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Application of EnHEBIS tool to assess economic impact due to health effects from $PM_{2.5}$ pollution – A case study at Long An province, Vietnam

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Abstract: Assessment of the effects of short-term $PM_{2.5}$ exposure on human health is one of the problems that need to be addressed within the framework of sustainable development. The goal of this study is to quantify the health-economic impacts of $PM_{2.5}$ pollution for a specific province - Long An province in Vietnam using the EnHEBIS (Environment, Public Health, and Economic Benefit Management Support Integrated System) software package. The study outcomes showed that significant health and economic effects could occur in areas with high $PM_{2.5}$ concentrations and dense population concentrations. Prominent results presented that acute exposure to $PM_{2.5}$ pollution from May to December 2018 caused 265 (95% CI: -12; 422) premature deaths, which approximately 60% of all early deaths due to all-caused respiratory diseases (RDs) with 155 (95% CI: 23; 170) cases. Corresponding to the health impacts, the economic values of Long An province also suffered a loss of around 1.15% of the total value of the gross regional product (GRDP) with about 1,270 (95% CI: -57; 2,021) billion VND, equivalent to roughly 170 million USD, along with a significant decline in the working time for the adult group. Although uncertainties have remained in this study, these results have shown the extent of economic, health, and environmental damage when $PM_{2.5}$ pollution occurs. The highlights are the basis for proposing measures to control and improve the local ambient air quality.

Keywords: Air pollution; $PM_{2.5}$; Premature mortality (PMOR); Health assessments; Economic impact.

1. Introduction

Air pollution issues have caused diverse impacts on human health, ecosystems, tourism, and climate [1–2], which is identified as a global health priority in the sustainable development goals (SDGs) related to health (Goal 3), cities (Goal 11) and energy (Goal 7) [3]. In particular, PM_{10} and $PM_{2.5}$ are among the most widely monitored and studied components of ambient air pollution [4]. Outdoor particulate matter (PM) is considered the most serious air pollutant in urban areas since it causes negative health effects and is also a cause of heart vascular diseases, respiratory irritation, as well as pulmonary dysfunction [5]. Especially, $PM_{2.5}$ is likely to easily penetrate deep into the lungs, reaching the alveoli and causing greater health risks than PM_{10} because the higher surface area per unit mass increases the absorption capacity and condensation of toxic substances [6]. Moreover, continuous acute (short-term) exposure or long-term (chronic) exposure to $PM_{2.5}$ can increase the risk of PMOR [7–8]. The cause-and-effect relationship between $PM_{2.5}$ pollution and the deterioration of public health from acute respiratory and cardiovascular diseases to related chronic diseases has been fully documented in the medical literature [9–10].

As $PM_{2.5}$ is an extremely important factor causing ambient air quality deterioration, it has become a notable research issue in the scientific community [11–12]. Many studies have been carried out to understand the physical, chemical, and optical properties of $PM_{2.5}$, and also to determine the driving factors affecting the spatio-temporal allocation of $PM_{2.5}$ [13–14]. The health risk assessment process includes three main components, such as hazard assessment based on air pollution concentrations, individual vulnerability based on dose-response functions, and exposure probability [15]. Both available epidemiological and toxicological studies have shown that the smaller the particle size, the greater the risk of human health effects occurring [16]. Furthermore, long-term exposure to $PM_{2.5}$ pollution is able to lead to increased risk by 6% of PMOR [17]. Based on the study results by [18–19] have shown that the number of premature deaths globally tends to grow sharply from 1.4 million cases in 2010 and is expected to increase to 3.6 million cases by 2050.

Besides, these health issues have caused a considerable economic burden due to growing medical spending, increased number of lost workdays, and decline in labor supply [2]. In 2017, there were about 1.24 million premature deaths in China attributed to air pollution [20], which also resulted in economic losses of 101.39 billion USD, accounting for 0.91% of the gross domestic product (GDP) [21]. According to available statistics, severe smog events occurred in the first quarter of 2013 in China, affecting approximately 13.5% of the land area and around 800 million people [22]. It was estimated that without applying a pollution control policy in China, the PM pollution problems were likely to cause a loss of roughly 2% of the GDP value and 25.2 billion USD in health costs in the year 2030 [23].

Based on the overview of previous study outcomes, it is emphasized the need to assess not only the health effects caused by $PM_{2.5}$ exposure but also the economic losses associated with these $PM_{2.5}$-related negative health impacts. Currently, although the complex socio-economic effects of outdoor $PM_{2.5}$ exposure are worthy of consideration. Nevertheless, most of the studies are focused on large urban areas in Vietnam, such as Hanoi and Ho Chi Minh City (HCMC), whilst Long An province is a satellite locality of HCMC, rarely paid attention to. Also, there is extremely little related information and data in Long An province. Thus, we chose Long An province as the study area to evaluate distributions of $PM_{2.5}$ pollution, one of the most concerned environmental issues, using a coupled WRF/CMAQ model in the period of May to December 2018. At the same time, a module of the EnHEBIS software for estimating human health-economic impacts was applied to better understand the health impact of outdoor $PM_{2.5}$ exposure in Long An province. How do acute human health effects associated with short-term $PM_{2.5}$ exposure impact local provincial macroeconomics, as well as what are the levels of economic losses caused by $PM_{2.5}$ pollution? It is considered as an advanced tool to enable planners and decision-makers to effectively quantify population exposure to outdoor $PM_{2.5}$ pollution issues.

Thus, the overall approach to conducting this study is the combination of the Weather Research and Forecast (WRF) model, the Community Multiscale Air Quality Modeling System (CMAQ) model, and a module of human health impact estimations and economic loss rapid quantification (Module 3) of the EnHEBIS software. EnHEBIS is the main product of the Vietnam National University Ho Chi Minh City (VNU-HCM) level project of type B with code B2023-20-23. The software allows quantifying benefits of reducing outdoor $PM_{2.5}$ pollution, public health, and economic value achieved from controlling, minimizing precursor emissions, and optimizing emissions control costs. The EnHEBIS software consists of four integrated modules, including (1) Module 1 to calculate and visualize the improvement of surface air quality under changes of controlled emission scenarios, (2) Module 2 to quantify the cost of implemented control measures to reduce precursor emissions, (3) Module 3 to estimate economic and public health benefits or losses, and (4) Module 4 to analyze and evaluate the effectiveness of the achieved benefit-cost relationship. Compared to some other models, such as AirQ+ or BenMAP-CE that merely allow the development of a single computing scenario discretely with many complex parameters which are almost difficult to access in Vietnam, EnHEBIS is likely to the setup and analysis of many different scenarios with relevant input parameters selected appropriately for Vietnam's unique conditions, especially for HCMC and its surrounding areas. Also, the EnHEBIS software has been built into the WebGIS platform and be accessed through authorized accounts without having to be installed on a computer, which is considered a main advantage. Therefore, the EnHEBIS software not only allows calculations but is also used for managing estimating databases simultaneously in a wide range of different regions.

