recognized the urgent need for developing an exhaustive data bank on meteorological parameters and also recommended methodologies to estimate various parameters governing atmospheric dispersion process. However, these guidelines were termed as purely tentative and emphasis was given for carrying out continuous monitoring of the relevant parameters emitting from the industrial operation on surrounding air quality in order to assess the situation rigorously for arriving at methodologies suitable for Indian conditions. The parameters in these guidelines are presented below:

Design parameters: These data are based on 100% plant capacity, fuel consumption rate, fuel analysis data, flue gas velocity, stack gas temperature, flue gas flow rate, density of flue gas, specific heat of flue gas, heat emission rate of flue gas at the top of the stack, buoyancy or momentum flux parameter, control device for the particulate matter collection and its efficiency of collection.

Emission rate: Emission rates of pollutants are to be calculated assuming 0.5% S-content, if % S-content is not greater than 0.5%; If % S-content > 0.5% then actual value to be considered; for particulate emission, the collection efficiency of the electrostatic precipitator along with the emission standard for PM to be used.

Meteorological parameters: Wind speed, wind direction (for hourly and half hourly mean values) are to be generated for all seasons in a year.

Site specific data: Ambient temperature, humidity, cloud cover, solar insolation, precipitation (monthly total, number of rainy days > 2.5 mm/day), barometric pressure.

Stability class: Pasquill-Gifford Stability Classification is to be used.

Wind speed: Irwin power law velocity profile is to be used for extrapolating wind speed.

Mixing height: Site-specific data are to be used as per availability or to be generated.

Plume rise: Briggs Plume rise equation with modification is to be used.

Urban-rural classification: When more than 50% land inside a circle of 3 km radius around the source comprises industries, commercial and residential establishments then the area is to be assumed as Urban. Downwash effects due to buildings and other elevated structures should be considered when tallest building or other structures in the area have a height equivalent to at least 40% of the source height of 5 times the height of such tall buildings.

3.1 Gaussian dispersion modeling

The prediction of the average concentration of a pollutant from a known emission source having specified emission rate is a critical problem in the pollution dispersion modeling. In fact, such prediction of concentration is not analytically possible since the basic momentum equation governing such dispersion process is highly non-linear. Numerical analysis is inevitable in such a situation considering physical phenomena governing turbulent flow, mixing and transportation processes of airborne species.

The departure of winds and other meteorological parameters from quasi-steady state constitutes a source of complexity in atmospheric dispersion calculations [12]. The assumption of quasi-steadiness may be considered as a reasonable approximation however, for limited temporal regimes and geographical distances. The complexity of the atmospheric dispersion modeling further increases considerably with the inception of chemical reactions that produces one or more secondary pollutants. In order to avoid this complexity to arrive at an effective model, the second requirement is that the pollutants in question are assumed to be chemically inert. Complex aerodynamic effects may be induced stemming from the severe obstructions as well as undulations in the flow field that may not be simulated in a simple model. Also, it is not possible to reproduce the variation in wind directions in vertical direction in the model. Thus, the wind profile in the boundary layer necessitated approximation by a single vector with constant direction. The temperature of the point source emission is assumed to be much higher than ambient temperature as a part of the modeling.

The proposed model also aims at estimating the GLC from the emissions from multiple elevated stacks. The diffusion of non-reactive buoyant plumes emanating from the stacks and their subsequent transport or advection to the adjacent regions in space is incorporated into the complete computational procedure. Therefore, the aforesaid dispersion that invokes diffusion as also advection phenomena will enable in estimating the ground level pollutant concentrations at legion of pre-selected receptors. The atmospheric diffusion stems from the mass exchange between regions in space especially, in the

lower atmosphere. This phenomenon is governed by eddy exchange owing to turbulent air movements, the magnitude of which is generally a function of atmospheric stability; an atmospheric property that characterizes the thermodynamic structure of the atmosphere in terms of ability to sustain disturbances. Advection, on the other hand, is a process of transport of an air parcel by the velocity flow field in the atmosphere represented by the wind velocity vector.

Besides accounting for atmospheric stability and wind velocity vector in any modeling for atmospheric dispersion process, the quantity and nature of emissions discharged and their spatial distributions are also considered. However, the fundamental assumption of inert pollutant with non-chemical transformation helps to simplify the model formulation as it avoids the incorporation of the effect of emission characteristics in the model. Gaussian plume equation with necessary modifications accounting for relevant atmospheric properties has been adopted for formulating the basic model, since Gaussian plume distribution provides an acceptable means to simulate the atmospheric dispersion mechanism. The following additional assumptions are therefore, necessary for the purpose of atmospheric dispersion process [12]:

1. A continuous emission source
2. Steady-state downwind plume
3. Gaussian distribution of pollutants within the plume in both the crosswind and vertical directions
4. Plume is assumed to have been discharged above the stack height to account for the effect buoyancy
5. Plume is diluted and transported downwind by the wind velocity vector as the plume expands due to eddy diffusion
6. Rate of expansion is characterized by a series of empirical dispersion co-efficient that are dependent on the stability of atmosphere.

