CHAPTER VI
Cochin is presently witnessing a boom in industrialization and a consequent explosion on the population front. The trend towards urbanization and industrialization has resulted in severe and wide spread environmental pollution of the atmosphere. Air over Cochin is nourished with different gaseous effluents from industries and smoke discharges from locomotive and ships. The main contributors are Cominco Binani Zinc Ltd., Trvancore Cochin Chemicals, FACT (Udyogamandal, Ambalamughal), Hindustan Insecticides, Indian Rare Earths, ASCL Caprolactum, Cochin Refineries, Carbon and Chemicals and many small scale industries. A considerable amount of air pollutants is also contributed by traffic and domestic emissions besides the contribution of sulfate ion from salt water spray. The latter may also be regarded as a source of \( \text{SO}_2 \) owing to the fact that sulfate ion can be reduced to \( \text{SO}_2 \).

There are innumerable number of air pollutants of which the major types are oxides of sulphur and nitrogen, carbon compounds, particulate matter and photochemical products. Among the various air pollutants sulfur dioxide is the most important one. In almost most all industrialized areas of the world which happened to be densely populated, adverse concentration of \( \text{SO}_2 \) has been reported (Zutski et al, 1978). Sulfur is a common impurity in
coal and other fossil fuels. Due to combustion it enters the atmosphere as sulfur dioxide, hydrogen sulfide; sulfuric and sulfurous acid and various sulfates.

In recent years, a number of models have been developed to predict the dispersion of air pollutants in the urban environment. These models require detailed information on various meteorological situations prevailing over the region. Accurate assessment of meteorological conditions leads to an accurate forecast of pollution level of an urban area. Simulation modeling which will predict the concentration of pollutants as a function of source strength and prevailing meteorological conditions have an important role to play in the air pollution control management for urban centers; especially in developing countries like India, because of the following reasons. Simulation modeling can help proper urban planning because the pollution map of future time can also be projected taking into account the existing meteorological conditions and the emission rates of coming up industries. Taking recourse to simulation modeling proper location of industries and proper zoning of industrial and residential sectors can be done effectively.

Some of the models used include 1) Gaussian, 2) NOAA Gaussian, 3) Geomat model, 4) Box model etc., . The first one is for flat terrain and second and third are for complexes terrain. In the first case the following assumptions are taken. a) Flat terrain considered, b) perfect reflection of the plume
considered at the ground, c) diffusion in the x direction is neglected, d) turbulence generated by strong winds neglected, e) the pollutant under consideration is assumed to be inactive. The second model does not differ much the standard Gaussian plume model. It was developed by a group in National Oceanic and Atmospheric Administration (NOAA). It is Gaussian plume model having terrain related assumptions. Geomet model for complex terrain was developed by a group of scientists under the leadership of G.C. Holzworth for US Environmental Protection Agency (EPA). It is basically a Gaussian plume model with certain modifications. Another widely used model is Box model in which complete vertical mixing is assumed. Diffusion between boxes are neglected and first order differencing is used. This would result in errors. The Langragian models should have many approximation to get the solutions and there by it's applicability and accuracy of solutions are limited. Gaussian diffusion model is still the most popular model, and there have been considerable modification to improve the validity of the model. In the present chapter this model is applied to find out the spatial concentration of sulfur dioxide over the study region.

6.1 Discussion of parameters included in the model

6.1.1 Mixing Height

The concept of mixing lies in the principle that the heat transferred to the atmosphere from ground results in convection, vigorous mixing and establishment of dry adiabatic lapse rate.
Extent of this vertical mixing is dependent on the initial temperature structure of the atmosphere and the heat input at the surface. Mixing height may be defined as the height above the ground at which relatively vigorous mixing occurs. Mixing height is maximum in the afternoon hours and minimum in the early morning hours. The mixing height can be obtained by extending a dry adiabat from the surface temperature, to its intersection with the early morning temperature sounding. The height of the intersection from the ground is termed as Mixing height. Usually the temperature sounding obtained from the suburban stations is used, so that the vertical thermal structure is free from urban effects. For the computation of the mixing height at any given time, the dry adiabat from the surface temperature corresponding to that time is followed up to the lifting condensation level (LCL) and then from LCL onwards the saturated adiabat is followed till it intersect the early morning temperature soundings. The change from dry adiabat to saturated adiabat is necessary because when an air parcel moves vertically upwards, it moves dry adiabatically till LCL and saturated adiabatically from LCL onwards. This is because of the condensation that takes place from LCL onwards, if the air parcel is moist initially. Maximum mixing height is obtained by the dry adiabat of maximum surface temperature to its intersection with the early morning temperature profile and minimum mixing height obtained by extending the dry adiabat of minimum surface temperature.

