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Long-term Assistance and SErvices for Research (LASER)
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THE REPORT ON

THE STATUS OF $PM_{2.5}$ AND ITS IMPACT ON PUBLIC HEALTH IN VIETNAM 2021

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THE REPORT ON

THE STATUS OF $PM_{2.5}$ AND ITS IMPACTS ON PUBLIC HEALTH IN VIETNAM 2021

Hanoi, September 2022

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The "Status of $PM_{2.5}$ and Its Impact on Public Health in Vietnam 2021" report was made by the research team from the University of Engineering and Technology, Vietnam National University, Hanoi in collaboration with the research team from the University of Public Health and the Citizen-Environmental science group at Live & Learn center (Live&Learn). This report is a product of the project "Improving air pollution monitoring and management of Vietnam with satellite $PM_{2.5}$ observation", which is part of the LASER (Long-term Assistance and SErvices for Research) PULSE (Partners for University-Led Solutions Engine) program in conjunction with United States Agency for International Development - USAID.

During the implementation of this product, our research group has received consultation from many experts and specialists inside and outside of Vietnam. We would like to express our gratitude towards **Prof. Nguyen Thi Kim Oanh** (Asian Institute of Technology Thailand), **PhD. Hoang Duong Tung** (Vietnam Clean Air Partnership - VCAP), **Assoc. Prof. To Thi Hien** (Vietnam National University Ho Chi Minh City - VNUHCM), **Assoc. Prof. Ho Quoc Bang** (Institute for Environment and Resources Ho Chi Minh City – IERHCM, Assoc. **Prof. Ly Bich Thuy** (Institute for environmental science and technology, Hanoi University of Science and Technology), **PhD. Pham Chau Thuy** (University of Engineering and Technology, Vietnam National University Hanoi – VNU UET), **PhD. Nguyen Ngoc Bich** (University of Public Health Hanoi – HUPH), **PhD. Tran Ngoc Dang** (University of Medicine and Pharmacy Ho Chi Minh City), **Ms. Nguyen Thi Nguyet Anh** (Northern Center for Environment Monitoring – NCEM), **Ms. Le Thanh Thuy** (Hanoi Environmental Protection Agency – Hanoi EPA), Vietnam National University Ho Chi Minh City – VNUHCM), **Mr. Do Manh Cuong** (Health Environment Management Agency, Ministry of Health), **Ms. Chu Thi Chung** (Hanoi Centers for Disease Control and Prevention – Hanoi CDC), and for your valuable opinions on this report. In addition, we would like to express our gratitude towards our experts from the U.S.: **Prof. Christopher Justice** and **Prof. Krishna Vadrevu** from the Department of Geographical Sciences, University of Maryland – UMD for providing us assistance with their expertise through out the process of developing our report.

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About LASER PULSE program

LASER (Long-term Assistance and SErvices for Research) PULSE (Partners for University-Led Solutions Engine) is a $70M program funded through USAID's Innovation, Technology, and Research Hub, that delivers research-driven solutions to field-sourced development challenges in USAID partner countries.

A consortium led by Purdue University, with core partners Catholic Relief Services, Indiana University, Makerere University, and the University of Notre Dame, implements the LASER PULSE program through a growing network of 3,000+ researchers and development practitioners in 74 countries.

LASER PULSE collaborates with USAID missions, bureaus, and independent offices, and other local stakeholders to identify research needs for critical development challenges, and funds and strengthens the capacity of researcher-practitioner teams to co-design solutions that translate into policy and practice. See more at laserpulse.org.

ABOUT US

Implementation process

This report was made by the research team from the University of Engineering and Technology, Vietnam National University, Hanoi in collaboration with the research team from the University of Public Health and the Citizen-Environmental science group at Live & Learn center, with the advice and cooperation of domestic and foreign experts.

Throughout the process of developing and finalizing this report, the implementation team has received consultation and advices from experts with many years of experience in air pollution research, state management of the environment and health. The first draft of the framework was consulted directly with experts in March 2022 before the implementation team worked on a detailed report. During the finalization of the report, the draft was sent to the experts and received detailed comments via email and in-depth discussions, direct comments in July and August 2022. The final report is commented, edited and approved by the Laser Pulse program.

About the implementation team

Research team at University of Engineering and Technology, Vietnam National University: proposed ideas for report content, developed content **related to $PM_{2.5}$ status** in the following sections: Introduction, Methodology, Current status of air quality in Vietnam, Air quality during COVID 19 social distancing, Conclusions, Recommendations, and related Appendices.

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The Citizen - Environmental science Team at the Center for Living and Learning for the Environment and Community (Live&Learn), Vietnam: edited the report content and connected stakeholders during the consultation process, developed and finalized the report.

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GENERAL INFORMATION

Overall goals:	Provide insight into the status of $PM_{2.5}$ across Vietnam in 2021 and assess the health benefits if $PM_{2.5}$ pollution was controlled
Target audience:	General public| Government agencies | Media, press
Nội dung:	• Status of $PM_{2.5}$ in 2021 on a national scale and in the Northern, Central, Southern regions • Status of $PM_{2.5}$ in 5 provinces/cities including Hanoi, Bac Ninh, Thai Binh, Nghe An, and Ho Chi Minh city • Analysis of $PM_{2.5}$ trends based on urban classification and during the social distancing period in Vietnam due to COVID-19 • Health benefits on a national scale if $PM_{2.5}$ pollution was controlled • Health benefits at district level if $PM_{2.5}$ pollution was controlled in 5 provinces/cities including Hanoi, Bac Ninh, Thai Binh, Nghe An, and Ho Chi Minh city • Recommendations for government agencies, schools/universities, and research institutes.
Scientific foundations:	National and international scientific research on air quality
Methodology:	Mixed Effect Model; Calculation of the number of Deaths Attributable to Air Pollution; Literature Review;
Data:	$PM_{2.5}$ estimation data from the Mixed Effects Model; $PM_{2.5}$ measurements at standard stations; Data of death percentages (General Statistics Office); Data of death percentage due to injuries (VNIS survey, 2010), population data from the Population and Housing Census 2019 results
Developed by:	The Vietnam National University – University of Technology and Engineering (VNU-UET) in collaboration with the Hanoi University of Public Health, as part of the project "Improvement of air quality management with satellite $PM_{2.5}$ observation", which is sponsored by the U.S. Agency for International Development (USAID) through the LASER PULSE program.
Assisting Organizations:	The Live and Learn for Environment and Community (Live&Learn)
Đơn vị hỗ trợ:	The Northern Center for Environmental Monitoring, Vietnam Environment Administration Institute for Environment and Resources – Vietnam National University Ho Chi Minh city

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This report is not meant to replace any other report on the environment in Vietnam, but rather a supplementary channel of information on the state of $PM_{2.5}$ and assessment of its effects towards human health in Vietnam in 2021. This report also does not reflect the views of the research teams' governing bodies or associated parties: Vietnam National University Vietnam University of Engineering and Technology, Hanoi University of Public Health, the Live&Learn Center, the Northern Center for Environmental Monitoring, Vietnam Environment Administrative, the Institute for Environment and Resources, Vietnam National University Ho Chi Minh City.

