Influence of urban air pollution on the population in the Klang Valley, Malaysia: a spatial approach

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Abstract

Background: Urban air pollution resulting from economic growth as well as urbanization impacts the health of inhabitants. This study aims to examine the spatial distribution of particulate matter (PM10) and the risk of exposure for the population in the Klang Valley, an urban conglomeration centred in Kuala Lumpur, Malaysia.

Methods: The inverse distance weighted (IDW) interpolation technique in the ArcGIS platform was used to map the air quality from five air monitoring stations. Spatial statistics of the Global Moran's I Spatial Autocorrelation and Optimized Hot Spot Analysis were used to estimate the spatial clustering of PM10. The population-weighted exposure level (PWEL) technique was used to calculate the population density susceptible to PM10 and the AirQ+ model was applied to estimate the proportion of the adult population at risk of chronic bronchitis due to long-term exposure to PM10 concentrations in the Klang Valley.

Results: The highest annual mean PM10 concentrations at the Klang station ranged between 80 and 100 μg/m³ from 2000 to 2009 and exceeded the New Malaysia Ambient Air Quality Standard (NMAAQS) and the World Health Organization Air Quality Guidelines (WHOAQG) levels of 40 and 20 μg/m³, respectively. The Moran’s I results indicated that the statistically significant clusters of high PM10 in Klang present a health risk to the local community. The PWEL results showed that levels of PM10 in Petaling Jaya exceeded the WHOAQG limits, potentially posing a health risk to the high-density population. The AirQ+ model found Klang to be a significantly high-risk area for chronic bronchitis among the adult population with 804,240 people (with a relative risk of 1.85) in 2009.

Conclusion: These high-risk values are due to rapid urbanization and high motor vehicle usage in the Klang Valley and therefore the impact of PM10 on the population needs to be reduced. This situation should be taken seriously by the Department of Environment and Kuala Lumpur City Hall in addressing air pollution issues through stricter rules on emissions and implementing low-carbon policies to improve the well-being of residents.

Keywords: Population, Urban air pollution, Spatial distribution, PM10, Adult chronic bronchitis risk

Introduction

Rapid urbanization is stimulated by population growth and increases in economic activities in city centres. The increase in air pollutants released from various sources causes the air quality to deteriorate, which is detrimental to the health of individuals. Air pollution in Malaysia is largely caused by point sources, specifically industrial manufacturing and energy generation, as well as from...
mobile sources (motor vehicles) and open burning activities (DOE 2017). These sources release a variety of toxic gases, such as carbon monoxide (CO), nitrogen dioxide (NO\(_2\)), sulphur dioxide (SO\(_2\)), and ozone (O\(_3\)), as well as suspended particles of less than 10 \(\mu\)m (PM\(_{10}\)). The total pollutants in 2017 consisted of 2,123,281 metric tonnes of CO, with 860,390 metric tonnes of NO\(_2\), 218,700 metric tonnes of SO\(_2\) and 23,964 metric tonnes of PM\(_{10}\), mainly from the use of petroleum and the use of coal for power generation (DOE 2017). Furthermore, for the year 2018, CO pollutant emissions of 2,210,634 metric tonnes, as well as 889,890 metric tonnes of NO\(_2\), 257,457 metric tonnes of SO\(_2\), and 26,789 metric tonnes of PM were recorded (DOE 2018). The pollutants were made up of PM\(_{10}\) power plants representing 36% of the total, while industrial activities (33%), motor vehicle exhaust (16%) and other sources (15%) such as residential, commercial, non-energy, and agricultural uses represented the rest (DOE 2017). CO emissions from motor vehicles still dominated the CO emissions in Malaysia with 95.6% for 2018 (DOE 2018).

The Malaysian ambient air quality guidelines (RMAQG) were developed by the DOE in 1989, and stipulate the limits of pollutants, including PM\(_{10}\), CO, NO\(_2\), SO\(_2\) and O\(_3\), that negatively affect the general health of the population. The New Malaysian Ambient Air Quality Standards (NMAAQS) were established in 2015 with improved limits for air pollutants, following three tier periods that were finally implemented in 2020 (DOE 2020). PM\(_{10}\) is the major air pollutant in most urban and suburban areas in Southeast Asia (Afroz et al. 2003; Abas et al. 2004b; Azmi et al. 2010; Jamalani et al. 2016).

Exposure to high PM\(_{10}\) levels and toxic gases can lead to an elevated risk of respiratory diseases, which increases the risks of heart and lung diseases (Botkin and Keller 2007). Exposure to high concentrations of pollutants in the air contributes to 7.6% of deaths out of all health problems worldwide (WHO 2016). Air pollution was identified as the fourth leading risk factor for death and disability worldwide with 6.7 million deaths associated with air pollution in 2019, and India and China continuously recorded the highest burdens of disease. Also, new research on the impacts of exposure to air pollution on newborn babies showed nearly 500,000 infants died in the first month after birth due to exposure to ambient air pollution, specifically in sub-Saharan Africa and Asia regions, in 2019 (HEI 2020).

Respiratory-related illnesses were the leading cause of death in Malaysia in 2011, at 10.35% (Ministry of Health 2012). An increase in PM\(_{10}\) concentrations of 10 \(\mu\)g/m\(^3\) could increase the mortality rate by 0.27% per day in Asia (HEI International Scientific Oversight Committee 2010). The middle-aged, young children and the elderly are also vulnerable to the effects of PM\(_{10}\) (Liu et al. 2020), which can also cause premature death (Wang et al. 2020) and elevate the risk of deaths due to asthma (Zhang et al. 2020). The correlation between air pollution in major cities and the risk of exposure can affect the population’s economy through increased costs for treatment and accessibility to quality healthcare.

