



Chronic and acute health effects of PM_{2.5} exposure and the basis of pollution control targets

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Abstract

Ho Chi Minh City (HCMC) is changing and expanding quickly, leading to environmental consequences that seriously threaten human health. PM_{2.5} pollution is one of the main causes of premature death. In this context, studies have evaluated strategies to control and reduce air pollution; such pollution-control measures need to be economically justified. The objective of this study was to assess the socio-economic damage caused by exposure to the current pollution scenario, taking 2019 as the base year. A methodology for calculating and evaluating the economic and environmental benefits of air pollution reduction was implemented. This study aimed to simultaneously evaluate the impacts of both short-term (acute) and long-term (chronic) PM_{2.5} pollution exposure on human health, providing a comprehensive overview of economic losses attributable to such pollution. Spatial partitioning (inner-city and suburban) on health risks of PM_{2.5} and detailed construction of health impact maps by age group and sex on a spatial resolution grid (3.0 km × 3.0 km) was performed. The calculation results show that the economic loss from premature deaths due to short-term exposure (approximately 38.86 trillion VND) is higher than that from long-term exposure (approximately 14.89 trillion VND). As the government of HCMC has been developing control and mitigation solutions for the Air Quality Action Plan towards short- and medium-term goals in 2030, focusing mainly on PM_{2.5}, the results of this study will help policymakers develop a roadmap to reduce the impact of PM_{2.5} during 2025–2030.

Keywords PM_{2.5} exposure · Health impact assessment · Chronic and acute health effects · Economic losses · WRF/CMAQ

Introduction

Ho Chi Minh City (HCMC), a megapolis with great economic potential, is the economic locomotive of Vietnam (Gubry & Le 2014; Phung et al. 2020). Along with the capital Hanoi in the North, HCMC is a city of special urban type

and is the country's largest economic, political, cultural, and educational centre (Linh et al. 2019; Department of Statistics Ho Chi Minh City-a, 2019). Air quality in HCMC is affected by meteorological conditions along with emissions from local sources, of which local emissions have the most significant influence (Bui et al. 2021). Accelerating the process of industrialisation, urbanisation, and mechanisation in urban areas has increased emissions and energy consumption significantly, leading to the emission of many pollutants, and air pollution has become an increasingly serious environmental problem (Ho et al. 2019; Phung et al. 2020). The results of the 2017 emissions inventories of Ho et al. (2019) and Vu et al. (2020) show that there are approximately 4029 tons of PM_{2.5}/year of emissions. Approximately 1813.1 tons/year, accounting for 45%, come from road sources (on-road and non-road). 926.7 tons/year (23%) come from regional waste sources (domestic activities), and 1289.3 tons/year (32%) come from point waste sources (public production activities).

PM_{2.5} concentration in the wet season is usually lower than that in the dry season (Phan et al. 2020) because

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rainfall and air humidity are often much lower (Pillai et al. 2002; Glavas et al. 2008). Different weather trends as well as meteorological conditions typically create seasonal fluctuations in $PM_{2.5}$ concentrations. From August to October 2014 (wet season), the average $PM_{2.5}$ concentration (measured) was $97.79 \pm 63.07 \mu\text{g}/\text{m}^3$, whereas the average $PM_{2.5}$ concentration from March to May 2015 (dry season) was $168.20 \pm 104.85 \mu\text{g}/\text{m}^3$ (about 1.72 times higher) (Phan et al. 2020). For $PM_{2.5}$ pollution, HCMC had a large variation between hours of the day but very little seasonal variation; it regularly had high levels of $PM_{2.5}$, lasting for several hours with concentrations above $75 \mu\text{g}/\text{m}^3$, but there were no long-term pollution episodes (Thu et al. 2018). Based on the research results of Thu et al. (2018) and Hien et al. (2019), $PM_{2.5}$ pollutants in HCMC are a combination of urban pollutants (from industrial, transport, energy, and residential sources) and pollutants from elsewhere carried through the circulation of air masses along the southern coast of the HCMC.

$PM_{2.5}$ pollution is formed through complex chemical and physical processes (B. Zhao et al. 2019), which is considered an important parameter for assessing the level of air pollution (Huy et al. 2018; Toledo et al. 2018; Chen et al. 2020; Ha Chi & Kim Oanh 2021). $PM_{2.5}$ concentrations are significantly influenced by anthropogenic emission sources, such as emissions from vehicles, biomass burning, and fossil fuel combustion, typically with sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), black carbon (BC), organic carbon (OC), and non-methane volatile organic compounds (NMVOCs) (Fiore et al. 2015; von Schneidmesser et al. 2015; Chen et al. 2020).

Low- and middle-income countries (LMICs) often suffer from the effects of air pollution on public health, with millions of deaths each year owing to fine particulate matter ($PM_{2.5}$) (Kuylenstierna et al. 2020). Therefore, protecting public health is an important goal of air pollution control (B. Zhao et al. 2019), and the effectiveness of these control strategies has been demonstrated at the regional scale and global (Kuylenstierna et al. 2020). Quantitative research on costs-economic benefits when implementing measures to control and reduce air pollution has attracted attention from many different countries, typically in Korea, with research by Chae and Park (2011) and Kim et al. (2019); the USA has a study by Pan et al. (2019) and Sacks et al. (2018); South Africa has the study of Altieri and Keen (2019); Spain has the study of Boldo et al. (2014), especially China with a block; and a large number of studies have been published, typically the study of Voorhees et al. (2014), Ding et al. (2016), Chen et al. (2017a, b, c), Li et al. (2019), Song et al. (2019), and Xing et al. (2019). Particularly in some Southeast Asian countries,

including Thailand, Ha Chi and Kim Oanh (2021) have also built basic technologies and frameworks for quantification about damage/benefit caused by $PM_{2.5}$ fine dust problems. Furthermore, to quantify the damage/benefit caused by $PM_{2.5}$ fine dust exposure, the analysis and evaluation of the spatial distribution of $PM_{2.5}$ concentrations is extremely important.

Several tools have been developed to rapidly estimate economic losses and public health risks due to changes in air quality, based on concentration–response functions (CRFs) (Bayat et al. 2019). The Benefits Mapping and Analysis Program (BenMAP) software has proven to be one of the most comprehensive tools (Anenberg et al. 2016), and the AirQ+ tool developed by the WHO has also been used (WHO 2018). Various methods have been studied and applied to determine the functions of CRFs in the relationship between surface changes in air quality and human health impacts, including linear, logarithmic, and hybrid methods (R. Burnett et al. 2018). Along with the above tools, a group of scientists from universities and research institutes in China and the USA have built a separate platform called ABaCAS (Air Benefit and Cost and Attainment Assessment System) to analyse, quantify, and evaluate the benefits achieved by reducing air pollution, especially $PM_{2.5}$ and ground-level O_3 , to achieve the goals of socio-economic development and a sustainable environment (Voorhees et al. 2014; Ding et al. 2016; Chen et al. 2017a, b, c; Li et al. 2019; Song et al. 2019; Xing et al. 2019). These studies have focused on analysing and clarifying how the current state of air quality (mainly $PM_{2.5}$) will benefit when applying a series of mitigation solutions and measures. Investment costs and cost optimisation when implementing measures to control and minimise air pollution were also evaluated. Finally, the benefits of air pollution control on public health and the local economy are quantified.

To improve the current state of residents' health in the HCMC facing environmental challenges, it is necessary to have solutions to overcome, minimise impacts of, and calculate economic benefits/costs due to short-term exposure to $PM_{2.5}$ pollution. Assessment of acute and long-term (chronic) impacts is an important step towards developing a sustainable solution. This study has the overall objective of shaping computational technology; assessing the environmental, economic, and social benefits based on integrated technology; and applying mathematical models, databases, and geographic information systems (GIS). The objective of this study was to quantify the damage caused by $PM_{2.5}$ pollution, taking 2019 as the base year. The results of this study will help clarify the limitations of enforcement policies and provide timely support for managers to adjust strategies and policies to effectively reduce air pollution.

Materials and methods

Description of study area

HCMC has 268,000 businesses, accounting for 31% of the country. A number of projects with foreign investment capital (FDI) in Ho Chi Minh City alone in 2019 had 1320 newly licenced projects (HCMC People's Committee 2019) reflecting the growth of this mega-urban economy. Strong economic development has brought many important achievements; typically, gross regional domestic product (GRDP) reached more than 1.34 million billion VND (up to 8.32% compared to 2018), and attracted foreign investment reached 8.3 billion USD (up 39.00% compared to 2018) (HCMC Statistical Office 2020). Provincial competitiveness index (PCI) of Ho Chi Minh City for 5 consecutive years (2015–2019) has been at a good level, of which the composite PCI score (PCI score) in 2019 reached 67.16 (1028 times higher than 2018) and had a similar trend with 10 component PCI indices (PCI subindices) (Loc et al. 2019; Vietnam 2021; Table S1).

Economic development also gives rise to environmental pollution problems, especially ambient air pollution and PM_{2.5} problem (HCMC DNRE 2018). For sustainable development for the period of 2020–2025 and orientation to 2030, the city government HCMC has continued to implement solutions to depollute the environment to achieve the goals of sustainable development. Specifically, the “Program to reduce environmental pollution in the period 2020–2030” focuses on the goals of promoting high-tech investment, encouraging the use of advanced technology and equipment in production and business, and minimising quality waste and control and thoroughly treat pollution, combine waste treatment to create energy, protect and improve the quality of the ecological environment, and focus on construction solutions to serve the work of pollution reduction environment (MPC 2020).

To facilitate further analysis and evaluation, in this study, HCMC was divided into five suburban areas (subdivisions) as follows: (1) the central urban area (SG1) includes districts 1, 3, 4, 5, 6, and 6. 8, District 10, District 11, Phu Nhuan District, Binh Thanh District, Tan Phu District, Tan Binh District, and Go Vap District; (2) the Eastern Urban Area (SG2) includes District 9, District 2, and Thu Duc; (3) Western urban areas (SG3) include Binh Tan District and Binh Chanh District; (4) Southern urban area (SG4) includes District 7, Nha Be District, and Can Gio District; and (5) Northern Urban Area (SG5) includes District 12, Hoc Mon District, and Cu Chi District. The study area and the characteristics of its PCI index in Fig. 1.

Analysis of PM_{2.5} concentration distribution

Meteorological factors can significantly affect the spatial and temporal distribution of PM_{2.5}. Therefore, meteorological conditions were considered during the simulation process of PM_{2.5} concentration in HCMC by the coupled WRF/CMAQ models, which has been demonstrated in various studies worldwide, typically in the USA (DeGaetano & Doherty 2004; Tai et al. 2010), China (Tu et al. 2007; Chen et al. 2017c; Ding et al. 2019; Hu et al. 2021), and Vietnam (Tran et al. 2020; Bui & Nguyen 2023). Meteorological factors can help reduce PM_{2.5} pollution levels and consequently lower human health risks. However, seasonal fluctuations in meteorological conditions have caused unexpected effects on air pollution. In HCMC, under a combination of meteorological factors and emission sources (mainly transportation and industrial processes), PM_{2.5} air pollution levels vary greatly during the day and have small seasonal fluctuations. The peak levels of PM_{2.5} often last for several hours with a few long-term episodes of pollution (Thu et al. 2018).