EXECUTIVE SUMMARY

Context

Air pollution is one of the major environmental challenges facing nations worldwide. According to the World Health Organization (WHO), there are around 7 million premature deaths due to exposure to polluted air around the world each year[1]. The 2022 Environmental Performance Index – EPI, showed that the level of exposure to air pollution in Vietnam was ranked 130 out of 180 nations[2]. In addition, the IQAir/Air Visual air report, an annual report on air quality constructed by IQAir utilizing the data from its extensive network of sensors, has ranked Vietnam's annual mean $PM_{2.5}$ value of 2021 number 36 out of 117 nations[3]. **Our research aims at shedding light on the state of $PM_{2.5}$ (particulate matter with a diameter smaller than 2.5 µm) and its effects on people's health in Vietnam.** The findings of our research can help the community as well as the authorities to gain knowledge on the air quality and take actions to improve air quality and the quality of their lives. Through our research, we have found out that the average $PM_{2.5}$ level of the whole nation in 2021 was lower than that of 2019 but somewhat higher than that of 2020. Across the country, there were only 6 out of 63 provinces that did not satisfy the nation standard for annual $PM_{2.5}$ concentration (25 µg/m³), but at the same time there was no province satisfying the World Health Organization's recommended level of annual average $PM_{2.5}$ concentration (5 µg/m³). Region-wise, there were 76% of the provinces in Northern region satisfying the nation standard for annual mean $PM_{2.5}$ concentration, while these numbers for the Central and Southern regions were both 100%. The level of $PM_{2.5}$ pollution also showed changes corresponding to the level of urbanization, with the highest-ranked urban areas (namely Hanoi and Ho Chi Minh City) having less days with good air quality than other lower-ranked urban areas by 20% on average. We also found out that big cities like Hanoi and Ho Chi Minh City were hotspots for $PM_{2.5}$ pollution in their own regions (Northern and Southern regions, respectively). In addition, the years 2020 and 2021 are considered special years in the aspect of air pollution because of the sudden events of COVID-19 and social restrictions, leading to a decrease in economic and living activities – major sources of air pollution. **We have analyzed the impact of air pollution on the community's health in 2019 and hypothesized what its impact would be if interventions had been applied to reduce the levels of pollution in 2019 to achieve $PM_{2.5}$ levels similar to that of 2021.** This analysis can show the impact of $PM_{2.5}$ on people's lives in a normal circumstance in Vietnam, and the effectiveness of interventions in controlling the anthropogenic sources. Our results indicate that the estimated number of $PM_{2.5}$-related deaths in Vietnam in 2019 accounted for one-tenth the number of deaths attributable to natural causes in Vietnam in that year; Hanoi and Ho Chi Minh City were two areas with the highest estimated numbers of deaths related to $PM_{2.5}$ across the country. On the other hand, if interventions had been applied, the number of deaths attributable to $PM_{2.5}$ would decrease by approximately 7%. From these findings, we hope to incentivize the authorities and the community to work on policies and take action to manage and reduce air pollution in order to improve not just the quality of the environment but quality of people's lives.

[1] WHO, 2014 [2] Wolf, M. J et al, 2022 [3] IQAir, 2022

Purpose

Up until now, efforts to monitor $PM_{2.5}$ along with other pollutants are being made by the Vietnam Environment Administration at a national scale and by each province's Department of Natural Resources and Environment at regional scale. In addition, data on $PM_{2.5}$ are also provided from different networks of standardized monitoring stations and sensors from multiple embassies, research organizations, and private companies. In recent years, modeling techniques using station data, satellite imagery (remote sensing) and ancillary data have been processed by a numeric or statistical model to produce $PM_{2.5}$ concentration maps, which are applied largely to provide information on $PM_{2.5}$[4]. This is a sufficient way to supplement for the on-ground station data, providing information on the spatial distribution of $PM_{2.5}$ on a large scale, especially in areas that lacks on-ground measurements. Based on current circumstances, our analyses were performed on our $PM_{2.5}$ data calculated using statistical machine learning[5] to provide more complete information on the spatial and temporal distribution of $PM_{2.5}$ in Vietnam in the period 2019-2021, as well as assessing the severity of its impact on human health, whose results are reported in the **"Status of $PM_{2.5}$ and its Impact on Public Health in Vietnam" 2021 report.** With our research, we expect the community as well as authorities to be more aware of nuances of the air pollution problem, which in turn can serve as an incentive for them to work on and implement policies and actions to reduce and control air pollution.

Methods

To achieve our goal in this research, we needed to look at the state of $PM_{2.5}$ pollution from different angles ($PM_{2.5}$ pollution on a national, regional, provincial level, $PM_{2.5}$ pollution based on urbanization, etc. as well as what harm it is causing to human health). Firstly, we constructed the daily $PM_{2.5}$ distribution maps in the period from 2019 to 2021 on a nation scale using the Mixed Effect Model and multisource data (including satellite, meteorology, and land use data)[6]. Then, we continued to aggregate the daily $PM_{2.5}$ maps to get the monthly and annual average $PM_{2.5}$ concentration values of the provinces as well as the districts in each province to facilitate further analyses. In addition, we calculated the average levels of $PM_{2.5}$ exposure of each province to assess how $PM_{2.5}$ is affecting people on a provincial level. **Urbanization status also correlates to the high levels of air pollution;** therefore, we also looked into the average $PM_{2.5}$ levels in each urban type by extracting and analyzing daily and annual average $PM_{2.5}$ of every area in each type. **Another aspect that needed to be assessed in the year 2021 is the possible influence of social distancing methods due to COVID-19 on the $PM_{2.5}$ concentration,** since these restrictions has reduced the economic, traffic and living activities substantially for a long period, especially in large cities where COVID-19 were most detrimental. We examined this hypothesis by looking at the changes in daily $PM_{2.5}$ concentrations in two cities Hanoi and Ho Chi Minh during lock down in 2021. At the same time, we estimated the $PM_{2.5}$ values in a hypothetical situation where social distancing was not accounted for (only natural factors such as meteorology) and compared the two dataset to reveal the effects that social distancing might have had on air pollution. After analyzing the state of $PM_{2.5}$ in 2021, we continued to assess its effects on human health in the year prior to COVID-19, when socio-economic activities in Vietnam were not hindered by any restriction. **To do this, we estimated the number of deaths attributable to $PM_{2.5}$ exposure in 2019 using data collected from multiple medical facilities in the country as well as population data and the $PM_{2.5}$ distribution dataset.** As the circumstances of COVID-19 in 2020 and 2021 could be considered a "natural experiment" to assess the effectiveness of invertention measures to reduce air pollution, we hypothesized that if before the year 2019, Vietnam had applied the same preventive measures as in 2020, the overall $PM_{2.5}$ concentration in 2019 would be similar to that of 2021. This would lead to a change in the number of deaths in 2019, which we analyzed.

Main findings

From the analyses that were performed in this research, we have discovered some key results on the state of $PM_{2.5}$ in Vietnam in 2021, as well as the impact of $PM_{2.5}$ on human health. **On a national scale, the annual average $PM_{2.5}$ concentration of 2021 showed a decline compared to 2019 and a slight increase compared to 2020.** Areas with high $PM_{2.5}$ concentration were located in the Red River Delta (including Hanoi City and adjacent provinces). In 2021, there were 6 out of 63 provinces exceeding the national standard for annual average $PM_{2.5}$ concentration (25 µg/m^3). However, the levels of exposure to $PM_{2.5}$ in the population in all provinces were higher than their annual average $PM_{2.5}$ concentrations. Moreover, the annual average $PM_{2.5}$ values of provinces across Vietnam were still many times higher than the WHO recommendation for 2021 (5 µg/m^3). **The distribution of $PM_{2.5}$ in each region were different with all the provinces not qualifying the national standard located in the Northern region, while the percentage of provinces satisfying the national standard for annual average $PM_{2.5}$ in the North being only 76%, whereas the percentages of provinces satisfying the national standard in the Central and Southern regions were both 100%.** When comparing average $PM_{2.5}$ values at district level between provinces, we also noticed that the Northern region also showed great discrepancies between the most and least polluted areas, with values ranging from 13.1 µg/m^3 to 43 µg/m^3. Meanwhile, the Central and Southern regions showed less variation in their district average $PM_{2.5}$ concentrations, with values ranging from 11.0 µg/m^3 to 23.1 µg/m^3 for the Central region and 11.4 µg/m^3 to 21.3 µg/m^3 for the Southern region. **In the aspect of urbanization, we observed that the levels of $PM_{2.5}$ pollution had a positive correlation with the level of urbanization.** Specifically, the percentage of days with good air quality in the Special type urban areas was only 64%, while this percentage for other lower urban types ranged from 79-85%. The percentages of days with air quality that is moderate and unhealthy for sensitive groups of the special type urban areas were also higher than those of the lower type urban areas were. The two special urban areas of Vietnam, Hanoi and Ho Chi Minh City, are both the socio-economic forefronts of the country; therefore, it is reasonable that these areas would exhibit higher levels of pollution compared to other provinces in their regions. For Hanoi, the annual average $PM_{2.5}$ concentrations of every district in the city were higher than the national standard, with the number of days with good air quality in 2021 only accounting for 42.2% of the total days of the year. For Ho Chi Minh City, even though the $PM_{2.5}$ concentrations all the districts in the city were under the national standard, these values were still 2 to 4 times higher than the WHO recommendation for 2021. The number of days with good air quality in Ho Chi Minh accounted for 87.1% of the total days of the year. Besides Hanoi and Ho Chi Minh City, we also looked into the status of $PM_{2.5}$ in Bac Ninh, Thai Binh and Nghe An in 2021. Close to Hanoi, Bac Ninh and Thai Binh are also located in the North and are characterized by the number of up-and-running industrial parks and activities in both provinces. In 2021, 100% of the districts in Bac Ninh were exceeding the national standard for annual $PM_{2.5}$ concentration with only 49.7% of the days in this year with good air quality; meanwhile, the percentage of districts satisfying the national standard in Thai Binh was 62.5% with the percentage of days with good air quality being 69.3%. Nghe An is located in the North-Central

