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Benefits of Short-term Premature Mortality Reduction Attributed to $PM_{2.5}$ Pollution: A Case Study in Long an Province, Vietnam

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Abstract

$PM_{2.5}$ pollution exposure is the leading cause of disease burden globally, especially in low- and middle-income countries, including Vietnam. Therefore, economic damage in this context must be quantified. Long An province in the Southern Key Economic (SKE) region was selected as a research area. This study aimed to evaluate $PM_{2.5}$-related human health effects causing early deaths attributable to respiratory, cardiovascular, and circulatory diseases in all ages and genders. Health end-points and health impact estimation, economic loss model, groups of $PM_{2.5}$ concentration data, data of exposed population, data of baseline premature mortality rate, and data of health impact functions were used. Hourly $PM_{2.5}$ concentration data sets were generated specifically using the coupled Weather Research and Forecasting Model (WRF)/Community Multiscale Air Quality Modelling System (CMAQ) models. Daily $PM_{2.5}$ pollution levels considered mainly in the dry season (from January to April 2018) resulted in 12.9 (95% CI − 0.6; 18.7) all-cause premature deaths per 100,000 population, of which 7.8 (95% CI 1.1; 7.1), 1.5 (95% CI − 0.2; 3.1), and 3.6 (95% CI − 1.5; 8.5) were due to respiratory diseases (RDs; 60.54%), cardiovascular diseases (CVDs; 11.81%), and circulatory system diseases (CSDs; 27.65%) per 100,000 population, respectively. The total economic losses due to acute $PM_{2.5}$ exposure-related premature mortality cases reached 62.0 (95% CI − 2.7; 89.6) billion VND, equivalent to 8.3 (95% CI − 0.4; 12.0) million USD. The study outcomes contributed remarkably to the generation and development of data sources for effectively managing ambient air quality in Long An.

$PM_{2.5}$ is a term used to refer to particulate matter with kinetic diameters less than or equal to 2.5 μm (Lei Chen et al. 2020a, b; Ha Chi and Kim Oanh 2021; Toledo et al. 2018), which is considered an important parameter in assessing the level of air pollution (Huy et al. 2018). $PM_{2.5}$ concentrations in Vietnam are often significantly higher than in many other cities of Europe and the United States (Gehrig & Buchmann 2003; Harrison et al. 2012; Levy and Hanna 2011), which indicates that Vietnamese people are breathing in air with high levels of pollutants (Hien et al. 2019).

According to data sources from AirNow (https://www.airnow.gov/), the 2016 annual mean $PM_{2.5}$ concentration in Hanoi City reached 50.5 μg/m^3, which was double the Vietnamese National Ambient Air Quality Standard (NAAQS). Furthermore, this annual average $PM_{2.5}$ concentration level was five times higher than the threshold recommended in the World Health Organization Air Quality Guidelines (WHO Guidelines) updated in 2005 for $PM_{2.5}$ (Thuy et al. 2018). By 2019, Hanoi City had surpassed Beijing City in the ranking of global capitals for $PM_{2.5}$ pollution and was also the most polluted city in Southeast Asia (excluding Indonesia) (IQAir, 2020). Meanwhile, the 2016 annual average $PM_{2.5}$ concentration was 29.6 μg/m^3 in Ho Chi Minh City (HCMC), which exceeded the corresponding thresholds in the NAAQS and WHO Guidelines by 1.2 and 3.0 times, respectively (Thu et al. 2018). In 2017, there were approximately 222 out of 365 days for which $PM_{2.5}$ levels in HCMC exceeded the 24-h mean threshold in the WHO Guidelines (25 μg/m^3) (Thu et al. 2018).

$PM_{2.5}$ pollution exposure has been shown to be the leading cause of the global burden of disease (Gao et al. 2021;

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Ke et al. 2022; Xing et al. 2021), especially in low and middle income countries (Forouzanfar et al. 2016; Nhung et al. 2018; Stanaway et al. 2018). Several epidemiological studies have been carried out in Vietnam to investigate the relationship between $PM_{2.5}$ levels and the risk of hospitalisation for children in Hanoi City (Luong et al. 2017; Nhung et al. 2013, 2019) and HCMC (Luong et al. 2020). A case study by Nhung et al. (2013) showed an increased risk of hospitalization for pneumonia by approximately 5.3% (95% CI 1.9; 8.8) and 6.3% (95% CI 1.1; 11.7) in children aged 0–117 years and 1–5 years, respectively, with an increase in the interquartile range (39.4 $\mu g/m^3$) of $PM_{2.5}$. Luong et al. (2017, 2020) reported that each 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration was associated with an increased risk of hospitalisation for respiratory illness in children under 5 years of age in Hanoi City, with approximately 2.3% (95% CI 1.2; 3.1) and 3.51% (95% CI 0.96; 6.12) acute lower respiratory tract infections in children in HCMC. Furthermore, short-term exposure to high concentration of $PM_{2.5}$ is associated with an increased risk of premature death in humans (Cohen et al. 2017; Landrigan et al. 2018; Lelieveld et al. 2015). Specifically, for every 10 $\mu g/m^3$ increase in $PM_{2.5}$, there is a direct increase in mortality rates from lung cancer and from cancer of the respiratory system by 0.07 (95% CI 0.004; 0.010) per 10,000 population and 0.08 (95% CI 0.005; 0.011) per 10,000 population in HCMC (Vien et al. 2021). According to an estimate by Dang et al. (2021) $PM_{2.5}$ directly caused 327 deaths from cardiovascular disease in HCMC, accounting for 6.4% of cardiovascular deaths (327/5,134) and 1.1% of all-cause deaths (327/29,173) in 2018. Furthermore, previous studies have reported that Vietnam's economic losses due to air pollution ranged from 10.8 to 13.2 billion USD per year, which contributed to around 5% of the Vietnamese gross domestic product (GDP) (IQAir, 2020). Specifically, economic losses due to air pollution in HCMC reached up to 125.46 million USD in 2018, accounting for 0.052% of Vietnam's GDP (Dang et al. 2021).

Vietnam is facing the problem of significant $PM_{2.5}$ risks, but there is still a lack of in-depth, interdisciplinary research on this topic. The objective of this study was to estimate the public health impacts of $PM_{2.5}$ pollution from premature deaths caused due to respiratory, cardiovascular, and circulatory diseases in all populations and age and sex groups. On this basis, the related preliminary economic loss impacts were quantified.

The 24-h average $PM_{2.5}$ pollution in the dry season (from January to April 2018) with a spatio-temporal resolution of 9 × 9 km grid obtained from the Weather Research and Forecasting Model (WRF)/Community Multiscale Air Quality Modelling System (CMAQ) was used in this study. Based on results from periodic manual monitoring studies carried out by the Department of Natural Resources and Environment of Long An from 2018 to 2021, the report on the environmental status of Long An from 2016 to 2020 (Long An DNRE 2020), and the research results of Bui et al. (2022), the concentration of $PM_{2.5}$ in the dry season was always much higher than in the wet season. Conversely, the $PM_{2.5}$ concentration in the wet season from 2016 to 2021 was continuously lower than the threshold value of NAAQS (known as QCVN 05:2013/BTNMT). Furthermore, unfavorable climatic conditions during the dry season in Vietnam have exacerbated the issue of $PM_{2.5}$ pollution (Thu et al. 2018). In particular, calm periods, low planetary boundary layer (PBL) levels, frequent daytime temperature inversions, and low precipitation have reduced the diffusion of $PM_{2.5}$ pollutant precursors, unable to escape to high altitudes and transported far away from other areas. This caused the concentration of $PM_{2.5}$ to increase significantly in the dry season. Moreover, during the dry season, hot weather and prolonged high temperatures (or heat waves) can lead to hazardous air quality situations. Therefore, the dry season was the time of significant $PM_{2.5}$ pollution in Long An and is one of the most urgent issues that need to be evaluated to have a basis for formulating future mitigation measures. After that, the Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE) model was applied to estimate public health impacts. These studies were carried out in Long An Province, one of the typical provinces in the SKE region.