2. Method

The research method is shown in Figure 1, which is a coupled WRF/CMAQ model system, and the quantification models of health impacts and economic losses (Module 3) of the EnHEBIS package software. The coupled WRF/CMAQ models generated data on hourly and daily mean $PM_{2.5}$ levels from May to August 2018 in the study area. Meanwhile, Module 3 of the EnHEBIS software has been built to quantify human health effects related to short- and long-term outdoor $PM_{2.5}$ exposure. PMOR and morbidity-related impacts are converted into total annual health expenditure and occupational injuries per capita due to $PM_{2.5}$ exposure. The study scope is limited to estimating and evaluating short-term health effects. A brief description is to introduce the coupled WRF/CMAQ modeling system since details of all setup processes and model inputs have been presented by [24]. The CMAQ (version 5.2.1) and WRF (version 3.8) models were applied for $PM_{2.5}$ level estimations. These models have a spatial resolution of 3.0 km × 3.0 km and a modeling setup similar to

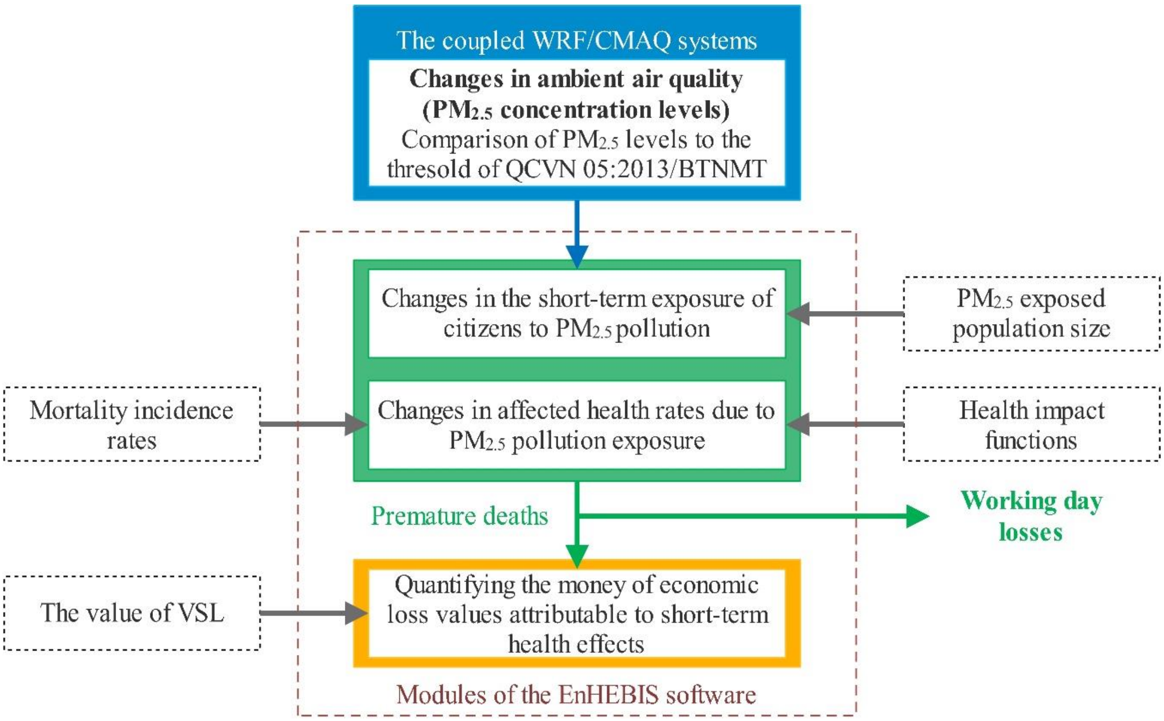

Figure 1. The diagram of research framework steps.

our previously available study [24]; in particular, WRF created meteorological conditions as input factors to CMAQ. Computing simulations in CMAQ used CB05, AER06, and the Regional Acid Deposition Model (RADM) as the gas phase mechanism, the aerosol module, and the aqueous phase chemistry module, respectively. In addition, CMAQ's boundary conditions are applied from the global model of GEOS-Chem [25] with a spatial resolution of 2.0° × 2.5°.

2.1. Study area

Long An belongs to both the Mekong Delta Region (MDR) and the Southern Key Economic Region, with geographical coordinates from 105°30'30" to 106°47'02" E and 10°23'40" to 11°02'00" N, far about 45 km from the center of Ho Chi Minh City along National Highway 1 (Figure 2). The entire study area has a natural land area of about 4,500 km^2, of which agricultural land accounts for 74% and more than 50% of the land area of Dong Thap Muoi region, including provinces of Long An, Tien Giang, and Dong Thap. Long An province's population was 1.678 million people in 2018 (Figure 2), of which about 1.406 million people live in rural areas, and 272 thousand inhabitants live in urban areas [26]. In general, the geographical location of Long An province is quite favorable for connecting MDR and the Southeast region of Vietnam. The province's economy is increasingly developing, affirming its role with an economic growth rate of 10.4% in 2018, including the sectors of agriculture, forestry and fishery rising by 4.9%, the industrial production and construction sector increasing by 15.4%, and the trade and service sector growing by 6.7% [26]. Furthermore, the province's economic structure has shifted towards industrial development, and the industry sector accounts for 47.5%. Also, Long An province ranked second among 13 localities in MDR and third in the country in terms of Provincial Competitiveness Index (PCI) in the year 2018 [26].

Acute health effects due to short-term $PM_{2.5}$ exposure are estimated across Long An province; hence, the exposed population size includes the entire population of one city and thirteen districts belonging to Long An province in 2018, as shown in Figure 2. This dataset is referenced in the Long An Statistical Yearbook for 2018, considered for all age and gender groups [26]. By 2018, the province's population contributed to around 9% of the total population of MDR, of which the districts of Duc Hoa, Can Giuoc, Can Duoc, and Ben Luc frequently have