Thus, the objective of this study is to examine the spatial relationship between the PM\(_{10}\) concentrations and the health risk posed to the population in the Klang Valley. Several spatial analyses from the Geographical Information System (GIS) include the inverse distance weighted (IDW) technique that was used to map the spatial distribution of PM\(_{10}\) concentrations in the Klang Valley for 10 years from 2000 to 2009. The years 2000 to 2009 were used as the analysis time period as the highest 24-h concentration of PM\(_{10}\) was recorded in 2005 at all stations, namely Klang, Petaling Jaya, Kajang, Shah Alam and Cheras. The highest 24-h concentration was 590 \(\mu\)g/m\(^3\) recorded at Klang station followed by the Shah Alam station which recorded 587 \(\mu\)g/m\(^3\) in August 2005 due to the impact from a transboundary haze episode which occurred in Indonesia and point and mobile sources such as industry and motor vehicles. For health risk analysis, data from 2000 to 2009 were used due to the constraints of population data obtained from The Census of Population and Housing Malaysia. The spatial statistical technique of Global Moran’s I Spatial Autocorrelation was used to assess the statistical significance of the locations of the clusters of the PM\(_{10}\) concentrations. The optimized hotspot analysis can identify clustering of high and low areas of PM\(_{10}\) concentrations. Lastly, the population-weighted exposure level (PWEL) technique and the AirQ+ model spatially assess the relationship between the air pollution levels and the risk of exposure to the population.

**Materials and methods**

**Study area: the Klang Valley**

The Klang Valley, located on the southwest coast of Peninsular Malaysia, is an upcoming developing urban area. The Klang Valley comprises 2911.5 km\(^2\) across several districts in Selangor, namely Rawang, Gombak, Selayang, Ampang, Petaling Jaya, Subang Jaya, Shah Alam, Klang, Serdang, Kajang, Puchong, Cyberjaya, Sepang and the Federal Territory of Kuala Lumpur (Rahman et al. 2015a, b) (Fig. 1). There are four main Administrative Districts or Local Authority areas in the Klang Valley, namely Klang, Petaling, Hulu Langat and the Federal Territory of Kuala Lumpur (FTKL). The largest district administrative council is the Klang administrative council (Table 1).

The land-use categories in the Klang Valley are settlement (dwellings and municipalities), cropland, forest
land, grassland, peat swamp, mangrove, wetland, and other land uses. Districts with the largest settlement areas include Klang, Shah Alam, Petaling Jaya, Kajang and Cheras, an area totalling 1,489.76 ha. In the Klang district, agricultural cropland covers 957.05 ha with forest land consisting of an area of 741.62 ha (Selangor Department of Agriculture 2011).

**Table 1** Districts and area (ha) in the Klang Valley

| District     | Area (ha) |
|--------------|-----------|
| Klang        | 23,004.60 |
| Petaling     | 9488.77   |
| Hulu Langat  | 5686.04   |
| FTKL         | 243.00    |

Source: Selangor State Structure Plan 2002

Data source

Measurements of daily concentrations of PM$_{10}$ were made available by the Air Quality Division, Department of Environment Malaysia (DOE) for the 10 years between 2000 and 2009. Five air quality stations representing different land uses were used: Klang (urban), Petaling Jaya (industrial), Kajang (residential), Shah Alam (urban), and Cheras (urban). However, data collection for the Cheras station only commenced in 2004. To ensure the reliability of the measurement process, Alam Sekitar Sdn Bhd (ASMA), a private company mandated by the DOE, conducts continuous monitoring and calibration of the equipment. Daily hourly PM$_{10}$ concentrations were recorded using a β-ray attenuation mass monitor BAM–1020 (Shaadan et al. 2015). In addition to the raw data, additional secondary data from DOE Annual Reports and the Annual Environmental Quality Report supplemented the data. Additional data from several DOE annual reports were intended only to support the problem statement, especially air pollutant emissions from various sources, and were not used in the data analysis process. The distribution trend of PM$_{10}$ annual concentrations in the Klang Valley showed that Klang station recorded the highest annual average concentration of 590 µg/m$^3$ and Shah Alam recorded 587 µg/m$^3$ in August 2005. Cheras station also recorded its maximum annual PM$_{10}$ concentration in August 2005, when it reached 465 µg/m$^3$. 
Population distribution data
The Census of Population and Housing Malaysia for 2000 and 2010 provided the input data for the population. For this study, the annual population data for 2001 to 2009 were extrapolated, since the census is only available every 10 years (Department of Statistics Malaysia 2000, 2010).

Spatial analysis
Interpolation techniques used to analyse spatial data utilized the Geographic Information System (GIS) with ArcMap version 10.3 in ArcGIS. The interpolation techniques comprised a set of procedures to predict new values in areas with limited sampling points by considering that adjacent or nearby sampling points had interdependent relationships. The inverse distance weighted (IDW) technique predicts the influence of the known sample point after weighting by the inverse distance between two points (De Mesnard 2013; Yu et al. 2017).

The surface characteristics of the interpolation data can be controlled and determined by limiting the observed sampling points or inputs used. The limited number of input points is very important in improving the flow of the forecasting process. It was found that input points located far from the cell location had very weak and inaccurate prediction analysis, resulting in less significant spatial relationships for each point. To avoid this issue, we directly specified the number of input points used in the IDW interpolation technique. The IDW was formulated as:

\[
z(x) = \frac{\sum_{i=1}^{n} w_i(x) z_i}{\sum_{i=1}^{n} w_i(x)}, \quad w_i(x) = \frac{1}{d(x, x_i)^p},
\]

where \(Z(x)=\) predicted value at the interpolated point; \(x_i=\) value of the \(i\)th known sample point, i.e. the annual average concentration of \(\text{PM}_{10}\) at five air quality stations; \(d=\) distance between the known sample point and the prediction point; \(n=\) total number of the known sample points and refers to the five air quality stations, namely Klang, Petaling Jaya, Kajang, Shah Alam and Cheras; \(w_i=\) weight assigned to \(i\)th known sample point and \(p=\) weighting power—commonly this value is considered to be 2.

