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Air Quality Mapping and Urban Planning for Sustainable Urban Ecology: A Case Study of Chandigarh, India

Shubham Saharan, Surinder Deswal*, Mahesh Pal

Department of Civil Engineering, National Institute of Technology Kurukshetra,
Kurukshetra-136119, Haryana, India
*Corresponding author e-mail: sdeswal@nitkkr.ac.in

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Abstract. In the fast urbanizing world, it has become vital to study urban ecology so as to understand where and how anthropogenic activities impair the urban environment, including air quality; and how living conditions can be improved by urban planning without mortifying urban ecology. This may require innovative technological ideas to efficiently and judiciously utilize the limited urban space. Air quality mapping using Geographic Information System (GIS) provides one such effective tool to urban planners to identify and target specific areas for air quality management in urban setting. In the present study, the air quality mapping of a well-planned city of Chandigarh (India) with proper environmental management zoning has revealed that the air quality index (AQI) of the city falls under "Moderately Polluted (101-200)" category primarily due to annual average concentrations of $PM_{2,5}$ (range: 44.17-68.87; overall: 56.64) and PM_{10} (range: 99.32-129.39; overall: 111.92) being higher than the permissible levels of 40 $\mu g/m^3$ and 60 $\mu g/m^3$ respectively as per Indian standards at all locations as well as for overall city. The study has identified vehicular traffic as the primary reason responsible for the moderately polluted air quality of the city that has the highest vehicle density (878 per 1000 population) in India. The paper has also suggested measures that may be incorporated during designing and developing the physical and social infrastructures in the city so as to judiciously and efficiently utilize the limited urban space.

Keywords: Chandigarh, vehicular traffic, air quality maps, GIS, AQI, $PM_{2,5}$, PM_{10}.

1. Introduction

Urban ecology is a multidisciplinary study area that deals with complex interactions between humans and the urban environment – such as building and housing, roads and transportation, green spaces and parks, wetlands, energy, manufacturing, and so on. It has emerged as one of the significant area of study in recent decades as 55% of the world's population lives in urban areas that is expected to increase to 68% (more than two-third) by 2050, with close to 90% of this increase in Asia and Africa (UN DESA, 2018). Therefore, it becomes pertinent to study urban ecology to understand where and how anthropogenic activities impair the urban environment, including ambient air quality with respect to noise and air pollution (Kallankandy & Deswal, 2023); and living conditions can be improved by urban planning without mortifying urban ecology.

Air quality and human health are directly linked to each other, which also affect the urban ecosystem. It is a critical environmental issue that affects millions of people worldwide in urban areas, and poses significant risks to human health, ecological systems, and economic development (Kampa & Castanas, 2008; Deswal & Deswal, 2012; Manisalidis et al., 2020). The anthropogenic sources of air pollution ranges from industrial, commercial, agricultural, residential, war-fares, etc.; however, automobile has been singled out as especially serious as transportation accounts for about 55% of all major air pollutants' emission. In fact, on-road vehicles are considered as one of the primary sources of fine particulate matter emission in urban areas (Uherek et al., 2010; Platt et al., 2014). Air quality is defined by particulate matter (such as, dust, smoke, fume, mist and haze) and gases and vapours (such as SO_x, NO_x, CO_x, HCs, H_2S, CH_4, O_3, PAN, CFCs, NH_3, etc.), present in the ambient atmosphere, and all contribute to the deterioration of air quality (Parmar et al., 2001; Kumar & Maharana, 2020). The particulate matter with an aerodynamic diameter ranging from 0.1 nm to 100 μm present in atmosphere is termed as suspended particulate matter (SPM). The particulate matter that is of major concern to human health and other environmental issues are – $PM_{2,5}$ (aerodynamic diameter ≤ 2.5 μm) and PM_{10} (aerodynamic diameter ≤ 10 μm). Air quality is continuously assessed in cities all over the world, and the air pollutants' concentrations and standards are normally measured/expressed in $\mu g/m^3$ that is not easily understandable by the general public. Therefore, to make the air quality data more understandable for the general public, air quality index (AQI) common to all air pollutants ranging from good to bad is being used as a tool to indicate the level of severity and disseminate the information on air quality to enable the public to understand the health and environmental impacts of air quality (Deswal & Verma, 2016).

