ELSEVIER
Journal of Hazardous Materials B81 (2001) 33–65
Journal of Hazardous Materials
www.elsevier.nl/locate/jhazmat

Effective design of greenbelts using mathematical models

Faisal I. Khan[1], S.A. Abbasi*

Centre for Pollution Control and Energy Technology, Pondicherry University, Pondicherry 605 014, India

Received 23 August 1999; received in revised form 30 June 2000; accepted 3 July 2000

Abstract

Trees, shrubs, and other vegetation can absorb and assimilate certain air pollutants if the pollutants are present within tolerable levels. This concept is being increasingly used in developing strips of vegetation, often called 'greenbelts' around sources of pollution.

But several intricacies are associated with the exercise of effective and optimal designing of greenbelts. The pattern of dispersion of air pollutants, as effected by the density of the gaseous plume and the meteorology of the area, must be studied with great precision because these aspects would determine the location and the geometry of the greenbelt. The species composition in the greenbelt should confirm to the pollutants to be attenuated as to the geoclimatic conditions of the region. Decisions on the tree heights, and the sequence of plantation of trees and other vegetation also similarly require complex inputs.

In this paper, the authors have addressed these issues and have presented a set of mathematical models, which may help in the rational and optimal design of greenbelts.

Keywords: Greenbelt design; Air pollution control; Environmental modelling

1. Introduction

A large number of gaseous and particulate air pollutants are emitted in the air environment. The physical and chemical properties and effects of these pollutants vary a great deal individually and synergistically. The nature and quantum of pollutant depends on the type of industry and the kind of raw material and energy used in its operation.

* Corresponding author. Tel.: +91-413-655363; fax: +91-413-65227/65565.
E-mail address: prof_abbasi@vsnl.com (S.A. Abbasi).
[1] Present address: Visiting Research Professor, The Memorial University of New Foundland, St. John, NF, Canada.

PII: S0304-3894(00)00288-0

The development of greenbelt (GB) around industries, by using pollution tolerant plants, can significantly contribute towards air quality improvement. This involves selecting suitable plant species, determining climatic parameters, studying wind and temperature profiles, nature of pollutants to be ameliorated, and general landscape of the locality. The design of the GB and its composition may vary from place to place and industry to industry. A general social forestry or tree plantation type approach will not be of much help in industrial plantations [1,21].

The planning of GB, shelter-belt, or pollution-sinks also involves bioaesthetics. Accordingly the selection of plant species is based on numerous plant characteristics, like tolerance, canopy structure, foliage form, height of plant and its overall flowering and production potential. This involves careful scrutiny of plants in nature as well as in horticultural conditions, in order to assess their suitability and performance in a stressed ecological situation of polluted environment.

It has been seen that the pollutants emanating from thermal power plants, cement factories, metal processing plants, lime and brick kilns, pulp and paper factories, fertiliser plants, mining area and quarries, oil refineries, etc., though varying in their physical and chemical properties, are identical with respect to their effects on plant, animal and human life [20,21].

The pollutants thus coming out from various sources may remain suspended for some time in the air-shed, but these eventually get deposited either as wet deposition or dry deposition on surfaces of vegetation, soil, water, buildings and other properties. These may also be deposited on outer surfaces of animal bodies or inhaled into their lungs.

The effect of these pollutants, either adsorbed on the surface or absorbed inside the system of plants will depend on the characteristics of the impinging surface and chemistry of the pollutant. In the case of plants, all the external and internal factors which affect the stomatal aperture will also affect the level of pollution interacting on plants. Several methods have been developed to evaluate the suitability of plants for the purposes mentioned above. Biomonitoring of air pollutants through the use of plants, microbes and animals has now become a standard procedure in the study of air pollution ecology [1,20,23,25,27].

According to Innes (Khan and Abbasi [11]), tree barriers between Industrial and residential areas can also reduce air pollution considerably. A plantation of 30 m depth gives almost complete dust interception and significant reductions in gaseous pollutant concentrations. Even a single row of trees can reduce pollution levels markedly if it is planted on green verges with or without an underlay of shrubs. One row can lead to 25% reduction of dust concentration observed in tree-lined streets. Free circulation of air within the canopy of a tree barrier also helps to promote the filtering of pollutants. The noise is also significantly reduced by tree barriers of <30 m depth. Furthermore, the cosmetic and psychological benefits of plantings are considerable.

Innes has argued that planting techniques such as contouring can help to reduce the impact of pollution on the area surrounding each source. The landscape architect can thus assist local planning authorities and industry by situating landscaping schemes around industrial and residential sites that will help to ameliorate the level of air pollution. Grass swards absorb twice as much of some pollutants as does bare soil. The scavenging effect increases with the inclusion of shrubs and trees. Thus, the average concentration of a pollutant in the atmosphere declines with increasing proportions of well-planted open space in industrial and urban areas [11].

1.1. The main objectives of greenbelt design (GB)

GB development envisages a multiplicity of objectives ranging from the micro-level air pollution abatement to enhancement of socio-economic values of the region. The prime objectives of GB is attenuation of air and noise pollution. It may also serve as a cushion against accidental fires, explosions, and toxic releases [12]. The additional benefits of GB are protection of soil from erosion, improving the micrometeorology of the area, and beautification of the landscape. Yet another major benefit can be generation of employment and fostering a sense of participation in lay people towards environmental protection.

1.2. Factors influencing the design of greenbelt

Green belt development mainly depends upon:

1. climatic factors;
2. nature and extent of pollution load;
3. assimilative capacity of the ecosystem; and
4. soil and water quality.

For optimum design of greenbelt, the key variables to be considered are:

1. height and canopy of trees,
2. mean wind velocity and direction,
3. distance from source or occurrence of maximum ground level concentration,
4. pollutant concentration,
5. nature of pollutants,
6. dry deposition velocity of plants (specific to pollutants and plants), and
7. topography and size of the land available.

2. Process of effective greenbelt design

We have emphasised the word 'effective' because until a greenbelt is designed on the basis of scientific studies — taking into account the nature of pollutant sources, the wind directions and other meteorological factors, and the way pollutants shall be dispersed during different seasons — it may not be effective.

It is a popular misconception that pollution emanating from an industry can be reduced *effectively* just by surrounding the industry with a greenbelt. In reality a great deal of sophistication, based on mathematical modelling and validation, is needed to design *effective* greenbelts because the gaseous pollutants do *not* uniformly and radially disperse from the source of emission but travel in certain directions dictated by various factors including (Fig. 1), among others:

(a) density, exit temperature and exit height of the pollutant gases;
(b) meteorology of the area;
(c) terrain characteristics, etc.

Gases emanating from an industry may not come close to the ground until they are several thousand meters from the point of emission. If a greenbelt is developed just close to such an

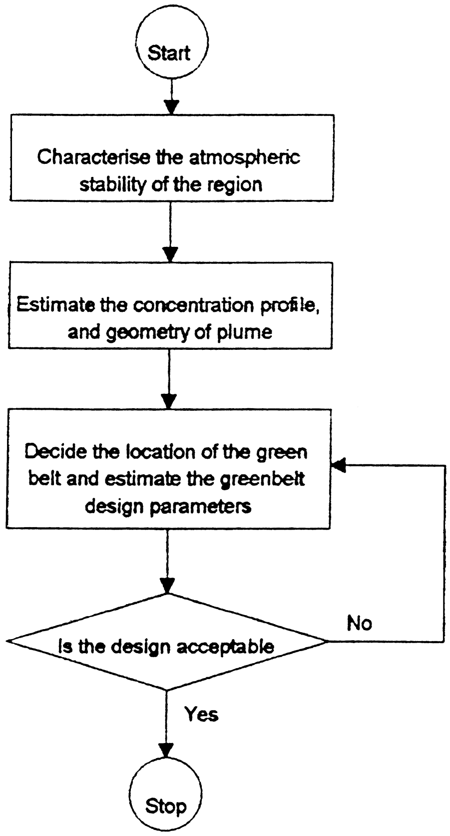

Fig. 1. The process of greenbelt design.

industry (and if it ends before the pollutant plume comes close to the ground), the greenbelt may serve no purpose at all. Likewise, a greenbelt need not be a strip of uniform width — indeed in most situations it would be a strip of *varying width,* the geometry of which would be dictated by factors such as the ones enumerated above.

Furthermore the species of trees and other vegetation that a greenbelt should contain is again dictated by several factors, of which local soil/water conditions are one set of guiding parameters. The type of pollutants that are to be controlled is a key governing aspect. It thus becomes necessary to have a tool based on gaseous dispersion modelling to help us decide the geometry of the greenbelt and its effective location. It is equally necessary to have knowledge-based systems developed on the premises of such specialized information as pollutant assimilation pathways (physical, chemical, biological, and biochemical), pollutant deposition pathways (dry *deposition*, wet deposition), and impacts of factors such as canopy density and plant anatomy on the control of different types of pollutants.

These steps are briefly described in subsequent sections, for detailed discussion please refer Khan and Abbasi [11,12].

3. Mathematical model for greenbelt design

Attempts to model the process of greenbelt design have been few and far between. After the initial efforts which had focussed on suspended particulate matter (Semel [24], Singh and Rao [26]), significant advancements were made by Gupta, Kapoor, and co-workers [3,7,8]), Smith [28], and Rawat and Banerjee [22]. These authors have developed a body of knowledge considering the atmospheric dispersion of pollutants and the manner of their interception in the greenbelt. We have built upon this work and advanced it in the following terms:

(a) whereas in the previous treatments the dispersion of pollutant plume has been treated as a first order concentration decay phenomena, we have incorporated much more rigorous treatments of pollutant dispersion, as these are central to the decisions on where to locate the greenbelts and how broad the greenbelts should be;
(b) we have also incorporated effects of atmospheric stability on plume shapes as these factors, too, are very important in deciding upon the geometry and the location of the greenbelts;
(c) we have included separate treatments for greenbelts to be located in coastal areas and deeper inland, as meteorological factors influencing dispersion in the two areas are significantly different;
(d) separate treatments have been given for dispersion and control of 'heavy gases'; and for as-dense-as-air and lighter-than-air gases.

The complete process of greenbelt design as developed by us is depicted in Fig. 1. The steps are discussed below.

3.1. Characterisation of atmospheric stability

Characterisation of atmospheric stability is the most important issue related to the dispersion of the pollutants and subsequently their attenuation [9–14,23]. There have been many schemes proposed to estimate the atmospheric stability. Among them, stability characterisation using Mohn–Obukhov length is the one most frequently used by the researchers, as it predicts results with better accuracy than achieved with other stability classifications, and the parameters used in the estimation are easily measurable and are frequently available. Further, it is applicable to most of the site characteristics (semi-urban, coastal, etc.). The algorithm of stability characterisation is presented in Fig. 2.