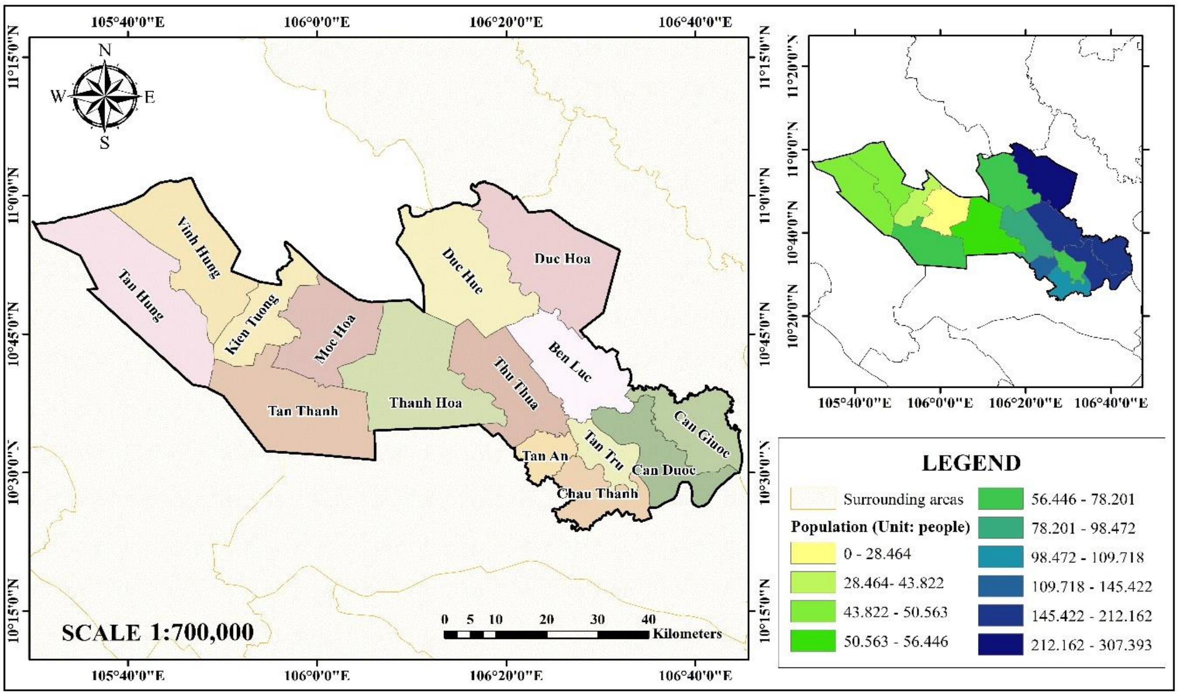

Figure 2. Geographic location (left) and district-level population size (right) of Long An province in the year 2018.

a larger population size than other districts. In particular, the population of these districts was 307,393 people (contributing to 18.31%), 212,162 people (accounting for 12.62%), 187,481 people (accounting for 11.17%), and 180,041 people (contributing to 10.72%), respectively. Nevertheless, the population density in Tan An City and the districts of Can Giuoc, Can Duoc, and Duc Hoa is the highest in Long An province, respectively being 1,779.2 people/km^2, 986,3 people/km^2, 850,3 people/km^2, and 723,1 people/km^2 [26–27].

2.2. The EnHEBIS module estimating health effects and economic losses

2.2.1. Model of health impact estimations

Short-term $PM_{2.5}$ exposure increase over time has resulted in potential health issues known as health damage, which is classified into morbidity and PMOR [23]. Table 1 lists all exposure–response functions (ERFs) (also known as health damage functions) that were used. Most studies have shown that the relative risk (RR) value for various types of health damage has a linear correlation with the pollutant concentration level [7, 28–29]. However, a few recent studies have suggested a non-linear relationship, especially when exposed to high pollution levels [30–31]. As shown in equation (1), we merely considered ERFs presenting a linear relationship with $PM_{2.5}$ exposure. There are three PMOR-related health endpoints are considered in this study, including PMOR due to all-caused diseases of respiratory (RDs), cardiovascular (CVDs), and other circulatory system (CSDs), respectively. It is assumed that ERFs are constant, specifically for the group (i) of PMOR-related health endpoints applied according to the studies of [32–34] and the group (ii) of occupational injuries due to illness based on the study by [23].

$$RR_{p,r,y,m,e,g}(C) = \begin{cases} 1, & C_{p,r,y} \le C_{0p} \\ 1 + ERF_{m,e,g}(C_{p,r,y} - C0_p), \text{linear function}, & C_{p,r,y} > C_{0p} \end{cases} \quad (1)$$

where $RR(C)$ is the RR value of the health endpoint type at concentration level C (unit: case/person/year or day/person/year), C is the concentration level of $PM_{2.5}$, C_0 is the threshold level of $PM_{2.5}$ that is likely to cause health effects (10 µg/m^3 for $PM_{2.5}$ according to available epidemiological studies applied according to [32–34]) and ERF is the health damage function or the concentration-response function. Moreover, the suffixes p, r, y, m, e, and g represent air pollutant ($PM_{2.5}$), area, year of calculation, health endpoint groups (premature death or illness-attributed occupational injuries), the specific type of health endpoints, and the value range (including medium, lower, and upper).

The total number of health-affected cases by each health endpoint is calculated by multiplying RR with the $PM_{2.5}$ exposed population and given incidence rates in equation (2) as follows:

$$EP_i = \begin{cases} POP_{r,y,m}(RR_{p,r,y,m,e,g}(C) - 1), \text{for linear morbidity function} \\ POP_{r,y,m} I_{r,\text{"all cause"}}(RR_{p,r,y,m,e,g}(C) - 1), \text{for linear mortality function} \end{cases} \quad (2)$$

where POP is the size of the exposed population (unit: person) including children (from 0 to 14 years old), adults (from 15 to 64 years old), and the elderly (≥ 65 years old) and $I_{r,\text{"all cause"}}$ is the baseline rate of annual mean natural deaths for all health endpoints.

Based on the equation (2) above and a method similar to the Global Burden of Disease 2019 of Risk Factors Collaborators [35], the total cases of premature deaths attributable to short-term $PM_{2.5}$ exposure are determined as shown in equation (3).

$$EP_i = \sum_a \sum_d \left(POP_i \times AgeP_{i,a} \times MB_{i,a,d} \times \frac{RR_{a,d} - 1}{RR_{a,d}} \right) \quad (3)$$

where POP_i is the population size exposed to $PM_{2.5}$ pollution in study area i, $AgeP_{i,a}$ is the proportion of population in age group a in study area i, $MB_{i,a,d}$ is the baseline mortality rate of disease type d for citizens in age group a in study area i, and $RR_{a,d}$ is the relative risk (RR) value of disease type d in the population of age group a.