Materials and Methods

Study Area

Information and data describing Long An province are provided in Figs. 1 and 2. In particular, Fig. 1 presents the geographical location of the study area within the Mekong Delta region (MDR) in Vietnam and the population size in each district/city of Long An. Figure 2A shows the structure of the population size (A1) and area (A2) in each district/city of Long An. Figure 2B reports the Provincial Competitiveness Index (PCI) values of Long An and other provinces/cities in MDR from 2008 to 2019. Long An is considered the gateway connecting MDR with southeast provinces in Vietnam and is located in both the SKE region and MDR (Fig. 1). The total area of Long An is approximately 4,495 km^2 (Long An Provincial Statistics Office 2021); Tan An Town is the smallest with approximately 82 km^2 (accounting for 1.82% of the province) of area, whereas Tan Hung District is the largest with approximately 502 km^2 (contributing to 11.17%) of area, as shown in Fig. 2-A (A2). By 2018, the population of Long An was 1,678,929 people, contributing to 9% of the MDR's population (GSO 2019; Long An Provincial Statistics Office

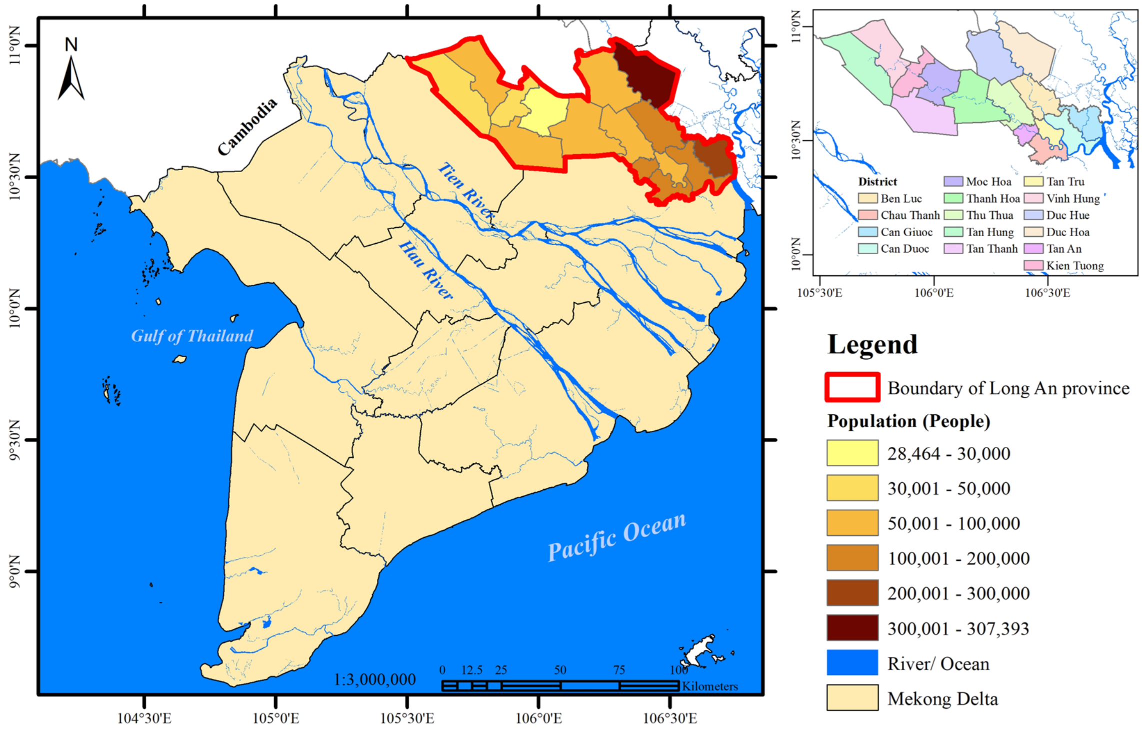


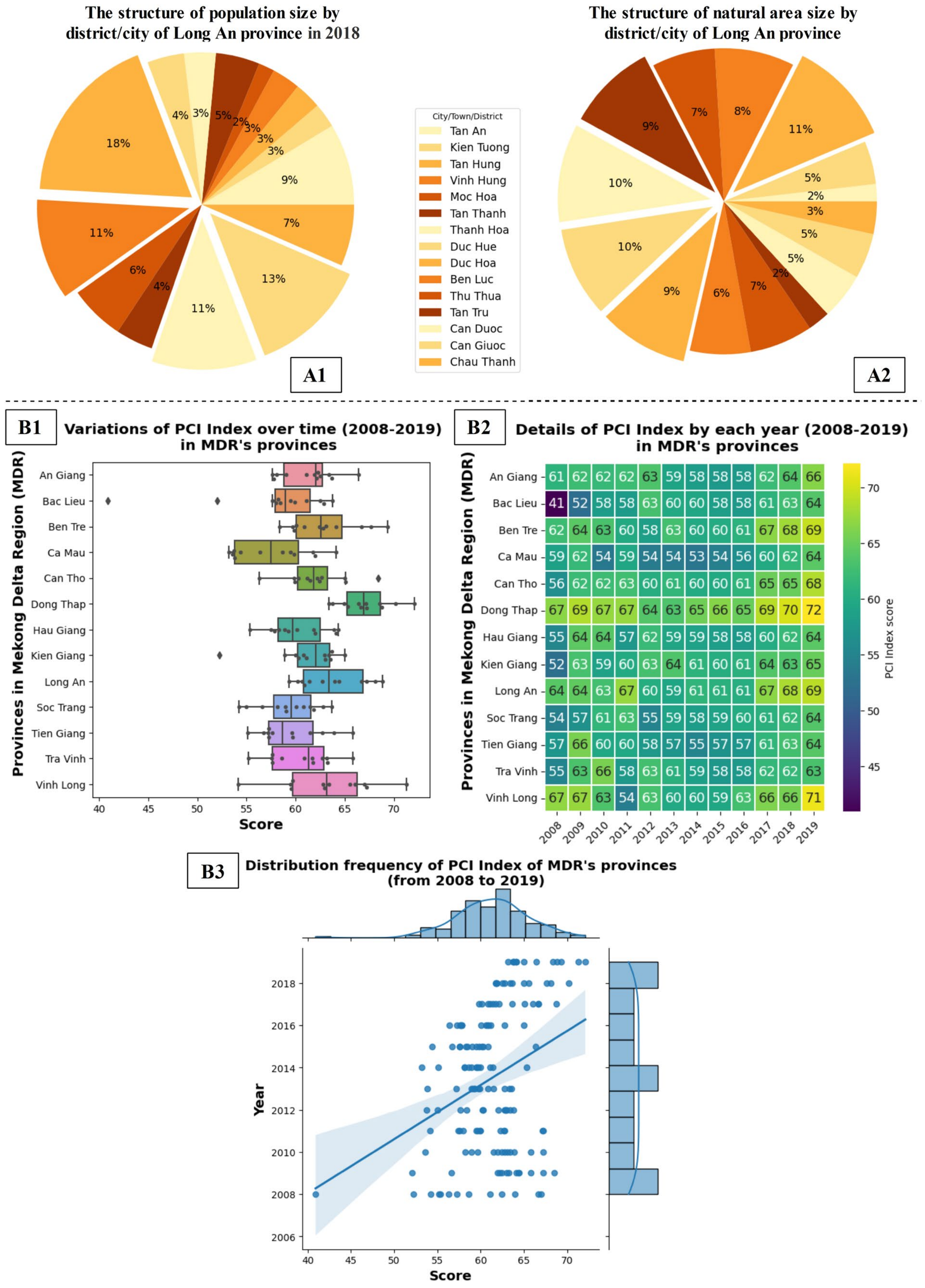
Fig. 1 The geographical location of the study area – Long An province

2021), as shown in Fig. 2-A (A1). The economic growth rate of Long An is fast, and there are prominent improvements in several essential indicators of the quality of economic growth, such as shifting the economic structure in a positive direction, deepening international economic integration, and improving the quality of life (Fan et al. 2019; Khanh 2020). Moreover, the gross regional domestic product of Long An reached roughly 78 trillion VND in 2018, with an economic growth rate of 10.36% compared to that in 2017 (9.53%) (GSO 2019). Between 2008 and 2019, the PCI scores of Long An ranged from 59.36 to 68.82 (average 63.70) (Malesky et al. 2020; Vietnam VCCI, 2021), as shown in Fig. 2-B (diagrams (B1) and (B2)). These PCI values reflect the private sector development and improvement in the socio-economic status of Long An. Overall, there are six levels to assess PCI ranking: the ranking scores of very low, low, mid-low, mid-high, high, and excellent levels are 0.0–58.0, 58.0–61.0, 61.0–63.5, 63.5–66.5, 66.5–70.0, and 70.0–100.0, respectively (Vietnam VCCI, 2021). Long An province's PCI scores continuously achieved high levels from 2014 to 2019. Specifically, the PCI scores ranked second out of thirteen provinces of the MDR in 2014, 2015, 2017, and 2018 (diagram (B3) in Fig. 2-B) (Malesky et al. 2020). The 2018 PCI score of Long An was notably third among all provinces/cities in Vietnam (Malesky et al. 2020).