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The computation of mixing heights at every three hour intervals have been carried out for the four months January, April, July and October which are representatives of winter, pre-monsoon, monsoon, and post monsoon seasons respectively. Fig. 6.1 shows the maximum mixing height occurring around 1430 hrs and minimum around 0530 hrs during all the four months. It is maximum for January which is the winter month and minimum for July. The highest value of maximum mixing height recorded in January is about 1.5km and that in July is about 0.9km. The highest values recorded in April and October are 1.25km and 0.95km respectively. In general, the winter representative month has shown the highest value and the pre monsoon and post monsoon representative months have shown in-between values. This gives a speculation as to whether January can be considered as representative for winter season. The normal winter characteristics are not normally found here, partly because the station is coastal. The minimum temperature occurs in the monsoonal months if one looks at the actual march of temperature. During monsoonal months the heat input in the surface is reduced and this results in the decrease of mixing height in this period. The diurnal range between the maximum and minimum value of the mixing heights is highest in the month of January followed by April, October and July.

The mixing height values for Cochin, in different seasons and the ranges between maximum and minimum values for the seasons are in good agreement with the results of the previous studies for this region by Anilkumar (1986). If one consider the major
Fig. 6.1  Diurnal variation of mean mixing heights for the four representative months
changes happened for this city due to urbanisation, during the last one decade, it implies that urbanisation does not cause much for the variation in mixing heights in Cochin. Days with low mixing heights during monsoon season should be viewed with caution because precipitation causes both for the wash out and rain out of air pollutants to the surface. The chances of built up of pollutant concentration is also more during low mixing heights days.

6.1.2 Wind

The plume moving away from the chimney, grows through the action of turbulent eddies, in the vertical as well as cross wind directions. Along the wind direction convection is more and diffusion in that direction is neglected. Wind is the only factor affecting the stretching of the plume.

Three hourly data of wind speed and direction are utilized. The wind speed and direction are split into five and sixteen classes respectively. The speed classes are 1 - 5 mph, 6 - 10 mph, 11 - 20 mph, 21 - 30 mph and greater than 30mph and the 16 directions are N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW. Frequency tables are prepared for the four representative months January, April, July and October. The weighted mean wind speed is then calculated for each of the sixteen directions. The weighted mean wind speed for the sixteen directions for the four representative months are calculated.
In the model the mean wind speed through the plume is considered. For this the vertical variation of wind has to be computed which is a function of stability. A simple power law profile is used for this purpose.

\[ u_z = u_1 \cdot (z/z_1)^{(1/p)} \]

where \( u_z \) is the wind speed at height \( z \), \( u_1 \) is the wind at height \( z_1 \) (10 meters). \( p \), having values of 9 for unstable conditions, 7 for neutral conditions and 3 for stable conditions.

At every downwind distance depending upon the stability the mean winds are obtained between \( H - 2 \sigma_z \) to \( H + 2 \sigma_z \). Weighted mean wind speed in different wind directions are used.

6.1.3 Atmospheric Stability

Atmospheric stability is an important factor which affects pollutant dispersal. Highly unstable conditions result in thorough mixing and dilution and a consequent reduction in ground level concentration. Whereas high stable conditions cause for an increase in the ground concentration of the pollutants. So stability gives an idea of dispersion capacity of air. Diffusion coefficients are also dependent on stability.