The offline WRF model ver.3.8 (Skamarock et al. 2008) is used to simulate meteorological conditions. The NCEP (the National Center for Environmental Prediction) Final (FNL) Operational Global Analysis data every 6 h that has a spatial resolution of 1.0° × 1.0° from the US National Center for Atmospheric Research (NCAR) (<https://rda.ucar.edu/datasets/ds083.2/>) was used as the initial and boundary conditions and the heuristic analysis for the WRF model. The NCEP FNL data is generated from the Global Data Assimilation System (GDAS) (NCEP 2000) based on continuously collected data sources. These are meteorological parameters such as surface pressure, sea level pressure, geologic temperature, sea surface temperature, soil temperature, ice cover, relative humidity, wind vector U, and wind vector V. FNL data have been used in many studies to simulate meteorological conditions and air quality in various regions of the world (Wang et al. 2021a, b). The global topographical surface data package used as input for the WRF model was acquired from the United States Geological Survey (USGS) provided by the University Corporation for Atmospheric Research (UCAR) (NCAR 2020). This dataset consists of seven main groups of data, namely, terrain elevation, topographic features, land use, soil type, soil temperature, vegetation cover ratio, and the Albedo index, with a detailed data resolution of approximately 2 min (~3.7 km).

These study simulations started on 15 December 2018 and continued for all 12 months of 2019 (from 00:00 local standard time (LST) of 1 January 2019 to 23:00 LST on 31 December 2019). The first 5 days of the simulation were used to establish the depth of soil temperature and humidity because soil effects are often used to optimise surface moisture and temperature parameters (Pleim & Xiu 2003; Pleim & Gilliam 2009; Qin et al. 2019). The CMAQ model

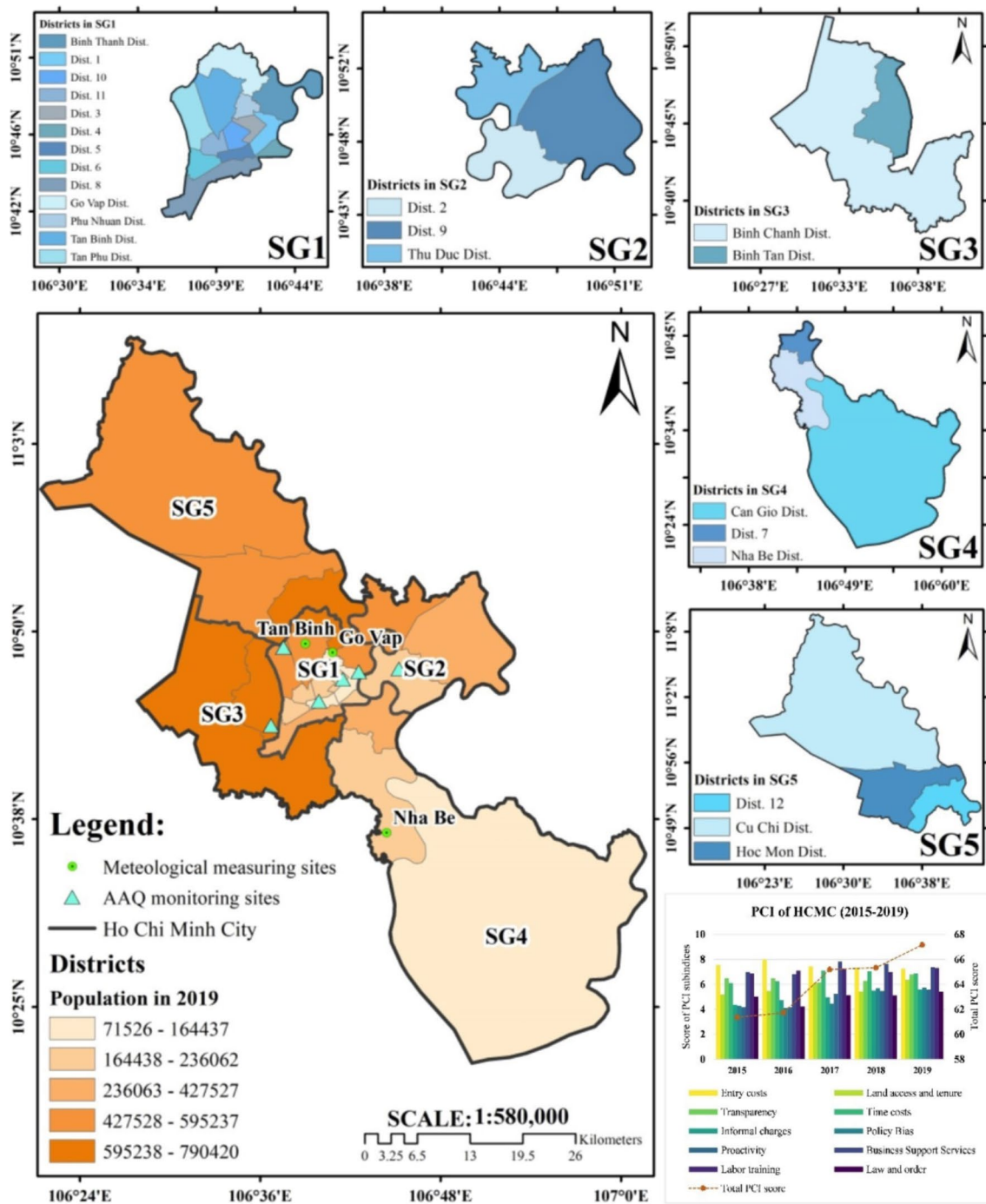


Fig. 1 Study area (HCMC): five urban sub-divisions, the population in 2019, and PCI changes during 2015–2019

ver.5.2.1 (<http://cmasceneter.org/cmaq/>) was updated and published in June 2017 by the US Environmental Protection Agency (U.S. EPA) (Borge et al. 2014; Hu et al. 2015; Lang et al. 2017) and was applied to simulate the concentration distribution of PM_{2.5} concentration in this study area between 1 January 2019 and 31 December 2019.

The meteorological factor characteristic data, which comprise the WRF model output and the CMAQ model

input data, were processed by the Meteorology-Chemistry Interface Processor (MCIP) tool (version 4.5.3) to generate input formats that satisfy the CMAQ model requirements. To ensure the accuracy of boundary conditions of meteorological fields, the horizontal domains of the conventional WRF model are slightly larger than that of the CMAQ model (Li et al. 2022). The CMAQ model in this study is configured with the same nested domains as the WRF model, but

three grid cells in each direction of the computed domains are removed from the domains D01, D02, and D03 of the WRF model. For the CMAQ model, there are a total of 29 classes in the sigma coordinate system; specifically, the sigma values (σ) for the CMAQ calculation domains at the class boundaries are 1000, 0.997, 0.990, 0.983, 0.976, 0.970, 0.962, 0.954, 0.944, 0.932, 0.917, 0.898, 0.874, 0.844, 0.806, 0.760, 0.707, 0.647, 0.582, 0.513, 0.444, 0.375, 0.308, 0.243, 0.183, 0.126, 0.073, 0.023, and 0.000. At the same time, the Carbon Bond 6 (CB6r3) (Yarwood et al. 2010; Emery et al. 2015; Luecken et al. 2019) for chemical substances has also been built in the CMAQ model. Man-made emissions of NO_x , CO, CH_4 , NH_3 , SO_2 , and VOCs (in the year 2018) are obtained from the global anthropogenic emission inventory including CAMS-GLOB-ANT ver.4.1 and CAMS-GLOB-AIR ver.1.1 (Granier et al. 2019) with a spatial resolution of $0.1^\circ \times 0.1^\circ$ grids and $0.5^\circ \times 0.5^\circ$ grids, respectively. For biogenic emissions obtained from the global biogenic emissions inventory such as CAMS-GLOB-BIO ver.2.1 (Granier et al. 2019) of NO_x and VOCs (in 2018), they are grids with a spatial resolution of $0.25^\circ \times 0.25^\circ$. All these emissions are interpolated linearly (Jiang et al. 2010; Liu et al. 2013; Wang et al. 2016) into the internal domain of resolution space of $3.0 \text{ km} \times 3.0 \text{ km}$ and used to simulate $\text{PM}_{2.5}$ concentration on the domain D03 (HCMC). The detailed technical description of the nested domains in the coupled WRF/CMAQ models used in this study is shown in Table S2.

Health impact assessment

Health impact functions (HIFs) have been widely used in many previous studies to assess the burden of disease associated with short- and long-term $\text{PM}_{2.5}$ exposure such as Lelieveld et al. (2013), Song et al. (2017), Zhao et al. (2019), Dedoussi et al. (2020), and Wang et al. (2021ab). Thus, we estimated the health effects for HCMC's residents due to acute $\text{PM}_{2.5}$ exposure using the log-normal model (Sacks et al. 2018, 2020) and chronic exposure by applying the integrated expose-response function (IER) (Burnett et al. 2014).

In this study, a Monte Carlo numerical simulation procedure was applied to estimate the 95% confidence intervals (CI) (Chen et al. 2017a; Sacks et al. 2018; Altieri & Keen 2019) for the average number of premature deaths and hospitalisations of each type of health endpoint. Each calculation was simulated in the short- and long-term health impact models. For each health endpoint type, we randomly selected values from the probability distribution of each CRF coefficient and combined them with the baseline incidence rate values to calculate the corresponding health impact level based on the selected values. All numerical simulation computations were run continuously (~ 5000 times) to determine

the 95% CI results for the distribution of health-affected cases (premature mortality and hospitalisation) due to exposure to $\text{PM}_{2.5}$.

Estimating long-term (chronic) health effects

The IER model (Burnett et al. 2014) was applied to estimate long-term health effects. This model is based on cohort studies of ambient $\text{PM}_{2.5}$ in the USA and Europe, consisting of cigarette smoke and household solid fuel burning included in the exposure calculation. $\text{PM}_{2.5}$ could be up to approximately $30,000 \mu\text{g}/\text{m}^3$ (Burnett et al. 2014; Cohen et al. 2017). This model also provides a concentration–response relationship for a range of $\text{PM}_{2.5}$ concentrations in the atmosphere (Wang et al. 2020). The IER model has been used in the Global Burden of Disease (GBD) studies by Lim et al. (2012) and Cohen et al. (2017). Furthermore, the IER model has also been used to assess premature mortality from $\text{PM}_{2.5}$ exposure in China, especially from 2013 to 2017 (Song et al. 2017; Gao et al. 2018; Maji et al. 2018; Wang et al. 2018; Liu et al. 2020; Wu et al. 2021). The IER function is expressed in Eqs. (1) and (2), the evaluation function that has been reviewed and proven to be the most suitable for calculating health risks among many different valuation functions (Burnett et al. 2014; Cohen et al. 2017).

$$HI_{long-term} = \Delta Y_i = BIR_i \times EP \times \frac{RR_i - 1}{RR_i} \quad (1)$$

$$RR_i = \begin{cases} 1, & C < C_0 \\ 1 + \alpha_i \left[1 - e^{-\gamma_i (C - C_0)^{\delta_i}} \right], & C \geq C_0 \end{cases} \quad (2)$$

where $HI_{long-term}$ or ΔY_i is the value of the public health impact related to the premature mortality of diseases caused by $\text{PM}_{2.5}$ pollution attributed to health endpoint i mentioned above; BIR_i is the baseline mortality incidence of health endpoint type i exposed at the 2019 annual average $\text{PM}_{2.5}$ concentration in the current state (C); EP is the population size exposed to $\text{PM}_{2.5}$ in the form of a grid with a resolution of $\sim 3.0 \text{ km} \times 3.0 \text{ km}$ consistent with the current $\text{PM}_{2.5}$ concentration data (C); C_0 is the level of $\text{PM}_{2.5}$ concentration below the threshold that is not expected to affect public health; C_0 is referenced between 5.8 and $8.0 \mu\text{g}/\text{m}^3$ (Hao et al. 2021); RR_i is the relative risk value for each type of calculated loss; and α_i , γ_i , and δ_i are the regression parameters studied for health endpoint type i .

