Chapter - 1

Introduction
The rapid urbanisation and large-scale industrialisation have given rise to a multitude of environmental problems. In particular, air pollution is one of the major environmental problems affecting both developed and developing countries worldwide. The air quality of the urban areas, in general, is getting deteriorated due to the increased industrial activities, growth of population and vehicular traffic. In addition, unfavourable meteorological conditions (Kassomenos et al., 1999) and complex topography further add to the already worsening urban air-quality. Increasing amounts of potentially harmful gases and particulates are being emitted into the atmosphere on a global scale resulting in damages to human health and the environment. Because of adverse impact on health, visibility and other associated effects a considerable effort has been devoted to monitor the air pollutants and to characterise the air quality status in terms of several ‘criteria air pollutants’ (coined by USEPA) or some of ‘classical air pollutants’ (coined by WHO) such as CO, SO₂, O₃, NO, NO₂, SPM (TSP, PM₁₀, PM₂.₅ and PM₁), particulate lead. The criteria ambient air pollutants are the most widespread pollutants that have been shown to be harmful to human health and welfare.

Urban air pollution has been a cause of concern for many years. The photochemical smogs experienced in Meuse valley (Belgium) in 1931, Los Angeles (Donora) in 1948 and surrounding areas are well documented. This is also evident from further literature on smog such as London smog (or killer smog), which affected London up to the late 1950s (Godish, 1997). In due course of time there has been considerable effort in monitoring individual air pollutants such as gases and particulates to evaluate their adverse impacts on living beings. Logan (1953) studied the mortality in London smog of 1952. Juhren et al. (1957) studied photochemical smog and its indicators. Heicklen and Cohen (1968) investigated the role of nitric oxide in atmospheric photochemistry. Aldiz (1969) measured atmospheric ozone flux over land and water separately. Dimitriades (1972) discussed the effects of hydrocarbons and NOx in formation of photochemical smog. Grosjean (1983) worked on the distribution of nitrogen pollutants at a smog receptor site in Los Angeles. Aneja (1990) investigated the natural source of sulphur in the atmosphere. He also observed that the possible sources of H₂S and other sulphur containing compounds might be the living plants. Hagerman and Aneja (1997) measured and characterised the non-methane hydrocarbons (NMHCs) at four sites in Southwest U.S. They found that the lighter NMHCs (C₂-C₄) show a seasonal variation attaining maximum during the winter and minimum during summer. Further the
biogenic hydrocarbons also exhibit a seasonal variation with a summer maximum and winter minimum.

The particulates also play an important role in the atmosphere. Therefore, it is of utmost importance to obtain accurate information on the total particulates in air including their various sources in any urban area. A number of research programmes have been carried out in this regard. Adams et al. (1975) studied the elemental composition of atmospheric aerosol particles at Chacaltaya, Bolivia. Alpert and Hopke (1980) attempted to determine the sources of Boston aerosol quantitatively. Kamath and Kelkar (1981) studied the primary source contributions to winter aerosols in Mumbai, India. The results concluded that natural sources contribute more than 50% to the winter aerosols whereas contributions from automobiles and fossil fuels were very low (~0.4%). Khemani et al. (1982) studied the chemical composition and sinking processes of aerosols over Deccan plateau in India. Lefohn and Mohnen (1986) characterised O₃, SO₂, NO₂ chemically in Germany. Mahadevan et al. (1986) investigated the presence of trace metals in precipitations over industrial areas in Bombay. Tripathi et al. (1989) examined the atmospheric pollution from toxic heavy metals in two cities of Moradabad and Mumbai in India. The study indicates that automobile exhaust is the dominant source for heavy metals in the environment of Mumbai whereas the brass industry is responsible for enhanced concentrations of these metals in Moradabad. Charron et al. (2004) observed the divergence between PM₂.₅ and PM₁₀ mass measurements by Tapered Elemental Oscillating Microbalance (TEOM) and Partisol (gravimetric) instruments. They found that TEOM gives lower readings of both PM₁₀ and PM₂.₅ as compared to that of Partisol instruments.