The Gaussian plume equation for a continuous emission source gives the total concentration C of a gas or particulate matter or aerosol at a ground level location (x, y) by the following expression:

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

where $C(x,y)$ is the ground level concentration ($\mu\text{g}/\text{m}^3$), Q is the uniform pollutant emission rate from the source (g/s), u is the stack gas velocity (m/s), σ_y is the dispersion coefficient along the crosswind direction y (m), σ_z is the dispersion coefficient along vertical direction z (m), x is the downwind distance (m), y is the crosswind distance (m), z is the vertical distance (m), H is the effective stack height (m).

It is assumed that complete reflection of the plume takes place at the earth's surface i.e., there is no atmospheric transformation or deposition at the surface. The concentration C is an average over the time interval equivalent to time interval of estimation of σ_y and σ_z (normally 1-hour).

The model calculates short-term concentrations without consideration of plume history i.e., each 1-hour period is completely independent. Equation (1) is valid for any consistent set of units.

3.1.1 Modifications in basic equation

The Gaussian plume equation is a solution to the simplified conservation of mass equation assuming non-zero wind speed and constant eddy diffusivities along the principal axes. However, to account for certain atmospheric properties, the basic equation is required to be modified. The most significant modification stems from the presence of a stable layer of air aloft, i.e. an inversion layer at a height of H above the ground level that does not permit the plume to penetrate it in either direction. As a result, plume released below this layer are trapped between this layer and the ground surface while, plumes released above this layer do not contribute to ground level pollutant concentration. Other modification is due to the observed fact that vertical mixing of the plume tends to be uniform beyond a critical distance downwind. The modified equations are presented as given below [12]:

Condition 1

(a) Plume trapped between ground level and mixing layer i.e., $H \leq 1$.

(b) Down wind distance of the receptor from the source is within non-critical zone i.e., $\sigma_z \leq 1.6 L$

$$C = \frac{Q}{\pi \sigma_y \sigma_z u} \times \exp \left[-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 \right] \times \sum_{N=-K}^{N=K} \exp \left[-\frac{1}{2} \left(\frac{H + 2NL}{\sigma_z} \right)^2 \right] \quad (2)$$

where L is the mixing height (m), K is the number of pollutant reflections +ve for $x > 0$; -ve for $x < 0$, N is the total number of reflections of pollutants.

Here reflection of plume has been considered based on multiple reflections proposed by Bierly and Hewson [15]. Theoretically, the number of image plumes will be infinite. However, in practice the numbers of image plumes are restricted to a finite value by restricting the imaginary height of image sources to a certain level beyond which the contributions from the image plumes to any ground level receptor will be significantly small to have any practical consequences. The value of K is limited to a maximum of 45 in order to converge rapidly the infinite series in Eq. (2) above.

Condition 2

Plume released above the mixing layer, i.e.,

$H > 1$ and $C = 0$.

(3)

Condition 3

(a) Plume trapped between ground level and mixing layer i.e., $H \leq 1$.

(b) Down wind distance of the receptor from the source is within non-critical zone i.e., $\sigma_z > 1.6L$.

$$C = \frac{Q}{\sqrt{2\pi} \sigma_y Lu} \times \exp \left[-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 \right] \quad (4)$$

The rural – urban consideration was also adequately taken care of in modeling. Radiative cooling produces temperature inversion on calm and clear nights, hence improves the atmospheric stability in rural environment. In contrast, in urban centers, radiation of stored heat from structural establishments during night prevents the onset of temperature inversion, resulting in the elimination of any stability improvement during night. These aspects have been aptly considered while computing various parameters in the model equations described earlier. Additionally, the model also accounts for undulations in the terrain around the study source.

4. Computational algorithms

The overall computational program comprises two modules written in efficient code using 'C' language [12]. Each module is independent and generates information to be used by other modules for achieving accurate computation. The first module is called "preprocessing module" that is developed for appropriate processing of basic environmental data and details of it is shown in Figure 1 as a flow chart.

It aims at preparing a data file of hourly meteorological parameters to be used in the second module for the computation of ground level concentration (GLC). It also creates a data file of daily temporal data of sunrise and sunset for computation regime that finally generates the output.

The second module, termed here as the "GLC computation module", receives information on hourly values of ambient temperature, wind speed, wind direction, stability class and mixing height those are created in the preprocessing module. The flow chart showing the details of its operation is shown in Figure 2. Additionally, it utilizes the detailed geometrical information of the site, stack and plume provided by the user and finally, achieves GLC computations at desired receptor locations at hourly interval. This information is stored in designated binary files to be used for delivering the outputs.