Pasquill suggested a scheme for computing the six stability categories ranging from A to F, based on wind speed, cloudiness and net radiation index. Table 6.2 gives the stability classes as a function of wind speed and net radiation index. The net radiation index ranges from 4, highest positive net radiation (directed towards the ground) to -2, highest negative net
Table 6.1 Stability class as a function of net radiation and wind speed

<table>
<thead>
<tr>
<th>Wind speed (Knots)</th>
<th>Net radiation index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>0,1</td>
<td>A</td>
</tr>
<tr>
<td>2,3</td>
<td>A</td>
</tr>
<tr>
<td>4,5</td>
<td>A</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
</tr>
<tr>
<td>8,9</td>
<td>B</td>
</tr>
<tr>
<td>11</td>
<td>C</td>
</tr>
<tr>
<td>12</td>
<td>C</td>
</tr>
</tbody>
</table>
Table 6.2. Insolation as a function of solar altitude

<table>
<thead>
<tr>
<th>Solar Altitude (a)</th>
<th>Insolation class No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$60^\circ &lt; a$</td>
<td>4</td>
</tr>
<tr>
<td>$35^\circ &lt; a &lt; 60^\circ$</td>
<td>3</td>
</tr>
<tr>
<td>$15^\circ &lt; a &lt; 35^\circ$</td>
<td>2</td>
</tr>
<tr>
<td>$a &lt; 15^\circ$</td>
<td>1</td>
</tr>
</tbody>
</table>
radiation (directed away from the ground). Instability occurs with high positive net radiation and low wind speed, stability with high negative net radiation and light wind and neutral conditions with cloudy skies or high wind speeds.

The net radiation index used with wind speed to obtain stability class is determined by the following procedure:

1) If the total cloud cover is 10/10 and the ceiling < 7000 feet use net radiation index equal to zero (whether day or night).

2) For night time (night is defined as the period from one hour before sunset to one hour after sunrise).

   a) If the total cloud cover < 4/10, use net radiation index equal to -2.
   b) If the total cloud cover is > 4/10, use net radiation index equal to -1.

3) For day time:

   a) Determine the insolation class number as a function of solar altitude from table 6.3.
   b) If total cloud cover < 5/10, use net radiation index in table 6.3 corresponding to the insolation class number.
   c) If total cloud cover > 5/10, modify the insolation class number by following these steps:

      i) Ceiling < 7000 feet., subtract 2.
      ii) Ceiling < 7000 feet., but less than 16000 feet., subtract 1.
iii) Total cloud cover equal to 10/10, subtract 1. (This will only apply to ceilings < 7000 feet. Since cases with 10/10 coverage below 7000 feet are considered in item 1 above).

iv) If insolation class number has not been modified by steps (1), (2) or (3) above, assume modified class number equal to insolation class number.

v) If modified insolation class number < 1, let it equal to 1.

vi) Use net radiation index in table 6.2 corresponding to the modified insolation class number.

Accordingly, the stability for every three hour intervals are computed on all days for the four months selected. The percentage frequency of occurrence of each of the stability classes for every three hour interval are computed and presented in Fig 6.2.

In January, the highly stable category, 'F', is noticed most of the time during night hours. A small percentage of 'E' is also noticed during night time. From 0830hrs. onwards a combination of neutral 'D' and the different classes of unstable conditions (A, B, C) are observed. During 1130hrs 'A', the highly unstable category has grown up considerably. A small percentage of 'B' and a very small percentage of 'C' is also noticed during this period. Around 1430hrs., 'B' is the dominating class
Fig. 6.2 Diurnal variation of percentage frequency of Pasquill's stability classes for the four representative months
followed by 'C' and 'D'. In the evening hours about 50% is by 'D' and the remaining is by 'C', together with a very small percentage of 'B'.

In April, night hours is again having mostly 'F' and 'E' categories. A small percentage of 'D' category is also noticed during night hours in this month. Between 0830 and 1130 hrs 'B' is nearly 70%. The rest is mostly by 'D'. 'A' is the most occurring class between 1130 hrs and 1430 hrs. The percentage of 'C' has come down and the percentage of 'D' has gone up during the evening hours, compared to January.

The 'D' frequency is about 25% during night hours in July. The rest is followed by 'E' and 'F' during these hours. 'D' frequency is also observed in good percentage throughout the day. The percentage of 'D' is even more than 75% between 0830 hrs and 1130 hrs and also during 1730 hrs. The percentage of the occurrence is more for 'B' followed by 'C' and 'A' during noon hours.

