551.551.8 : 551.511.12 (545)

Atmospheric diffusion model for Delhi for regulatory purposes

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सार — शहरी क्षेत्र में एक घंटे से लेकर पूरे दिन उपस्थिति रहने वाले स्थायी प्रदूषकों वाली वायु की गुणता का अनुमान लगाने के लिए एक नि-दर्श विकसित किया गया है । बिंदु स्रोतों के लिए स्थायी स्थिति गांस विसरण समीकरण और क्षेत्रीय स्रोतों के लिए उसके समाकलन का उपयोग किया गया है । क्षेत्र एवं बिंदु स्रोतों का चारों ऋतुओं में से किसी भी ऋतु में दिल्ली में सल्फर डाइआक्साइड का इस निदर्श से निकाला गया, 24 घंटे का अधिकतम औसत सांद्रण संयुक्त र,ज्य पर्यावरण संरक्षण अभिकरण के प्राथमिक वायुगुणता मानकों से अधिक नहीं है । लेकिन दिल्ली के औद्योगिक क्षेत्रों के इर्द-गिर्द के दिल्ली के कुछ स्थलों में 24 घंटे का अधिकतम सांद्रण संयुक्त राज्य पर्यावरण संरक्षण अभिकरण क द्वितीयक मानकों से अधिक है ।

ABSTRACT. To assess the air quality over short periods of the order of an hour to a day of relatively stable pollutants over an urban area, a model has been developed. The steady state Gaussian diffusion equations for point sources and their integration for area sources have been utilised. The maximum concentrations of sulphur dioxide averaged over 24 hours by this model during any of the four seasons at Delhi due to area and point sources, has not exceeded United States Environmental Protection Agency's (US EPA) Primary Air Quality Standards. However, in some pockets in Delhi around industrial areas, 24-hour maximum concentration exceeded US EPA secondary standards.

1. Introduction

Urban planners often are required to know the effects of new source locations to adopt control strategies over short term air quality. Also by knowing the meteorological conditions a day in advance with reasonable accuracy, they would like to predict ambient air quality levels primarily over the 24 hours averaging time which could also be used in designing monitoring network in urban area. With this in view a model based on steady state Gaussian diffusion equations to provide short term concentration (24 hours) has been developed to determine urban air quality resulting from pollutants released from point and area sources. This model is applicable for locations with level or gently rolling terrain where a single wind vector for each hour is a reasonable approximation of the flow. A single mixing height and a single stability class for each hour are considered representative of the area. This model is applicable for non-reactive pollutants.

2. Methodology

A narrow plume hypothesis (Turner 1978) has been used for calculating short term concentration of area sources at various distances on a line directly upward from receptor. Area source sizes are used as given in the emission inventory. Emission data used for point sources consist of source coordinates, pollutant emission

rate, physical stack height and exit diameter and heat emission rate. Emission information for area sources consists of southwest corner coordinates, source side length, total area emission rate and effective area source height.

It has been assumed that the dispersion from point and area sources result in Gaussian distribution in both the horizontal and vertical directions through the dispersing plume and therefore steady state Gaussian plume equations have been used for point sources and the integration of these for area sources. Concentration estimates have been made for each hourly period using the mean meteorological conditions appropriate for each hour.