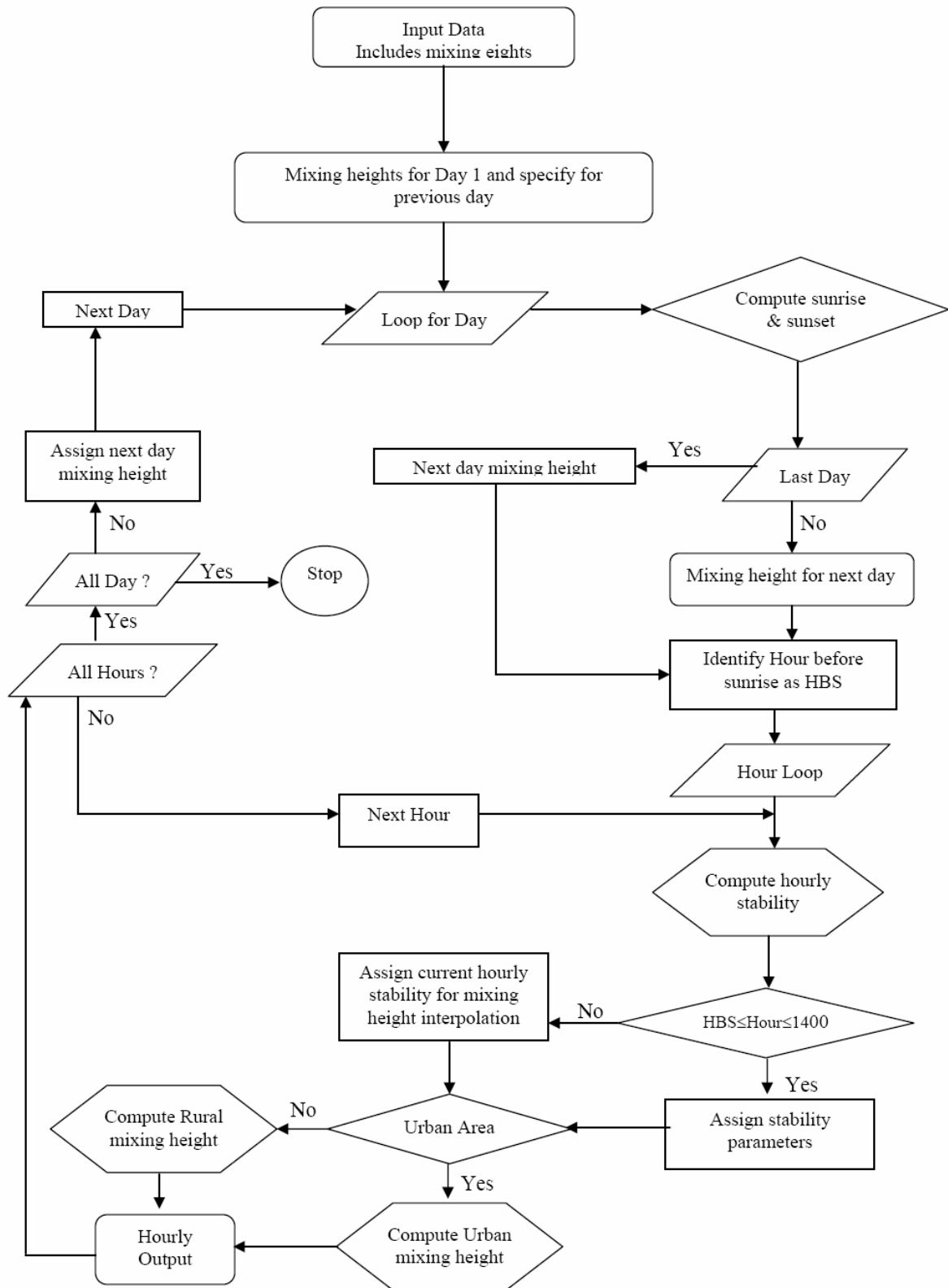


Figure 1. Flow chart showing preprocessing