In October more or less same conditions as in July are observed. However the frequency of 'D' has come down both day and night hours. Between 0830hrs and to 1130 hrs, both 'B' and 'D' are nearly equal in percentage. The percentage of 'A' during noon hours is higher than that in July, but lower than that in April or January. Afternoon hours showed 'B' category more followed by 'D' and 'C'.

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Highly stable conditions during night hours and unstable conditions during day time is the common feature in all the four seasons. The occurrence of the neutral category 'D' is more in July, which is the peak monsoon season with overcast conditions and high wind speed occasionally. 'D' is observed almost throughout the day in different percentages in July this month and also in October. The highly unstable category 'A' is observed maximum during the noon hours in January followed by April, October and July.

6.1.4 Dispersion parameters

It is the standard deviation of the plume center line expressed in meters (Pasquill 1962). Mc.Elroy (1969) proposed to the relation between $\sigma_y$ and $\sigma_z$ in terms of downwind distance as follows.

$$\sigma_y = b^p, \sigma_z = a^k$$

where $a$, $b$, $p$ and $k$ are constants whose values are functions of stability. In the present study the nomograms developed by Turner (1970) are used to compute $\sigma_y$ and $\sigma_z$. These values are representative only for a sampling time of ten minutes and for open country and may probably under estimate the plume dispersion potential. On clear nights with light winds for ground level sources free of topographic influences frequent shift in wind directions occur which serve to spread the plume horizontally. For elevated sources under the extremely stable conditions significant
concentrations do not reach ground level until the stability changes. The weighted mean $\bar{z}$ according to stability classes are computed.

6.1.5 Effective stack height

To determine the concentrations downwind from a source it is essential to estimate the effective stack height. Seldom this height corresponds to the physical height of the stack. High emission velocity and higher temperature of the effluents than the ambient air at the stack top, enhances the effective stack height above the physical stack height. Aerodynamic downwash, eddies caused by the flow around buildings or the stack and the evaporative cooling of moisture droplets in the effluent may cause lowering of the plume to the extent that it may be lower than the physical stack height. Several investigators have proposed formulae for the estimation of effective stack height under given conditions. A comparative study of different formulae suggest that there is no one formula which is outstanding in all respects.

Plume rise can be calculated as a function of source parameters such as buoyancy and meteorological conditions. Techniques for deriving this have been developed by several people and organizations, but hardly any of them agree either with each other or with new observations. There are many formulae such as, Holland's equation, Brigg's equation, TVA 1971 model, TVA 1972 model, Whaley's formula, CONCAWE formula, Lucas formula,
Morton et al. formula and Slawsen and Scandy formula. A most sophisticated formula needs additional parameters which are not conventionally measured at any meteorological observatory. Therefore a necessity arouse to seek simple formula which require minimum data and the accuracy secured by using more refined formula is not seriously affected. Among the various formula tested except Slawsen and Scandy formula, all other give under estimate values. Therefore Slawsen and Scandy formula is used for the present work. The formula can be written below.

\[ \Delta H = \frac{250 \text{ FT}}{U^3} \]

where \( \text{FT} = g w_0 R_0 (T/T_a) \)

\( \Delta H \) is the plume rise, \( U \) is the mean horizontal wind speed, \( w_0 \) stack gas velocity at the exit, \( T \) is the temperature difference between plume and ambient air, \( T_a \) is the ambient air temperature.

6.2 Results and Discussion

The spatial distribution of the concentration of sulfur dioxide by means of Gaussian Plume model for multiple sources is studied for Cochin. Fig 6.3 shows the 4km x 4km grids over Cochin in which two major sources are identified, namely source I and source II (fig.6.3). The major industries in source I are Travancore Cochin Chemicals, FACT (Udyogmandal), Hindustan Organic Chemicals, Hindustan Insecticides, Indian Rare Earths, Cominco Binani Zinc Ltd., ASCL, Caprolactum. The major industries in source II are FACT (Ambalamughal), Carbon and Chemicals and Cochin refineries. Source I have an emission of
Fig. 6.3 4km x 4km grids of Cochin with sources
246601 kg/day of SO₂ and source II have an emission of 26985 kg/day. Emission of source I is more than 9 times that of source II. For the sake of convenience, all the physical stack heights falling in each source are averaged to have one representative stack height, from which the total emission from the corresponding source is assumed to occur. The plume rise is calculated by Slawson and Scandy formula and effective stack height is calculated. For source I it is 128.5 m and for source II it is 249 m. The SO₂ concentration from the two sources identified, is computed for the four representative months, at various distances from the source, depending upon the stability, mixing height and wind direction. In each grid considered, the contribution from the two sources are added and the twenty hour mean values have been worked out. The isolines in μg/m³ are drawn and are presented for the four seasons.