We have also opted for the Mohn–Obukhov stability characterisation (Ebink [2]) model with coastal effects. In this model the stability is classified using Mohn–Obukhov length (L) and Mohn–Obukhov coefficient (ξ), which are defined as [18]:

$$L = \frac{{U_x}^3 C_\mathrm{p} \rho T}{K_\mathrm{y} g H}$$

$$\xi = \frac{Z}{L},$$

H is the sensible heat flux — can be estimated using the routine meteorological parameters as [5]:

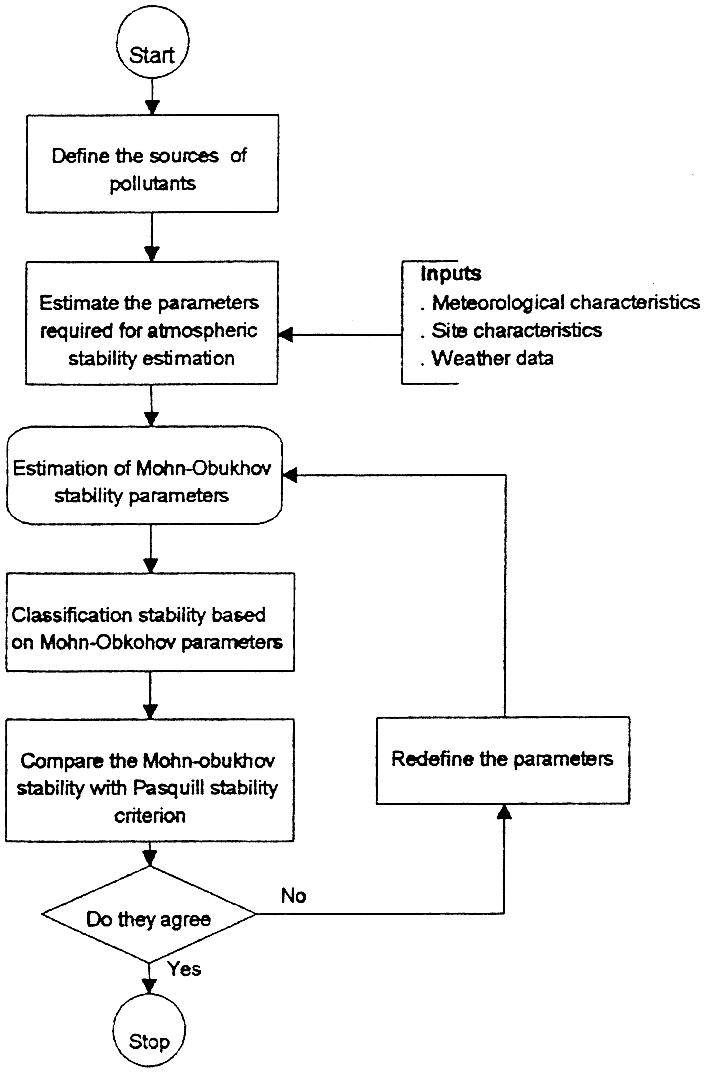

Fig. 2. Steps involved in characterising atmospheric stability.

$$H = \frac{\{(1-\alpha)+(\gamma/s)\}}{\{1+\gamma/s\}}(Q^* - G) - \beta$$

where s is defined as $\partial q_s/\partial T$ — change of humidity with temperature, α and β are the parameters that depends on surface moisture, Q^* the net surface radiation flux can be estimated by applying the balance on heat radiation:

$$Q^* = (1-r)K^+ + L^+ - L^-$$

where K^+ is incoming total solar radiation (W/m^2), L^+ the incoming long wave radiation (W/m^2), L^- the outgoing long wave radiation (W/m^2).

G, the soil heat flux (W/m^2), can be computed using net surface radiation as

$G = C_G Q^*$, where C_G is a constant for which a value of 0.1 is suggested [5].

H can also be estimated using empirical equation [2]:

$$H = 0.4(s - 100)$$

where 0.4 is the empirical constant, and 100 is the value of sensible heat flux at ideal conditions. Compared to the previous equation of H estimation, this equation has limited applicability, but it is simpler and requires only one input parameter. The use of this equation is justifiable if the empirical constant is known for the area under study.

The relationship between Pasquill stability categories and Mohn–Obukhov stability criterion is summarised below

Pasquill stability criterion	Mohn–Obukhov length (L)	Physical significance
A	−2 to 3	Very unstable
B	−4 to −5	Moderately unstable
C	−12 to −15	Slightly unstable
D	∞	Neutral
E	35 to 75	Moderately stable
F	0 to 35	Very stable

4. Pollutant dispersion modelling

This involves study of the dispersion of air pollutants released from various sources under one of the above mentioned atmospheric stability conditions. It includes the estimation of plume path, plume geometry, and concentration of pollutants at various locations. Several broad models have been proposed and these fall in three categories: analytical models; numerical models; and statistical models.

In the present context, analytical models are of particular interest. The other types of models can also be used, but they require large sets of data inputs and higher computational load without producing proportionally better results in terms of precision or accuracy.

On the basis of a detailed study of the available models, and their limitations, we have chosen the modified Gaussian model (Pasquill and Smith [18]; Semel [24]; Khan and Abbasi, [9–11]) to which we have done further modifications appropriate to the application in coastal areas. The set of steps involved in the estimation of dispersion characteristics of a pollutant by this model are presented in Fig. 3.

The equations to be used for concentration estimation are as follows:

$$C(x, y, z) = \left(\frac{Q_0}{2\Pi\sigma_y\sigma_z u}\right) \exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left[\exp\left[\frac{-(z-\mathrm{hh})^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+\mathrm{hh})^2}{2\sigma_z^2}\right]\right]$$

where $\sigma_{y,}\sigma_z$ are the modified dispersion coefficients (standard deviation of concentration in y and z directions), and are estimated using the recently proposed scheme of Erbrink [2];

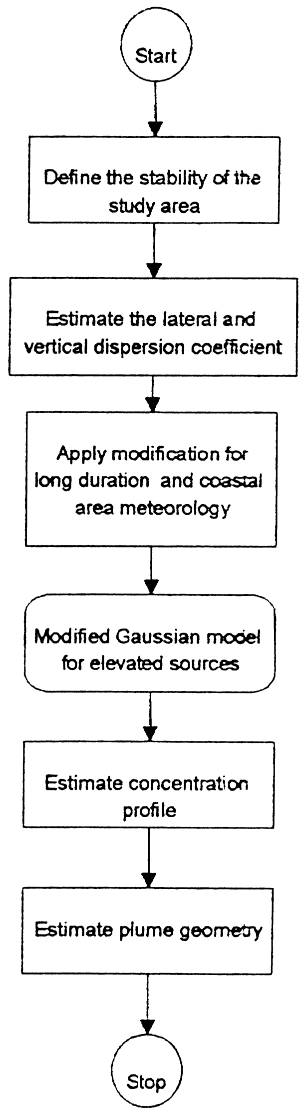

Fig. 3. Steps involved in the estimation of dispersion characteristics.

u is wind speed; x, y, z are the co-ordinates, and hh is the height of release, in other words *effective* height of the source.

The other related characteristics of dispersion used in the design of greenbelts are:

Concentration of pollutants at cloud axis on ground level:

$$C_{\text{cloud}} = \left[\frac{Q_0}{\Pi \sigma_y \sigma_z u}\right] \exp\left[-\frac{\text{hh}^2}{2\sigma_z^2}\right]$$

4.1. Maximum ground level concentration

$$C_{\text{mgl}} = \left[\frac{2Q_0}{e\Pi u \text{hh}^2}\right]\left[\frac{\sigma_z}{\sigma_y}\right]$$

The maximum ground level concentration can also be estimated using the empirical equation:

$$C_{\text{mgl}} = K_{\text{t}}\left(\frac{Q_0}{\text{hh}^2}\right)$$

where K_{t} is constant.

Maximum ground level concentration would occur at

$$\sigma_z = 0.707\text{hh}$$

5. Modifications incorporated to suit long-term application in coastal areas

5.1. Longer duration

Generally, the lateral dispersion coefficient (σ_y) is modelled for 10–15 min of release. But we have wished to develop a model, which can be applicable for long duration (a full day, a month, even a year). To incorporate this effect, a new factor σ_{ywz} has been defined (Lees [15]). This factor modifies the original value of σ_y as:

$$\sigma_y^2 = \sigma_y^2 + \sigma_{ywz}^2$$

where the σ_{ywz} is defined as

$$\sigma_{ywz} = 0.065\left(\frac{7t}{u}\right)^{1/2} X$$

5.2. Coastal area effect

The original model discussed above is generally applicable to flat terrain of nearly constant roughness. Application of this model to the highly urban areas, valleys, or coastal areas may give erroneous results. Therefore, we have modified the model to account for the coastline effect in dispersion estimation. This effect has been accounted using lateral and vertical dispersion coefficient [2,4,6,15,16,29]. These coefficients are modified as:

$$\sigma_y = \sigma_y(R)\left[\frac{x}{R}\right]\alpha$$

$$\sigma_z = \sigma_z(R)\left[\frac{x}{R}\right]\beta$$

where, $\sigma_y(R)$ and $\sigma_z(R)$ are the values of σ_y and σ_z at the reference distance R (=100 m), α and β are indices (Erbink [2]; Lees [15]).

Atmospheric stability	Water (α)	Land (α)	Water (β)	Land (β)	σ_y (R) water	σ_y (R) land	σ_z (R) water	σ_z (R) land
B	0.75	1.00	0.75	1.00	25.0	19.0	10.0	11.0
C	0.70	1.00	0.70	0.90	20.0	12.5	8.0	7.5
D	0.69	0.90	0.65	0.85	15.1	8.0	3.2	4.5
E	0.65	0.80	0.62	0.80	16.1	6.0	1.8	3.5

6. Pollutant attenuation

6.1. Deposition process

Pollutants are attenuated by two different processes: dry deposition and wet deposition. A brief description on estimation of deposition rate and other parameters such as attenuation coefficients, attenuation factor, greenbelt width and density of pollution is presented below.

- Dry deposition and wet deposition are of comparable importance in the ease of SO_x. Dry deposition is most significant where ground level concentrations are high; in other words, close to the source.
- Wet scavenging is defined as the natural process by which atmospheric pollutants are attached or dissolved in a cloud and the pollution droplets are adsorbed on the surfaces (animal or vegetation). The amount of compounds thus received per unit of surface area is defined as wet deposition. Wet deposition is an efficient removal mechanism for soluble gases.
- Another mechanism of deposition is when fog or cloud droplets remove the pollutant directly to the ground or to the vegetation. This is termed as ‘occult deposition’.

The higher the ground level concentration, the more rapid the deposition. Efficiency of deposition, which is also called deposition *velocity*, is defined as:

$$V\,(\text{deposition velocity}) = \frac{\text{deposition rate}}{\text{concentration in air}}$$

Deposition (adsorption) velocity has been measured experimentally for SO_2 and ranges from 5×10^{-3} m/s to 5×10^{-2} m/s . A value 1×10^{-2} m/s is generally assumed.

Deposition (dry and wet) is a series of processes where gas molecules and small particles are entrained from the air stream by turbulent eddies erected by the friction of air mass moving over the forest canopy [28]. Gases/particles that move through the boundary layer surrounding a leaf will either get adsorbed to the surface of the leaf or enter the leaf through stomatal opening. The dry as well as wet deposition flux of gases and particles from the atmosphere to the receptor surface is governed by:

1. concentration in the air and the transport through the boundary layer;
2. the chemical and physical nature of depositing species; and
3. the efficiency of the surface to capture or adsorb gases and particles.

