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Measurement and modeling of respirable particulate (PM$_{10}$) and lead pollution over Madurai, India

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Abstract Samples of particulate matter less than or equal to 10 μm (PM$_{10}$) were collected round the clock duration by using a respirable dust sampler (APM 460 BL) in Madurai, the second largest and most densely populated city of Tamil Nadu, India. The Environmental Protection Agency (EPA)-recommended standard methods were adopted not only for sample collection but also for subsequent analysis of respirable particulate pollutants. The observed PM$_{10}$ concentrations varied from 88.1 to 226.9 μg/m^3, and lead concentrations ranged between 0.21 to 1.18 μg/m^3. The annual averages of the concentrations of the pollutants of current concern manifested that they were mostly below the Indian air quality standards and were generally comparable with those concentrations observed in most other Indian urban areas. The AERMOD model was validated simultaneously by comparing the predicted levels with the estimated levels of PM$_{10}$. The generated database of the present investigation on the degree of pollution may be used for further research investigation and pollution abatement in the city.

Keywords Urban air pollution · Monitoring · PM$_{10}$ · Pb · AERMOD

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Introduction

It is well known that the health effects associated with the airborne particles are dependent on their toxicity. The extent to which air borne particles penetrate into the human respiratory system is mainly determined by the size of the penetrating particles (Balachandran et al. 2000). There are several epidemiological studies present in the literature (Dockery 1993; Hoek et al. 1997; Harrison and Yin 2000; Sammet et al. 2000), which have demonstrated a direct association between atmospheric inhalable particulate matter and respiratory diseases, pulmonary damage, and mortality especially in the urban areas. Therefore, the estimation of the levels of respirable particulate and its major toxic constituent lead (Pb) present in the urban atmosphere is a prime requirement of epidemiological investigation, air quality management, and air pollution abatement (Chow et al. 2002; Querol et al. 2001). For this purpose, we have monitored the levels of particulate matter less than or equal to 10 μm (PM$_{10}$) and Pb. In addition, we have modeled the dispersion of PM$_{10}$ over Madurai, the second largest city in the state of Tamil Nadu, India. The measurements (sample collection) and chemical analysis were made using the standard method recommended by the Environmental Protection Agency (EPA), USA, for the period of 1 year viz. July 2005 to June 2006. To investigate the dispersion of pollutants over Madurai city, we have used AERMOD model (EPA 2005; Cimorelli et al. 2005; Kesarkar et al. 2007) developed by EPA. The results obtained from the monitoring of PM$_{10}$ and Pb along with modeling of PM$_{10}$ is presented in this investigation.

This paper is organized as follows. "Details of the experiments" of this paper presents the details of the monitoring of PM$_{10}$ and Pb over Madurai city. The results of monitoring and modeling of PM$_{10}$ dispersion using

AERMOD, a steady-state plume dispersion model, are discussed in "Results and discussions." The major conclusions are presented in "Conclusions."

Details of the experiments

Monitoring of respirable particulate matter

Madurai city (9°54′ N, 78°84′ E and 100 m above sea level), popularly known as the City of Temples, has an important historical, cultural, and religious heritage in South India. This city has a surface area of 52.8 km^2 with an estimated population of 1.2 million in 2001 (Jeba Rajasekhar et al. 2004). The ambient air quality of the city is greatly affected due to combustion of fossil fuels in stationary and mobile sources, and it was observed that the rate of combustion of fossil fuels had an increasing trend over the decades. To study the distribution of pollutants over Madurai city, the measurements of respirable particulate matter and Pb were carried out at six different sampling sites. The selections of these sites were made based on the existing anthropogenic activities occurring at these sites, which were responsible for atmospheric pollution. These anthropogenic activities included the varying density of road traffic, industrialization, and domestic activities within the urban limits of the city. The air samples were collected periodically for 1 year to estimate the concentrations of the particulate pollutants of current concern.

A description of the land use and likely sources of atmospheric pollution in the vicinity of the sites is given below.

Periyar bus stand

This is the main bus station situated at the heart of the city. The area of this bus station is very limited, and it is surrounded by narrow roads. Therefore, at this site, there are always traffic jams and congestion leading to slow movement of traffic. The contribution to air pollution at this site is mainly due to the emissions from public and commercial transportation (buses, trucks, autorickshaws, and two-wheelers). The accumulation of the air pollutants may be endured at this site due to the presence of tall roadside shops, houses, and buildings.

Goripalayam

This is a very busy commercial site located in the northern part of the city. A large number of shops, restaurants, and workshops, in addition to some Government establishments such as Government Rajaji Hospital (the biggest hospital in the southern Tamil Nadu region), colleges, and schools, are

situated near this site. Although the roads are relatively wider than those at the central parts of the city, the movement of the traffic is highly congested and slow due to high density of vehicles and encroachment on the road sides.

Palanganatham

This site is surrounded by many cottages and small-scale industries mostly related to furniture, grill works, plastic, and rubber and also by lathe works, electroplating units, rice mills, and residential colonies. The continuous traffic flow witnessed at this site is due to the bus station located near by. Besides the emissions from automobiles, the emissions from commercial and domestic sectors contribute to the total air pollution load at this sampling site.

