



# Evaluation of the annual economic costs associated with PM<sub>2.5</sub>-based health damage—a case study in Ho Chi Minh City, Vietnam

Long Ta Bui<sup>1,2</sup> · Phong Hoang Nguyen<sup>1,2</sup>

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## Abstract

Pollution-related air quality deterioration has affected public health in many large cities worldwide, including Ho Chi Minh city (HCMC) in Vietnam. The health effects in this area attributed to fine particulate matter (PM<sub>2.5</sub>) account for 81.31% of all major air pollutant-related deaths. Over the past two decades, epidemiological studies have demonstrated that both short- and long-term PM<sub>2.5</sub> pollution exposures are associated with increased mortality and morbidity. However, research on the economic damages caused by this type of pollution is lacking. The goal of this study was to assess PM<sub>2.5</sub>-related human health impacts and the corresponding economic damage in HCMC. The modelling approach applied in this study, including the coupled Weather Research and Forecasting (WRF)/Community Multiscale Air Quality Modelling System (CMAQ) models, for estimating PM<sub>2.5</sub> distribution was combined with the models of short-term human health impacts and economic valuation quantification. Results indicated the short-term effects of health endpoints caused by PM<sub>2.5</sub>, including 174 (95% CI: 16; 340) premature deaths, 117,632 (95% CI: 231, 850; 368,926) hospital admission cases and 162,455 (95% CI: – 710,465; 531,153) emergency visits. The total economic losses have been estimated to exceed 3 trillion VND (equivalent to approximately 410 million USD), accounting for approximately 0.25% of the total gross regional domestic product (GRDP) of HCMC in 2018. Therefore, the results of this study provide compelling and up-to-date evidence for HCMC's policymakers to propose PM<sub>2.5</sub> pollution control measures and develop a clean air action plan with Vision 2025 to reduce adverse impacts on public health and obtain economic benefits.

**Keywords** PM<sub>2.5</sub> exposure · Health impact assessment · Premature mortality · Hospitalisation · Economic losses

## Introduction

Vietnam is among the top 10 countries most strongly affected by air pollution, tending to increase in big urban and industrial zones. The current rapid urbanisation and accelerating economic development in large cities, such as Ho Chi Minh city (HCMC), have caused a multitude

of environmental and social issues, posing a serious challenge to PM<sub>2.5</sub> pollution management. Short- and long-term exposures to PM<sub>2.5</sub> pollution has been shown to be one of the leading causes of the global burden of disease, especially in low- and middle-income countries (Stanaway et al., 2018). According to the World Air Quality Report of 2020 (IQAir, 2020), Vietnam suffers 10.8 to 13.2 billion USD in economic losses related to ambient air pollution each year, equivalent to approximately 5% gross domestic product of the entire nation. Associations between PM<sub>2.5</sub> concentrations and human health have been demonstrated in several epidemiological studies in Vietnam. However, there have not been any available studies that comprehensively clarify the true impact of PM<sub>2.5</sub> on public health and quantify the losses in economic valuation due to PM<sub>2.5</sub> pollution in Vietnam. This is a crucial foundation for the development of a clean air action plan for HCMC, and the basis for determining compensation for damage caused by pollution, as the principle of “polluters must pay money” is clearly defined

✉ Long Ta Bui  
longbt62@hcmut.edu.vn

✉ Phong Hoang Nguyen  
nhphong@dcselab.edu.vn

<sup>1</sup> Laboratory for Environmental Modelling, Faculty of Environment and Natural Resources, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam

<sup>2</sup> Vietnam National University Ho Chi Minh City (VNU-HCM), Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam

in the Law on Environmental Protection 2014 and the Civil Code 2015 of Vietnam.

Additionally, the legal policy on air pollution control that focuses on  $PM_{2.5}$  is still quite limited and lacks synchronisation among localities in Vietnam. As of the end of October 2013, this is the first time that the Ministry of Natural Resources and Environment of Vietnam has added a new threshold for  $PM_{2.5}$  concentrations to the national ambient air quality standard (NAAQS), also known as QCVN 05:2013/BTNMT, based on the proposal of the Vietnam Environment Administration. When comparing NAAQS with international standards, such as the European Union air quality guidelines (Europe, 2000) or the World Health Organisation air quality guidelines (WHO Standard) (WHO, 2021), Vietnam's NAAQS on the average limit of  $PM_{2.5}$  concentration in the short-term ( $50 \mu\text{g}/\text{m}^3$ , 24-h mean) and long-term ( $25 \mu\text{g}/\text{m}^3$ , annual mean) is relatively low. This demonstrates the fact that if controlled according to NAAQS, the people of Vietnam, who are breathing in the  $PM_{2.5}$ -contaminated air, still face a higher health risk than by other countries in the world, such as Europe and North America. In June 2016, the Prime Minister of Vietnam issued a decision approving the National Action Plan on air quality management to 2020, with a vision to 2025 (hereinafter referred to as the National Action Plan) (Decision on Approving the National Action Plan on Air Quality Management to 2020, Vision to 2025, 2016), which includes objectives to determine the current status of  $PM_{2.5}$  pollution in special urban areas; these are defined as urban areas directly under Central government, able to implement measures to reduce  $PM_{2.5}$  pollution from the main emission sources. However, currently in HCMC, the  $PM_{2.5}$  monitoring system from the National Environmental Monitoring Network managed by the Department of Natural Resources and Environment has not yet been formed. The reference  $PM_{2.5}$  concentration measurement results are extracted primarily from the database source of AirNow from one monitoring station located at the US Consulate General located in District 1, HCMC. The recorded results showed that the  $PM_{2.5}$  pollution levels in HCMC are relatively serious. The average  $PM_{2.5}$  concentration in 2016 at  $29.6 \mu\text{g}/\text{m}^3$  also exceeded the limit specified by NAAQS and WHO Standard by approximately 1.2 and 3.0 times, respectively; and in 2017, there were 222 days (61% of the total number of days in the year) when  $PM_{2.5}$  concentration exceeded the daily average of WHO Standard 2006 ( $25 \mu\text{g}/\text{m}^3$ ) (Thu et al., 2018).

Therefore, given the urgency of the situation, to develop an effective air quality management strategy focusing on the main target of  $PM_{2.5}$ , according to the future National Action Plan, an assessment of the current spatiotemporal variation of pollution levels of  $PM_{2.5}$  affecting public health and economic loss in HCMC is necessary to serve as a scientific basis for the proposal of  $PM_{2.5}$  control measures. The

objectives of this study were to evaluate the acute mortality/morbidity burdens due to short-term  $PM_{2.5}$  exposure and the corresponding economic burden due to the types of health endpoints associated with respiratory and cardiovascular diseases in 2018. The research was implemented by applying modelling methods from the combined model system from the Weather Research and Forecasting and Community Multiscale Air Quality Modelling Systems (WRF/CMAQ) and Environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE) to maximise the limitations from the lack of  $PM_{2.5}$  data in HCMC and provide spatiotemporal estimation results. The results obtained from this study have contributed to determining the current status of  $PM_{2.5}$  pollution in HCMC, a city directly under the central government, and providing evidence for proposing measures to reduce  $PM_{2.5}$  pollution levels when the HCMC's authority organises and implements them according to the National Action Plan with an orientation towards 2025.

## Literature review

Exposure to  $PM_{2.5}$ , a major urban air pollutant (Fold et al., 2020), has various adverse health effects and ultimate societal costs (Chowdhury and Dey, 2016; Fold et al., 2020; Jie Li et al., 2021; Yin et al., 2017a). Rapid urbanisation and industrialisation in developing countries are continuing to increase the concentration of air pollutants, attracting public attention (Xiong et al., 2019). Over the past two decades, the number of research papers on the relationship between  $PM_{2.5}$  pollution and its socioeconomic losses has increased rapidly, especially in studies from China (Y. Li et al., 2017; Lu et al., 2019; Luo et al., 2020; Xiao et al., 2022; Ye et al., 2021). In particular, a large number of epidemiological studies have demonstrated an increased risk of premature death (Apte et al., 2015; Arden Pope et al., 2011; Krewski et al., 2009; Lim et al., 2012; Mehta et al., 2013; A. C. Pope et al., 2009) and acute respiratory and cardiovascular diseases (Brook et al., 2004; Englert, 2004; C. A. Pope & Dockery, 2006) associated with short-term exposure to  $PM_{2.5}$  pollution. There is also evidence suggesting that exposure to  $PM_{2.5}$  exacerbates asthma and cardiovascular and pulmonary diseases (Yu et al., 2019; Zhang et al., 2021). According to the estimates of the Global Burden of Disease project, the number of premature deaths each year due to  $PM_{2.5}$  rose sharply from approximately 3.2 million people in 2010 (Evans et al., 2013) to 4.2 million by 2015 (Forouzanfar et al., 2016; Huy et al., 2018; Jin Li et al., 2018). The studies by Chen et al. (2017), Krewski et al. (2009) and Bayat et al. (2019) reported that when the  $PM_{2.5}$  concentration increased by  $10 \mu\text{g}/\text{m}^3$ , the related risks of all deaths, cardiopulmonary disease, lung cancer and ischaemic heart

disease (IHD) increased by approximately 4%, 9%, 9% and 17%, respectively.

Several recent epidemiological studies in Vietnam, performed by Nhung et al. (2013) and L. M. T. Luong et al. (2017, 2020) have shown the impact of air pollution on the number of hospitalisations for respiratory and cardiovascular diseases in HCMC. However, these studies only investigated the effects of PM<sub>10</sub>, ground-level O<sub>3</sub> and common air pollutants (SO<sub>2</sub> and NO<sub>2</sub>), without much attention paid to PM<sub>2.5</sub>, which is considered a risk factor that affects human health and leads to premature death (Cohen et al., 2017; Fu et al., 2020; Huy et al., 2018). One study, by L. T. M. Luong et al. (2020), reported a 3.51% increase in the risk of hospitalisation for acute lower respiratory tract infection in children with every 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub>. The studies that have reported on health risks due to PM<sub>2.5</sub> were conducted mainly in Hanoi City (Chi et al., 2020; L. M. T. Luong et al., 2017; Nhung et al., 2013, 2018, 2019). Typically, an increase in the risk of hospital admission for respiratory disease and pneumonia by about 2.3% and 6.3%, respectively, was associated with an increase in PM<sub>2.5</sub> exposure to 10 µg/m<sup>3</sup> in children under five years of age as reported by L. M. T. Luong et al. (2017) and Nhung et al. (2013).

Illnesses due to PM<sub>2.5</sub>, the levels of which show wide regional variations, can have global impacts owing to its transboundary transport (Tang et al., 2018). The limitations of ground monitoring stations and their location-specific dispersion have created significant challenges for large-scale, high-resolution air quality monitoring in Vietnam (Do et al., 2021). Therefore, air quality models are considered a simpler approach to solving the problem of large-scale air pollution to provide air quality management and regional pollution conversion, long-range transport and community risk assessment studies (Chen et al., 2017; Do et al., 2021). Studies by Ho et al. (2020) and Vu et al. (2020) have presented the negative impacts of PM<sub>2.5</sub> pollution on public health in HCMC via modelling, showing that up to 81.45% of total deaths were caused by PM<sub>2.5</sub>, SO<sub>2</sub> and NO<sub>2</sub> (1397 cases), with roughly 1136, 89 and 172 deaths, respectively, in 2017. Over the past decade, air quality models have been widely used to understand the physical and chemical processes involved in PM<sub>2.5</sub> pollution (Tao et al., 2020). These models can perform air quality simulations from local to global scales with different resolutions depending on the research purpose (Tao et al., 2020). In particular, the CMAQ model system has been developed to study environmental issues and has been applied to multiscale (urban and regional) air pollution problems as well as multi-pollutant contamination (oxidants, acid deposits, and particulate matter) (Jun and Stein, 2004; Toledo et al., 2018).