6.2. Resistance analogy

$$R_1(z) = \frac{C(z_1) - C(z_2)}{Q_0}$$

where z_1 and z_2 are two heights and Q_0 the flux of pollutant (kg/s).

Dry deposition rate (mg/cm^2, s)=deposition velocity (cm/s)×pollutant concentration (mg/cm^3). Deposition velocity=rate of deposition/concentration of pollutant in the boundary layer.

Deposition velocity depends on 16 micrometeorological variables, 14 potential characteristics, 4 gas characteristics, and 10 receptor variables [17,19,26]. In general, deposition velocity increases with

1. solubility of pollutant,
2. particle diameter and density,
3. wetness and roughness of surface, and
4. turbulence and wind speed.

Deposition velocity of a few gases determined under managed environmental conditions is as follows:

Species	Deposition velocity (cm/s)
O_3	0.2–0.7
NO	0.01–0.1
NO_2	0.1–0.8
MNO_3	0.5–5.0
NH_3	0.2–0.6
PAN	0.1–0.6
SO_2	0.2–3.0
H_2S	0.2–0.4

Most of the gases have 0.1 cm/s deposition velocity under stable conditions and 10 cm/s in unstable conditions. It is not uncommon to assume a deposition velocity of 1 cm/s for general purpose.

7. Mathematical model for the removal of pollutant by vegetation (Figs. 4 and 5)

In the canopy of greenbelt, the concentration of pollutants is assumed to decrease exponentially [3,7,8,12–14,28].

$$Q_c = Q_A \exp(-\lambda x)$$

where λ is pollutant attenuation coefficient (m^{-1}) and is commonly defined as:

$$\lambda = \frac{K \rho_t V_d}{U_c d}$$

where K is defined as

$$K = \frac{\rho_c}{\rho_t}$$

7.1. Pollutant attenuation factor

The pollutant attenuation factor is defined as

$$AF = \frac{Q_{WB}}{Q_B}$$

where Q_{WB} is pollutant flux without greenbelt and Q_B the pollutant flux exiting from the greenbelt.

The model estimates the source of pollutant at the starting point of the greenbelt using the source depletion equation.

$$Q_x = Q_0 FD(X)$$

FD(X) is source depletion factor as defined by Kapoor and Gupta [7,8]. It is based on a simple Gaussian model, and can be represented as: $FD(X) = [\exp \int_0^x 1/\sigma_z \exp[-h^2/2\sigma_z^2] dx]^{-(2/\Pi)1/2[V_d/U_c]}$, while these authors suggest that FD(X) is nothing but the surface integral of the concentration of the pollutant estimated using latest model (modified PGT in case of light gas while plume path theory based model in case of gases heavier-than-air; [11]). It can be represented as:

$$FD(X) = \int_0^y \int_0^z \text{function } (C(x, y, z, \text{hh}))U(\text{hh})\, dy\, dz$$

Q_x is further divided in two parts, one passes through greenbelt (Q_A), one goes above the greenbelt (Q_{AA}).

$Q_A = Q_x \text{erf}(h_e/\sqrt{2}\sigma_z)$, where erf is error function and defined as:

$$\text{erf}(x) = \frac{2}{\sqrt{\Pi}} \int_0^x \exp(-t^2)\, dt$$

C is the concentration at the edge of greenbelt and can be estimated using dispersion model (modified Gaussian model with additional modifications incorporating effects of coastal area, complex terrain, long duration, etc.)

Finally the pollutant flux going above the greenbelt is estimated as:

$$Q_{AA} = Q_x - Q_A$$

Flux of the pollutant coming out of the canopy:

$$Q_{BC} = Q_A \exp[-\lambda x_2]$$

Flux going above the canopy but depleted due to source depletion:

$$Q_{BA} = Q_{AA} FD(x_2)$$

and

$$Q_{\mathrm{B}} = Q_{\mathrm{BA}} + Q_{\mathrm{BC}}$$

Pollutant flux when greenbelt canopy is not present:

$$Q_{\mathrm{WB}} = Q_0 \mathrm{FD}(x_1 + x_2)$$

Finally,

$$\mathrm{AF} = \frac{Q_{\mathrm{WB}}}{Q_{\mathrm{B}}}$$

On simplification, this equation can be written as:

$$\mathrm{AF} = \frac{\mathrm{FD}(x_1 + x_2)}{\mathrm{FD}(x_1)} \left[\mathrm{erf} \left\{ \frac{h_{\mathrm{e}}}{\sqrt{z}\sigma_z(x_1)} \right\} \mathrm{e}^{-\lambda^{x_2}} + \mathrm{erfc} \left\{ \frac{h_{\mathrm{e}}}{\sqrt{z}\sigma_z(x_1)} \mathrm{FD}(x_2) \right\} \right]$$

where h_{e} can be calculated using

$$\int_0^{h_{\mathrm{e}}} U_{\mathrm{c}}(z)\,\mathrm{d}z = \int_0^{h} U_{\mathrm{e}}(z)\,\mathrm{d}z$$

U_{e} is defined as

$$U_{\mathrm{e}} = \left[\frac{U_x(h)}{(\rho_{\mathrm{c}} h^3 / 2 l_{\mathrm{h}}^2)} \right] [1 - \exp(-a)]$$

where $l_{\mathrm{h}}=k(h-d)$ and k is constant having a value of 0.41.

8. Estimation of the parameters considering interfacial mass exchange

Interfacial mass exchange coefficient (λ^i) in open terrain is given as

$$\lambda^i = \frac{0.1}{x_i}$$

x_i is travel distance x_i where σ_z reaches h/1.625.

Mass flux through the greenbelt canopy (I_0) and above the greenbelt canopy (O_0) is given as (Fig. 5).

$$I_0 = \mathrm{erf} \left\{ \frac{h_{\mathrm{e}}}{\sqrt{2}\sigma_z(x_1)} \right\} \mathrm{FD}(x_1)$$

$$O_0 = \mathrm{erfc} \left\{ \frac{h_{\mathrm{e}}}{\sqrt{2}\sigma_z(x_1)} \right\} \mathrm{FD}(x_1)$$

The complete greenbelt width is divided in n boxes. The flux in the first box is given as:

$$I_1 = I_0\,(\mathrm{e}^{-}\lambda\Delta^{x_2})(\mathrm{e}^{-}\lambda^i\Delta^{x_2}) + O_0 \mathrm{FD}(\Delta x_2)(1 - (\mathrm{e}^{-}\lambda^i\Delta^{x_2}))$$

$$O_1 = O_0 \mathrm{FD}(\Delta x_2)\,(\mathrm{e}^{-}\lambda^i\Delta^{x_2}) + I_0(\mathrm{e}^{-}\lambda^i\Delta^{x_2})(1 - (\mathrm{e}^{-}\lambda^i\Delta^{x_2}))$$

Similarly for *n*th box

$$I_n = I_{n-1}(\mathrm{e}^{-}\lambda\Delta^{x_2})(\mathrm{e}^{-}\lambda^{i}\Delta^{x_2}) + O_{n-1}\mathrm{FD}(\Delta x_2)(1-(\mathrm{e}^{-}\lambda^{i}\Delta^{x_2}))$$

$$O_n = O_{n-1}\mathrm{FD}(\Delta x_2)(\mathrm{e}^{-}\lambda^{i}\Delta^{x_2}) + I_{n-1}(\mathrm{e}^{-}\lambda\Delta^{x_2})(1-(\mathrm{e}^{-}\lambda^{i}\Delta^{x_2}))$$

where $\mathrm{FD}(\Delta x_2)$ can be estimated as:

$$\mathrm{FD}(\Delta x_2) = [\mathrm{FD}(\Delta x_2)]^{1/n}$$

Using these equations finally the AF can be computed as:

$$\mathrm{AF2} = \left[\frac{\mathrm{FD}(x_2 + x_1)}{I_n + O_n}\right]$$

AF2=[source depletion/pollution attenuated due to greenbelt, considering interfacial mass exchange].

The algorithm to solve these models is presented in Figs. 4 and 5.

9. Results and discussion

The results of model solution, for a set of inputs given in Table 1, is presented in Table 2. For a source releasing pollutant at the rate of 45 kg/s in neutral atmospheric conditions at a distance of 1100 m downwind, the greenbelt width is estimated as 200 m. This width of greenbelt reduces the source strength from 43.33 kg/s (at a distance of 1300 m downwind when greenbelt is not present) to 14.06 (at the same distance). This signifies more than 65% removal of pollutant, and a pollutant attenuation factor of 3.1. Further, a study to compare the results obtained by the present model with Kapoor and Gupta [7,8] (Fig. 6), depicts comparison of concentration profile as predicted by the present model and the one reported by Kapoor and Gupta [3,7,8]. It is evident from the figure that a good agreement

Table 1
Typical input data used in the solution of the model

Parameters	Values
Pollutant release rate (kg/s)	45
Wind speed (m/s) at 10 m height	3.5
Downwind distance (m)	1100
Cross wind distance	150
Vertical distance (m)	170
Height of pollutant release (m)	25
Atmospheric temperature (K)	300.1
Density of air (kg/m^3)	2.1
Incoming solar radiation (W/m^2)	135
Friction velocity (m/s)	0.35
Pollutant deposition velocity (m/s)	0.025
Height of tree (m)	25
Proposed greenbelt width (m)	200