In this study, the health endpoints and IER parameters, including α_i , γ_i , and δ_i as studied by Burnett et al. (2014) and Song et al. (2017), were applied and used. The parameters and selection of HIFs for the different types of health endpoints were classified according to the ICD-10 report (10th version of the International

Table 1 Fitted parameters (α , γ , and δ) and threshold (C_0) applied in long-term health impact model

Health endpoints	ICD-10 code ^(*)	α value (lower; upper)	γ value (lower; upper)	δ value (lower; upper)	C_0 ($\mu\text{g}/\text{m}^3$) value (lower; upper)
IHD ^{(a),(b)}	I20-I25	0.843 (0.864; 1.202)	0.0724 (0.0613; 0.0095)	0.5440 (0.4286; 1.1554)	6.9600 (8.9856; -0.2221)
Stroke ^{(a),(b)}	I64	1.010 (1.307; 1.410)	0.0164 (0.0213; 0.0296)	1.1400 (0.4940; 1.0817)	8.3800 (10.9023; 9.4645)
COPD ^{(a),(b)}	J44	18.300 (5.361; 75.118)	0.000932 (0.000718; 0.000442)	0.682 (0.8510; 0.6327)	7.1700 (7.3557; 5.8099)
LC ^{(a),(b)}	C34.80–82, 90–92; C39.9; C45.7, 9; C46.50–52; C7A.090	159.000 (19.433; 23.406)	0.000119 (0.0000852; 0.0017)	0.7350 (1.0156; 0.6690)	7.2400 (7.0580; 6.5535)
ALRI ^{(b),(c)}	J20-J22, J44.0	7.985 (1.660; 2.851)	0.00281 (0.01058; 0.00125)	1.2174 (0.7995; 1.4173)	7.3716 (14.3579; 4.2402)

*International Statistical Classification of Diseases and Related Health Problems 10th Revision (ver.2019) (<https://icd.who.int>)

^(a)R. T. Burnett et al. (2014)

^(b)C. Song et al. (2017)

^(c)B. Zhao et al. (2019)

Classification of Diseases). Within this classification, circumstances that may overlap with other health effects (ICD-10, 2016) are shown in Table 1. The types of damage assessed include chronic obstructive pulmonary disease (COPD), ischaemic heart disease (IHD), lung cancer (LC), and stroke in adults and elderly groups, while acute lower respiratory infection (ALRI) occurs in children. The map showing the relative risk distributions of premature deaths from IHD, stroke, COPD, and LC in a $\sim 3.0 \times 3.0$ km² grid is reported in Fig. S1.

Estimating short-term (acute) health effects

To assess the health effects of short-term PM_{2.5} exposure (premature mortality and hospitalisation), concentration–response functions (CRFs) were developed by epidemiological studies, based on time series analysis of interactions between PM_{2.5} concentrations and health (Zhao et al. 2019). Notably, in most of the studies by Dominici et al. (2002), Kan et al. (2007), Huang et al. (2012ab), Shang et al. (2013), Wang et al. (2015), and Sui et al. (2021), the baseline mortality and morbidity incidence rates caused by PM_{2.5} pollution were considered to have a Poisson distribution. Subsequently, the relationship between the number of deaths and diseases and PM_{2.5} concentration could be determined by Poisson or Log-linear regression or several similar methods (Dominici et al. 2002; Kan & Chen 2004; Kan et al. 2008; Shang et al. 2013). In this study, the model had a log-normal form, as described by Eq. (3) (Chen et al. 2017b; Sacks et al. 2018, 2020), which are used to

estimate the daily short-term effects of PM_{2.5} on human health. The coefficients of the CRFs (β) were determined using Eq. (4), based on the RR values (Andre a et al. 2020).

$$HI_{short-term} = \Delta Y_i = BIR_i \times EP \times \left[1 - e^{\beta_i(C - C'_0)} \right] \quad (3)$$

$$\beta_i = \ln(RR_i) / \Delta Q \quad (4)$$

where ΔY_i is the number of hospitalisations in this study due to short-term exposure to the type of health endpoint i ; BIR_i is the baseline incidence rate of health endpoint type i (the mortality/morbidity rate before the change in PM_{2.5} concentration); EP is the exposed population with short-term exposure to PM_{2.5}; C'_0 is the level of PM_{2.5} concentration below the threshold that is not expected to affect public health (24-h average); $C - C'_0$ or $\Delta PM_{2.5}$ is the change in PM_{2.5} concentration level in the current state compared with the recommended threshold; β_i is the regression coefficient of CRFs determined from epidemiological studies that describe the corresponding RR _{i} of health endpoint type i with 95% confidence interval (CI); and ΔQ is the change in PM_{2.5} concentration that epidemiological studies have used to estimate RR, typically $\Delta Q = 10 \mu\text{g}/\text{m}^3$ or $1 \mu\text{g}/\text{m}^3$. The details of all coefficients β_i and RR _{i} used in this study were obtained from our previous detailed study of HCMC in 2018 (Bui & Nguyen 2022).

Economic valuation estimates

In the absence of a market for human lives, the monetary quantification of deaths is based primarily on non-market

valuation approaches (OECD 2012). A standard method for estimating the monetary cost of a positive welfare effect, such as a reduction in mortality risk, is to create a hypothetical market for death risk to be considered and analysed based on the value of statistical life (VSL) (Braathen et al. 2010; Xie 2011; Maji et al. 2018). The VSL value is calculated in survey studies assessing individuals' Willingness to Pay" (∂WTP) to partially reduce the risk of death ∂R (Maji et al. 2018). Thus, for a relatively small value of ∂R , the VSL value is defined as $VSL = \partial WTP / \partial R$ (Persson et al. 2001; Huang et al. 2012a, b). When no studies assessed the economic value of life lost, the "Conversion of Benefits' approach was used. This approach converts unit health costs from international studies to local contexts' (Johnson et al. 2015; Narain & Sall 2016; Kim et al. 2019), with the main idea being to account for income differences to expand VSL (Yin et al. 2017). The economic cost of illness-related loss is estimated using WTP as well as the Cost of Illness (COI) approach (Maji et al. 2018). The COI method calculates the cost of a disease in terms of medical treatment costs, hospital stay, and reduced productivity (Hoffmann et al. 2012).

In this study, the method of determining VSL and COI values was applied, similar to that described in our previous studies (Bui et al. 2020), (Bui et al. 2021; Bui & Nguyen 2022). Therefore, the total economic valuation cost (EC) or economic health burden due to the decline in public health was evaluated according to Eq. (5) as follows:

$$\begin{aligned} \text{Economic Burden} &= HI_i \times HC_{i,2019} \\ \text{or EC} &= \sum_{i=1}^n \Delta Y_i \times Cost_i \end{aligned} \quad (5)$$

where HI_i or is the impact level of health endpoint i associated with short- and long-term $PM_{2.5}$ exposure; $HC_{i,2019}$ or is the corresponding unit economic value of health endpoint type i (units of VND or USD), and EC (or Economic Burden) is the total value of economic losses due to various types of health damage estimated cause (in VND or USD). The EC value considered in this study corresponds to the total economic value of damage due to both acute and chronic health impacts caused by exposure to $PM_{2.5}$ pollution in the ambient air in HCMC. Detailed statistics of unit economic values for each specific type of health endpoint caused by $PM_{2.5}$ pollution are shown in Table S3.

Assessing $PM_{2.5}$ exposure risks

Regional $PM_{2.5}$ exposure risk (C. Zhao et al. 2021) was used to quantify differences in exposure to $PM_{2.5}$ exposure risk across urban and suburban areas, calculated according to Eq. (6) (Zhang et al. 2022) as follows:

$$R_i = \frac{EP_i \times C_i}{\sum_{i=1}^n \frac{EP_i \times C_i}{n}} \quad (6)$$

where i is the position of the i^{th} grid in the study area, R_i is the risk value of $PM_{2.5}$ exposure in the population at grid i , EP_i is the population size exposed to $PM_{2.5}$ in grid i , C_i is the $PM_{2.5}$ concentration level (monthly 24-h average and 2019 annual mean) in the i^{th} grid cell, and n is the total number of grid cells covering the entire study area.

Threshold of $PM_{2.5}$ concentration (C'_0) and baseline incidence rate (BIR)

With the assessment of acute health impacts, the selection of the daily average $PM_{2.5}$ threshold concentration (C'_0) affects the magnitude of the results of the calculation of the number of affected cases (Chinh Nguyen 2013). A wide range of available studies (Vu et al. 2020; Vien et al. 2021; Dang et al. 2021; Bui & Nguyen 2022) have evaluated the HCMC. These studies used the Vietnamese National Ambient Air Quality (NAAQS), such as QCVN 05:2013/BTNMT, and the WHO global air quality guidelines (WHO AQG). The assessment based on these two systems of technical standards can allow detailed quantification of the extent of damage or costs incurred by society as a basis for applying mitigation solutions of $PM_{2.5}$ concentration to the allowable threshold (Chinh Nguyen 2013). Therefore, the reference C'_0 value in this study could be used to include $C'_0 = 50 \mu\text{g}/\text{m}^3$ according to the NAAQS or $C'_0 = 15 \mu\text{g}/\text{m}^3$ according to the WHO AQG (WHO 2021).

National baseline values for premature mortality-specific deaths were obtained from the GBD study 2019 (<https://ghdx.healthdata.org/gbd-2019>) of the Institute for Health Metrics and Evaluation (IHME) (Health Effects Institute, 2020). Values of baseline mortality incidence due to stroke, IHD, COPD, LC, and ALRI for long-term impacts were determined for all regions of Vietnam from the GBD study 2019, being 141.12 (95% CI: 114.81; 166.30), 77.45 (95% CI: 63.76; 92.27), 29.52 (95% CI: 11.07; 36.96), 26.11 (95% CI: 20.23; 32.90), and 22.15 (95% CI: 18.43; 26.68) cases per 10^5 population, respectively. Meanwhile, the baseline mortality incidence due to all-cause respiratory and cardiovascular diseases for the short-term effects were 79.16 (95% CI: 49.65; 95.68) and 249.20 (95% CI: 209.90; 289.45) cases per 10^5 population, respectively. The baseline morbidity incidence of all-cause respiratory diseases is approximately 13.79%, and all-cause cardiovascular disease is approximately 8.44%, as captured in the Health Statistical Yearbook (<https://moh.gov.vn/thong-ke-y-te>) of

the Ministry of Health of Vietnam for the provinces of the southeast region in 2019. Moreover, the details of baseline rate values (BIR_i) for the types of health endpoints for both mortality and morbidity for each district of HCMC, including stroke, IHD, COPD, and LC, are applied to the short- and long-term impact assessments associated with statistical exposure to $PM_{2.5}$, as shown in Table S4.

$PM_{2.5}$ -exposed population size (EP)

The population data in this study were collected from the City's Statistical Yearbook of HCMC in 2019 (HCMC Statistical Office 2020) and the General Statistics Office of Vietnam based on the Report of Results of the 2019 Population and Housing Census (GSO 2020). The national population and housing data of the (GSO 2020) were surveyed as of 1 April 2019 with the resolution of the census data for each province carried out to county levels, divided by sex group, age group, and urban and rural areas of each county.