Table 1. Summary of ERFs with 95% Confidence Interval (CI**).**

Type of damage	Unit	ERFs		
		Mean	Lower	Up
Early deaths due to RDs [a]		0.00090	0.00023	0.00156
Early deaths due to CVDs [b]		0.00017	-0.00002	0.00035
Early deaths due to CSDs [c]		0.00040	-0.00016	0.00096
Work loss days [d]	day/(person.µg.m.year)	0.02070	0.01760	0.02380

[(*)] Note: [a] referenced from [34]; [b] referenced from [35]; [c] referenced from [36]; [d] referenced from [23]

2.2.2. Model of estimations of annual per capita work loss rate

The region's total annual work loss day (WLD) is the sum of the number of days lost from work due to illness, and the cumulative number of days lost from work due to chronic mortality in adults (ages 15 to 65) is presented in equation (4). Based on the study results by [23], it is assumed that about 4% of the total number of chronic deaths in the total calculated early deaths are because of $PM_{2.5}$ exposure in the adult group. The annual per capita work loss rate (WLR) may be determined by dividing WLD by the annual number of working days and the number of workers in the population, shown in equation (5). Simultaneously, WLR is also applied to estimate the actual labor force after subtracting the number of lost works, shown in equation (6).

$$WLD_{p,r,y,g} = \sum_{m} EP_{p,r,y,m,"wld",g} + \sum_{e,y'\leq y} EP_{p,r,y',"mt",e,g} \times 4\% \times DPY \tag{4}$$

$$WLR_{p,r,y,g} = \frac{WLD_{p,r,y,g}}{DPY_{p,r,y,"adult"}} \tag{5}$$

$$LAB_{p,r,y,g} = LAB0_{r,y}(1 - WLR_{p,r,y,g}) \tag{6}$$

where WLD is the total number of work loss days per year (unit: days/year), WLR is the per capita annual work loss rate, LAB is the number of the labor force after considering lost works, LAB0 is the number of the labor force under normal circumstances (not affected), DPY is the annual average number of working days per capita (commonly the mean level being 5 $days.week^{-1} \times 52\ weeks.year^{-1} = 260\ days.year^{-1}$), the corresponding subscripts "wld" and "mt" of e and m are the cases of "days lost from work" and "chronic mortality" respectively, as well as the subscript "adult" represents for adults.

2.2.3. Rapid assessment model of PMOR-associated economic losses

Techniques of the economic loss determination attributable to health effects due to short-term $PM_{2.5}$ exposure have been developed quite early. Most of the approaches to assess and quantify into the money $PM_{2.5}$ pollution-related human health effects in many nations have been built on the basis of applying survey, assessment, and estimation methods developed by the World Health Organization and the World Bank and currently widely used in China, the United States (the U.S.), Canada, and Australia [36]. In the cost-benefit analysis method of environmental programs of the U.S. and the European Union, PMOR is considered a special value called the "Value of Statistical Life" (VSL). This is the total value that inhabitants have to pay for reducing their risks of death, which means growing life.

VSL is a function that increases with income level in the study area, which may be estimated according to equation (7) based on the method of benefit value transfer. Meanwhile, the quantification of the VSL value for Vietnam is inherited from research [24]. From there, changes in the total number of PMOR cases can be quantified into money using equations (7) and (8) [37–38] as follows:

$$\mathrm{VSL} = \mathrm{VSL}_0 \times \left(\frac{\mathrm{I}}{\mathrm{I}_0}\right)^{\alpha} \quad (7)$$

$$\Delta\mathrm{E} = \mathrm{VSL} \times \Delta\mathrm{H} \quad (8)$$

where VSL is the value of statistical life of the province in the estimating year (unit: VND or USD), VSL_0 is the VSL value in the base year (unit: VND or USD), I is the annual per capita average income of the province in a given year (unit: VND or USD), I_0 is the local annually per capita income in the base year (unit: VND or USD), α is the coefficient adjusted according to income for calculating VSL value, and ΔE is the total economic losses associated with early deaths because of $PM_{2.5}$ pollution (unit: VND or USD).

3. Results and Discussion

3.1. Results of spatio-temporal PM2.5 allocation changes

Figures 3 and 4 showed that in the period from May to December 2018, the 24-hour mean $PM_{2.5}$ level ranged from 13.8-67.8 µg/m^3, in which $PM_{2.5}$ levels in some areas exceeded the threshold (with 50 µg/m^3) of the national ambient air quality standard

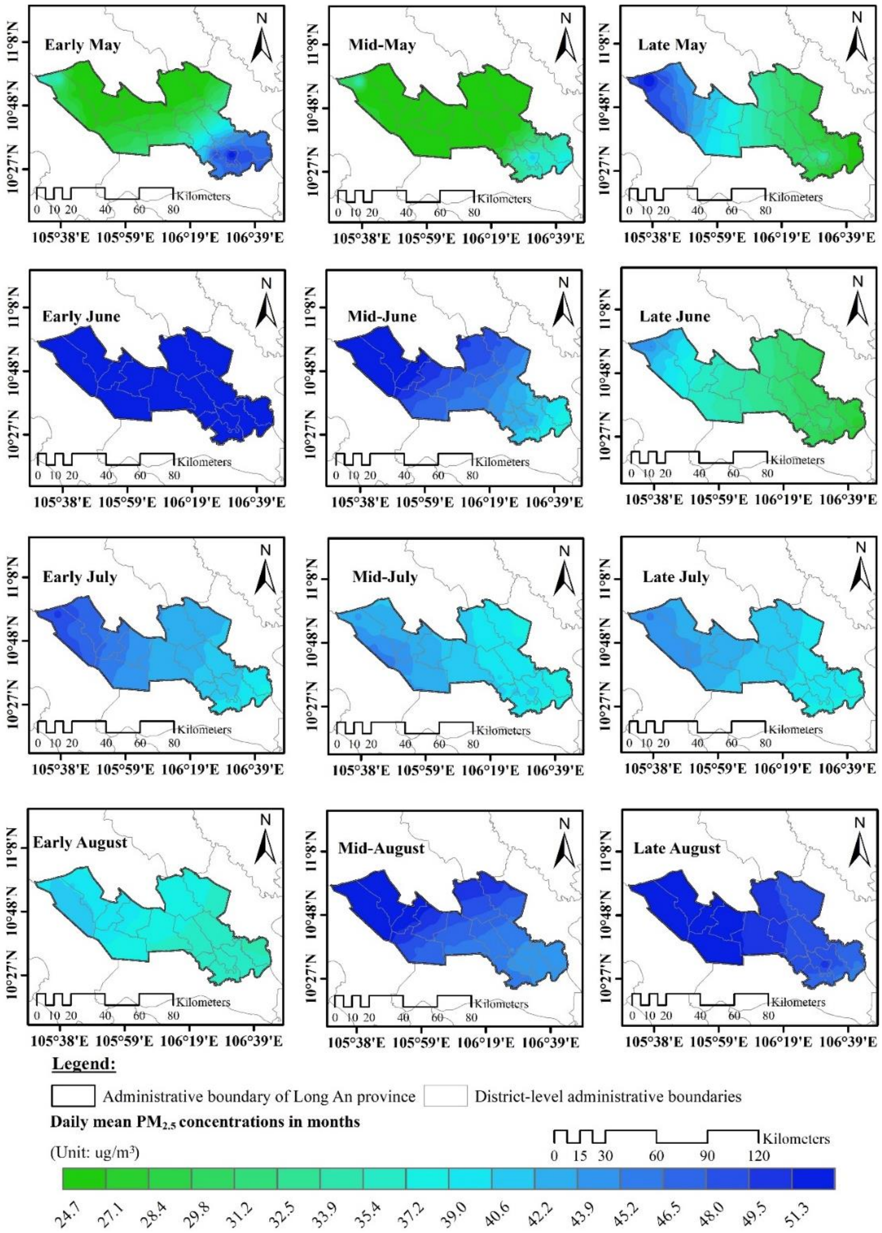

Figure 3. Spatio-temporal distributions of 24-hour average PM2.5 levels (early, mid-, and late of the months) in Long An province from May to August 2018.