Based on the hourly surface wind speed and cloud data hourly stabilities have been determined using Pasquill Turner Scheme (Holzworth 1974). It is well known that the lower atmosphere upto first few hundred feet over a city is well mixed due to enhanced surface roughness and the heat capacity. Hence it becomes necessary to consider this lower atmosphere to be adiabatic even if the rural stabilities obtained by Turner Scheme are stable. It has been always customary that the stabilities of the atmosphere over a city have to be upgraded by one letter category of what has been obtained by Pasquill Turner Scheme. For instance, A class condition in the rural environment is replaced
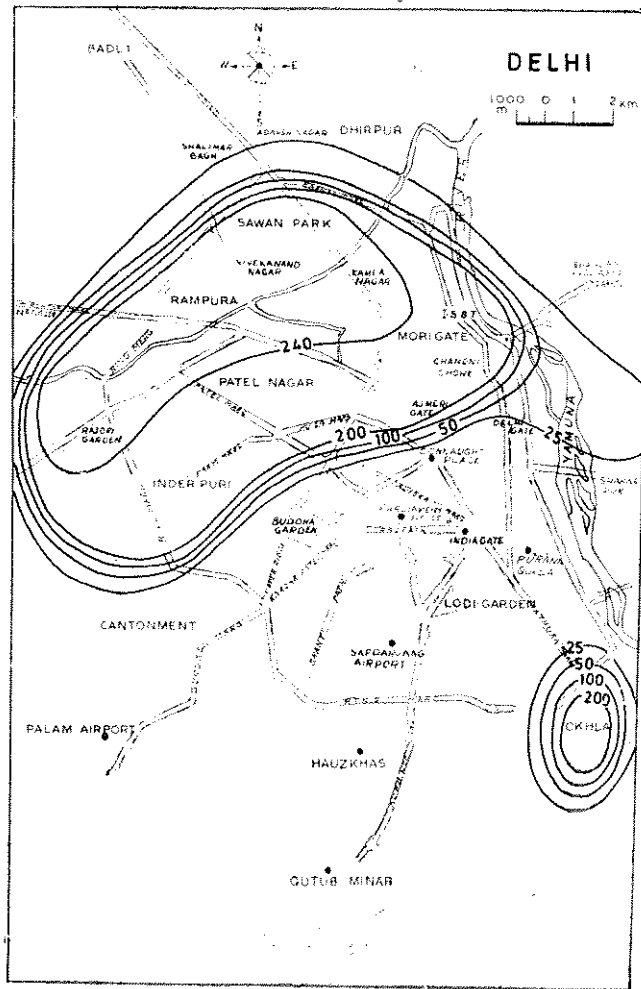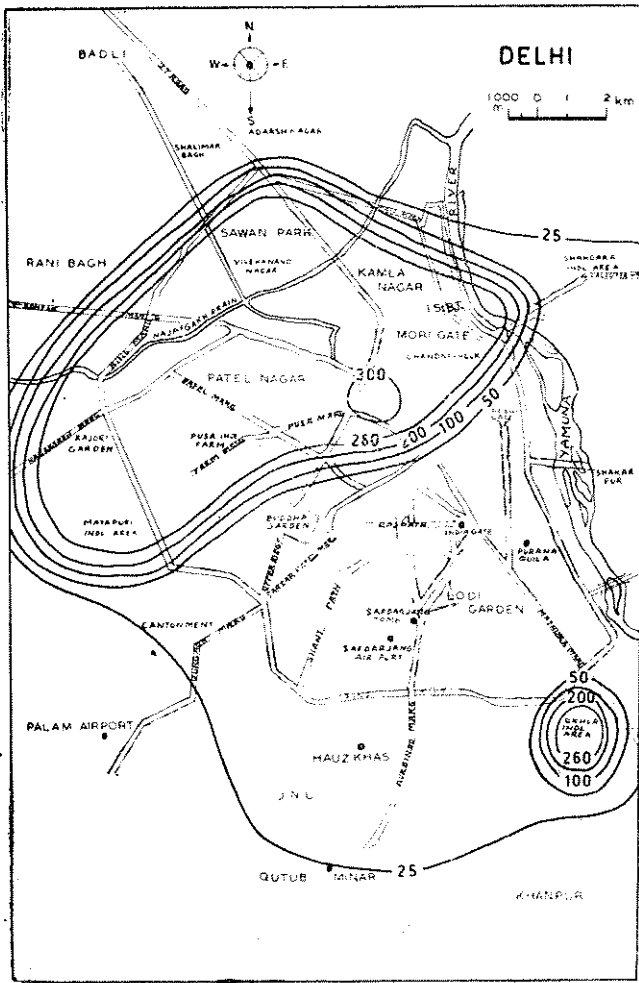
Fig. 1. 24 hours maximum sulphur dioxide concentration (μg/m³) during pre-monsoon of 1976

Fig. 2. 24 hours maximum sulphur dioxide concentration (μg/m³) during monsoon of 1976

by Class B over a city. This has been compensated by using appropriate equations of σ_y and σ_z valid for urban area applicable to rural stabilities recommended by Briggs (Gifford 1976). Hourly urban mixing depths have also been calculated by utilizing radiosonde data of Yahya Nagar and hourly surface temperature of Safdarjung Observatory according to Ludwig technique (1970).

The effect of heat island (difference between urban and rural temperatures) and the enhanced roughness has been considered upto 300 m (Tyson et al. 1973).