In this study, the five DOE air quality stations represented the Klang Valley area. In the IDW space interpolation process, default values interpolate the spatial variation of \(\text{PM}_{10}\) concentration. In this regard, the nearest points were projected to record higher or almost similar concentrations and vice versa.

Spatial statistical analysis
Global Moran’s I spatial autocorrelation (Moran’s I)
The spatial autocorrelation method measures the relationship among variables across a georeferenced space (Getis 2008). Two types of spatial autocorrelation were used in this study, namely Global Moran’s I statistic and Getis-Ord general G. Global Moran’s I tests for spatial correlation or clustering (Ya’acob and Mar Iman 2018). The Moran’s I test indicates positive spatial autocorrelation if \(I>0\), negative spatial autocorrelation \((I<1)\) and no spatial autocorrelation if \(I=0\) (Yang et al. 2020).

Spatial correlation is significant if both the \(z\)-score and \(p\)-value from the Moran’s I are significant at a \(p\)-value < 0.05. Furthermore, a positive \(z\)-score indicates a clustering of \(\text{PM}_{10}\) concentrations among the five stations. A negative \(z\)-score value indicates the presence of an outlier, while a \(z\)-score of 1 represents an insignificant relationship where the \(\text{PM}_{10}\) concentrations varied across the stations. In this study, the null hypothesis \((H_0)\) refers to the insignificant relationship between the distribution of \(\text{PM}_{10}\) concentrations and the locations of air quality stations.

Optimized hot spot analysis
Hot spot analysis measures the high-value hotspots, low-value cold spots and identifies spatial clusters that have statistical significance (Kang et al. 2018; Douglas et al. 2019). The optimized hot spot analysis (OHSA) is a tool extension (Holm 2018) that implements the Getis-Ord Gi* method and analyses all spots in administrative border or grid cell units to obtain the optimal results (Kang et al. 2018). In this study, the study area was gridded into a 1 km x 1 km lattice and the concentrations of \(\text{PM}_{10}\) were calculated according to the pixel of each grid. The Getis-Ord Gi* statistics formula for the hot spot analysis is shown below:

\[
G_i^* = \frac{\sum_{j=1}^{n} W_{ij} x_j - \bar{X} \sum_{j=1}^{n} W_{ij}}{\sqrt{\frac{\sum_{j=1}^{n} W_{ij}^2 - (\sum_{j=1}^{n} W_{ij})^2}{n-1}}},
\]

\[
\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n}, \quad s = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2},
\]

where \(n=\) total number of features; \(w_{ij}=\) value of spatial weight between \(i\) and \(j\); \(x_j=\) attribute value for feature \(j\). The Gi* \(z\)-score value obtained represents statistically significant hot spots and cold spots. Gi* \(z\)-score values for cold spots were recorded as \(-21.28 < z\text{-score} < -12.0\); \(-12.01 < z\text{-score} < -6.30\), and \(-6.20 < z\text{-score} < -2.21\) for cold spots with 99%, 95% and 90% confidence.
levels respectively, while \( -2.21 < z\text{-score} < 1.00 \) are not significant. For hot spots it showed a \( Gi^* \) \text{-score} value of \( 1.00 < z\text{-score} < 3.97 \) for a significant value of 90% confidence, \( 3.97 < z\text{-score} < 7.61 \) for 95% confidence, and \( 7.61 < z\text{-score} < 12.35 \) for significant value at 99% confidence.

**Population-weighted exposure level (PWEL)**

The population-weighted exposure level (PWEL) technique can indicate the exposure of the population to suspended particulate matter, based on the population distribution data and particulate matter (PM\(_{10}\)) concentrations in a given area (Liu et al. 2017). The PWEL calculation is performed using the following equation (Ivy et al. 2008):

\[
PWEL = \sum \left( \frac{P_i \times C_i}{\sum P_i} \right),
\]

where \( P_i \) = population in area \( i \); \( C_i \) = PM\(_{10}\) concentration in area \( i \).

In this study, the concentration of PM\(_{10}\) is potentially harmful if the level exceeds the criteria limit set by the local authorities for the vulnerable population in the Klang Valley. The PWEL value obtained was compared with the standard limit stated in the New Malaysian Ambient Air Quality Standard (NMMAQS) and World Health Organization (WHO) guidelines of 40 \( \mu \text{g/m}^3 \) and 20 \( \mu \text{g/m}^3 \), respectively. However, this study only focused on the four districts in Selangor: Klang, Hulu Langat, and Petaling and Gombak. Data from Kajang and Sepang were not included in this study due to the limited availability of data.

**The AirQ+ model**

The AirQ+ model was developed by the WHO Regional Office for Europe to calculate the health risks to individuals due to air pollution. The main purpose of the AirQ+ model is to provide useful information concerning the impacts of air pollutants in order to minimize the health effects based on human exposure, and further applying practical and effective solutions by stakeholders for the community (Khaniabadi et al. 2018). The calculation process in the AirQ+ model involves several important items, namely the risk duration period (long- and short-term), the type of pollutants for analysis [PM\(_{10}\), PM\(_{2.5}\), NO\(_2\), O\(_3\) and black carbon (BC)] and the type of individual health risk (mortality and morbidity, particularly serious acute respiratory problems such as bronchitis cases among adults and children).

The purpose of the application of the AirQ+ model version 2.0 in this study was to estimate the risk of respiratory-related diseases such as chronic bronchitis among the adult age group due to the long-term impact of PM\(_{10}\) concentrations according to district in the Klang Valley. The data used in the analysis process of the AirQ+ model were the annual average concentration of PM\(_{10}\) by district (Klang, Petaling, Hulu Langat, and Kuala Lumpur), the total cumulative population, and the population density by each district. The process of analysing the estimated risk of chronic bronchitis among adults using the AirQ+ model began with the first step, which was entering the data in “Analysis Properties” which consisted of annual averages of PM\(_{10}\) concentration in each district by year, total population and population density by district. The second step was the “Impact Assessment”, which was to calculate the estimated risk of chronic bronchitis among adults for each district and each year of the study.