Kochadai

This is an industrial site of Madurai city, where two major coal-based rubber industries that produce rubber-based domestic appliances are situated. The National Highway (NH-47) Extension passing near this site has a substantial flow of traffic. Hence, the emissions from the industries and automobiles are the major sources of air pollution in this region. At this site, there are also some residential colonies of high-profile people.

Pudur

Pudur is a fast emerging extension area of the city with many residential colonies. There are also a number of Government offices, educational institutions, and commercial establishments in this area of study. Traffic flow consists mainly of light-tonnage vehicles especially two-wheelers and heavy-tonnage vehicles mainly the public buses. Since the roads are narrow and their conditions are poor, traffic emissions are substantial. An industrial estate that consists of small-scale industries including electroplating and welding units is situated in the outskirts of Pudur, which may also contribute by means of background concentrations.

Sree Meenakshi temple

Having a large number of temples, Madurai is popularly referred as the temple city of south India. Sree Meenakshi temple, the landmark of the city, is located at the central part of the city. Around the temple, there are many commercial establishments. This causes the site to be very crowded with continuous traffic flow almost round the clock. The emissions from automobiles, commercial establishments, and residences contribute to the air pollution loads of this sampling site.

Topographical features of Madurai

The topography of the Madurai city very slightly increases in all directions as one moves away from the heart of the city except in the south direction, and this city is surrounded by the gently sloping terrain. There are no hills in the region of the Madurai Corporation limit. Therefore, the existing topography of this city experiences horizontally homogeneous wind flow and more or less steady-state meteorological conditions. Such conditions do not allow the accumulation of pollutants (Benson 1989). However, for the central regions of this city, building geometry on both sides of the narrow roads is an important parameter for characterizing the transport and dispersion of pollutants. This geometry can be treated as a tunnel, which is open at the top, and this is commonly referred as street canyon. The elevated pollutant concentrations at some of the sampling sites, which are located in the central parts of the city, may also be determined by this parameter (Copper and Alley 1986; Buckland and Middleton 1999).

Measurement of PM_{10} sampling

The PM_{10} samples were collected round the clock duration by using commercially available Respirable Dust Sampler (Envirotech APM 460BL). The sampler had a free-flow condition without filter, and the flow rate of air sampler varied between 0.9 and 1.4 m^3/min. It could be operated up to 28 h. Whatmann microfiber filter papers (EPM 2000) were used for the collection of PM_{10} particles. The glass fiber filter of the dimensions 8×10 in. was used for this measurement in such a way that a 7×9-in. area of the filter was exposed on the respirable dust sampler. The centrifugal force method was adopted to remove the large particles. Continuous and simultaneous samplings were carried out at all the sites for a period of 1 year viz. July 2005 to June 2006. The ground level meteorological conditions required for air quality modeling viz. temperature, wind speed, wind direction, solar radiation, rainfall, and relative humidity were collected simultaneously on a 30-min basis during sampling of PM_{10} for the period of July 2005 to June 2006.

Chemical analysis of PM_{10} measurements

For this study, airborne PM_{10} concentrations were determined gravimetrically using a system of filter papers. Filters used for PM_{10} particle collection were dried, before and after the weighing, in the high-volume desiccator under 5% relative humidity for 48 h. Experiments of conservation, drying, and weighing were conducted in the dark room with relative humidity of $50 \pm 5\%$ and temperature of $20 \pm 1°$C. The exposed filter paper was cut into 4×5-cm strips. The strips for the metal analysis were ashed in a low-temperature asher, and the ashed filter was then placed in a glass tube, which was treated with 10 ml nitric acid, 5 ml hydrochloric acid, and 5 ml perchloric acid and warmed for 5 h. To complete the digestion process, the digestion was done three times, and the sample was evaporated to dryness. The sample residues were dissolved in 1% nitric acid, cooled, and made up to 50 ml in a volumetric flask with the help of double-distilled dematerialized water. Following the dilution, the samples were centrifuged at 2,000 rpm for about 30 min, and the supernatant liquid was decanted into polypropylene tubes that were then capped and stored for pending analysis (Katz 1969; Tripathi 1994).

A blank filter paper was also similarly digested, and the same procedure was carried out. The analysis was subsequently made by atomic absorption spectroscopy (AAS). A commercially available AAS (Varian Spectra 220) was used to estimate the concentrations, which were calculated by comparing the absorbance of sample solutions with the standard metal solutions. The standard solutions for the metals under investigations were prepared from the stack solutions just before their utilization.

Meteorological observations

Meteorology plays a crucial role in air pollution studies. In fact, there is a strong seasonality in the meteorological factors, which modulates the air quality levels (Espinosa et al. 2004; Karar et al. 2005). The important meteorological variables having influence on the levels of the pollutants over Madurai are wind (speed and direction), rain (amount and duration), air temperature, and relative humidity (Singal and Prasad 2005). The analysis of the meteorological observations during the period of July 2005 to June 2006 showed the maximum solar radiation of 1,024 w/m^2, and the highest atmospheric temperature of 44.8°C was recorded during the summer season (March–May). It was observed that the velocity of wind was maximum during the months of July (8.4), followed by August (6.8) and September (5.5) and ranged between 0.3 and 8.4 m/s. The predominant wind velocity was observed in the northeast monsoon season. In the summer months, the observed wind speed was relatively lower than those in the winter season and varied from 0.2 to 6.2 m/s. The predominant wind directions during the period of this study were northeast, east, southeast, and west. The maximum number of rainy days (41) and the average maximum rainfall (501 mm) took place in the month of October followed by November due to presence of the northeast monsoon. The variation of relative humidity showed a steep decrease from winter to summer (66% to 57%) and then a slow increase in the rainy season (67% to 78%) and remained steady in winter (68%).