In addition to the above, the modelling aspect of the air pollution got the momentum in due course of time. The mathematical tools and models were used to study the complicated relationships between the air quality and other factors related to it. There have been a number of attempts in this regard, some of which are discussed in the following: Blifford and Mecker (1967) developed a factor analysis model of large-scale pollutants. Reynolds et al. (1973) used mathematical tools for modelling photochemical air pollutants. Gibson Jr. and Peters (1977) developed a short-term air quality model for SO₂ in Kentucky. Sanchez et al. (1986) studied the temporal and spatial distribution of SO₂ by principal component factor analysis. Ku et al. (1987) developed a three-dimensional grid-based numerical air pollution model for the estimation of air pollutants in an urban area. The modelling system
incorporated the combined influences of advective transport, turbulent diffusion, chemical transformation, source emissions and surface removal of air contaminants. Pio et al. (1989) assessed the air pollution sources by using principal component and multi-linear regression analysis. Ziomas et al. (1995) used analytical models to forecast the peak pollutant concentrations from the meteorological and other variables. The model equations were used to forecast the pollutants with a certain degree of success. Hunova (2001) studied the spatial interpretation of ambient air quality in Czech Republic. The study identified three essential factors of ambient air quality which are ‘ambient air pollution’, ‘ground-level ozone’ and ‘wet atmospheric deposition’. Hunova et al. (2004) studied ambient air quality and deposition trends of SO$_2$, NO$_x$, O$_3$, SO$_4^{2-}$ and NO$_3^-$ at rural stations in the Czech Republic during 1993–2001. The results showed that there was remarkable decrease in SO$_2$ emission and SO$_4^{2-}$ concentrations with an increased trend of ozone at all stations. The concentrations of NO$_x$ and NO$_3^-$ showed a downward trend at only few locations.

In the Indian context the study on air quality carries a great significance due to unprecedented industrial and economic development of the urban areas during the last three decades. India has 23 cities of over one million people. The urban air quality is worsening due to upward trend in power consumption, industrialisation and vehicle use. In India daily ambient air quality data are available only for few cities (Dave, 1986). The data available for many cities viz. Mumbai, Kolkata, Agra, Delhi, Ahmedabad, Kanpur and Varanasi show severe air pollution problems. Two-hour average concentrations of SO$_2$ for the cities of Bombay and Calcutta were found in the ranges of 113-262 $\mu$g/m$^3$ and 73-568 $\mu$g/m$^3$ respectively (Mathur, 1986). The ambient air pollution levels in these cities have exceeded WHO health standards on many occasions (Pandey et al., 1992 and Gupta et al., 2002). Sharma and Patil (1992) studied the size distribution of atmospheric aerosols and identified their sources using factor analysis technique. Kulshrestha et al. (1994) reported the chemical characteristics of aerosols and the relative contribution of fine and coarse mode particles at Agra in India. The results of the study suggested that the acidity in fine mode was neutralised by ammonium ion, Ca and Mg. And alkalinity in coarse mode was due to the presence of soil-oriented compounds. In another study, Saxena et al. (1996) investigated the chemical characterisation of the precipitations at Agra city during July-Sept, 1991. It has been determined that acid neutralisation is brought about by Calcium rather than ammonium ion. Further, the factor analysis based on principal component analysis was carried out to identify the sources of the heavy metals present in the atmosphere of Agra. Kulshrestha et
al. (1996) investigated the atmospheric deposition through precipitation studies at New Delhi. The results indicated that the free acidity of the rain water was found to be due to $\text{SO}_4^{2-}$ rather than $\text{NO}_3^-$. Further the calculations of sea salt fraction and enrichment factor revealed that this site is free from marine influence. Saxena et al. (1997) studied the dry deposition of sulphate and nitrate in a semi-arid area of India. The results revealed that the deposition rates were maximum during the winter followed by summer and minimum during the monsoon. Mondal et al. (2000) studied ground level concentrations of nitrogen oxides ($\text{NO}_x$) at a traffic intersection point in Calcutta. The results indicate that $\text{NO}_x$ concentrations show a seasonal variation with a maximum average concentration of 222 $\mu\text{g/m}^3$ during winter and minimum average concentration of 55 $\mu\text{g/m}^3$ during peak monsoon. Jain et al. (2000) reported the influence of crustal aerosols on wet deposition at urban and rural sites in India. The study suggested that crustal sulphate is not responsible for the acidity or the lowering the pH of rainwater in India. Aneja et al. (2001) studied and analysed the criteria pollutants in Delhi. The results showed that the mobile sources are responsible for $\text{NO}_x$ pollution whereas point sources are responsible for sulphate pollution. Sharma et al. (2003) studied the formation of atmospheric sulphate under high $\text{PM}_{10}$ concentrations in Kanpur. The study concluded that high level of $\text{PM}_{10}$, Ca and high pH of aerosols in atmosphere provide a conducive environment for conversion of $\text{SO}_2$ to $\text{SO}_4$. It was also concluded that the important migration pathway in the study area for the transformation of $\text{SO}_2$ to $\text{SO}_4$ appears to be oxidation of $\text{SO}_2$ on the surfaces (of particulate) available in the ambient atmosphere. Naja et al. (2003) studied the diurnal and seasonal variations in surface ozone at the high altitude site Mt. Abu in India. The study reported that the unique meteorological conditions over this region seem to play an important role in seasonal as well as diurnal variations in Ozone. Kulshrestha et al. (2003) studied the estimation of $\text{SO}_4$ contribution by dry deposition of $\text{SO}_2$ onto the dust particles in India. The results showed that a significant fraction of $\text{SO}_4$ in dust is contributed by oxidation of $\text{SO}_2$ gas on the dust particles during suitable meteorological conditions. Kulshrestha et al. (2004) reported the emissions and accumulation of metals in the atmosphere due to crackers and sparkles during Diwali festival in India. The study indicated that burning of crackers and sparkles on Diwali are a very strong source of air pollution which contributes significantly high amount of metals in the air of Delhi.