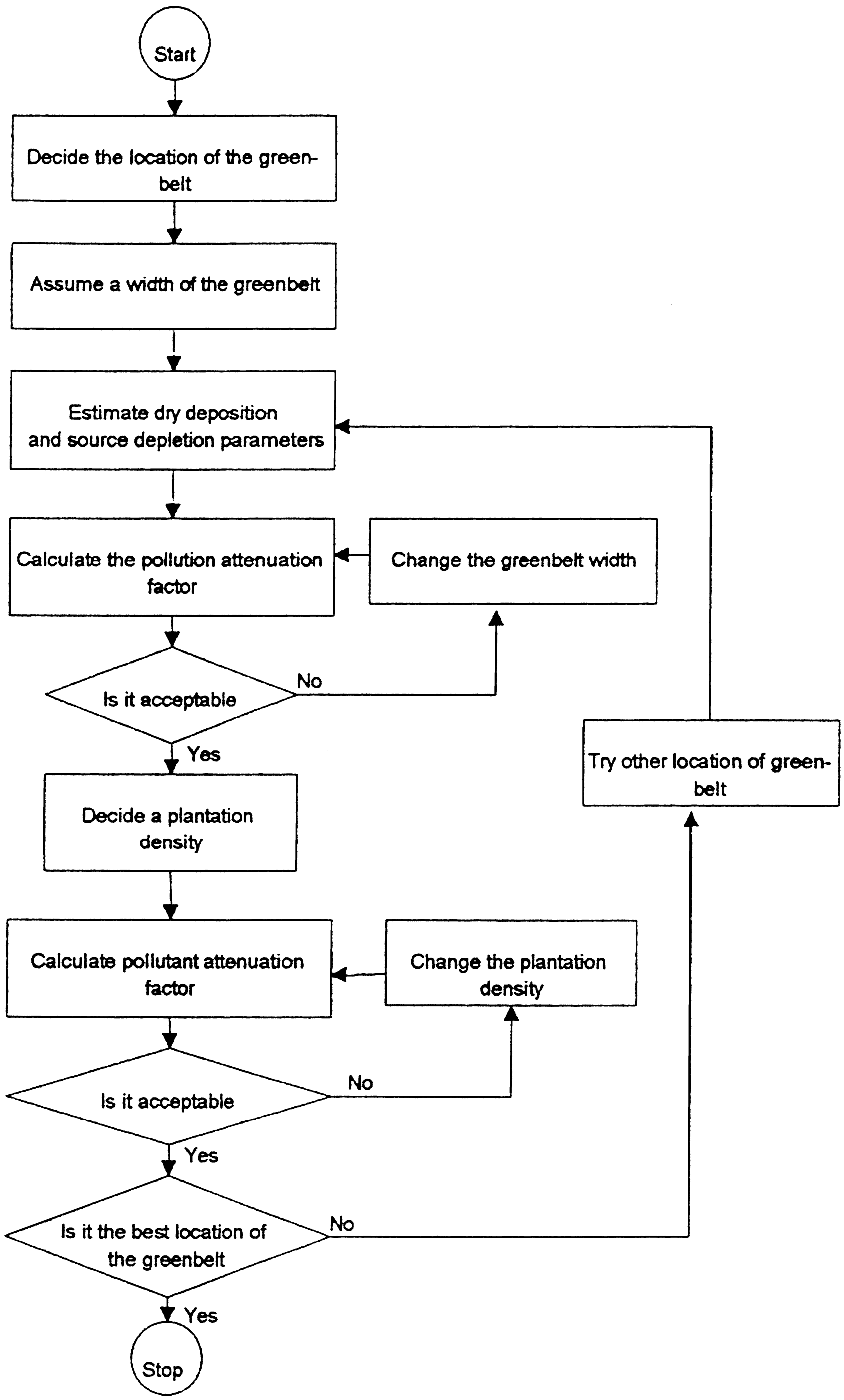

Fig. 4. Algorithm for the design of greenbelt.

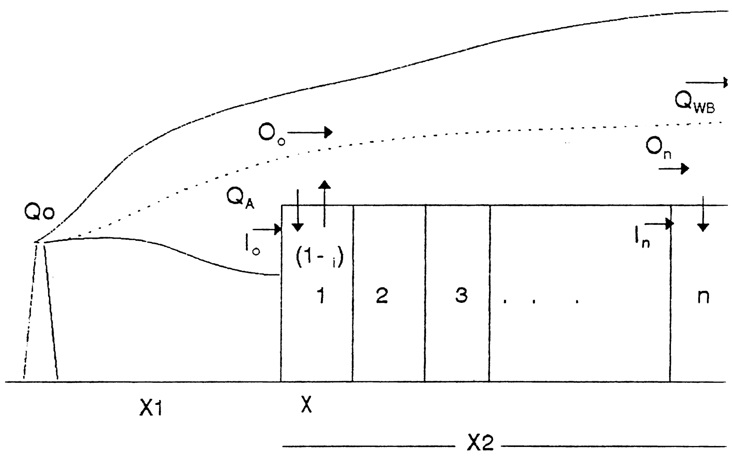

Fig. 5. Interaction of pollutant flux with the greenbelt.

of predicted and reported profiles has been observed. It is particularly so up to a distance of 900 m. Thereafter, the deviation between these two increases. The little deviation that exists between the reported and the predicted values is due to the following reasons:

- The present model has incorporated coastal area effects, while the reported one is an essentially inland-terrain model [7,8].
- The present model has incorporated the effect of longer duration of release.
- The present model has accounted for the elevated release sources (30 m height, while in the reported model the height of release has been restricted to 7 m).

We have compared the profile of pollutant attenuation factor (AF) as predicted by the present model with the one reported by Kapoor and Gupta [7,8]. Fig. 7 presents comparison of profiles of AF1 as function of greenbelt width. It is evident that a good agreement (more than ∼95%) exists between the profile predicted by present model and the one reported by

Table 2
Typical results from the model for an input set presented in Table 1

Parameters	Values
Stability class	D, Neutral
The concentration at x=1100.0, y=150.0, z=170.0 (kg/m^3)	1.23e^{-04}
The concentration at cloud axis (kg/m^3)	6.48e^{-04}
The maximum ground level concentration at cloud axis (kg/m^3)	1.09e^{-03}
The maximum ground level concentration at cloud edge (kg/m^3)	1.11e^{-04}
Distance at which maximum ground level concentration occurs (m)	770.00
Width of greenbelt (m)	200.00
The height of tree as (m)	25.00
The value of K (plantation density parameter)	1.00
The source strength without passing through green (kg/s)	4.33e^{+01}
The source depletion when passing through greenbelt (interaction) (kg/s)	1.40e^{+01}
The value of attenuation factor considering interaction	3.09

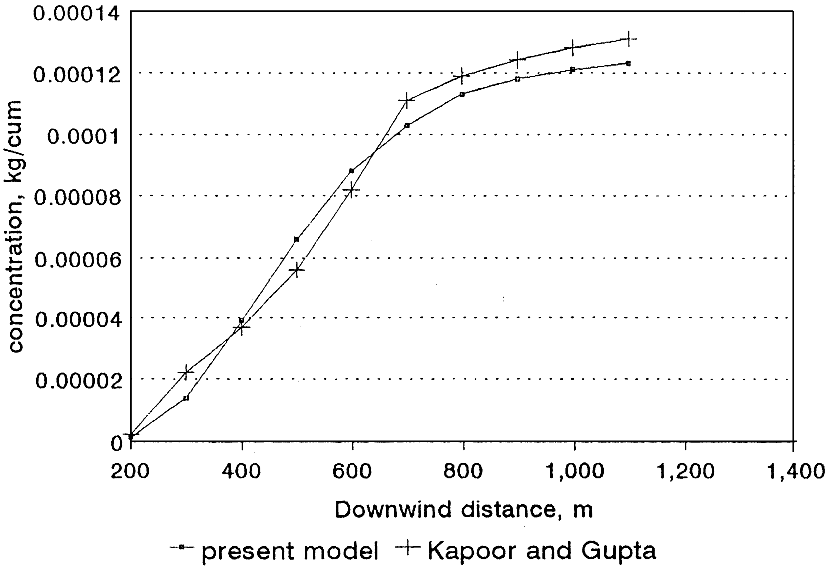

Fig. 6. Comparison of the pollutant (SO_2) concentration estimated by the present model and the model reported by Kapoor and Gupta (1992) stability class D, source strength 45 kg/s, source height 25 m.

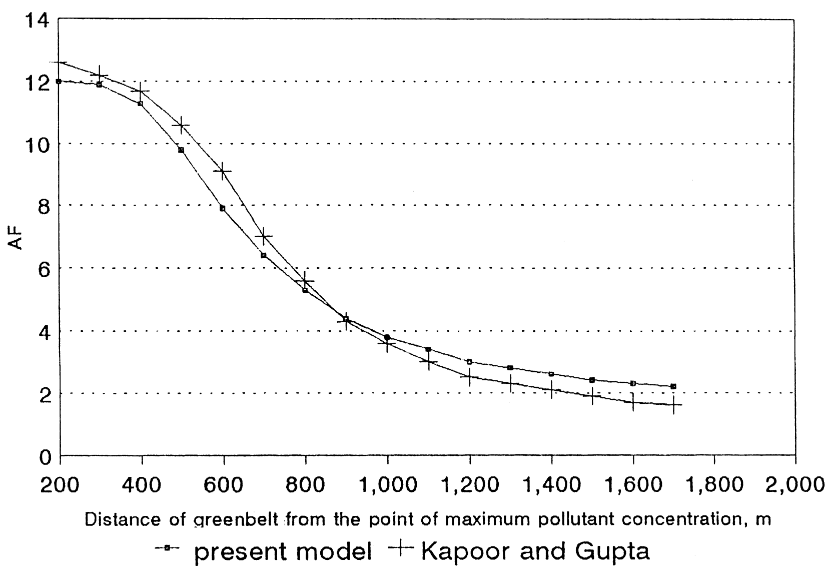

Fig. 7. Comparison of the pollutant attenuation factor estimated by present model and the model reported by Kapoor and Gupta (1992) stability class D, greenbelt width 200 m.

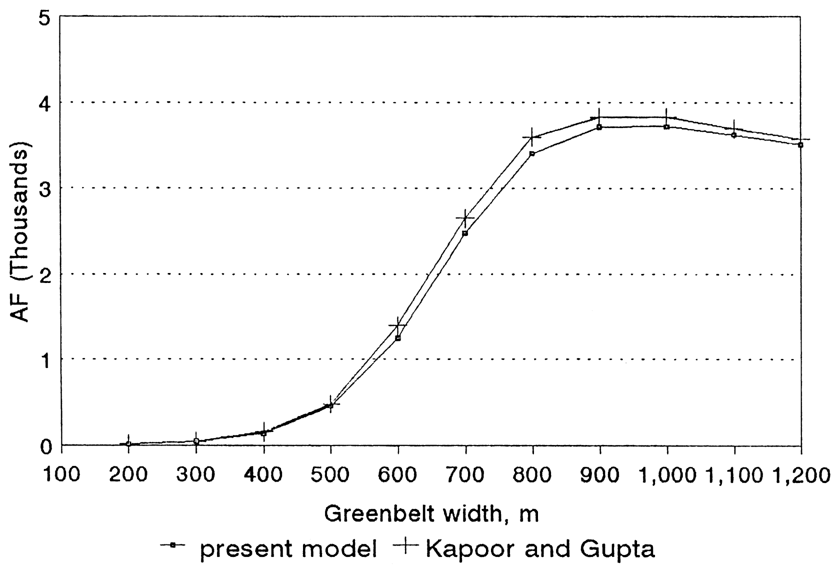

Fig. 8. Comparison of pollutant attenuation factor (AF) estimated by the present model reported by Kapoor and Gupta (1992) stability class D, distance from the source of release 1100 m.

Kapoor and Gupta [7,8]. It is also observed from the profile that initially up to a width of 500 m, AF1 increases non-linearly. Later, upto a distance of 800, it increases linearly (with a slope of more than one). Thereafter, the rate of increase of AF1 decreases sharply. Thus, the greenbelt of about 800 m width may be optimal. The values of AF1 as a function of distance from the maximum ground level concentration to greenbelt edge (X) have been plotted in Fig. 8. As distance increases, the value of AF decreases. The rate of decrease in AF1 is steep upto a distance of 1000 m, followed by a decline. Similar profile (Fig. 8) has been observed with the model of Kapoor and Gupta [7,8].

10. Simulations

These authors have modelled two different pollution attenuation factors: one considering interfacial mass interaction between greenbelt and the open space above greenbelt, and the other neglecting this effect. A detailed comparative study of these two attenuation factors under different conditions is now presented.