Results and discussions

Statistical analysis

The observed PM_{10} and lead concentrations are summarized in Tables 1 and 2, respectively. It was observed that the maximum average PM_{10} concentration was found at Goripalayam (site 2) followed in decreasing order by Periyar (site 1), Pudur (site 5), Palanganatham (site 3), Kochadai (site 4), and Sree Meenakshi Temple (site 6), respectively. The maximum standard deviation was observed for Goripalayam (site 2) followed in decreasing order by Periyar (site 1), Kochadai (site 4), Sree Meenakshi Temple (site 6), Pudur (site 5), and finally for the Palanganatham (site 3). Similarly, it was observed that the average concentration of Pb was highest at Goripalayam (site 2) followed in decreasing order by the Periyar (site 1), Palanganatham (site 3), Pudur (site 5), Kochadai (site 4), and Sree Meenakshi Temple (site 6). The Goripalayam (site 2) had maximum variability of Pb concentrations with the standard deviation of 16%.

PM_{10} had a very good positive correlation with atmospheric temperature (0.71 to 0.91) and a negative correlation with humidity (0.68 to 0.94) at most of the sampling stations. In the case of multiple regression analysis, it was found that PM_{10} had a positive relationship with temperature (0.33 to 0.49) in most of the sampling stations. The qualitative information revealed by the statistical analysis indicated that the temperature had a positive correlation (0.49) with particulate pollutant concentrations. However, in the case of Pb, temperature, wind speed, and humidity had no correlation. The calculated coefficient of variance (CV), which is a measure of the correlation between two ranges of data (Zar 2004), of the recorded concentrations of PM_{10} were 16.4%, 19.6%, 8.5%, 23.1%, 10.7%, and 13.9% for the sites Periyar bus stand, Goripalayam, Palanganatham, Kochadai, Pudur, and Sree Meenakshi Temple, respectively. Similarly, calculated CV of the recorded concentrations of Pb were 14.1%, 18.4%, 14.6%, 16.7%, 18.0%, and 12.2% for the sites

Periyar bus stand, Goripalayam, Palanganatham, Kochadai, Pudur, and Sree Meenakshi Temple, respectively. The calculated CV of the recorded concentrations ranged from 8.5% to 23.1% for PM_{10} and from 12.2% to 18.4% for Pb (Tables 3 and 4).

Seasonal distribution

To understand the seasonal variability of the concentrations of pollutants, seasonal distribution has been calculated, and it is presented in Tables 5 and 6. It was observed from Table 5 that PM_{10} had the maximum concentrations in the summer season (March–May) and minimum concentrations during monsoon season (June–September). The highest concentration of particulate matter in summer might be described with photochemical reactions along with other factors like source strength and other meteorological parameters. The lowest concentration of PM_{10} in the monsoon could be attributed to the scavenging of particulate pollutants from the atmosphere due to rainfall (Stern 1976). The maximum variability of PM_{10} was observed at site 2 during the southwest monsoon season. The concentration of Pb (Table 6) showed nearly the same average concentrations at all sites except at sites 1 and 2 during all seasons. The maximum variability of Pb was observed at site 6 with a CV equal to 21.9% (Table 7).

Monthly distribution

The monthly variations of concentrations of PM_{10} and Pb are depicted in Fig. 1a–f. From this figure, it was noticed that the month of May showed the highest recorded PM_{10} levels in all sites, whereas the lowest concentration could be observed in the month of December. The summer season had an average value of 158.8 $\mu g/m^3$, whereas a winter month had an average value of 109.1 $\mu g/m^3$. The lowest recorded Pb levels among all the sampling sites was 0.52 $\mu g/m^3$ in the summer month, whereas the highest concentration of Pb could be observed in December, a winter month, with an average value of 0.66 $\mu g/m^3$.

Table 1 Summary of PM_{10} concentrations at six sites of Madurai city

Sl number	Site	PM_{10} concentration ($\mu g/m^3$)			Max	Min	Mean	SD
		Percentile						
		25th	50th	75th				
1	Site 1	134.9	147.2	175.2	210.4	108.5	152.9	25.2
2	Site 2	139.1	170.9	190.7	226.9	108.5	166.8	32.8
3	Site 3	121.2	126.1	135.1	149.5	100.2	127.8	10.9
4	Site 4	80.8	89.6	111.1	149.5	70.5	97.2	22.5
5	Site 5	120.1	130.7	139.6	155.2	102.1	129.4	13.9
6	Site 6	102.0	115.2	129.1	145.1	88.1	115.6	16.1

Table 2 Summary of Pb concentrations at six sites of Madurai city

Sl number	Site	Pb concentration ($\mu g/m^3$)			Max	Min	Mean	SD
		Percentile						
		25th	50th	75th				
1	Site 1	0.78	0.86	0.93	1.07	0.49	0.85	0.12
2	Site 2	0.76	0.86	0.97	1.18	0.49	0.87	0.16
3	Site 3	0.44	0.49	0.52	0.76	0.31	0.48	0.07
4	Site 4	0.39	0.42	0.44	0.62	0.21	0.42	0.07
5	Site 5	0.42	0.51	0.58	0.71	0.35	0.50	0.09
6	Site 6	0.46	0.49	0.52	0.62	0.38	0.49	0.06

The Department of Environment, School of Energy, Environment, and Natural Resources, Madurai Kamaraj University, studied the levels of pollution at various locations in Madurai city since 1987. In fact, there is continuous measurement of particulate levels in the ambient air of Madurai city from the year 1998. The recorded average concentrations of particulate matter are shown in Fig. 2. It is obvious from the figure that the concentration of particulate pollutants shows an upward trend during the years.