In the context of urban ecology, geospatial mapping of ambient noise and/or air pollutant levels using GIS can be integrated into urban planning processes to improve environmental quality, public health, and social equity (Kallankandy & Deswal, 2023). One of the earliest studies on the use of GIS for air quality mapping was conducted by Gualtieri et al. (1997) highlighting the potential of GIS-based tools in developing predictive models for air pollution levels, aiding in the development of effective air quality management strategies in urban planning. In another study, Zou et al. (2011) used GIS-based tools to estimate the spatial-temporal variations of regional ambient sulphur dioxide concentration and source contribution analysis by accurately identifying sources of air pollution and developing targeted strategies for reducing air pollution in urban areas. Kumar et al. (2016) also highlighted the importance of GIS-based tools for estimating health impacts of air pollution in urban areas and developing strategies to mitigate the impact. Kumar et al. (2016) used GIS to map air quality in Mumbai, India, and assess the economic impact of air pollution on human health. Remote sensing and GIS-spatial technologies were utilized by Al-Aloha et al. (2022) to estimate air quality along a train pathway in Al-Qurayyat City in Saudi Arabia to estimate air quality in areas where ground-based monitoring is limited. With increasing focus on the air quality management zones for urban planning, Badach et al. (2020) used GIS-based tools for air quality management zones (AQMZs) in two European cities, Antwerp, and Gdansk. The study found that the current air quality management zones were not effective in reducing air pollution and suggested that a new zoning system should be developed based on pollutant sources and population density. Recently, Wang et al. (2023) utilize machine learning models and GIS-based tools to estimate $PM_{2,5}$ concentrations in Beijing with high spatio-temporal resolution. This model can help in predicting pollutant concentrations in different areas of the city, and this approach could be used to develop more effective air quality management strategies. All these reviewed studies provide valuable insights into the use of air quality mapping using GIS for air quality management and suggest that further research is needed to develop effective air quality management strategies in urban areas.

In view of this, the present study was carried out for Chandigarh – one of the earliest planned city and having the largest number of vehicles per capita in India, with the objective to identify areas having higher air pollution levels or relatively lower air quality, the reasons thereof, and the possible remedial measures required in urban management and planning to achieve healthy urban ecosystem. To achieve the objective, monthly mean data and annual average data of air pollutants and Air Quality Index (AQI) for the latest calendar year 2022 at eight continuously monitored locations within the city has been used.

2. Materials and Methodology

2.1. Study Area

Chandigarh is one of the earliest planned city of India and is internationally known for its modern architecture and urban design. The foundation stone of Chandigarh city was laid in 1952, and on 01.11.1966 designated as the shared capital of two northern states of India – Punjab and Haryana, and declared as the Union Territory under Central Government. The city proudly describes itself by the motif or sobriquet "The City Beautiful". The city developed on the gently sloping fertile plains situated near the foothills of the Shivalik range of the Himalayas spread over an area of 114 km^2. between 30^{o}39'N to 30^{o}49'N latitude and 75^{o}41'E to 75^{o}51'E longitude at an average elevation of 321 m. The city has a humid sub-tropical climate characterized by characterized by very hot summers, severe winters, moderate to heavy rainfall in monsoon. The temperature in Chandigarh varies from -1 to 45^{o}C, having average annual temperature of 23.2^{o}C and average annual precipitation of about 793 mm. Winds are generally light and blow from north-west to south-east.

The city is mainly dominated with urban land use. In spite of this, the total green cover (forest cover + tree cover) of Chandigarh stands at 37.88 km^2. that includes forest cover of 22.88 km^2 accounting for 20.07% and tree cover of 15 km^2 accounting for 13.16% of its geographical area as per ISFR (2021). The prominent flora incudes *Ficus benghalensis*, *Eucalyptus globulus*, *Saraca indica*, *Cassia fistula*, *Morinda* *citrifolia* and other trees that flourish in the forest ecosystem. Further, 31 trees which are 100 years or more old have been designated as Heritage Trees. The forest and lake ecosystems of the city are habitat to a variety of animal and bird species including the migratory birds from Siberia and Japan in winters.

