Mortality Burden due to Exposure to Outdoor Fine Particulate Matter in Hanoi, Vietnam: Health Impact Assessment

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Objective: This study reports the mortality burden due to PM2.5 exposure among adults (age >25) living in Hanoi in 2017.

Methods: We applied a health impact assessment methodology with the global exposure mortality model and a PM2.5 map with 3 × 3 km resolution derived from multiple data sources.

Results: The annual average PM2.5 concentration for each grid ranged from 22.1 to 37.2 μg/m³. The district average concentration values ranged from 26.9 to 37.2 μg/m³, which means that none of the 30 districts had annual average values below the Vietnam Ambient National Standard of 25 μg/m³. Using the Vietnam Ambient National Standard as the reference standard, we estimated that 2,696 deaths (95% CI: 2,225 to 3,158) per year were attributable to exposure to elevated PM2.5 concentrations in Hanoi. Using the Interim Target 4 value of 10 μg/m³ as the reference standard, the number of excess deaths attributable to elevated PM2.5 exposure was 4,760 (95% CI: 3,958–5,534).

Conclusion: A significant proportion of deaths in Hanoi could be avoided by reducing air pollution concentrations to a level consistent with the Vietnam Ambient National Standard.

Keywords: Vietnam, mortality burden, PM2.5, HIA, GEMM

INTRODUCTION

The negative health effects of particulate matter (PM) with aerodynamic diameter ≤2.5 μm (PM2.5), including increased risk of death, have been documented in many previous epidemiologic and toxicological studies. There is consistent evidence of associations between air pollution and risk of death due to circulatory diseases, ischemic heart diseases, chronic obstructive pulmonary diseases, and lung cancer [1, 2]. Furthermore, PM2.5 is also linked to disease associated with DNA damage, including cancer [2, 3]. PM2.5 contributes to a huge burden of mortality worldwide, estimated at 4.1 million deaths annually in 2019 [4].

The World Health Organization (WHO) has categorized Vietnam among the countries with high concentrations of PM2.5. Estimated mean population-weighted PM2.5 exposure in Vietnam in 2019
was 20 μg/m³ (the range from 16.6 to 25.0 μg/m³) [5]. The Government of Vietnam has implemented measures to improve air quality, especially, they established a network of fixed monitoring stations and lower cost sensors. This network provides information for authorities and Hanoi citizens, therefore, is contributing to an increased awareness of air pollution [6]. As a result, annual average PM$_{2.5}$ concentrations in Vietnam have gone down during the period of 2011–2020 [7], though they still exceeded the Vietnamese National Ambient Air Quality Standard (QCVN 05:2013).

Hanoi, the capital, is the most air polluted city in Vietnam. The main emission sources of air pollutants in Hanoi include on-road transport, residential and commercial combustion, especially use of honeycomb coal briquettes, and small industrial activities in craft villages [8].

Several studies have reported short-term effects of PM$_{2.5}$ on children’s respiratory health [9, 10] and on cardiovascular disease in Vietnam [11]. Global studies estimating the health burden attributable to PM$_{2.5}$ exposure for Vietnam have relied on low spatial resolution satellite data covering about 11 × 11 km [5]. Besides, only a recent study reported attributable mortality due to exposure to PM$_{2.5}$ in Ho Chi Minh city in 2017 [12]. However, there has been no estimate based on locally relevant highly resolved data such as district level and/or of the overall health burden attributable to PM$_{2.5}$ exposure using QCVN 05:2013 as a reference. This lack of local data impedes the capacity of local authorities to take action to reduce air pollution and improve health in Vietnam.

The aim of this study was to quantify the annual mortality burden attributable to exposure to high levels of PM$_{2.5}$ air pollution in Hanoi, using highly spatially resolved data acquired locally and with reference to QCVN 05:2013. We also reported the numbers of excess attributable deaths with the reference standards of the Interim Target 4 (IT-4) value and the lowest estimated grid-level value within Hanoi in 2017.