[4] A. J. Cohen et al, 2015; B. N. Duncan et al, 2014; Yale, 2020; Health Effects Institute, 2020

[5, 6] Thanh T.N. Nguyen, 2022; Truong X Ngo et al, 2022

Coast of Vietnam and is covered by a large area of natural forest; this can be beneficial for Nghe An in keeping the $PM_{2.5}$ low but can also cause $PM_{2.5}$ concentration to spike often via sudden forest fires. In 2021, 100% of the districts in Nghe An satisfied the national standard with $PM_{2.5}$ concentration still higher than the WHO recommendation, and across the province, 89% of the days in this year were observed with good air quality. The distribution of $PM_{2.5}$ in all the cities and provinces that we have looked into above shared a similarity in their seasonal variation, specifically the $PM_{2.5}$ concentration in the winter (or dry season, typically from October or November till February or March of next year) seemed to be higher than that in summer (or wet season, typically from May to August). **As for the possible effects of COVID-19 restrictions on air quality, we decided to look into the air quality Hanoi and Ho Chi Minh City, which suffered the most from the pandemic with some of the longest restriction periods across the country.** Although having overall high levels of $PM_{2.5}$ in the year 2021, there were considerable drops in $PM_{2.5}$ concentration during the lock down periods in each city. For Hanoi, when comparing the real $PM_{2.5}$ values to our estimations under normal conditions, we noticed that the real values of $PM_{2.5}$ about 22.7% lower during the lock down. The discrepancy was more evident in Ho Chi Minh City with a 41.4% difference between real and estimated $PM_{2.5}$ values during the lock down. Both cities also exhibited lower levels of $PM_{2.5}$ during the periods of social distancing compared to before and after.

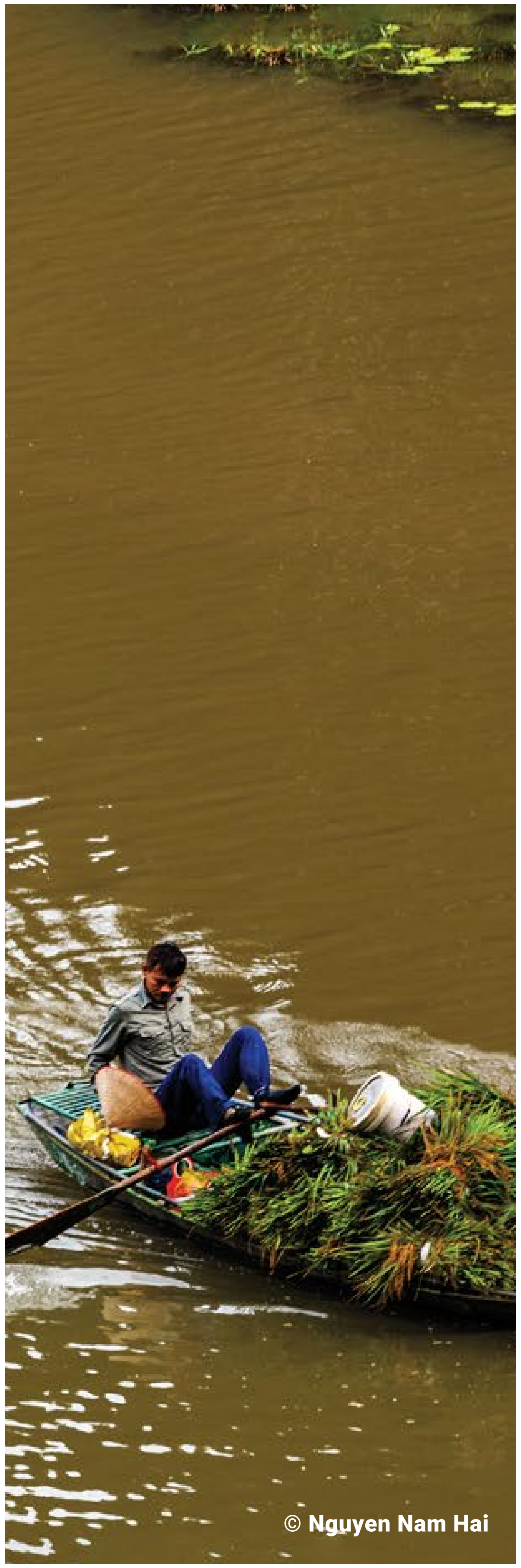
Based on our $PM_{2.5}$ distribution data for 2019, along with data from different medical facilities and population data, **we estimated that there were 56.8 thousand cases of deaths due to $PM_{2.5}$ exposure, accounting for 9.9% of the number of deaths due to natural causes in Vietnam in 2019.** Regions with high number of deaths were the Red River Delta and the North-Central and South-Central Coast. Hanoi and Ho Chi Minh City were the two areas with the highest numbers of deaths estimated due to $PM_{2.5}$ exposure with 6,250 and 4,130 cases, respectively. The number of deaths attributable to $PM_{2.5}$ in Bac Ninh, Thai Binh and Nghe An were 1,047, 1,697 and 1,930 cases. **Moreover, according to our estimations, if intervention measures were applied to make $PM_{2.5}$ levels in 2019 to decrease to levels similar to that of 2021, then the number of deaths due to $PM_{2.5}$ would decrease by 6.7% across the country.** Specifically, the number of deaths attributable to $PM_{2.5}$ per district in Hanoi would decline by 5.6-6.8%, while Ho Chi Minh would decrease by 6.9% the total number of deaths due to $PM_{2.5}$ of the whole city. Bac Ninh province would be able to cut from 5.1-5.8% of its number of deaths per district, and Thai Binh would be able to reduce 6.1% of its total number of deaths. As for Nghe An, the number of deaths attributable to $PM_{2.5}$ per district of the provinces would be reduced by 5.1-7.4%.

Recommendations

With evidence of the effects of $PM_{2.5}$ on human health that we have presented, we recommend that there should be a joint effort between multiple parties (scientists, researchers, government bodies, NGOs, private sectors, the community, etc.) to take action in order to manage and reduce air pollution so that the quality of the environment as well as quality of people's lives can be improved.

For organizations and government units, we recommend the use of $PM_{2.5}$ dust distribution maps from the model and in the future can be extended to other pollutants for a comprehensive view of the current state of air quality at the national, regional, and provincial levels every year. In addition, priority should be given to monitoring and managing (including the development of a standard air monitoring network) and the development of air quality management plans for provinces and cities and urban areas with high levels of pollution as detailed in this report. In addition, the development of a mechanism to share data and information for quality assurance/control at stations for scientific research and education-communication activities. In addition, there is a need for periodic review and updating of the national air quality standards, as there is currently a large gap between the national standard and WHO recommendations, which refers to the $PM_{2.5}$ level that can start to cause harm to human health. Besides national standards for ambient air, Vietnam also needs standards for indoor air pollution as this is also an urgent problem in middle-and-low-income countries. In addition to air quality management, we also recommend periodic monitoring of the effects of air pollution on health because the results from this assessment will also be a useful source of data to help quantify the effectiveness of the policies being implemented. In addition, it is also necessary to improve the system of recording deaths and illnesses at health facilities for timely and complete updates. Furthermore, there is a need for inter-disciplinary cooperation (in particular, air quality management agencies and health facilities together with population statistics agencies) to ensure efficiency in assessing the level and impact of air pollution on the health of the community.