module

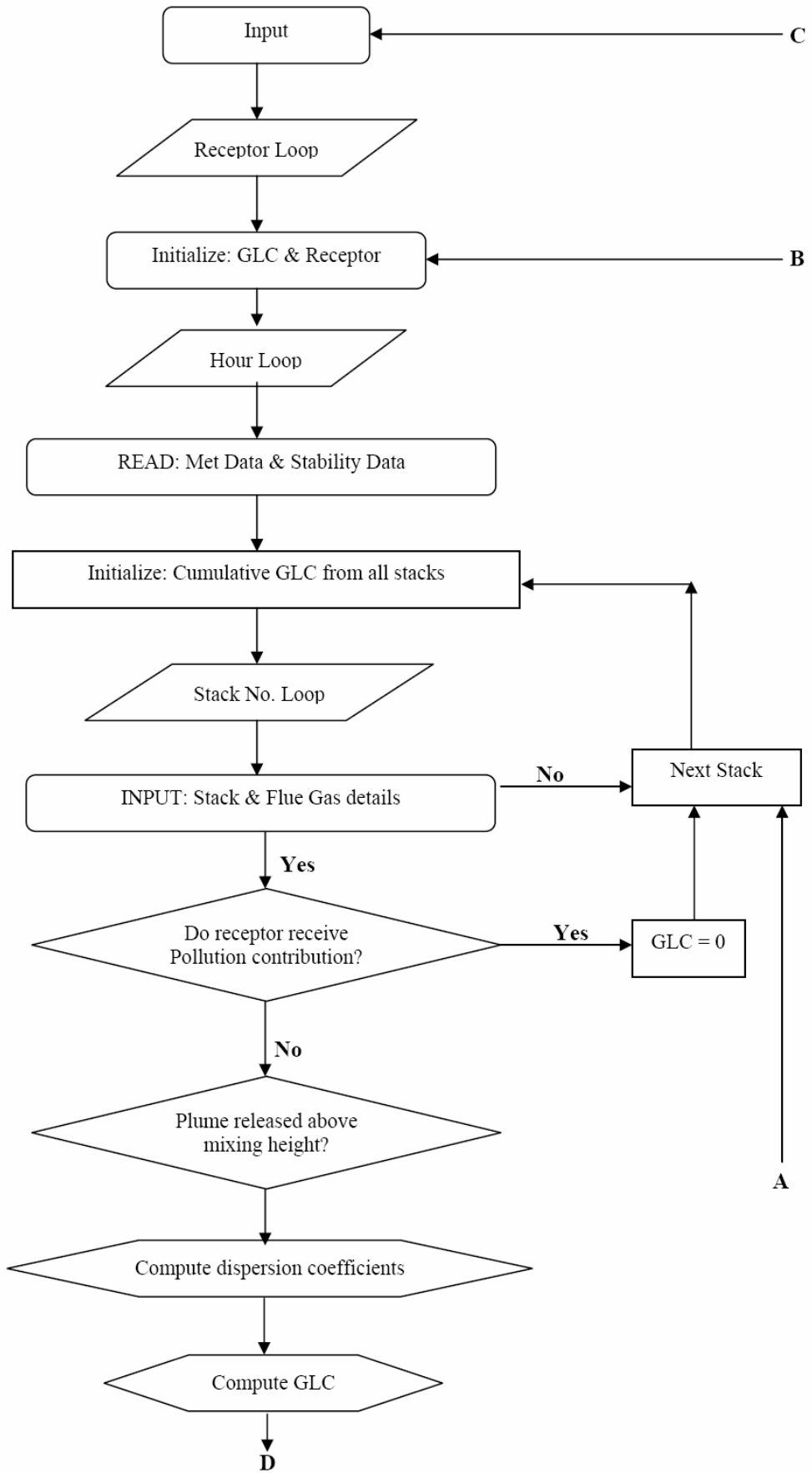


Figure 2. (Continued)