In Delhi, considered to be one of the most polluted cities in the world (Aneja et al., 2001 and Kathuria, 2002), the air quality has reached alarmingly high levels over past decades.
due to increasing consumption of fossil fuels (in vehicles, industries, etc.), expansion of transport network and of course the diverse activities of humans. It is estimated that the industrial and anthropogenic sources add 3000 different types of chemicals daily to the environment of Delhi. An estimated 2000 metric tones of air pollutants are emitted into the atmosphere every day in Delhi. The maximum SPM varied from 1360 µg/m³ in 1987 to 1448 µg/m³ in 2000, and peak value of 2340 µg/m³ was observed in 1992 (CPCB, 1996; 2001). It is believed that the serious pollution episodes in this city are generally caused by sudden increase in the emissions of pollutants and unfavourable meteorological conditions.

Other pollutants such as nitrogen oxides, sulphur dioxide, carbon monoxide and ozone are reported to be present in moderate to high concentrations in Delhi (CPCB, 2001). But the data from monitoring stations set up by Central Pollution Control Board (CPCB), India in Delhi show that the concentration of SO₂ and NOₓ are much higher than permissible limits (Goyal and Sidhartha, 2003). The annual mean concentration of NO₂ has increased from 20.4 µg/m³ in 1987 to 41.5 µg/m³ in 2000 and that of SO₂ has increased from 16.5 µg/m³ in 1987 to 21 µg/m³ in 2000 (CPCB, 1996 and 2001). The ambient ozone varied between 20 to 273 µg/m³ during 1989 to 1991 (Varshney and Aggarwal, 1992). It is reported that the hourly peak ground level Ozone varied between 72.15-80.84 µg/m³ during August-October 1996 with an hourly average variation of 46.8-64.89 µg/m³. The hourly peak Ozone concentration varied between 113-125 µg/m³ and the hourly average concentration varied between 88 –90 µg/m³ in March-June, 1997 (Varshney and Rout, 1998). The data of CPCB shows the Ozone concentration varied between 26-82 µg/m³, 20-104 µg/m³ and 29-77 µg/m³ in 1998, 1999 and 2000 respectively (CPCB, 2001).