Models

Health Endpoints and Health Impact Estimation

Short-term direct exposure to $PM_{2.5}$ pollution is considered one of the major risk factors for respiratory diseases (RDs), including lung cancer, cardiovascular diseases (CVDs), and other circulatory system diseases (CSDs) (Kampa and Castanas 2008). This health problem is one of the leading causes of premature death and is defined as the health endpoint (Sacks et al. 2018). Further, following the basis of the International Classification of Diseases, 10th Revision and excluding circumstances that may overlap with other health effects (ICD-10) (ICD-10, 2016), these diseases are identified as all-cause respiratory diseases [I00-I99, excluding I88] and all-cause other circulatory system diseases [I98.8]. Many studies have demonstrated that premature mortality accounts for the highest proportion (up to about 85%) of all forms of health loss due to $PM_{2.5}$ exposure (Guan et al. 2019; Quan and Shiqiu 2015; Xie et al. 2016). Therefore, the scope of this study was to assess the number of premature deaths (all causes) of the three diseases mentioned above (RDs, CVDs, and CSDs) related to $PM_{2.5}$ exposure. Estimates of health losses due to short-term exposure to $PM_{2.5}$ pollution were developed based on the theoretical basis of the Environmental Benefits Mapping and Analysis Program



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
An Giang	61	62	62	62	63	59	58	58	58	62	64	66
Bac Lieu	41	52	58	58	63	60	60	58	58	61	63	64
Ben Tre	62	64	63	60	58	63	60	60	61	67	68	69
Ca Mau	59	62	54	59	54	54	53	54	56	60	62	64
Can Tho	56	62	62	63	60	61	60	60	61	65	65	68
Dong Thap	67	69	67	67	64	63	65	66	65	69	70	72
Hau Giang	55	64	64	57	62	59	59	58	58	60	62	64
Kien Giang	52	63	59	60	63	64	61	60	61	64	63	65
Long An	64	64	63	67	60	59	61	61	61	67	68	69
Soc Trang	54	57	61	63	55	59	58	59	60	61	62	64
Tien Giang	57	66	60	60	58	57	55	57	57	61	63	64
Tra Vinh	55	63	66	58	63	61	59	58	58	62	62	63
Vinh Long	67	67	63	54	63	60	60	59	63	66	66	71

◀**Fig. 2** Description of socio-economic characteristics of Long An province: **a** the structure of the population size and natural area size by each district/city, and **b** PCI values of MDR's provinces from 2008 to 2019

(BenMAP) model (Sacks et al. 2018), which is similar to several previous studies (Li Chen et al. 2017a, b; Linh Nguyen et al. 2022; Sacks et al. 2018) and our own published studies (Bui et al. 2020, 2021; Le Khanh et al. 2022) applying the following Eqs. (1) and (2):

$$HL_{Dist/City/Town}(C) = S_{Dist/City/Town} \cdot P_{Dist/City/Town} \cdot \sum_{i=1}^{n} BM_{Dist/City/Town,i} \left(1 - \frac{1}{HR_{Dist/City/Town,i}}\right) \quad (1)$$

where $HL_{Dist/City/Town}(C)$ is the total loss of public health (total number of premature deaths) related to $PM_{2.5}$ pollution; specifically *Dist/City/Town* are districts in Long An province (Table S1). In Eqs. (1) and (2), i is the type of health damage considered; $S_{Dist/City/Town}$ is the percentage of days heavily polluted with $PM_{2.5}$ during the review period in the dry season of 2018, in the districts, cities, and towns in Long An province; $P_{Dist/City/Town}$ is the background mortality rate for damage type i; and $BM_{Dist/City/Town,i}$ are the health risk values for each type of health loss i. *HR* (health risk) values usually have a nonlinear relationship for high levels of $PM_{2.5}$ pollution (Hoek et al. 2013) and are calculated according to Eq. (2) (Burnett et al. 2014; F. Lu et al. 2015; Xie et al. 2016):

$$HR_{Dist/City/Town,i} = \exp\left[\left(C_{Dist/City/Town} - C_0\right) \cdot \beta_i\right] \quad (2)$$

where, β_i is the coefficient of the exposure–response for health damage type i, where β_i, $\beta_{i,lowerbound}$ (lower bound), and $\beta_{i,upperbound}$ (upper bound) (with a confidence level of 95% CI) are determined through relative risk (RR) values (Cai et al. 2019; C. Chen et al. 2018; Ferreira et al. 2016; Huang et al. 2012; Kan et al. 2007; Nascimento et al. 2017; Orellano et al. 2020; Qu et al. 2018; Sui et al. 2021); $C_{Dist/City/Town}$ is the 24-h average, C_0 is the $PM_{2.5}$ concentration level of the days; is the average 24-h threshold of $PM_{2.5}$ concentration that is not harmful to human health. In this study $C_0 = 50\ \mu g/m^3$ according to the Vietnamese National Ambient Air Quality Standard (NAAQS), known as the standard threshold of QCVN 05:2013/BTNTMT. The process of estimating the coefficients of the exposure-interaction functions (β_i, $\beta_{i,lowerbound}$, and $\beta_{i,upperbound}$) is performed in a manner similar to that described in the studies by Bui et al. (2021); Li Chen et al. (2017a, b); and Le Khanh et al. (2022).

Modelling Changes in $PM_{2.5}$ Concentration Distributions

The CMAQ simulation is a modern scientific method widely used today, helping to analyse and evaluate physical and chemical processes to determine the transport, formation, and deposition of $PM_{2.5}$ (Luecken et al. 2019; Ring et al. 2018). In this study, the Weather Research and Forecasting (WRF) model version.3.8 (Byun and Schere 2006; Skamarock et al. 2008) and CMAQ air quality model version 5.2.1 (Borge et al. 2014; Hu et al. 2015; Lang et al. 2017) were used to simulate the distribution of $PM_{2.5}$ concentrations over the study area. The selected simulation period was the dry season period of 2018, from 00:00 local standard time (LST) of January 1, 2018 to 23:00 local standard time (LST) of the following day April 30, 2018. The dates in the dry season were selected because the measurement results and publications on public health in Vietnam were published for this period (Hien et al. 2019; Long An DNRE 2020; Thu et al. 2018; Thuy et al. 2018). Local environmental agencies warned that pollution levels exceeding NAAQS on days in the dry season were higher than those in the wet season (from May to November). To focus the analysis and evaluate only the impact caused by local pollutants, the zero-out emission method was applied during the development of emission data for the CMAQ simulations (Chen et al. 2017a, b; Pitiranggon et al. 2021; Zhang et al. 2021). In particular, the input emission data for CMAQ simulations were turned off for the anthropogenic emissions of $PM_{2.5}$ precursors of all grid cells out of Long An province. Based on the inventory of emission sources, primary emissions of $PM_{2.5}$ and precursor species of $PM_{2.5}$ were estimated and spatially distributed over the entire study area. The effectiveness of simulating $PM_{2.5}$ concentration from the CMAQ model has also been validated at the measurement locations (Table S2) through statistical indicators of normalised mean bias (NMB), normalised mean gross error (NME), and correlation coefficient (COR) (Emery et al. 2017), all of which ensure the applicable conditions. NMB ranged from − 3.17 to 3.88%, NME from 3.79 to 10.53%, and COR from 0.91 to 0.97 under conditions including NMB < ±30%, NME < 50%, and COR > 0.40 (Eder and Yu 2006; Morris et al. 2005) (Table S3).

To generate a dataset about short-term exposure levels for each district/city/town ($C_{Dist/City/Town}$) in Long An, daily mean $PM_{2.5}$ concentration levels were estimated by the ArcGIS 10.4.1 tool based on grid cell-based hourly $PM_{2.5}$ results from CMAQ simulations for the 2018 dry season. The $C_{Dist/City/Town}$ from January to April 2018 in this study area is considered a crucial input parameter, which is decisive for the assessment of human health effects and economic losses using public health damage models.

