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To cite this article: Smaranika Panda & S.M. Shiva Nagendra (2017) Assimilative capacity-based emission load management in a critically polluted industrial cluster, Journal of the Air & Waste Management Association, 67:12, 1353-1363, DOI: [10.1080/10962247.2017.1372319](https://doi.org/10.1080/10962247.2017.1372319)

To link to this article: <https://doi.org/10.1080/10962247.2017.1372319>



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Accepted author version posted online: 25 Sep 2017.
Published online: 09 Nov 2017.



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TECHNICAL PAPER



Assimilative capacity-based emission load management in a critically polluted industrial cluster

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ABSTRACT

In the present study, a modified approach was adopted to quantify the assimilative capacity (i.e., the maximum emission an area can take without violating the permissible pollutant standards) of a major industrial cluster (Manali, India) and to assess the effectiveness of adopted air pollution control measures at the region. Seasonal analysis of assimilative capacity was carried out corresponding to critical, high, medium, and low pollution levels to know the best and worst conditions for industrial operations. Bottom-up approach was employed to quantify sulfur dioxide (SO₂), nitrogen dioxide (NO₂), and particulate matter (aerodynamic diameter <10 µm; PM₁₀) emissions at a fine spatial resolution of 500 × 500 m² in Manali industrial cluster. AERMOD (American Meteorological Society/U.S. Environmental Protection Agency Regulatory Model), an U.S. Environmental Protection Agency (EPA) regulatory model, was used for estimating assimilative capacity. Results indicated that 22.8 tonnes/day of SO₂, 7.8 tonnes/day of NO₂, and 7.1 tonnes/day of PM₁₀ were emitted from the industries of Manali. The estimated assimilative capacities for SO₂, NO₂, and PM₁₀ were found to be 16.05, 17.36, and 19.78 tonnes/day, respectively. It was observed that the current SO₂ emissions were exceeding the estimated safe load by 6.7 tonnes/day, whereas PM₁₀ and NO₂ were within the safe limits. Seasonal analysis of assimilative capacity showed that post-monsoon had the lowest load-carrying capacity, followed by winter, summer, and monsoon seasons, and the allowable SO₂ emissions during post-monsoon and winter seasons were found to be 35% and 26% lower, respectively, when compared with monsoon season.

Implications: The authors present a modified approach for quantitative estimation of assimilative capacity of a critically polluted Indian industrial cluster. The authors developed a geo-coded fine-resolution PM₁₀, NO₂, and SO₂ emission inventory for Manali industrial area and further quantitatively estimated its season-wise assimilative capacities corresponding to various pollution levels. This quantitative representation of assimilative capacity (in terms of emissions), when compared with routine qualitative representation, provides better data for quantifying carrying capacity of an area. This information helps policy makers and regulatory authorities to develop an effective mitigation plan for air pollution abatement.

PAPER HISTORY


Received March 22, 2017
Revised August 22, 2017
Accepted August 22, 2017

Introduction

After advent of the industrial revolution in the 18th century, air quality in all the major countries has drastically deteriorated due to increase in fossil fuel consumption (Douglas et al., 2002). However, with advent of air pollution control systems, air quality has significantly improved in the developed countries (U.S. Environmental Protection Agency [EPA], 2012). On the other hand, due to improper register of the emission loads, usage of low-quality fuels, poor handling of the pollution control mechanisms, and lack of technical expertise on the carrying capacity of the regions (Garg et al., 2002; Goyal and Rao, 2007), industrial air pollution is still one of the major concerns in developing countries.

India is one of the G-20 major economies, with a large young population, abundant natural resources, and increasing integration into global economy (World Bank, 2015). These features promoted an impressive industrial growth (World Bank, 2015), while also resulting in increase of pollutant emissions at an alarming rate (Garg et al., 2001a, 2001b). The assessment of environmental quality of 88 major industrial clusters of India indicated that 43 industrial clusters were critically polluted, with a comprehensive environmental pollution index (CEPI; defined as a rational number quantified by following the algorithm of source, pathway, and receptor to assess the environmental quality of an industrial cluster) value greater than 70, on a scale of 0–100 (Central Pollution Control Board [CPCB], 2009b). Manali industrial cluster, situated in the northern

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part of Chennai, India, is one among the critically polluted industrial clusters with CEPI value of 76.03. This industrial area hosts many major industries, which include petrochemicals, fertilizers, and refineries (Tamil Nadu Pollution Control Board [TNPCB], 2010). These industries are identified as the most polluting industries (17-category industries; CPCB, 2009a) and are responsible for major health hazards (Garg et al., 2006). Among the major Indian cities, Chennai was reported to emit the maximum sulfur dioxide (SO₂) emissions due to significant usage of coal and furnace oil (having higher sulfur content) in industries (Garg et al., 2001a, 2001b). Past studies at Manali area reported poor air quality (Manju et al., 2002; Subramanian and Natarajan, 2006) and increased health problems in this area. Jayanthi and Krishnamoorthy (2006) indicated an increase of 17.58% in the mortality rate over last 6 yr, with an annual increase rate of over 10% in the hospital admissions at Manali industrial area. To improve the air quality of Manali, many control measures were recommended and implemented by Central Pollution Control Board (CPCB), Ministry of Environment, Forests and Climate Change, Government of India, in 2009 (TNPCB, 2011).