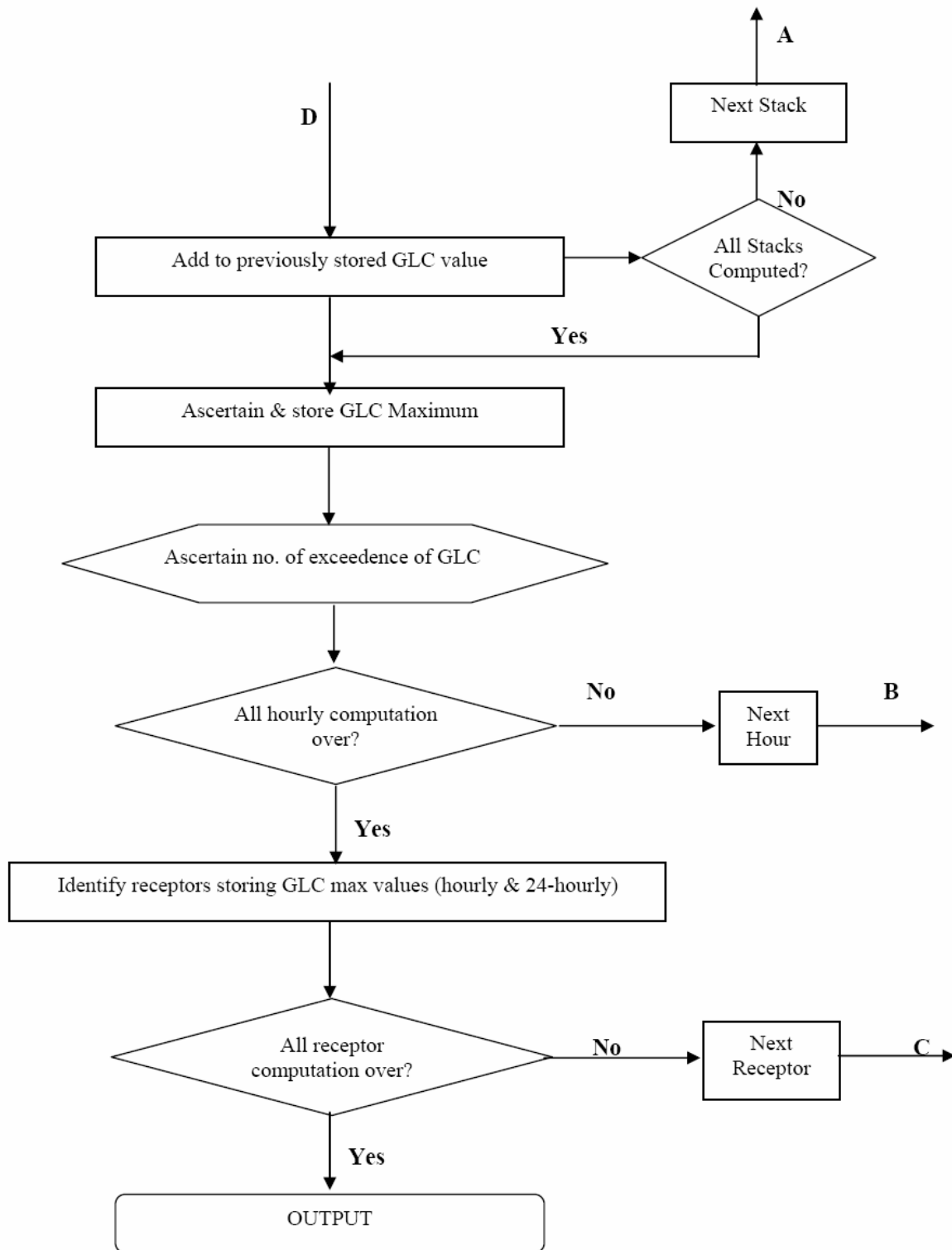


Figure 2. Flow chart showing computation of GLC

5. Results and discussion

Some case studies are analyzed in order to demonstrate the features of the computational algorithm developed. Four major distinct cases are elucidated as given below:

- Case 1:** Single industrial operation [2×500 MW power plant]
- Case 2:** Single industrial operation [3×500 MW power plant]
- Case 3:** Single industrial operation [1×100 TPD Sponge Iron]
- Case 3(a):** Single industrial operation [1×100 TPD Sponge Iron] with Flue Gas Desulfurization (FGD) system having 80% SO₂ removal efficiency
- Case 4:** Cumulative effect of the above three cases.
- Case 4(a):** Cumulative effect of Case 1, Case 2 and Case 3(a).

The co-ordinates of the three industrial establishments are different. These industrial units are located in rural environment that means these are not located in an industrial area. The pollutant under consideration is SO₂, background concentration of which is 22 µg/m³. The dispersion study was carried out considering the winter season anticipating that results would yield worst scenario. And in that the decision taken with the help of such data on worst scenario would be more realistic for the design purpose as also for the purpose of policy making. It was planned to establish three units under consideration at that locality. Therefore, it is mandatory to carry out an Environmental Impact Assessment (EIA) for such industrial activities as per the EIA Notification of India [13] so as to maintain the background level of pollutant well within the permissible level. The area under question has been earmarked for further industrial development. Since the pollutant SO₂ is deleterious and no stack emission standard has so far been fixed in India for its discharge from the stack for such industrial activities, its GLC value is necessary to be evaluated. Based on such predictive value, decision could be taken by the regulatory authority.

The details of the point sources are furnished in Table 1. The stack details and flue gas details are all presented in Table 2.