Economic Loss Model

The Value of a Statistical Life (VSL) represents an economic value used to quantify how well a group of people would pay to mitigate the risk of premature death in a population (Persson et al. 2001; Viscusi and Aldy 2003; Yin et al. 2017a, b). It is one of the simplest approaches to assess the economic impact of health losses by multiplying the number of premature deaths with a calculated locally determined VSL (Bayat et al. 2019). In this study, the selected value of VSL in 2018 as the unit economic value of health effects was obtained from research conducted by Bui et al. (2021) as well as Le Khanh et al. (2022). Values were adjusted based on purchasing power parity (PPP), in Eq. (3), according to the "Benefit-Transfer Approach" (Hammitt and Robinson 2011; Johnson et al. 2015; Kim et al. 2019; Narain and Sall 2016). In 2018, the VSL value of the study area was determined as VND 4,788.95 million (approximately USD 0.642 million). Furthermore, based on the assessment of losses of various types of health damage, the total Economic Health Losses (EHL) (in equation [4]) due to short-term exposure to $PM_{2.5}$ was assessed according to the economic value model for health loss (Ding et al. 2016; X. Lu et al. 2019; J. Wang et al. 2015a, b; H. Yin et al. 2017a, b):

$$VSL_{VN} = VSL_{OECD} \cdot \left(\frac{Y_{VN}}{Y_{OECD}}\right)^{e} \tag{3}$$

$$EHL = \sum EHL_{Dist/City/Town} = \sum HL_{Dist/City/Town}(C) \cdot VSL_{Dist/City/Town} \tag{4}$$

where VSL_{VN} is the value of Vietnam's VSL in USD; VSL_{OECD} is the mean baseline VSL estimated from sample WTP studies in OECD countries; Y_{VN} is GDP per capita based on Vietnam's PPP in USD; and Y_{OECD} is the GDP per capita base model of the OECD country group based on PPP in USD. In Eq. (3), e is the income volatility coefficient of VSL, which is chosen to be 1.3, to reflect the significant disparity between Vietnam and developed countries in the OECD group in terms of income levels (L. T. Bui et al. 2020, 2021; OECD 2012). $EHL_{Dist/City/Town}(C)$ are the economic values of the public health loss (early death) from average daily exposure to $PM_{2.5}$ pollution, also known as the health loss economic value for the districts/Cities/Towns of the study area, respectively; and $VSL_{Dist/City/Town}$ is the statistical life value of the districts/Cities/Towns, respectively, of the study area that the public is willing to pay to minimise the risk of premature death. All quantified health loss values were estimated and converted to monetary equivalents in 2018 (VND and USD).

Data

Population Exposure Data

The impact of short-term $PM_{2.5}$ pollution on people's health in the study area of the entire Long An province was analysed and evaluated; therefore, size of the exposed population in Long An province in 2018 was calculated. Population data were obtained from the Long An Statistical Yearbook for the year 2020 (Long An Provincial Statistics Office 2021). In this study, calculations were performed for all age- and sex-groups. The 24-h population-weighted average $PM_{2.5}$ concentration level ($C_{Dist/City/Town}\prime$) for all districts/Cities/Towns combined in 2018 of the study area was also transformed by Eq. (5) (Fann et al. 2018):

$$C_{Dist/City/Town}\prime = \frac{\sum_{j=1}^{13} C_{Dist/City/Town} \cdot P_{Dist/City/Town}}{P} \tag{5}$$

where $C_{Dist/City/Town}$ is the 24-h average $PM_{2.5}$ concentration level in each district/city/town of Long An province in the dry season of 2018, $P_{Dist/City/Town}$ is the population of the districts/Cities/Towns of the province, respectively, and P is the total population of the entire Long An province in 2018.

Data of Baseline Premature Mortality Rate

The baseline mortality rate ($BM_{Dist/City/Town,i}$) is the probability that the population of an area is at risk of premature death from all causes within a given period (Shang et al. 2013). The dataset $BM_{Dist/City/Town,i}$ of each type of health loss in 2018 for all gender and age groups in the study area was collected from the National Health Statistics Yearbook period 2017–2020 (https://moh.gov.vn/), as announced by the Ministry of Health of Vietnam (Ministry of Health 2019). Furthermore, for compatibility with the calculations of short-term exposure to $PM_{2.5}$ pollution, the daily value (person/day) was estimated by dividing by 365 days (Shang et al. 2013). This is an important input data source for health loss estimation models. The baseline mortality ($BM_{Dist/City/Town,i}$) for the identified damage categories, i.e., early deaths from RDs, CVDs, and CSDs occurring in the study area were 0.00007987, 0.00004142, and 0.00004142, respectively (Ministry of Health 2019).

Health Impact Function Data

Epidemiological studies that construct exposure—interaction (E-R) functions to assess the degree of health risk (HR) by the impact of exposure to $PM_{2.5}$ short term pollution (24-h average values) are still limited (Li et al. 2019). In this

Table 1 Summary of the available epidemiological studies linking short-term $PM_{2.5}$ exposure to premature mortality estimation used in this study

Health endpoints	Variables	Relative risk—RR (95% CI, 10 μg/m^3)	References
Mortality due to all-cause respiratory diseases (RDs) [J00-J99]	All ages, gender Children (0–14)	1.0090 (1.0023, 1.0157); 1.0304 (1.0060, 1.0555); 1.0095 (1.0016, 1.0173); 1.0019 (0.9980, 1.0059); 1.0073 (1.0029, 1.0116); 1.0382 (0.9900, 1.0890)	Sui et al. (2021), Cai et al. (2019), Kan et al. (2007), Huang et al. (2012), Orellano et al. 2020), Nascimento et al. (2017)
Mortality due to all-cause cardiovascular diseases (CVDs) [I00-I99, excepting I88]	All ages, gender Male Female Children (0–14), Adults (14–64) Elderly (≥ 65)	1.0093 (1.0060, 1.0126); 1.0092 (1.0061, 1.0123); 1.0041 (1.0001, 1.0082); 1.0027 (1.0008, 1.0046); 1.0017 (0.9998, 1.0035); 1.0009 (0.9994, 1.0025); 1.0013 (0.9980, 1.0046); 1.0029 (0.9999, 1.0059)	Sui et al. (2021), Orellano et al. (2020), Kan et al. (2007), Huang et al. (2012), Chen et al. (2018), Chen et al. (2018), Chen et al. (2018) Chen et al. (2018)
Mortality due to all-cause other circulatory system diseases (CSDs) [I98.8]	Elderly (≥ 65), All gender Elderly (≥ 65), Male Elderly (≥ 65), Female	1.0044 (1.0004, 1.0085); 1.1960 (1.0640, 1.3460); 1.0040 (0.9984, 1.0096); 1.0065 (1.0011, 1.0119)	Qu et al. (2018) Ferreira et al. (2016) Qu et al. (2018) Qu et al. (2018)

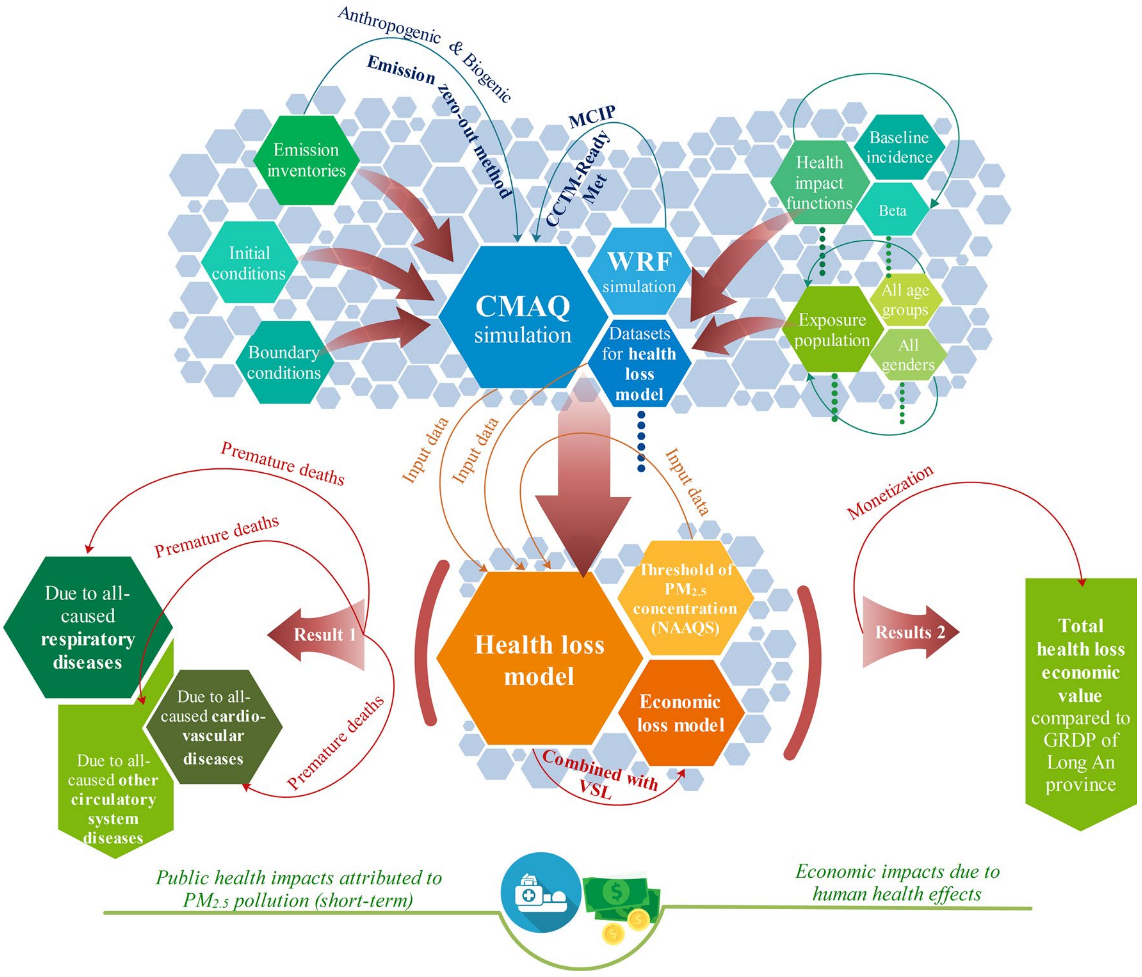


Fig. 3 Research framework

Table 2 Modeling performance based on estimated statistical metrics, including normalized mean bias (NMB), normalized mean gross error (NME), and the correlation coefficient R at the air quality monitoring sites in the domain D02 in the dry season of 2018