Fig. 6.4 shows the spatial distribution of SO₂ concentration for January. As expected the major contribution to SO₂ concentration is due to source I. The maximum values of concentration are observed near the source. There is a sharp fall in concentration as one goes a few kilometers away from the source region in any direction. However, a concentration between 770 μg/m³ to 520 μg/m³ are recorded about 5 Km² are surrounded by the source region. This include areas like Bloor, north of Cheranalloor and Varapuzha region which are located to the North of the central region of the city. A concentration between 500 μg/m³ to 120 μg/m³ are recorded in the most part of the thickly
Fig. 6.4 Isolines of average $SO_2$ concentration for January
populated areas of Cochin. In the Southeast sector the extreme portions have shown low values of the order of 20 µg/m³. Concentration is slightly above 20 µg/m³ near the source II, which is located in the Southeast sector of the city. The northern part of the region also showed lower concentration of the order of 20 µg/m³.

Fig. 6.5 shows the spatial distribution of SO₂ concentration in April. The higher concentration is again near the source. Comparatively lower concentration is observed near the central region of the city which lies in the Southwest direction with respect to the major source. This may be due to the effect of sea breeze blowing from west to east, comparatively longer period of the day, in this month. The gas is transported more towards the east of the city. The rate of decrease of SO₂ concentration with distance form the source is more in this month compared to that in January. The central part of the city showed the least concentration compared to other pre seasons. Southern half portion of the region is having a concentration between 270 µg/m³. The concentration surrounding 5 to 6 square kilometer from the source II is much higher and it is greater than 800 µg/m³. The concentration very nearer to source I is of the order of 1700 µg/m³. The effect of source II is not felt much during this month also. The extreme southern part and the western part of the city recorded the lowest concentration.
Fig. 6.5 Isolines of average SO$_2$ concentration for April
The sulfur dioxide distribution in July is shown in fig. 6.6. The concentration near the source is least compared to the other three seasons. This can be due to the effect of heavy monsoon rainfall during the season. Continuous rainfall causes for the cleaning of the atmosphere to a certain extent by the washout and rainout processes. A concentration between 50 \( \mu g/m^3 \) to 500 \( \mu g/m^3 \) has been observed in most of the thickly populated region of the city. The distribution is slightly towards the eastern part of the region. Generally the concentration in different places are lower in this season compared to the other three seasons. This also may be due to the effect of monsoon rainfall.

Fig. 6.7 shows \( S_2O \) distribution in October. Distribution is some what similar to that of January with slightly lesser concentration near source I. Near source II concentration is comparatively more. A slight spreading is shown towards south and southeast direction. The concentration decreases at a faster rate towards the western part of the city. A concentration 50 \( \mu g/m^3 \) to 500 \( \mu g/m^3 \) has been noticed in most of the thickly populated areas. Within five to six square kilometers surrounded by the source region the concentration is above 500 \( \mu g/m^3 \). In general, it is observed that the maximum is always recorded near the source region with their magnitude differing from season to season. The concentration near the source region is maximum in January, which is the representative month of winter season. The concentration near the source is minimum in the month of July.
Fig. 6.6 Isolines of average SO₂ concentration for July
Fig.6.7 Isolines of average $SO_2$ concentration for October
which is the representative month of south west monsoon season. The concentration near the source is comparable during April and October, which are representative months of premonsoon and postmonsoon seasons respectively.

The variations in mixing height doesn't seem to be contributing more to the difference in concentration in various seasons. On the otherhand wind speed appears to have more control in determining the spatial concentration and the direction of spreading.