In order to calculate short term concentrations from point sources, the upwind distance x and the crosswind distance y of each source from each receptor are calculated according to the following equations :

$$x = (S_p - S_r) \cos \theta + (R_p - R_r) \sin \theta \qquad (1)$$

$$y = (S_p - S_r) \sin \theta - (R_p - R_r) \cos \theta \qquad (2)$$

where R_p, S_p are the E-W and N-S coordinates of the point source and R_r, S_r are the E-W and N-S coordinates

of the receptor and θ is the wind direction (the direction from which the wind blows starting from north in the clockwise direction).

The contribution to the concentration ψ_p (gm/m³) from a single point source to a receptor at the ground is given by one of the three following equations for stable condition or unlimited mixing :

$$\psi_p = \frac{Q}{\pi u \sigma_y \sigma_z} \, e^{-\frac{H^2}{2\sigma_z^2}} \, e^{-\frac{y^2}{2\sigma_y^2}} \qquad (3)$$

where Q is the point emission rate in gm/sec, u is the wind speed in m/sec at the top of the stack, obtained from power law, σ_y & σ_z are the standard deviations of plume concentration distribution in the horizontal and vertical as function of upward distance x and stability class (Holzworth 1974) and H (m) is the effective plume rise obtained from modified Lucas formula (Padmanabhamurty & Gupta 1980).

In unstable or neutral conditions and if σ_z is greater than 1.6 times the mixing depth (L), the distribution

TABLE 1

24-hr maximum ground level concentration (μg/m³) of sulphur dioxide

Season	Location	Computed by the present model	Measured by NEERI
Pre-monsoon	Netaji Nagar	30	22
	Town Hall	200	66
	Fire Station, Moti Nagar	270	474
Monsoon	Netaji Nagar	15	13
	Town Hall	110	60
	Fire Station, Moti Nagar	250	83
Post-monsoon	Netaji Nagar	30	67
	Town Hall	260	130
	Fire Station, Moti Nagar	340	65
Winter	Netaji Nagar	20	30
	Town Hall	200	109
	Fire Station, Moti Nagar	290	135

below the mixing height is uniform with height provided that the effective height, H is below the mixing height :

$$\psi_p = \frac{Q}{(2\pi)^{1/2} u \, L \sigma_y} e^{-\frac{y^2}{2\sigma_y^2}} \tag{4}$$

In all other unstable or neutral condition, that is, if σ_z is less than 1.6 times the mixing height :

$$\psi_p = \frac{Q}{2\pi u \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} \left[\sum_{N=-4}^{N=+4} e^{-\frac{(2NL-H)^2}{2\sigma_z^2}} + e^{-\frac{(2NL+H)^2}{2\sigma_z^2}} \right] \tag{5}$$

Likewise the concentration due to one point source on all the receptors have been calculated and the same procedure has been repeated with other point sources also.

In the case of area sources, they are considered to have an effective stack height of 10 m, thus requiring

the integration of Eqns. (6) to (8) to be performed numerically. The short term concentration from area source at all the receptors is determined by performing the integration using Simpson's technique (McCormick 1968) in the upwind direction until the farthest end of the source boundary is reached.

The Eqn. (1) is used to determine the upwind distances (x) for all the four corners with coordinates (R_p, S_p) from a receptor with coordinates (R_r, S_r). If all x's are negative for all four corners, indicating the entire area source is downwind, no calculation is performed. Among all four x's the minimum x is negative, the minimum is considered zero as no computation-need to be performed for that portion of the area source downwind of the receptors.

The short term concentration ψ_A (gm/m³) from a uniform area source directly upwind of a receptor at the ground has been calculated by one of the three following equations for stable conditions or unlimited mixing :

$$\psi_A = \frac{Q_A}{u_{10}} \int_{x_1}^{x_2} \frac{2 \exp\left[\frac{-(10)^2}{2\sigma_z^2}\right]}{\sigma_z (2\pi)^{1/2}} \, dx \tag{6}$$

where Q_A is the area source emission rate in gm/ m²/sec, u_{10} is the wind speed at 10 m height in m/sec, x_1 is the distance in m from the receptor to the locus of upwind ray (extending from the receptor) and the closest boundary of the area source.

x_2 is again the distance from the receptor to the locus of the upwind ray (extending from the receptor and the distant boundary of the area source). The integral has been evaluated numerically using Simpson's technique (McCormick 1968).