Sign/Benchmark	NMB	NME	Correlation coefficient R
DOSTE	0.6204	5.2614	0.9568
TN	− 0.3635	4.7141	0.9383
HB	− 3.1731	4.6744	0.9786
BT	-0.3670	3.7866	0.9429
ZOO	0.7773	4.0573	0.9762
Q2	2.7859	5.2368	0.9764
TSH	1.4043	5.5944	0.9540
TB	3.8871	10.5271	0.9102
Benchmarks	− 30% < NMB < + 30%	NME < 50%	$R > 0.40$

study, the RR values were selected from available epidemiological studies published in other regions of (Cai et al. 2019; C. Chen et al. 2018; Ferreira et al. 2016; Huang et al. 2012; Kan et al. 2007; Nascimento et al. 2017; Orellano et al. 2020; Qu et al. 2018; Sui et al. 2021). These localities also had many similarities in terms of speed, level of socio-economic development, and population distribution density in the study area. Table 1 presents the RR values with 95% CI from the published results of epidemiological studies. This is the basis for determining the values of the coefficients of the exposure-interaction functions (β_i, $\beta_{i,lowerbound}$, and $\beta_{i,upperbound}$).

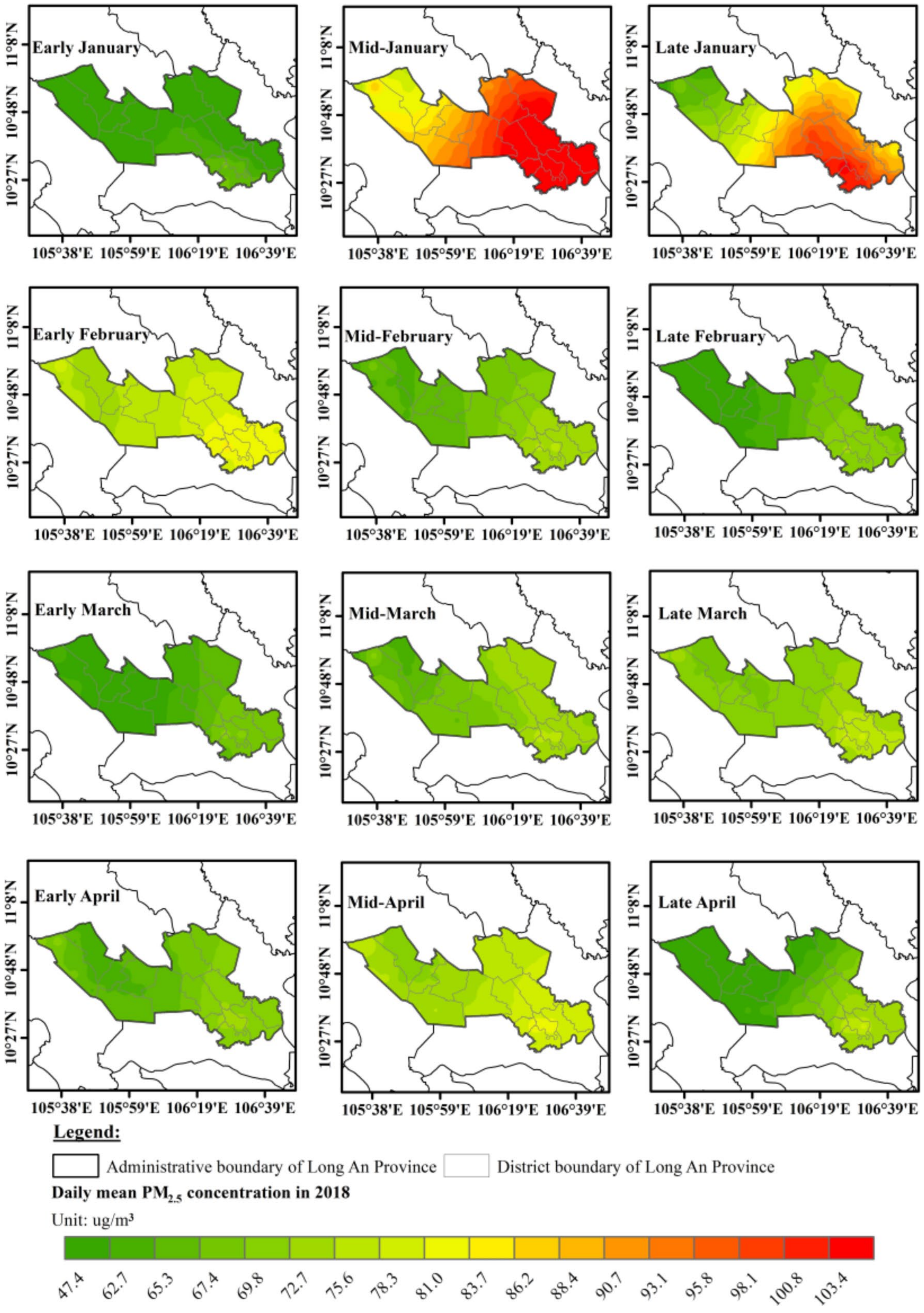


Fig. 4 Spatio-temporal distributions of 24-h average $PM_{2.5}$ concentrations of the phases (early, mid, and late) occurring in the 2018 dry season (January – April) in Long An province

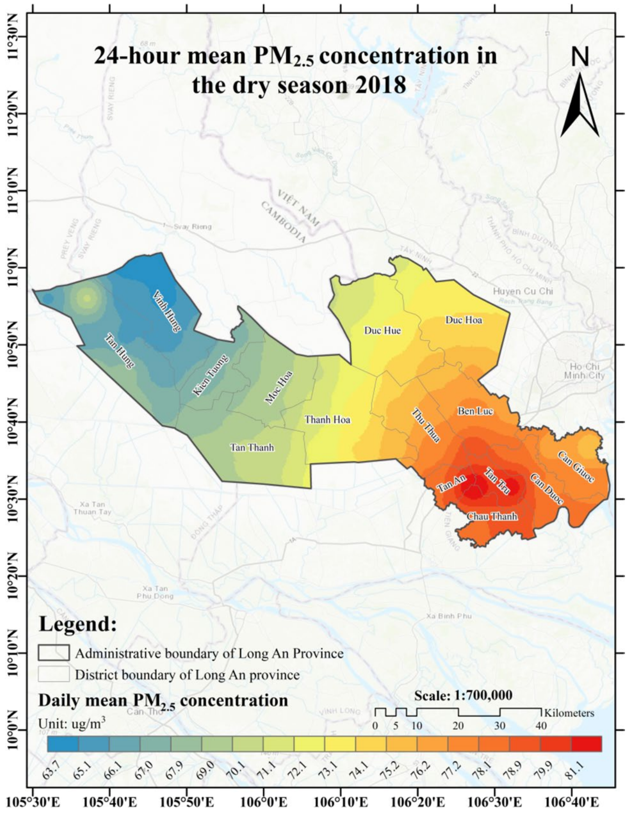


Fig. 5 Spatio-temporal distribution of the average $PM_{2.5}$ concentration in the 2018 dry season in Long An province

Research Framework and Implementation Steps

Figure 3 describes the research framework in detail. First, the data set related to the CMAQ model, such as the initial conditions, boundary conditions for the model, and the data of the $PM_{2.5}$ precursor biological and anthropogenic emission datasets are shown. To build a dataset of the spatial distribution of $PM_{2.5}$ concentrations, WRF model was applied to generate meteorological data (hourly). The coupled WRF/CMAQ models were used to generate the hourly $PM_{2.5}$ concentration data set used in the next step. Next, the data set on the distribution of 24-h average $PM_{2.5}$ concentration levels during the dry season in 2018 for districts/Cities/Towns in Long An province were calculated and used. Spatiotemporal variation in the study area was analysed and evaluated. The 24-h average $PM_{2.5}$ concentration limit according to the threshold value of NAAQS (50 μg/m^3) was extracted. The dataset is related to the health loss model, including the health loss functions, damage function coefficient (β), population exposure, and background mortality to estimate and analyse. Assessments of loss of health, specifically the number of premature deaths from respiratory, cardiovascular, and other circulatory diseases (due to all causes) were performed. Combined with VSL values, the corresponding economic loss values owing to the health effects caused by short-term exposure to $PM_{2.5}$ were also quantified for the entire study area.