### METHODS

#### Study Design

This study used a health impact assessment methodology [13, 14] to estimate the mortality burden of ambient PM$_{2.5}$ in Hanoi in 2017. This approach involves the application of established exposure-response functions to the local study population using local mortality data and local measured and modeled exposure data [14]. The mortality burden was estimated as the attributable number of deaths, years of life lost (YLL), and loss of life expectancy (LLE). This study underwent ethical review by the Ethical Committee in Hanoi University of Public Health, decision number 322/2019/YTCC-HD3.

#### Study Setting

Hanoi is the second largest city in Vietnam covering an area of 3,359 km$^2$, just behind Ho Chi Minh city. Hanoi is the capital of Vietnam and had 7.8 million inhabitants in 2017. The city incorporates 30 districts, the population density in the inner district is 4.9 times higher than in outer districts. The districts of Dong Da and Hoan Kiem were the most densely populated with 37,311 and 36,997 persons per km$^2$, respectively, (Figure S1, supplementary material). Life expectancy at birth in Hanoi in 2017 was 73.0 for men and 77.9 for women.

### Mortality and Population Size Data

Individual death records including date of death, date of birth or age, gender, and causes of death were extracted from the “A6 registration” for Hanoi in 2017 and provided by Hanoi Center of Disease Control. It has good reliability for completeness of death in Vietnam (about 89.3%) and no significant difference in the completeness in the registration between urban and rural regions [15]. The detailed quality assurance process of the A6 death document was published elsewhere [15–17].

Population data by age group and sex for each district in Hanoi in 2017 were provided by the Hanoi Population and Family Planning Agency for each district in Hanoi.

### Ambient PM$_{2.5}$ Concentrations

PM$_{2.5}$ exposure for 2017 in Hanoi was estimated using daily modeled PM$_{2.5}$ concentrations over Vietnam at a 3 × 3 km resolution using a similar modeling approach as previous studies in Europe [18] and the US [19]. Data used in the development of the PM$_{2.5}$ model included ground monitoring stations operated by Vietnam Environment Administration, remote sensing products of aerosol optical depth, meteorological data including temperature, humidity, pressure, wind direction, wind speed, mixing height, and rainfall, and land use data.

We estimated daily PM$_{2.5}$ over Vietnam with a resolution of 3 × 3 km using a mixed effect model (MEM) [18, 19]. The daily MEM was developed from 4-years datasets from 2016–2019 with the following steps: data pre-processing and enhancement, data integration, model development, and daily map estimation.

The pre-processing step converted the ground monitoring station data (multiple stations) into the same format and structure, and outliers were removed using min-max thresholds. All the raster maps were resampled into the same spatial resolution at 3 × 3 km. Because the observations of satellite aerosol optical depth (AOD) are often missing due to cloud coverage, especially in the North of Vietnam, the AOD satellite data were collected from multiple sources and fused together using the Terra regression method to improve the AOD data coverage and quality [20].

After the pre-processing and enhancement step, all data were aligned with daily average PM$_{2.5}$ at the ground from monitoring stations to train the dataset for the daily MEM. In terms of space, different buffers (circular with different diameters) were used to calculate the average value around each station to create new predictor variables. To choose the optimal predictors for the mode, the forward stepwise method [21, 22] and practical experience were applied. The MEM was built on these selected predictors. Since AOD data were often missing due to heavy cloud cover, we proposed to build an auxiliary MEM, which included the AOD parameter along with the primary MEM. Based on the two trained MEMs, daily PM$_{2.5}$ maps over Vietnam in 2017 were estimated separately and combined following a
principle in which the location without PM$_{2.5}$ estimation from the primary MEM would be supplemented by corresponding PM$_{2.5}$ estimation from the auxiliary model. Thus, the PM$_{2.5}$ maps would have full spatial coverage. Daily PM$_{2.5}$ maps were then converted into monthly and yearly average maps, and then clipped for Hanoi city. Daily 3 × 3 km PM$_{2.5}$ data were summarized to produce annual average maps for the Hanoi study region and for each district. Details of the data sources and model validation are presented in Supplementary material (pages 3–4). We also validated the 2017 annual Vietnam PM$_{2.5}$ map with the annual observations from seven ground stations by matching the pixel value on the map at the ground monitoring station with the annual station’s observation (see Figure S3, supplementary material). The average root mean squared error (RMSE) between annual estimated and observed values in 2017 was 5.82 μg/m³ while the mean relative error (MRE) error was at 22.1%.