(NAAQS) (or QCVN 05:2013/BTNMT) up to 1.36 times. Between May and August 2018, high $PM_{2.5}$ allocations almost occurred in the west and northwest of Long An province, consisting of Tan Hung, Vinh Hung, Kien Tuong, Tan Thanh, and Moc Hoa Districts. In contrast, from September to December 2018, high $PM_{2.5}$ distributions were observed commonly in the south and southeast of Long An province, such as Duc Hoa, Chau Thanh, and Can Duoc Districts. These are localities with large populations and strongly developed industrial activities. In general, $PM_{2.5}$ concentrations tended to be high at the month beginning, then gradually declined from the 11th to the 20th monthly, and increased gradually towards the end of May, June, and July 2018. The daily mean $PM_{2.5}$ variations in May, June, and July 2018 are from 21.6-53.5 μg/m^3, 27.8-67.8 μg/m^3, and 37.4-49.9 μg/m^3, respectively. Meanwhile, PM2.5 levels in August and October 2018 grew steadily from the beginning to the end of these months, varying from 34.7-58.7 μg/m3 and 14.1-46.5 μg/m^3, respectively. In contrast, $PM_{2.5}$ concentrations tended to reduce steadily from the beginning to the end of September, November, and December 2018, which were $PM_{2.5}$ level fluctuations of 13.3-33.3 μg/m^3, 18.3-65.5 μg/m^3, and 37.6-64.8 μg/m^3, respectively.

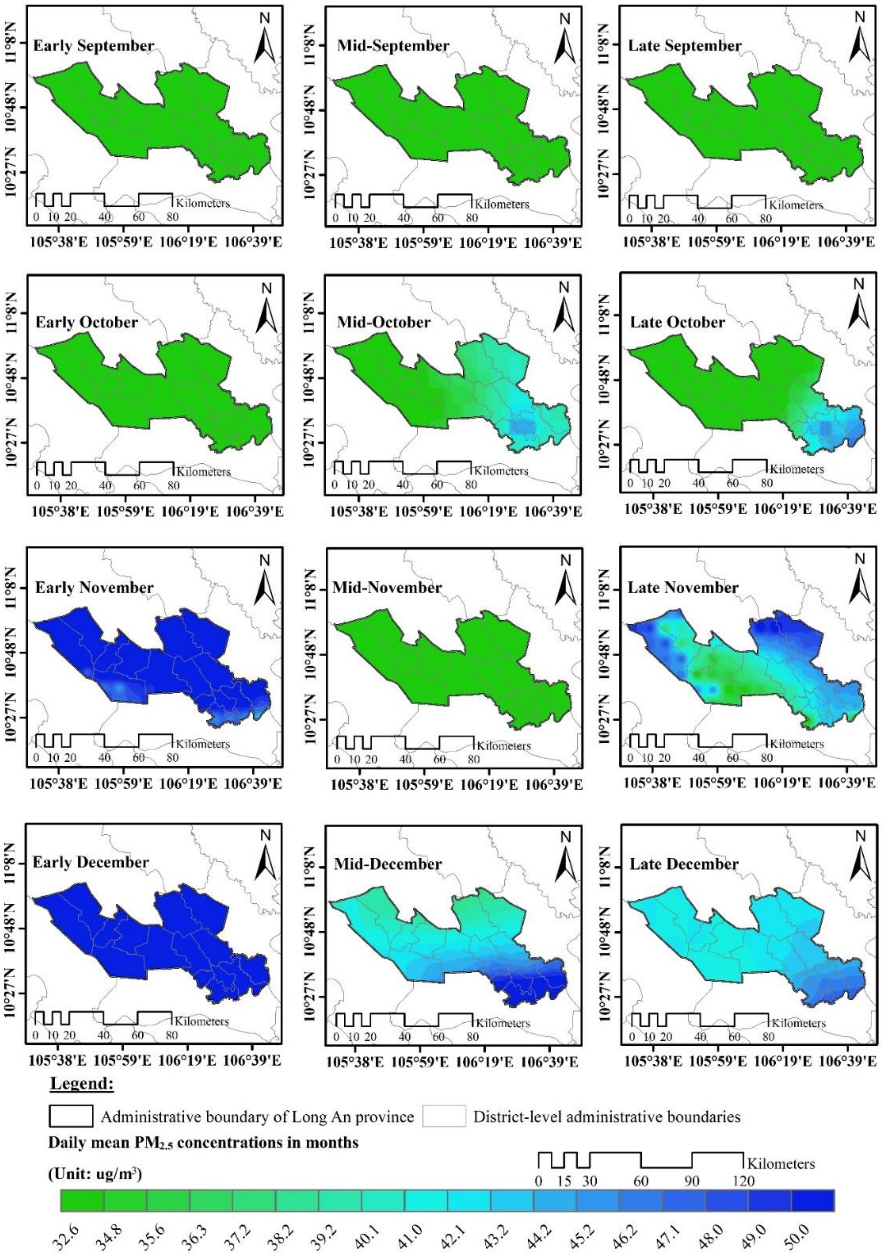

Figure 4. Spatio-temporal allocations of daily mean $PM_{2.5}$ levels (early, mid-, and late of the months) in Long An province from September to December 2018.