Results and Discussion

Estimated Daily $PM_{2.5}$ Exposure Levels

The results of the simulation validation of $PM_{2.5}$ concentration in the study area estimated through other statistical indicators, including NMB, NME, and COR, gave quite good results. Details are presented in Table 2.

The simulation results from the WRF/CMAQ system show that the 24-h average $PM_{2.5}$ concentration fluctuations in the dry season months ranged from 63.17 to 82.84 μg/m^3. Figures 4 and 5 show the average $PM_{2.5}$ concentration (24-h) and the spatial and temporal distribution of 24-h average $PM_{2.5}$ concentrations of three typical periods in a month, namely the period from the beginning of the month (early), from the 1st to the 10th of every month; the middle of the month (Mid), from the 11th to the 20th of every month; and the end of the month (Late), from the 21st to the 28th or the 30th or 31st depending on different months.

In January 2018, the 24-h average concentration tended to increase towards the middle of the month and decrease towards the end of the month, and concentrations tended to be higher than those of February, March, and April. From the beginning to the middle and the end of January 2018, the 24-h average $PM_{2.5}$ concentration ranged from 47.48 to 67.85 μg/m^3, 76.17 to 122.01 μg/m^3, and 60.29 to 106.33 μg/m^3.

These daily mean $PM_{2.5}$ concentrations exceeded the threshold value (50 μg/m^3) of the NAAQS by 1.21 to 2.44 times. From February to April 2018, 24-h mean $PM_{2.5}$ levels were almost stable and lower than in January 2018, ranging between 53.29 and 84.82 μg/m^3. Nevertheless, these values also exceeded the threshold value of NAAQS by 1.07 to 1.70 times. During the dry season, $PM_{2.5}$-polluted areas where daily mean $PM_{2.5}$ concentration exceeded NAAQS' threshold value were commonly allocated in eastern and southeastern areas of Long An, including the Tan Tru, Chau Thanh, Can Duoc, and Can Giuoc Districts, as well as a part of the south and southeast of Thu Thua District, Ben Luc District, and Tan An City. Meanwhile, the west and northwest areas of Long An were often less polluted than other areas; specifically, the 24-h average $PM_{2.5}$ concentration was lowest in Vinh Hung District, as shown in Fig. 4.

Spatio-temporal distributions of $PM_{2.5}$ pollution in Long An were mainly influenced by local emission sources and meteorological conditions occurring in the dry season of

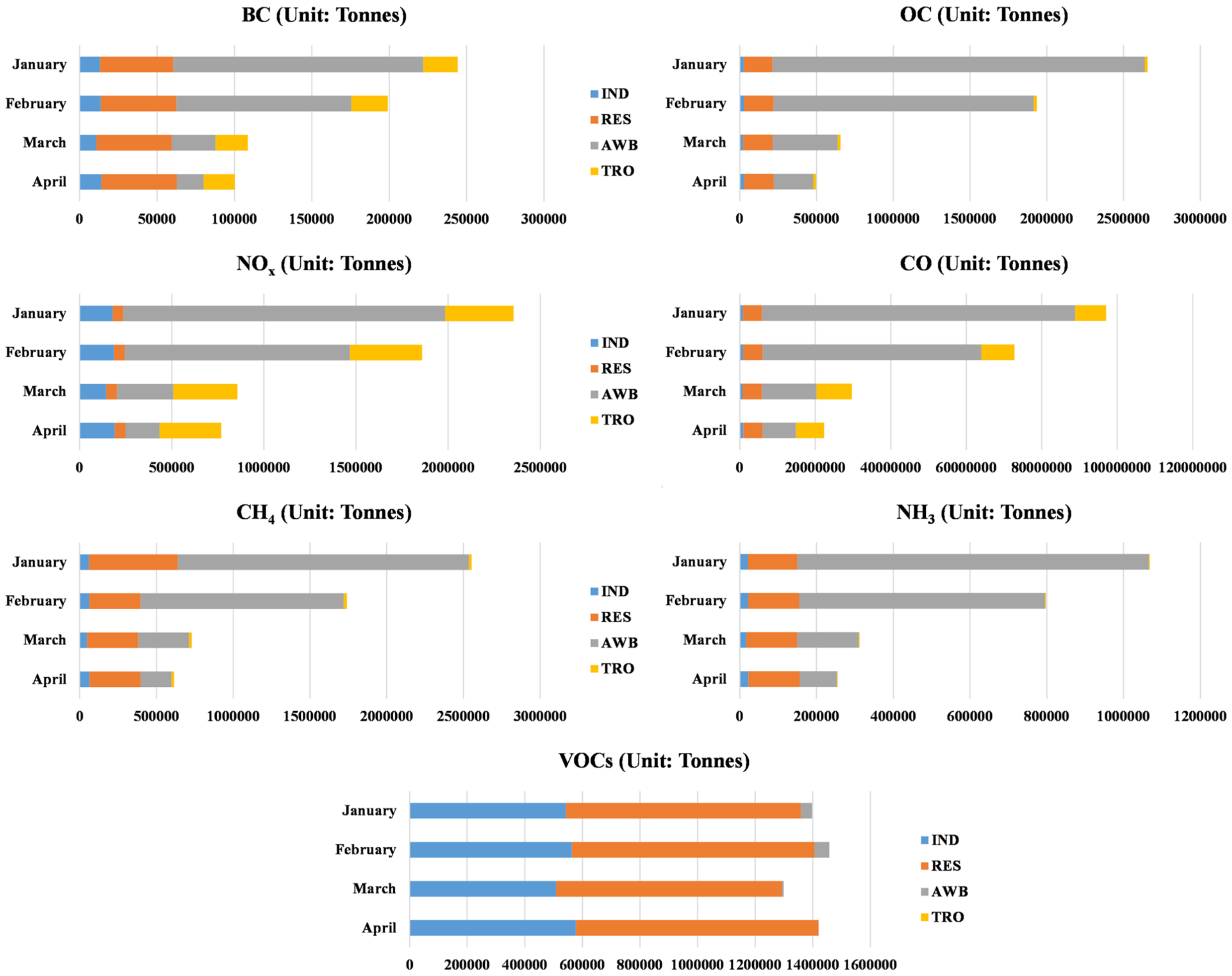


Fig. 6 Emissions of $pPM_{2.5}$ (BC and OC) and $PM_{2.5}$ precursors (NO_x, CO, CH_4, NH_3, VOCs) contributed from four main sectors (IND, RES, AWB, and TRO) in the 2018 dry season (January – April) in Long An province

2018. Results of emission inventories during the dry season (January to April 2018) for primary $PM_{2.5}$ ($pPM_{2.5}$) components ($pPM_{2.5}$) such as black carbon (BC) and organic carbon (OC) showed that there was a significant decrease over time during the dry season (January > February > March > April) (Fig. 6). Particularly, January 2018 had the highest total BC and OC emissions of around 240 and 2,670 thousand tonnes, respectively. For BC, emission sources contributing mainly from sectors including agricultural waste burning (AWB), residential areas (RES), road transportation (TRO), and industrial processes were approximately 17–66%, 19–49%, 9–20%, and 5–14%, respectively. For OC, emission sources were mainly contributed by AWB and RES from 51.77 to 90.77% and 7.03 to 39.01%, respectively. Meanwhile,

Table 3 Estimation results of premature mortality cases by each month and health endpoint with 95% CI (lower and upper values) in the dry season of 2018 (January – April)

Month	ΔY_1	$\Delta Y_{1,\ lower}$	$\Delta Y_{1,\ upper}$	ΔY_2	$\Delta Y_{2,\ lower}$	$\Delta Y_{2,\ upper}$	ΔY_3	$\Delta Y_{3,\ lower}$	$\Delta Y_{3,\ upper}$
January	2.836	0.390	2.558	0.557	– 0.066	1.141	1.302	– 0.530	3.072
February	1.661	0.226	1.506	0.323	– 0.038	0.662	0.756	– 0.306	1.796
March	1.638	0.223	1.484	0.318	– 0.038	0.653	0.745	– 0.301	1.770
April	1.705	0.233	1.544	0.332	– 0.039	0.681	0.777	– 0.315	1.844
Total	7.840	1.072	7.092	1.530	– 0.181	3.137	3.581	– 1.451	8.482

*Y_1: Premature mortality due to all-caused respiratory diseases (RDs); Y_2: Premature mortality due to all-caused cardiovascular diseases (CVDs); Y_3: Premature mortality due to all-caused other circulatory system diseases (CSDs)