From the modelling perspective, most studies investigating the extent of illnesses caused by air pollution in Vietnam are based primarily on the response–exposure

approach, based on the theory of the BenMAP-CE model. Table 1 summarises the above research for different localities in Vietnam. This approach typically considers pollutant concentration, concentration–response functions (CRFs), exposed population and baseline mortality/morbidity instances as the main factors that determine the number of affected cases. The role of pollutant concentration in these models is decisive, followed by population (Guan et al., 2021). Some studies, such as Maji et al. (2019) and Wang et al. (2020a, b), used population-weighted PM<sub>2.5</sub> concentrations to estimate health risks. As detailed in Table 1, this is a significant limitation of previous studies. Furthermore, previously published data have become obsolete because of rapid industrialisation, and urbanisation must be considered to a greater extent.

## Data and methods

### Study area

HCMC is the nucleus of the southern key economic regions, one of the three largest key economic regions in Vietnam. Although it accounts for only 0.6% of the country's area and 9% of the population, HCMC contributes 22% of the country's GDP. The total GDP value of the whole country in 2018 reached approximately 236.1 billion USD (Ho Chi Minh City Statistical Office, 2019), while that of HCMC itself has reached 52.2 billion USD. The area of the whole city is 2095.4 km<sup>2</sup>, divided into 19 urban districts and 5 rural districts. The GRDP Contribution of HCMC in 2010 was 21.8 billion USD, accounting for approximately 24%, which is roughly 1/4 of the national contribution (Ho Chi Minh City Statistical Office, 2019) (Fig. 1).

PM<sub>2.5</sub> pollution in HCMC has a large variation between hours of the day but little seasonal variation (GreenID, 2017), and the highest dust concentration occurs immediately after the morning rush hour (Huy et al., 2018). The average PM<sub>2.5</sub> dust concentration from 2013 to 2017 was 28.0 ± 18.1 µg/m<sup>3</sup>, and the average concentration over the years almost exceeded NAAQS (25 µg/m<sup>3</sup>, annual mean) as well as WHO Standard 2006 (10 µg/m<sup>3</sup>, annual mean) (Huy et al., 2018). Most of the time, PM<sub>2.5</sub> concentration peaks were related to air masses moving along the coast, accumulating pollution from transport, power plants and public facilities (GreenID, 2017; Hien et al., 2019; MONRE, 2018). Moreover, the concentration of PM<sub>2.5</sub> also fluctuated between monitoring locations, and the relative PM<sub>2.5</sub> concentration values increased in the following order: city zoo (background monitoring) < rural area < residential area < roadside < city road; at the same time, the concentration of PM<sub>2.5</sub> in the roadside and city road areas has a corresponding clear linear

**Table 1** Literature on air-pollution-related health effects in Vietnam

Study area	Time series	Pollutant	Main outcomes	Reference
Dong Nai province	January and February 2019	O <sub>3</sub>	The total number of inpatient hospitalisations for respiratory and cardiovascular diseases (all causes) were 440.49 NAAQS estimates and 1556.94 WHO Standard Interim target 2 estimates	Khanh et al. (2022)
HCMC	October 2017	PM <sub>10</sub>	<ul style="list-style-type: none"> <li>Health effects due to PM<sub>10</sub> are estimated as 0.029946 premature deaths from respiratory and cardiovascular diseases (all causes), 0.0026432 hospitalisations (all causes), and 0.0901258 emergency visits (all causes);</li> <li>Total economic loss is estimated at 125.119 billion VND</li> </ul>	Bui et al. (2021)
Bac Tan Uyen district, Binh Duong province	2018	PM <sub>10</sub>	<ul style="list-style-type: none"> <li>Total number of premature deaths, inpatient hospitalisations, and outpatient visits (all causes) was 4030, 10,299, and 837, respectively;</li> <li>Total economic loss is estimated at 9.643 trillion VND, equivalent to 15.03 million USD</li> </ul>	Bui et al. (2020)
HCMC	2017	NO <sub>2</sub> , SO <sub>2</sub> , PM <sub>2.5</sub>	<ul style="list-style-type: none"> <li>NO<sub>2</sub>, SO<sub>2</sub>, and PM<sub>2.5</sub> pollution caused 172, 89, and 1136 deaths, respectively;</li> <li>Number of deaths due to PM<sub>2.5</sub> accounts for approximately 81% of total cases, of which 64 were due to lung cancer, 715 were due to cardiopulmonary disease, 715 were due to cardiopulmonary disease, and 357 were due to IHD</li> </ul>	Vu et al. (2020)
District 5, HCMC	July 2012	PM <sub>10</sub>	<ul style="list-style-type: none"> <li>Total number of deaths in District 5, HCMC was 5 (accounting for 0.0025% of the district's population), equivalent to an economic loss of more than 45 million USD;</li> <li>Estimated health and economic losses for the entire HCMC was 204 individuals and 1.836 billion USD, respectively</li> </ul>	Ho (2017)
27 Southeast and East Asian cities	2009	PM <sub>10</sub> , PM <sub>2.5</sub>	<ul style="list-style-type: none"> <li>In HCMC, total number of deaths from all causes related to PM<sub>2.5</sub> and PM<sub>10</sub> was 3,756 and 3,571, respectively;</li> <li>In Hanoi, total number of deaths from all causes related to PM<sub>2.5</sub> and PM<sub>10</sub> was 2,924 and 3,326, respectively</li> </ul>	Yorifuji et al. (2015)
Hanoi city	2007–2009	PM <sub>10</sub>	Total number of deaths from non-external causes related to traffic air pollution (PM <sub>10</sub> ) in 2007, 2008, and 2009 was 2785, 3007, and 3129, respectively	Hieu et al. (2013)

relationship with traffic activities (Hien et al., 2019; Phan et al., 2020), which showed that the mobile form of traffic emission sources contributed the largest amount of emissions for all air pollutants in HCMC: 99%, 97%, 93%, 78%, 76%, 64% and 45% of the total emissions of CO, NMVOCs, NO<sub>x</sub>, SO<sub>2</sub>, TSP, CH<sub>4</sub> and PM<sub>2.5</sub>, respectively. Meanwhile, the proportion of BC/PM<sub>2.5</sub> composition in HCMC ranged from 6.5 to 43%; the highest percentage was found in city road areas, and the lowest was mainly in city zoos and rural areas (Phan et al., 2020). The variability in BC composition is directly related to changes in meteorological conditions and has a significant impact on regional air quality (Hien et al., 2019; Phan et al., 2020). In addition, other important heavy metal components present in PM<sub>2.5</sub> dust (Cr, As, Cd, Cu, Fe, Mn, Mo, Ni, Pb and Zn) account for  $131.77 \pm 42.13$  to  $233.13 \pm 79.88$  µg/m<sup>3</sup> (Phan et al., 2020).

## Data and models

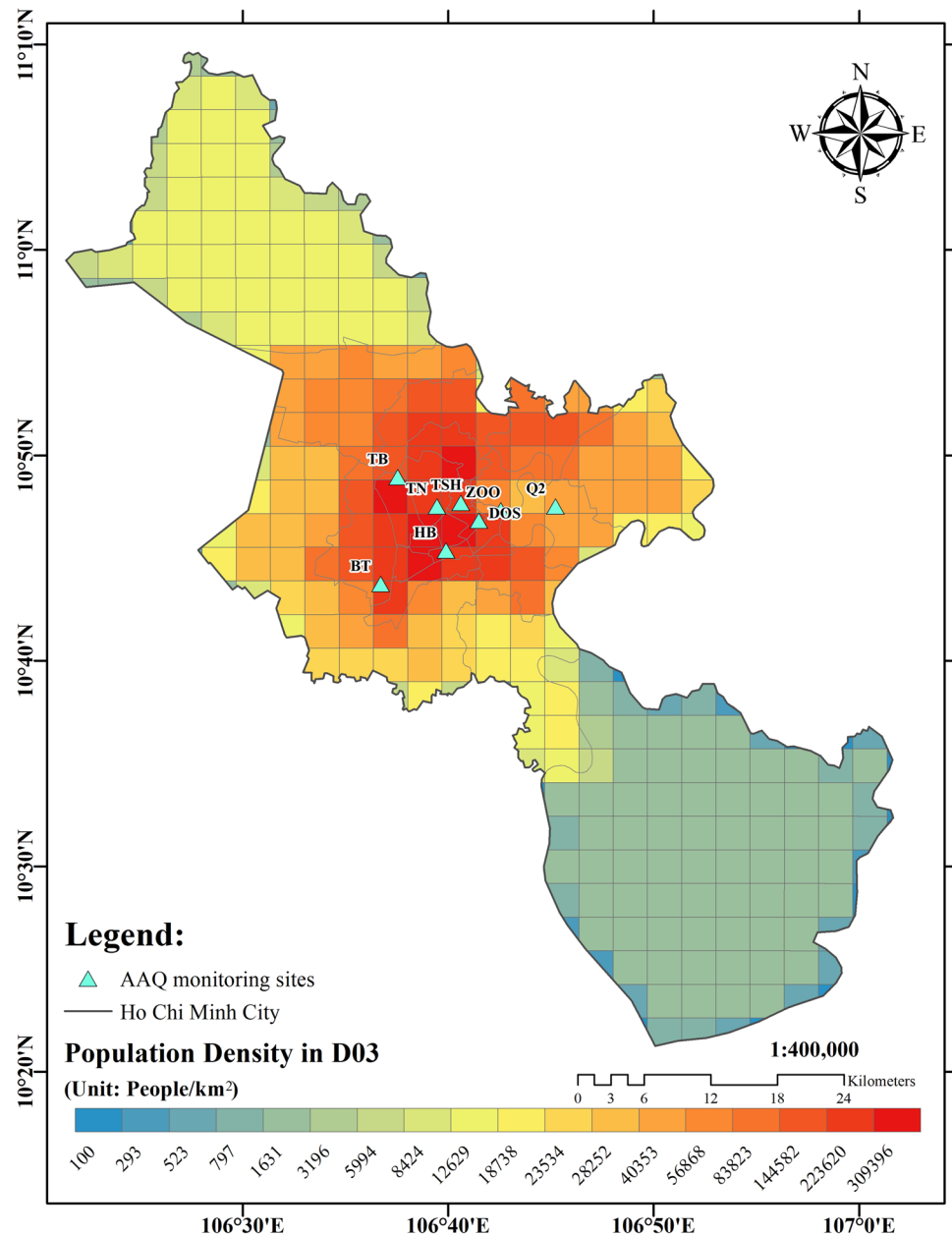
To determine the excess number of early deaths and disease treatment due to ambient PM<sub>2.5</sub> and quantify the

economic losses, six types of input data needed to be captured: (i) datasets in terms of the grid-based exposed population size, (ii) estimations of modelled 24-h mean ambient PM<sub>2.5</sub> concentrations to consider and assess the effects of short-term exposure, (iii) health endpoint types associated with premature mortality and morbidity, (iv) baseline incidence of premature mortality and morbidity rates, (v) estimates of concentration–response functions (CRFs) corresponding to the selected human health impact categories, and (vi) estimates of the unit economic value of the respective considered health endpoint types. Based on this, the following sections explain in detail the information and data sources, as well as the crucial models.