The equation of the AirQ+ model used in the analysis is shown in Eq. 5 below:

\[
AP = \frac{(RR - 1) \cdot P}{(RR \cdot P)},
\]

where \( AP \) = an attributable proportion of chronic bronchitis in adults; \( RR \) = the relative risk for a particular health outcome determined by exposure to PM\(_{10}\)'s; and \( P \) = the fraction of the population exposed to PM\(_{10}\) in each district.

The outcome from the AirQ+ model analysis was the estimated proportion of the adult population at risk of chronic bronchitis for each district, shown in spatial form, for every year from 2000 to 2009 in the Klang Valley.

**Results and discussion**

**Spatial variations of PM\(_{10}\) concentrations**

The spatial variation of PM\(_{10}\) concentrations in the Klang Valley showed fluctuating changes from 2000 to 2009. The highest average annual PM\(_{10}\) concentration was 100 \( \mu \text{g/m}^3 \) in the Klang Valley. In 2000, the Klang and Kajang stations recorded elevated PM\(_{10}\) concentrations of between 80 and 100 \( \mu \text{g/m}^3 \) and the Petaling Jaya station also displayed a similar but smaller distribution range (Fig. 2). Shah Alam also showed high average PM\(_{10}\) concentrations of between 60 and 80 \( \mu \text{g/m}^3 \). A similar pattern of high concentrations at almost the same locations occurred in 2001 (Fig. 2). Klang and Petaling Jaya stations again recorded high PM\(_{10}\) concentrations of between 80 and 100 \( \mu \text{g/m}^3 \). Similar patterns were displayed in 2002 (Fig. 2) and 2003 (Fig. 2), with slight differences in the PM\(_{10}\) distributions. The downward trend continued at Kajang and in 2002 it recorded PM\(_{10}\) concentrations of between 40 and 60 \( \mu \text{g/m}^3 \).

The declining trend of PM\(_{10}\) concentrations continued in 2005 at Kajang and Cheras, both of which recorded average values of below 40 \( \mu \text{g/m}^3 \) (Fig. 2). A similar decline was found at Shah Alam and Petaling Jaya where PM\(_{10}\) distributions of between 40 and 60 \( \mu \text{g/m}^3 \) were
recorded. Klang still showed the highest PM$_{10}$ range of between 60 and 100 μg/m$^3$ in 2005 and 2006, followed by the Shah Alam, Petaling Jaya, Cheras and Kajang stations where values of between 20 and 40 μg/m$^3$ were recorded (Fig. 2).

In short, high average PM$_{10}$ concentrations occurred from 2000 to 2003 in the Klang Valley, which subsequently decreased from 2004 to 2009. Maximum PM$_{10}$ concentrations consistently occurred in Klang, ranging from 80 to 100 μg/m$^3$ and 60 to 80 μg/m$^3$ from 2000 to 2009. The other stations displayed lower concentrations of between 40 and 100 μg/m$^3$ from 2000 to 2003, which then declined to below 60 μg/m$^3$ from 2004 to 2009.

**Clustering of PM$_{10}$ concentrations**

The Moran's $I$ results measure the intensity of clustering based on the z-score value at a $p$-level of 0.05. These results demonstrate the existence of spatial PM$_{10}$

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**Legend**

- DOE_Monitoring Station
- Klang Valley_Boundary

**PM$_{10}$ Annual Concentration**

- 0-20
- 20-40
- 40-60
- 60-80
- 80-100

**Fig. 2** Spatial variations of annual-averaged PM$_{10}$ concentration (μg/m$^3$) at five DOE monitoring stations in the Klang Valley; Klang, Shah Alam, Petaling Jaya, Cheras and Kajang station from 2000 to 2009

| Year | Moran's $I$ | Relationship | Pattern |
|------|-------------|--------------|---------|
|      | Index value | z-score      | p-value |          |
| 2000 | 0.49        | 41.31        | 0.00    | Cluster |
| 2001 | 0.51        | 43.10        | 0.00    | Cluster |
| 2002 | 0.60        | 50.91        | 0.00    | Cluster |
| 2003 | 0.53        | 45.26        | 0.00    | Cluster |
| 2004 | 0.32        | 27.24        | 0.00    | Cluster |
| 2005 | 0.31        | 25.91        | 0.00    | Cluster |
| 2006 | 0.29        | 24.15        | 0.00    | Cluster |
| 2007 | 0.28        | 23.94        | 0.00    | Cluster |
| 2008 | 0.30        | 25.24        | 0.00    | Cluster |
| 2009 | 0.28        | 24.14        | 0.00    | Cluster |
concentration clusters across the Klang Valley over the ten years studied (Table 2).

Positive and significant autocorrelations exist between stations from 2000 to 2003, as represented by high z-scores of 41.31, 43.10, 50.01 and 45.26, for those years, respectively. This indicates that there was a significant relationship between the concentrations of PM$_{10}$ at all stations. Subsequently, in later years (2004 to 2009), the positive z-score values were lower. There still existed a strong autocorrelation of the PM$_{10}$ spatial concentration located near each other, indicating the formation of clusters (Table 2). The p-value of 0.00 also confirms that there were significant relationships and the presence of PM$_{10}$ concentration clustering in the Klang Valley.

**Hot spot areas of the PM$_{10}$ concentrations**

Klang was the highest zone of PM$_{10}$ clustering with 99% confidence. Besides Klang, Shah Alam was also a high-risk area for PM$_{10}$ from 2000 to 2009, as it recorded high concentrations of PM$_{10}$ between 2001 and 2005 with hot spots distribution of statistically confident levels of 95 to 99%. Towards the end of 2009, Shah Alam displayed a statistically high level of 99% with cold spots in 2007 and 2008 (Fig. 3).