**Estimation of Burden of the Premature Death Attributable to Exposure to PM$_{2.5}$**

We applied the mortality and PM$_{2.5}$ risk function from the global exposure mortality model (GEMM) [14] for non-communicable diseases (NCD) and lower respiratory infection (LRI) (denoted as GEMM NCD + LRI) to quantify the deaths from non-injury causes that were attributable to exposure to PM$_{2.5}$ among Hanoi residents aged 25 years and older. GEMM used a non-linear exposure-response relationship between ambient PM$_{2.5}$ and mortality (non-accidental) from 41 cohorts from 16 countries including high concentration regions (i.e., China). GEMM provides a hazard ratio for each 5-years age group based on the concentration of PM$_{2.5}$ and the model parameters for the specific age group and outcome. Death at age 25 was not considered in the assessment to avoid the higher proportion of communicable disease mortality [14].

Hazard ratios (HRs) for a given PM$_{2.5}$ concentration were calculated as:

$$GEMM(z) = \exp\{\theta \times \log\left(\frac{z + 1}{\alpha} + \frac{\mu}{v}\right)\}$$

where $z$ is the difference between PM$_{2.5}$ concentration and the counterfactual concentration, $\theta$, $\alpha$, $\mu$, and $v$ represent model parameters for the shape of the exposure response function, $\theta$ and standard error of $\theta$ extracted from Burnett [14] are listed in Table S3 for each specific age range.

From the hazard ratio, the burden of mortality relating to exposure to PM$_{2.5}$ for each age group and district was calculated as:

$$AN = (1 - HR) \times y_0 \times pop$$

where AN is the attributable number of premature deaths associated with the concentrations of PM$_{2.5}$ above the counterfactual in each district and age group. HR is the hazard ratio for the specific age group and PM$_{2.5}$ concentration in each district, $y_0$ is the death rate in the age group and district, and pop is the population in each age group and district in Hanoi in 2017.

To limit the error in reporting death registration between districts as indicated in a previous study [15], we applied the death rate for all Hanoi to the district level population by age group to estimate the district level death rate. The attributable number was then summed across age groups to estimate the burden in each district. These numbers were aggregated to calculate the estimate for all of Hanoi.

To assess the burden of PM$_{2.5}$, we set the counterfactual concentration as defined by QCVN 05:2013 at 25 μg/m$^3$. Concentrations in excess of this value, per district, were used in the calculation of attributable deaths.

We also calculated attributable YLL as the sum of the attributable deaths per age group multiplied by the life expectancy in that age group. Life expectancy was estimated using a life table with the baseline mortality rates in the Hanoi population by 5-years age groups. The time of death was assumed to be in the midpoint of each 5-years interval. This method was implemented using the iomlifetR package in R [23]. The LLE, in days, was calculated as the difference between the life expectancy calculated with and without the PM$_{2.5}$ attributable deaths. Confidence intervals (CI) in this study were calculated using the standard errors estimated in the GEMM and only reflected uncertainty in health risk modeling and did not represent the uncertainty in the exposure assessment. The attributable number of each indicator (death or YLL) for each district and all Hanoi was also represented as a rate per 100,000 inhabitants by dividing the attributable number by the population size of the corresponding district.

We also estimated the annual mortality burden due to PM$_{2.5}$ concentration in Hanoi above the lowest estimated grid-level value within Hanoi in 2017 (i.e., 22 μg/m$^3$) and IT-4 value (i.e., 10 μg/m$^3$).

**Sensitivity Analyses**

In addition, we also conducted sensitivity analysis by using log-linear exposure response functions with a uniform effect across age groups. The attributable number was calculated as:

$$RR_{Difference} = e^{\ln(RR) \times \Delta PM_{2.5}}$$

We chose relative risk (RR) estimates for the PM$_{2.5}$ exposure mortality (non-accidental) response function as RR = 1.07 (95% CI:1.04–1.09) of mortality (non-accidental) per 10 μg/m$^3$ increase in PM$_{2.5}$ in age groups ≥20 years [24].