Numerous epidemiological studies conducted since the early 1970s have found that particulates have a statistically significant impact on the mortality and morbidity rates (Vincent and Tan, 1997). The epidemiological evidence for SO₂, NO₂, O₃ and CO has shown increasingly adverse morbidity impacts (Tietenberg, 1998). Beard and Wertheim (1967) studied the behavioural impairment associated with small doses of CO. Peterson and Allen (1982), and Flachsbart et al. (1987) had investigated the exposure of CO to the commuters of Los Angeles and Washington, respectively. Chan et al. (1991) studied the exposure of commuters to volatile organic compounds (VOCs) in Boston. Chan et al. (1994) studied exposure of bicycle commuters to vehicular pollution in Guangzhou, China.
Introduction

In one of the World Bank Studies (Brandon, 1995) on the ambient air pollution levels of SPM, SO\textsubscript{2}, Lead and NO\textsubscript{2} in India, WHO have reported that standards exceeded in 36 major Indian cities and towns. These increased levels of pollutants account for 40350 premature deaths, around 19,805,000 thousand-hospital admissions and sickness requiring medical treatment, and also 1201 million incidences of minor sickness annually (Gupta et al., 2002).

It is clear from the foregoing that various monitoring programmes have been undertaken to know the quality of air by generating vast amount of air pollutant data in various parts of the world. These encyclopaedic volumes of data neither give a clear picture to the decision maker nor to the common man who simply wants to know “how good or bad the air is”. The interpretation and understanding become tedious and confusing even to the scientific and technical community. The information is required to be presented in a simple and lucid manner for the general public who may take interest in pollution mitigation efforts. Moreover, air is a matter of life and breath. The people want to know quickly and simply the state of their chances - hence air quality index. Further no scientific reference scale was developed for uniform reporting of these air pollutants. Therefore the Environmental Protection Agency (EPA) of US for the first time developed and established a national uniform reference scale known as Pollution Standard Index (PSI) to protect the public against adverse health effects due to major pollutants (Federal Register, 1999). These indices are referred to by various names including Air Quality Index (AQI) or Regional Pollution Index (RPI), and are based on national legal standards, objectives and guidelines.

The advance information on Air Quality in the form of AQI would forewarn the public against exposure to the unhealthy air and at the same time it will encourage people to reduce emission-producing activities. The AQI is being used as a useful tool to monitor and forecast the pollution levels for any or more of the following reasons (Ott and Thom, 1976):

1. It is easily understood by the public as it transforms the scientific concentrations units of each pollutant into a non-dimensional number.
2. It includes major pollutants and is flexible enough to include other pollutants.
3. It represents the relationship between air pollution levels and national air quality goals.
4. It is measured in a simple manner using reasonable assumptions and is easily convertible to pollutant concentrations through simple equations or appropriate plots.
5. It is based on sound scientific premises as statistical tools are used.
6. It is highly consistent with the individual air pollution levels.
7. It is spatially meaningful as the average or highest pollution levels over the monitoring stations are taken into consideration.
8. It exhibits a noticeable day-to-day as well as hourly variation (if desired).
9. It can be used for advance forecasting of pollutant concentrations as the meteorological variables are taken into consideration.
10. It helps in developing and establishing a meaningful long-term trend of air quality.

Specific indices vary greatly from country to country and also vary within the country. The different indices have been developed to describe either the level of air quality, the level of pollution, or the potential for health effects worldwide. The AQI developed by the USEPA relates to the ranges of air quality (such as ‘good’, ‘moderate’, ‘unhealthy’, ‘very unhealthy’ and ‘hazardous’) and the corresponding severity of health effects.