The current population of the city is estimated to be 1.13 million with a density of 9883/km^2, and having a literacy rate of 86.05%. Chandigarh city's Human Development Index (HDI) of 0.744 in 2021 is very high and ranked at 3rd position in India as per Global Data Lab estimated by using UNDP method. It is one of the richest towns in India having an average household monthly income of R. 199,000 (USD 2500), and a GDP of Rs. 436,743.4 million (USD 6195.8 million) in 2019-20 (IBEF, 2023). A significant percentage of city's population comprises of government employees (in service and pensioners), and public and private sector employees. Apart from government organisations, educational, medical and research institutes; the other occupational activities include manufacturing trade and commerce. There are about 15 medium-to-large scale industries and over 2500 small-scale units in private and public sectors in the areas of information & technology, manufacturing, basic metals and alloys, machine tools, food products, sanitary ware, auto parts, pharmaceuticals, electrical appliances, etc. Chandigarh also has the distinction of largest number of vehicles per capita (vehicle density = 878 per 1000 population) in India accounting for over two vehicles per capita household that has been contributing immensely to air pollution and traffic congestion (SoER, 2016).

2.2. Monitoring Locations and Data Acquisition

The Chandigarh city's air quality is being continuously monitored by Central Pollution Control Board (CPCB), New Delhi and Chandigarh Pollution Control Committee (CPCC), Chandigarh at three and five monitoring locations respectively. These monitoring locations are: Sector-22, Sector-25 and Sector-53; and PEC Sector-12, Vill. Kaimbwala, Sector-17, IMTECH (Sector-39) and Industrial. Out of these 8 monitoring locations, PEC Sector-12 is institutional (sensitive: academic) zone located in the northern edge of the city, Sector-17 is commercial zone located in the heart of the city, Industrial Area is industrial zone located on the south-eastern side of the city in the leeward wind direction, and the rest of the 6 monitoring locations are in residential zones. The plan map of Chandigarh city, along with the adjoining cities of Mohali (south-western side) and Panchkula (south-eastern side), showing the monitoring locations has been presented in Figure 1.

Figure 1. Plan map of Chandigarh city with monitoring location

In the present study, monthly mean data and annual average data of $PM_{2,5}$, PM_{10} and Air Quality Index (AQI) for the calendar year 2022 has been obtained from Chandigarh Pollution Control Committee (CPCC), Chandigarh and Central Pollution Control Board (CPCB), New Delhi website in the form of Excel sheets. The other air pollutants (namely NO_2, O_3, CO, SO_2 and NH_3) that are part of AQI were not considered in the present study – firstly, their levels were observed to be within the permissible levels as per Indian ambient air quality standards; secondly and consequently, their weightage has negligible impact on AQI due to their low concentrations at all monitoring locations in Chandigarh city. The Indian ambient air quality standards with respect to $PM_{2,5}$ and PM_{10} have been reproduced in Table 1 (CPCB, 2009); whereas, the Indian AQI category, pollutants and health breakpoints has been reproduced in Tables 2 and associated health impacts with AQI in Table 3 (CPCB, 2015).

Table 1. Indian national ambient air quality standards

S. No.	Pollutant	Time Weighted Average	Concentration in Ambient Air	
			Industrial, Residential, Rural and other Area	Ecologically Sensitive Area (Notified by Central Government)
1	Particulate Matter (size < 10 μm) or PM_{10} in $\mu g/m^3$	Annual	60	60
		24 hours	100	100
2	Particulate Matter (size < 2.5 μm) or $PM_{2,5}$ in $\mu g/m^3$	Annual	40	40
		24 hours	60	60

2.3. Data Analysis and Software Used

The obtained/downloaded data was first processed in Excel for computing annual average values for $PM_{2,5}$, PM_{10} and AQI at individual monitored location and for overall Chandigarh city; and inter-location variation of the air indices was analysed and compared with Indian standards. Thereafter, the data was imported into open-source QGIS V.3.28 software. Air quality mapping was then performed by adding the data to the delimiting layer. Longitudes and latitudes were plotted on X-axis and Y-axis respectively to represent point coordinates on the map. After data entry, layer styling was done for thematic representation of the points. Plug-in, such as open street map (OSM) was used for geographical representation on the map. Air quality maps for $PM_{2,5}$, PM_{10} and AQI were created for the city. Color-coding was used to indicate the air quality, with red indicating areas with poor air quality (i.e. high air pollution levels) and green indicating areas with good and/or satisfactory air quality (i.e. low air pollution levels).