The hot spots trend in the Petaling Jaya area was variable, where the district recorded high hot spot distributions in 2000, 2001 and 2003 at 99% confidence, but this declined to only 90% in 2005. In 2008 and 2009, Petaling Jaya recorded cold spot distributions of statistical significance at 95 to 99%, which indicated it was an area with lower health risks to the local population. Kajang was a hot spot area in the early years from 2000 to 2001 but became a statistically significant (95 to 99%) cold spot area from 2004 to 2009. This decreasing trend in the PM$_{10}$ concentrations in Kajang implies improving air quality in the district (Fig. 3).

In short, Klang is the district with the highest PM$_{10}$ concentrations that pose a significant health risk to the local community. Inhabitants are more susceptible to various chronic diseases, such as respiratory tract
diseases, particularly the elderly and children, due to the consistent exposure to high PM$_{10}$ concentrations over a long period.

**Population exposure to PM$_{10}$ concentrations**

According to records from the 2010 Malaysian Population and Housing Census, Department of Statistics Malaysia, the estimated cumulative total population in the Klang Valley between 2000 and 2009 was 54,619,961 across the Gombak, Hulu Langat, Klang, Petaling, and Sepang districts in Selangor, as well as the Kuala Lumpur. The highest population was concentrated in the Petaling district with 27.28% (14,905,076 people), followed by Kuala Lumpur with 26.03% or 14,220,633 people. Sepang had the lowest population, with 1,536,905 people, encompassing 2.81% of the total population in the Klang Valley (Fig. 4).

In terms of population density, the Kuala Lumpur recorded the highest density with 58,281.28 people/km$^2$ compared to 29,990.09 people/km$^2$ in Petaling. Other districts recorded population densities of 12,544.49 people/km$^2$ (Klang), 12,058.00 people/km$^2$ (Hulu Langat), 9,887.05 people/km$^2$ (Gombak) and 2600.52 people/km$^2$ (Sepang) from 2000 to 2009. The high population density in Kuala Lumpur is due to factors such as higher employment opportunities, better access to education (especially tertiary education), and the rapid development of the economic and service sectors (Fig. 4).

**Population-weighted exposure level (PWEL) for the Klang Valley (2000–2009)**

The risk to the population in the Klang Valley from the mean annual PM$_{10}$ exposure was small, as the PWEL values of 28 μg/m$^3$ from 2000 to 2009 were within the guidelines of the NMAAQS (2020) of 40 μg/m$^3$. However, the PWEL values exceeded the WHO Air Quality Guideline (AQG) values of 20 μg/m$^3$ (WHO 2005) (Fig. 5). The high population density area in Petaling was also at risk of respiratory health problems as a PWEL value of 15 μg/m$^3$ existed from 2000 to 2009. The densely populated area in the Kuala Lumpur had a higher health risk as it recorded a PWEL value of above 15 μg/m$^3$ from 2004 to 2009 (Fig. 5).
The Klang district, on the other hand, recorded varied PWEL values from 2000 to 2009 of between 11 and 15 μg/m³ in 2002, 2004, 2005 and 2008 compared to lower values of 6 to 10 μg/m³ in other years. This situation occurred due to the high PM₁₀ concentrations in Klang of between 80 and 100 μg/m³ in 2002. However, the PWEL in Hulu Langat of between 6 and 10 μg/m³ in 2002, 2004, 2005 and 2008 showed that the PM₁₀ exposure in Hulu Langat was minimal due to the low PM₁₀ concentrations and lower population density compared to other districts in the Klang Valley (Fig. 5).

The results of the analysis of the AirQ+ model found that the overall relative risk (RR) was greater than 1, which shows that the rate of exposure for the population of the Klang Valley to PM₁₀ concentrations was relatively high in all districts from 2000 to 2009 (Fig. 6, Table 3). This situation is evidenced by the spatial distribution of the estimated population exposed to the highest PM₁₀ concentrations recorded in Klang. This population showed an increasing trend each year from 300,000 to 600,000 people (542,952 people in 2000) with further increases to an estimated 900,000 people from 2002 to 2009, with 790,303 people and 804,240 people, recorded in Klang in those years, respectively.

During the 10 years of the study, the Klang population was very vulnerable to high PM₁₀, especially in 2009 and 2008 with 804,240 people at risk (RR: 1.85) and 803,062 people at risk (RR: 2.14), respectively. The estimated trend of the proportion of the population of Klang being exposed to high PM₁₀ concentrations was high due to the PWEL value obtained being significantly high in 2008—between 11 and 15 μg/m³. In addition, the cumulative population of Klang was high compared to other districts, increasing from 1,254,800 people in 2000 to 1,750,631 people in 2009.

Besides Klang, Kuala Lumpur was also identified as a high-risk district with a vulnerable population due to long-term exposure to PM₁₀ concentrations. Kuala
Fig. 6  Spatial estimated proportion among adult population (people) of chronic bronchitis disease at four districts in the Klang Valley: Klang district represented Klang DOE monitoring station, Petaling district (Shah Alam and Petaling Jaya stations), Kuala Lumpur district (Cheras station) and Hulu Langat district (Kajang station) from 2000 to 2009. Note Gombak and Sepang districts are not included.

Table 3  Estimated proportion among adult population (people) and relative risk (RR) of chronic bronchitis disease at four districts in the Klang Valley: Klang, Petaling, Hulu Langat and Kuala Lumpur district from 2000 to 2009.