Table 1. Particulars of point sources

Parameters	Case 1	Case 2	Case 3
Site Status	Rural and Residential		
Pollutant	SO ₂		
Background Value	22.0 µg/m ³		
Computation Period	Winter 1995 – 1996		
Area Covered	50 km × 50 km	50 km × 50 km	50 km × 50 km
No. of Receptors	51×51 along X-Y co-ordinates	51×51 along X-Y co-ordinates	51×51 along X-Y co-ordinates

Table 2. Stack and flue gas details

No.	Detailed Stack Data					Detailed Flue Gas Data		
	D _s (m)	H _s (m)	X	Co-ordinates (m)		Q _g (g/s)	v _g (m/s)	T _g (°C)
				Y	Z			
Case 1								
1	6.94	275	25	25	0	1442.2	25	126
Case 2								
1	4.58	275	9	11	0	211.1	25	126
Case 3								
1	2.90	30	13	36	0	600	20	240
Case 4								
1	6.94	275	25	25	0	1442.2	25	126
2	4.58	275	9	11	0	211.1	25	126
3	2.90	30	13	36	0	600	20	240

The meteorological data for the winter months of 1995 – 1996 was considered for evaluating the worst scenarios. The industrial area is located close to Durgapur at Bardhaman District located in the State of West Bengal. The GLC distribution pattern was evaluated on a rectangular area of 50 km × 50 km area having 51×51 receptors as square grids along X-Y co-ordinates. In fact, the EIA study conducted for the industrial operation as described in Case 1, 2, 3 and 3(a) as per the requirement of Indian guidelines has been envisaged here. The NAAQS [16] of India is furnished in Table 3 for assessing the 24 hourly maximum GLC values of SO₂ obtainable for a specific case as to whether exceeded the permissible limit of the specific class. Thus the impacts of each of the three units in isolation as also the cumulative impact of the three units taken together are evaluated from the computational work.

Table 3. National Ambient Air Quality Standards (NAAQS) of India

Pollutant	Time Weighted Average	Concentration in Ambient Air [$\mu\text{g}/\text{m}^3$]		
		Industrial Area	Residential, Rural and other Areas	Sensitive Area
Sulfur Dioxide (SO ₂)	Annual Average*	80	60	15
	24 Hours Average**	120	80	30
Oxides of Nitrogen as NO ₂	Annual Average*	80	60	15
	24 Hours Average**	120	80	30
Suspended Particulate Matter	Annual Average*	360	140	70
	24 Hours Average**	500	200	100
Respirable Particulate Matter (Size less than 10 μm)	Annual Average*	120	60	50
	24 Hours Average**	150	100	75

* Annual Arithmetic mean of minimum 104 measurements in a year twice a week 24 hourly at uniform interval.

** 24 hourly/8 hourly values should be met 98% of the time in a year. However, 2% of the time, it may exceed but not on two consecutive days.

Note

1. National Ambient Air Quality Standard: The levels of air quality necessary with an adequate margin of safety, to protect the public health, vegetation and property.
2. Whenever and wherever two consecutive values exceed the limit specified above for the respective category, it would be considered adequate reason to institute regular/continuous monitoring and further investigations.
3. The State Government / State Board shall notify the sensitive and other areas in the respective states within a period of six months from the date of notification of National Ambient Air Quality Standards [Four parameters relevant to the present study are shown]

The detailed results of 24 hourly maximum GLC values are shown in Table 4. This table includes 24 hourly maximum predicted GLC values of SO₂, respective receptor co-ordinates, resultant values and comments as per NAAQS of India.

It can be seen from the table that the 24 hourly maximum GLC values of SO₂ for Case 1 and Case 2 would be 31.26 $\mu\text{g}/\text{m}^3$ and 52.11 $\mu\text{g}/\text{m}^3$ respectively. The respective resultant values were found to be 53.26 $\mu\text{g}/\text{m}^3$ and 74.11 $\mu\text{g}/\text{m}^3$ and were conformed to the value of Rural and Residential area specified in the NAAQS of India. Case 3 while yielded 24 hourly maximum GLC value of 109.31 $\mu\text{g}/\text{m}^3$ with the resultant value of 131.31 $\mu\text{g}/\text{m}^3$ that was well above the value of Industrial area stipulated in the NAAQS of India. Therefore, further computational work was necessary considering installation of FGD system having 80% SO₂ removal efficiency in the Sponge iron plant [Case 3(a)]. The 24 hourly maximum GLC value and the respective resultant value achieved were 26.11 $\mu\text{g}/\text{m}^3$ and 48.11 $\mu\text{g}/\text{m}^3$ both of which were well below the value of Industrial area stipulated in the NAAQS of India. Furthermore, these values were well within the value of Rural and Residential area specified in the NAAQS of India. The cumulative impact of SO₂ emission from all these three proposed industrial units (Cases 1, 2 and 3) were further predicted and observed that the 24 hourly maximum