As for research institutes and universities, we recommend that there be research investment in air pollution modeling at national, regional, and city/province scale to provide data of either the status or forecast of air pollution with high accuracy. In addition, it is also necessary to develop a method for assessing the health impact of air pollution specifically for Vietnam, to increase the accuracy of the assessment. With the status of $PM_{2.5}$ dust pollution, it is necessary to develop methods to identify accurately the sources of pollutant emissions from which to take reasonable mitigation measures. Finally, in each stage of the research and evaluation process, it is necessary to consult experts as well as state management agencies to ensure the quality of the process as well as the correctness of the result interpretation. This will also provide more information and strengthen the interest and commitment of regulatory agencies to the application of research results to management activities.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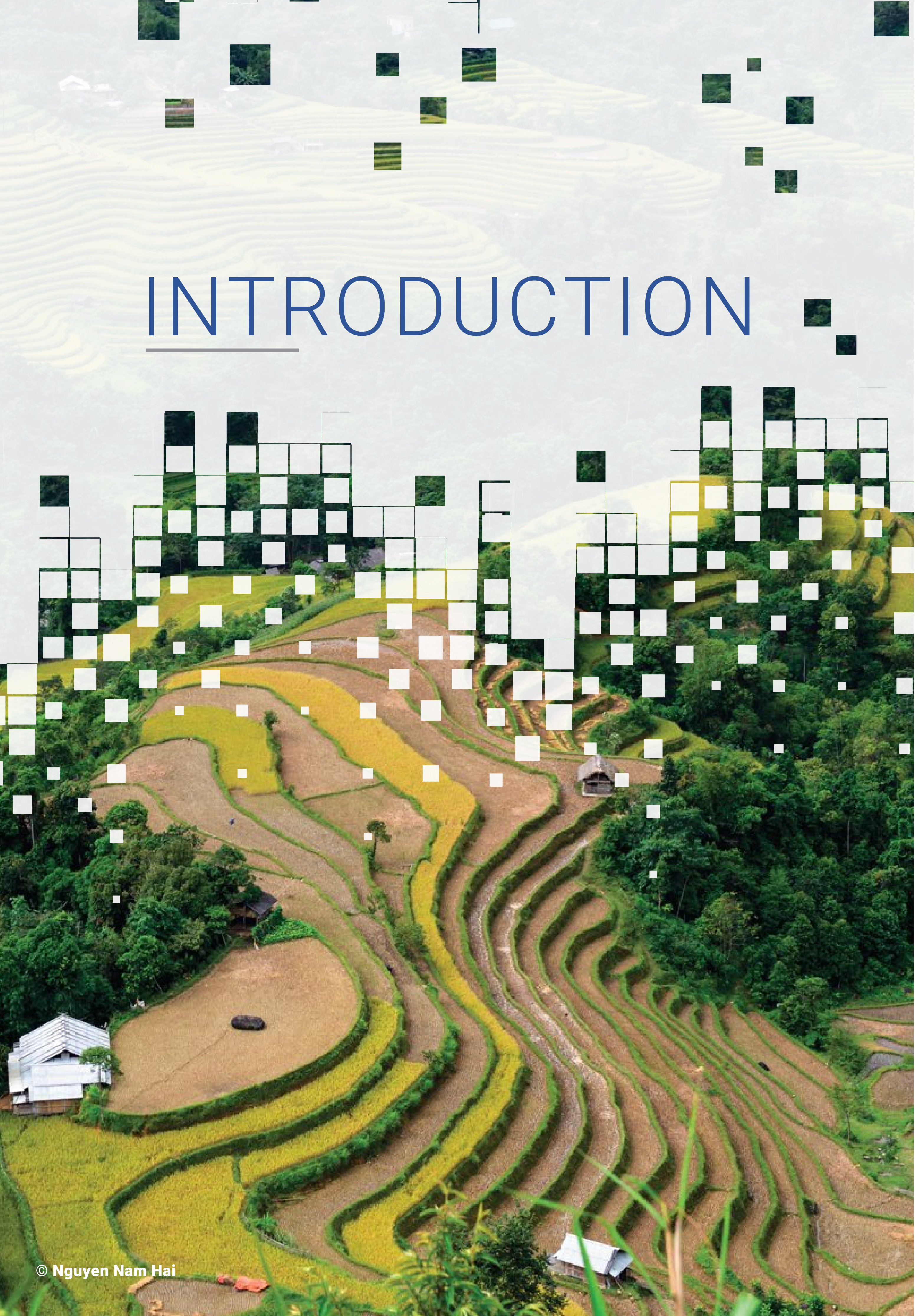
LIST OF ABBREVIATIONS

Bộ TNMT/BTNMT – MONRE	Bộ Tài nguyên và Môi trường – Ministry of Natural Resources and Environment
CLKK	Chất lượng không khí – Air quality
ĐHQG	Đại học Quốc gia – Vietnam National University
ONKK	Ô nhiễm không khí – Air pollution
QCVN	Quy chuẩn kỹ thuật quốc gia - National Technical Regulations
TNMT	Tài nguyên và Môi trường – Environment and Natural resources
TP. Hồ Chí Minh	Ho Chi Minh city
AOD	Aerosol Optical Depth
COVID-19	Coronavirus Disease-19
EPI	Environmental Performance Index
HEI	Health Effects Institute
HN EPA	Hanoi Environmental Protection Agency
MEM	Mixed Effect Model
MRE	Mean Relative Error
PM	Particulate Matter
$PM_{2.5}$	Particulate matter with aerodynamic diameter ≤2.5 µm
RMSE	Root Mean Square Error
US EPA	United States Environmental Protection Agency
VN_AQI	Vietnam Air Quality Index
WHO	World Health Organization
World Bank	Ngân hàng Thế giới
WRF (model)	Weather Research and Forecasting model

INTRODUCTION



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Overview of $PM_{2.5}$ in Vietnam

Air pollution is one of the major environmental challenges facing nations worldwide. According to the World Health Organization (WHO), there are around 7 million premature deaths due to exposure to polluted air around the world each year[7]. The 2022 Environmental Performance Index – EPI, showed that exposure to air pollution in Vietnam ranked 130 out of 180 nations[8]. In addition, the IQAir/Air Visual air report, an annual report on air quality constructed by IQAir utilizing the data from its extensive network of sensors, has ranked Vietnam's annual mean $PM_{2.5}$ value of 2021 number 36 out of 117 nations[9].

The national environment status report for the period from 2016 to 2020 shows particulate matter with diameter smaller than 2.5 µm – $PM_{2.5}$, had a steady increase from 2017 to 2019, followed by a decrease in 2020[10]. The "State of $PM_{2.5}$ in Vietnam during 2019-2020 based on Multisource Data and Application Of Satellite Technology in Air Pollution Monitoring and Research" report has pointed out that in 2019 there were 13 of 63 cities and provinces with annual mean $PM_{2.5}$ exceeding the national standard, 11 of which were cities or provinces of the Northern region. In 2020, there were 10 of 63 cities and provinces exceeding the national standard, and all these cities or provinces were of the North[11].

Up til now, efforts to monitor $PM_{2.5}$ along with other pollutants are being made by the Vietnam Environment Administration at a national scale and by each province's Department of Natural Resources and Environment at regional scale. In addition, data on $PM_{2.5}$ are also provided by different networks of standardized monitoring stations and sensors from multiple embassies, research organizations, and private companies. In the recent years, modeling techniques using station data, satellite imagery (remote sensing) and ancillary data have been used to produce $PM_{2.5}$ concentration maps are applied largely to provide information on $PM_{2.5}$[12]. This is a sufficient way to supplement for the on-ground station data, providing information on the spatial distribution of $PM_{2.5}$ on a large scale, especially in areas that lacks on-ground measurements.

Based on current circumstances, our research will utilize modelled $PM_{2.5}$ data to provide a more complete view of both the spatial and temporal aspect of the $PM_{2.5}$ pollution situation in Vietnam in 2021. 2020 and 2021 were special years as there were many social distancing episodes occurring in many provinces/cities in Vietnam to limit the spread and impact of the COVID-19 pandemic, leading to a decline in $PM_{2.5}$ emissions from human activities. The $PM_{2.5}$ data used in this report is the map dataset of $PM_{2.5}$ distribution calculated from the Mixed Effect Model – MEM[13] on station measurement, satellite imagery and ancillary data. The use of this data will allow for more in-depth $PM_{2.5}$ distribution analysis nationwide and per province/city, as well as analysis into chronological trends. The findings in this report will assist in determining the provinces/cities, along with adjacent areas with critical levels of $PM_{2.5}$ pollution that highly require policies to control and improve air quality.