There is no single direction in all the seasons, in which the spread is very prominent. It should be noted here that the concentrations are 24 hour values and hence the effect of reversal of wind direction from day time to night time or vice versa is not felt much. However the day time wind speed being more, there is a possibility of a slight domination of the wind directions during day time.

However one notable feature of the distribution is the spread towards south and a sudden fall from the center of maximum towards north. This is mainly due to the effect of prevailing wind direction. During day time, Cochin is experiencing sea breeze most of the time from west-northwest direction and also from west direction. During night time winds are generally weak and is from north or northeast direction. In both the cases these directions modified by the urban structure of the city cause for
the spreading of pollutants towards either south or southeast.

Another interesting feature is the effect of variation of the magnitude of the concentration at the source is not felt much in the suburban region of the city. This is also true in the case of central parts of the city which is located southsouthwest of the major source. The concentration is mostly around 100 μg/m3 in the built up areas of the city. In the case of increased concentration at the source region, the values in the thickly populated areas have not shown a proportionate increase, though there is a marginal difference. The observation is very interesting in view of the fact that even if the source strength goes up in the present source identified, the increase of concentration will not be proportionate in many built up areas of Cochin, but it causes concern only in a region about 20 square kilometers surrounded by the major source.

The maximum concentration interestingly is well below 1 ppm in all the cases. But if one compares the standards of environmental protection agency, USA the values exceeded the limit of 365 μg/m3 in most of the places in Cochin. The concentrations show in the present study appears to be more representative compared to the computations made by Anilkumar (1986) for Cochin. The concentration obtained by him were very high due to the very small wind velocity taken for the calm conditions. In addition the stack height used in some of the cases were very low.
It is in the interest of community that the level of $\text{SO}_2$ concentration should be reduced considerably. The stack heights in different cases can be raised instead of altering the structure and capacity of the sources. Even though the emission from source II, that considered in the present study is actually high, its contribution to $\text{SO}_2$ concentration is not predominant. One of the reasons why the source II does not contribute much to the concentration is because of comparatively higher stack heights there. The effect of effective stack height, as is seen in this case is very important and hence it is suggested that the average physical stack height in source I could go up by at least five times the present heights. It should be noted that it is on an average only. For further bringing down the values of concentration one can also suggest devices to control at the source itself. Apart from these two the plume temperature can also be made to be slightly higher to have further rise of the plume due to buoyancy or some device should be installed that pump out the smoke through the stack exit, so as to have considerable vertical velocity of the plume. Even though comparatively lower concentration are recorded in the month of July, the monsoon period should be viewed with caution. This is because of a good percentage of pollution in the atmosphere can be brought to the ground by washout or rainout due to the heavy precipitation occurring in this period. This can also cause for
the occurrence of acid rain fall. Also one should not forget the low mixing heights in this period, which cannot dilute the pollutants in the vertical.

6.3 Summary

The spatial distribution of the 24 hour $SO_2$ concentration for different seasons for a ten year period has been studied in this chapter. In general the maximum concentration is always recorded near the source I region with their magnitude differing moderately from season to season. The emission from source I is more than 9 times that of source II and the effective stack height for source one is only half of that of source II. Hence the contribution due to source II is very less. Towards the north the effect of source II is not at all significant.

There is no single direction in which the spread is very prominent. However a slight spread towards south or southeast is noticed. A sudden fall in concentration from the center of maximum is noted in all the seasons.

The variation in mixing height does not seem to be contributing more to the difference in concentration. On the other hand, wind appears to have more control in determining the spatial concentration.

The concentration observed south of the central parts of the city are comparatively low. But the values are found
increasing as we go to the northern parts of the city center. Between Ayrur and Edapplly in the northsouth and between NAD and Tattapallir in the eastwest the observed values are often very high. It is often greater than the permissible limit suggested by the Indian standard. Therefore the present trend of the expansion of the city mostly towards the northern direction must be considered very seriously.

As for the locations of the existing industries are concerned, the ideal place would have been the extreme southeast portions of the city so that the city interior and all the densely populated areas would be relatively free from pollution. In such a case most of the spread of the pollutants is over the ocean. However it is not worthwhile to think of a change for the existing industries. In the present situation any newly coming industries can be located towards the far south of the city or far east of the city. This helps the interior of the city for no further increase in the concentration levels.