## Exposed population size

The spatial distribution of the grid-based exposed population was performed from the datasets recording HCMC population in 2018. Population density exposed to PM<sub>2.5</sub> was allocated on each grid cell belonging to the domain D03 with a resolution size of  $\sim 3.14 \times 3.14$  km<sup>2</sup>. Specific

**Fig. 1** HCMC—selected study area, grid-based PM<sub>2.5</sub>-exposed population, 2018

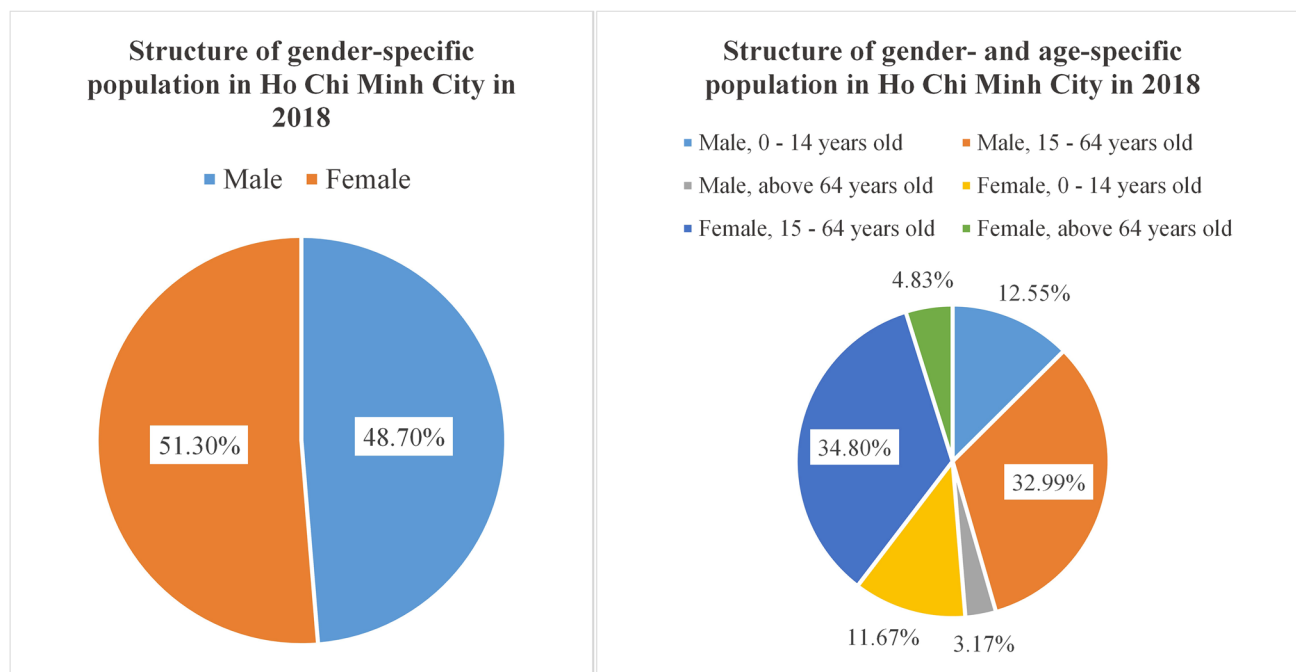


population exposure datasets, including age- and gender-specific populations, were collected from the Statistical Yearbook reports (GSO, 2020; HCMC Statistical Office, 2019b, 2020). These datasets were divided into three main age groups by sex (male and female): children (0–14 years old), adults (15–64 years old) and elderly ( $\geq 65$  years old). Details of the population data of the HCMC hierarchy, in accordance with, administrative unit, age groups and gender are shown in Figs. 1 and 2.

The process of estimating spatial exposed population distribution was conducted according to these following steps (L. Chen et al., 2017; Bayat et al., 2019): (1)

determine the general exposed population density in 2018 ( $Den_{Dist,i,2018}$ ) for each district  $i$  of HCMC by taking the total population ( $POP_{Dist,i,2018}$ ) divided by the total area ( $S_{Dist,i}$ ) of district  $i$  as in Eq. (1); (2) to calculate the average population density for each grid cell  $j$ , it is necessary to estimate the area ratio ( $Ratio_{Dist,i,j}$ ) of the area of district  $i$  ( $S_{Dist,i,j}$ ) at the grid cell  $j$  compared to the total area of the whole district  $i$  ( $S_{Dist,i}$ ) according to Eqs. (1,2); (3) the estimated population density outcomes at each grid cell  $j$  ( $Den_{i,j,2018}$ ) based on  $POP_{Dist,i,2018}$  and calculated  $Ratio_{Dist,i,j}$  that  $n$  is the number of districts included in the estimated grid cell  $j$  as in Eq. (3).





**Fig. 2** The structure of the gender- and age-specific population in HCMC, 2018

$$Den_{Dist,i,2018} = \frac{POP_{Dist,i,2018}}{S_{Dist,i}} \quad (1)$$

$$Ratio_{Dist,i,j} = \frac{S_{Dist,i,j}}{S_{Dist,i}} \quad (2)$$

$$Den_{i,j,2018} = \sum_{i=1}^n POP_{Dist,i,2018} \times Ratio_{Dist,i,j} \quad (3)$$

where  $Den_{i,j,2018}$  is the HCMC population density at each estimated grid cell  $j$ ;  $POP_{Dist,i,2018}$  is the total population in 2018 as per district  $i$  in the study area;  $S_{Dist,i}$  is the total area of district  $i$ ; and  $S_{Dist,i,j}$  is the total area of district  $i$  in grid cell  $j$  in the range of the computing domain D03 covering the entire HCMC.

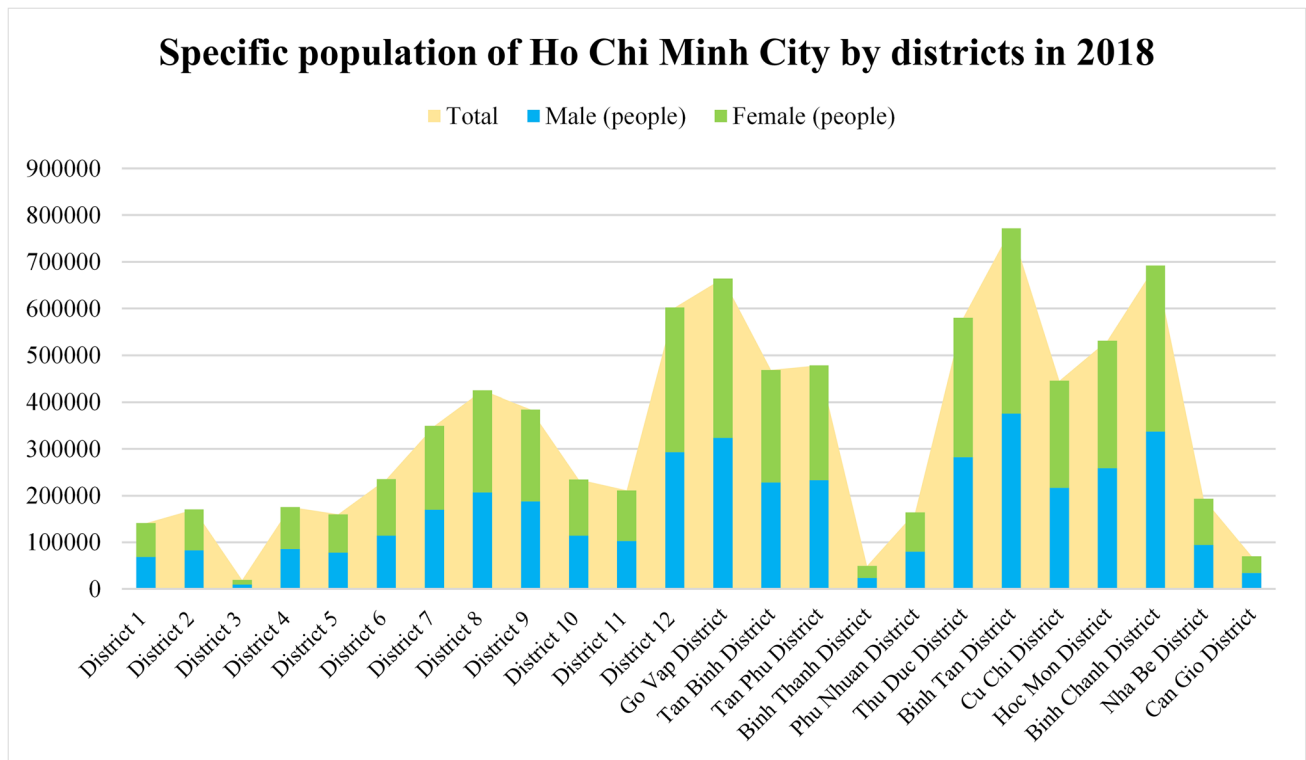
Based on the calculated and analysed results (HCMC Statistical Office, 2019a, b; HCMC Statistical Office, 2020; Ministry of Health, 2019), the total population exposed to ambient  $PM_{2.5}$  pollution was 8,831,865 people, of which it was estimated that there were 4,301,118 men (accounting for approximately 48.70%) and 4,530,747 women (approximately 51.30%); see Fig. 2, as well as the HCMC's exposed population by district shown in Fig. 3. According to the age group structure, there were 2,275,088 people 0 to 14 years old (25.76%); 5,982,705

15 to 64 years old (67.74%) and in the age group of over 65 years old, 574,071 (6.5%) (Figs. 2 and 3).

#### Simulated 24-h mean $PM_{2.5}$ concentration distribution

The hourly simulated  $PM_{2.5}$  concentration datasets were obtained from the coupled WRF/CMAQ, in which the three-level nested computational domains of D01, D02 and D03 were set up to meet the requirements of the coupled WRF/CMAQ. The domain D01 had a spatial resolution of approximately  $30.43 \text{ km} \times 30.43 \text{ km}$ , which was the highest. The area of the D01 domain was approximately  $5.41 \times 10^6 \text{ km}^2$ . The domain D02 had a spatial resolution of roughly  $9.55 \text{ km} \times 9.55 \text{ km}$ ; this was the second nested domain within D01. The D02 domain area was approximately  $2.11 \times 10^5 \text{ km}^2$ . The D03 domain had a spatial resolution of approximately  $3.14 \text{ km} \times 3.14 \text{ km}$ ; it was the smallest calculation domain nested within D01 and D02, with an area of approximately  $2.64 \times 10^4 \text{ km}^2$ .

On an hourly  $PM_{2.5}$  concentration data basis for domain D03, the daily average  $PM_{2.5}$  concentration level (or  $C$  in Eq. (4)) at each estimated grid cell location was identified (Fig. S1–Fig. S12). It was the input data source for estimates in human health impact modelling for different health endpoint types attributed to short-term  $PM_{2.5}$  exposure and corresponded to the choice of the estimated threshold value.