From the data source as shown in Fig. 1 and Table 2, it can be seen that the total population of HCMC in 2019 is 9038 million people with the total number of men being 4403 million people (accounting for 48.7%) and the total number of women being 4635 million people (contributed 51.3%). In terms of age group distribution, the children (≤ 14 years old) had 1708 million people (18.9%), while the adult (15–64 years old) and elderly (≥ 65 years old) groups had 6824 (75.5%) and 0.506 million people (5.6%). The lowest population is in Can Gio district (71,526 people), with a density of 0.102 thousand people/km², and the highest population is in Binh Tan district (790,420 people), with a density of 15,195 thousand people/km².

According to the sub-divisions (Fig. 1), SG1 has the highest exposed population of 4088 million people (45.23%), followed by SG5, SG3, and SG2 with 1630 million people (18.03%), 1506 million people (16.66%), and 1174 million people (12.99%), respectively, and the lowest is in SG4 with only 0.641 million people (7.09%). Detailed statistics on population (total and sex distribution) and population density distribution by district, as well as by the sub-divisions, are shown in Table 2. The gridded spatial distribution data of the total exposed population, the age-specific population, and gender-specific population of HCMC in 2019 with a resolution of ~ 3.0 km \times 3.0 km was similarly constructed from a previous study (Bui & Nguyen 2022) which was shown in Fig. 2. The gridded spatial distribution of EP corresponds to the average annual and monthly 24-h average $PM_{2.5}$ concentration values obtained from the coupled WRF/CMAQ simulation results. These results were incorporated into HIFs to

assess the health effects of long-term and short-term $PM_{2.5}$ exposure in the study area.

Conceptual model

The conceptual model and implementation steps are illustrated in Fig. 3. The steps include (1) setting up related databases (database) and (2) selecting the health-economic impact calculation models (computing models) and using the data from steps (1) and (3) performing analysis and evaluation based on the estimated results achieved outcomes. To perform step (1), there are three main groups of data that need to be prepared: data on changes in $PM_{2.5}$, health datasets, and population size datasets. Statistical exposure, database on health (health damage function, mortality rate, and underlying disease) as well as population size exposure (by age group and sex group) were collected from national statistical sources, from the Global Burden of Disease database 2019 as well as from previously available scientific studies. The dataset on the change in $PM_{2.5}$ concentration according to the daily and annual average was obtained from the simulation results using the combined WRF/CMAQ models (this result has been evaluated and tested in a single and detailed way). In step (2), the values (BIR_i , EP_i , C_i , C_0) and the set of coefficients (RR_i , α_i , γ_i , δ_i , C_0') were identified specifically from the company databases. These values are used for (i) acute health impact models (log-normal type model) and (ii) chronic health impact assessment models (IER) to estimate short- and long-term health effects in a population. The respective economic values of each type of loss were combined to calculate the corresponding economic valuation (economic valuation). Finally, in step (3), the results are analysed, evaluated, and visualised using maps of the distribution of health effects from short- and long-term $PM_{2.5}$, as well as zoning maps of health risk effects from $PM_{2.5}$, between inner-city and suburban areas of the HCMC.

Results and discussion

Evaluation of $PM_{2.5}$ concentrations

The spatial distribution of monthly $PM_{2.5}$ concentrations (early month: from 1 to 10; mid-month: from 11 to 20; and late-month: from 21 to 28/30/31 depending on the specific month) and variation in 24-h mean $PM_{2.5}$ pollution distribution ($\Delta PM_{2.5} = C - C_0$) compared to NAAQS (50 $\mu\text{g}/\text{m}^3$) and WHO-AQG (15 $\mu\text{g}/\text{m}^3$) are shown in Fig. 4 and Fig. S2. Within HCMC, December 2019 had the lowest concentration of 0.077 $\mu\text{g}/\text{m}^3$, and September 2019 had the highest concentration of 218.24 $\mu\text{g}/\text{m}^3$, more than 4.36 times higher than that of NAAQS

Table 2 Summary of population exposure and density by each district and sub-division in HCMC in 2019

District	Sub-division	Total population (unit: persons)	Area (unit: km ²)	Population density (unit: thousand person/km ²)	Total male (unit: persons)	Total female (unit: persons)
District 1	SG1	142,016	7.72	18.396	65,646	76,370
District 2	SG2	182,605	49.79	3.668	88,334	94,271
District 3	SG1	191,521	4.92	38.927	88,056	103,465
District 4	SG1	176,131	4.18	42.137	82,467	93,664
District 5	SG1	164,437	4.27	38.510	75,405	89,032
District 6	SG1	235,194	7.14	32.940	111,234	123,960
District 7	SG4	360,317	35.70	10.093	172,015	188,302
District 8	SG1	427,527	19.11	22.372	204,395	223,132
District 9	SG2	396,528	113.97	3.479	198,032	198,496
District 10	SG1	236,062	5.72	41.270	109,772	126,290
District 11	SG1	210,901	5.14	41.031	99,373	111,528
District 12	SG5	624,957	52.74	11.850	312,614	312,343
Go Vap District	SG1	682,358	19.73	34.585	332,144	350,214
Tan Binh District	SG1	476,040	22.43	21.223	230,619	245,421
Tan Phu District	SG1	485,141	15.97	30.378	238,370	246,771
Binh Thanh District	SG1	496,684	20.79	23.891	233,523	263,161
Phu Nhuan District	SG1	164,168	4.86	33.779	76,023	88,145
Thu Duc District	SG2	595,237	47.80	12.453	294,417	300,820
Binh Tan District	SG3	790,420	52.02	15.195	393,679	396,741
Cu Chi District	SG5	467,824	434.77	1.076	229,399	238,425
Hoc Mon District	SG5	536,944	109.17	4.918	267,350	269,594
Binh Chanh District	SG3	715,262	252.56	2.832	360,216	355,046
Nha Be District	SG4	208,766	100.44	2.079	104,060	104,706
Can Gio District	SG4	71,526	704.45	0.102	36,288	35,238
Total	-	9,038,566	2,095.39	4.314	4,403,401	4,635,165

(50 $\mu\text{g}/\text{m}^3$) and 14.55 times higher than that of WHO-AQG (15 $\mu\text{g}/\text{m}^3$). In each region as follows, in SG1 area, December 2019 had the lowest concentration of 0.88 $\mu\text{g}/\text{m}^3$ and with the highest concentration of 190.57 $\mu\text{g}/\text{m}^3$ in October 2019, being 3.81 times higher than NAAQS (50 $\mu\text{g}/\text{m}^3$) and 12.7 times that of WHO-AQG (15 $\mu\text{g}/\text{m}^3$). In SG2 area, December had the lowest concentration with 0.47 $\mu\text{g}/\text{m}^3$ and with the highest concentration of 174.43 $\mu\text{g}/\text{m}^3$ in December 2019, being 3.49 times higher than NAAQS (50 $\mu\text{g}/\text{m}^3$) and 11.63 times higher than WHO-AQG (15 $\mu\text{g}/\text{m}^3$). In SG4 area, May 2019 had the lowest concentration with 0.78 $\mu\text{g}/\text{m}^3$ and with the highest concentration of 216.7 $\mu\text{g}/\text{m}^3$ in September, being 4.33 times higher than NAAQS (50 $\mu\text{g}/\text{m}^3$) and 14.45 times higher than WHO-AQG (15 $\mu\text{g}/\text{m}^3$). In SG5 area, December 2019 had the lowest concentration with 0.08 $\mu\text{g}/\text{m}^3$ and with the highest concentration of 192.6 $\mu\text{g}/\text{m}^3$ in October 2019, being 3.85 times higher than NAAQS (50 $\mu\text{g}/\text{m}^3$) and 12.84 times higher than WHO-AQG (15 $\mu\text{g}/\text{m}^3$).

The spatial distribution of average $\text{PM}_{2.5}$ concentration in 2019 across the entire HCMC ranges from 0.0077 to

218.24 $\mu\text{g}/\text{m}^3$ (as shown in Fig. 5). Specifically in each area as follows, $\text{PM}_{2.5}$ concentration in SG1 area ranged from 0.88 to 190.57 $\mu\text{g}/\text{m}^3$ with the maximum concentration occurring at $X=677,122.895$ and $Y=1,185,252.996$. SG2 area ranges from 0.47 to 174.43 $\mu\text{g}/\text{m}^3$ with the maximum concentration occurring at $X=689,169.4797$ and $Y=1,203,449.403$. SG3 area ranges from 0.17 to 218.24 $\mu\text{g}/\text{m}^3$ with the maximum concentration occurring at $X=661,907.2451$ and $Y=1,188,175.847$. SG4 area ranges from 0.78 to 217.46 $\mu\text{g}/\text{m}^3$ with the maximum concentration occurring at $X=701,667.0029$ and $Y=1,146,152.322$. SG5 area ranges from 0.08 to 202.21 $\mu\text{g}/\text{m}^3$ with the maximum concentration occurring at $X=652,608.1011$ and $Y=1,215,297.183$. Compared with the allowable annual average threshold of $\text{PM}_{2.5}$ according to NAAQS (QCVN 05:2013/BTNMT, annual average 25 $\mu\text{g}/\text{m}^3$), all five sub-divisions above exceeded the threshold from 1.001 to 7.62 times in the SG1 area, from 1.12 to 6.98 times in the SG2 area, from 1.09 to 8.73 times in the SG3 area, from 1.09 to 8.7 times in the SG4 area, and from 1.3 to 8.09 times in the SG5 area. The simulation results showed that the pollution level