Assimilative capacity of an industrial area

Assimilative capacity is a crucial parameter to know the extent of pollution and load-carrying capacity of an area during various atmospheric and industrial conditions. It can be defined as the maximum amount of pollutant load an area can take without exceeding the specified standards (Goyal et al., 2003). It varies significantly with respect to changing meteorological conditions, types of pollutants, and stack characteristics. In the past, the assimilative capacity of an area was estimated qualitatively either in terms ventilation coefficients or model-simulated concentrations (Goyal et al., 1994, 2003, 2006; Goyal and Rao, 2007; Murty and Mandal, 1979; Murty and Tangirala, 1990; Nandankar, 1999; Ramakrishna et al., 2004, 2005; Singh et al., 1990; Viswanatham and Anil Kumar, 1989). However, the estimations made in these studies do not provide assimilation potential (load-carrying capacity) for any given pollutant. Therefore, it is important to quantify the amount of emission loads an area can assimilate without violating the standards, which can give useful information to the decision and policy makers for formulating effective regulations to mitigate air pollution. In the present study, a modified approach has been illustrated with a case study to estimate the assimilative capacity in terms of emissions and the amount of emission reduction required to keep the air quality within the prescribed standard at Manali industrial area. We further estimated season-wise load-carrying capacities of the area under various pollution levels.

Methodology

Description of study area

Manali (latitude: 13°10'4"N, longitude: 80°15'43"E) is one of the major Indian industrial clusters located in the northern side of Chennai City, Tamil Nadu (Figure 1), with a total population of around 36,000 (Census of India, 2011). This area has a typical tropical climate, with persistent higher temperatures throughout the year. The extent of Manali area is 20 km², in which more than 33% of the area is occupied by industries. A total of 26 major industries are located in Manali industrial area. SO₂, nitrogen dioxide (NO₂), and particulate matter (aerodynamic diameter <10 μm; PM₁₀) pollutants were identified as the three primary air pollutants that are significantly released from industries at this area (TNPCB, 2010).

Data

Industrial emissions

A bottom-up approach was used to estimate NO₂, SO₂, and PM₁₀ emissions from the 99 stacks present in Manali industrial area for the base year 2012. We geo-coded all the stacks and procured information regarding type and amount of fuel consumptions, height and diameter of stacks, and temperature and exit velocity of flue gases from the central and state pollution control boards. Equation 1 was used to calculate the emissions from the industrial stacks.

$$\text{Emission rate} \left(\frac{\text{g}}{\text{sec}} \right) = \text{Discharge} \left(\frac{\text{m}^3}{\text{sec}} \right) \times \text{Concentration} \left(\frac{\text{g}}{\text{m}^3} \right) \quad (1)$$

Air quality

Five-minute average NO₂, SO₂, and PM₁₀ concentrations were collected from continuous ambient air quality monitoring station (CAAQMS) located in Manali industrial area for the year of 2012. The CAAQMS is located at a residential complex, which is approximately 6 km from the major industrial stacks. In the station, ambient NO₂, SO₂, and PM₁₀ levels were monitored at a height of 3 m above ground level using chemiluminescence analyzer (model AC32M; Environment S.A., Dehli, India), ultraviolet (UV) fluorescence analyzer (model AF22M; Environment S.A.), and beta attenuation monitor (model MP101; Environment S.A.), respectively. Further details on the instrumentation and calibration procedures adopted at CAAQMS were described elsewhere (CPCB, 2003). Outliers in the air quality data were removed using *z* score method suggested by Torres et al. (2011), and the



processed data were averaged to 1-hr values for subsequent analysis.

Meteorological parameters such as wind speed, wind direction, and temperature were collected from the nearest airport weather station (data available online at <http://www.wunderground.com/>). The data pertaining to mixing heights were obtained from Indian meteorological department (Attri et al., 2008). We divided the whole year into four seasons: winter (January, February), summer (March to May), monsoon (June to September), and post-monsoon (October to December). In order to understand the impact of meteorology on the dispersion of air pollutants

Quantification of assimilative capacity using dispersion model

Critical assimilative capacity (ACc) can be defined as the maximum pollutant emission (load) an area can take at a

given point of time without exceeding the permissible limits. In the present study, we considered National Ambient Air Quality Standards (NAAQS) prescribed by CPCB as the permissible standards (24-hr NAAQS for $\text{SO}_2 = 80 \mu\text{g}/\text{m}^3$, $\text{NO}_2 = 80 \mu\text{g}/\text{m}^3$, $\text{PM}_{10} = 100 \mu\text{g}/\text{m}^3$; CPCB, 2012). These standards fall between the World Health Organization's (WHO) Interim Target-1 (IT-1) and Interim Target-2 (IT-2) (WHO, 2006). Assimilative capacity remained (ACr) is computed as the difference of critical assimilative capacity and the present loading in a given region.