Babcock (1970) developed a combined pollution index for total air pollution. Shenfeld (1970) had given a note on air pollution index and alert system. Inhaber (1975) had suggested a set of Air Quality Indices for Canada by taking the five criteria pollutants and visibility near the airports. Bezuglaya et al. (1993) described a technique for calculating the index of air pollution with several pollutants in Russia. Further they described the effect of air pollution potential on atmospheric pollutant concentrations. Malakos and Wong (1999) proposed an AQI by incorporating synergistic effects so that advisory notices could be issued for those of the population more susceptible to the effects of pollution. Swamee and Tyagi (1999) presented an ambiguity and eclipsity-free function for aggregation of air pollution sub indices. The sub indices have been expressed as full range functions of the pollutant concentrations for computer adaptation. Cogliani (2001) studied the forecasting of daily air pollution index with the help of meteorological variables. He considered daily thermic excursion, previous day measured air pollution and daily average wind speed to forecast the air pollution index. Bortnick et al. (2001) used the continuous PM$_{2.5}$ data to report the AQI. They used statistical linear regression models for this purpose. Cheng et al. (2004) have developed a revised air quality index by associating pollution standard index of five pollutants (PM$_{10}$, O$_3$, SO$_2$, CO and NO$_2$) and entropy function. This index has comparative index function and supplies the public with a better indicator of air quality. Moreover, it is investigated that there exists a relationship between pollutant concentrations
and meteorological parameters (e.g. McCollister and Wilson, 1975; Aron and Aron, 1978; Lin, 1982; Robeson and Steyn, 1990; Ziomas et al., 1995). Further, the relationship between the AQI and meteorological conditions prevalent in the urban atmosphere has been examined by Cox and Chu (1993) and Kassomenos (1995). Therefore a concentrated effort is underway to develop an AQI coupled with meteorological parameters (Cogliani, 2001).

Sharma et al. (2001) have developed an AQI in Indian context by considering three pollutants: sulphur dioxide (SO$_2$), nitrogen dioxide (NO$_2$) and Suspended Particulate Matter (SPM). Sharma et al. (2003) have proposed an AQI for the city of Kanpur by using a maximum operator concept, which takes the maximum value of sub-indices of each pollutant. The mathematical functions for calculating sub-indices of each pollutant, such as SO$_2$, SPM, O$_3$, NO$_2$, CO and PM$_{10}$, are based on health criteria of the USEPA and Indian air quality standards. The AQI of Kanpur has shown that air quality worsens (very poor to severe) in winter months and also during early summer months.

The Oak Ridge Air Quality Index (ORAQI) has been examined for Delhi. But it is found that the index suffers from eclipsing effect (when one pollutant exceeds its standard without the index exceeding its critical value). The maximum operator concept has been suggested to be introduced to overcome the eclipsing or ambiguity problems (Swamee and Tyagi, 1999). The limitation of this method is that it does not take the meteorological parameters into account. Further it did not propose any relationship between the AQI and meteorological variables. However, it is believed that a statistically based index is the ultimate answer to these problems as the air quality measurements follow a definable statistical distribution (Shults and Beauchamp, 1971). In this regard the widely used statistical technique is factor analysis assisted by principal component analysis. Therefore, it would be worth developing an air quality index for Delhi which would combine statistically the measured concentrations of some of criteria or classical air pollutants and meteorological parameters. Further, it would also be interesting to examine the relationship between the Air Pollution Index and the Meteorological Index. These considerations have prompted the present research work with the following objectives:

i) To measure the concentrations of air pollutants (CO, SO$_2$, O$_3$, NO, NO$_2$, and PM$_{10}$) in different seasons along with measurements of meteorological parameters (temperature, wind speed, wind direction, relative humidity and solar flux).
ii) To determine Air Quality Indices (AQI) for different seasons [summer, monsoon, post-monsoon and winter] in Delhi by considering air pollutants and meteorological parameters.

iii) To examine the relationship between Pollution Index (PI) (by taking only pollutants) and Meteorological Index (MI) (by taking only the meteorological parameters).

Chapter-II gives a brief account of the characteristics, sources of criteria air pollutants and their adverse effects. A review of the Air Quality Indices is presented in chapter-III. Chapter-IV describes the study area, design of experiment and principles of instrumentation of the proposed work. Chapter-V deals with the mathematical aspects for computation of Air Quality Index, Pollution Index and Meteorological Index. The results and discussion are presented in chapter-VI.