GLC value would be $156.34 \mu\text{g}/\text{m}^3$ with the resultant value of $178.34 \mu\text{g}/\text{m}^3$. These values were well above the value of Industrial area stipulated in the NAAQS of India. Further, it was suggested to consider Case 3(a) in addition to Case 1 and Case 2 to predict the cumulative impact of SO_2 emission and found that the 24 hourly maximum GLC value was $77.22 \mu\text{g}/\text{m}^3$ with the resultant value of $99.22 \mu\text{g}/\text{m}^3$. Though the absolute cumulative value of $77.22 \mu\text{g}/\text{m}^3$ was below the value stipulated for Rural and Residential area stipulated in the NAAQS of India, the resultant value of $99.22 \mu\text{g}/\text{m}^3$ was 25% higher than $80 \mu\text{g}/\text{m}^3$, the value stipulated for Rural and Residential area and is falling under Industrial area specified in the NAAQS of India. The location of the three industrial units and their 24 hourly maximum GLC values are shown in Figure 3 on a 50×50 grids covering an area of $50 \text{ km} \times 50 \text{ km}$. The cumulative impacts were also shown in the figure. The location of the power plant having capacity of $2 \times 500 \text{ MW}$ was considered Case 1 and its co-ordinate was fixed at (25 km, 25 km). Accordingly, the co-ordinates of other units were located. Figure 3 also described the receptor numbering system for the present study. This would help in understanding the receptor location with the specific Cartesian co-ordinate system.

Table 4. Maximum 24-hourly and 1-hourly GLC values in $\mu\text{g}/\text{m}^3$

Cases Studied	24-hourly max GLC value	Receptor Co-ordinate	Resultant Values Background value = 22	Comments as per NAAQS of India
Case 1	31.26	45,18	$31.26 + 22 = 53.26$	Rural & Residential
Case 2	52.11	29,4	$52.11 + 22 = 74.11$	Rural & Residential
Case 3	109.31	36,32	$109.31 + 22 = 131.31$	Industrial
Case 3(a) [with 80% FGD]	26.11	34,32	$26.11 + 22 = 48.11$	Rural & Residential
Case 4	156.34	43,12	$156.34 + 22 = 178.34$	Industrial
Case 4(a) [Case 1 & 2 + 80% FGD at Case 3]	77.22	41,12	$77.22 + 22 = 99.22$	Industrial

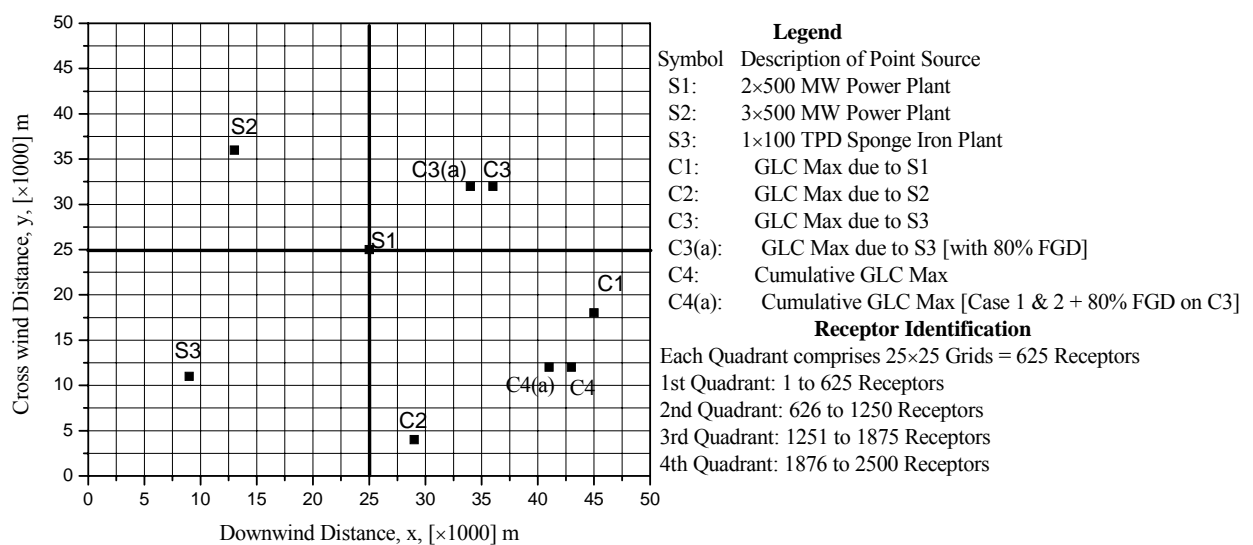


Figure 3. Location of three industrial units with predicted receptor locations for attaining 24 hourly maximum GLC values

The prediction was processed to compute maximum GLC values for 24 hour, 1 hour, 3 hour, 8 hour and 12 hour averaging periods. Maximum GLC values were then arranged in descending order with respect to 24-hourly averaging periods. Such detailed break up of maximum GLC values obtained through the rigorous computational work for Case 1 as a typical case has been detailed in Table 5 for our improved understanding.