In the present work, we computed assimilative capacity in two steps. In the first step, SO_2 , NO_2 , and PM_{10} levels due to current stack emissions were modeled for our study domain. AERMOD (American Meteorological Society/U.S. Environmental Protection Agency Regulatory Model), an EPA-approved regulatory model, was used to predict ground-level concentrations for all the four seasons of 2012 (EPA, 2004). AERMOD is a steady-state dispersion model employed to understand the short-range (up to 50 km) dispersion of air pollutants from stationary industrial stacks. The model consists of a meteorological data preprocessor (AERMET) and terrain preprocessor (AERMAP) (Venkatram, 2008). We obtained AERMET data for the year 2012 for our study domain from M/s Lakes Environmental, Waterloo, Ontario, Canada. The meteorological data contain surface meteorological data and upper air meteorological data. Surface meteorological data contain hourly averaged values of 20 meteorological parameters, which include wind speed (m/sec), wind direction (degrees), surface friction velocity (m/sec), sensible heat flux (W/m^2), convective velocity (m/sec), surface roughness length (m), albedo, Bowen ratio, potential temperature gradient above the mixing height (K/m), convectively driven mixing height (m), mechanically driven mixing height (m), Monin-Obukhov length (m), reference height for wind speed and direction (m), temperature ($^{\circ}\text{C}$), reference height for temperature (m), precipitation type, precipitation amount (mm/hr), relative humidity (%), station pressure (mb), and cloud cover (tenths). Upper air meteorological data contain a total of five meteorological parameters, which include wind direction and speed (degrees, m/sec), temperature ($^{\circ}\text{C}$), standard deviation of the lateral wind direction (degrees), and standard deviation of the vertical wind speed (m/sec). Further, we obtained digital elevation map (DEM) of our study domain (at 90-m resolution) from Shuttle Radar Topography Mission Global Coverage (<http://www.webgis.com/srtm3.html>). Surface characteristics of the study area were obtained by classifying the land uses into eight types, namely, urban, water, shrub land, deciduous and coniferous forests, grassland, swamps, and cultivated land. The study domain ($10 \times 10 \text{ km}^2$) was divided into eight sectors (each of 45°

arc). The land use map of the study domain was employed for identifying surface characteristics of each sector. The land use and normalized difference in vegetation index (NDVI) maps of the domain for the base year, 2012, were prepared using Landsat 7 imagery in Arc GIS 10.4.1 platform. The imagery is available at a very fine spatial resolution of 30 m (U.S. Geological Survey [USGS], 2017). The image was processed and atmospheric and geo reference corrections were applied. We opted unsupervised classification scheme and used NDVI values for classifying the image into eight land uses. Since Manali is a critically polluted industrial cluster, the government imposed restriction on new settlement and expansion of industries or built-up structures within the study area (CPCB, xxx, 2009b; Kumar, 2016). This industrial cluster lies on the coast of Bay of Bengal Sea and also on the thermal equator, which prevents the extreme variation in the seasonal temperature. As there is no significant variation in land use patterns in the study area, annual scale for land use values were considered. Data pertaining to emissions, stacks (dimensions), flue gas (velocity and temperature), terrain, and meteorological parameters were used as inputs to the model. Tier 1 approach was opted for NO_2 modeling. A domain of $10 \times 10 \text{ km}^2$ was considered with Manali area at center and was divided into $500 \times 500 \text{ m}^2$ grids, which are considered as the minimum value for neighborhood scale (CPCB, 2011b). The pollutant concentrations were simulated at the center points of these grids.

In the second step, season-wise ACc was estimated based on the prescribed NAAQS. We calculated ACc by decreasing or increasing the current emissions in 5% interval steps (decreased in case of the pollutants whose concentrations were observed higher than the permissible limits and increased in case of the pollutants whose concentrations were within the permissible limits). The assimilative capacity remained (ACr) was also calculated, as a difference of ACc and current emission. The air quality of the area was classified into four types (low, medium, high, and critical; shown in Table 1) based on the levels prescribed by CPCB (CPCB, 2011a), and assimilative capacities corresponding to different pollution levels were quantified. Loads corresponding to critical and high pollution categories were considered hazardous and noncompliance with standards, whereas loads corresponding to medium and low pollution levels were within the acceptable and safe limits. To quantify the contribution from

Table 1. Pollution level classification for SO_2 , NO_2 , and PM_{10} .

Pollution level	SO_2 ($\mu\text{g}/\text{m}^3$)	NO_2 ($\mu\text{g}/\text{m}^3$)	PM_{10} ($\mu\text{g}/\text{m}^3$)
Low	0–25	0–20	0–30
Medium	26–50	21–40	31–60
High	51–75	41–60	61–90
Critical	>75	>60	>90

different types of industries for critical assimilative capacity, all the industries present at Manali industrial area were broadly divided into two major categories, namely, petrochemical and non-petrochemical.