The analysis was conducted in R version 4.0.3 (R Core Team Vienna, R Foundation for Statistical Computing, Vienna, Austria) and MS Excel (Microsoft, Redmond, Washington, DC, United States).

**RESULTS**

**PM$_{2.5}$ Concentration**

The 3 × 3 km grid annual average PM$_{2.5}$ concentration map for Hanoi in 2017 is shown in Figure 1A. The annual average PM$_{2.5}$ concentration for each grid ranged from 22.1 to 37.2 μg/m$^3$. The
concentrations were higher in the central districts in the city, such as Badinh or Dongda districts. The annual PM$_{2.5}$ concentrations were lower in suburban districts, especially Bavi, Sontay, Thachthat, Quocoai, Chuongmy, and Myduc districts located next to the Bavi mountains.

We aggregated the PM$_{2.5}$ values from the $3 \times 3$ km grid by district for the purposes of the health impact assessment (Figure 1B). The district average concentration values ranged from 26.9 to 37.2 μg/m$^3$ and all exceeded 25 μg/m$^3$ (QCVN 05: 2013).

Mortality Pattern in Hanoi in 2017
Demographic and death data for Hanoi are presented by district in Table 1. In 2017, Hanoi had 4,892,548 inhabitants aged above 25 representing 62.2% of total inhabitants. Number of deaths due to all causes and excluding injury in 2017 in Hanoi were 27,674 and 26,621, respectively. Death rates were 5.66 per 1,000 all cause deaths and 5.44 per 1,000 deaths without injury (Table 1).

The highest death rate was observed in Hoan Kiem districts, 8.93 per 1,000 population for all causes amongst inhabitants above 25 years of age. Nam Tu Liem and Thanh Xuan districts had the lowest death rates, 2.46 and 2.44 per 1,000 for death from all causes.

Attributable Mortality Estimates of Exposure PM$_{2.5}$
The absolute number of deaths, YLL (years), and loss of LE (annual average) attributable to PM$_{2.5}$ exposure are shown in Table 2. The annual mortality attributable to PM$_{2.5}$ in Hanoi above the level of QCVN:05 2013 was 2,696 premature deaths (95% CI: 2,225 to 3,158). The annual YLL and average LE lost due to PM$_{2.5}$ exposure in Hanoi was 68,708 years (95% CI: 56,050 to 81,412) and 659 days (95% CI: 535–785) (~1.8 years), respectively. We estimated that 9.7% of all deaths amongst the population above 25 years of age in Hanoi were premature deaths attributable to exposure to a PM$_{2.5}$ air pollution level of QCVN 05:2013 (see Table S5, Supplementary material).

The mortality burden attributable to PM$_{2.5}$ exposure above the “background” level of 22 μg/m$^3$ in Hanoi was 3,250 (95% CI: 2,649–3,748) annual premature deaths, or 11.6% of the annual mortality in Hanoi (Table 3, Supplementary Table S5). The mortality burden attributable to PM$_{2.5}$ exposure above the IT-
4 of 10 μg/m³ was 4,760 (95% CI: 3,958–5,534) annual premature deaths, 17% of the annual deaths in Hanoi.

**Sensitivity Analysis**

Findings from sensitivity analysis of the 2017 annual PM₂.₅ concentrations compared with the three alternative scenarios (QCVN-2013, IT-4, and the lowest measured value) are presented in Table 3.

**DISCUSSION**

We found that the mortality burden due to the annual average of ambient PM₂.₅ above the QCVN 05:2013 PM₂.₅ standard of 25 μg/m³ was 2,696 annual deaths (7.3 deaths per day) or 68,708 YLL. The mortality burden from PM₂.₅ exposure above the lower IT-4 of 10 μg/m³ was 4,760 annual premature deaths. This suggests that there would be substantial health benefits if the Hanoi government implemented policies that were effective in reducing air pollution to the levels recommended by these standards.