Modeling of air quality

AERMOD is a steady-state plume dispersion model for the assessment of pollutant concentrations from a variety of sources (EPA 2005; Cimorelli et al. 2005; Kesarkar et al. 2007). AERMOD has an improved approach for characterizing the fundamental boundary layer parameters and vertical profile of the atmosphere along with better representation of plume buoyancy, penetration, and urban nighttime boundary layer (Cimorelli et al. 2005) as compared to the industrial source complex (ISC) model. It provides variable urban treatment of vertical dispersion as a function of city population and can selectively model sources as rural or urban. AERMOD requires hourly surface and upper air meteorological observations for simulating the pollutant dispersion. AERMOD simulates transport and dispersion from multiple points, area, or volume sources based on an up-to-date characterization of the atmospheric boundary layer. Sources may be located in the rural or urban areas, and receptors may be located in simple or complex terrain. AERMOD also accounts for building wake effects (i.e., plume downwash). The model employs hourly sequential preprocessed meteorological data to estimate concentrations for averaging times from 1 h to 1 year (EPA 2004). This model assumes the probability distribution function for the concentration of a pollutant to be Gaussian both in the vertical as well as horizontal directions in a stable boundary layer. In the convective boundary layer, the horizontal dispersion is Gaussian, whereas the vertical distribution is represented by a bi-Gaussian probability distribution function. The vertical distribution required meteorological variables that are generated based on meteorological observations using a similarity relationship. The AERMOD model has a AERMET processor to calculate planetary boundary layer parameters viz. friction velocity, Monin–Obukhov length, convective velocity scale, temperature scale, mixing height, surface heat flux by using local surface characteristics in the form of surface roughness, and Bowen ratio in combination with standard meteorological observations (wind speed, wind direction, temperature, and cloud cover). Then, these parameters are used to calculate vertical profiles of wind speed, lateral and vertical turbulent fluctuations, and the potential temperature gradient in AERMOD. This model is intended to be useful for the simulation of short-range (<50 km) pollutant dispersion.

The AERMOD model assumes that the plume exists in two states and that the concentration at a receptor, located at a position (x, y, z), is the weighted sum of the two concentration estimates. While the first one is where the plume is horizontal (representing plume material below the dividing streamline), the other one is where the plume travels over the terrain (representing plume material above the dividing streamline). Under stable conditions, the horizontal plume "dominates" and is given greater weight, while under neutral and unstable conditions, the plume traveling over the terrain is more important (heavily

Table 3 Multiple regression coefficients for PM_{10} pollutant

Variables	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Temperature	0.38	0.50	−0.40	0.43	0.44	0.48
Wind speed	−0.33	−0.27	−0.26	−0.38	−0.30	−0.27
Humidity	−0.18	0.062	−0.19	−0.10	−0.19	−0.15

Table 4 Multiple regression coefficients for Pb pollutant

Variables	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Temperature	−0.09	−0.10	−0.20	0.06	−0.24	−0.20
Wind speed	−0.39	0.07	0.19	0.13	0.17	−0.06
Humidity	−0.09	0.30	0.08	0.15	0.09	0.05

weighted). In flat terrain, the concentration equation reduces to the form for a single plume. The general form for the total concentration at any terrain elevation is:

$$C_t(x,y,z) = f_* C(x,y,z) + (1-f)_* C(x,y,z_{eff}) \quad (1)$$

where $C(x, y, z)$ is the flat-terrain concentration equation appropriate for given stability conditions, z is the height of the receptor (this includes the height above local terrain), f is the weighting factor related to the fraction of plume material that is below the height, H_c, of the dividing streamline, and z_{eff} is an "effective" receptor height (which is equal to z in flat terrain). The first term on the right-hand side of Eq. 1 represents the contribution from the horizontal plume and is evaluated at a receptor height (z), whereas the second represents the contribution from the plume adjusted by terrain and is evaluated at an effective receptor height.

The form of the AERMOD concentration expression $C(x, y, z)$ in Eq. 1 that is appropriate for stable conditions ($L>0$) in flat terrain (and is similar to that of ISC2) is the Gaussian expression:

$$C(x,y,z) = Q/U \times Fz(x, z, hp) \, Fy(y) \quad (2)$$

where

$$F_z = \frac{1}{\sqrt{2\pi}\sigma_z} \times \sum_{n=\infty}^{\infty} \left[\exp\left[\frac{(z - h_p + 2nh_a)^2}{2\sigma_z^2} \right] + \exp\left[\frac{(z + h_p + 2nh_a)^2}{2\sigma_z^2} \right] \right] \quad (3)$$

$$F_y = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left[\frac{y^2}{2\sigma_y^2} \right] \quad (4)$$

In these equations, plume dilution and plume spread are calculated using effective boundary layer variables. In fact, h_p is the plume height, σ_y and σ_z are plume dispersion parameters, and h_a is the level where vertical mixing is limited (=max (h_p, h)) where h is the stable (mechanical) mixed layer height and h_p is equal to the stack height plus plume rise (Δh).