Table 5. Case study 1: maximum 24 hourly GLC of SO₂

Receptor No.	Maximum GLC of SO ₂ (µg/m ³)				
	24 Hr	1 Hr	3 Hr	8 Hr	12 Hr
1946	9.93	123.75	79.45	29.79	19.86
2126	9.72	121.63	77.78	29.17	19.45
2108	9.63	119.64	77.01	28.88	19.25
1884	9.60	120.28	76.83	28.81	19.21
2428	9.53	117.37	76.27	28.60	19.07
2144	9.35	117.38	74.83	28.06	18.71
1984	9.18	114.56	73.41	27.53	18.35
2266	9.12	112.83	72.97	27.36	18.24
1983	9.03	113.42	72.26	27.10	18.07
1909	8.99	112.72	71.91	26.97	17.98
1889	8.91	111.29	71.27	26.73	17.82
1863	8.83	110.97	70.63	26.49	17.66
1905	8.76	109.78	70.06	26.27	17.51
1879	8.73	109.65	69.82	26.18	17.46
2501	8.42	105.84	67.35	25.26	16.84
2456	8.40	102.75	67.19	25.20	16.80
2345	8.34	104.82	66.68	25.01	16.67
2134	8.28	104.17	66.25	24.85	16.56
2098	8.20	102.98	65.58	24.59	16.40
2269	8.07	99.93	64.53	24.20	16.13
1987	8.05	101.07	64.38	24.14	16.10
1945	7.93	99.72	63.45	23.79	15.86
2230	7.89	98.87	63.13	23.67	15.78
2056	7.83	94.50	62.60	23.48	15.65
1933	7.79	97.38	62.30	23.36	15.58
2104	7.73	95.92	61.81	23.18	15.45
2339	7.63	95.96	61.05	22.89	15.26
2114	7.48	93.90	59.88	22.45	14.97
2090	7.37	89.17	58.98	22.12	14.74
2149	7.20	89.73	57.57	21.59	14.39
2185	7.09	89.16	56.70	21.26	14.18
2354	7.07	88.90	56.58	21.22	14.15
2057	7.06	88.74	56.49	21.18	14.12
2147	6.83	85.78	54.67	20.50	13.67
2534	6.77	82.52	54.13	20.30	13.53
2323	6.62	83.29	52.98	19.87	13.24

6. Recommendations

The computational results clearly revealed that the 24 hourly maximum GLC values under worst scenario for Case 1 and Case 2 in isolation would not affect the air quality in respect of SO₂ discharge from the stacks in the surrounding area. In contrast, Case 3 affect the air quality adversely but suggesting FGD system having 80 % SO₂ removal efficiency drastically reduced the 24 hourly maximum GLC value. The cumulative impact of Cases 1, 2 and 3 showed adverse predicted value while Case 3(a) that assumes FGD system having 80 % SO₂ removal efficiency resulted in the predicted value of 24 hourly maximum GLC of SO₂ favorable. It is therefore, recommended that these three industrial units would be permitted to be established with the condition that the sponge iron plant should have a FGD system that is at least 80 % efficient in removing SO₂ from the waste gas stream of the sponge iron plant. Since Gaussian dispersion modeling does not take into account any chemical reaction, the model reported in this article can be squarely applicable for similar other pollutants like particulate matter, NO_x etc. emitted in association with the SO₂ from stacks.

7. Conclusions

Gaussian dispersion modeling necessitates the knowledge of stability of the atmosphere, mixing height, plume rise, dispersion parameters etc. In India, the methods of obtaining values of these parameters are all taken from available literatures and to ascertain their applicability in Indian context has not gained any attention. Validation of these formulations is thus necessary through extensive monitoring of various parameters. It is thus aimed in this article to propose computational algorithm in order to validate these formulations through extensive monitoring of various parameters. In the process, various strategies of pollution control are elucidated so that the most appropriate combination of industrial activities would be chosen for arriving at an environment friendly air quality. An assessment of suitability of a site for setting up of new industry would thus be possible. However, the full strength of the model proposed can only be exploited if sufficient information on environmental parameters is available for reasonable period of time. In view of the fact of sparse Indian mixing height data, efforts are needed to generate mixing height data.

Broadly four different cases were analyzed based on worst scenario. Results obtained through prediction were compared with NAAQS of India. One specific case found to overshoot the ambient air quality adversely in respect of SO₂ and was therefore, suggested to install a FGD system with at least 80 % SO₂ removal efficiency. With this recommendation, the cumulative prediction yielded a very conservative resultant value of 24 hourly maximum GLC of SO₂ as against a value that exceeded well above the stipulated value without considering the FGD system. The computational algorithm developed can be gainfully utilized for the purpose of EIA analysis in Indian condition.

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