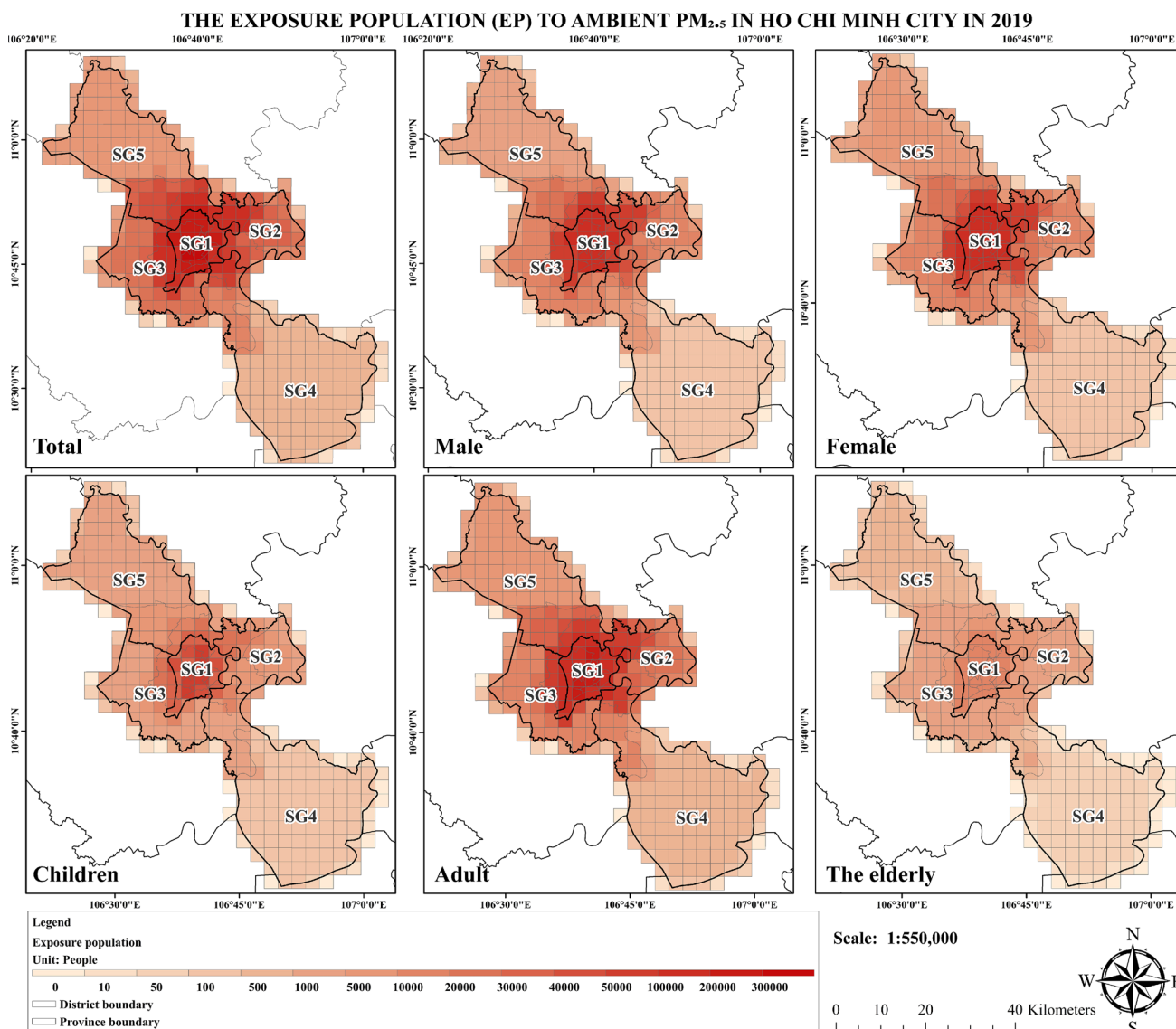


Fig. 2 The gridded spatial distribution of population by age and gender groups in HCMC in 2019

was highest in SG4, followed by SG3, SG1, and SG2. In particular, SG1 has the lowest pollution level among the five areas in HCMC. In each area, the PM_{2.5} concentration tends to climb gradually from east to west and from northwest to southeast. Figure 5 shows the distribution of mean PM_{2.5} concentrations in 2019 as a grid with a resolution of ~3.0 km × 3.0 km.

Premature mortality attributable to long-term (chronic) exposure to PM_{2.5} pollution

For the case of premature deaths due to 4 diseases (IHD, stroke, COPD, and LC), the average was in 2019 across the whole HCMC totalled 3,108.714 (95% CI: 1,024.707; 5,322.132) cases (as shown in

Fig. 6). Premature mortality for men was 1,513.944 (95% CI: 499.032–2,591.879) and 1,594.770 (95% CI: 525.674–2,730.254). Meanwhile, considering the age group, the groups of children, adults, and the elderly had an early death of 587.547 (95% CI: 193.670; 1,005.883) cases, 2,347.079 (95% CI: 773.653; 4,018.210) cases, and 174.088 (95% CI: 57.384; 298.039) cases, respectively. Stroke had the highest number of deaths, followed by IHD, COPD, and LC, with the fewest deaths. Summarize the results described above for cases of premature death from IHD (HI_{IHD, mort}), stroke (HI_{stroke, mort}), COPD (HI_{COPD, mort}), and LC (HI_{LC, mort}) due to long-term exposure to average PM_{2.5} concentrations in 2019 across the study area is shown in Fig. 6.

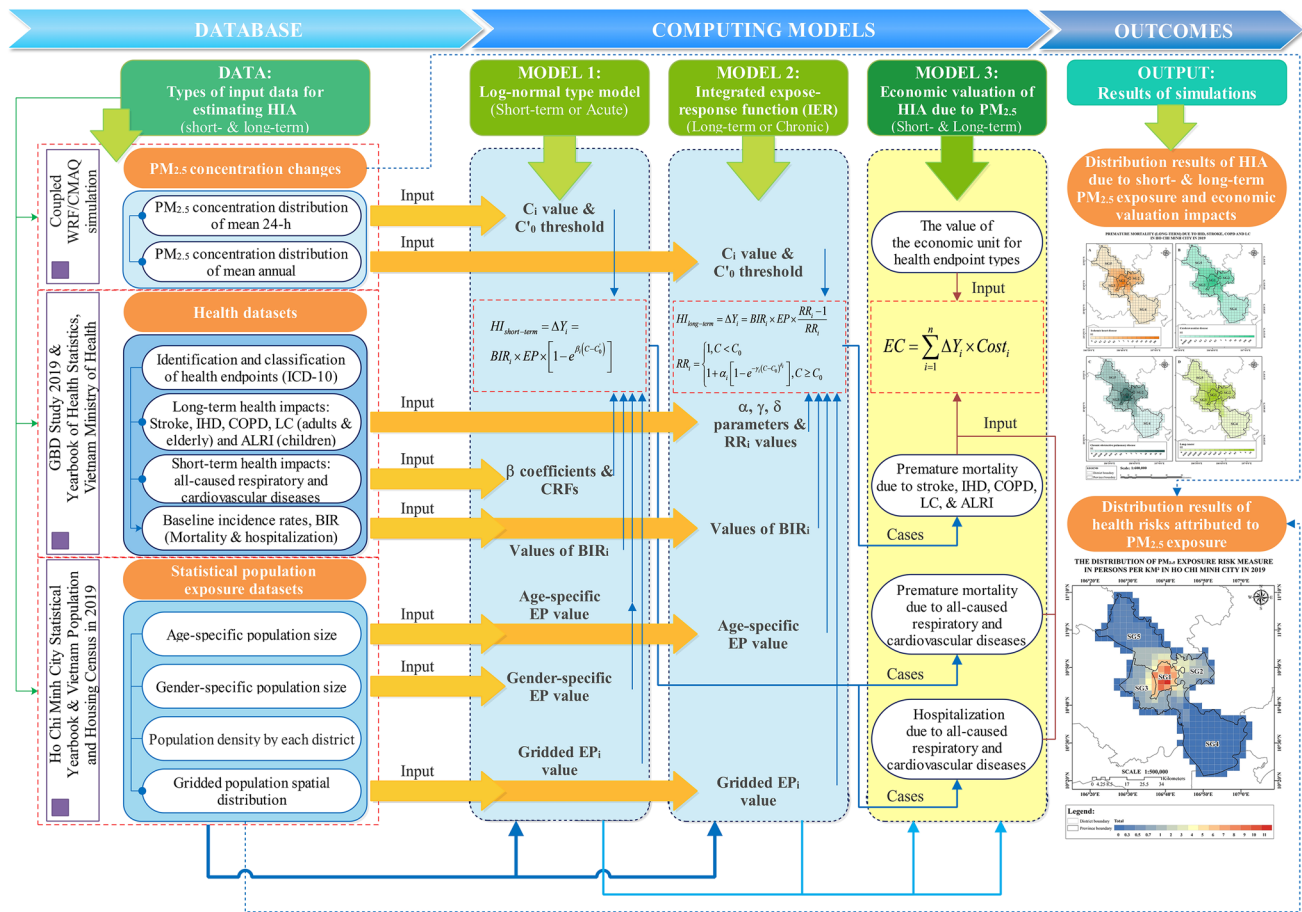


Fig. 3 Conceptual model and sequence of steps

The study results showed that the number of premature IHD deaths ($HI_{IHD, mort}$) across the whole HCMC totalled 752.898 (95% CI: 427.8; 1,320.26) cases (as shown in Fig. S3). In terms of sex, the premature mortality was 366.662 (95% CI: 208.338; 634.330) for men and 386.237 (95% CI: 219.461; 668.196) for women. According to age group, children, adults, and the elderly had early deaths of 142.298 (95% CI: 80.854; 246.177), 568.438 (95% CI: 322.989; 983.407), and 42.162 (95% CI: 23.957; 72.941), respectively. Specifically, in each region, the average early deaths in SG1, SG2, SG3, SG4, and SG5 were 579.955, 43.577, 60.654, 36,756, and 31,956, respectively.

For early stroke deaths ($HI_{stroke, mort}$), throughout HCMC totalled 2,083.026 (95% CI: 549.779–3,288.486) cases (as shown in Fig. S4). By sex, the premature mortality was 1,014.434 (95% CI: 267.742; 1,601.493) cases and 1,068.592 (95% CI: 282.036; 1,686.993) cases for women. Considering age, the groups of

children, adults, and the elderly had health risks of 393.692 (95% CI: 103.908; 621.524) cases, 1,572.685 (95% CI: 415.083; 2,482.807) cases, and 116.649 (95% CI: 30.788; 184.155) cases, respectively. In each region as follows, the average early death rate in SG1 was 1,604.618 cases, in SG2 area is 120.189 cases, in SG3 area is 168.226 cases, in SG4 area is 101.776 cases, and in the SG5 area is 88.216 cases.

In the case of premature deaths from COPD ($HI_{COPD, mort}$), across HCMC, there were 188.226 (95% CI: 32.385; 344.247) cases (as shown in Fig. S5). By sex, the number of early deaths for men was 91.666 (95% CI: 15.820; 167.648) cases, and for women, it was 96.560 (95% CI: 16.665; 176.599) cases. Considering age, the groups of children, adults, and the elderly had health risks of 35.575 (95% CI: 6.140; 65.063) cases, 142.111 (95% CI: 24.526; 259.907) cases, and 10.541 (95% CI: 1.819; 19.278) cases, respectively. In each region as follows, the average early mortality rate in SG1 is 144.998 cases, in SG2 area is 10.822 cases, in

**CHANGES IN THE DAILY MEAN PM_{2.5} CONCENTRATION
(DIFFERENCE BETWEEN BASELINE AND PM_{2.5} POLLUTION CONTROL THRESHOLD OF QCVN) IN 2019**