For unstable conditions, AERMOD uses the expression,

$$C_d(x, O, z) = \frac{Q}{2\pi U \sigma_y} \frac{\lambda_1}{\sigma_{2d1}} \sum_{m=0}^{\infty} \left[\exp\left(-\frac{(z - h_{ed i} - 2mz_i)^2}{2\sigma_{2d1}^2} \right) \right.$$
$$\left. + \exp\left(-\frac{(z + h_{ed1} + 2mz_i)^2}{2\sigma_{2d1}^2} \right) \right]$$
$$+ \frac{\lambda_2}{\sigma_{2d2}} \sum_{m=0}^{\infty} \left[\exp\left(-\frac{(z - h_{ed2} - 2mz_i)^2}{2\sigma_{2d2}^2} \right) \right.$$
$$\left. + \exp\left(-\frac{(z + h_{ed2} + 2mz_i)^2}{2\sigma_{2d2}^2} \right) \right] \quad (5)$$

In fact, h_{edi} and σ_{zdj} are the effective source height and vertical dispersion parameter, and σ_b is the dispersion due to buoyancy-induced entrainment. Equation 5 is the general expression for the concentration distribution along the plume center line. By providing the required inputs like emission and meteorological factors, the concentrations for the pollutants at all the sampling stations of the present investigation were predicted by using the AERMOD model.

The emissions of particulate matter in the study area are characterized by anthropogenic sources like transportation, industries, and domestic activities. There are two major industries that produce rubber-based domestic and commercial appliances. The domestic activities mainly include

Table 5 Seasonal variations of PM₁₀ concentrations in Madurai city

Sl number	Site	PM₁₀ seasonal concentrations (µg/m³)			
		Southwest monsoon	Northeast monsoon	Winter	Summer
1	Site 1	146.1 (CV=10%)	130.2 (CV=9.2%)	147.5 (CV=8.9%)	187.8 (CV=8.0%)
2	Site 2	163.2 (CV=20.1%)	149.3 (CV=15.8%)	152.3 (CV=18.1%)	202.4 (CV=7.6%)
3	Site 3	135.3 (CV=6.1%)	115.8 (CV=6.6%)	128.5 (CV=13.7%)	137.9 (CV=5.7%)
4	Site 4	126.0 (CV=4.1%)	119.8 (CV=7.9%)	126.0 (CV=8.4%)	139.4 (CV=5.1%)
5	Site 5	116.5 (CV=9.1%)	102.9 (CV=10.2%)	109.4 (CV=13.9%)	133.4 (CV=6.8%)
6	Site 6	89.0 (CV=14.8%)	79.8 (CV=4.6%)	96.3 (CV=19.0%)	123.8 (CV=17.5%)

Table 6 Seasonal variations of Pb concentrations in Madurai city

Sl number	Site	Seasonal concentrations (µg/m³)			
		Southwest monsoon	Northeast monsoon	Winter	Summer
1	Site 1	0.92 (CV=7.6%)	0.76 (CV=10.0%)	0.80 (CV=16.0%)	0.90 (CV=13.8%)
2	Site 2	0.70 (CV=12.0%)	0.87 (CV=13.5%)	0.92 (CV=6.0%)	0.93 (CV=18.0%)
3	Site 3	0.56 (CV=13.5%)	0.43 (CV=16.1%)	0.48 (CV=16.9%)	0.55 (CV=10.6%)
4	Site 4	0.49 (CV=8.7%)	0.49 (CV=13.3%)	0.48 (CV=12.5%)	0.49 (CV=13.0%)
5	Site 5	0.51 (CV=5.3%)	0.45 (CV=17.0%)	0.47 (CV=17.2%)	0.51 (CV=17.9%)
6	Site 6	0.44 (CV=9.2%)	0.39 (CV=15.2%)	0.39 (CV=13.4%)	0.45 (CV=21.9%)

burning of fuels like liquefied petroleum gas, kerosene, fuel wood, and agricultural residues. To generate an emission inventory, a traffic survey was conducted by the physical counting of automobiles round the clock all over the city including the sampling stations of the present investigation. In fact, the study area was divided into a number of square grids of 1 km dimension. The total kilometer run for each

Table 7 Automobile source strength of particulate pollutants

Sl Number	Survey points	PM emissions (10^{-3} g m^{-1} s^{-1})	Pb emissions (10^{-3} g m^{-1} s^{-1})
1	West Tower street	53.41	1.949
2	West Masi street	84.69	2.656
3	North Masi street	51.84	1.422
4	East Masi street	75.32	2.260
5	South Masi street	126.80	3.910
6	Nethaji street	122.24	3.849
7	East Veli street	119.74	3.183
8	Simmakkal	202.99	6.168
9	South Gate	114.25	2.724
10	Nirmala School	196.21	5.022
11	Madura College	226.52	6.466
12	Aarapalayam	115.01	2.754
13	Kalavasal	233.85	6.599
14	Sellur	87.82	2.427
15	Avaniyapuram	172.44	4.468
16	Corporation office	198.99	5.517
17	Jaihind Puram	77.05	1.943
18	Kochadai*	119.88	3.497
19	Anna bus stand	146.76	3.989
20	K. Pudhur*	130.66	3.587
21	Periyar*	374.86	10.237
22	Goripalayam*	410.64	12.358
23	Palanganatham*	197.05	5.324
24	Meenakshi Temple*	100.98	3.084
25	Teppakulam	91.81	2.544

*Sampling stations

grid was developed by using the data on number of vehicles and road lengths. The automobile source strength was calculated subsequently by using the total kilometer run by the vehicles and the emission rate of Indian vehicles.