Air quality varied substantially in Hanoi over the period 2010 to 2018, with annual average PM₂.₅ concentrations varying from 29 to 55 μg/m³ [25], with an annual average PM₂.₅ concentration in 2017 of 26.9 to 37.2 μg/m³, which was in the middle of this range. Our results also illustrate the high concentration of PM₂.₅ in the industrial districts in Hanoi such as Gia Lam and Long Bien, with many small and middle-sized factories located in these districts. In recent years, the Hanoi government has attempted to relocate small factories from urban to suburban areas and moved big factories to other provinces outside Hanoi. This has contributed to recent declines in annual ambient PM₂.₅ concentrations in Hanoi [6, 25].

Population variation between districts is another important factor in the variation in the attributable rate due to exposure to PM₂.₅ between districts. For instance, districts such as Son Tay, Tay Ho, and Dan Phuong have relatively small populations. Hence the overall health burden from PM₂.₅ exposures was low compared to higher population districts. In contrast, Hoan Kiem and Ba Dinh are high-population districts and their associated mortality burdens were the highest, even though the exposure was low compared to many other districts.

Our estimate that mortality attributable to long-term exposure to PM₂.₅ was 34.3 per 100,000 population was slightly lower than the GBOD estimation for all of Vietnam (i.e., 36.82 per 100,000 population in 2017) [4]. That number is much higher than the estimate for metropolitan Bangkok, about 21 per 100,000 population [26]. Metropolitan Bangkok, close to Vietnam, shares similar emission sources, population, and weather, therefore, this confirms the size of the problem in Hanoi.

### TABLE 1 | Population, number of deaths, and death rate amongst inhabitants aged above 25 (Hanoi, Vietnam, 2017).

| Name of District | Population above 25 | Number of deaths | Death rates (per 1,000) |
|-----------------|---------------------|-----------------|-------------------------|
| Total           | 4,892,548           | 27,674          | 26,621                  |
| Hoan Kiem       | 131,893             | 1,178           | 1,144                   |
| Ung Hoa         | 128,070             | 1,135           | 1,083                   |
| Hai Ba Trung    | 183,815             | 1,608           | 1,588                   |
| Thanh Oai       | 120,271             | 922             | 887                     |
| Ba Dinh         | 173,642             | 1,238           | 1,182                   |
| My Duc          | 139,126             | 984             | 908                     |
| Dan Phuong      | 103,582             | 732             | 704                     |
| Quoc Oai        | 117,434             | 812             | 777                     |
| Dong Da         | 266,727             | 1,843           | 1,826                   |
| Phu Xuyen       | 131,276             | 906             | 872                     |
| Gia Lam         | 163,396             | 1,126           | 1,086                   |
| Phuc Tho        | 120,008             | 792             | 751                     |
| Thuong Tin      | 156,457             | 1,017           | 963                     |
| Ba Vi           | 181,748             | 1,155           | 1,105                   |
| Dong Anh        | 222,838             | 1,367           | 1,297                   |
| Thach That      | 124,936             | 764             | 714                     |
| Soc Son         | 190,069             | 1,126           | 1,046                   |
| Chuong My       | 200,387             | 1,173           | 1,103                   |
| Tay Ho          | 112,637             | 625             | 620                     |
| Me Linh         | 134,791             | 721             | 683                     |
| Thanh Tri       | 151,528             | 792             | 771                     |
| Hoai Duc        | 165,126             | 769             | 744                     |
| Ha Dong         | 187,794             | 795             | 766                     |
| Cau Gai         | 165,222             | 616             | 612                     |
| Long Bien       | 215,889             | 779             | 758                     |
| Bac Tu Lieu     | 195,065             | 678             | 655                     |
| Son Tay         | 103,977             | 340             | 327                     |
| Hoang Mai       | 255,229             | 824             | 796                     |
| Thanh Xuan      | 190,404             | 468             | 462                     |
| Nam Tu Lieu     | 159,211             | 389             | 381                     |

This table was sorted into descending values of death rates of all causes.
Solving this problem for Hanoi requires attention to sources. Previous studies on sources of air pollution in Hanoi have shown that traffic [27], industrial processes, rice stubble burning, and open burning of waste [28] are major contributors. However, a detailed assessment of the contribution of the various emission sources of Hanoi air pollution is absent to date. More detailed data are required on the relative importance of the various emission sources.