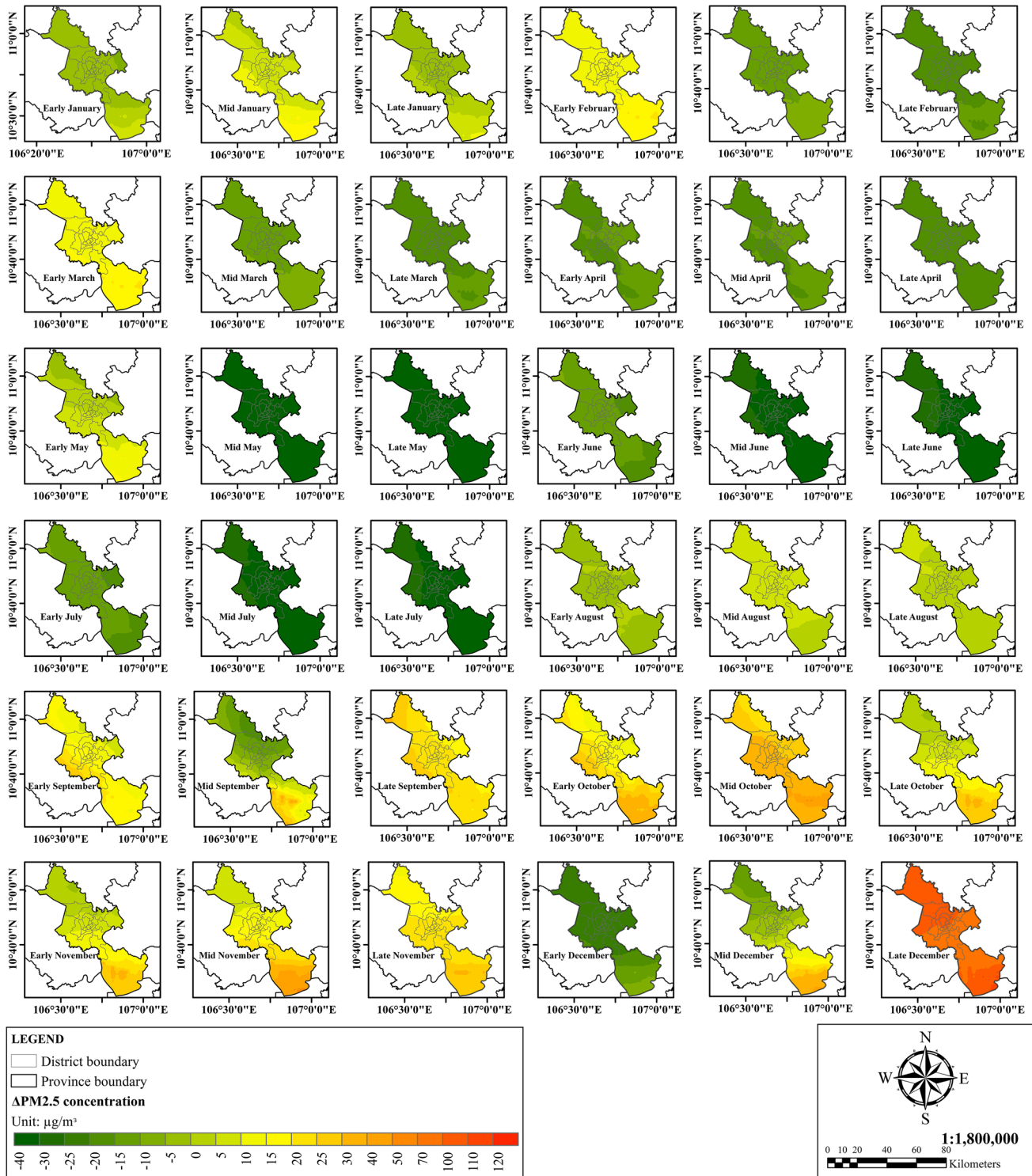


Fig. 4 Changes in monthly 24-h mean PM_{2.5} concentration (early, mid, and late) compared to the threshold of NAAQS ($\Delta PM_{2.5}$) in HCMC in 2019

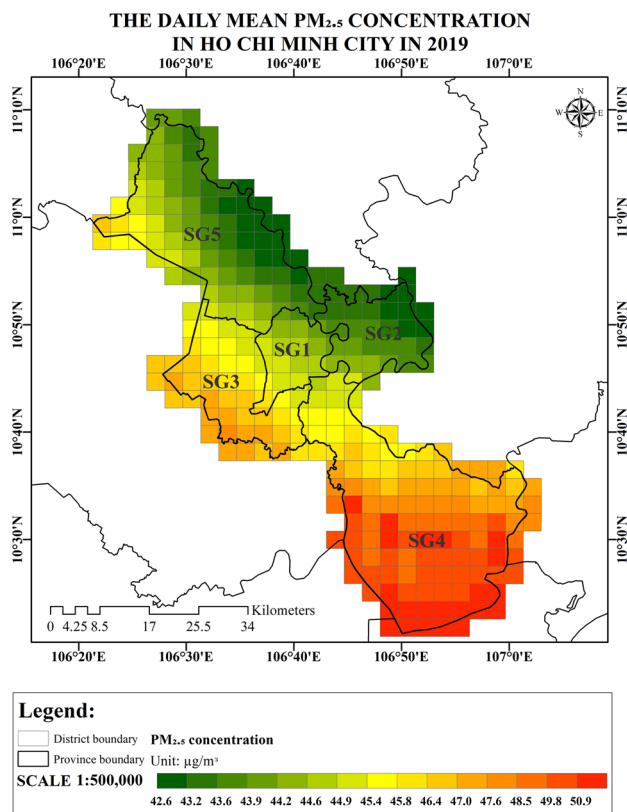


Fig. 5 Spatial distribution of annual mean PM_{2.5} concentration in HCMC in 2019

SG3 area is 15.250 cases, in SG4 area is 9.206 cases, and in SG5 region, there are 7.951 cases.

For the case of LC premature deaths ($HI_{LC, mort}$), there are a total of 84.563 (95% CI: 14.643; 386.873) cases (as shown in Fig. S6). By sex, the number of early deaths was 41.182 (95% CI: 7.131; 188.407) for men and 43.381 (95% CI: 7.512; 198.466) for women. Considering age, the groups of children, adults, and the elderly had health risks of 15.982 (95% CI: 2.767; 73.119), 63.845 (95% CI: 11.055; 292.089), and 4.736 (95% CI: 0.820; 21.665) cases, respectively. In each region as follows, the average early mortality rate in SG1 is 65.146 cases, in SG2 area is 4.816 cases, in SG3 area is 6.907 cases, in SG4 area is 4.146 cases, and in the SG5 area is 3.548 cases.

For the case of ALRI premature deaths ($HI_{ALRI, mort}$), there are a total of 99.937 (95% CI: 44.965–132.131) cases (as shown in Fig. S7). By sex, the early death rate for men was 91.666 (95% CI: 15.820; 167.648) cases, and for women, it was 96.560 (95% CI: 16.665; 176.599) cases. In each region as follows, the average early death rate in SG1 is 101.784 cases, in SG2 area is 7.626 cases, in SG3 area is 10.668 cases, in SG4 area is 6.455 cases,

and in the SG5 area is 5.597 cases. The SG1 region had the highest number of deaths, followed by SG3, SG2, SG4, and SG5, with the lowest number of deaths among the five sub-divisions.

Premature mortality attributable to short-term (acute) exposure to PM_{2.5} pollution

For the case of premature deaths from RDs from short-term exposure to PM_{2.5} pollution ($HIA_{RD, mort, QCVN}$) 2019 average across HCMC according to QCVN, there are a total of 6,107.627 (95% CI: 2,109.655; 9,935.407) cases. By gender, the early mortality was 3,450.628 (95% CI: 890.600; 5,960.590) cases and 383.965 (95% CI: 653.302; 6,902.560) cases for women. Considering age, the age groups of children, adults, and the elderly had an early mortality of 1,339.155 (95% CI: 299.000–2,313.248), 4,349.949 (95% CI: 1,739.340–6,886.664), and 418.523 (95% CI: 71.316–753.496) cases, respectively. In each region as follows, the rate of early deaths in the SG1 region was 4,706.114 (95% CI: 1,410.166; 7,655.537) with the maximum premature death occurring at X=683164.3839 and Y=1191330.519; in the SG2 area, there were 339.122 (95% CI: 132.511; 551.791) cases with the maximum premature death occurring at X=689206.7516 and Y=1197408.37; in the SG3 region, there were 509.222 (95% CI: 196.994; 828.189) cases with the maximum premature death occurring at X=677104.1165 and Y=1188272.616; in the SG4 region, there were 301.476 (95% CI: 207.381; 490.385) cases with the maximum premature death occurring at X=686222.6482 and Y=1188329.305; and in the SG5 region, there were 251.693 (95% CI: 162.604; 409.505) cases with the maximum premature death occurring at X=677046.9887 and Y=1197332.802. Early deaths from RDs due to short-term exposure to PM_{2.5} pollution according to WHO ($HIA_{RD, mort, WHO}$) totalled 12,204.218 (95% CI: 4,330.308; 19,752.847) cases. By gender, premature deaths were 6,887.044 (95% CI: 5,887.044; 11,819.136) cases and 7,648.385 (95% CI: 1,313.493; 13,665.780) cases. Considering age, the age groups of children, adults, and the elderly had an early death from RDs of 2,672.795 (95% CI: 694.427; 4,586.893), 8,696.511 (95% CI: 3,492.498; 13,674.173), and 834.911 (95% CI: 143.383; 1,491.781), respectively. In each region, the early death rate from RD in SG1 was 9,401.911 (95% CI: 3,333.995; 15,217.226) cases, in SG2, 695.074 (95% CI: 246.567; 1,125.268) cases, in SG3, 996.754 (95% CI: 353.742; 1,612.935) cases, in the SG4 region, 598.411 (95% CI: 212.342; 968.479) cases, and in the SG5 area, 512.068 (95% CI: 181.661; 828.939) cases with the maximum impact at coordinates such as $HIA_{RD, mort, QCVN}$.

The early deaths from CVDs due to short-term exposure to PM_{2.5} pollution ($HIA_{CVD, mort, TCVN}$) according to QCVN totalled 2,006.210 (95% CI: – 2,528.565;

7,133.484) cases. By sex, there were 1,194.888 (95% CI: – 129.713; 2,606.679) premature deaths in men and 667.152 (95% CI: – 410.159; 1,964.226) cases in women. Based on age, the age groups of children, adults, and the elderly had early deaths from RDs of 354.823 (95% CI: – 504.756; 1,327.404), 1,417.416 (95% CI: – 2,016.353; 5,302.592), and 233.971 (95% CI: – 7.457; 503.488), respectively. In each region, premature mortality from RDs in SG1 was 1,545.847 (95% CI: – 1,948.337; 5,496.568) cases; in SG2, it was 111.360 (95% CI: – 140.331; 396.023); in SG3, it was 167.311 (95% CI: – 210.904; 594.829) cases; in SG4, it was 99.036 (95% CI: – 124.827; 352.127) cases; and in SG5, it was 82.657 (95% CI: – 104.166; 293.937) cases with the maximum impact level at positions such as $HIA_{RD, mort, QCVN}$. Early deaths from CVDs due to short-term exposure to $PM_{2.5}$ pollution ($HIA_{CVD, mort, WHO}$) according to the WHO totalled 4,034.032 (95% CI: – 5,102.099; 14,298.205) cases. By gender, premature deaths were 2,402.135 (95% CI: – 261.263; 5,230.949) and 1,342.276 (95% CI: – 826.457; 3,945.627) cases. Considering by age, the age groups of children, adults, and the elderly had early deaths from RDs of 713.601 (95% CI: – 1,018.494; 2,660.862), 2,850.630 (95% CI: – 4,068.588; 10,629.368), and 469.801 (95% CI: – 15.018; 1,007.975) cases. In each region, as follows, the early mortality due to RDs in SG1 was 3,107.750 (95% CI: – 3,930.573; 11,015.088) cases, in the SG2 region, 229.683 (95% CI: – 290.447; 814.213) cases, in SG3, 329.557 (95% CI: – 416.872; 1,167.925) cases; in the SG4 region, 197.817 (95% CI: – 250.204; 701.114) cases; and in the SG5 area, 169.225 (95% CI: – 214.004; 599.865) with the maximum impact level at positions such as $HIA_{RD, mort, QCVN}$.

Morbidity cases attributable to short-term exposure to $PM_{2.5}$ pollution

The study results revealed that for ($HI_{IHD, morb}$), there were a total of 2,175.979 (95% CI: 1,105.159; 2,757.440) cases (as shown in Fig. 7). By sex, the morbidity of IHD in men was 1,059.702 (95% CI: 538.213; 1,342.873) and in women was 1,116.277 (95% CI: 566.947; 1,414,567) cases. Considering age, the groups of children, adults, and the elderly had IHD rates of 411.260 (95% CI: 208.875; 521.156) cases, 1,642.864 (95% CI: 834.395; 2,081.867) cases, and 121.855 (95% CI: 61.889; 154.417) cases, respectively. In each region, the rate of IHD in the SG1 area was 2,124.024 cases, in SG2 area is 160.072 cases, in SG3 area is 221.553 cases, in the SG4 area is 134.507 cases, and in the SG5 area is 117.285 cases, respectively. Summarize the results described above for cases of IHD ($HI_{IHD, morb}$), stroke ($HI_{stroke, morb}$), COPD ($HI_{COPD, morb}$), and LC ($HI_{LC, morb}$) over the entire HCMC is shown in Fig. 7.