The calculated automobile source strengths with special reference to particulate matter and lead all over the city showed that they ranged from 51.84×10^{-3} to 410.64×10^{-3} and from 1.42×10^{-3} to 12.36×10^{-3} g m^{-1} s^{-1}, respectively. In the case of particulate matter emissions, it was noted that the heavy-tonnage vehicles had relatively higher emission rates than the medium-tonnage vehicles. The two- and three-wheelers also contributed notably (more than 70% at many traffic areas) in the total lead load of Madurai city. Even though the lead emission factor (g/km) for two- and three-wheelers is relatively lower in comparison with medium-tonnage vehicles, their contribution was about three to five times greater, which was due to the operation of a large number of motorized two- and three-wheelers (Pundir et al. 1994; Sivacoumar 1990). The automobile-based emission inventory was prepared, and it was used to initialize the AERMOD model. The emission inventory was generated for the sampling period only. However, the annual emission inventory by our team for both stationary and mobile sources is being generated for further research studies.

In the present paper, AERMOD was used for the prediction of PM$_{10}$, and it was compared with the observations recorded during experiments. Figure 3a–f showed the variation of predicted and observed concentrations of PM$_{10}$ at all six different sites, respectively. The predicted concentrations ranged from 121.7 to 226.9 µg/m³ for PM$_{10}$. It was noticed that sites 1 and 2 had the highest observed and predicted PM$_{10}$ concentrations, which might be attributed directly to the traffic emissions, use of biomass for cooking, paved and unpaved road (resuspension) dusts, vehicular exhausts, and diesel-based electric generators in these sampling sites. It was observed from the generated database pertaining to the predicted and observed concentrations that the pattern of variation of predicted and observed concentrations behaved consistently, even though AERMOD underpredicted pollutants by a factor of 1–1.5 in
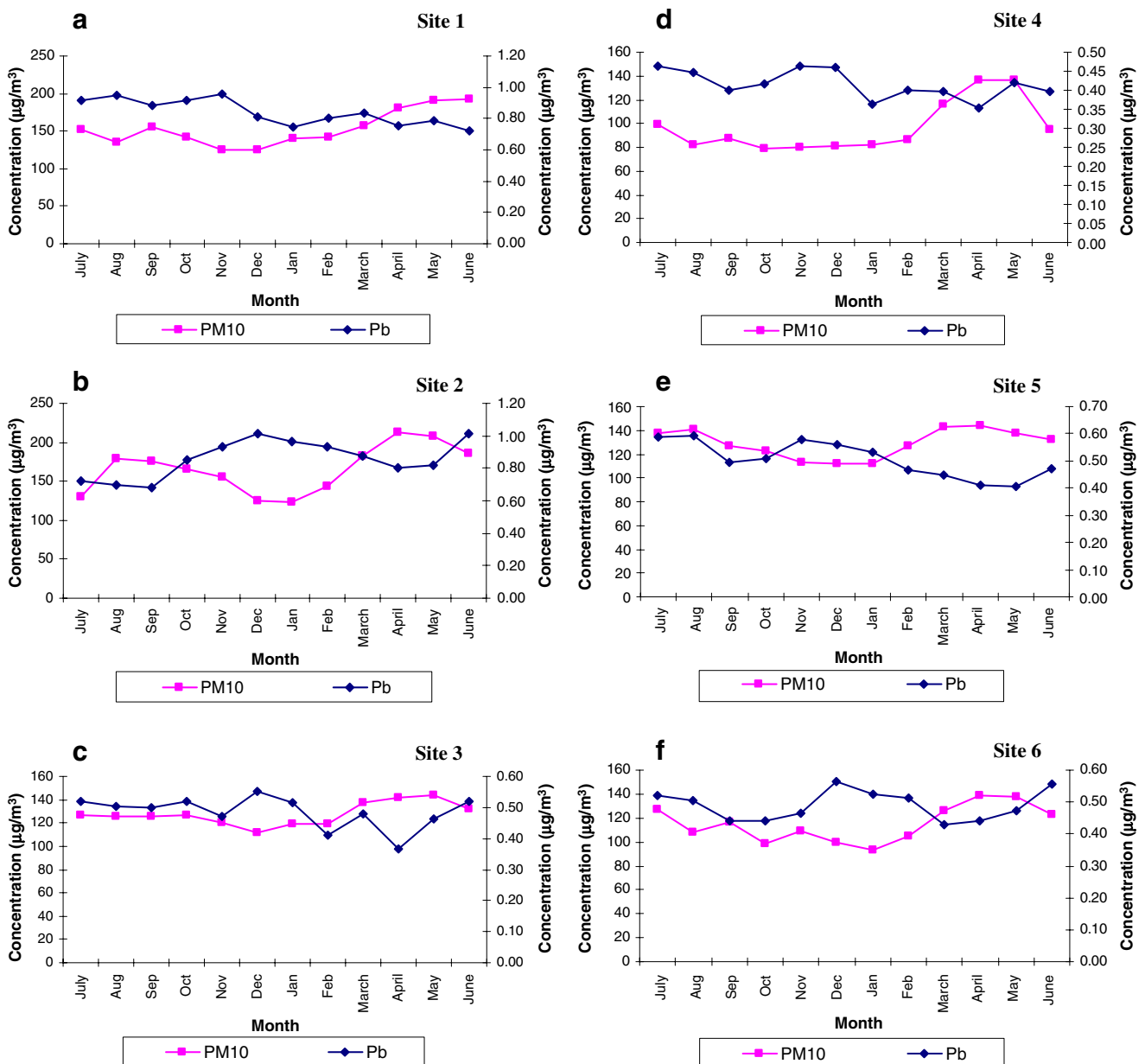
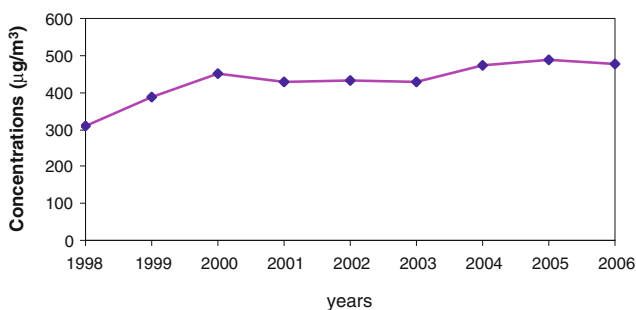Fig. 1 a–f Monthly average pollutants concentrations at different sites