Table 2. Air quality index (AQI) category, pollutants and health breakpoints

AQI Category (Range)	PM_{10} (24hr)	$PM_{2.5}$ (24hr)	NO_2 (24hr)	O_3 (8hr)	CO (8hr)	SO_2 (24hr)	NH_3 (24hr)
Good (0–50)	0–50	0–30	0–40	0–50	0–1.0	0–40	0–200
Satisfactory (51–100)	51–100	31–60	41–80	51–100	1.1–2.0	41–80	201–400
Moderately polluted (101–200)	101–250	61–90	81–180	101–168	2.1–10	81–380	401–800
Poor (201–300)	251–350	91–120	181–280	169–208	10–17	381–800	801–1200
Very poor (301–400)	351–430	121–250	281–400	209–748	17–34	801–1600	1200–1800
Severe (401–500)	430+	250+	400+	748+	34+	1600+	1800+

Table 3. Associated health impacts with air quality index (AQI)

AQI	Associated Health Impacts
Good (0–50)	Minimal Impact
Satisfactory (51–100)	May cause minor breathing discomfort to sensitive people.
Moderately polluted (101–200)	May cause breathing discomfort to people with lung disease such as asthma, and discomfort to people with heart disease, children and older adults.
Poor (201–300)	May cause breathing discomfort to people on prolonged inhaling, and problems to people with heart disease.
Very Poor (301–400)	May cause respiratory illness to the people on prolonged inhaling. Effect may be more severe in people who are living with lung and heart diseases.
Severe (401-500)	May cause respiratory impact even on healthy people, and serious health impacts on people with lung/heart disease. The health impacts may be experienced even during normal walk also.

3. Results and Discussion

3.1. Inter-location Variation of $PM_{2,5}$, PM_{10} and AQI

The annual average concentrations of $PM_{2,5}$ and PM_{10}, and annual average AQI at all the 8 monitored locations have been presented in Figure 2. The overall Chandigarh city AQI and $PM_{2,5}$ and PM_{10} concentrations on annual average basis have been computed by taking the mean of values at the 8 monitored locations and have been presented alongside in Fig. 2 for analysis.

The inter-location $PM_{2,5}$ concentration was observed to be in the range of 44.17 – 68.87 $\mu g/m^3$, having the overall Chandigarh city concentration of 56.64 $\mu g/m^3$ in comparison to the permissible annual average concentration of 40 $\mu g/m^3$ as per Indian Standards. Four locations – namely Sector-25, Sector-17, PEC Sector-12 and IMTECH (Sec-39), have $PM_{2,5}$ concentration lower than the overall City average; whereas, the remaining four locations – Vill. Kaimbawala, Sector-22, Industrial Area and Sector-53, have higher $PM_{2,5}$ concentration than the overall City average. The lowest concentration was observed at Sector-25 location; whereas, the highest at Sector-53.