In general, it has been observed that AF1 (pollution attenuation factor neglecting interfacial mass interaction) predicts lower values compared to AF2 (pollution attenuation factor with interfacial mass interaction). It is because of the interfacial mass interaction of two fluxes: one from greenbelt to open space and another from open space to greenbelt. The second type of flux would always be denser, as while going downwind more and more pollutant mass (from open space above greenbelt) would interact with the greenbelt. This would cause high pollution attenuation compared to the assumption of no mass interaction.

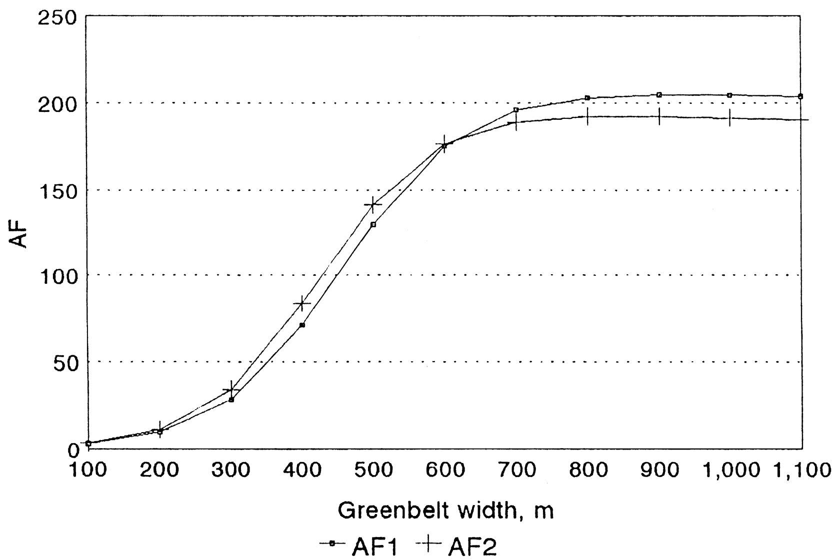

Fig. 9. Attenuation factors as influenced by the greenbelt width (distance from pollutant source 400 m, height of trees, 25 m, stability class D).

Therefore, the values of AF2 are more realistic compared to AF1, as it models a more realistic process. Similar trend has been reported in the model proposed by Kapoor and Gupta [7,8]. Subsequently, we have conducted simulations to assess the impact of various parameters on the values of AF1 and AF2. The results are summarized below.

Vis-à-vis the relationship of AFs with the belt width, Fig. 9 indicates increase in the values of AFs with increase in the width of the greenbelt. The rate of increase in the AF values is high upto a distance of 700 m, while later it becomes almost constant. Another noteworthy feature of Fig. 9 is that upto a distance of 600 m the values of AF2 are higher than AF1, but subsequently the trends reverses. It is because the incoming (open space to greenbelt) and outgoing (greenbelt to open space) pollutant fluxes would increase going along the downwind direction; but after a certain distance the incoming flux would become almost constant. This results in the decrease in the value of AF2 after a certain distance when compared to the value of AF1.

Fig. 10 depicts the values of AFs under different atmospheric stability conditions. It is evident that during unstable conditions (Pasquill stability classes, A, B and C) the values of AFs are very low (far less than 10), while the same are quite high for neutral and stable conditions (Pasquill stability classes D and E). This indicates that the greenbelts are more effective during neutral and stable atmospheric conditions than when the atmosphere is unstable. This fact hardly weighs against the effectiveness of greenbelts because it is during neutral and stable conditions that the dispersion of pollutants by air is not efficient and the greenbelts are needed the most. When the atmosphere is unstable, the air movements are sufficient to attenuate the pollutants by rapid dispersion and dilution.

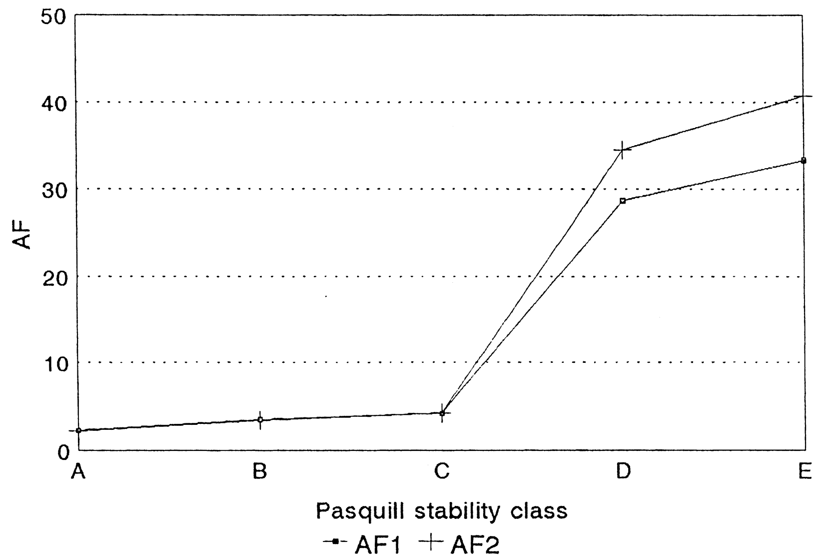

Fig. 10. Attenuation factors as influenced by the stability conditions (distance from pollutant source 400 m, greenbelt width 200 m, height of trees, 25 m).

11. Impact of the distance of greenbelt from the pollution source, and greenbelt width on attenuation (AF2)

We have explained in earlier section that after a gaseous plume containing pollutant has been released from a tall stack into the atmosphere, it would travel some distance before it would come close to the ground level. During this travel, the plume shall get diluted by air to some extent, and its shape would also go through alterations (Khan and Abbasi, [12], Chapter 5). A large number of variables influence this phenomenon, mainly the atmospheric conditions and the physical, chemical, and physico-chemical properties of the plume. This being the situation, the maximum ground level concentration of an air pollutant exiting from a stack in a buoyant plume would occur some distance from the stack. This distance, for a plume of given characteristics, would be dependent on atmospheric conditions.

One major component of mathematical modelling for greenbelt design is to work out this distance from the stack at which the air pollutant(s) shall reach maximum ground level concentrations, because the front edge of the greenbelt should ideally begin at that point. We have simulated the effect on attenuation of pollutants by the greenbelt if this edge is located farther and farther away from the point of occurrence of maximum ground level pollutant concentration (Figs. 11 and 12). The studies as expected, reveal that the farther greenbelt edge is from the point mentioned above, the lesser shall be the attenuation. In other words, the values of AF2 decline sharply as the distance of the greenbelt edge increases with reference to the point of occurrence of maximum ground level pollutant concentration.

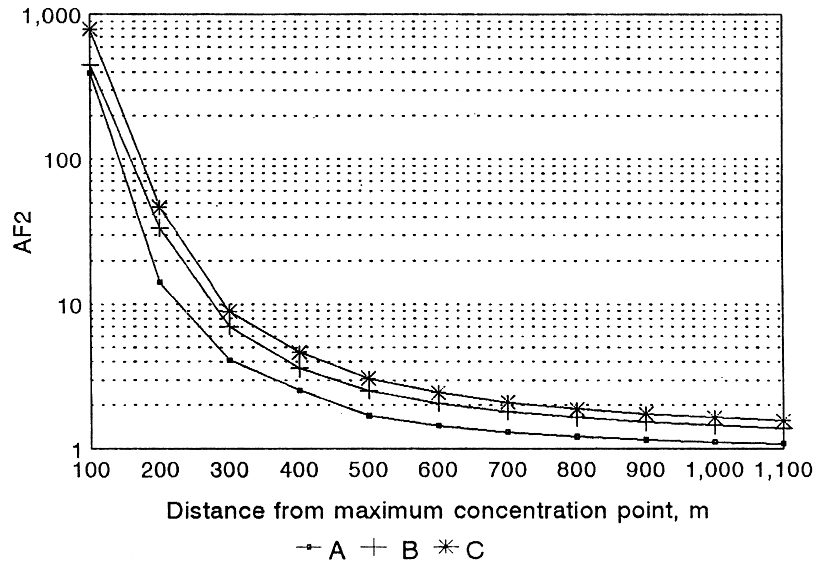

Fig. 11. Attenuation factors as influenced by distance from the maximum concentration point (greenbelt width 400 m, height of trees, 25 m, stability classes A, B, C).

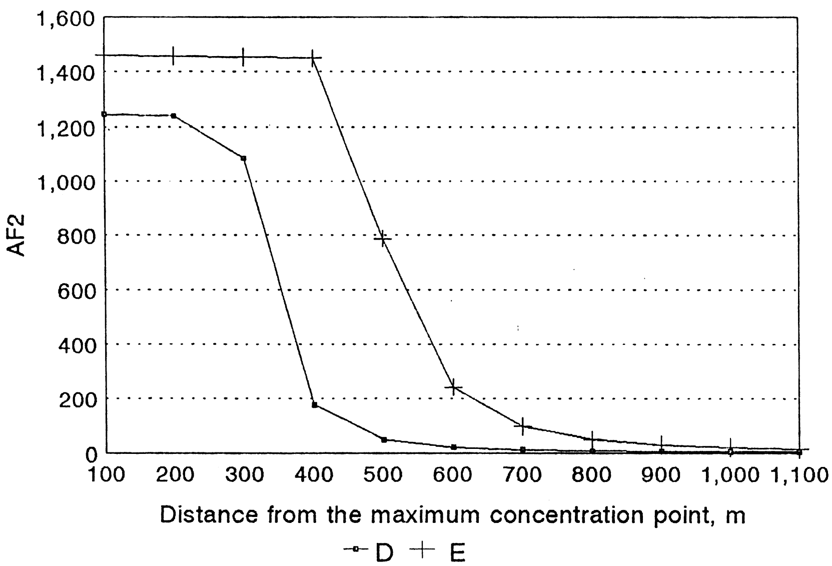

Fig. 12. Attenuation factors as influenced by the distance from the maximum concentration point (greenbelt width 400 m, height of trees 25 m, stability classes D, E).

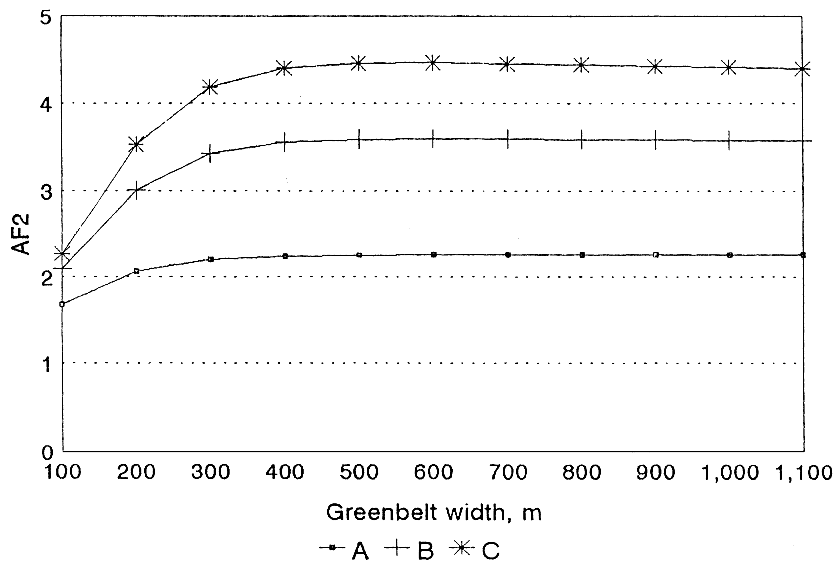

Fig. 13. Attenuation factor as influenced by the greenbelt width (distance from pollutant source 600 m, height of trees 25 m, stability classes A, B, and C).