Statistical analysis

AERMOD model performance was evaluated by using coefficient of determination (R^2), root mean square error (RMSE), and index of agreement (d) (for definitions, see Supplementary Table 2). These indicators are being widely used in air quality model performance evaluation (Jaiprakash et al., 2010; Nagendra and Khare, 2006; Sivacoumar et al., 2001).

Results

Quantification of emission load

Daily SO_2 , NO_2 , and PM_{10} emissions at the study area were found to be 22.8, 7.8, and 7.1 tonnes, respectively. The observed stack emissions ranged from 2 kg/day to 5.74 tonnes/day for SO_2 , 1 kg/day to 1.94 tonnes/day for NO_2 , and 1 kg/day to 2.06 tonnes/day for PM_{10} . Further, grid-wise total SO_2 , NO_2 , and PM_{10} emissions were 1.87 ± 2.85 , 0.64 ± 0.87 , and 0.59 ± 0.86 tonnes/day, respectively. It was observed that more than 60% of the total emissions (14.65 tonnes/day, i.e., 64% of total of SO_2 ; 4.7 tonnes/day, i.e., 60% of NO_2 ; and 4.8 tonnes/day, i.e., 68% of PM_{10}) were released from the industries located within 2 km proximity from densely populated residential areas of Manali. Figure 2–4 present grid-wise emission

inventory of SO_2 , NO_2 , and PM_{10} , respectively. Higher SO_2 emissions in Manali industrial area were attributed to significant usage of furnace oil as raw material in the boilers (TNPCB, 2010). Percentages of usage of furnace oil, naphtha, and diesel as raw materials at Manali are provided in Supplementary Figure 1. Similar to our findings, Reddy and Venkataraman (2002) also observed that SO_2 emissions in India are predominantly released from the industrial sectors. Similarly, Bhanarkar et al. (2005) reported that about 59% of SO_2 and 37% of PM_{10} emissions at a residential locality in Mumbai industrial area were contributed from elevated stacks located in its suburbs.

Impact of meteorology on dispersion of criteria pollutants

The atmospheric transport analysis for the year 2012 at Manali industrial area indicated that a total of 112 days were under stagnation, 63 days were recirculation, and 91 days were under ventilation. The concentrations of SO_2 , NO_2 , and PM_{10} were found to be 1.21, 2.82, and $1.92 \mu\text{g}/\text{m}^3$ higher and 2.18, 2.29, and $3.46 \mu\text{g}/\text{m}^3$ lower than daily average concentrations during stagnation and ventilation conditions, respectively. Further, during recirculation period, the concentrations of SO_2 , NO_2 , and PM_{10} were found to be 1.12, 1.40, and $2.01 \mu\text{g}/\text{m}^3$ lower than the 24-hr average concentrations, respectively. Seasonal analysis of the atmospheric transport events showed that occurrence of stagnation events during winter was 12% and 15% higher than that in summer and monsoon seasons, respectively, and ventilation and

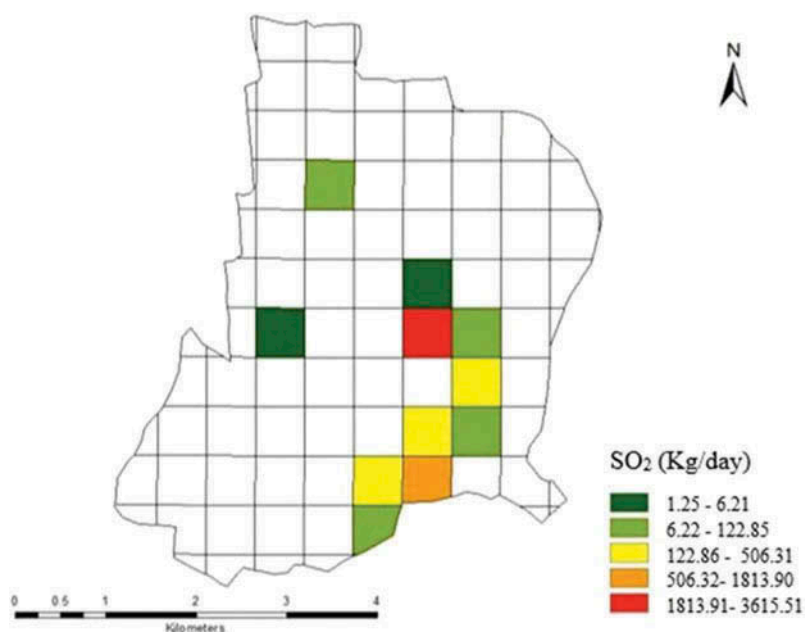


Figure 2. Grid-wise SO_2 emissions (kg/day) from the industrial stacks of Manali.