Health impacts assessment

The health impact assessment of a certain environmental factor can help legislators to gain proof on the levels of overall impacts of that factor. Regarding air pollution, these impacts can be quantified by the total number of cases, hospital admissions or deaths attributable to air pollution exposure in a population. One of the common pollutants used to conduct health impact assessment is $PM_{2.5}$, since $PM_{2.5}$ can easily

[7] WHO, 2014 [8] Wolf, M. J et al, 2022 [9] IQAir, 2022 [10] Vietnam Environment Administration, 2021
[11] VNU-UET & Live&Learn & USAID, 2021
[12] A. J. Cohen et al, 2015; B. N. Duncan et al, 2014; Yale, 2020; Health Effects Institute, 2020
[13] I. Kloog et al, 2014, H. J. Lee et al, 2016

penetrate and cause harm to the human respiratory system and overall heath.

From January 2020 to the start of 2021, Vietnam has taken many preventive measures to slow down and control the spread of the SAR-COVID-2 virus. These measures include reduced travel and social distancing in a partial or the entire region. These measures might have somewhat disrupted the industrial and economic processes. However, they have also created a "natural experiment", in which different emission sources of air pollution have been cut down. We hypothesize that if before the year 2019, Vietnam had applied the same preventive measures as in 2020, the overall $PM_{2.5}$ concentration in 2019 would have been similar to that of 2021. This would lead to a change in the number of deaths in 2019, which will be analyzed in this research.

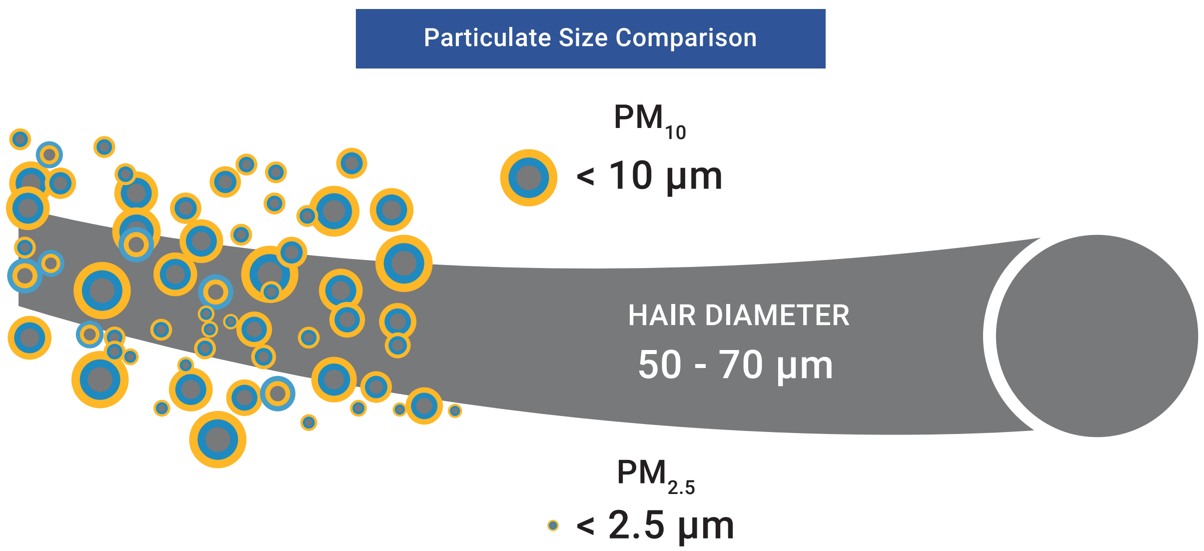


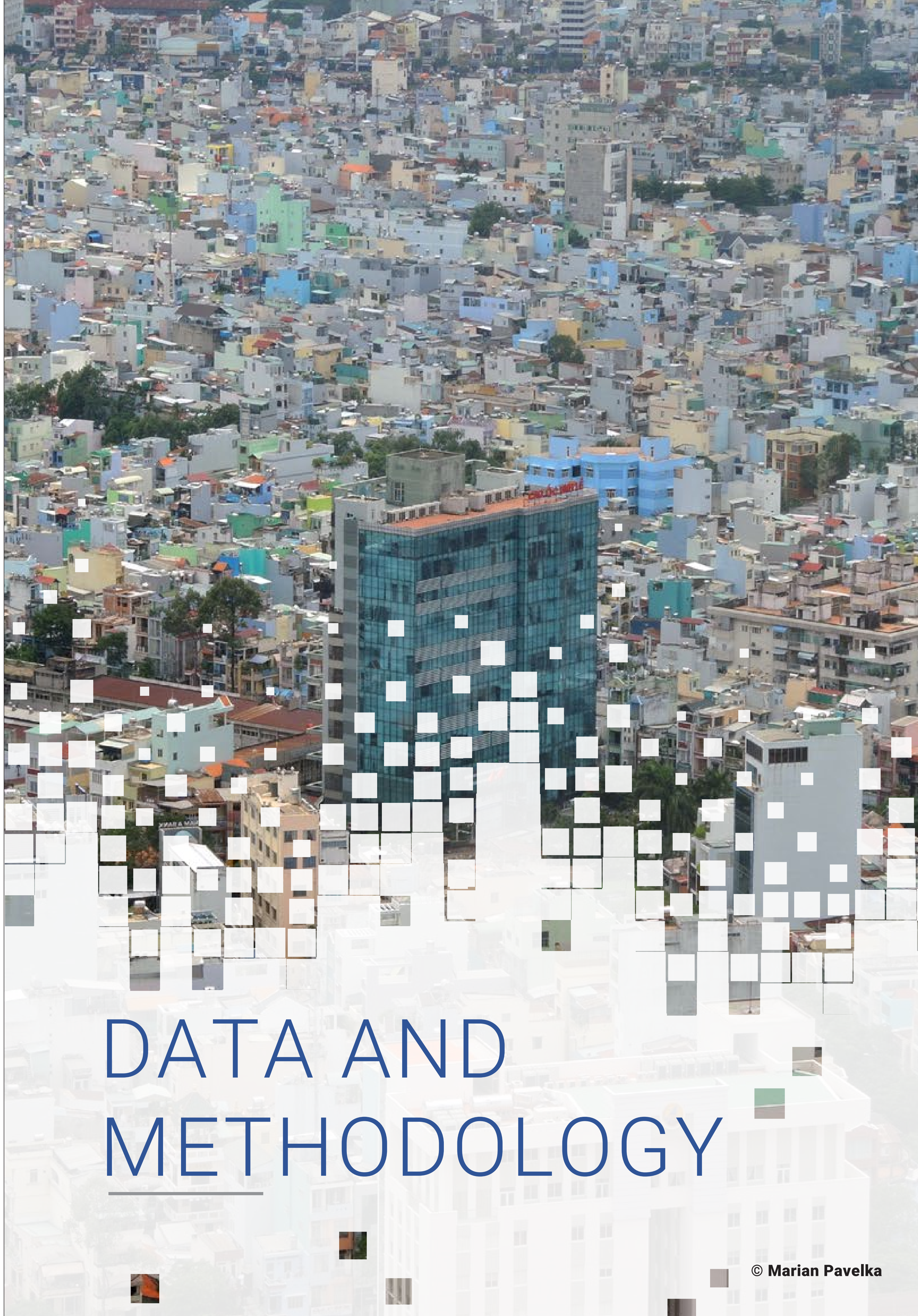
Figure 1. Illustrate the size of $PM_{2.5}$

Source: https://ww2.arb.ca.gov/resources/inhalable-particulate-matter-and-health

What makes this report distinctive?