12. Parametric effect of greenbelt width on AF2 under different atmospheric conditions

Fig. 13 depicts the profiles of AF2 for various greenbelt widths under different conditions of atmospheric stability. The following conclusions have been drawn.

1. The values of AF2 decrease as the instability in the atmosphere increases.
2. AF2 values increases with the increase in the greenbelt width.
3. The impact of greenbelt width is pronounced only upto a distance of 400 m; thereafter the values of AF2 become constant.
4. The rate of increase in the value of AF2 decreases as the atmosphere becomes more and more unstable.

Fig. 14 also reveals similar profiles for neutral and stable atmospheric conditions. It is seen that:

1. The values of AF2 increase exponentially during stable atmospheric conditions while the rate of increase is comparatively slower in neutral conditions.
2. The effect of greenbelt width is more pronounced upto a distance of 400 m while later the value of AF2 remains almost constant.

In summary, greenbelt width strongly helps in pollutant attenuation upto a limit; thereafter the impact of increase in greenbelt width does not cause significant attenuation. Further, for a given greenbelt width, the degree of attenuation increases as the atmospheric stability increases.

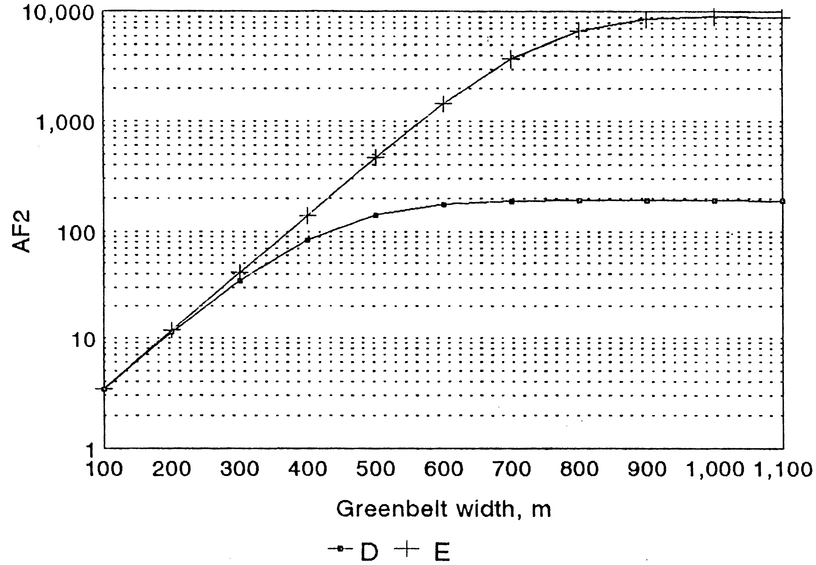

Fig. 14. Attenuation factors as influenced by the greenbelt width (distance from pollutant source 600 m, height of trees 25 m, stability classes D, E).

13. Effect of height of trees on AF2 under different atmospheric stability conditions

The results of simulations are plotted in Fig. 15. The following observations have been made:

1. Values of AF2 increase with the increase in tree height.
2. The rate of increase in the value of AF2 as above is very slow for stability class A (highly unstable) and linear for stability class B (moderately unstable).
3. For the stability class C initially the value of AF2 increases linearly (upto a height of 20 m) while later it becomes almost constant.
4. Similar trends, as observed for stability class C, have also been observed for stability classes D and E. However, in these situations (classes D and E) the rate of increase in the value of AF2 is higher compared to class C.

In summary, increase in the tree height increases the pollution attenuation. This effect diminishes as atmospheric conditions move towards greater instability. Under neutral or stable conditions, a tree height of 20 m appears optimal.

14. Effect of plantation density on AF2 under different atmospheric conditions

Simulations were done to assess the impact of plantation density under different atmospheric stability conditions on AF2. The plantation density in the present context is defined as the ratio of foliage area of one tree to the foliage area of the total greenbelt. The simulation results are plotted in Fig. 16. It is inferred from Fig. 16 that an increase in the value of

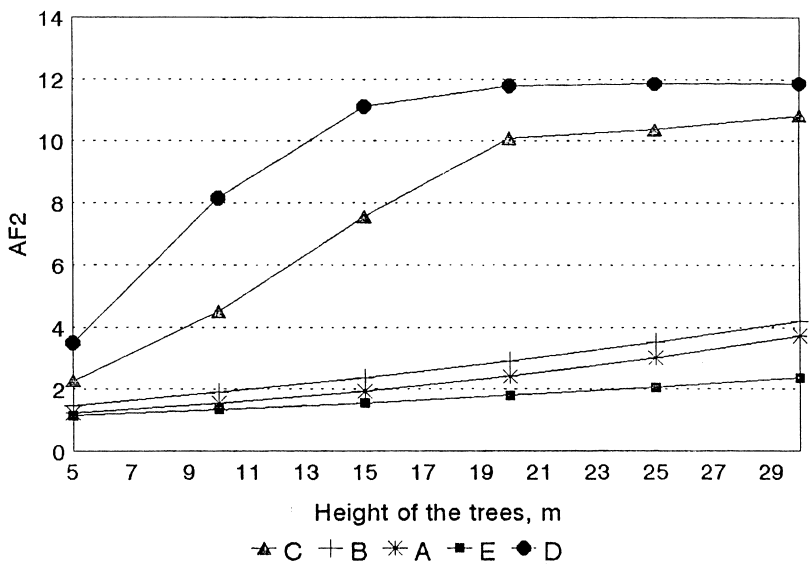

Fig. 15. Attenuation factors as influenced by the height of the trees (distance from pollutant source 600 m, greenbelt width 200 m).

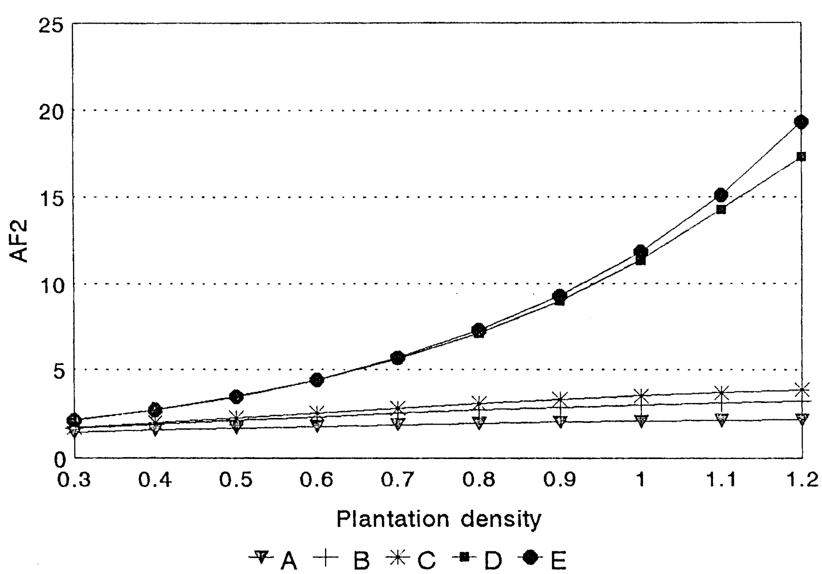

Fig. 16. Attenuation factors as influenced by the density of plantation (distance from pollutant source 600 m, height of trees 25 m, width of greenbelt 400 m).

plantation density increases the values of AF2. For all the three stability classes (A, B, and C) illustrated in Fig. 16 the increasing trend is almost linear. The slope for stability class C is the highest, while it is the lowest for class A. Unlike stability classes A through C, the trend of increase in the value of AF2 is non-linear for stability classes D and E (Fig. 16).

It is interesting to note that atmospheric stability does not play as important a role in the relationship of plantation density with AF2 as it does in the other simulations, discussed earlier.

In summary, an increase in plantation density increases the value of AF2. However, trees cannot be planted more densely than a maximum *viable* value. A density of 0.6–1 (as per above mentioned definition) appears optimal.

15. Application of the proposed model: design of greenbelt for an industrial area

15.1. The Sedarapet industrial estate

Sedarapet is one of the main industrial estates of Pondicherry state (situated on the East coast of the Bay of Bengal). The main pollutants emitted from the various sources in Sedarapet are: SO_2, NO_x, SPM, H_2S, Cl_2 and H_2SO_4 mist. It has been observed from the air quality study of the area that the area is highly polluted, necessitating control measures including greenbelt [30,31]. The present study has been conducted taking SO_2 as reference pollutant with a source strength of 45 kg/s.

Using synoptic meteorological data, atmospheric turbulence has been estimated for each month. It is seen that the turbulence intensity is lower during January and February, and maximum during May and June. Based on the turbulence intensity and Mohn–Obkov length, the atmospheric stability have been characterised for each month. For the sake of making the calculations easier, we have divided the year into three different seasons and the stability has been averaged for these seasons. During winter (December to February) the stability conditions have been observed as slightly stable, while during summer (March to June) unstable, and during rainy season (July to October) neutral. Using dispersion models earlier proposed by these authors (modified plume path theory, detailed at Khan and Abbasi, [9–13]), dispersion of pollutant (SO_2) has been assessed for various seasons as a function of downwind distance. It has been observed that during summer the dispersion is fastest while it is slowest during winter (Fig. 17). The values of maximum ground level concentration are highest during winter, at a larger distance from the release source. It is expected to be so because if the rate of pollutant dispersion is low, the maximum ground level concentration shall occur at a larger distance from the source than when the dispersion is swift (Fig. 17).

15.2. Designing of greenbelt

The values of pollution attenuation factors, AF2, have been computed for various sets of seasons (Figs. 18–20). Fig. 18 illustrates the profile of AF2 during the rainy season. It reveals that a width of 150 m would be optimal, when the wind blows from the north–west direction (predominant wind direction). Fig. 19 indicates that 150 m width of greenbelt

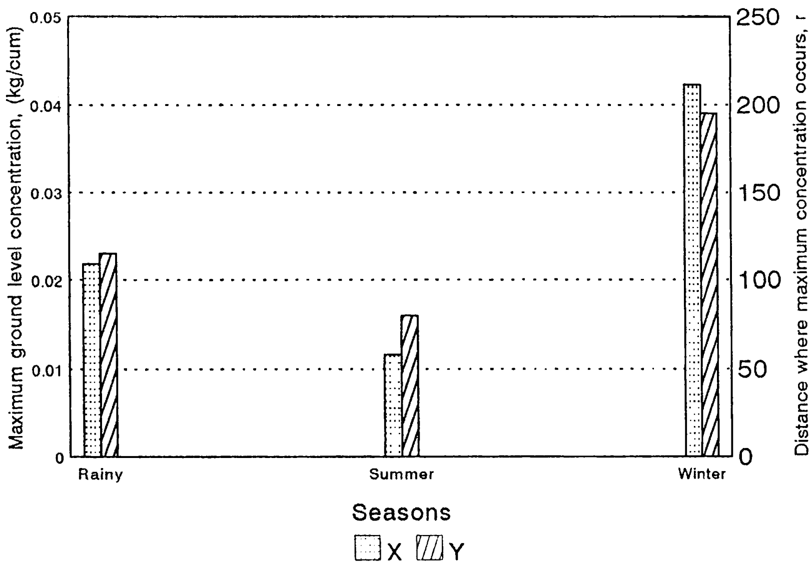

Fig. 17. Variation of maximum ground level concentration (*X*) and distance where this concentration (*Y*) occurs in different seasons in Saidapet industrial estate.