| Year | Klang | Petaling | Hulu Langat | Kuala Lumpur |
|------|-------|----------|-------------|--------------|
|      | Relative risk (RR) | Estimated proportion (people) | Relative risk (RR) | Estimated proportion (people) | Relative risk (RR) | Estimated proportion (people) | Relative risk (RR) | Estimated proportion (people) |
| 2000 | 1.76 | 542,952 | 1.46 | 214,122 | 1.62 | 349,797 | No data |
| 2001 | 1.65 | 511,203 | 1.53 | 243,030 | 1.46 | 295,531 |
| 2002 | 2.41 | 790,303 | 1.90 | 337,623 | 1.53 | 333,760 |
| 2003 | 1.89 | 659,691 | 1.77 | 316,701 | 1.53 | 341,133 |
| 2004 | 2.02 | 734,899 | 1.87 | 348,135 | 1.49 | 337,571 | 1.91 | 668,359 |
| 2005 | 2.14 | 803,062 | 1.83 | 346,828 | 1.57 | 371,061 | 1.67 | 573,595 |
| 2006 | 1.87 | 727,109 | 1.66 | 311,778 | 1.58 | 384,950 | 1.57 | 530,614 |
| 2007 | 1.60 | 611,124 | 1.47 | 256,651 | 1.48 | 351,203 | 1.46 | 466,857 |
| 2008 | 1.84 | 767,772 | 1.52 | 280,649 | 1.48 | 355,412 | 1.54 | 531,104 |
| 2009 | 1.85 | 804,240 | 1.54 | 292,797 | 1.55 | 397,695 | 1.58 | 571,814 |

Gombak and Sepang districts are not included.
Lumpur recorded the highest population exposure rate of between 600,001 to 900,000 with 668,359 people in 2004. As a result, the population exposure rate was significantly high with a RR value of 1.91. This situation was due to the PM$_{10}$ concentrations at Cheras station of between 60 and 80 µg/m$^3$ in 2004 and the highest population density of 58,281.28 people/km$^2$, leading to a PWEL value of 20 µg/m$^3$ in 2009. However, from 2005 to 2009, there was a downward trend in the population's estimated exposure to PM$_{10}$ in Kuala Lumpur, only recording 573,595 people in 2005 and decreasing to 571,814 people in 2009 with accounted exposures rates of between 300,001 and 600,000 people although the value of PWEL remained high (Fig. 6).

For the Petaling district, the results showed an estimated population exposure to PM$_{10}$ concentrations from 2000 to 2009 of from 1 to 300,000 people in 2000 and 2001 with 214,122 and 243,030 people, respectively (Fig. 6). Then, the trend significantly increased between the rates of 300,001 and 600,000 people from 2002 to 2006, from 337,623 people to 311,778 people and decreased back to ranging from 1 to 300,000 people for the years 2007 to 2009 with 256,651 people and 292,797 people. However, the value of PWEL in Petaling was the highest every year at 16 to 20 µg/m$^3$, influenced by the high population density, reaching 29,990.09 people/km$^2$, with an average PM$_{10}$ concentration of between 60 and 100 µg/m$^3$, especially in 2000 to 2004. Also, the same situation occurred in Hulu Langat district, where the population's exposure to PM$_{10}$ was estimated between 300,001 and 600,000 people each year from 349,797 people to 397,695 people, except for 2001, which recorded a range of 1 to 300,000 people (349,797 people). This situation is in line with the PWEL value recorded which was also uneven at between 6 and 16 µg/m$^3$ according to the year, although the population of Hulu Langat was among the highest from 915,700 people in 2000 to 1,126,295 people in 2009 (Fig. 6).

The spatial distribution pattern of PM$_{10}$ in the Klang Valley region (2000–2009) revealed that most of the areas in the Klang Valley were contaminated with annual PM$_{10}$ levels exceeding the recommended DOE threshold of 50 µg/m$^3$ and the WHOAQG level. These PWEL results revealed that the population in Klang Valley, particularly in the districts of Petaling and the Kuala Lumpur, was at risk from the exposure to the mean annual PM$_{10}$ concentrations that exceeded the annual NMAAAQS and the WHOAQG levels.

According to Jamalani et al. (2016), the Klang, Petaling Jaya, Kajang and Shah Alam stations have been found to be affected by PM$_{10}$. Serious traffic congestion, especially during peak hours, inefficient public transport services, and the poor physical condition of the roads directly contribute to increased emissions of traffic (Awang et al. 2000) and significantly increase the exposure of the population to health risks in the Klang Valley. The PWEL values obtained indicated that Petaling Jaya and Shah Alam were the most at risk areas for PM$_{10}$ pollution in 2000 and 2009. The increasing number of vehicles led to higher use of hydrocarbons like petrol. This contributed to the increase in emissions from vehicles, which was classified as the major cause of air quality deterioration in Malaysia (DOE 2015). The total number of new motor vehicles registered from 2010 to 2014 included private cars, motorcycles, goods vehicles, and buses. The annual trend in new vehicles showed a continuous increase of 3.71% per year from 2010 to 2014 in Kuala Lumpur. Consequently, the total PM$_{10}$ emissions from all classes of motor vehicles in Kuala Lumpur estimated from the tail-pipe exhaust was 1,029,883 kg, with newly registered private cars at 214,427 kg, followed by emissions from motorcycles at 118,582 kg in 2014. Private cars also contributed 14,605 kg of CO and 5726 kg of NO$_x$ in 2014, compared with 9830 kg of CO and 3854 kg of NO$_x$ in 2010 (Shafie and Mahmud 2020). The concentrations of all pollutants peaked in the hours between 7:00 a.m. and 9:00 a.m. and at 5:00 p.m., when people were going to work, taking their children to school and returning home from work (Azmi et al. 2010; Rahman et al. 2015b). Meanwhile, Klang station was located near main roads and industrial and residential areas and thus experienced a high density of vehicles which significantly contributed to high concentrations of air pollutants (Azid et al. 2015). However, the decreasing trend of PM$_{10}$ concentrations, particularly after 2007, was due to reduced regional biomass burning activities, as well as meteorological variables. Meteorological variables such as humidity, temperature, wind speed and wind direction were also found to contribute to the concentrations and distribution of air pollution, these having a strong correlation with temperature and a weak correlation with precipitation and humidity (Tarmizi et al. 2014; Noor et al. 2015; Mohtar et al. 2018).