The "Status of $PM_{2.5}$ and Its Impact on Public Health in Vietnam 2021" presents information on $PM_{2.5}$ in 2021 and at the same time, analyzes the health benefits if $PM_{2.5}$ pollution was under control on a national scale. Here are some key points that makes this report unique:

- This is the first report that combines the analysis of the $PM_{2.5}$ pollution and assessment of $PM_{2.5}$'s impact on public health for 63 provinces across Vietnam, along with detailed analysis at district level for several provinces/cities.
- The $PM_{2.5}$ data used for analysis in this report is the daily $PM_{2.5}$ concentration dataset with a spatial resolution of 3x3km that covers the Vietnam region (hereby called maps). This dataset was produced from the data collected from multiple automatic and continuous air quality monitoring stations (hereby called standardized stations) and other supplementary data, updated to the year 2021.
- This report contains analysis results on the status of $PM_{2.5}$ nationwide, in three regions, and in 5 provinces/cities in 2021
- This report also contains information on the health impact assessment on a national scale. This is the avoidable deaths if Vietnam had implemented different measures to cut down emission sources of $PM_{2.5}$ like the measures taken in 2020 to prevent the spread of COVID-19.



DATA AND METHODOLOGY

© Marian Pavelka

METHODS FOR ASSESSING THE STATUS OF $PM_{2.5}$

Method of Analyzing the Status of $PM_{2.5}$ in Vietnam

For most air quality reports, monitoring station data is often used instead of model data. Standardized monitoring stations, which are operated and managed by government agencies, have data with high quality and frequency. However, they require high cost for installation and operation, are distributed unevenly, and are limited in quantity across the country. Meanwhile, the daily $PM_{2.5}$ concentration maps provides information of $PM_{2.5}$ on a large scale and over a long period of time, especially in places where monitoring stations have not existed yet. But the data frequency and quality of the map data are both lower than that of the standard monitoring stations.

To assess the Status of $PM_{2.5}$ in 2021 in Vietnam, we analyzed the daily $PM_{2.5}$ maps with spatial resolution of 3x3 km during 2019 - 2021. The maps were developed using Mixed Effects Model (MEM) with input data including standardized ground monitoring station's data, satellite Aerosol Optical Depth (AOD), meteorological data, and land use data from 2012 to 2021 (Appendix A1). The maps have been verified and evaluated by comparison with observations at the ground monitoring stations (Appendix B).

In this research, we aggregated and analyzed daily $PM_{2.5}$ maps according to multiple spatial levels (national, region, province/city, and district) and time levels (annual, monthly, daily). Please see details in Appendix A1.

Method of Developing $PM_{2.5}$ concentration maps

We developed the daily $PM_{2.5}$ concentration maps in Vietnam based on the Mixed Effect Model using different data sources collected from 2012 - 2021. Input data include standard monitoring station data, satellite AOD images, meteorological data (humidity, Planetary Boundary Layer Height (PBLH)), land use maps (traffic density, Normalized Difference Vegetation Index (NDVI), terrain). A detailed description is in Appendix A2.

Method of calculating monthly/annual average and mean of province/city or district

After developing the daily $PM_{2.5}$ maps from the MEM model estimations, we aggregated these maps into monthly average maps. The composite method is to average the $PM_{2.5}$ value of a 3x3km grid cell in all days of a month. A monthly average $PM_{2.5}$ map is obtained by performing the same calculations for all grid cells in Vietnam. Then we used the monthly average $PM_{2.5}$ maps to produce the annual average maps by the same method. To calculate the mean $PM_{2.5}$ value at provincial/city or district levels, we extracted all the $PM_{2.5}$ values at 3x3 km in the region of interest and averaged those values to obtain a mean for the whole region. Details can be found in Appendix A3.

Method of calculating $PM_{2.5}$ exposure (population-weighted $PM_{2.5}$)

The population-weighted $PM_{2.5}$ concentration in an area represents the exposure to $PM_{2.5}$ of the population living in that area. The $PM_{2.5}$ value for an area, instead of being averaged over all locations in the area, is averaged by population weight, in which, the $PM_{2.5}$ value will be weighted higher in densely populated locations than less populated locations. Details of the method can be found in Appendix A4.

Analyzing $PM_{2.5}$ pollution based on urban classification

In order to assess the overall air quality trends according to different levels of urbanization, we collected the list of different urban regions identified based on the criteria in the Resolution no.1210/2016/UBTVQH13 of the Prime Minister on the approval of the National Urban Classification Plan for the period 2021-2030 (Appendix A5). Based on the list, mean $PM_{2.5}$ concentration values of each urban classification were aggregated. After that, the number of urban areas with annual $PM_{2.5}$ values exceeding the QCVN 05:2013/BTNMT standard and the mean percentage of days with different air quality levels were analyzed.

Method of assessing the effects of social distancing due to COVID-19 on air quality

Air quality is always under the influence of many factors, one of which is the weather. In this research, the research team estimated $PM_{2.5}$ concentrations in the scenario where $PM_{2.5}$ was only influenced by different elements of the weather – temperature, humidity, atmospheric pressure, wind speed and direction, vision (referred to as $PM_{2.5}$ under normal weather conditions) were made. These values were then compared to the $PM_{2.5}$ values from the MEM in the same period in order to examine the effects of factors other than the weather on air quality during social distancing. Details of the method can be found in Appendix A6.

Exchanging between $PM_{2.5}$ and the Vietnam Air Quality Index

The value exchange table between various pollutants and AQI, constructed and issued in Decision on Promulgating Technical Guidelines for Calculation and Publication of Air Quality Index in Vietnam[14] on November 12th, 2019, by the Vietnam Environmental Administration, was used to exchange between $PM_{2.5}$ values and the Vietnam Air Quality Index.

Table 1. Air quality values and corresponding color

Air quality	AQI	$PM_{2.5}$ ($\mu m/m^3$)	Health recommendation
Good	0÷50	0÷25	Air quality is satisfactory and poses little or no risk
Moderate	51÷100	25.1÷50	Sensitive individuals should avoid outdoor activity as they may experience respiratory symptoms.
Unhealthy for Sensitive group	101÷150	50.1÷80	General public and sensitive individuals in particular are at risk to experience irritation and respiratory problems.
Unhealthy	151÷200	80.1÷150	Increased likelihood of adverse effects and aggravation to the heart and lungs among general public.
Very unhealthy	201÷300	150.1÷250	General public will be noticeably affected. Sensitive groups should restrict outdoor activities.
Hazardous	301÷500	250.1÷500	General public is at high risk to experience strong irritations and adverse health effects. Everyone should avoid outdoor activities.

[14] Vietnam Environmental Administration, 2019

METHODS FOR ASSESSING THE IMPACT OF $PM_{2.5}$ ON HUMAN HEALTH

This study followed the WHO's guideline for health risk assessment of air pollution as described in Figure 2:

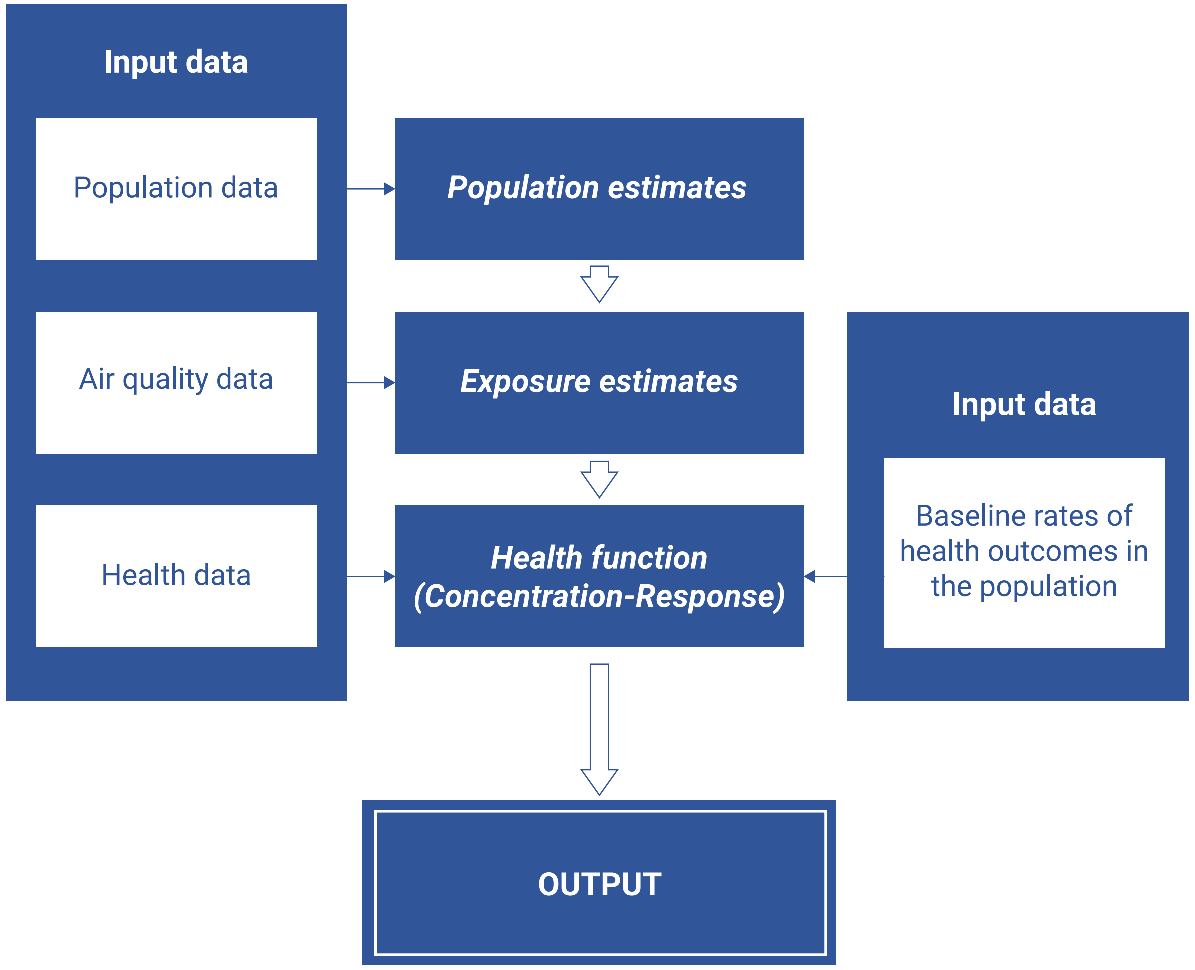


Figure 2. Air pollution health risk assessment method (WHO-EU- 2016)

Input data

Population data in 2019 for each district was stratified by age groups. This data was extracted from the report of the 2019 Vietnam Population and Housing Census of the General Statistics Office. This survey, which was carried out in 2019 on all 63 provinces/cities, includes complete statistics on the population, the mortality rates, and birth rates based on the forms of the General Statistics Office[15].

- Mortality rate (reported by the General Statistics Office (www.gso.org.vn)), and the National Survey on Injuries in Vietnam in 2010[16],

- Annual mean of $PM_{2.5}$ concentration in 2021 and 2019: the map data of annual mean of $PM_{2.5}$ in Vietnam in 2019 and 2021 was used in this study.

- The health function, which is based on Global Exposure Mortality Model (GEMM) by Burnett, 2018[17]. The number of non-accidental deaths per each unit of $PM_{2.5}$ increase was estimated from the meta-analysis of 41 cohorts from around the world, including countries with high $PM_{2.5}$ concentration such as China. Non-accidental deaths were chosen due to the lack of concrete proof of the association between injuries and air pollution. This study will only consider the burden of mortality for the population of people aged 25 and over based on the recommendation of the GEMM. The calculation of mortality burden for this population also minimizes the error due to reproductive, pregnancy and perinatal diseases among children and genetic disorders.

The Attributable Number of deaths is calculated using the following formula:

Attributable Number of deaths: AN = Health function x Population x Mortality rate

The calculations were performed by BenMAP-CE[18]

Results

1)The number of attributable deaths to air pollution exposure in 2019 in Vietnam (Scenario 1): The number of deaths due to the $PM_{2.5}$ concentrations in Vietnam in 2019 exceeding the WHO recommendation (5 µg/m^3).

2) The number of avoidable deaths if Vietnam had applied measures to control emission (Scenario 2): The number of avoidable deaths in 2019 if Vietnam had applied measures to control $PM_{2.5}$ emission sources similar to those before the pandemic.

3) The number or the proportion of avoidable deaths if Vietnam had applied the emission control measures prior to 2019 (similar to the pandemic preventive measures and other factors) to reduce the $PM_{2.5}$ concentration in 2019 at the $PM_{2.5}$ concentration level in 2021. This can be interpreted as health benefits in 2019 in Vietnam if we could apply the interventions to control the emission sources, and it can be calculated by this formula: (the attributable deaths (in scenario 2) – the attributable deaths (in scenario 1)) / The attributable deaths (in scenario 1).

NOTES FOR RESULT INTERPRETATION

Purpose of these notes

These notes will clarify the assumptions and limitations on data and results that were present in our research. Besides, notes on data presentation were also stated.

[15] 2019 Population and Housing Census
[16] National survey on injuries in Vietnam in 2010
[17] Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter
[18] BenMAP-CE

The limitations of $PM_{2.5}$ data

- Due to the limited number of monitoring stations in Vietnam, the $PM_{2.5}$ maps may have high errors and uncertainties in places where there are no monitoring stations. Errors of maps can also be attributed to errors of input data sources including satellite data, meteorological data, and land use data.
- The $PM_{2.5}$ maps are divided into subregions (3x3km grid cells) represented by an averaged $PM_{2.5}$ concentration value for that area. To evaluate the quality of the $PM_{2.5}$ map, the $PM_{2.5}$ value of the 3x3km area on the map was compared to the $PM_{2.5}$ value measured at the location of ground monitoring station. There should be certain variations between values of an area on the map and value of a station.
- Averaged $PM_{2.5}$ concentration of provinces/cities/districts were calculated based on all 3x3km grid cells located in that area. The provinces/cities (districts) have unequal areas, with different large areas and small areas, so the average concentration of provinces/districts can reach low values, however in some inner areas may have high $PM_{2.5}$ concentration values and vice versa.

The representation of $PM_{2.5}$ data

- Daily $PM_{2.5}$ maps estimated from the MEM model are calculated to monthly and annual maps and used to analyze the Status of $PM_{2.5}$ concentration nationwide, in regions, provinces, and cities.
- The color scale of the maps, figures and tables is based on the color scale of the Vietnam Air Quality Index (VN_AQI) with the $PM_{2.5}$ concentration values converted to the equivalent colors of VN_AQI values based on the Promulgating Technical Guidelines for Calculation and Publication of Air Quality Index in Vietnam on November 12th, 2019, by the Vietnam Environmental Administration.
- The annual mean of $PM_{2.5}$ concentration from the MEM model was compared to the national technical regulation on the annual averaged $PM_{2.5}$ concentration (25 µg/m^3) (QCVN 05:2013/BTNMT) to assess the $PM_{2.5}$ pollution level in the region or province/city and also compared to the WHO recommendation for public health in 2021 (5 µg/m^3).
- The calculated $PM_{2.5}$ exposure (population-weighted $PM_{2.5}$) map shows the average exposure of the population of an area (country, province, district) to $PM_{2.5}$ dust.

The results of the health impact assessment

- Due to the limitations of injury and mortality data, the study used injury and mortality data in 2010 to estimate the injury and mortality rate in 2019. However, in the past 10 years, Vietnam has taken a series of actions in order to reduce the injury mortality rate, so in reality, the overall injury rate in Vietnam might have declined. In other words, the actual number of attributable deaths may be higher than we reported.
- This research used the health function estimated from the risk of death from air pollution of countries around the world, not including Vietnam.
- This research assumed the possible changes in $PM_{2.5}$ concentrations in 2019 if there had been restrictions were similar to those of 2020: this is only true when the emission sources in 2019 were the same as in 2020.
- This research only evaluated the long-term impacts because of the usage of the long-term health function.