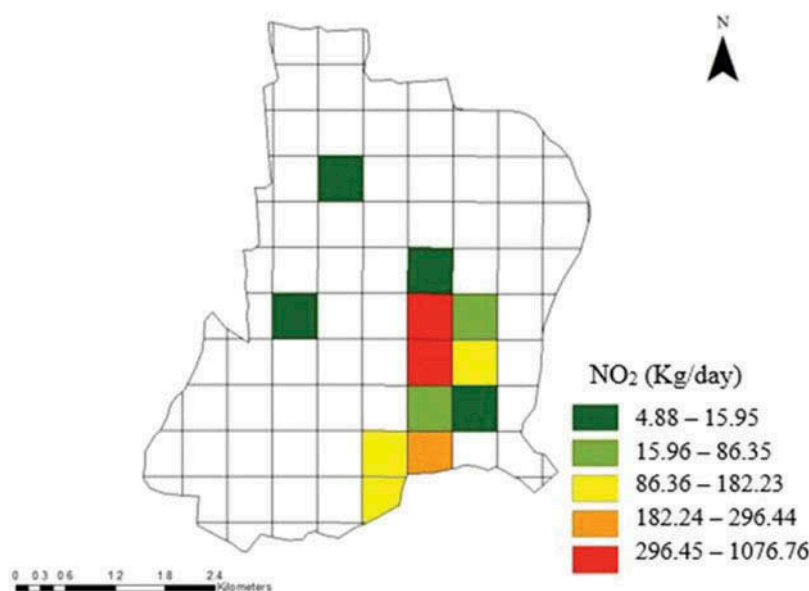


Figure 3. Grid-wise NO₂ emissions (kg/day) from the industrial stacks of Manali.

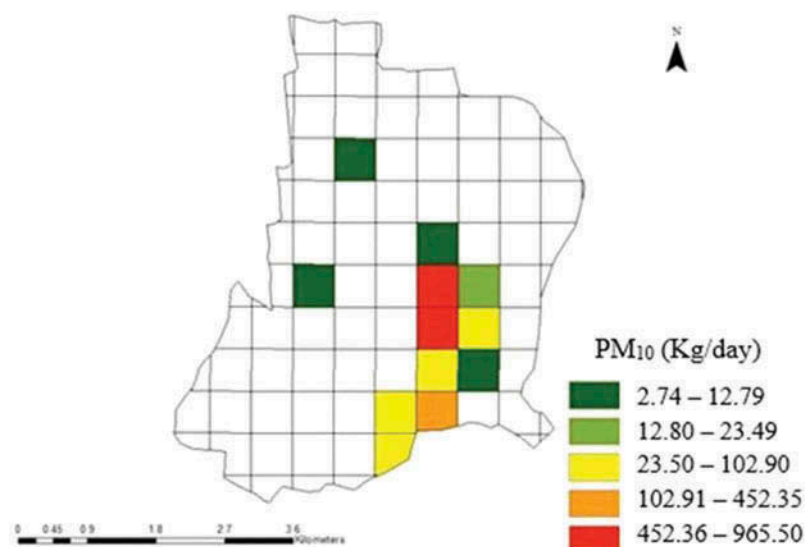


Figure 4. Grid-wise PM₁₀ emissions (kg/day) from the industrial stacks of Manali.

recirculation conditions were found to be 13% and 8% higher in monsoon than in winter season. Lower wind velocities, lower temperatures, and shallow convective boundary layer heights resulted in prevalent stagnation events in winter (Supplementary Table 1), resulting in accumulation of pollutants and increase in their concentrations (Figure 5), whereas higher wind speeds, temperatures, and convective boundary layer heights increased the number of ventilation and recirculation events during monsoon (Supplementary Table 1), thereby reducing the pollutant concentrations. Figure 5 presents the season-wise variation of SO₂, NO₂, and PM₁₀ levels measured at continuous ambient air quality monitoring station (CAAQMS) in Manali area. The measured pollutants

showed the highest concentrations during winter season. Further, the analysis of diurnal variation of pollutants showed two peaks: one during morning peak hours (8:00–10:00 a.m.) and the other during evening peak hours (6:00–9:00 p.m.). These spikes were attributed to heavy traffic movements, higher local activities, and shallow mixing heights during the corresponding periods of the day. The diurnal pattern of pollutants was found to be similar for all seasons.