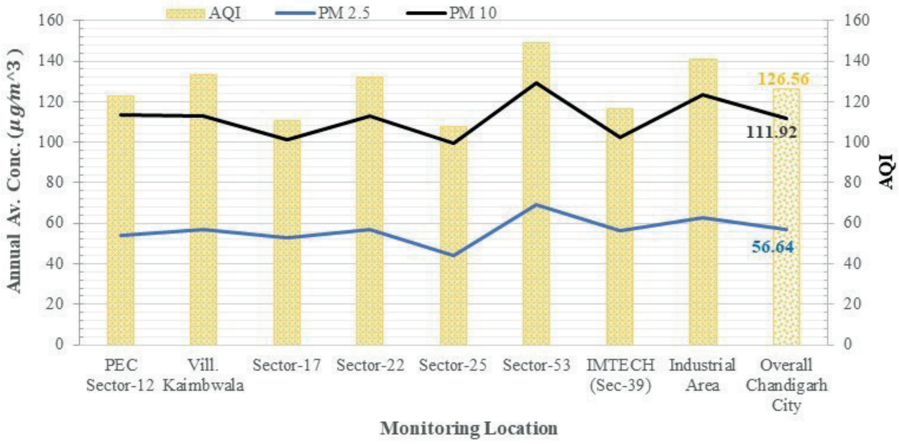

Figure 2. Inter-location variation of the $PM_{2,5}$, PM_{10} and AQI

The inter-location PM_{10} concentration was observed to be in the range of 99.32 – 129.39 $\mu g/m^3$, having the overall Chandigarh city concentration of 111.92 $\mu g/m^3$ in comparison to the permissible annual average concentration of 60 $\mu g/m^3$ as per Indian Standards. Three locations – namely Sector-25, Sector-17 and IMTECH (Sec-39), have $PM_{2,5}$ concentration lower than the overall City average; whereas, the remaining five locations – Vill. Kaimbawala, Sector-22, PEC Sector-12, Industrial Area and Sector-53, have higher $PM_{2,5}$ concentration than the overall City average. Like $PM_{2,5}$ variation, the lowest concentration of $PM_{2,5}$ was observed at Sector-25 location; whereas, the highest at Sector-53.

The inter-location annual average AQI was in the range of 107.38 – 149.24, having the overall Chandigarh city AQI of 126.56 falling in the "Moderately Polluted (101-200)". Four locations – namely Sector-25, Sector-17, IMTECH (Sec-39) and PEC Sector-12, have lower AQI than the overall City average; whereas, the remaining four locations – Sector-22, Vill. Kaimbawala, Industrial Area and Sector-53, have higher AQI than the overall City average. As in case of $PM_{2,5}$ and $PM_{2,5}$, the lowest AQI was of Sector-25 location; whereas, the highest at Sector-53.

3.2. Mapping of $PM_{2,5}$, PM_{10} and AQI

The air quality maps have been plotted using GIS for $PM_{2,5}$, PM_{10}, and AQI by using the annual average values of the respective air indices at the 8 monitored locations for analysis purpose and have been presented in Figures 3, 4 and 5 respectively. The lowest concentration

A glance at the Figure 3, reveals that the $PM_{2,5}$ concentration has been lower in the northern part of the city, and hot-spots of higher concentrations in south-west and south-east parts of Chandigarh. The lowest concentration has been around Sector-25 areas in the northern part of the city; whereas, the highest $M_{2,5}$ concentration areas have been areas around Sector-53 followed by Industrial area in the south-west and south-east part of the city respectively.

In case of PM_{10} concentration (Fig. 4), the lower concentration areas have been in the central and north-west part of the city; whereas, hot spots of higher concentration have been along peripheral southern, western and north-eastern areas of the city, having highest concentration around Sector-53. The possible reasons include:

- Higher concentrations of $PM_{2,5}$ and PM_{10} in south-western parts of the city may be due to the adjoining industrial area of Mohali city, and relatively higher industrial, commercial and infrastructural developmental activities coupled with less stringent pollution control measures and lower awareness in Mohali city.
- Higher concentrations in south-eastern parts of the city may due to the leeward wind direction, and location of industrial area of Chandigarh in south-eastern side.
- Higher concentration along peripheral southern, western and north-eastern areas of the city may be due to relatively higher industrial, commercial and construction activities, and traffic in the peripheral satellite townships and major national highways.
- Lower concentrations of $PM_{2,5}$ and PM_{10} in north and central parts of the city may be due to:
  - locations of facilities – such as academic, health, administrative secretariats, high court, parks and open landscapes, etc., and predominantly residential areas;
  - direction of wind, which is most often from the north (more than 7 months) and from west (about 4.5 months) (https://weatherspark.com/y/108778/