3.2. Results of the effect assessment on public health attributable to $PM_{2.5}$ exposure

Table 2 and Figure 5 reported that the total health-affected cases in Long An province from May to December 2018 were about 265 (95% CI: -12; 422) PMOR cases. In particular, there were about 148 (95% CI: -7; 236) premature deaths between May and August 2018, including around 86 (95% CI: 13; 95) cases related to RDs (accounting for 58.1%), 19 (95% CI: -2; 38) cases due to CVDs (contributing to 12.8%), and 43 (95% CI: -18; 103) cases attributable to CSDs (contributing to 29.1%). Meanwhile, the PMOR cases from September to December 2018 tended to decline roughly 1.3 times, having about 117 (95% CI: -5; 186) PMOR cases. Specifically, there were respectively around 68 (95% CI: 10; 74) cases, 15 (95% CI: -2; 30) cases, and 34 (95% CI: -14; 81) cases, which related to RDs, CVDs, and CSDs, respectively. In this period, the proportion of PMOR cases due to RDs was the highest (58.2%), whilst the percentage of premature deaths associated with CVDs was the lowest (12.7%). Generally, the types of RDs-associated health endpoints are the most frequent health issues caused by short-term $PM_{2.5}$ exposure in the study area, followed by CSDs and CVDs. In particular, the total early deaths because of RDs, CVDs, and CSDs in Long An province during the evaluated period were 155 (95% CI: 23; 170) cases (accounting for 58.5%), 33 (95% CI: -4; 68) cases (accounting for 12.5%), and 77 (95% CI: -31; 184) cases (contributing to 29.1%), respectively.

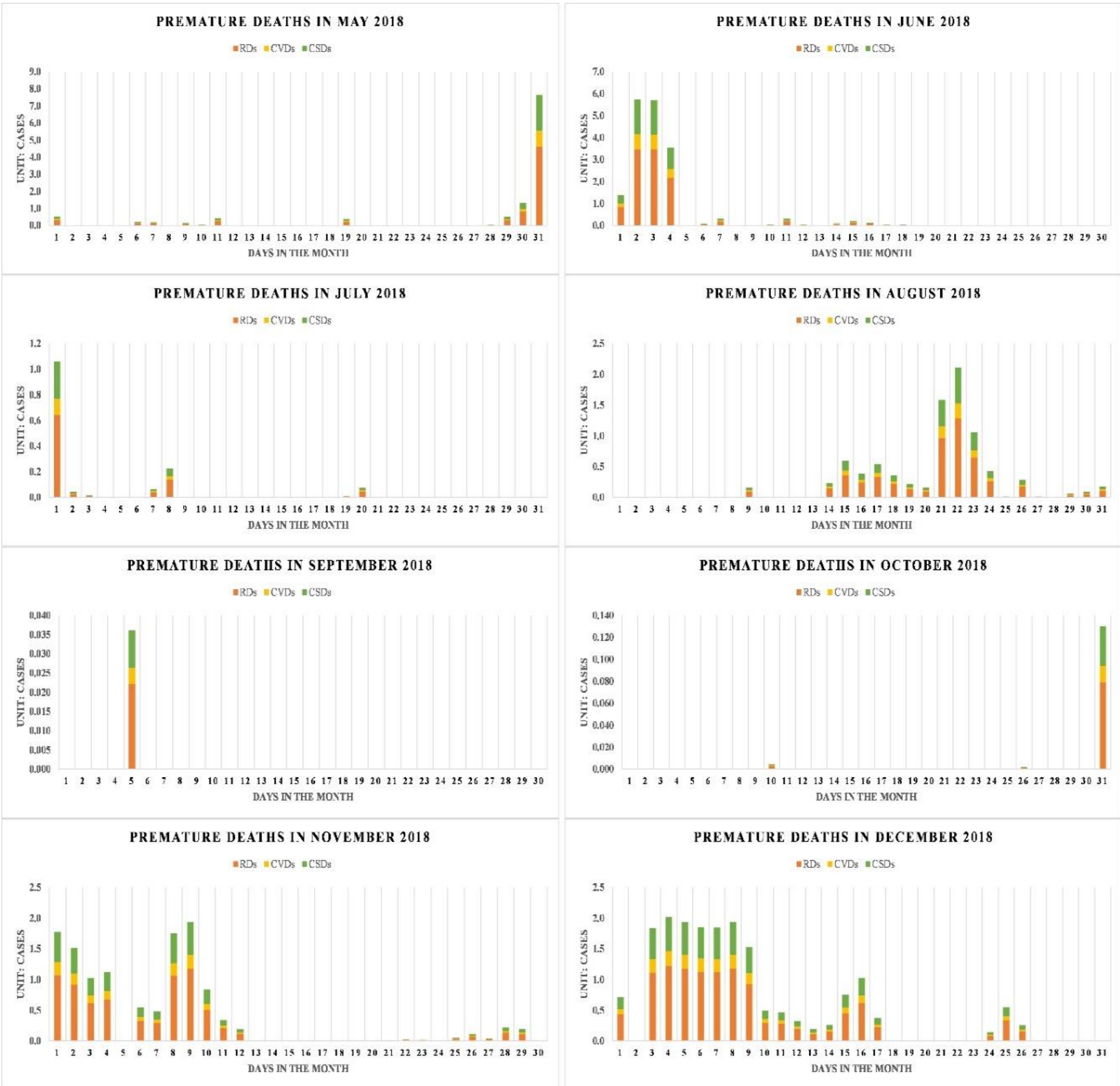

Figure 5. Changes in daily PMOR cases because of RDs, CVDs, and CSDs attributable to acute $PM_{2.5}$ exposure in Long An province from May to December 2018.

By each month, the total PMOR cases declined from May to October 2018, then rose sharply until December 2018. September and October 2018 had the lowest number of early deaths with 68 (95% CI: -3; 109) cases, whilst June and December 2018 had the highest number of PMOR cases with 69 (95% CI: -3; 110) cases.

Moreover, it could be found that the higher cases of PMOR occurred commonly from the early to the middle of June, July, and December 2018. In contrast, they almost happened from the middle to the end of May and August 2018, whilst the total PMOR cases were observed majorly at the beginning and the end of November 2018. Specifically, the highest number of PMOR cases occurring by each assessed month was approximately 8 (95% CI: 0; 11) cases on 31 May 2018, 6 (95% CI: 0; 8) cases on 2 June 2018, 1 (95% CI: 0; 2) cases on 1 July 2018, 2 (95% CI: 0; 3) cases on 22 August 2023, 2 (95% CI: 0; 3) cases on 9 November 2023, and 2 (95% CI: 0; 3) cases on 4 December 2018.

Table 2. Results of the estimations of PMOR cases in each month and each kind of health endpoint because of acute $PM_{2.5}$ exposure (with 95% CI).