Validation of model prediction

AERMOD model predictions were in good agreement with measured SO₂ ($R^2 = 0.74$) and NO₂ ($R^2 = 0.72$)

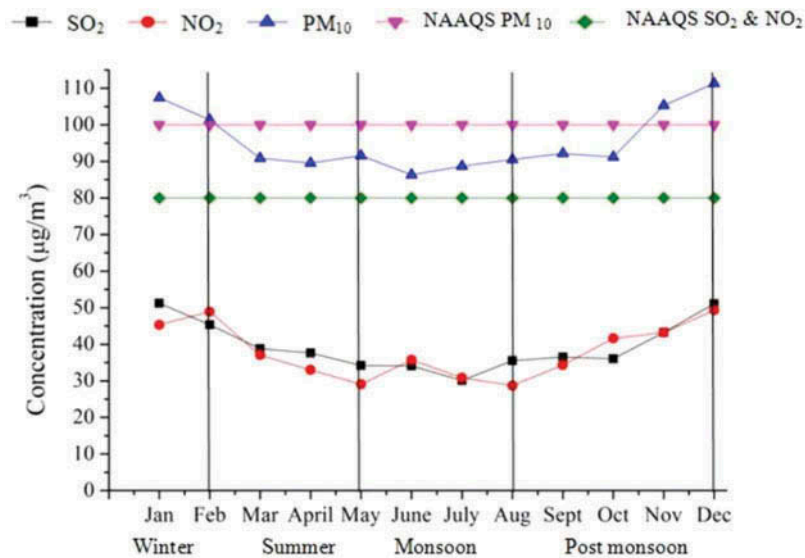


Figure 5. Monthly average SO₂, NO₂, and PM₁₀ concentrations at Manali (permissible standards presented in the figure correspond to 24-hr standards).

concentrations. However, its performance was relatively moderate for PM₁₀ ($R^2 = 0.61$), which could be due to unaccounted resuspension dust that contributes more than 70% of total PM₁₀ emissions in Chennai (Chithra and Nagendra, 2013, 2014; Gargava and Rajagopalan, 2016; Kumar et al., 2014). The root mean square error (RMSE) values for PM₁₀, SO₂, and NO₂ were found to be 31.12, 19.35, and 23.82, respectively, and degree of agreement values were found to be 0.68, 0.73, and 0.71, respectively. This explains that 68% of PM₁₀, 73% of SO₂, and 71% of NO₂ predictions are error free.

Assimilative capacity analysis

Estimation of critical assimilative capacity (ACc) and assimilative capacity remained (ACr) for an industrial airshed

The AERMOD prediction results indicated that SO₂ levels exceed the NAAQS for the present loading (22.8 tonnes/day) for more than 12 times in a year. (Table 2) shows the predicted mean, maximum, and permissible concentrations, present emissions, and critical and remained assimilative capacity values for the industrial area. Results indicated a safe SO₂ load of 16.05 tonnes/day compared with the present loading of 22.8

tonnes/day (Table 2). We observed a daily load exceedance of 6.75 tonnes beyond the safe load for SO₂ with zero remaining assimilative capacity (ACr) in Manali. Further, the number of exceedances was found to be high during post-monsoon (6 days) and winter (4 days) seasons and low during summer and monsoon seasons (1 day). Maximum daily average SO₂ concentrations were as high as 112–122 µg/m³ during post-monsoon and winter, whereas they were in the range of 92–93 µg/m³ during summer and monsoon seasons. Table 3 presents the season-wise assimilative capacities for SO₂, NO₂, and PM₁₀. Our season-wise assimilative capacity estimates also indicated lower load-carrying capacities for post-monsoon (14.8 tonnes/day) and winter (15.96 tonnes/day) than summer (19.39 tonnes/day) and monsoon (20.06 tonnes/day) seasons (Table 3). Thus, we observed that the present SO₂ load is exceeding the ACc for all seasons. The predicted daily average NO₂ concentrations were within the prescribed NAAQS levels. The estimated safe NO₂ load (17.36 tonnes/day) were found to be higher than the present loading (7.8 tonnes/day) (Table 2). The ACr for NO₂ was around 9.56 tonnes/day at Manali. The season-wise assimilative capacities were in the range of 15–21 tonnes/day, lowest during post-monsoon (15.4)

Table 2. Predicted mean and maximum concentrations, NAAQS, current emissions, estimated critical assimilative capacities, and remaining assimilative capacities of SO₂, NO₂, and PM₁₀ at Manali.

Pollutant	Predicted maximum concentration (µg/m ³)	Predicted mean concentration (µg/m ³)	Permissible maximum concentration (µg/m ³)	Present load at Manali (tonnes/day)	Critical assimilative capacity (tonnes/day)	Assimilative capacity remained (tonnes/day)
SO ₂	121.67	24.54	80	22.8	16.05	Exceeded
NO ₂	39.04	12.61	80	7.8	17.36	9.56
PM ₁₀	34.85	10.32	100	7.1	19.78	12.68

Table 3. Assimilative capacities (AC) for SO₂, NO₂, and PM₁₀ during different seasons.