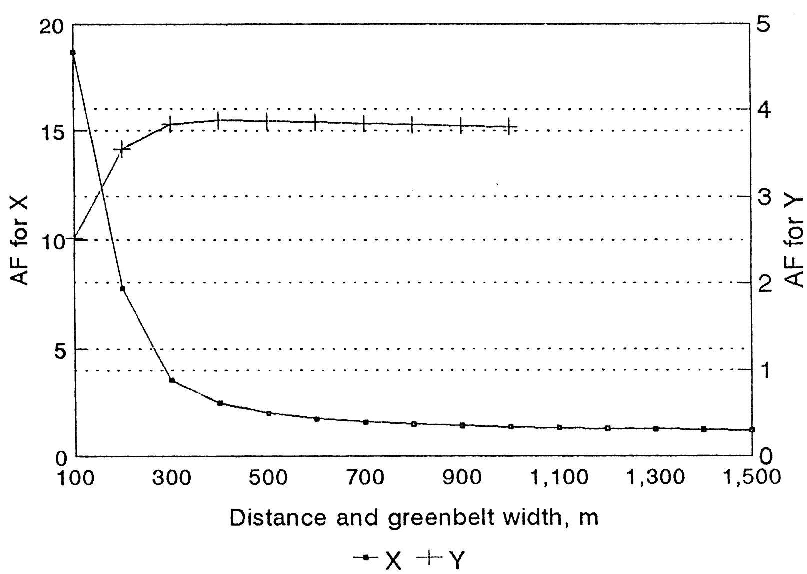

Fig. 18. The variation of AF as a function of distance between greenbelt and pollutant source (*X*) and greenbelt width (*Y*) for rainy season at Sedarapet industrial estate.

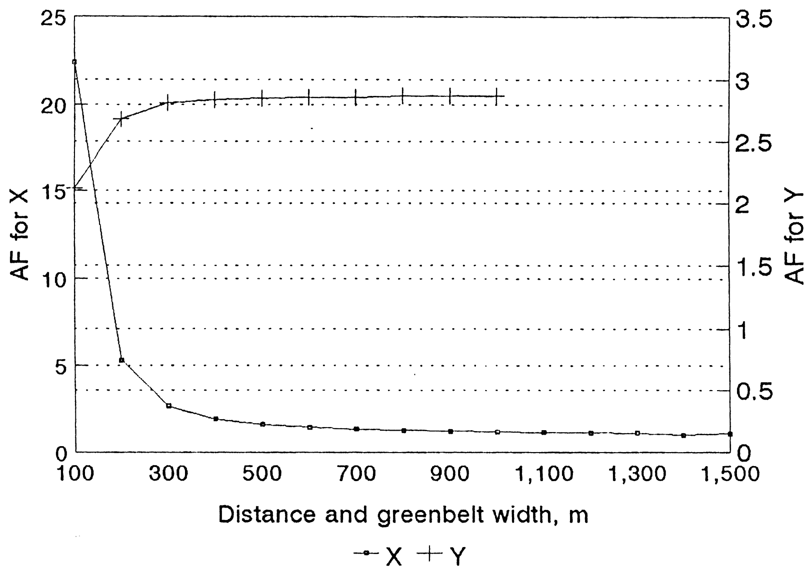

Fig. 19. The variation of AF as a function of distance between greenbelt and pollutant source (*X*), and greenbelt width (*Y*) for summer season at Sedarapet industrial estate.

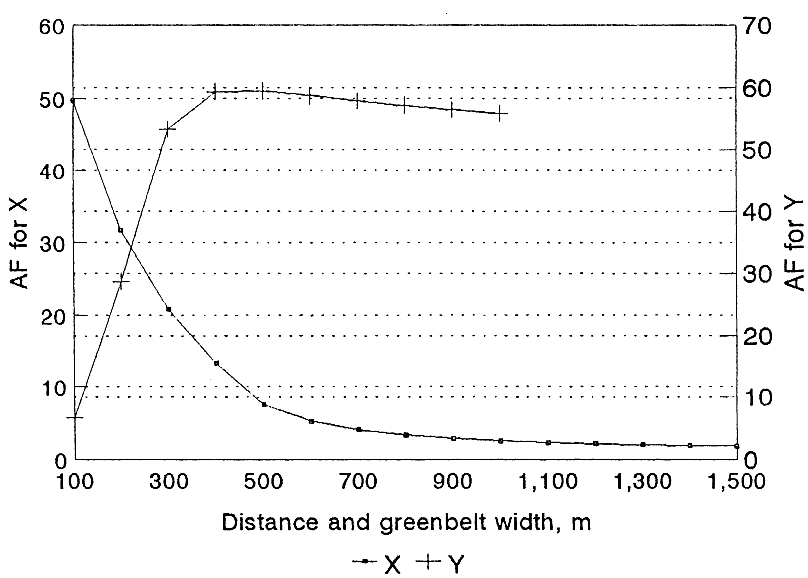

Fig. 20. The variation of AF as a function of distance between greenbelt and pollutant source (*X*), and greenbelt width (*Y*) for winter season at Sedarapet industrial estate.

Table 3
Greenbelt design parameters for Sedarapet industrial estate

Parameter	Values
Distance form pollutant source to greenbelt	75–100 m
Greenbelt width	
North	125 m
West	150 m
South	110 m
East	95 m
Value of K (ρ_c/ρ_t)	0.9
Pitch	Triangular
Inter tree spacing for tall tree	6–7 m
Inter tree spacing for middle height tree	7–9 m
Inter tree spacing for shrub	4–6 m
Pollution attenuation factor	3.0
Tree species	As given in Table 4

would be sufficient to achieve desired pollution attenuation during summer, while the same could be achieved by a width of 100 m during winter (Fig. 20). Thus, all things considered, a greenbelt of 150 m width would serve the purpose of considerable pollution attenuation (AF2=3.0).

The full set of design parameters is presented in Table 3. The proposed layout of the greenbelt is depicted in Fig. 21.

15.3. Canopy and selection of trees

Triangular pitch canopy has been recommended for plantation. A distance of 25–30 ft should be maintained between the trees. The shrubs can be planted with a spacing of 5–10 ft intermittently between the trees (Table 3).

A list of trees suitable for the plantation with respect to macroclimatic conditions and capacity to tolerate the given pollutants [1], is presented in Table 4.

16. Summary and conclusions

In this paper, we have presented mathematical models with which the pattern of dispersion of pollutant plume (to determine the location and geometry of the greenbelt) and the processes of pollution attenuation (to determine greenbelt species and sequence of their planting may be studied). The resultant information is subsequently used to design a typical greenbelt.

The process of greenbelt design involves three main steps. The first step characterises the atmospheric stability using synoptic meteorological data (which are generally available). This step uses Mohn–Obukhov model to estimate the stability dependent parameters (Mohn–Obukhov length), which are later used to characterise the atmospheric stability. The effect of coastal area, and long duration of release have been accounted in the model. The

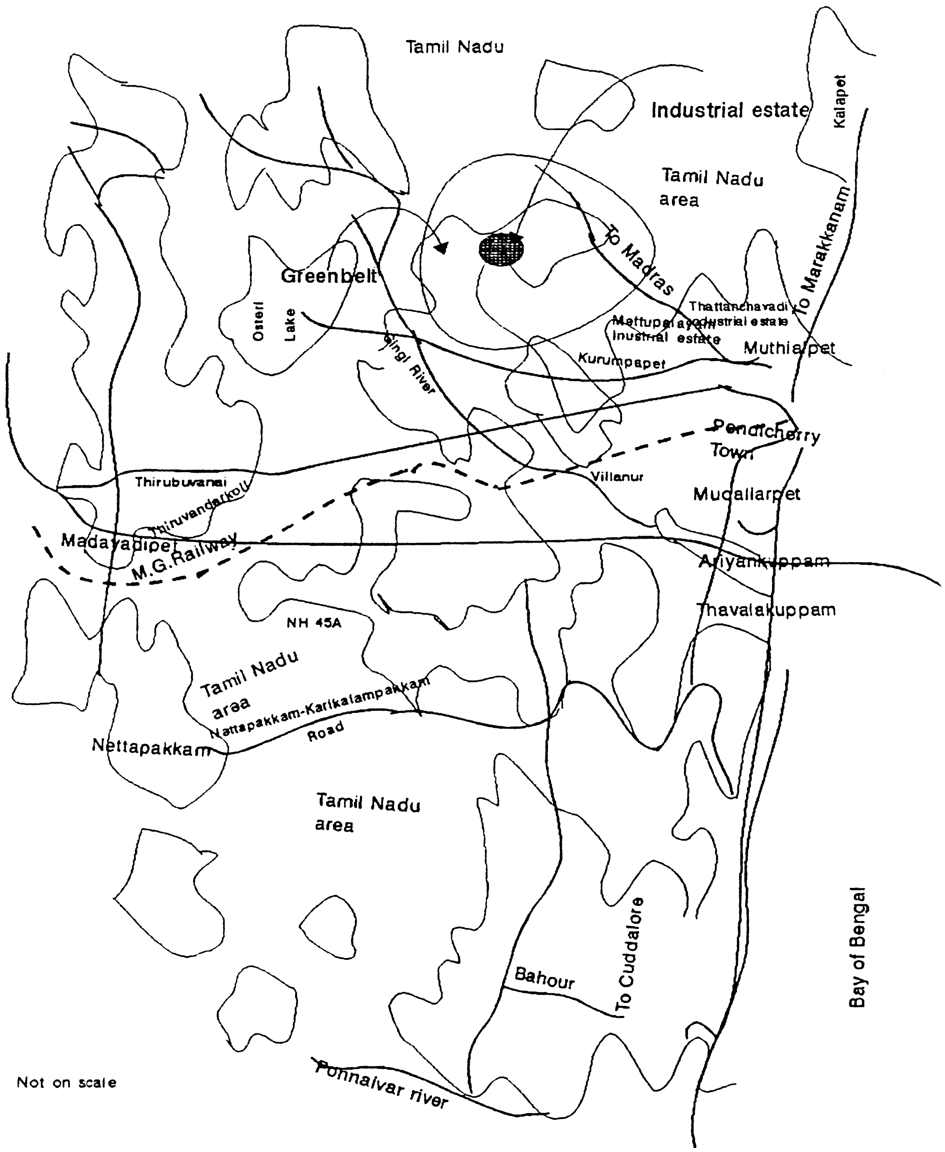

Fig. 21. Proposed greenbelt around the Sedarapet industrial estate.

model of atmospheric stability characterisation has been solved for a wide range of data and tested against other reported data.