A strength of our study is the use of a high resolution PM$_{2.5}$ concentration map (3 × 3 km) to obtain district-specific PM$_{2.5}$ concentrations. We also used detailed local data on mortality, not previously used in health impact assessment studies in Vietnam. However, the study has several limitations. First, our study estimated district level mortality by applying Hanoi-wide death rates to the local district population. This value was estimated from our data as 5.66‰ for all causes. This is similar to the all-cause death rate for all ages in Hanoi in 2017 [29]. The A6 document that was the source of the deaths data is known to only cover around 86% of the total deaths in Vietnam [15]. Moreover, the A6 document deaths data we used only records the death of inhabitants with permanent addresses in Hanoi. In fact, a large number of inhabitants live in Hanoi without having a permanent address, and death records of them have been issued by their home provinces. So, our estimation of the death rates due to district pollution is likely to be an underestimate, and this would also result in an underestimate for our mortality burden calculations. Second, the GEMM exposure–response function for PM$_{2.5}$ applied in this health impact assessment relies on the results of

**TABLE 2** | The annual burden of mortality relating to exposure to fine particulate matter (Hanoi, Vietnam. 2017).

| Name       | Attributable Deaths | Year of Life Lost | Loss of Life Expectancy (days) |
|------------|---------------------|------------------|-------------------------------|
|            | Number              | 95% CI            | Number                        | 95% CI                         | Number | 95% CI                         |
|            | Lower | Upper | Lower | Upper | Lower | Upper | Lower | Upper | Lower | Upper | Lower | Upper |
| All Hanoi  | 2,696 | 2,225 | 3,158 | 68,708 | 56,050 | 81,412 | 659 | 535 | 785 |
| Dong Da    | 215   | 177   | 251   | 5,164  | 4,207  | 6,127  | 759 | 616 | 904 |
| Long Bien  | 142   | 118   | 166   | 3,628  | 2,958  | 4,300  | 770 | 625 | 917 |
| Hoai Duc   | 135   | 111   | 157   | 3,607  | 2,944  | 4,272  | 768 | 623 | 915 |
| Hoang Mai  | 134   | 111   | 157   | 3,085  | 2,513  | 3,661  | 661 | 536 | 787 |
| Dong Anh   | 133   | 110   | 156   | 3,470  | 2,831  | 4,112  | 749 | 607 | 892 |
| Ba Dinh    | 126   | 104   | 148   | 3,149  | 2,567  | 3,734  | 761 | 618 | 907 |
| Thanh Xuan | 109   | 90    | 127   | 3,149  | 2,567  | 3,734  | 752 | 610 | 896 |
| Gia Lam    | 104   | 86    | 122   | 3,628  | 2,958  | 4,300  | 792 | 642 | 944 |
| Thuyong Tin| 101   | 84    | 118   | 2,556  | 2,085  | 3,030  | 739 | 600 | 880 |
| Ha Dong    | 97    | 80    | 114   | 2,574  | 2,101  | 3,048  | 692 | 562 | 824 |
| Cau Giay   | 94    | 78    | 111   | 2,487  | 2,029  | 2,946  | 747 | 606 | 890 |
| Chuong My  | 84    | 69    | 98    | 2,181  | 1,780  | 2,583  | 765 | 621 | 912 |
| Hoan Kiem  | 82    | 68    | 96    | 2,181  | 1,780  | 2,583  | 756 | 613 | 900 |
| Thanh Tri  | 80    | 66    | 94    | 2,016  | 1,643  | 2,390  | 758 | 615 | 904 |
| Ung Hoa    | 80    | 66    | 93    | 2,393  | 1,956  | 2,829  | 763 | 619 | 910 |
| Soc Son    | 79    | 66    | 93    | 2,012  | 1,641  | 2,385  | 721 | 585 | 859 |
| Tay Ho     | 79    | 65    | 92    | 2,212  | 1,807  | 2,618  | 731 | 593 | 871 |
| Nam Tu Liem| 79    | 65    | 93    | 1,964  | 1,603  | 2,236  | 463 | 377 | 550 |
| Me Linh    | 79    | 65    | 92    | 2,181  | 1,781  | 2,581  | 688 | 542 | 796 |
| Bac Tu Liem| 78    | 64    | 91    | 1,931  | 1,575  | 2,289  | 679 | 551 | 808 |
| Hai Ba Trung| 75    | 62    | 88    | 1,792  | 1,481  | 2,124  | 558 | 454 | 664 |
| Phuc Tho   | 74    | 61    | 87    | 1,755  | 1,431  | 2,080  | 586 | 476 | 697 |
| Thanh Oai  | 71    | 59    | 83    | 1,760  | 1,436  | 2,087  | 660 | 536 | 785 |
| Ba Vi      | 64    | 52    | 74    | 1,573  | 1,283  | 1,864  | 673 | 547 | 802 |
| Son Tay    | 63    | 52    | 74    | 1,754  | 1,432  | 2,076  | 691 | 561 | 823 |
| Dan Phuong | 56    | 46    | 65    | 1,251  | 1,020  | 1,483  | 417 | 339 | 495 |
| My Duc     | 51    | 42    | 60    | 1,221  | 996   | 1,447  | 454 | 369 | 539 |
| Phu Xuyen  | 49    | 40    | 58    | 1,174  | 939   | 1,391  | 344 | 260 | 408 |
| Quoc Oai   | 42    | 35    | 50    | 1,011  | 826   | 1,197  | 247 | 210 | 293 |
| Thach That | 42    | 35    | 49    | 1,032  | 842   | 1,221  | 379 | 308 | 450 |