Pollutant	Winter AC (tonnes/day)	Summer AC (tonnes/day)	Post-monsoon AC (tonnes/day)	Monsoon AC (tonnes/day)
SO ₂	15.96	19.38	14.82	20.06
NO ₂	16.17	16.94	15.4	20.79
PM ₁₀	16.33	17.75	16.33	21.3

and highest during monsoon (20.79) seasons (Table 3). Similarly, PM₁₀ levels were found to be within the prescribed NAAQS levels during all seasons. The estimated safe load was 19.78 tonnes/day, which is higher than the present loading (7.1 tonnes/day) (Table 2). The present study indicated that AC_r corresponding to PM₁₀ was around 12.68 tonnes/day at Manali. The season-wise safe loads ranged between 16 and 22 tonnes/day, lowest during winter and post-monsoon with a load-carrying capacity of 16.3 tonnes/day, followed by summer (17.75 tonnes/day) and monsoon (21.3 tonnes/day) seasons (Table 3). Previous studies on assimilative capacity at Delhi (Goyal et al., 2003), Visakhapatnam (Ramakrishna et al., 2004), and Gangtok (Goyal et al., 2006) also reported low assimilative capacities during winter and post-monsoon seasons.

Assimilative capacity for low, medium, high, and critical pollution levels

Manali industrial area falls under critical pollution zone with respect to SO₂, as the present loading of 22.8 tonnes/day is higher than the estimated safe load of 16.05 tonnes/day. The present emission was found to be higher than the critical loads in winter, summer, post-monsoon, and monsoon seasons at the study region. To achieve levels under low pollution category, the amount of SO₂ emission reduction required for winter, summer, post-monsoon, and monsoon seasons were estimated to be 80%, 75%, 81%, and 71%, respectively. The industrial area falls under medium pollution zone for NO₂ with the present loading of 7.8

Table 4. Assimilative capacity (AC) ranges for SO₂, NO₂, and PM₁₀ in low, medium, high, and critical pollution levels during different seasons.

Pollutant	Pollution level	Winter AC (tonnes/day)	Summer AC (tonnes/day)	Post-monsoon AC (tonnes/day)	Monsoon AC (tonnes/day)
SO ₂	Low	0–4.5	0–5.7	0–4.3	0–6.4
	Medium	4.6–9.2	5.8–12.5	4.4–9.3	6.5–12.3
	High	9.3–12.5	12.6–15.5	8.4–13.2	12.4–18.2
	Critical	>12.6	>15.6	>13.3	>18.3
NO ₂	Low	0–4.0	0–4.2	0–3.9	0–5.7
	Medium	4.1–8.3	4.3–8.4	4–8.0	5.8–10.2
	High	8.4–12.4	8.5–13.0	8.1–11.7	10.3–16.2
	Critical	>12.5	>13.1	>11.8	>16.3
PM ₁₀	Low	0–6.9	0–7.0	0–6.8	0–8.1
	Medium	7.0–13.4	7.1–12.6	6.9–13.6	8.2–14.5
	High	13.5–14.3	12.7–14.1	13.7–14.4	14.6–19.2
	Critical	>14.4	>14.2	>14.5	>19.3

tonnes/day, which was found to be less than AC_c for all seasons. Similarly, for PM₁₀ emissions, the site falls under medium pollution category for winter, summer, and post monsoon seasons with a current loading of 7.1 tonnes/day. However, in case of monsoon season, the location falls under low pollution category due to reduction in particulate levels as a result of increase in dilution rates and particle scavenging, i.e., wet deposition (Dumka et al., 2013). Table 4 presents the ranges of ACs for SO₂, NO₂, and PM₁₀ emission loadings corresponding to critical, high, medium, and low pollution levels in Manali industrial area.

Contribution of industrial emissions to ambient air quality

Daily SO₂, NO₂, and PM₁₀ emissions from the petrochemical and non-petrochemical industries were found to be 14.72, 4.98, and 3.52 tonnes and 8.08, 2.89, and 3.64 tonnes, respectively (Table 5). The SO₂, NO₂, and PM₁₀ emission contributions from petrochemical industries to the ambient environment were found to be 71%, 70%, and 51%, respectively (Table 5). The contributions of non-petrochemical industries were found to be 29%, 30%, and 48% for SO₂, NO₂, and PM₁₀, respectively. It was found that emissions from the petrochemical industries were dominating in Manali industrial area.

Discussion

In the present study, a fine-resolution PM₁₀, NO₂, and SO₂ emission inventory and model predictions were made to estimate the present assimilative capacity as well as season-wise allowable industrial emissions under high, medium, and low pollution levels for Manali Industrial area. Poor assimilative capacity was observed for SO₂, with estimated safe emissions 16.05 tonnes/day compared with the present emissions of 22.8 tonnes/day. The extensive usage of furnace oil, which has high sulfur content, augmented SO₂ emissions of the industrial cluster. Corroborating our claim, other studies that were carried out in other major Indian industrial clusters also reported higher SO₂ emissions as a result of large-scale usage of fuels with high sulfur content (Garg et al., 2002; Sivacoumar et al., 2001).

Table 5. Amounts of SO₂, NO₂, and PM₁₀ emissions (tonnes/day) and percentages of contribution of emissions from petrochemical and non-petrochemical industries to the ambient environment.