The 2019 mean cases ($HI_{stroke, morb}$) across HCMC totalled 2,412.826 (95% CI: 2,258.405; 4,204.063) cases (as shown in Fig. S8). By sex, the morbidity of stroke in men was 1,175.046 (95% CI: 1,099.843; 2,047.379), and in women, it was 1,237.779 (95% CI: 1,158.562; 2,156.684). Considering age, the groups of children, adults, and the elderly have health risk levels of 456.024 (95% CI: 426.838; 794.568) cases, 1,821.683 (95% CI: 1,705.096; 3,174.067) cases, and 135.118 (95% CI: 126.471; 235.428) cases, respectively. The average number of stroke cases in the SG1 region is 1,858.777 cases; in SG2 area, it is 138.030 cases; in SG3 area, it is 196.295 cases; in SG4 area, it is 118.164 cases; and in SG5 area, it is 101.56 cases.

For the COPD case ($HI_{COPD, morb}$), there are a total of 38.672 (95% CI: 11.249–23.065) cases (as shown in Fig. S9). By sex, the morbidity of COPD was 18.833 (95% CI: 5.478; 11.233) cases and 19.839 (95% CI: 5.771; 11.833) cases. Considering age, the groups of children, adults, and the elderly had health risks of 7.309 (95% CI: 2.126; 4.359), 29.198 (95% CI: 8.493; 17.414), and 2.166 (95% CI: 0.630; 1.292) cases, respectively. Specifically, in each region, the average morbidity of COPD in SG1 was 29.793 cases, in SG2 was 2.200 cases, in SG3 was 3.162 cases, in SG4 was 1.897 cases, and in SG5 was 1.621 cases.

For the LC case ($HI_{LC, morb}$), there are a total of 4.425 (95% CI: 2.450–77.341) cases (as shown in Fig. S10). By sex, the morbidity of LC was 2.155 (95% CI: 1.193; 37.665) cases and 2.27 (95% CI: 1.257; 39.676) in women. Considering age, the groups of children, adults, and the elderly had health risks of 0.836 (95% CI: 0.463; 14,617) cases, 3.341 (95% CI: 1.850; 58.393) cases, and 0.248 (95% CI: 0.137; 4.331) cases, respectively. In each region as follows, the average morbidity of LC in SG1 is 3.409 cases, in SG2 area is 0.252 cases, in SG3 area is 0.362 cases, in SG4 area is 0.217 cases, and in the SG5 area is 0.185 cases.

Thus, for the cases due to four diseases (IHD, stroke, COPD, and LC), there are a total of 5,213.363 (95% CI: 4,448.083; 5,409.629) cases (as shown in Fig. S11). When considering sex, the morbidity in males was 2,538.908 (95% CI: 2,166.21; 2,634.489) cases, and in females, it was 2,674.455 (95% CI: 2,281.866; 2,775.139) cases. Considering age, the groups of children, adults, and the elderly had morbidity cases of 985.326 (95% CI: 840.688; 1,022.420), 3,936.089 (95% CI: 3,358.302; 4,084.270), and 291.948 (95% CI: 249.093; 302.939) cases, respectively. There, IHD has the most cases of IHD, followed by stroke, COPD, and LC in the fewest cases.

Assessment of economic valuation impacts

Estimation of economic value is lost because of the short- and long-term impacts of $PM_{2.5}$ exposure in HCMC in 2019 that is calculated on the basis of VSL value and COI cost

PREMATURE MORTALITY (LONG-TERM) DUE TO IHD, STROKE, COPD AND LC IN HO CHI MINH CITY IN 2019

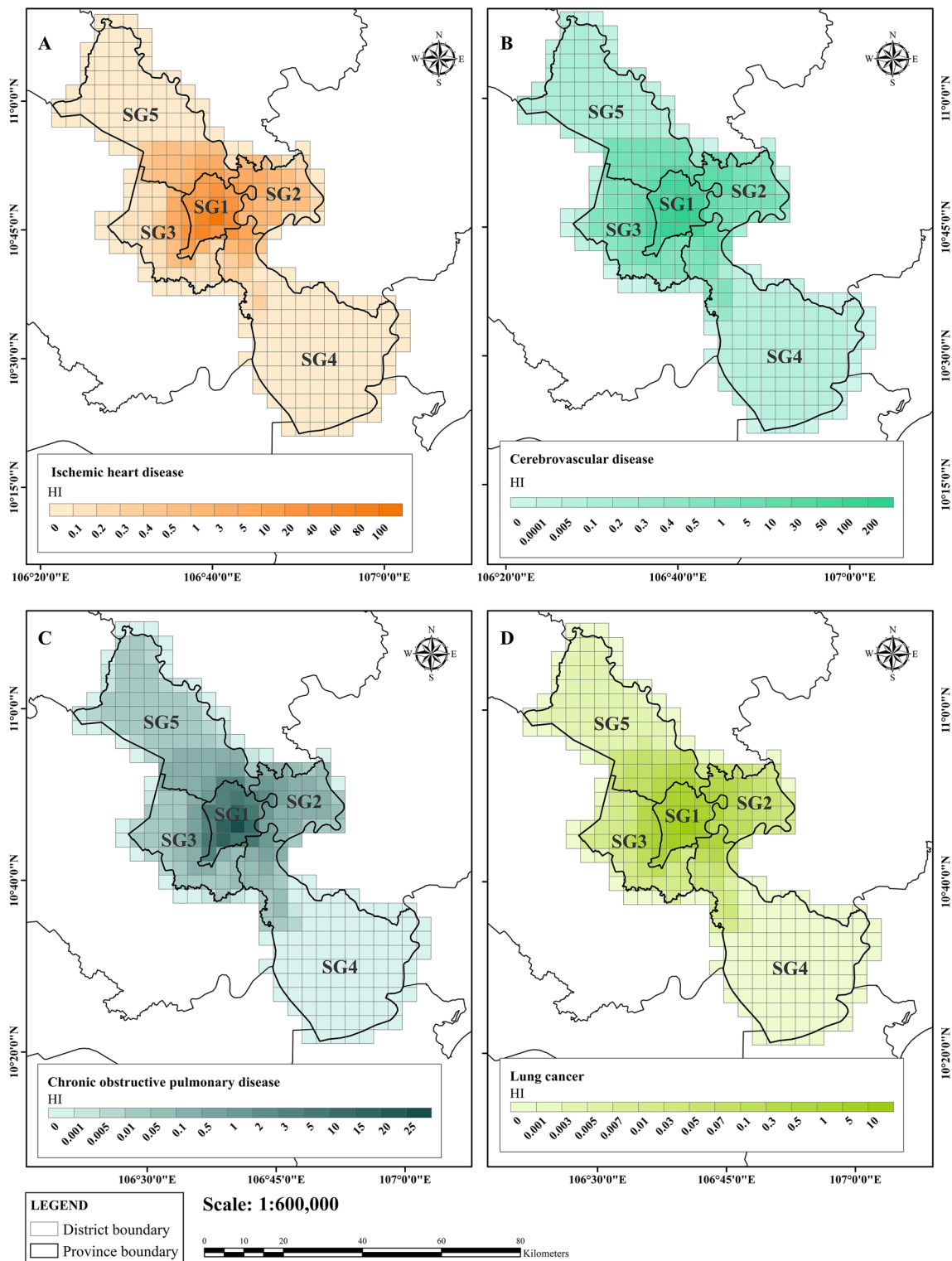


Fig. 6 Summary of premature mortality due to IHD, stroke, COPD, and LC attributed to long-term $PM_{2.5}$ exposure in HCMC in 2019

assumptions according to Chinh Nguyen (2013), Bui et al. (2020), Bui et al. (2021), and Bui and Nguyen (2022). The total economic value of the damage caused by PM_{2.5} pollution to public health due to long-term exposure is as high as 14,887.48 (95% CI: 4,907.271; 25,487.42) billion VND, equivalent to about 1,995.794 (95% CI: 657.862; 3,416.809) billion USD, accounting for approximately 1.105% of the HCMC GRDP in 2019 (about 1,347,369 billion VND). Specifically, the number of premature deaths from long-term exposure to IHD was 3,605.591 (95% CI: 2,048.713; 6,323.933) billion VND; stroke was 9,975.507 (95% CI: 2,632.864; 15,748.400) billion VND; COPD was 901.405 (95% CI: 155.090; 1,648.582) billion VND; LC was 404.968 (95% CI: 70.125; 1,852.715) billion VND; and ALRI was 478.593 (95% CI: 215.335; 632.769) billion VND. Meanwhile, the total economic value of the damage caused by PM_{2.5} pollution to public health due to short-term exposure is up to 38,856.760 (95% CI: -2,006.140; 81,742.070) billion VND, equivalent to approximately 5,209.083 (95% CI: -268.940; 10,958.230) billion USD, accounting for about 2.884% of the GRDP of HCMC in 2019. Thus, the short-term health impact is relatively more pronounced than the long-term effects of exposure to PM_{2.5} pollution in HCMC.

PM_{2.5} exposure and risk zoning

The highest average PM_{2.5} exposure risk in 2019 (Fig. 8) occurred in the SG1 area, while the lowest risk (5.33) occurred in the SG4 area. Overall, the risk of PM_{2.5} exposure in the central area was 1.24–2.18 times higher than that in the surrounding area. Among the five sub-division areas, the PM_{2.5} exposure risk of SG1 was the highest, followed by SG4, SG3, and SG5, and the lowest in SG2. Specifically in each area as follows, the risk of PM_{2.5} exposure in the SG1 area ranges from 1.274581 to 11.630498 with the maximum risk occurring at $X=683164.3839$ and $Y=1191330.519$; in the SG2 region ranges from 0.004646 to 6.495985 with the maximum risk occurring at $X=686204.0094$ and $Y=1191349.219$; in the SG3 region ranges from 0.00001 to 9.402697 with the maximum risk occurring at $X=680143.703$ and $Y=1188291.725$; in the SG4 region ranges from 0.000049 to 5.336322 with the maximum risk occurring at $X=686222.6482$ and $Y=1188329.305$; and in the SG5 region ranges from 0.000293 to 9.252161 with the maximum risk occurring at position $X=683126.69$ and $Y=1197370.864$. In the SG1 region, October has the highest risk of PM_{2.5} exposure of the year (11.73), while the lowest risk (11.5) occurs in August. In the SG2 region, April has a risk of exposure to the highest PM_{2.5} of the year (6.58), while the lowest risk (6.37) occurred in June. In the SG3 region, September has the highest risk of PM_{2.5} exposure in the year (9.68), while when the lowest risk (9.2) occurs in

August. In the SG4 region, May 2019 has the highest risk of PM_{2.5} exposure of the year (5.39), while the lowest risk (5.2) occurs in June 2019. In the SG5 region, April 2019 has the highest risk of PM_{2.5} exposure in the year (9.38), while the lowest risk (9.25) also occurs in April 2019. Figs. S12–S16 represent PM_{2.5} exposure risk by age group and by sex group based on the 2019 mean PM_{2.5} concentration exposure.