We used the counterfactual concentration as defined by the Vietnam Ambient Air Pollution Standard (25 µg/m$^3$). Abbreviation: CI: confidence interval.

**TABLE 3** | Number of attributable deaths relating to exposure to fine particulate matter with three scenarios (Hanoi, Vietnam.2017).

|                          | GEMM$^1$ | WHO$^2$ (RR$^3$ = 1.07) |
|--------------------------|----------|-------------------------|
| Attributable Deaths (95% CI) | Attributable Deaths (95% CI) |
| PM$_{2.5}$ lowest levels | 3,205 (2,649–3,748) | 2,068 (1,220–2,604) |
| QCVN-2013$^4$            | 2,696 (2,225–3,158) | 1,565 (920–1,975) |
| WHO guideline            | 4,760 (3,958–5,534) | 3,983 (2,388–4,964) |

$^1$Abbreviations: GEMM, global exposure mortality model.

$^2$WHO, World Health Organization.

$^3$RR, relative risk.

$^4$QCVN-2013, the Vietnam Ambient National Standard; CI, confidence interval.

Solving this problem for Hanoi requires attention to sources. Previous studies on sources of air pollution in Hanoi have shown that traffic [27], industrial processes, rice stubble burning, and open burning of waste [28] are major contributors. However, a detailed assessment of the contribution of the various emission sources of Hanoi air pollution is absent to date. More detailed data are required on the relative importance of the various emission sources.
epidemiology research from other countries and may not capture the true PM$_{2.5}$ and mortality exposure-response relation in Hanoi. Third, the areas of districts in Hanoi differ from that of the grids and this may introduce some bias in assigning concentrations from grid levels to district levels since areas of districts do not align exactly with the grids. However, the concentrations for each district were assigned by using values of grids covering the majority of district areas. Hence, we consider it unlikely that this would have a substantial impact on our results.

**Conclusion**
The attributable deaths due to exposure to PM$_{2.5}$ in Hanoi above the Vietnam QCVN 05:2013 of 25 μg/m$^3$ was 2,696 deaths or 34.3 per 100,000 inhabitants, with large variation in the mortality burden by district. This means that there would be substantial health benefits by reducing air pollution in Hanoi. While outside the scope of our current study, health risk assessment research can provide estimates of the financial benefits to health from reducing air pollution that can be used in cost-effectiveness assessments of air pollution control measures.

**AUTHOR CONTRIBUTIONS**
GMM, GBM, NTTN and NTNT drafted idea and concept. NTTN and NXT write original draft. NTKN, EJ, NTTN and NXT conducted the data analysis. All author contributed to revising and editing the manuscript.

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