Fig. 2 Comparison of observed particulate concentrations from 1998 to 2006

the concentrations for all the sites of measurements. The lack of good emissions factors from nontransportation sources might be one of the reasons for lower predicted concentrations.

Conclusions

In general, transportation, small-scale industries, and an elevated rate of combustion of conventional fuels for domestic and commercial purposes in the city are found to be the sources of particulate pollutants of the present investigation (Kulandai 2003; Adachi and Tainosho 2004). Except automobiles, the operation of diesel-powered gen-

Fig. 3 a–f Comparison of predicted and observed PM10 concentration at different sites
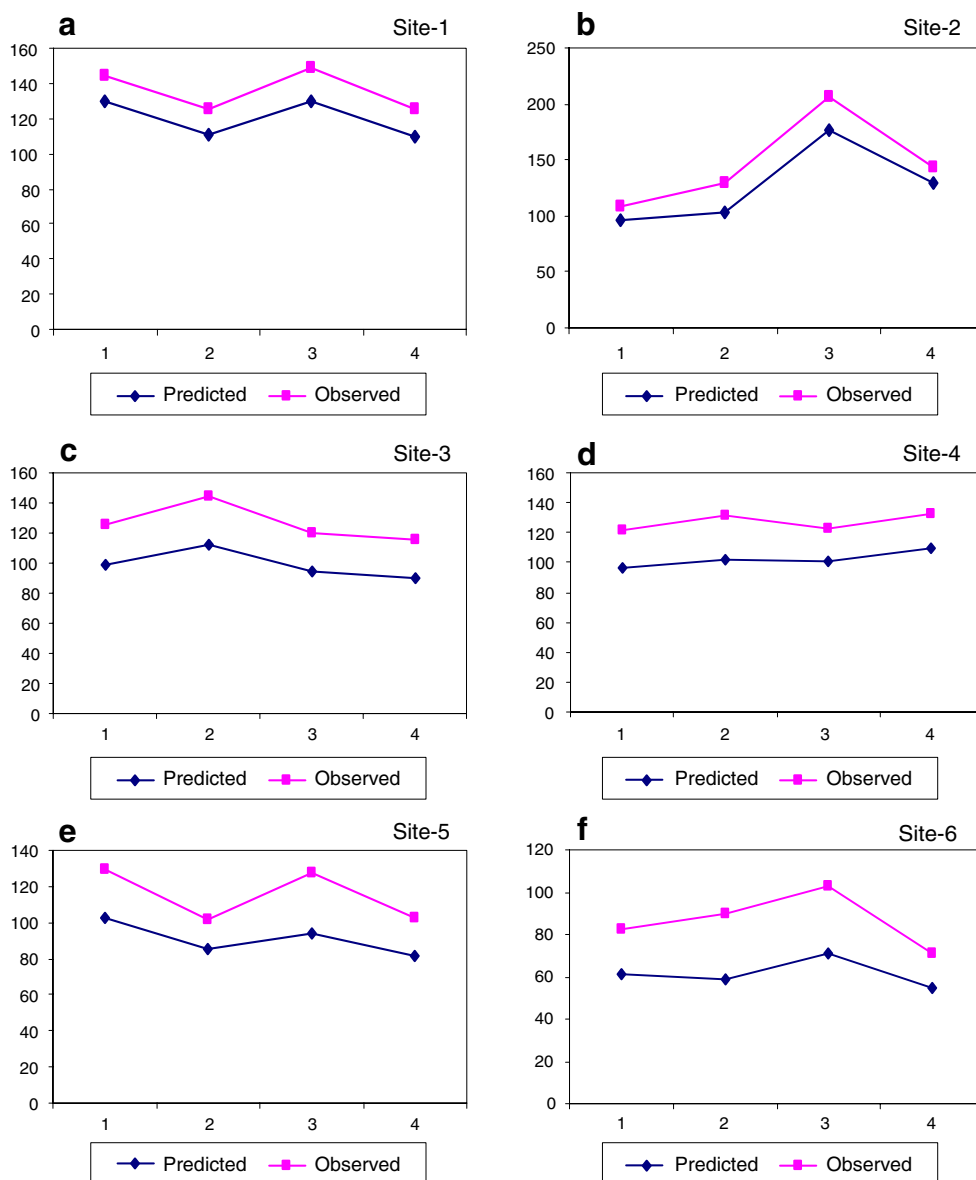
erators (which were used in commercial establishments during power failures especially at summer seasons), emissions from paved roads, and background concentrations from industrial and semi-industrial areas of the city also contribute to particulate pollution. Cooking in houses, school and commercial establishments, and refuse incineration in houses and public places and municipal incineration in open grounds may also contribute to the total pollutant load as well as the atmospheric particulate matter concentrations in an Indian city (Surya Prakash and Alappat 1999; Salve et al. 2006). The sand along the sides of the roads, which is dusty in nature, is not removed periodically all over the city. Hence, all these factors cumulatively contribute to the PM_{10} concentrations in the range of 88.1 to 226.9 μg/m^3 in the city. Madurai is surrounded by