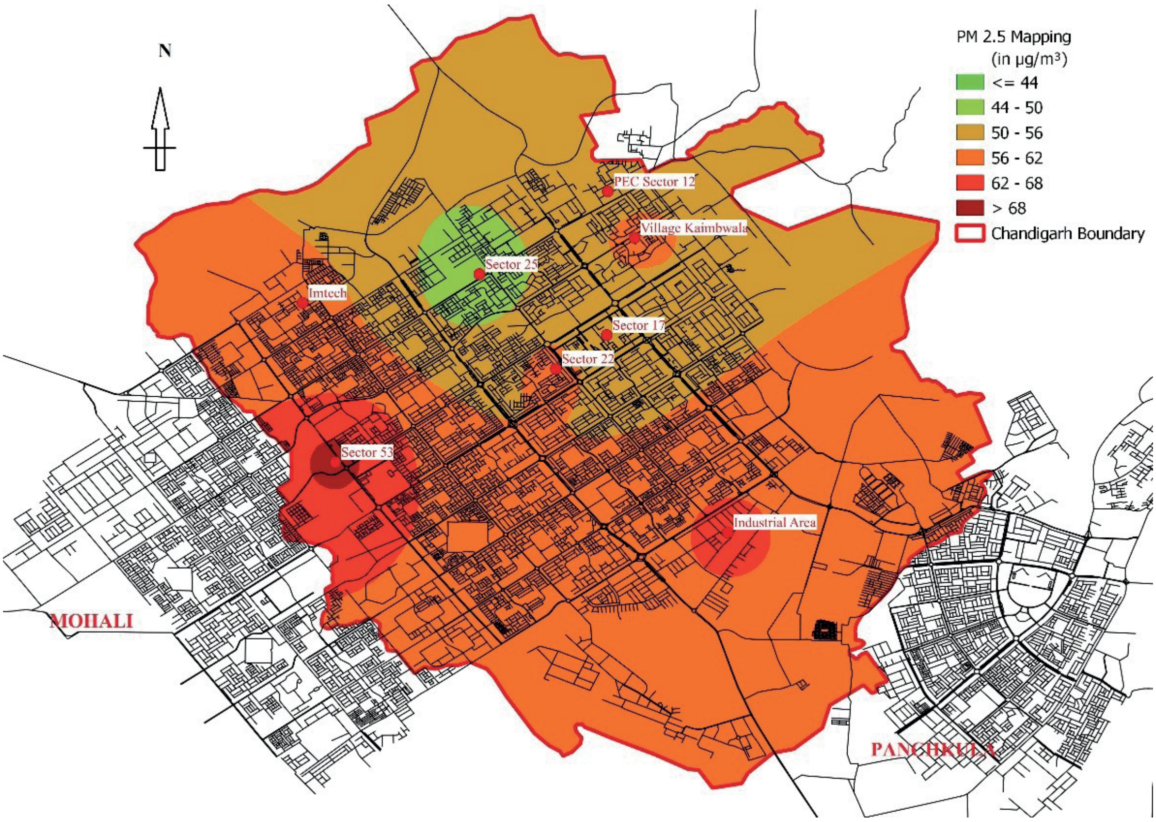

Figure 3. Air quality map of Chandigarh city for $PM_{2,5}$

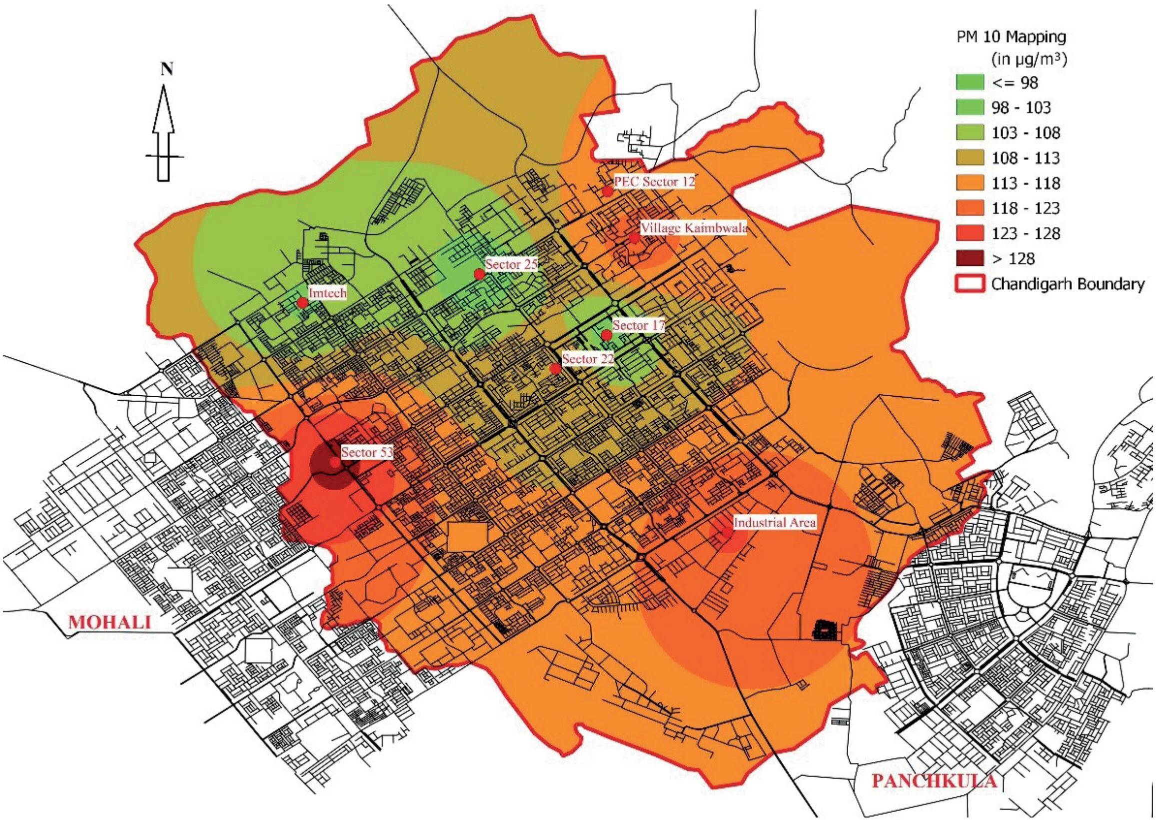

Figure 4. Air quality map of Chandigarh city for PM_{10}

Average-Weather-in-Chandigarh-India-Year-Round);
– presence of hilly terrain of Shivalik hills of lower Himalayan ranges in the north of the Chandigarh city; and
– no major town and/or industrial area in the northern side of the city.

The AQI map (Fig. 5), shows that the air quality of the entire region of the Chandigarh city falls under "Moderately Polluted" category (Range: 101-200; Colour Code: yellow) implying that it may cause breathing discomfort to people with lung disease such as asthma, and discomfort to people with heart disease, children and older adults (Table 3). The range bound uniformity of AQI (107.38 – 149.24, as shown in Fig. 2) points towards a common source of $PM_{2,5}$ and PM_{10} well distributed in the city. An examination of the characteristics of the study area (i.e. Chandigarh) and the sources of $PM_{2,5}$ and PM_{10} points towards the emission of these pollutants by and due to vehicular traffic in the city. It is being substantiated by the following:

- high vehicle density (878 per 1,000 population) in Chandigarh, that is about 1 million vehicle ownerships, and more than 45,000 vehicles are being registered every year (SoER, 2016);
- traffic or automobiles contribute 34 and 37% in PM_{10} and $PM_{2,5}$ respectively to air pollution load, and that too at the breathing level of air quality (Karagulian et al., 2015);
- factors, such as traffic volume and vehicle speed also add up to the non-exhaust emission sources of pollution (Chen et al., 2006a; Chen et al., 2006b; Gustafsson et al., 2008);
- release of particulate matter of size less than 10 µm into the atmosphere from vehicle's brake wear which includes brake lining and disc abrasion caused by grinding, volatilization and condensation of brake pad material (Garg et al., 2000; Wahlin et al., 2006; Varrica et al., 2013). A passenger car has the potential of emitting brake dust to the extent of 44 g per car per year (Iijima et al., 2007).

In view of the above results and findings based on air quality maps, the following measures have been suggested to be incorporated in planning and management process of Chandigarh city during designing and developing the physical and social infrastructures:

- Transportation planning – reduce traffic congestion and vehicle density by developing diverse, effective and efficient public transportation on priority; promoting