**Fig. 3** A chart comparing the  $PM_{2.5}$ -exposed populations hierarchically in accordance with different districts of HCMC, 2018

To ensure the reliability of the simulated dataset, validation comparisons were also performed on the basis of the measurement results of ambient  $PM_{2.5}$  concentration at the monitoring sites. However, the threshold  $PM_{2.5}$  concentration (or  $C_0$ ) in (4) was applied to the human health impact models. This is the 24-h average  $PM_{2.5}$  threshold value according to the guidelines of the National Ambient Air Quality Standard (NAAQS); specifically, QCVN 05:2013/BTNMT with a threshold value of  $50 \mu\text{g}/\text{m}^3$  was used as the reference for the human health effect calculations.

#### Identification and classification of short-term health endpoints due to $PM_{2.5}$ pollution

Most non-accidental premature deaths (>99.0%) are caused by non-communicable diseases (NCDs) and lower respiratory infections (LRIs) (Bayat et al., 2019; Liu et al., 2021; Burnett et al., 2018). Thus, this study limited the estimation and assessment of non-accidental premature deaths and diseases and focused on two subgroups: NCDs and LRIs. The study was also limited to health endpoints with concentration–response coefficients clearly classified according to the 10th version of the International Classification of Diseases (ICD-10, 2016). In particular, there are six main categories

of diseases related to ambient  $PM_{2.5}$ , including circulatory system, respiratory, endocrine, nutritional and metabolic diseases, neoplasms, mental and behavioural disorders and nervous system diseases (ICD-10, 2016).

In this study, three different health endpoint groups were estimated; specifically, for the health impact group (1) of premature mortality, all-cause diseases were assessed, including mortality due to all-cause respiratory diseases (RDs), cardiovascular diseases (CVDs), and other circulatory system diseases (CSDs) (Yin et al., 2017b). With the health effect group (2) of hospital admissions includes hospitalisations attributed to the RDs such as acute LRI due to pneumonia and acute bronchiolitis in children, chronic obstructive pulmonary disease (COPD), community-acquired pneumonia (CAP); and related to the CVDs such as heart failure (HF), myocardial infarction (MI), and stroke. Moreover, the health endpoint group (3) of emergency visits consisted of emergency cases caused by RDs, such as COPD and CAP, and CVDs, such as HF, HF MI and stroke (Table 2).

#### Baseline incidences of premature mortality and morbidity

The early death and morbidity baseline data are statistics that estimate the average number of people with disease or death in a given population over a given period of time

**Table 2** Summary of the epidemiological studies linking short-term PM<sub>2.5</sub> exposure to mortality and morbidity that were used in this research

Health endpoints	Variables	Relative risk—RR (95% CI, 10 µg/m <sup>3</sup> )	References
<i>(1) Non-accidental mortality</i>			
Mortality due to all-cause respiratory diseases (RD) [J00-J99]	All ages, gender	1.0090 (1.0023, 1.0157); $p < 0.05$	Sui et al. (2021)
	Children (0–14)	1.0304 (1.0060, 1.0555); $p < 0.05$	Cai et al. (2019)
		1.0095 (1.0016, 1.0173); $p < 0.05$	Kan et al. (2007)
		1.0019 (0.9980, 1.0059); $p < 0.05$	W. Huang et al. (2012)
		1.0073 (1.0029, 1.0116); $p < 0.05$	Orellano et al. (2020)
		1.0382 (0.9900, 1.0890); $p < 0.05$	Nascimento et al. (2017)
Mortality due to all-cause cardio-vascular diseases (CVD) [I51.6]	All ages, gender	1.0093 (1.0060, 1.0126); $p < 0.05$	Sui et al. (2021)
	Male	1.0092 (1.0061, 1.0123); $p < 0.05$	Orellano et al. (2020)
	Female	1.0041 (1.0001, 1.0082); $p < 0.05$	Kan et al. (2007)
	Children (0–14), Adults (14–64)	1.0027 (1.0008, 1.0046); $p < 0.05$	W. Huang et al. (2012)
	Elderly (≥ 65)	1.0017 (0.9998, 1.0035); $p < 0.05$	C. Chen et al. (2018)
		1.0009 (0.9994, 1.0025); $p < 0.05$	C. Chen et al. (2018)
Mortality due to all-cause other circulatory system diseases (CSD) [I98.8]	Elderly (≥ 65), All gender	1.0044 (1.0004, 1.0085); $p < 0.05$	Qu et al. (2018)
	Elderly (≥ 65), Male	1.0040 (0.9984, 1.0096); $p < 0.05$	Ferreira et al. (2016)
	Elderly (≥ 65), Female	1.0065 (1.0011, 1.0119); $p < 0.05$	Qu et al. (2018)
<i>(2) Hospital admissions (HA)</i>			
<i>HA due to respiratory diseases (RD)</i>			
HA due to acute lower respiratory infection (Pneumonia) [J09-J18]	All gender, Children (0–14)	1.0153 (0.9861, 1.0453); $p < 0.05$	Luong et al. (2020)
HA due to acute lower respiratory infection (acute bronchiolitis) [J20-J22]	All gender, Children (0–14)	1.0868 (1.0396, 1.1362); $p < 0.05$	Luong et al. (2020)
HA due to chronic obstructive pulmonary disease (COPD) [J44]	All ages, gender	1.0590 (0.9620, 1.0450); $p < 0.05$	Pothirat et al. (2019)
HA due to community-acquired pneumonia (CAP)	All ages, gender	1.0030 (0.9620, 1.0450); $p < 0.05$	Pothirat et al. (2019)
<i>HA due to cardiovascular diseases (CVD)</i>			
HA due to heart failure (HF) [I50]	All ages, gender	1.0040 (0.9060, 1.1130); $p < 0.05$	Pothirat et al. (2019)
HA due to myocardial infarction (MI) [I21–I22]	All ages, gender	1.0070 (0.9080, 1.1160); $p < 0.05$	Pothirat et al. (2019)
HA due to stroke [I64]	All ages, gender	1.0500 (0.9860, 1.1180); $p < 0.05$	Pothirat et al. (2019)
<i>(3) Emergency visits (EV)</i>			
<i>EV due to respiratory diseases (RD)</i>			
EV due to chronic obstructive pulmonary disease (COPD) [J44]	All ages, gender	1.1240 (1.0300, 1.2270); $p < 0.05$	Pothirat et al. (2019)
EV due to community-acquired pneumonia (CAP)	All ages, gender	0.9920 (0.9500, 1.0360); $p < 0.05$	Pothirat et al. (2019)
<i>EV due to cardiovascular diseases (CVD)</i>			
EV due to heart failure (HF) [I50]	All ages, gender	1.0020 (0.9250, 1.0840); $p < 0.05$	Pothirat et al. (2019)
EV due to myocardial infarction (MI) [I21–I22]	All ages, gender	1.0070 (0.8470, 1.1960); $p < 0.05$	Pothirat et al. (2019)
EV due to stroke [I64]	All ages, gender	1.0480 (0.9720, 1.1300); $p < 0.05$	Pothirat et al. (2019)

(Bayat et al., 2019; Liu et al., 2021). In this study, the statistical data were applied from the 2018 Health Statistical Yearbooks published by the Vietnamese Ministry of Health (Ministry of Health, 2019), based on the number of cases of each health endpoint and population data, and

combined with references from the open-source website of the Institute for Health Metrics and Evaluation (IHME) on the website of GDP 2019 (Global Burden of Disease Collaborative Network, 2019), which is a dataset that provides annual, age-specific, sex-specific estimates for each of the



**Table 3** Summary of the baseline incidences of mortality and morbidity due to short-term PM<sub>2.5</sub> exposure that were used in this study

The groups of health endpoints	The types of health endpoints	Baseline incidences, $Y_0$
Premature mortality	Premature mortality due to all-caused respiratory diseases (RDs) [J00-J99] in all age groups	From 0 to 14 years old: 0.000005567 From 15 to 64 years old: 0.000005567 About 65 years old: 0.000006680
	Premature mortality due to all-cause cardiovascular diseases (CVD) [I51.6] in all age groups	From 0 to 14 years old: 0.000001533 From 15 to 64 years old: 0.000001533 About 65 years old: 0.000001840
	Premature mortality due to all-cause other circulatory system diseases (CSD) [I98.8] in the elderly group	About 65 years old: 0.000001260
Hospital admissions (HA)	HA due to acute lower respiratory infection (Pneumonia) [J09-J18] in the children group	From 0 to 14 years old: 0.000377778
	HA due to acute lower respiratory infection (acute bronchiolitis) [J20-J22] in the children group	From 0 to 14 years old: 0.000618778
	HA due to chronic obstructive pulmonary disease (COPD) [J44] in all age groups	From 0 to 14 years old: 0.000206259 From 15 to 64 years old: 0.000206259 About 65 years old: 0.000309389
	HA due to community-acquired pneumonia (CAP) in all age groups	From 0 to 14 years old: 0.000125926 From 15 to 64 years old: 0.000125926 About 65 years old: 0.000188889
	HA due to heart failure (HF) [I50] in all age groups	From 0 to 14 years old: 0.000151502 From 15 to 64 years old: 0.000151502 About 65 years old: 0.000227254
	HA due to myocardial infarction (MI) [I21-I22] in all age groups	From 0 to 14 years old: 0.000154416 From 15 to 64 years old: 0.000154416 About 65 years old: 0.000231624
	HA due to stroke [I64] in all age groups	From 0 to 14 years old: 0.000160593 From 15 to 64 years old: 0.000160593 About 65 years old: 0.000240889
Emergency visits (EV)	EV due to chronic obstructive pulmonary disease (COPD) [J44] in all age groups	From 0 to 14 years old: 0.000309389 From 15 to 64 years old: 0.000309389 About 65 years old: 0.000464083
	EV due to community-acquired pneumonia (CAP) in all age groups	From 0 to 14 years old: 0.000188889 From 15 to 64 years old: 0.000188889 About 65 years old: 0.000283333
	EV due to heart failure (HF) [I50] in all age groups	From 0 to 14 years old: 0.000227254 From 15 to 64 years old: 0.000227254 About 65 years old: 0.000340881
	EV due to myocardial infarction (MI) [I21-I22] in all age groups	From 0 to 14 years old: 0.000231624 From 15 to 64 years old: 0.000231624 About 65 years old: 0.000347436
	EV due to stroke [I64] in all age groups	From 0 to years old: 0.000240889 From 15 to 64 years old: 0.000240889 About 65 years old: 0.000361333

five age groups with categorical detail and also incorporates available studies (L. M. T. Luong et al., 2017; L. T. M. Luong et al., 2020; Bui et al., 2021) to determine the baseline incidence of premature deaths and morbidities in HCMC (Table 3).

#### Concentration—response function coefficients

The coefficients of CRFs or beta ( $\beta$ ) coefficients were determined based on the parameters from the original epidemiological studies for each type of health endpoint (Table 3). In

epidemiological studies, a Cox proportional hazards model or a log-linear model was used to calculate relative risk (RR) values, from which the beta coefficient values were calculated according to Eqs. (5), (6) and (7) (L. Chen et al., 2017; Sacks et al., 2018; Luo et al., 2020) as follows:

$$\beta = \frac{\ln(RR)}{\Delta C_{PM2.5}} \quad (4)$$

$$\beta_{\min} = \beta - (1.96 \times \sigma_{\beta}) \quad (5)$$

$$\beta_{\max} = \beta + (1.96 \times \sigma_{\beta}) \quad (6)$$

where RR values for related health endpoints including early deaths and morbidities can be found in the available epidemiological studies of health endpoint  $i$  due to short-term ambient  $PM_{2.5}$  exposure;  $\Delta C_{PM_{2.5}}$  is the change in ambient  $PM_{2.5}$  concentration, commonly  $\Delta C_{PM_{2.5}} = 10 \mu\text{g}/\text{m}^3$  (William Lemker Andreão et al., 2020) or  $1 \mu\text{g}/\text{m}^3$  (Zhao et al., 2019);  $\sigma_{\beta}$  (the standard error of  $\beta$ ) is calculated as the average of the standard errors implied by the reported lower ( $RR_{\min}$ ) and upper bounds ( $RR_{\max}$ ) of the RR in the corresponding epidemiologic studies.