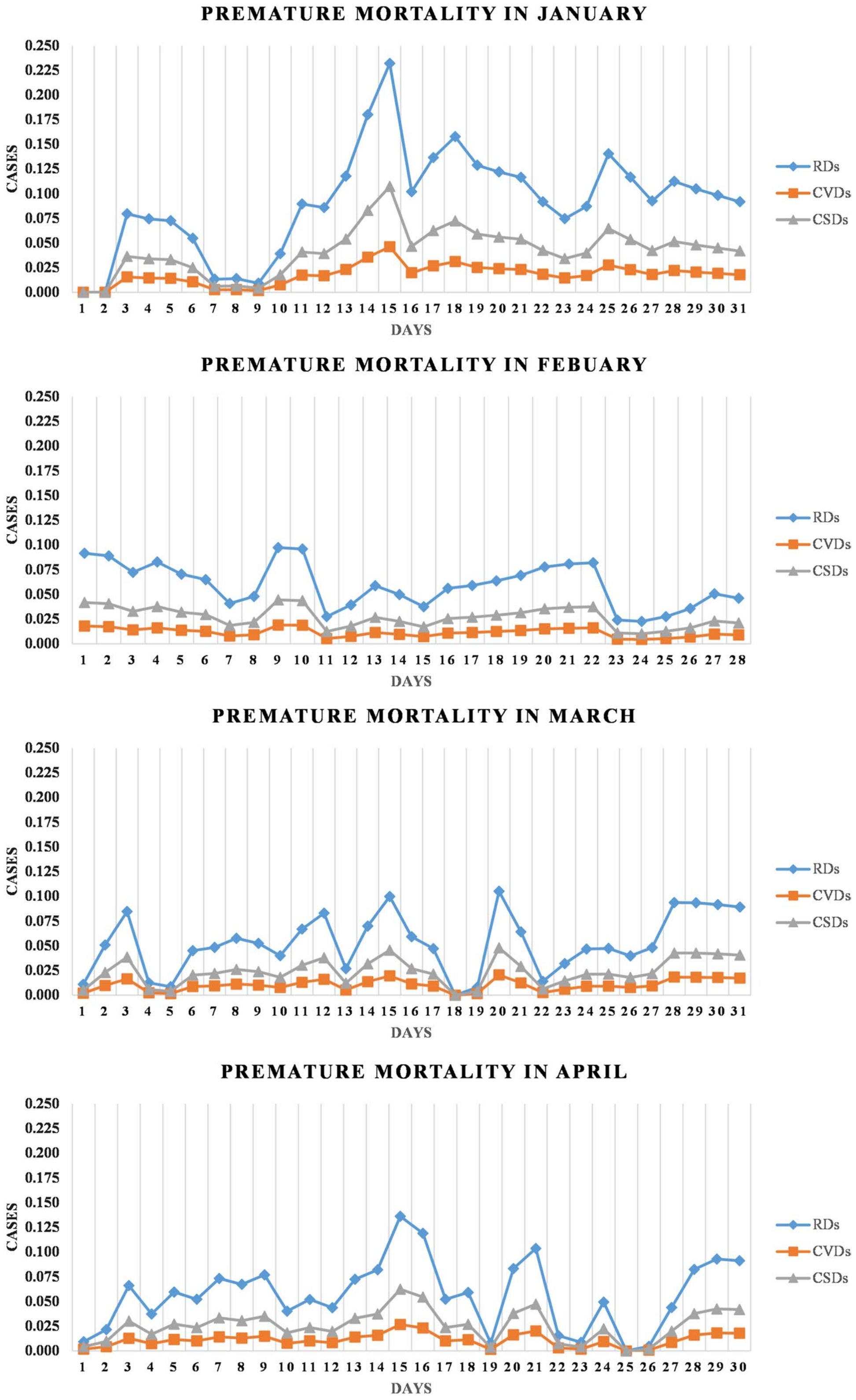


Fig. 7 Changes of premature deaths due to short-term $PM_{2.5}$ exposure in Long An province between January and April 2018

precursor emissions involved in chemical processes to form secondary $PM_{2.5}$ also tended to contribute during the dry season (January > February > March > April), and January 2018 had the highest emissions (Fig. 6). In January 2018, NO_x, CO, NH_3, and CH_4 emissions were about 2,410; 97,570; 1,350; and 4,450 thousand tonnes, respectively. Particularly for VOCs, emission levels in the months of the dry season were quite similar, with the highest emission occurring in

February 2018 was about 1,590 thousand tonnes. Therefore, the emissions of $pPM_{2.5}$ and $PM_{2.5}$ precursors (such as CO, CH_4, NH_3, NO_x, and VOCs) had a significant contribution from man-made activities in the following order: AWB, RES, TRO, and IND. Notably, AWB sectors, which mainly burned rice straw after harvest from January 2018 to early February 2018 of the winter–spring rice crop in localities where rice was grown with two crops/year and three crops/year. Furthermore, cooking activities mainly using firewood, rice straw, and rice husks considerably contributed to $PM_{2.5}$ pollution in Long An during this period.

The characteristics of unfavorable meteorological conditions in January 2018 compared to other months of the dry season in 2018 in Long An, such as factors of 2-m temperature, 2-m surface pressure, and 10-m wind speed, also contributed significantly to the allocation of $PM_{2.5}$ concentration. High temperatures promoted the vertical convection of the atmosphere, and high wind speeds accelerated the diffusion of particles in the atmosphere, causing the mass concentration of $PM_{2.5}$ to decrease markedly in the months towards the end of the dry season (Chen et al. 2020a, b; Wang et al. 2015a, b). The temperature and wind speed showed an increasing trend towards the end of the dry season (Figures S1 and S2). Specifically, the range of temperature and wind speed fluctuations in the months was around 25.7–27.4 °C and 2.1–2.7 m/s (January), 25.4–27.7 °C and 2.1–2.9 m/s (February), 27.1–28.4 °C and 1.8–3.3 m/s (March), and 27.6–30.2 °C and 1.8–3.0 m/s (April), respectively. Meanwhile, the surface pressure factor tended to decrease towards the end of the dry season (Figure S3), in particular about 100.8–101.2 kPa (January), 100.9–101.3 kPa (February), 100.8–101.0 kPa (March), and 100.8–109.6 kPa (April).

$PM_{2.5}$-attributed Premature Mortality

The average number of premature deaths from $PM_{2.5}$ daily exposure was assessed to be associated with three types of damage, i.e., deaths from all-caused respiratory diseases and all-caused cardiovascular diseases, and other circulatory diseases of all causes (Table 3 and Fig. 7).

$PM_{2.5}$ pollution levels during the dry season caused 12.951 (95% CI – 0.560; 18.711) premature deaths (all causes), of which 7.840 (95% CI 1.072; 7.092) cases were due to respiratory system diseases (accounting for 60.54%), 1.530 (95% CI – 0.181; 3.137) cases due to cardiovascular diseases (accounting for 11.81%), and 3.581 (95% CI – 1.451; 8.482) cases due to other circulatory system diseases (accounting for 27.65%).

The highest total number of deaths occurred in the month of January, with 4.695 (95% CI – 0.206; 6.771) cases, details of the number of cases due to three types of damage previously described being 2.836 (95% CI 0.390; 2.558), 0.557 (95% CI – 0.066; 1.141), and 1.302 (95% CI – 0.530; 3.072), respectively. In the following months, the impact gradually decreased and tended to be approximately the same as the total number of deaths from all causes, which were 2.740 (95% CI – 0.118; 3.965) in February 2018, 2.701 (95% CI – 0.116; 3.907) in March 2018, and 2.814 (95% CI – 0.121; 4.069) in April 2018.

Moreover, when assessing the variation in the number of deaths by day, it can be seen that in January, the number of deaths tended to increase sharply from the beginning to the middle of the month, peaking on 15 January with 0.232 (95% CI 0.032; 0.206) respiratory disease, 0.046 (95% CI – 0.005; 0.094) cardiovascular disease, and 0.107 (95% CI – 0.04; 0.250) cases due to other circulatory system diseases; from then to the end of the month, the total number of all-cause deaths dropped sharply to 0.152 (95% CI – 0.007; 0.219) cases on 31 January 2018. In February, the total number of deaths tended to increase in the beginning and middle of the month and decrease sharply towards the end of the month; specifically, the total number of deaths in these three stages was 1.242 (95% CI – 0.053; 1.795), 0.888 (95% CI – 0.038; 1.286), and 0.610 (95% CI – 0.026; 0.883). In March and April 2018, the number of daily premature deaths tended to be similar and both peaked in the middle of the month, namely on 20 March 2018 with a total number of deaths (all causes) of 0.174 (95% CI – 0.008; 0.251) and on 15 April 2018 with 0.225 (95% CI – 0.010; 0.324) premature deaths.