Month	$EP_{PM2.5,\ RDs}$[1]	$EP_{PM2.5,\ CVDs}$[2]	$EP_{PM2.5,\ CSDs}$[3]
May 2018	24.8 (95% CI: 3.8; 27.5)	5.4 (95% CI: -0.6; 11.0)	12.6 (95% CI: -5.1; 29.7)
Jun. 2018	39.6 (95% CI: 6.0; 44.0)	8.6 (95% CI: -1.0; 17.5)	20.0 (95% CI: -8.1; 47.4)
Jul. 2018	3.3 (95% CI: 0.5; 3.6)	0.7 (95% CI: -0.1; 1.4)	1.6 (95% CI: -0.7; 3.9)
Aug. 2018	18.5 (95% CI: 2.7; 20.4)	3.9 (95% CI: -0.5; 8.0)	9.2 (95% CI: -3.7; 21.9)
Sept. 2018	0.08 (95% CI: 0.01; 0.09)	0.0 (95% CI: 0.0; 0.0)	0.0 (95% CI: 0.0; 0.1)
Oct. 2018	0.30 (95% CI: 0.04; 0.33)	0.1 (95% CI: 0.0; 0.1)	0.1 (95% CI: -0.1; 0.4)
Nov. 2018	27.5 (95% CI: 4.1; 30.0)	5.8 (95% CI: -0.7; 12.0)	13.7 (95% CI: -5.5; 32.7)
Dec. 2018	40.5 (95% CI: 6.0; 44.0)	8.6 (95% CI: -1.0; 17.7)	20.2 (95% CI: -8.1; 48.1)
Total	**154.6 (95% CI: 23.2; 169.8)**	**33.1 (95% CI: -3.9; 67.9)**	**77.5 (95% CI: -31.3; 184.2)**

(*) Notes: [1] PMOR cases due to RDs; [2] PMOR cases due to CVDs; [3] PMOR cases due to CSDs

3.3. Results of the impact assessment associated with labor time decline

Based on datasets from the Long An Statistical Yearbook in 2018 [26], the labor force (> 15 years old) in this study area obtained 1,006.7 thousand people, including male workers with 544.6 thousand people (contributing to 54.1%) and female workers with 462.1 thousand people (accounting for 45.9%). Furthermore, the labor force in rural areas was significantly higher than that in urban areas; specifically, there were 156.3 thousand laborers in urban areas (accounting for 15.5%) and 850.4 thousand laborers in rural areas (accounting for 84.5%). Simultaneously, by age group division, there were 126.3 thousand laborers aged 15 to 24 years old, 604.0 thousand laborers aged 25 to 49 years old, and 276.4 thousand people over 50 years old in Long An province.

High outdoor $PM_{2.5}$ concentration exposure often results in declining working days because of additional morbidity and PMOR. Citizens who live in environmental conditions with better ambient air quality are likely to work more due to their living quality (or even their children) being less able to get sick. In particular, the cases occurring in the adult group (< 65 years old) have significantly reduced their working time. The outcomes presented that the average number of days lost from work during the period of May to December 2018 was approximately 16.5 days/person. It contributed around 6.35%, compared to the annual average number of working days per capita of 260 days/year. At the same time, the highest number of days lost from work occurred respectively in June and December 2018, with about 5.2 days/person (accounting for 2.0%) and 8.3 days/person (accounting for 3.2%).

3.4. Results of the estimations of PMOR-related economic losses

The combinations of PMOR-related health impact results due to acute $PM_{2.5}$ exposure based on the specific types of health endpoints and the theories of Modue 3 in the EnHEBIS software had been applied to rapidly quantify the economic loss values ($HE_{PM2.5,\ mortality}$) in Long An province between May and December 2018. The determination of economic losses was based on Vietnam's VSL in 2018 of 4,789 million VND (equivalent to about 642 million USD, 2018 US$). The value of VSL measures inhabitants' willingness to pay for better and safer living and working conditions, as well as being used to assess the benefits of policies and implementing solutions from agencies and units in both private and public sectors of the national authorities [36, 39]. Thus, the total economic loss values caused by $PM_{2.5}$ pollution was estimated at 1,270 (95% CI: -57; 2,021) billion VND, which was equivalent to approximately 170 (95% CI: -7; 271) million USD during the study period. Comparisons to the gross regional product (GRDP) in Long An province in 2018 of 110,077 trillion VND referenced from [40], the total PMOR-related economic loss values contributed to around 1.15% of the province's GRDP value in 2018.

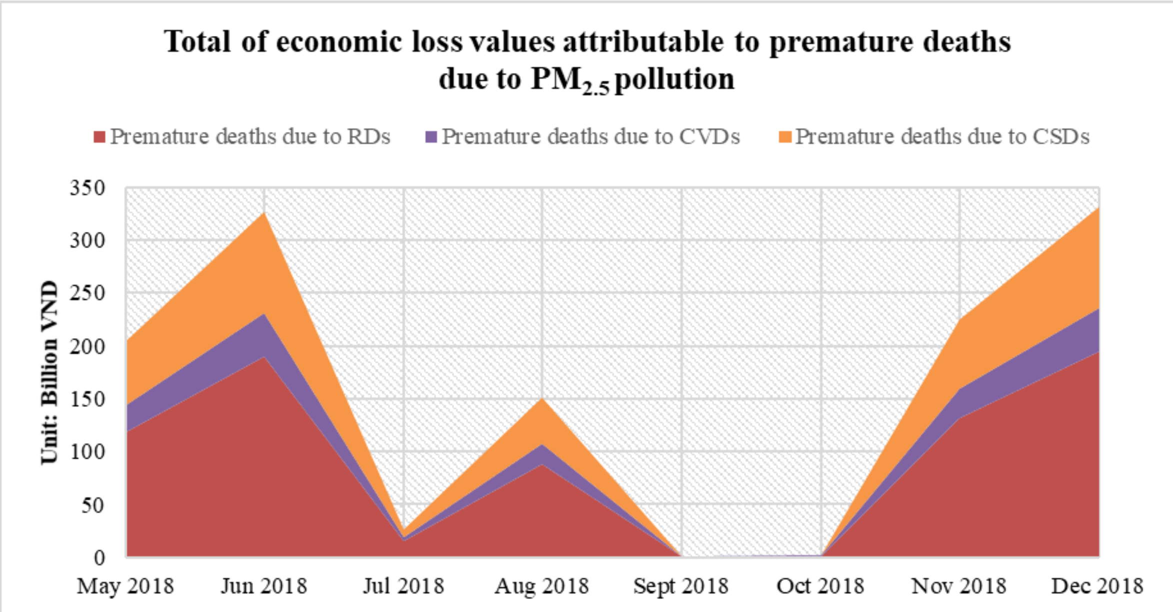

Figure 6. Results of economic loss values in each month due to $PM_{2.5}$-related short-term health impacts between May and December 2018 in this study area.

As shown in Figure 6, the total economic loss values (from May to August 2018) in Long An province attributable to PMOR cases were caused by daily $PM_{2.5}$ levels exceeded the threshold of NAAQS (QCVN 05:2013/BTNMT) with the damage of around 709 (95% CI: -32; 1,132) billion VND, equivalent to 95 (95% CI: -4; 152) million USD. In detail, the total RDs-related PMOR cases resulted in the total economic losses during this period of 413 (95% CI: 62; 457) billion VND, equivalent to approximately 55 (95% CI: 8; 61) million USD (accounting for 13.3%). In comparison to RDs, the total PMOR cases due to CVDs and CSDs caused the corresponding loss values around 89 (95% CI: -10; 182) billion VND (average of about 12 million USD) accounting for 21.5% and 208 (95% CI: -84; 493) billion VND (average of roughly 28 million USD) contributing to 6.8% of the total loss values, respectively.