Parameter	Type of industry	Pollutants		
		SO ₂	NO ₂	PM ₁₀
Emissions (tonnes/day)	Petrochemical	14.72	4.98	3.52
	Non-petrochemical	8.08	2.89	3.64
Emission contribution (%)	Petrochemical	71	70	51
	Non-petrochemical	29	30	48

Significance of the study

Manali is a hinterland site of Chennai City. Being one of the major industrial hubs of India, it is designated as a nonattainment area for air pollution, with a CEPI value of 76.03. In the past, SO₂, NO₂, and PM concentrations reached a level of 70–500 µg/m³ at Manali (TNPCB, 2010). As a result, several pollution abatement measures were formulated and implemented by CPCB in 2009. A detailed description of the implemented measures is presented elsewhere (TNPCB, 2010). In the present study, the effectiveness of the implemented measures in terms of assimilative capacity was estimated. Results indicated that the current PM₁₀ and NO₂ emissions are within the allowable range; however, SO₂ emissions are alarmingly higher than the safe limits. It was observed that the SO₂ emissions need to be reduced by 6.7 tonnes/day to achieve safe ambient levels.

Further, the study showed significant variability in local meteorology that influences air quality of Manali area (e.g., occurrence of stagnation events during winter were 12% and 15% higher than that of summer and monsoon seasons, respectively), and the allowable SO₂ emissions during post-monsoon and winter were found to be 35% and 26% lower compared with monsoon season, respectively. Therefore, similar regulation measures may not be applicable throughout the seasons. Our season-wise safe loads were worked out considering meteorological factors. The estimated emission loads for critical, high, medium, and low pollution levels were helpful in quantifying the control measures required to achieve desired pollution level at the industrial area.

In order to control emissions at source, seawater scrubbing is one of the efficient and cost-effective SO₂ removal techniques widely used globally (Andreasen and Mayer, 2007). It can serve a great purpose at Manali industrial area due to the area's close proximity to seashore. In addition, usage of liquefied natural gas and naphtha in place of liquid fuels in petrochemical industries and husk in place of furnace oil in non-petrochemical industries are few other control options that could be implemented in Manali industries to reduce SO₂ emissions (TNPCB, 2010). Previous studies reported various methods to achieve low sulfur emissions at industries, which include use of liquefied petroleum gas (LPG), natural oil, and low-sulfur-content furnace oil, to reduce SO₂ emissions (Jafarinejad, 2016). Further, desulfurization of liquid fuel, acid treatment (e.g., absorption with amine) of flue gas (i.e., removal of H₂S), use of catalytic additives, adoption of hydrotreatment process, sulfur recovery, and tail gas treatment units are few more control options that can reduce the SO₂ emissions at our study site (EPA, 2015; European Commission and Joint Research Center, 2013).

Our quantitative representation of assimilative capacity (in terms of emissions), when compared with routine qualitative representation, would provide better data for estimating the carrying capacity of an area. This information also helps in allowing or denying permission for the new industries at the vicinity. A thorough knowledge of assimilative capacity in different seasons can help the decision makers to know the safe periods for the industrial operation and associated control measures. The assimilative capacity of the region can be further enhanced by implementing proper scheduling of activities related to source emissions, such as change to fuels with low sulfur content, increase in the stack height, and emission characteristics. Thus, the present analysis of assimilative capacity for various pollutants can provide useful information to policy makers to design an effective, industry-friendly plan to control air pollution in Manali industrial area.

Future implications

India is experiencing a rapid industrial and urban growth. The total number of critically polluted areas has drastically increased from 23 to 43 over the last decade (CPCB, 2003; CPCB, 2009b; Mukhopadhyay and Forssell, 2005). The primary air pollutants levels at various urban and industrial centers are more than 2 times higher than the prescribed standards (Guttikunda et al., 2014; Kaushik et al., 2006; Mukhopadhyay and Forssell, 2005). The evolution of smart cities and tier I and II cities is promoting industrial investments and urbanization, which may further increase air pollution. In this regard, the existing methods for air quality management would not be sufficient to quantify load-carrying capacity of regions and propose suitable action plans for local areas. The methodology presented in our study could serve as an effective technique for designing source-specific and season-specific air pollution control strategies at an air quality control region.

Acknowledgment

The authors would like to thank the member secretaries of Central Pollution Control Board and Tamil Nadu Pollution Control Board for providing the data required for this research work. The authors would like to acknowledge Alan J. Cimorelli, Steven G. Perry, Akula Venkatram, Jeffrey C. Weil, Robert J. Paine, Robert B. Wilson, Russell F. Lee, Warren D. Peters, and Roger W. Brode for their contribution towards the development of AERMOD model. The authors thank the anonymous reviewers for their constructive suggestions, which improved the overall quality of our paper.

Funding

The authors are thankful to the China Section of the Air & Waste Management Association for the generous scholarship to cover the cost of page charges and make the publication of this paper possible. This work was supported by the China Section of the Air & Waste Management Association (jawma23).

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