The El Niño/Southern Oscillation (ENSO) episodes during the southwest monsoon also exacerbated the PM$_{10}$ concentrations, whereas dry weather conditions affected the intensity of combustion and haze events (Mohtar et al. 2018; Sentian et al. 2018). In the El Niño dry period in the years 2002, 2004, 2006 and 2009, the numbers of detected hot spots were 3 to 4 times higher than in non-El Niño years (Latif et al. 2018). There are also specific topographic conditions of the Klang Valley that can lead to the accumulation of pollution. It is located near the coastal area facing the straits of Malacca and is mainly dominated by localized wind circulation from land and sea breezes.
Malaysia and other Southeast Asian countries have been experiencing periodic haze episodes for decades due to forest fires on Indonesia's Sumatra Island. The Department of Environment (DOE) also stated that forest fires in Sumatra and Kalimantan, Indonesia, caused haze across the border and affected the increase in API readings in all areas along the west coast of Peninsular Malaysia and west Sarawak (DOE 2016). A total of 10,173 active fire counts were detected during August 2004 and the PM$_{10}$ daily concentrations measured exceeded the 24-h Recommended Malaysian Air Quality Guidelines of 150 µg/m$^3$ in three separate periods from the 13th to the 30th August 2004 (Mahmud 2012). From 2000 to 2009, Petaling Jaya stations showed the highest values (PWEL) with readings of 15 µg/m$^3$ compared to 2004 and 2008. Apart from the high population density (29,990 people/km$^2$) affecting the rise of PM$_{10}$, strong haze events in those years, especially 2005 also influenced the rise. This area was a hot spot area in 2005 and the situation was declared an emergency by the government after air pollution there reached a dangerous level (defined as a value greater than 500 in the Air Pollution Index or API). Fine particulate matter released in the air during transboundary haze can have a severe impact on human health (Shao et al. 2016). Epidemiological evidence from acute and chronic exposure to PM in ambient air has been linked to a number of different health outcomes, ranging from modest transient changes in the respiratory tract and impaired pulmonary function, through increased risk of symptoms requiring emergency room or hospital treatment, to increased risk of death from cardiovascular and respiratory diseases or lung cancer (Hanafi et al. 2018). During a haze event, in urban atmospheres such as Kuala Lumpur pollutants are likely to comprise both those from biomass burning and vehicular emissions. According to Abas et al. (2004a), the molecular composition of organic compounds found in airborne particles revealed that the total suspended particulate (TSP) and organic carbon concentrations were higher than on a non-hazy day, where 24 to 36% of TSP was organic matter and around 2% was elemental carbon (soot). The high concentrations of PM$_{10}$, mostly affected by PM$_{2.5}$ and carbonaceous elements, were also the most dominant fraction in biomass burning aerosol (Rahman et al. 2015a; Fujii et al. 2016). PM$_{10}$ produces a high concentration of NO$_3$ anions due to bacterial nitrification and oxidation during biomass peat soil combustion, as well as heavy metals from peatland soil being converted to particulate matter, with heavy metal characteristics found in the ash suspended in the air (Abdullah et al. 2020).

As such, contaminated particulate matter has a strong correlation with exposure to health risks in the Klang Valley.

Furthermore, most of the urbanization process was represented by the agglomeration of the population in the major metropolitan areas (Mira et al. 2017) and Malaysia has witnessed rapid urban population growth in the past 90 years (Masron et al. 2012). Malaysia’s urban population has been growing faster than the rural population owing to huge economic opportunities in the urban centres along with the growth of industrial, commercial, financial, and administration activities, especially in the Kuala Lumpur conurbation areas (Hasan and Nair 2014). Urbanization has increased the impact of urban air pollution in the Klang Valley. Klang Valley is Malaysia’s main economic region with rapid industrialization, urbanization and infrastructure development, which have noticeably caused the deterioration of air quality (Rahman et al. 2015b). According to Ling et al. (2014), the size of the pollution-prone land-use coverage has the potential to raise air pollution levels. Abdullah et al. (2012) found that the PM$_{10}$ concentrations in Klang, which is an urban area, were higher than that of suburban and rural areas. This is due to the high population growth, especially in the urban centres and major cities, as a result of the rapid economic growth, which has created many job opportunities and infrastructure in the area. Shakor (2020) indicated that the central regions such as Kuala Lumpur, Putrajaya and Selangor were considerably more urbanized with the level of urbanization about 91.4 to 100%. In the year 2010 Selangor received higher urban migration rate, which was 33.3%, and the KL was recorded at 7.0% (Abdul Rashid 2017). Urban green spaces (UGS) in the Klang Valley have increased by 318.02% in proportion to built-up areas (high-density built-up (HDB) and low density built-up (LDB) areas) from 1989 to 2014. The percentages of UGS compared to both HDB and LDB in 1989, 2001, and 2014 were 12.62%, 19.43%, and 22.51%, respectively. However, the fragmentation of UGS increased by approximately 100% in two decades and mainly occurred in areas with higher HDB (Men and Thuy 2017).

**Recommendations and strategies to tackle PM$_{10}$ concentrations and human exposure**

Based on the results of the analysis, the average annual trend of PM$_{10}$ concentrations was the highest for the first five years and declined in the last 5 years across the 10 years of analysis, except in Klang, which retained higher PM$_{10}$ concentrations. In terms of exposure and risks of PM$_{10}$ concentrations to the health of the population, Kuala Lumpur, Petaling and Klang are high-risk districts and dangerous to the community’s health. Therefore, several strategies and control measures are suggested as
guidelines to reduce the impact of PM$_{10}$ on the population. In terms of PM monitoring, several aspects need to be emphasized comprehensively and improved. The combination of the PM emission inventory and the PM air quality model was necessary to develop the New Malaysia Ambient Air Quality Standard (NMAAQS), which is used as a guideline for impacts on human health. In addition, the comprehensive measurement of PM involves the chemical composition, particle size distribution and precursor gases, especially from motor vehicle emission sources as they are identified as the dominant source of PM. In terms of delivering information to the community, the DOE has developed a complete air quality database (API) on the DOE website, the Air Pollutant Index of Malaysia (APIMS) for each Continuous Air Quality Monitoring (CAQM) station in Malaysia. In addition, the DOE also developed the application MyIPU, which is a mobile application that provides information on the latest API readings at Continuous Air Quality Monitoring (CAQM) stations in Malaysia, based on standard health classifications. Both of these applications have been introduced with the aim of continuously delivering information on air quality that is easily accessible for everyone.