$$I = \frac{h}{3} (y_0 + 4y_1 + 2y_2 + 4y_3 + 2y_4 + \dots + \\ + 2y_{n-4} + 4y_{n-3} + 2y_{n-2} + 4y_{n-1} + y_n)$$

where,

$$h = (x_2 - x_1)/n, \quad n \text{ is an even integer}$$

In unstable or neutral conditions, and if σ_z is greater than 1.6 times the mixing height, L, the distribution below the mixing height is uniform with height, provided the effective height, H, is below the mixing height:

$$\psi_A = \frac{Q_A}{u_{10}} \int_{x_1}^{x_2} \frac{dx}{L} \tag{7}$$

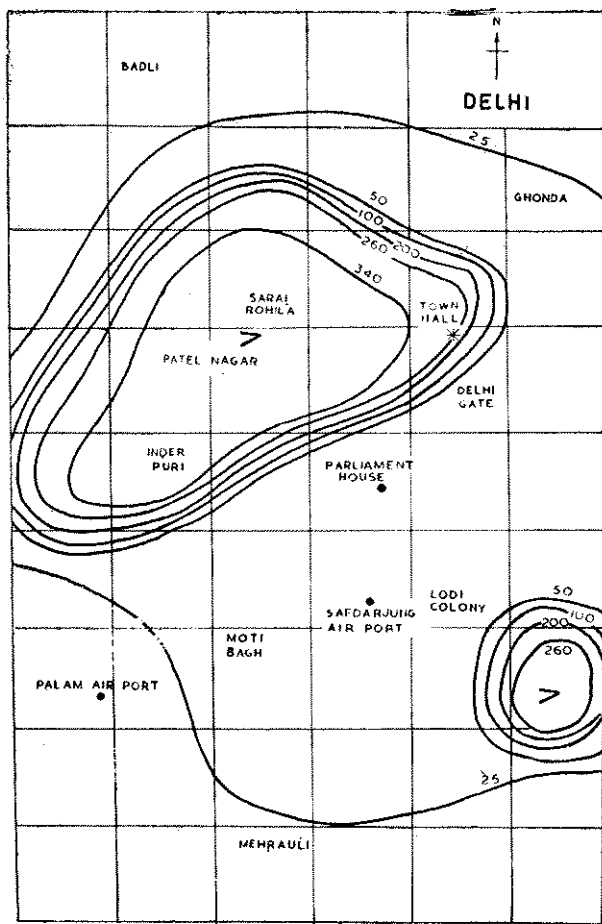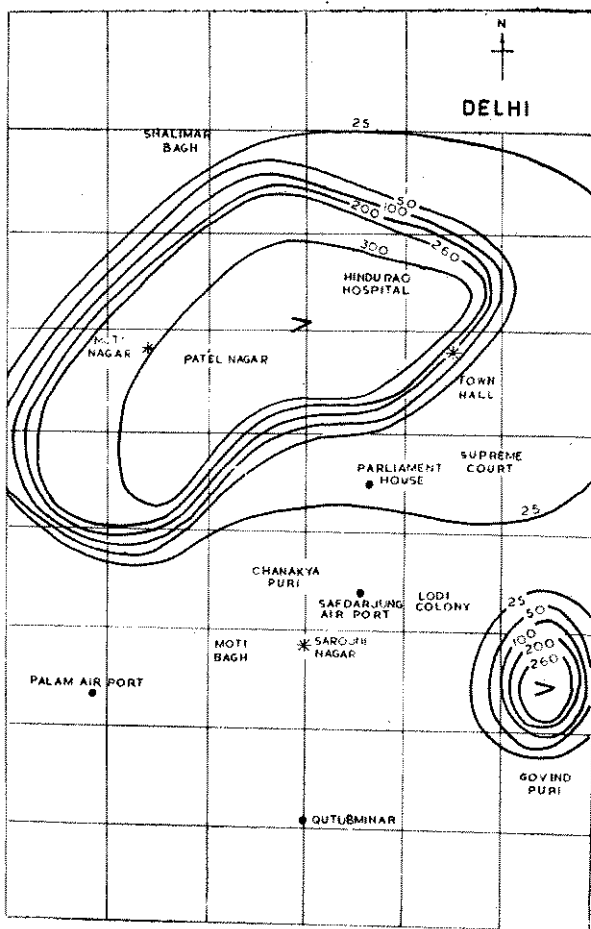Fig. 3.   24 hours maximum sulphur dioxide concentration (μg/m^3) during post-monsoon of 1976