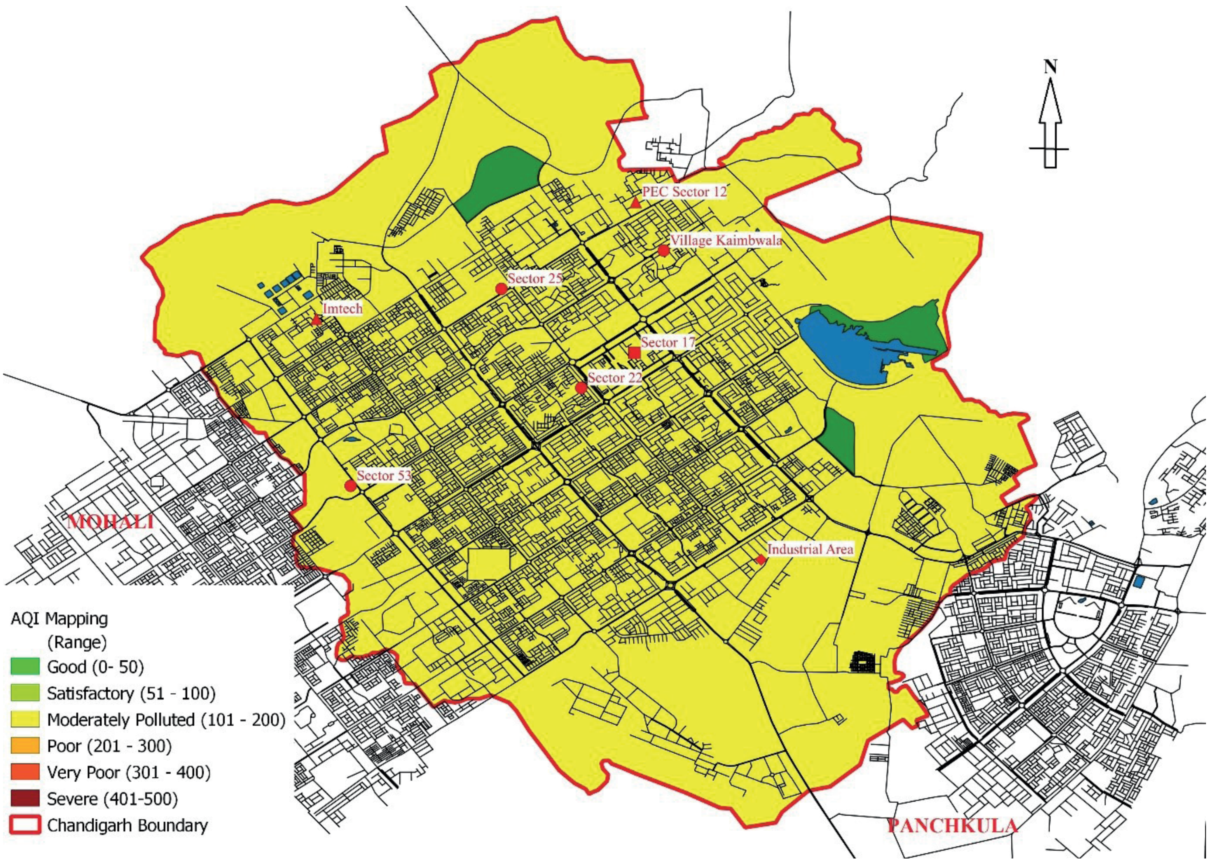

Figure 5. Air quality map of Chandigarh city for AQI

the use of public transportation, carpooling, and use of bicycles so as to reduce the vehicle ownership.

- Environmental planning – strict regulations on industrial and vehicular emissions; promoting use of clean fuels (Ezzati et al., 2002; Beelen et al., 2014); and the emission source control measures, such as the end-of-pipe control policies and the energy climate policies to improve air quality (Geng et al., 2012; EPA, 2020).
- Land use planning – new developments to be in areas/zones with good air quality so as to minimize the impact of pollution on the residents; increasing the tree cover by developing forest and shrub lands; developing green spaces (parks, open landscapes, recreational areas) in areas with poor air quality (Nowak et al., 2014; Nowak et al., 2018); and new or revised zoning system may be developed based on pollutant sources and population density (Badach et al., 2020).

4. Conclusion

Air quality mapping using GIS provides an effective and efficient tool for urban planning and management by providing spatial distribution of air quality that helps in identifying the areas with poor air quality, the reasons thereof and prioritize the hot spots for intervention. The present study revealed that despite being the well-planned city with proper environmental management zoning, the air quality is not good – instead "Moderately Polluted" as per AQI of India, primarily due to annual average concentrations of $PM_{2,5}$ and PM_{10} at all locations as well as overall being higher than the permissible levels of 40 $\mu g/m^3$ and 60 v $\mu g/m^3$ respectively as per Indian standards. The study points towards the vehicular traffic in the city as the major reason responsible for the moderately polluted air quality of the Chandigarh city that has highest vehicle density in India. The paper has suggested measures that may be incorporated in transportation, land use and environmental planning and management process of Chandigarh city during designing and developing the physical and social infrastructures. The pace at which the world continues to urbanize, city planners would require more space for urban ecology having ingredients of innovative technological ideas (such as air quality mapping using GIS) to efficiently and judiciously utilize the limited urban space.

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