For the health endpoint group (1) of premature mortality due to RDs, CVDs and other CSDs, beta coefficients were determined for all age and sex groups. This was similar for some cases in the health impact group (2) of hospital admission attributed to COPD, CAP, HF, MI, stroke and for all cases in the health effect group (3) of emergency visits. In particular, for the remaining cases in the health endpoint group (2), such as hospitalisation for acute LRIs due to pneumonia and acute bronchiolitis, the beta coefficients were only determined for the group of children (from 0 to 14 years) in both men and women.

### Economic valuation of $PM_{2.5}$ human health impacts

The value of a statistical life (VSL) is applied to assess the willingness of individuals to pay to reduce premature mortality risks (Yin et al., 2017b). To calculate the economic losses for the health endpoint of early death, a specific VSL was applied. However, there are currently no national studies assessing VSL loss; therefore, (9) was used to transfer unit health costs from international studies to the local context in HCMC, a “Transfer Benefits” approach as suggested by Narain and Sall (2016), Kim et al. (2019) and Johnson et al. (2015), with the main idea of the adjustment taking into account differences in income levels to expand the VSL (Yin et al., 2017b). Therefore, to determine the VSL for Vietnam, this study used VSL data from the Organisation for Cooperation and Development (OECD) ( $VSL_{OECD}$ ) as the starting value for calculation. Vietnam’s VSL value for the target year 2018 was estimated based on the base VSL starting in 2011 applied from Eq. (8) (Long et al., 2020; Bui et al., 2021s; Hammitt and Robinson, 2011).

$$VSL_{Vietnam-2011,USD} = VSL_{OECD-2011,USD} \times \left( \frac{Y_{Vietnam-2011}}{Y_{OECD-2011}} \right)^e \quad (7)$$

where  $VSL_{Vietnam-2011,USD}$  is the VSL of Vietnam in 2011 calculated in USD (USD in 2011);  $VSL_{OECD-2011,USD}$  is the background average VSL estimated from the WTP’s available research for OECD countries in 2011 calculated in USD (USD in 2011);  $Y_{Vietnam-2011}$  is the real GDP per capita at the purchasing power parity (PPP) of Vietnam in 2011 (USD

in 2011);  $Y_{OECD-2011}$  is the baseline real GDP per capita at the PPP of OECD countries in 2011 (USD in 2011); and  $e$  is the income elasticity of the VSL. In this study, coefficient  $e$  is equal to 1.3 (according to the OECD study) to reflect the significant difference between Vietnam and the developed countries of the OECD group in terms of income level (OECD, 2012; Long et al., 2020; Bui et al., 2021). The Eq. (9) below (Long et al., 2020; Bui et al., 2021; Kim et al., 2019) describes the VSL adjustment for the target year 2018 based on the baseline VSL of 2011 ( $VSL_{Vietnam-2011,USD}$ ).  $PPP_{2011-2018}$ , the PPP-adjusted exchange rate for each year of the 2011–2018 period, was applied to convert the US dollar (USD) to Vietnam dong (VND).

$$VSL_{Vietnam,2018(VND)} = (VSL_{Vietnam-2011,USD} \times (1 + \% \Delta P_{2011-2018})^e \times (1 + \% \Delta Y_{2011-2018})^e) \times PPP_{2018} \quad (8)$$

where  $VSL_{Vietnam,2018(VND)}$  is Vietnam’s VSL adjusted for the year 2018 calculated in VND;  $\Delta P_{2011-2018}$  is the percentage (%) that increased in consumer price from 2011 to 2018;  $\Delta Y_{2011-2018}$  is the percentage (%) that rose in the real GDP per capita growth between 2011 and 2018; and  $PPP_{2011-2018}$  is the PPP-adjusted exchange rate of the year 2011 by the World Bank data (2018) and the year 2018 from the World Bank data (2020). Thus, based on the above estimation framework, it was determined that the value of  $VSL_{Vietnam,2018}$  was 4788.95 million VND (equivalent to approximately 0.642 million USD on the basis of the exchange rate adjusted for purchasing power parity in 2018 or  $PPP_{2018}$ ).

For the economic valuation of losses related to disease treatment, the cost of illness (COI) approach has been applied, including the assessment of the costs of medical treatment, hospitalisation and emergency visit costs and productivity losses (Hoffmann et al., 2012; D. Huang et al., 2012; Quah & Boon, 2003; Kalkan et al., 2014). In this study, the total costs of the COI approach associated with the health endpoint groups (2) and (3) were determined using the average values from previous studies by Chinh Nguyen (2013), Long et al. (2020) and Bui et al. (2021). Finally, based on assessments of the public health impacts of  $PM_{2.5}$ , combined with the unit economic values for each type of health impact, the total risk of economic losses when quantified into money was estimated using Eq. (10) (Long et al., 2020; Bui et al., 2021; Ding et al., 2016; Yin et al., 2017) as follows:

$$EC = \sum_{i=1}^n \Delta Y_i \times Cost_i \quad (9)$$

where  $\Delta Y_i$  is the impact degree of the type of health effects  $i$ ,  $Cost_i$  is the value of the economic unit of the type of health endpoint  $i$  (Vietnam Dong, VND or US Dollar, USD) and  $EC$  is the total economic loss from the results of the health

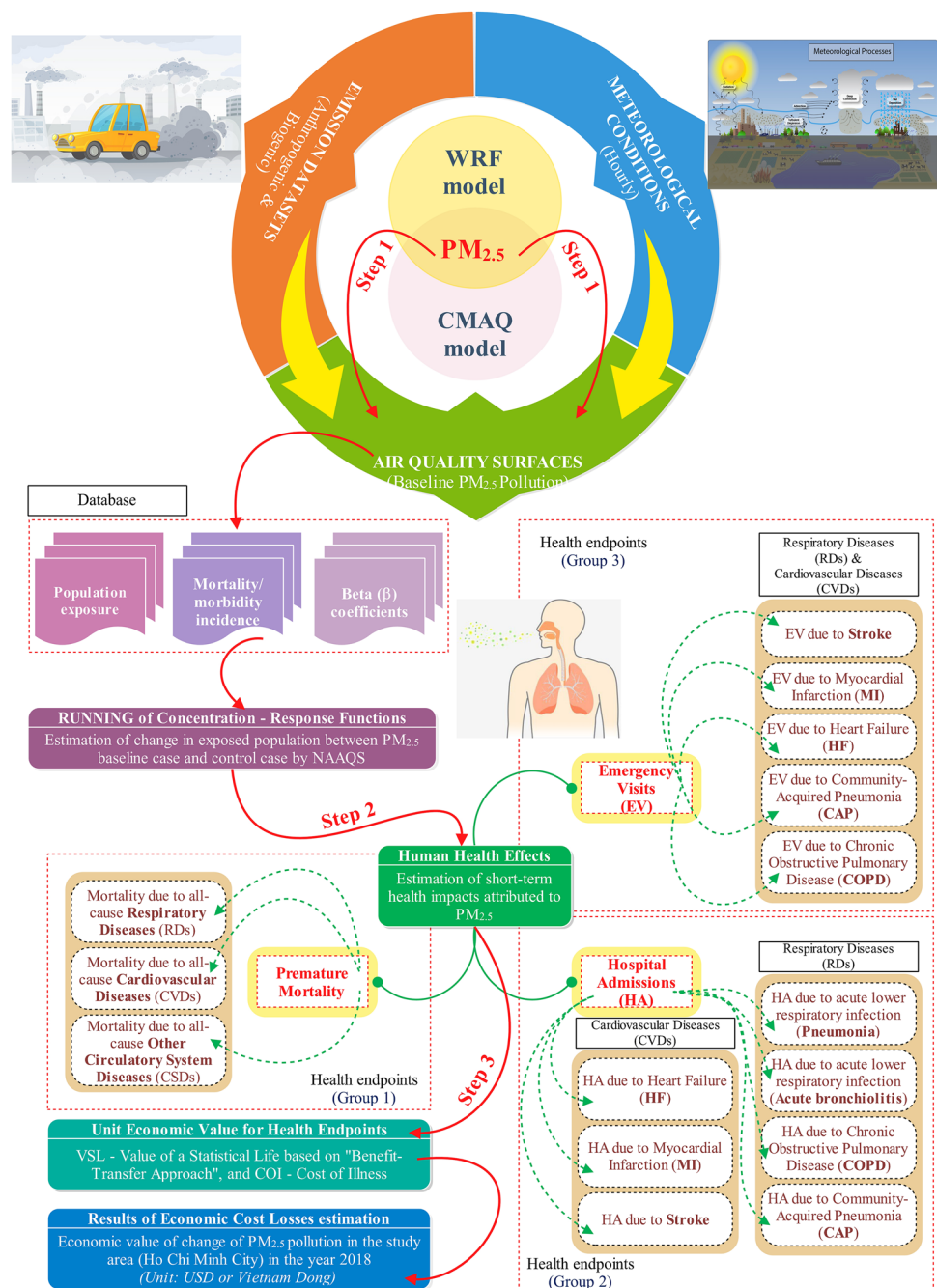
impact types (Vietnam Dong, VND or US dollar, USD). The result of the estimated *EC* value is relative to the total economic impact of public health effects due to exposure to  $PM_{2.5}$ , pollution in the ambient air in HCMC.

### Conceptual model and procedural steps

This study was carried out in three steps, as shown in Fig. 4. First, to build the  $PM_{2.5}$  concentration data set, WRF/CMAQ models were used. The WRF model

generates hourly meteorological datasets, while the CMAQ model generates the hourly  $PM_{2.5}$  levels. As a next step, a dataset of mean  $PM_{2.5}$  concentrations was used, combined with a dataset of population exposure estimates, short-term health classification, background rates of early mortality and morbidity and a set of concentration–response function coefficients for public health impact analysis. This is the end of step 2. Finally, the results of step two, combined with the VSL method, were used to assess economic losses.