Fig. 4.   24 hours maximum sulphur dioxide concentration (μg/m^3) during winter of 1976

In all other unstable or neutral conditions, that is, σ_z is less than 1.6 times the mixing height:

$$\psi_A = \frac{QA}{u_{10}} \int_{x_1}^{x_2} \left[e^{\frac{-(2NL-H)^2}{2\sigma_z^2}} \frac{}{\sigma_z(2\pi)^{1/2}} + \sum_{n=-4}^{n=4} \right.$$

$$\left. + e^{\frac{-(2NL+H)^2}{2\sigma_z^2}} \frac{}{\sigma_z(2\pi)^{1/2}} \right] dx \qquad (8)$$

The numerical integration using Simpson's technique is done using varying size intervals as small as 1 metre for x less than 100 metres and as large as 1 km for x greater than 20 km. The concentration from the area sources are computed receptor by receptor.

Computations are performed hour by hour as if the atmosphere had achieved a steady-state condition. Therefore, an error will occur where there is a gradual build up (or decrease) in concentrations from hour to hour such as change of stability and with light wind conditions. Also under light wind condition the definition of wind direction is likely to be inaccurate and coordinates in the wind flow from location to location in the area are quite variable.

3. Data used

3.1. Emission inventory

Emission of sulphur dioxide in Delhi from 360 industries in six industrial belts is estimated to be 175 tonnes of sulphur dioxide per day. Likewise the emission of sulphur dioxide from automobiles is estimated to be 2 tonnes/day. The elevated sources in Delhi are Indraprastha Thermal Power Plant and Raj Ghat Power Plant: emission data of which have been obtained from Delhi Electricity Supply Undertaking. Delhi has been divided into 9×6 square grids of 4 km each, i.e., nine grids from north to south and six grids from east to west. The total estimated discharge of sulphur dioxide is 175 tonnes/day and is considered to have been released uniformly from the six industrial belts falling in 12 grids. The area source emission thus comes out to be 1.0 $\mu g/m^2$-sec from those 12 grids. Similarly, vehicular traffic discharge of 2 tonnes/day is considered to have been released uniformly from 21 traffic artery grids which came out to be 0.07 $\mu g/m^2$-sec.

3.2. Meteorological data

As the terrain features of Delhi are more or less flat, meteorological data from a single location are considered to be reasonably good for the entire area. There-fore, hourly wind speed, direction, temperature, cloud amount and their heights recorded at Safdarjung Observatory have been utilised. Radiosonde data from Yahya Nagar Observatory has been used to calculate the urban mixing depth.

4. Results and discussion

24-hour (maximum) concentration of sulphur dioxide $(\mu g/m^3)$ at the centre of each grid during all four seasons, i.e., pre-monsoon, monsoon, post-monsoon and winter of 1976 due to area sources, elevated sources and vehicular traffic were plotted and isopleths were drawn in Figs. 1 to 4. Environmental Protection Agency of US have designed two standards, primary and secondary standards where primary standards are designed to protect the public health while secondary standards are designed to protect public welfare from any known or anticipated adverse effects of pollutants. It can be seen that there is not even one instance when 24 hours maximum concentration of sulphur dioxide exceeded EPA primary standards (365 $\mu g/m^3$). But 21 hrs maximum values of ground level concentrations of sulphur dioxide have exceeded secondary standards (260 $\mu g/m^3$) during pre-monsoon, post-monsoon and winter season mainly in two pockets. One pocket is comprising of complete western part of Najafgarh industrial zone extending upto Chandni Chowk of Delhi in the east, Pusa Road in the south and Viveka Nagar in the north. The second pocket confines only to Okhla Industrial area and its surroundings. In general, it has been found that ground level concentrations are maximum in post-monsoon than in winter in comparison to pre-monsoon and it is least in monsoon. This difference is only due to low ventilation coefficients in post-monsoon and winter seasons. A comparison with the monitored values by NEERI (1980) shown in Table 1 points out that the model in general gives higher values than the monitored values. It is well known that Gaussian distribution always predicts higher values of short term concentration and the longer the averaging time the greater will be the proximity to the monitored values.

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