This study was conducted at the provincial level within a country, although the health impact estimates presented in grid form differ. Several studies comprise results in an administrative unit form, but all have shown a similar interest in the intracity and neighbouring spatial distribution of health effects due to PM_{2.5}. Innovations in the study methodology have resulted in outcomes that may explain the short- and long-term effects of PM_{2.5} on the health of HCMC residents. A combination of different models, including the precursor emission model, meteorological model (WRF), and air quality model (CMAQ), was used to achieve this goal to explain the spatiotemporal distribution of PM_{2.5} and health impact models to focus on analysing the relationship between PM_{2.5} concentrations, populations, and specific types of health damage caused by PM_{2.5}. Simulation development revealed that PM_{2.5} emissions and precursors and meteorological factors influence the hourly formation of PM_{2.5} across the entire HCMC area. This aid overcomes the significant limitations of the monitoring station data sources, particularly in situations where guaranteeing spatial coverage over the entire city is not feasible.

HIFs, one of the classical health risk assessment approaches, have been applied and recommended by the US Environmental Protection Agency (US EPA) and have been used throughout China and several other countries worldwide (Lelieveld et al. 2013; Lelieveld et al. 2015; J. Wang et al. 2015; Xue et al. 2019; Guan et al. 2021). HIFs have demonstrated the impact of PM_{2.5} pollution on the HCMC residents. Specifically, the short-term health effect estimation model evaluates the daily effects of PM_{2.5}, to demonstrate the monthly and seasonal variations in human health risks. Models that estimate long-term health effects have shown cumulative health risks over 1 year.

This study has certain limitations that must be addressed. First, the population data of HCMC used for the calculations are based on a fixed-year basis (2019); thus, this population data source cannot fully support the health impact calculations for a day, month, or season. Second, the mortality reports are incomplete, with significant variation between different districts in HCMC, particularly regarding the number of child deaths (mainly under 5 years old). Data on nonfatal health outcomes are based on surveys of a different quality. Third, shortcomings were observed in determining the cause of death, as

MORBIDITY CASES (LONG-TERM) DUE TO IHD, STROKE, COPD AND LC IN HO CHI MINH CITY IN 2019

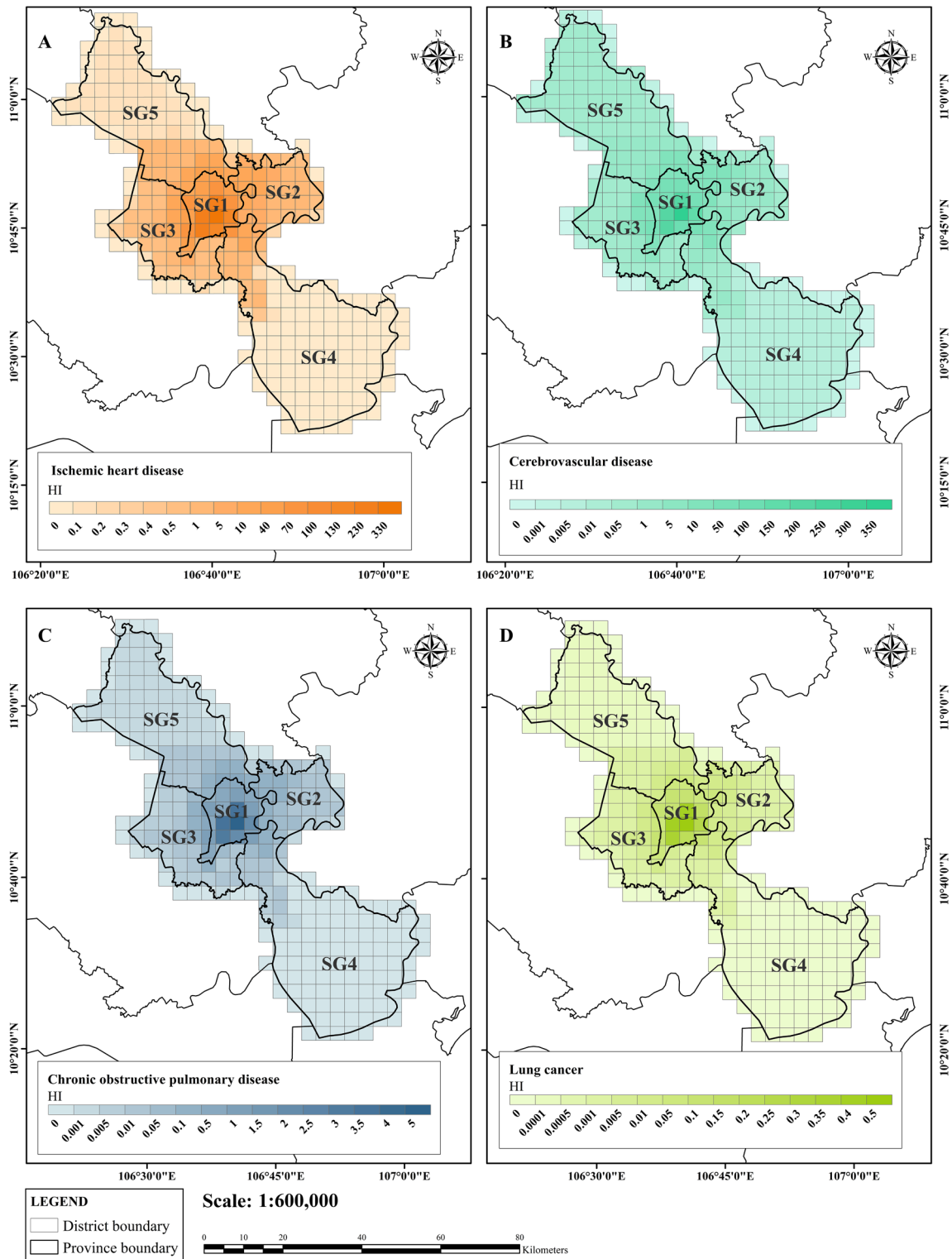


Fig. 7 Summary of morbidity cases due to IHD, stroke, COPD, and LC attributed to PM_{2.5} exposure in HCMC in 2019

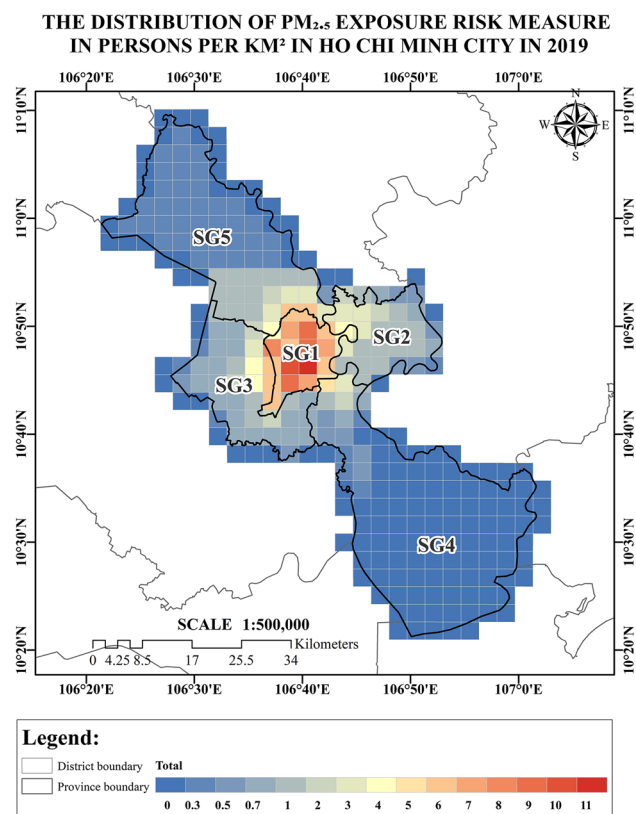


Fig. 8 Risks associated with PM_{2.5} exposure in HCMC population in 2019

these findings were based solely on verbal autopsy interviews. This method is considered an acceptable alternative to the absence of a valid civil status registration system, as is the case in Vietnam (Ngo et al. 2010; Nhung et al. 2013). Finally, comprehensive hospital records are unavailable for ALRI in children and IHD, stroke, COPD, and LC in adults and the elderly. These limitations are a consequence of the largely paper-based patient record system, which lacks patient details, such as age, gender, and cause of death. Furthermore, data on daily hospital admissions for RDs and CVDs were collected from the four largest provincial and central hospitals in HCMC: the Children's Hospital No. 2, Gia Dinh People's Hospital, 115 People's Hospital, and Thong Nhat Hospital.

Conclusions

This study modelled the spatiotemporal changes in PM_{2.5} concentrations in urban, suburban, and rural areas across HCMC. The annual average concentration of PM_{2.5} in 2019 ranged from 42.6 to 50.9 $\mu\text{g}/\text{m}^3$, and most of them exceeded the allowable thresholds of NAAQS and WHO

AQG. The results showed different levels of human health impacts in HCMC due to PM_{2.5} exposure. Both the short- and long-term public health burdens (mortality and morbidity) were analysed in detail. Additionally, the burdens of the related economic losses were clarified. The typical outcomes were as follows:

First, the total number of premature deaths were 3109, which were due to circulatory system diseases (IHD and stroke) and RDs (COPD and LC) resulting from long-term exposure to PM_{2.5}. The highest number of cases was due to strokes, accounting for up to 67% of the total cases. Females and adults had the highest number of deaths, with 1595 and 2347 premature deaths, respectively. Second, the total number of premature mortality cases was 6,08 (caused by RDs and CVDs) due to short-term exposure to PM_{2.5}. This finding shows a trend similar to that of the long-term exposure results. The number of premature deaths in females (63%) and adults (71%) still accounted for most cases. The total number of hospitalisations due to IHD, stroke, COPD, and LC was 5213.

Finally, economic losses caused by PM_{2.5} pollution averaged 53.7 trillion VND (equivalent to 7.2 trillion USD) and contributed to 3.9% of the total GRDP value of HCMC in 2019. The level of economic loss caused by short-term health effects (39 trillion VND) was 2.6 times higher than that caused by long-term impacts (15 trillion VND).

The research framework was selected to evaluate the short- and long-term effects of PM_{2.5} pollution, focusing on the health endpoints attributed to RDs and CVDs and documenting the specific diseases along with the associated individuals' age and sex. The outcomes of the study are an important scientific basis for assessing the socio-economic impacts of PM_{2.5}. Calculating the economic loss value is essential for encouraging investment into the implementation of future structural and non-structural measures to control PM_{2.5}, which may benefit local communities and city authorities.

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Author contribution Long Ta Bui: Conceptualisation, funding acquisition, investigation, project administration, resources, supervision, methodology, models, writing—original draft, writing—review and editing.

Nhi Hoang Tuyet Nguyen: Data analysis, models, GIS.

Phong Hoang Nguyen: Data curation, data analysis, formal analysis, validation, GIS.

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Data availability We declare that all data relating to this manuscript are truthful, and we will gladly share it with any interested readers or at the request of the editor board.

Declarations

Ethical approval The authors declare the following:

The manuscript is not submitted to more than one journal for simultaneous consideration.

The manuscript is original and not have been published elsewhere in any form or language (partially or in full), unless the new work concerns an expansion of previous work.

The manuscript is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time (i.e. “salami-slicing/publishing”).

Results are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. We adhere to discipline-specific rules for acquiring, selecting, and processing data.

We have provided all data and proper mentions of other works.

Consent to participate I consent to participate to publish my manuscript entitled “Chronic and acute health effects of PM_{2.5} exposure and the basis of pollution control targets” to the Environmental Science and Pollution Research (ESPR).

Consent to publish I consent to publish my manuscript entitled “Chronic and acute health effects of PM_{2.5} exposure and the basis of pollution control targets” to the Environmental Science and Pollution Research (ESPR).

Competing interests The authors declare no competing interests.

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