The second step — *dispersion characteristic estimation* — works out the concentration profile of pollutant and the geometry of the plume. The dispersion process has been modelled considering release of pollutant from an elevated source. We have incorporated PGT modifications to cater to the effect of release for long duration [15]. Similarly, the

Table 4
Tree species recommended for greenbelt plantation for the present study area

Tall trees	
1	*Azadirachta indica* (*Neem*)
2	*Tamarindus indica* (*Tamarind*)
3	*Ficus religiosa* (*Peepal*)
4	*Mangifera indica* (*Mango*)
5	*Tectona grandis* (*Teak*)
Medium dwarf trees	
1	*Butea monosperma*
2	*Poinciana regia* (*Gulmohar*)
3	*Parkinsonia aculeta*
4	*Thevetia nerifolia*
5	*Acaccia arabica* (*KateriaBabu*)
Shrubs	
1	*Bougainvillea* (*Baganvillas*)
2	*Calotropis Procera* (*Madar*)
3	*Ipomoea fistula* (*Behaya*)
4	*Nerium odorum* (*Lal kaner*)
5	*Thevetia nerifolia* (*Peela kaner*)
Herbs	
1	*Vinca rosea*
2	*Cynodon dactylon*
3	*Ipomaea cornea*
4	*Achyranthes aspera* (*Latjira*)
5	*Solanum xanthocarpum* (*Bhatkatauja*)

effect of coastal area meteorology has also been accounted for pollutant dispersion. The complete model of pollutant dispersion (as illustrated in previous sections) has been solved for predefined inputs and the results have been compared with the ones obtainable with the previously reported models.

The last step — *designing of greenbelt* — uses the information obtained in previous steps. The first part of this step helps to decide the location of the greenbelt, considering the zone of occurrence of maximum pollutant concentration (plume touching the ground), height of the planned greenbelt, pollutant deposition and depletion rates, and the surface available for the attenuation of pollutants (foliage area of one tree as well as the complete greenbelt). Subsequently, the design parameters of greenbelt such as greenbelt width, pollutant attenuation factor, plantation density, etc. are worked out. The model for this step includes set of non-linear algebraic equations, definite integrals, and error functions. These have been solved using numerical algorithms for non-linear function as well as numerical integral techniques.

Further, simulations have been conducted to analyse the impact of various parameters on the design of greenbelt. The study concludes that several variables have to be considered and balanced for an optimal and effective design of a greenbelt. As most of the design parameters are strongly dependent on the site characteristics (meteorology, land availability, soil type, water availability, horticultural factors, etc.) as also the characteristics of the pollutant source (stack dimensions, source strength and source characteristics), no single recipe can be given for all greenbelts.

We do hope that the set of models developed by us covers most of the variables that influence greenbelt design. It should, therefore, be possible to design cost effective and useful greenbelts under widely different situations using these models.

Nomenclature

AF1	pollution attenuation factor neglecting interfacial mass exchange
AF2	pollution attenuation factor considering interfacial mass exchange
C	concentration at particular location (x,y,z) (kg/m^3)
C_G	constant
C_p	specific heat (kJ/kg/°C)
d	diameter of tree (m)
E	evaporation rate (kg/s)
FD(X)	atmospheric depletion function
g	gravitational acceleration (m^2/s)
G	soil heat flux (W/m^2)
h	height of tree (m)
h_e	effective height of plume (m)
hh	height of release (m)
H	sensible heat flux (W/m^2)
K	constant (ρ_c/ρ_t)
K^+	incoming total solar radiation (W/m^2)
K_t	constant
K_y	conductivity (W/m/K)
L^+	incoming long wave radiation (W/m^2)
L^-	outgoing long wave radiation (W/m^2)
L_e	latent heat of evaporation (kJ/kg)
q_s	saturation specific humidity
Q_0	mass flux at the source (kg/s)
Q_B	pollutant flux with after passing through greenbelt (kg/s)
Q_c	mass flux enters the greenbelt (kg/s)
Q_x	mass flux at distance x in the greenbelt (kg/s)
Q_{WB}	pollutant flux without greenbelt (kg/s)
Q^*	net surface heat flux (W/m^2)
t	time of release (h)
T	absolute temperature (K)
u	wind velocity at the release height (m/s)
U_c	average wind speed through greenbelt (m/s)
U_e	effective wind velocity as height h_e in greenbelt (m/s)
U_x	friction velocity (m/s)
U(10)	wind velocity at the height of 10 m (m/s)
V_d	dry deposition velocity (m/s)

X distance in downwind direction (m)
z distance in vertical direction (m)

Greek letters
α parameter depend upon surface moisture (dimensionless)
β surface moisture heat flux (W/m^2)
γ ratio of specific heat and latent heat (C_p/λ_l)
λ_l latent heat (kJ/kg)
λ pollutant attenuation coefficient (m^{-1})
ρ density (P/RT, where P pressure (kPa), R gas constant) (kg/m^3)
ρ_c average foliage surface area density of the greenbelt (m^2/m^3)
ρ_t foliage surface area density of a single tree (m^2/m^3)
σ_z dispersion coefficient in z direction
ξ Mohn–Obukhov coefficient

Acknowledgements

The authors thank All India Council of Technicl Education (AICTE), New Delhi, for supporting a Computer-Aided Environmental Management Unit which enabled us to take up a study on greenbelt design funded by the Government of Pondicherry.

References

[1] A.B. Chaudhury, Tree and the Environment: An Indian Scenario. Personal communication with the Executive Director, Forest Survey of India, New Delhi, 1993.
[2] H. Erbrink, Turbulent diffusion from tall stacks: the use of advanced boundary layer meteorological parameters in the Gaussian dispersion model stacks, PhD thesis submitted to Vrije University, DC Boelelaon 1105, The Netherlands, 1995.
[3] V.K. Gupta, R.K. Kapoor, Attenuation of air pollution by greenbelt-optimisation of density of tree plantation. Operating Plant safety Division, Atomic Energy Regulatory Board, BARC, Bombay, 1990.
[4] S.R. Hanna, L.L. Schulman, R.J. Paine, J.E. Leim, M. Baer, Development and evaluation of offshore and coastal dispersion model, J. Air Pollution Control Assoc. 35 (1985) 1039–1047.
[5] A.A.M. Holslag, A.P. Van Ulden, A simple scheme for day time estimates of the surface fluxes from routine weather data, J. Clim. Appl. Meteorol. 22 (4) (1983) 517.
[6] S.A. Hsu, An over-water stability criterion for the offshore and coastal dispersion model, Bound. Layer Meteorol. 60 (1992) 397–402.
[7] R.K. Kapoor, V.K. Gupta, Air pollution attention coefficient concept for optimisation of greenbelt, Atmos. Environ. 18 (1984) 1107–1113.
[8] R.K. Kapoor, V.K. Gupta, Attenuation of air pollution by greenbelt, in: Shukla, Hallam, Capasso (Eds.), Mathematical Modelling of Environmental and Ecological Systems, PHI Press, New York, 1992.
[9] F.I. Khan, S.A. Abbasi, Applications of the recently modified plume path theory on dispersion on some gases, Symposium on Air Quality Management at Urban, Regional and Global scales, 23–26 September 1997, Turkey, 1997.
[10] F.I. Khan, S.A. Abbasi, Risk assessment in chemical process industries: advanced techniques, Discovery Publishing House, New Delhi, XI+423, 1998.

[11] F.I. Khan, S.A. Abbasi, Modelling and control of the dispersion of hazardous heavy gases, J. Loss Prevention Process Industries 12 (1999) 235–244.

[12] F.I. Khan, S.A. Abbasi, Greenbelts for pollution abatement: concepts, design applications, Discovery Publishing House, 2000, 246 pp.

[13] F.I. Khan, S.A. Abbasi, Attenuation of Gaseous Pollutants by Greenbelts, Environmental monitoring and Assessment, 2000, accepted for the publication.

[14] F.I. Khan, S.A. Abbasi, Cushioning the impact of toxic release from runaway industrial accidents with greenbelts, J. Loss Prevention Process Industries 13 (2000) 109–124.

[15] F.P. Lees, Loss Prevention in Process Industries, vol. 1–3, Butterworts, London, 1996.

[16] P.K. Misra, Dispersion from tall stacks into a shoreline environment, Atmos. Environ. 14 (1980) 396–400.

[17] M.P. Nayar, Tree canopies. Air pollution and plants — A state of the art report, Ministry of Environment and Forests, New Delhi, 1985.

[18] F. Pasquill, F.B. Smith, Atmospheric diffusion, third ed., Wiley, New York, 1983.

[19] V.J. Patel, Utilisation of industrial waste through high-density plantation, Proceedings of National Conference on energy plantation, Bangalore, 1982, pp. 1–12.

[20] D.N. Rao, Plants and particulate pollutants, in: S.K. Wahi, J.S. Agnihotri, J.S. Sharma (Eds.), Environmental Management in Petroleum Industry, Wiley, New Delhi, 1992.

[21] D.N. Rao, Sulphur dioxide pollution versus plant injury with special reference to fumigation and precipitation, Proc. Syom.. on Air pollution Control, vol. 1, Indian Association for Air Pollution Control, New Delhi, 1983, pp. 91–96.

[22] J.S. Rawat, S.P. Banerjee, Urban forestry for improvement of Environment, Energy Environ. Monitor 12 (2) (1996) 109–116.

[23] R.K. Roy, S.C. Sharma, Green Belt for Minimising Industrial and Urban Pollution, Encology, vol. II (9), 1997.

[24] G.A. Semel, Particle and gas dry deposition: a review, Atmos. Environ. 14 (1980) 983.

[25] S.C. Sharma, A.N. Sharma, R.K. Roy, Abatement of industrial pollution by landscaping, Indian J. Environ. Protection. 14 (2) (1994) 95–97.

[26] S.K. Singh, D.N. Rao, Evaluation of plants for their tolerance to air pollution, Proc. Symp. Air Pollution Control 1 (1983) 218–224.

[27] N. Sivasamy, V. Srinivasan, Environmental Pollution and its Control by Trees, I.A.R.I, Pusa, New Delhi, 1996.

[28] W.H. Smith, Air pollution and Forest, Introduction between Air Contaminants and Forest Ecosystem, Springer, New York, 1990.

[29] M.J. Stunder, S. Sethuraman, A statistical evaluation and comparison of coastal point source dispersion models, Atmos. Environ. 20 (2) (1986) 301–315.

[30] S. Vineethan, S.A. Abbasi, Impact of industries on suburban environments, Discovery, New Delhi, 1997, 151 pp.

[31] S. Vineethan, S.A. Abbasi, Airshed studies in Southern Pondicherry, Chemical & Environmental Research 6 (1997) 249–258.