Evaluations based on similar studies conducted in various regions of Vietnam from 2017 to 2019 were also compared with Long An Province, Vietnam (the study area). Generally, the estimated human health impacts due to $PM_{2.5}$ exposure from these studies are significantly higher than that estimated in Long An province. From a case study by Nhung et al. (2022a), the number of premature deaths (per 100,000 population) in 2019 in HCMC was 45.3 (95% CI 37.5; 52.9), which was higher than about 3.5 times compared

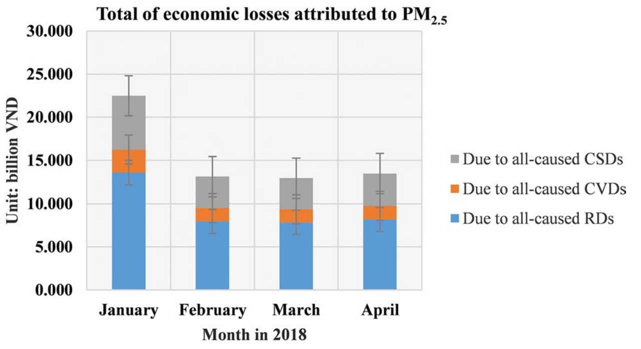


Fig. 8 Quantification of monthly economic losses due to 24-h average $PM_{2.5}$ pollution in the 2018 dry season (January – April) in Long An province

to the study area. This is also the same for the studies of Vu et al. (2020) and Bui and Nguyen (2022) in 2017 and 2018, respectively. Meanwhile, for Hanoi Capital, the number of early deaths per 100,000 population in 2019 with 63.2 (95% CI 52.8; 73.1) (Nhung et al. 2022a, 2022b) was about 4.9 times higher than that of Long An province. Based on these comparisons, it could be seen that although $PM_{2.5}$ pollution has occurred in Long An province, the pollution level is still lower than that of HCMC and Hanoi Capital. Furthermore, because of the difference in population between provinces/cities is also another important factor in the difference in early mortality rates between areas. Long An province has a relatively smaller population (about 1.67 million people) than HCMC (around 8.59 million people) and Hanoi Capital (around 7.52 million people) (GSO 2019). As a result, the overall health burden from $PM_{2.5}$ exposure is also generally low compared with these areas.

Economic Valuation Losses Assessment

From the input data presented above, the BenMAP-CE software was applied to quantify the economic benefits lost from the number of premature deaths associated with the estimated 95% CI due to short-term $PM_{2.5}$ exposure. The quantification process is based on the estimated VSL value for Vietnam for 2018 of 4,788.95 million VND, equivalent to about 642 million USD (converted in 2018 US$). The calculation results show that the total value of economic damage causing short-term public health impacts (deaths) in the dry season in 2018 was approximately 62.020 (95% CI – 2.683; 89.605) billion VND, equivalent to approximately 8.308 (95% CI – 0.359; 12.004) million USD (Fig. 8). Compared with the value of gross domestic product (GRDP) of Long An Province in 2018 of 110.077 trillion VND (Department of Statistics Ho Chi Minh City 2019), the total value of economic loss accounted for approximately 0.0563% of the total value of Provincial GRDP. In general, economic loss levels in this study are about 48.9 times lower than HCMC's total losses in 2018 due to exposure to $PM_{2.5}$ pollution (Bui and Nguyen, 2022).

The total number of premature deaths due to respiratory diseases caused a loss of approximately 37.545 (95% CI 5.133; 33.965) billion VND, equivalent to roughly 5.030 (95% CI 0.688; 4.550) million USD (about 60.54% of the total value of economic cost losses), whereas the total number of premature deaths due to cardiovascular and other circulatory diseases caused economic losses of 7.327 (95% CI – 0.866; 15.022) billion VND, equivalent to about 0.982 (95% CI -0.116; 2.012) million USD (around 11.81% of total valuation losses), and 17.148 (95% CI -6.950; 40.619) billion VND, equivalent to about 2.297 (95% CI -0.931; 5.441) million USD (accounting for 27.65%), respectively. However, when considering the total economic loss for each month in the dry season in 2018, the value of economic losses is in the order of January > April > February > March. Specifically, the total economic loss is in the order January > April > February > March. The estimated total number of premature deaths from all causes for each month was as follows: 22.486 (95% CI -0.984; 32.425) billion VND, equivalent to 3.012 (95% CI -0.132; 4.344) million USD, in January 2018; 13.121 (95% CI -0.563; 18.986) billion VND, equivalent to 1.758 (95% CI -0.075; 2.543) million USD, in February 2018; 12.935 (95% CI -0.555; 18.709) billion VND, equivalent to 1.733 (95% CI -0.074; 2.506) million USD, in March 2018; and 13.478 (95% CI -0.580; 19.485) billion VND, equivalent to 1.806 (95% CI -0.078; 2.610) million USD, in April 2018.

Uncertainty Analysis

The input data in this study included data on air quality (average 24-h $PM_{2.5}$ concentration), exposed population, C-R functions, and corresponding β coefficients from the epidemiology of the studies. Each type of model input data has errors that can affect the final calculation results to different degrees. The results of the estimated population size exposure were obtained from reliable local data sources: the Long An Provincial Statistical Yearbook 2020 and the Health Statistical Yearbook 2017–2020. Therefore, the results on health damage basically depends on the choice of C-R functions and coefficient β. Currently in Vietnam, there have not been any quantitative studies on the relationship between air pollution and health traits, especially epidemiological studies on the short-term relationship between $PM_{2.5}$ and health impact on premature deaths in provinces. Therefore, in this study, β coefficients and C-R functions from recent studies in cities of neighbouring countries were used. This is one of the main factors that can lead to errors in the calculated results because the coefficients β and the C-R functions have obvious differences in the data of the evaluation area (results of the regression function estimation). However, during the calculation and evaluation, the mean values and 95% confidence intervals (CIs) of health losses were considered and used to reflect the range of error.

Conclusion

The research results showed that the daily mean $PM_{2.5}$ concentration in Long An had complicated changes in the 2018 dry season, ranging from 47.48 to 106.33 $\mu g/m^3$, exceeding the NAAQS by 1.07 to 2.44 times and leading to health impacts and economic losses. The results obtained were as follows:

First, human health effects were quantified for the 2018 dry season. $PM_{2.5}$ pollution caused health damage to the study area, estimated at 12.9 (95% CI -0.6; 18.7) premature deaths (all causes) per 100,000 population, of which 7.8 (95% CI 1.1; 7.1), 1.5 (95% CI -0.2; 3.1), and 3.6 (95% CI -1.5; 8.5) cases per 100,000 population were due to RDs, CVDs, and CSDs.

Second, the total value of economic losses related to daily exposure to $PM_{2.5}$ concentrations during the study period reached 62.0 (95% CI -2.7; 89.6) billion VND, equivalent to 8.3 (95% CI -0.4; 12.0) million USD.

Third, a modeling framework for rapidly quantifying human health damage caused by exposure to short-term $PM_{2.5}$ pollution is suitable for the proposed study area. These results could be a solid basis for further development, contributing to the construction and development of data sources for effective air environment management in Long An.

In low- and middle-income countries in Asia and Africa, socio-economic development is remarkably dependent on fossil fuels. Therefore, dwellers in these countries invariably face higher risks of premature mortality due to outdoor $PM_{2.5}$ pollution-related diseases. Due to a lack of ambient air quality monitoring data, local authorities and environmental managers have encountered many difficulties in assessing $PM_{2.5}$ pollution status, determining pollution causes, estimating impacts on public health attributed to $PM_{2.5}$ exposure, and proposing effective mitigation measures. This study has proposed an appropriate implementation framework based on simulations by the coupled WRF/CMAQ, public health impact, and rapid quantification models of economic losses. This framework could be applied in these countries under conditions of limited measurement data to support the analysis and quantitative assessment of the factors that contribute to $PM_{2.5}$ pollution and their impact on local socio-economic through the implementation of numerical simulations. Furthermore, based on these assessment results, technical and non-technical measures to control and mitigate both primary and secondary $PM_{2.5}$ could be proposed to be conducted efficiently and cost-effectively.

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Authors Contributions Long Ta Bui: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Methodology, Models, writing—original draft, writing—review\& editing. Han Thi Ngoc Lai: Data analysis, Formal analysis. Phong Hoang Nguyen: Models, Validation, GIS.

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Availability of Data and Materials 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

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval 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 "*Benefits of short-term premature mortality reduction attributed to* $PM_{2.5}$ *pollution: A case study in Long An province, Vietnam*" to the Archives of Environmental Contamination and Toxicology (AECT).

Consent to Publish I consent to publish my manuscript entitled "*Benefits of short-term premature mortality reduction attributed to* $PM_{2.5}$ *pollution: A case study in Long An province, Vietnam*" to the Archives of Environmental Contamination and Toxicology (AECT).

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