**Fig. 4** Conceptual model and procedural steps



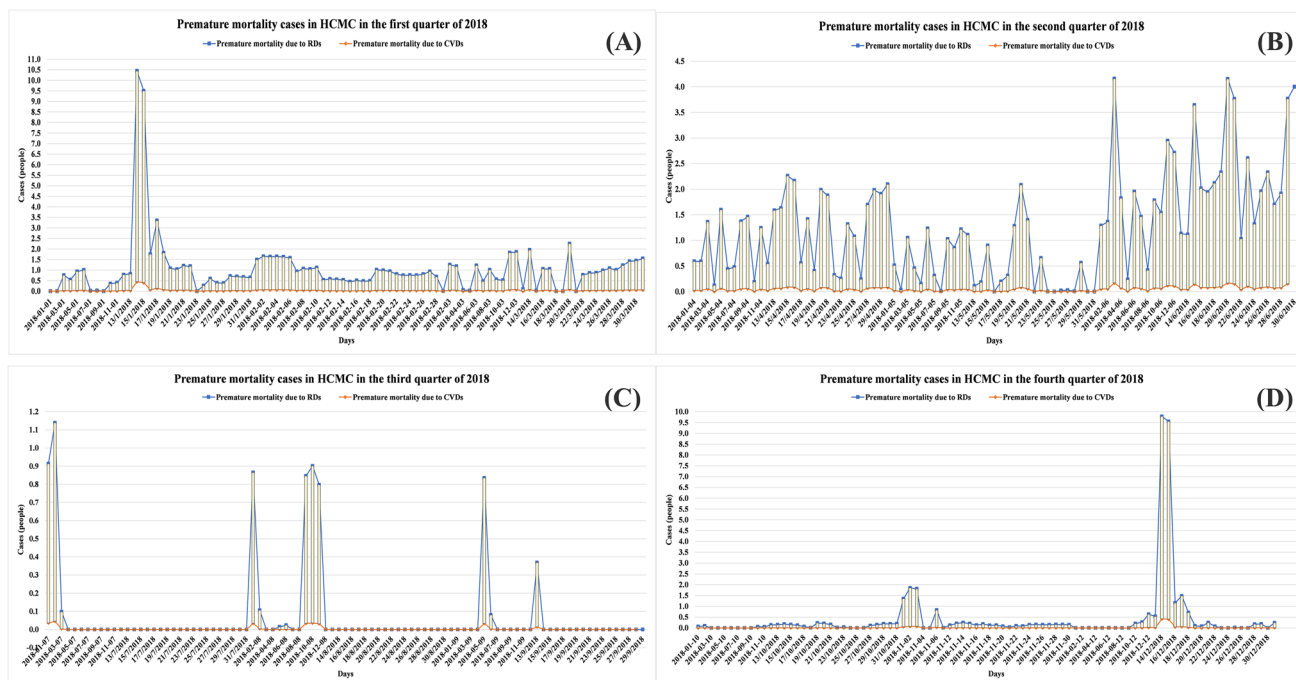
## Results

### Health impact analysis

Short-term (acute) health damage based on average daily  $PM_{2.5}$  concentrations exceeding the NAAQS threshold (24-h mean;  $50 \mu\text{m}^3$ ) was estimated. The results show that the total number of losses due to premature death is estimated at 174 (95% CI: 16; 340) cases; due to hospitalisation for inpatient treatment was 117,632 (95% CI: 231,850; 368,926) cases; and due to emergency examination was 162,455 (95% CI: -710.465; 531,153) cases. Table 3 summarises the level of health damage by month; each group of objects and each group of different types of health damage, especially for the damage group (1) all daily premature deaths (by respiratory and cardiovascular diseases (all causes) are illustrated in Fig. 5 A, B, C and D.

In the first quarter, there were 61 (95% CI: 5; 127) deaths from all causes. The details of the impact level in damage group (1) for each type of damage are as follows: 56,805 (95% CI: 6,077; 117,085), 3851 (95% CI: -1,133; 8,747) and 0.614 (95% CI: 0.056; 1.168) cases were due to respiratory, cardiovascular and other circulatory diseases of all causes, respectively. The level of damage was the highest in the first quarter, with the number of cases due to 27 cases of early death (95% CI: 5; 53). The second quarter was considered to have the highest total number of

premature deaths; specifically, the loss due to premature death was 78 (95% CI: 7; 164) cases, which was 1.28 times higher than that of the first quarter. A detailed assessment of the impact level in the damage group (1) for each type of damage in the second quarter showed that respiratory diseases still prevailed. The number of deaths due to respiratory diseases, cardiovascular and other circulatory systems by all causes reached 72.66 (95% CI: 8282; 152,116) cases, 4602 (95% CI: -1.349; 10,475) cases and 0.737 (95% CI: 0.067; 1.409) cases, respectively. In the third and fourth quarters, the total number of premature deaths due to  $PM_{2.5}$  decreased significantly compared to the first and second quarters, with a sharp decrease in the third quarter and a slight increase again in the fourth quarter. In the third quarter, the loss due to premature death was 5 (95% CI: 0; 7) cases, which was 15.60 times lower than that in the second quarter and 21 (95% CI: 4; 42) cases in the fourth quarter. Detailed assessment of the impact level by type of disease in the third quarter showed there were 4,678 (95% CI: 0.077; 6284) deaths due to respiratory diseases, 0.277 (95% CI: -0.081; 0.631) deaths from cardiovascular diseases and 0.045 (95% CI: 0.004; 0.085) deaths from other circulatory diseases; the fourth quarter had 16,254 (95% CI: 4.424; 29,142) deaths from respiratory diseases, 1508 (95% CI: -0.446; 3,409) deaths from cardiovascular diseases, and 0.238 (95% CI: 0.022; 0.449) deaths from other circulatory diseases (Table 4).



**Fig. 5** The total number of premature deaths due to short-term exposure to  $PM_{2.5}$  in quarters 1 (A), quarter 2 (B), quarter 3 (C) and quarter 4 (D) occurred in HCMC, 2018 (due to all respiratory and cardiovascular diseases of all causes)



**Table 4** Summary of the effects of the short-term exposure to PM<sub>2.5</sub> on human health in HCMC, 2018

Quarter in 2018	Group of short-term PM <sub>2.5</sub> exposed subjects	The types of health endpoint groups		
		The health endpoint group (1) of premature mortality	The health endpoint group (2) of hospital admissions	The health endpoint group (3) of emergency visits
The first quarter	Children (from 0 to 14 years old)	6 (95% CI: 0; 29)	29,004 (95% CI: – 18,243; 58,353)	16,568 (95% CI: – 79,658; 49,700)
	Adults and elderly (≥ 15 years old)	55 (95% CI: 5; 98)	25,309 (95% CI: – 76,280; 79,319)	50,336 (95% CI: – 240,425; 151,045)
	<b>Total</b>	61 (95% CI: 5; 127)	54,313 (95% CI: – 94,523; 137,672)	66,904 (95% CI: – 320,083; 200,745)
The second quarter	Children (from 0 to 14 years old)	13 (95% CI: 0; 53)	36,469 (95% CI: – 13,773; 73,966)	20,901 (95% CI: – 47,826; 62,254)
	Adults and elderly (≥ 15 years old)	65 (95% CI: 7; 111)	31,370 (95% CI: – 68,119; 100,218)	62,881 (95% CI: – 143,869; 187,291)
	<b>Total</b>	78 (95% CI: 7; 164)	67,839 (95% CI: – 81,892; 174,184)	83,782 (95% CI: – 191,695; 249,545)
The third quarter	Children (from 0 to 14 years old)	0 (95% CI: 0; 0)	2385 (95% CI: – 606; 5,045)	1411 (95% CI: – 2297; 4,454)
	Adults and elderly (≥ 15 years old)	5 (95% CI: 0; 7)	2005 (95% CI: – 3546; 6801)	4248 (95% CI: – 6912; 13,401)
	<b>Total</b>	5 (95% CI: 0; 7)	4,390 (95% CI: – 4152; 11,846)	5659 (95% CI: – 9209; 17,855)
The fourth quarter	Children (from 0 to 14 years old)	4 (95% CI: 0; 12)	9994 (95% CI: – 10,999; 19,191)	5486 (95% CI: – 47,273; 15,717)
	Adults and elderly (≥ 15 years old)	17 (95% CI: 4; 30)	8910 (95% CI: – 40,284; 26,033)	16,506 (95% CI: – 142,205; 47,291)
	<b>Total</b>	21 (95% CI: 4; 42)	18,904 (95% CI: – 51,283; 45,224)	21,992 (95% CI: – 189,478; 63,008)

In the damage group (2) in the first quarter, the number of inpatient hospitalisations accounted for a significant proportion of the total number of cases of short-term health damage (only after the number of emergency visits), at approximately 54,313 (95% CI: – 94,523; 137,672). Detailed assessment for each type of damage (disease) in the second quarter showed that there were 26,895 (95% CI: 903.9; 77,674.7) cases due to respiratory diseases with mainly 21,847.9 (95% CI: 6371.4; 34,522.2) cases due to COPD and 18,427.4 (95% CI: 9536.1; 26,020.9) cases due to acute bronchiolitis (ALRI) and 18,185.5 (95% CI: – 116,332.3; 82,650.2) cases due to cardiovascular diseases mainly due to stroke with 14,628.9 (95% CI: – 5152; 29,294.5) and 1369.4 (95% CI: – 54,979.5; 26,612) cases due to MI. The trend of inpatient hospitalisation changed significantly in the second, third and fourth quarters. The number of hospital admissions for inpatient treatment in the second quarter was 67,839 (95% CI: – 81,892; 174,184), 1.25 times higher than that in the first quarter; approximately 4390 (95% CI: – 4,152; 11,846) cases in the third quarter were 15.45 times lower than that in the second quarter, and approximately 18,904 (95% CI: – 51,283; 45,224) cases in the fourth quarter. A detailed assessment of the impact level for each type of damage in the second quarter resulted in

54,233.2 cases due to respiratory diseases (95% CI: 2,735.2; 97,023.7) with the majority being 27,219.9 (95% CI: 7731; 43,263.5) cases due to COPD and 23,079.6 (95% CI: 11,784.2; 32,530.6) cases due to acute bronchiolitis (ALRI). The number of cases due to cardiovascular diseases was 22,444.1 (95% CI: – 103,234.4; 105,028) mainly caused by stroke and MI with 18,167 (95% CI: – 6016.8; 36,690.7) and 2730.6 (CI: – 6,016.8; 36,690.7) cases, respectively. 95% CI: – 48,383.4; 34,830 cases. For the third and fourth quarters, the number of inpatient hospitalisations due to respiratory and cardiovascular diseases was 3532.8 (95% CI: 258.1; 6547); 1494.8 (95% CI: – 5379.5; 7190.9) cases in the third quarter and 14,904.3 (95% CI: – 721.2; 25,514) cases, 9159.2 (95% CI: – 222,683.6; 44,163) cases in the fourth quarter (Table 4).

In the damage group (3), there were 66,904 (95% CI: – 320,083; 200,745) cases, of which there were approximately 55,786.8 (95% CI: – 6692.1; 103,565.1) due to respiratory diseases of all causes. However, when evaluating the details based on the CRFs classified for each specific disease in the respiratory group (typically COPD), the number of cases tended to be higher, with 59,193.9 (95% CI: 18,158.8; 90,512.5) cases and only approximately 25,564.4 (95% CI: – 377,522.1; 139,895.8) cases due to



cardiovascular diseases (mainly stroke) (21,187.4 (95% CI: –16,537.7; 47,245.9), MI disease with 3404.1 (95% CI: –304,261; 60,823.5), HF with 973.1 (95% CI: –56,724.5; 31,826.4) cases (Table 4).