agricultural lands, and so no potential sources are available in the vicinities of the city or from upwind sites.

Even though the PM_{10} pollution activities were widespread all over the city, it was noticed that during the period of experiment, Goripalayam endured the highest traffic densities among the sampling stations. The highest average concentrations of PM_{10} and lead at Goripalayam might be attributed to the pollution from automobiles. In fact, at this place, there were a large number of light-tonnage vehicles, especially motorized two-wheelers (62,145), in the operation. Extreme congestion (resulting the slow movement of vehicles and random urban driving modes of operation), long waits at the signals, and traffic bottlenecks are observed commonly during the peak hours of traffic, as this site connects almost all the northern parts of the city

(Tripathi et al. 2000; Katiyar et al. 2005). In addition, traffic-derived aerosol particles were emitted into the atmosphere due to abrasion processes of automobile components such as the brake or tire wear (Viana et al. 2006). Therefore, the emissions and abrasion of the components of automobiles might be the major contributors to the mass of total particles along with emissions from some small-scale industrial sources (Harrison et al. 2004). Traffic diversions from other parts of the city along the roads of this sampling station might be correlated with the maximum standard deviation that endured at Goripalayam.

The lowest concentrations of PM_{10} and lead were recorded at Sree Meenakshi temple sampling station, which could be considered as a sensitive area with the lowest traffic densities among the sampling stations. As the roads around this temple are one-way roads, the traffic density was very limited. In addition, there was restriction for the flow of heavy-tonnage vehicles in this area. The traffic survey results showed that at this site, a low number of automobiles were plying. Most of the vehicles that are operated in this area are gasoline-powered light-duty vehicles, which emitted almost negligible amount of particulates (Pundir et al. 1994; Jeba Rajasekhar et al. 2005; Gertler et al. 2006). The elevated buildings could restrict the background concentrations from the nearby semi-industrialized areas. It was also noted that among the commercial establishments, only a few are related to combustion activities. As the number of sources was substantially less, the calculated source strengths of particulate matter as well as the recorded concentrations of PM_{10} were also found to be low.

The experimental investigation on air pollution with special reference to average particulate pollutants revealed that the pollutants PM_{10} and Pb over Madurai were near to the permissible limits at all the sampling sites during most of the times of the year. It is worth mentioning here that PM_{10} has the permissible limits (for 24 h) of 150, 100, and 75 $\mu g/m^3$ for the industrial and mixed, residential and rural, and sensitive areas, respectively, whereas Pb has the permissible limits of 1.5, 1.0, and 0.75 $\mu g/m^3$ for the industrial and mixed, residential and rural, and sensitive areas, respectively. However, PM_{10} has permissible limits (annual averages) of 120, 60, and 50 $\mu g/m^3$ for the industrial and mixed, residential and rural, and sensitive areas, respectively, whereas Pb has the permissible limits of 1.0, 0.75, and 0.50 $\mu g/m^3$ for the industrial and mixed, residential and rural, and sensitive areas, respectively. It was anticipated that with increase in the population, traffic, industrialization, and per capita energy consumption in the future might increase the emission load, which in turn will deteriorate the quality of the air more over Madurai. The increases in the atmospheric pollutant with this rate have created a threat for long-range adverse effects on the public

health and social wellbeing of this city. The earlier studies pertaining to particulate pollution shows that the concentration of particulate pollutants shows an upward trend during the years. Therefore, the strict implementation of adequate abatement measures and environmental regulations are necessary for the pleasant present and the sustainable future. The AERMOD model under predicts patterns of PM_{10} by a factor of 1–1.5 in the concentrations. Hence, monitoring of PM_{10} concentration in the city over a longer period coupled with inclusive emission inventories for additional stationary sources are needed.

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