Motor vehicles are the major source of air pollution, particularly in urban areas. In Malaysia, Euro 4M RON97 petrol has been used since September 2015, followed by Euro 4M RON95 in October 2018, while the government has decided to leapfrog from Euro 2M diesel to Euro 5 diesel in September 2020, and all gasoline stations offer RON95, RON97, and car diesel (Euro 2M/Euro 4M/Euro 5) (Ramlan et al. 2016; Hirota and Kashima 2020). Additionally, on December 1, 2015, the government published the Euro 5 fuel quality specification and regulation, which comes into force in phases between September 2020 and September 2022 for diesel fuel and between September 2025 and September 2027 for gasoline fuel. As a result, even though the price is slightly higher than diesel Euro 2M, all diesel users should switch to diesel Euro 5 to reduce air pollution. Electric cars (EVs) are gaining attention as a better solution in high-energy consumption and pollutant emission issues to ensure sustainable development in cities and transportation systems (Sofia et al. 2020; Lang et al. 2013; Hu et al. 2021). The implementation of strict regulatory vehicle emissions policies and standards has promoted zero-emission vehicles and many countries are introducing policies to increase the production and adoption of EVs (Liao et al. 2017; Sofia et al. 2020).

In addition, Malaysia and Klang Valley must learn from the United Kingdom in emphasizing reducing pollutant emissions from motor vehicles through the formation of integrated and comprehensive plans for implementation measures. The United Kingdom has introduced a National Transport Plan by creating Clean Air Zones (CAZ) by 2020 that involve restrictions on car drivers and motorcyclists from entering the city centre to achieve pollutant emission standards set in Birmingham. In addition, several major cities in the United Kingdom have also formed Low Emission Zone (LEZ) plans in 2020, which focused on efforts to reduce pollutant emissions in terms of fuel, namely Euro 6 for diesel vehicles and Euro 4 for petrol, through restrictions on commercial vehicle users in city centres. In fact, high charges are also imposed on vehicle users when entering city centres, in addition to improving traffic management, to measure and regulate the flow of traffic in and around the city centre (Hull 2020).

The implementation of Green Infrastructure (GI) by governments and stakeholders significantly reduces air pollution problems, especially in urban areas. Greening cities is essential due to the numerous health benefits as well as ecosystem services, as due to the rough texture and wide contact area of leaves, foliage serves as a biofilter of air pollution and improves air quality in urban areas (Chen et al. 2017; Abhijith et al. 2019). Previous studies in China found that trees eliminated 1,261 metric tonnes of pollutants, of which 772 metric tonnes were PM$_{10}$. Studies in the United Kingdom also found that planting trees on a quarter of the available urban area significantly reduced PM$_{10}$ concentrations by between 2 and 10% (Chen et al. 2017).

Also, public awareness is an important key in reducing the impact of air pollution on public health in cities through the education system. The implementation of an environmentally based education system to various groups of the community aims to disclose and provide detailed and up-to-date information to protect and limit public exposure to air pollution. Environmental education needs to be introduced and implemented in detail and practically as well as covering a variety of accurate curricula and learning modules. For example, educational criteria that prioritize public awareness need to be enhanced and introduced to the public using transport services, walking and cycling in the city, which are environmentally friendly practices that can reduce air pollutant emissions.

**Conclusion**

The high level of pollution in the Klang Valley can endanger the health of the local urban community. The annual spatial distribution of PM$_{10}$ in Klang was an average of between 60 and 100 μg/m$^3$ from 2000 to 2009. The PM$_{10}$ concentrations below 60 μg/m$^3$ decreased from 2004 to 2009 over the rest of the Klang Valley. In terms of spatial pattern characteristics of annual PM$_{10}$ concentrations,
this shows that clustering was formed between all study stations in the Klang Valley, evidenced by positive z-score values each year from 2000 to 2009. Furthermore, positive and significant relationships were also recorded between all stations, especially from 2000 to 2003 with higher z-score values of 41.31, 43.10, 50.01 and 45.26, respectively. For the next years, 2004 to 2009, lower z-score values were recorded, but these still showed significant relationships of PM$_{10}$ concentrations between all stations through a p-value of 0.00 to form a cluster. The effect of clustering between all stations further indicated the existence of a serious hot spot distribution, especially in Klang station at 99% confidence compared to other stations from 2000 to 2009 and this situation proved that Klang was identified as the hottest district and severely polluted by PM$_{10}$ in Klang Valley. Apart from Klang, Petaling and Kuala Lumpur are also classified as districts that recorded the highest PWEL values of more than 15 µg/m$^3$, as the total cumulative population and PM$_{10}$ concentrations were significantly higher from 2000 to 2009. Therefore, this situation further found that Klang was a high-risk area to the population for chronic bronchitis among the adult age group due to the long-term exposure, with an estimated proportion of the population affected ranging from 600,001 and reaching up to 900,000 people from 2002 to 2009. Therefore, cooperation between the government, stakeholders and the community especially, is the crucial component to reduce and control PM$_{10}$ emissions through various strategies and purposeful implementation is required to achieve a sustainable environment and improve the quality of life among the community in Klang Valley.

Abbreviations
PM$_{10}$: Suspended particles of less than 10 µm; CO: Carbon monoxide; NO$_2$: Nitrogen dioxide; NOx: Nitrogen oxide; SO$_2$: Sulphur dioxide; O$_3$: Ozone; DOE: Department of Environment; FTKL: Federal Territory of Kuala Lumpur; GIS: Geographic Information System; IDW: Inverse distance weighted; PWEL: Population-weighted exposure level; RMAAQG: Malaysian Ambient Air Quality Guidelines; NMAAQS: New Malaysian Ambient Air Quality Standards; WHO AQG: World Health Organization Air Quality Guidelines.

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