In the second quarter, the number of emergency visits reached 83,782 (95% CI: –191,695; 249,545), which was 1.26 times higher than in the first quarter; while in the third and fourth quarters, respectively, 5659 (95% CI: –9209; 17,855) cases were 14.81 times lower than in the second quarter, and 21,992 (95% CI: –189,478; 63,008) cases occurred in the quarter. In the second quarter, there were approximately 70,085 (95% CI: –6,075.8; 127,173.7) cases of respiratory diseases with 74,103.1 (95% CI: 22,307.5; 111,077) cases due to COPD and 31,549.1 (95% CI: –223,647; 174,688.6) due to cardiovascular diseases, mainly stroke. MI and HF with 26,289.4 (95% CI: –13,855.2; 59,644.2) cases, 4095.9 (95% CI: –150,004.4; 75,193.4) cases and 1163.7 (95% CI: –54,855.9; 39,851) cases, respectively. In the third quarter, the number of cases occurred as follows: respiratory diseases had 4798.8 (95% CI: –189.8; 9,344.3) cases, mainly due to COPD with 5033 (95% CI: 1391.5; 8332.9) cases, total cardiovascular disease with 2016.9 (95% CI: –10,901.7; 12,258.4) cases, with the majority due to stroke. MI and HF caused 1675.7 (95% CI: –1083; 4101.4) cases, 268.6 (95% CI: –6888.5; 5513.8) cases and 72.5 (95% CI: –2930.2; 2643.3) cases, respectively. In the fourth quarter, the total number of emergency visits due to respiratory diseases was 17,512 (95% CI: –5537.8; 29,055.7), mainly due to COPD 18,881.7 (95% CI: 6633.1; 27,347.8). The total number of cases due to cardiovascular diseases was 9159.2 (95% CI: –222,683.6; 44,163), with the majority of cases due to strokes. MI and HF caused 7465.4 (95% CI: –7067.8; 14,994.2) cases, 1313.4 (95% CI: –169,125.1; 18,569.4) cases and 380.4 (95% CI: –28,516.4; 10,599.4) cases, respectively. Thus, the total number of cases of premature death and disease treatment (including hospitalisation and emergency) in the second quarter of 2018 was the highest, with approximately 151,699 (95% CI: –273,580; 423,923) cases, followed by the first and fourth quarters with 121,278 (95% CI: –414,601; 338,544) cases and 40,917 (95% CI: –240,757; 108,274) cases, respectively, and the lowest was in the third quarter of 2018 with only approximately 10,054 (95% CI: –13,361; 29,708) cases (Table 4).

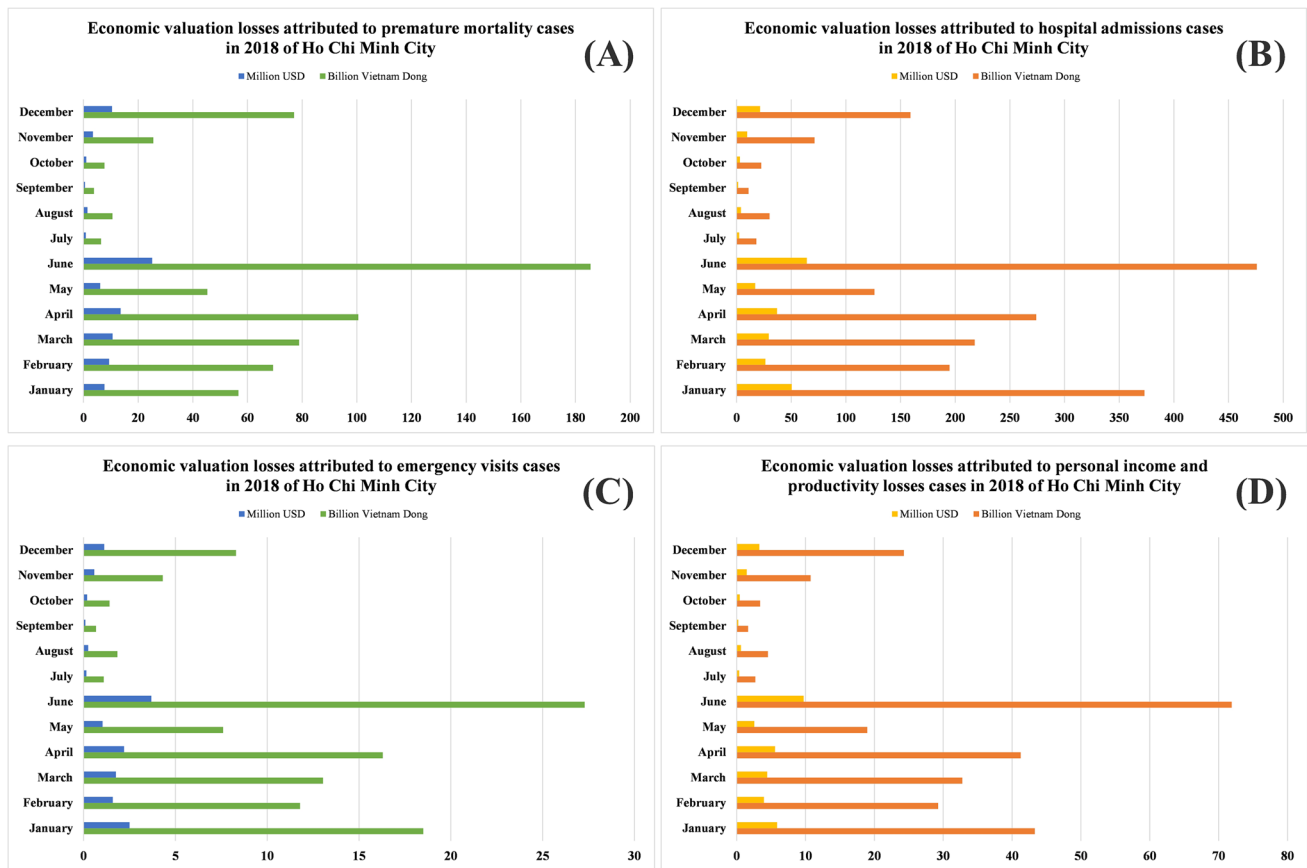
### Assessment of economic valuation loss

The economic (monetary) value lost is quantified here. The quantification is based on Vietnam's estimated 2018 VSL value of 4788.95 million VND, or approximately 642 million USD (converted to US\$ 2018) and COI cost assumptions (Chinh Nguyen, 2013; Bui et al., 2020, 2021). In the first quarter, the loss of economic value from short-term

impacts due to the risk of premature death was estimated at 204.89 billion VND (approximately 27.71 million USD), with an increasing trend from 1 January to March. The highest loss occurred in March at approximately 78.86 billion VND (equivalent to approximately 10.66 million USD). The loss of economic value due to the costs of hospitalisation for inpatient treatment and emergency visits reached approximately VND 785.48 billion (equivalent to approximately USD 106.27 million) and VND 43.33 billion (equivalent to approximately 5.85 million VND). Economic losses also occurred due to loss of income and reduced labour productivity in the adult population (from 15 to 64 years old), with the loss reaching approximately 100.60 billion VND (equivalent to approximately 13.61 million USD) and 4.72 billion VND (equivalent to approximately 631.21 thousand USD). Thus, the total economic value of the damage to public health caused by PM<sub>2.5</sub> in the first quarter was VND 1139.02 billion (equivalent to approximately USD 154.07 million), among which costs and losses due to hospitalisation for treatment inpatients and due to the number of premature deaths accounted for the highest proportion, accounting for approximately 68.96% and 17.99%, respectively (Fig. 6A).

For the second quarter (Fig. 6B), the economic value of losses due to premature deaths increased compared to the first quarter, whereas those in the third quarter decreased significantly compared to the first and second quarters. The second quarter reached approximately 331.35 billion VND (equivalent to approximately 44.81 million USD), 1.62 times higher than the first quarter and for the third quarter reached 20.86 billion VND (equivalent to 2.83 million USD), 9.82 times lower than the first quarter. The total economic losses due to the costs of hospitalisation for inpatient treatment and emergency visits in the second quarter were VND 875.94 billion (equivalent to approximately USD 118.45 million) and VND 51.18 billion (equivalent to approximately 6.92 million USD, respectively); for the third quarter, these values are VND 59.24 billion (approximately USD 8.02 million) and VND 3.61 billion (approximately USD 487.96 thousand) respectively (Fig. 6C). Total losses due to loss of income as well as decrease in labour productivity in both the second and third quarters reached approximately 132.11 billion VND (equivalent to approximately 17.86 million USD) and 8.90 billion VND (equivalent to 1.21 million USD), respectively. Thus, the costs of loss due to inpatient hospitalisation and premature death accounted for the highest proportion, reaching 63.05% and 23.75% of the total lost economic costs in the second quarter and the second quarter, respectively. III is 1483.19 billion VND (equivalent to approximately 199.38 million USD).

For the fourth quarter, the economic value of loss due to premature deaths increased slightly compared to the third quarter, reaching approximately 110.25 billion VND (equivalent to 14.91 million USD), which was 5.27 times



**Fig. 6** Estimation of the economic impacts of short-term  $PM_{2.5}$  exposure in HCMC in 2018 (including **A** premature mortality cases, **B** hospital admission cases, **C** emergency visit cases and **D** losses of personal income and productivity)

higher than that of the third quarter. Meanwhile, for the total economic loss due to the costs of hospitalisation for inpatient treatment and emergency visits in the fourth quarter, respectively, VND 252.94 billion (equivalent to approximately USD 34.21 million) was 4.94 times higher, respectively, compared to the third quarter and 14.02 billion dong (equivalent to approximately 1.89 million USD) 3.88 times higher than that of the third quarter. Similarly, the total loss due to loss of income as well as the decrease in labour productivity in the fourth quarter was approximately 4.29 times higher than in the third quarter, with the loss reaching approximately 38.40 billion VND (equivalent to approximately 5.19 million USD) (Fig. 6D).

Thus, the total value of economic losses due to  $PM_{2.5}$  daily in HCMC exceeded the meeting threshold of NAAQS (QCVN 05:2013/BTNMT) in 2018 by approximately 3038.31 billion VND (equivalent to 410.79 million USD). If compared with the value of GRDP of HCMC in 2018 (1225.6 trillion VND (HCMC Statistical Office, 2019a), the total economic loss value accounts for approximately 0.248% of the total GRDP.

## Uncertainty analysis

In this study, it is inevitable that some uncertainty points must be discussed. Among the types of health damage, premature deaths are considered the most significant, accounting for over 90% of the exposure to air pollution (mainly  $PM_{10}$  and  $PM_{2.5}$  dust), which has been demonstrated in several studies (Ho, 2017; Vu et al. 2020; Bui et al., 2021). Identifying categories of acute health damage to premature mortality from  $PM_{2.5}$ , and applying CRFs relationships suggests that the selection of time-series epidemiological studies has some limitations in comparing the use of cohort epidemiological studies based on quantitative studies. In this study, CRFs functions were based on cohort studies for analysis and evaluation. The relationship between  $PM_{2.5}$  pollution levels and early mortality in HCMC is based on epidemiological cohorts that have not been performed. Therefore, the  $\beta$  coefficients for the estimate of the damage group (1) early death were obtained from China and Brazil. This leads to an error that is usually higher. This is exactly the same for the estimates of the effects of the damage group (2) inpatient

hospitalisation (except for the type of hospitalisation loss due to acute lower respiratory tract infection by pneumonia and acute bronchiolitis in children aged 0–14 years) and damage group (3) emergency visits.

Second, the general application of CRFs to districts in HCMC for calculation is also an uncertainty factor in this study. The impact of  $PM_{2.5}$  pollution is not only caused by the total concentration level but is also significantly influenced by the aerosol chemical constituents of  $PM_{2.5}$  (such as  $PSO_4^{2-}$ ,  $PNO_3^-$  and  $PNH_4^+$ ), the size distribution of  $PM_{2.5}$  aerosols varies and the emission sources contribute from different geographical areas. This issue was discussed by Bart et al. (2015) and Wang et al. (2020a, b). It proved to be one of the factors that created errors in the calculation results. Therefore, further studies and future epidemiological studies need to focus on developing and updating CRFs functions for each district of HCMC; HCMC has classified each specific exposure group.