From September to December 2018, the total economic loss values caused by acute $PM_{2.5}$ exposure-related early deaths due to RDs, CVDs, and CSDs was roughly 561 (95% CI: -25; 889) billion VND, equivalent to 75 (95% CI: -3; 119) million USD in Long An province (Figure 6). The economic losses were about 1.3 times lower than in the period of May to August 2018. Specifically, by each kind of health endpoint, the total loss values were 328 (95% CI: 49; 356) billion VND, equivalent to approximately 44 (95% CI: 7; 48) million USD (accounting for 58.5%) caused by RDs. Meanwhile, there were approximately 70 (95% CI: -8; 143) billion VND (average of about 9 million USD) and 163 (95% CI: -66; 389) billion VND (average of around 22 million USD), respectively, in a total of economic losses caused by CVDs (contributing to 12.5%) and CSDs (contributing to 29.1%).

Besides, by each month, the total loss values were in the order as follows: September < October < July < August < May < November < June < December. In particular, the loss value was the highest in December 2018 with 349 (95% CI: -15; 509) billion VND (average about 47 million USD), whilst the lowest loss value occurred in September 2018 with 0.7 (95% CI: 0.0; 1.0) billion VND (average about 0.1 million USD). Meanwhile, the total economic losses in May, November, and June 2018 were respectively 204 (95% CI: -9; 326) billion VND (average around 27 million USD), 237 (95% CI: -10; 346) billion VND (average about 32 million USD), and 327 (95% CI: -15; 522) billion VND (average about 44 million USD). Generally, the loss values in October, July, and August 2018 were much lower than in May, November, and June 2018. There were 3 (95% CI: -0.1; 4) billion VND (average roughly 0.3 million USD), 27 (95% CI: -1; 43) billion VND (average around 4.0 million USD), and 151 (95% CI: -7; 241) billion VND (average about 20 million USD), respectively in the total values of economic losses in October, July, and August 2018.

3.5. Discussion

On the basis of the approach taken in this study and the estimation results of acute health impacts, as well as the economic loss values achieved, it could be found that the $PM_{2.5}$ concentration level in each district plays an important role in the estimations and also has a linear relationship to these damage values. However, the exposed population size and the population density of each locality in Long An province are the most crucial factors that have a decisive influence on the values of the estimated damage. This is completely similar and supports observations from previously available studies, such as [24, 41–42]. Compared to a similar study by [43] that evaluated PMOR due to acute $PM_{2.5}$ exposure in HCMC, the total number of PMOR cases was about 1.12 times lower. It could be seen that the study by [43] estimated for all months in 2018; moreover, the population size of HCMC in 2018 (about 8.832 million people) was also 5.26 times higher than that of the study area. Though the total economic losses caused by short-term exposure to $PM_{2.5}$ in HCMC (around 410 million USD) are significantly higher than this study results (roughly 170 million USD), they only account for 0.25% of HCMC's total GRDP compared to 1.15% of Long An's total GRDP in 2018. This is obviously because the GRDP value of HCMC is remarkably higher than that of Long An province. Nevertheless, the study by [43] noted the health effects of morbidity types, such as hospitalizations and emergency visits, and also estimated several specific types of RDs and CVDs, including acute lower respiratory infections (LRIs) due to pneumonia and acute bronchiolitis in children, chronic obstructive pulmonary disease (COPD), community-acquired pneumonia (CAP), heart failure (HF), myocardial infarction (MI)), and stroke. Simultaneously, the total corresponding economic losses are not only estimated for PMOR but are determined by the costs of illness treatment, loss of income and declined productivity labor in adults. Similarly, the total economic loss value of this study is also 2.32 times lower than the results of [44], which evaluated PMOR related to CVDs occurring in HCMC in 2018. Compared with a similar study by [45] in Guangzhou, China in 2010, the total PMOR cases in our study was 1.46 times higher. Meanwhile, compared to the results by [24], the total loss values in Long An province from May to December 2018 (around 170 million USD) were much higher than that in the period of January to April 2018 (roughly 8.3 million USD). However, the estimated VSL value for Long An province in 2018 was used to quantify economic losses because of PMOR in our study instead of using Vietnam's VSL in 2018 as in the study by [24] since this is likely to reduce errors in estimating total economic losses.

4. Conclusion

The study outcomes provided evidence that $PM_{2.5}$ concentration levels in this study area during the period of May to December 2018 exceeded the threshold of NAAQS (QCVN 05:2013/ BTNMT) and caused negative health impact issues, which contributed to rose PMOR and created a considerable economic burden in Long An province. Specific highlights are as follows:

Acute health effects associated with short-term $PM_{2.5}$ exposure commonly caused around 155 (95% CI: 23; 170) PMOR cases due to RDs, 33 (95% CI: -4; 68) PMOR cases due to CVDs, and 77 (95% CI: -31; 184) PMOR cases related to CSDs in Long An province in 2018.

Exposure to high $PM_{2.5}$ levels in ambient air resulted in the decline of working hours in the adult group by an average of about 16.5 days/person between May and December 2018.

The total economic losses caused by $PM_{2.5}$ pollution in this period of 2018 were quantified at 1,270 (95% CI: -57; 2,021) billion VND, equivalent to about 170 (95% CI: -7; 271) million USD (2018 US$). These PMOR-related economic losses attributable to short-term outdoor $PM_{2.5}$ exposure accounted for about 1.15% of the total GRDP of the province in 2018.

Although the highlights have remarkably contributed in terms of scientific basis to clarify the acute effects of $PM_{2.5}$ causing PMOR cases, as well as corresponding economic losses in Long An province in 2018, this study has not yet completely looked at the cases of hospitalizations, emergency visits, or even long-term $PM_{2.5}$ exposure issues (chronic). Since chronic $PM_{2.5}$ exposure is likely to result in much greater potential health risks than short-term $PM_{2.5}$ exposure. At the same time, more specific health endpoint types of all-cause RDs and CVDs have not been noted in this study; thus, it is crucial to extend and update the latest ERFs for health effect assessment in further studies. Furthermore, future studies need to continue evaluating the distributions of $PM_{2.5}$ concentrations throughout Long An province for the following years in order to make specific comments on spatio-temporal fluctuation trends. They will be a solid basis for policymakers to develop strategies and measures to control and mitigate $PM_{2.5}$ precursor emissions in Long An province in Vietnam. In particular, these solutions should focus on the major sources of the province, typically industry, construction, residential, transportation, and agriculture activities.

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