Selecting only  $PM_{2.5}$  as an indicator of air pollution, ignoring  $NO_x$ ,  $SO_2$  and other harmful compounds will lead to certain errors. In addition,  $SO_2$  and  $NO_x$  lead to the formation of secondary  $PM_{2.5}$ , which further increases the damage caused by particulate pollution. The current research results only consider the public health effects of  $PM_{2.5}$  pollution outside and have not mentioned the negative effects caused by exposure to  $PM_{2.5}$  indoors. The process of burning fuel in households, cooking for people's living, operation of decorative materials and household and personal care products can all emit gaseous and particulate pollutants. Thus, the assessment of types of health damage related to  $PM_{2.5}$ , when considering only outdoor exposure, does not fully and comprehensively reflect the impacts on human health. From there, developing CRFs that consider future indoor  $PM_{2.5}$  exposure in HCMC is an important basis for subsequent analysis and evaluation.

Third, research focuses on some types of damage, while many other types of health damage such as subclinical symptoms, reduced lung function and human health effects from exposure to infection causing lung cancer have not been included in the calculation and detailed analysis in this study because of the limitation of the accessible CRFs; however, in previous cohort epidemiological studies, possible associations have been demonstrated by Pope III et al. (2002).

Fourth, simulation of the combined coupled WRF/CMAQ models in the study was performed at a resolution of  $\sim 3.14 \times 3.14 \text{ km}^2$  over the entire HCMC area has a low resolution. One of the results of a case study by Wang et al. (2020a, b) demonstrated that estimating the number of premature deaths/illnesses is relatively sensitive to the resolution of the simulation system because of the persistence of time levels of  $PM_{2.5}$  is relatively long, and it has the potential to be transferred on a regional scale. In addition, the top-down emission inventory dataset used in this study has

errors in the level of detail when simulating heavily polluted and densely populated areas when there is no certainty in approximating the emission load of the precursors. Therefore, in future studies, higher-resolution models incorporating small-scale precursor emission load datasets should be encouraged as they may be more useful for estimations of health impact due to their smoothed resolution. Uncertainty may arise regarding the  $PM_{2.5}$  concentration values. In this study,  $PM_{2.5}$  measurement data was performed manually and intermittently for one month only at 7:30 am and 15:00 pm in the period from 8 to 12 measurement days from January to June 2018 at 8 locations, and at 9:00, 11:00, 13:00 and 15:00 in the period from 8 to 12 measuring days from July to December 2018. Therefore, uncertainty may arise from the simulation results of the WRF/CMAQ model because of the lack of data for detailed verification.

Fifth, the current level of change in  $PM_{2.5}$  concentrations is a sensitive parameter for both health impacts and loss cost estimates. Some case studies include Smith and Jantunen (2002) and R. T. Burnett et al. (2014) recommends using the threshold value recommended by the World Health Organisation WHO (with  $25 \mu\text{g}/\text{m}^3$ , 24-h average) (WHO, 2006); in this study, the cut-off value of NAAQS (with  $50 \text{ g}/\text{m}^3$ , 24-h average) was used, leading to lower health impact estimates than when WHO standards are applied.

Finally, a further uncertainty that needs to be discussed is the approach to assessing the economic benefits of premature deaths caused by  $PM_{2.5}$  pollution. The present study used the VSL value as the basis for calculating economic value losses for premature deaths; however, a certain limitation to the use of VSL values is the lack of adequate consideration of the age structure between the population susceptible to exposure to air pollution and the normal population size. This has caused the evaluation results with VSL values to tend to be higher than when using the same approach from the Years of Life Lost (YOLL) or the YOLL value. The WTP was surveyed in detail using different classifications in the study area.

## Discussion

This is the first study in Vietnam, specifically HCMC, to comprehensively evaluate the impact of  $PM_{2.5}$  pollution on public health in the form illnesses, such as premature death and hospitalisation, inpatient treatment and outpatient visits, and successfully quantify economic losses by applying combined simulation methods from the WRF/CMAQ and BenMAP-CE.

Our results show that the average  $PM_{2.5}$  concentration in 2018 was estimated to range from 55.8 to 65.3  $\mu\text{g}/\text{m}^3$ , which exceeded the threshold of NAAQS ( $25 \mu\text{g}/\text{m}^3$ ) by 2.23–2.61 times. Previous studies have also suggested similar  $PM_{2.5}$

pollution. Specifically, the report of the HCMC Department of Natural Resources and Environment states that the average  $PM_{2.5}$  concentration in 2016 was  $42.0 \mu\text{g}/\text{m}^3$  (1.68 times higher than NAAQS) (Nguyen et al., 2018), and by 2017, the annual average  $PM_{2.5}$  had decreased to  $29.6 \mu\text{g}/\text{m}^3$  (1.18 times higher than NAAQS) (Thu et al., 2018), and only  $23.0 \mu\text{g}/\text{m}^3$  (lower than NAAQS threshold) (Vu et al., 2020). Previous evidence combined with our research results demonstrates that  $PM_{2.5}$  pollution in HCMC tends to increase dramatically. Specifically, the average concentration in 2018 was increased by 1.33–1.55 times compared to that in 2016 and 1.89–2.21 times compared to that in 2017. The total number of premature deaths due to respiratory and cardiovascular diseases (all causes), when estimated according to the WHO Standard (WHO, 2006) in 2018, may reach 5,440 cases > 1136 cases in 2017, according to the results of Vu et al. (2020).

Furthermore, with the trend of days in 2018, the 24-h average concentration level in the dry season (January–April and December) is typically higher than that in the rainy season (May–November), similar to the trend in 2017 (Thu et al., 2018). Because the 24-h average  $PM_{2.5}$  concentration is a major determinant of the number of cases of short-term health problems, this leads to a much higher damage estimate in the dry season than in the wet season of 2018. Specifically, the total number of deaths was 105 (95% CI: 8; 188) in the dry season and > 69 (95% CI: 10; 117) in the rainy season. Moreover, the total number of hospitalisations for inpatient treatment was 68,349 (95% CI: – 126,269; 186,623) in the dry season and > 49,283 (95% CI: – 54,623; 126,804) in the rainy season, and the total number of emergency visits was 95,956 (95% CI: – 491,756; 292,881) in the dry season and > 66,498 (95% CI: – 147,900; 198,892) in the rainy season. However, when we comprehensively estimated short-term health losses from  $PM_{2.5}$ , including premature death, inpatient hospitalisation and outpatient visits, the total economic loss (approximately 3.050 trillion VND) is also much higher than the previous estimate of Dang et al. (2021) at 2.942 trillion VND (approximately 1.04 times higher) when assessing only the number of deaths from cardiovascular disease.

Moreover, our 2018 estimate of 174 (95% CI: 16–340) premature deaths is similar to the studies performed in China and Spain. In particular, Ding et al. (2016) reported that premature deaths occurred in 106 (95% CI: 44–162) cases in 2010 in Guangzhou, China, resulting in economic losses of approximately 150 million yuan (equivalent to 24 million USD). In Spain, there were approximately 30 premature deaths in 2007, which increased by 18% in 2014, as reported by Boldo et al. (2014), which is 4.92 times lower than that reported in our results. However, a wide range of similar studies in South Africa, India, Iran and Brazil showed several times higher values than those in this study. A study

by Altieri and Keen (2019) showed that the number of premature mortality cases in 2012 was 14,000, calculated on the basis of South Africa's NAAQS ( $20 \mu\text{g}/\text{m}^3$ ), 80.5 times higher than that in HCMC. The related damage valuation was estimated at roughly 14 billion USD (in 2011), which was also 33.9 times higher than in this study (Altieri and Keen, 2019). Manojkumar and Srimuruganandam (2021) reported that the  $PM_{2.5}$ -attributed premature deaths in 2019 reached 2.10 million individuals in India, in which the lowest number of deaths occurred mainly in the north-eastern states with 0.79 million people (4.54 times higher than in our study). According to the studies of Bayat et al. (2019) and Willian L. Andreão et al. (2018), public health effects and economic losses due to  $PM_{2.5}$  exposure were significantly higher than those in this study. In particular, the total number of mortality cases in 2017 was 7146 (95% CI: 6,596; 7,513) in Tehran and its 349 surrounding districts (41.07 times higher), and the total economic losses were up to 2.894 trillion USD (7.02 times higher) (Bayat et al., 2019). In São Paulo, Brazil, the numbers of premature deaths in 2000 and 2017 were 28,874 and 82,720, respectively (Willian L. Andreão et al., 2018), which were 165.94 and 475.40 times higher than in HCMC, respectively.

The results of this study provide convincing, up-to-date scientific evidence on the impact of  $PM_{2.5}$  pollution on public health. This information can be the basis for supporting the development of appropriate intervention policies to reduce  $PM_{2.5}$  levels according to the National Action Plan to 2025 (Decision on Approving the National Action Plan on Air Quality Management to 2020, Vision to 2025, 2016) and protect human health.

## Conclusion

The results of the study provide evidence that the concentration of  $PM_{2.5}$  in HCMC exceeds safe air quality standards of NAAQS and causes adverse health effects, contributing to increased mortality and morbidity as well as the significant economic burden. The specific results are as follows.

*First*, acute health impacts due to  $PM_{2.5}$  exposure mainly included premature mortality in 174 (95% CI: 16; 340) cases, hospitalisation for inpatient treatment in 117,632 (95% CI: 231,850; 368,926) cases and emergency visits in 162,455 (95% CI: – 710,465; 531,153) cases.

*Second*, the total economic damage caused by  $PM_{2.5}$  pollution in a year, quantified using 2018 as an example, was found to be approximately 3.03831 trillion VND (equivalent to approximately 410.79 million USD), accounting for 0.248% of the total gross regional domestic product (GRDP) value of HCMC, varying by month and quarter.

*Third*, a modelling framework that integrates models and databases was proposed to quantify the economic



damage resulting from short-term PM<sub>2.5</sub> pollution exposure. The model combines five groups of data on exposed population size, 24-h average PM<sub>2.5</sub> concentration, health endpoint types related to early deaths and morbidity, baseline incidents and unit economic values of health impact types calculated using the WRF/CMAQ simulation, human health impact assessment and economic loss assessment models for reduced health effects.

These results are an important source of information for health communication programs to reduce the harm caused by PM<sub>2.5</sub>, and a reference source for policymakers to develop warning strategies and reduce environmental pollution to protect public health. Specifically, the solutions aim to control and minimise PM<sub>2.5</sub> concentration in the main emission sources of HCMC, such as industry, energy, traffic and construction. Moreover, the applied research framework is considered a typical model that can be extended to many other localities in Vietnam to determine the status of PM<sub>2.5</sub> as required by the National Action Plan.

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

**Ethics approval** The authors declare that 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 publish my manuscript entitled “Evaluation of the annual economic costs associated with PM<sub>2.5</sub>-based health damage—A case study in Ho Chi Minh City, Vietnam” to the Air Quality, Atmosphere & Health (AIRQ).

**Consent for publication** I consent to publish my manuscript entitled “Evaluation of the annual economic costs associated with PM<sub>2.5</sub>-based health damage—A case study in Ho Chi Minh City, Vietnam” to the Air Quality, Atmosphere & Health (AIRQ).

**Competing interests** The authors declare no competing interests.

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