STATUS OF AIR QUALITY IN 2021

© Peter Nguyen

THE STATUS OF $PM_{2.5}$ NATIONWIDE

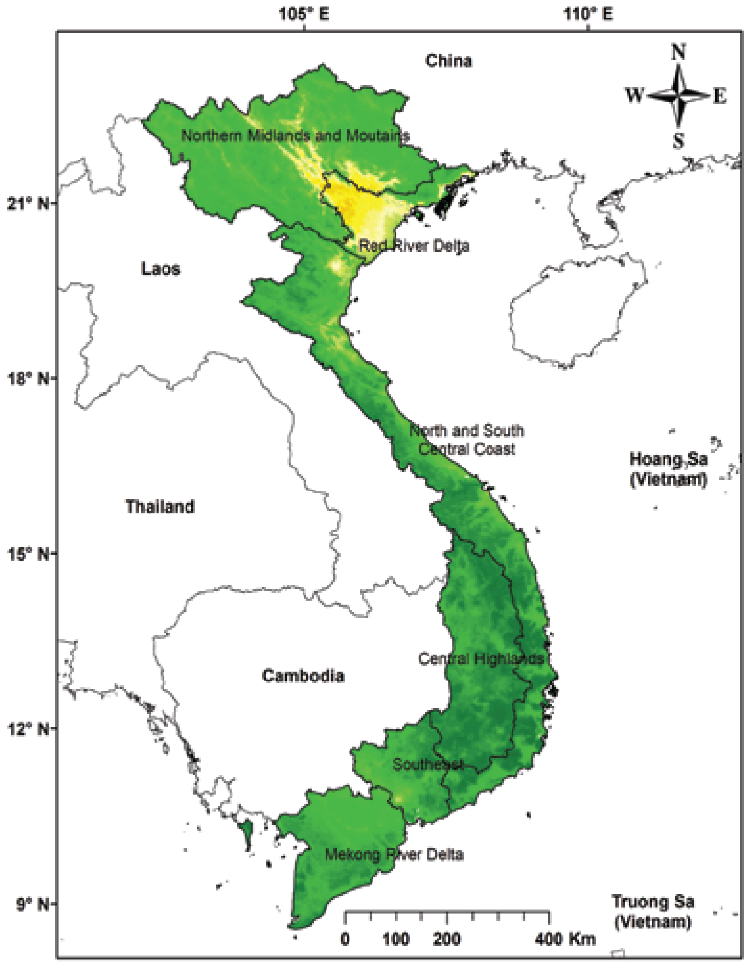


Figure 3.
Annual mean of $PM_{2.5}$ concentration in 2021

Social – economic zones

Vietnam has 63 provinces and cities directly under the central government and is divided into 6 socio-economic regions according to Decree 92/2006/NĐ-CP[19] as follows: the Northern Midlands and Mountains (14 provinces), the Red River Delta (11 provinces), the North and South-Central Coast (14 provinces), the Central Highlands region (5 provinces), the Southeast region (6 provinces) and the Mekong River Delta region (13 provinces).

$PM_{2.5}$ situation

At national scale, high levels of $PM_{2.5}$ concentration were observed in the Red River Delta. In this region, air quality was partly affected by climate conditions aside from local emission sources. As a result, $PM_{2.5}$ concentration tends to increase periodically, specifically in winter[20]. The annual average $PM_{2.5}$ concentrations per province nationwide in 2021 ranged from 11.4 µg/m³ in Lam Dong to 34.9 µg/m³ in Hanoi. These numbers were from 1.1% to 5.2% higher than the annual average values of 2020 in most of the provinces. Some provinces including Long An, Tien Giang, Can Tho, Bac Lieu, Ca Mau and Soc Trang had annual average $PM_{2.5}$ concentrations of 2021 slightly lower than their values in 2020 with the percentages of difference under 1%. Meanwhile, all provinces had average $PM_{2.5}$ concentrations in 2021 lower than their values in 2019, which was in accordance with the observations at various monitoring stations (appendix B). Social distancing due to the COVID-19 pandemic has slowed down socio-economic activities across the country in 2020 and 2021, reducing the $PM_{2.5}$ emission sources. Compared to 2019, the province with the lowest decrease in annual $PM_{2.5}$ concentration in 2021 was Lai Chau (5.8%) and while the highest decrease was in Phu Yen province (10.4 %).

[19] Government, 2006

[20] Hai, C.D. & Kim Oanh, N.T., 2013; Hien, P.D. et al., 2002; Hien, P.D. et al., 2004; Vinh, T. et al., 2018.

$PM_{2.5}$ emission sources

An emission inventory done for the year 2018 in Vietnam reported that the composition of primary sources of $PM_{2.5}$ emission included open burning of agriculture residuals (40%), cooking (17%), transport (13%), forest fires (12.7%), industrial activities (11%), and thermal power plants (3.3%). Other aspects of human activities contributed to about 3% to total emission of $PM_{2.5}$ nationwide[21].

Air quality management plan at provincial levels

According to the Vietnam Environment Law 2020, Decision No. 985a/QD-TTg (June 2016), Directive No. 03/CT-TTg (January 2021) of the Prime Minister, the Ministry of Natural Resources and Environment was assigned to lead in technical guidance for the development of a provincial environmental quality management plan. In January 2022, Decree 08/2022/ND-CP was issued to stipulate a few articles of the law on environmental protection, in which the content, order, and procedures for issuing the provincial air quality management plan were specified.

The provincial air quality management plan includes 6 steps. One of the steps in the management plan is assessing the status of the provincial air quality and the impact of air pollution on public health, which is important in order to determine the goals and scope of air quality management, develop tasks and solutions for air quality management and organize implementation.

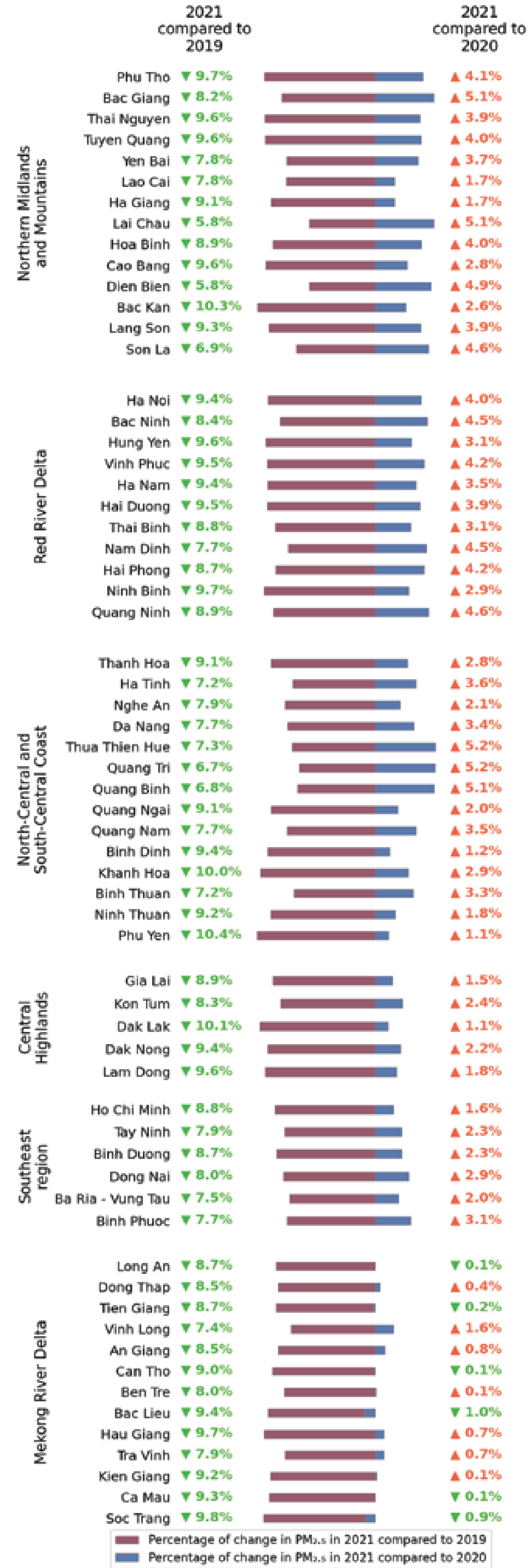


Figure 4.
The average increase/decrease ratio of $PM_{2.5}$ concentration in 2021 compared to the average in 2019 and 2020.

[21] VNU-UET & Live&Learn & USAID, 2021

ANNUAL MEAN $PM_{2.5}$ PER PROVINCE IN 2021

In 2021, 6/63 provinces/cities exceeded the QCVN 05:2013/BTNMT (25 µg/m³). The number of provinces/cities exceeding the national standard were similar to those of 2020 (6/63 provinces/cites) and less then those of 2019 (10/63 provinces/cites). These provinces/cites, which include Hanoi, Bac Ninh, Hung Yen, Vinh Phuc, Ha Nam and Hai Duong, are all part of the Red River Delta region.

The levels of exposure to $PM_{2.5}$ per person (population weighted $PM_{2.5}$) were higher than the annual average $PM_{2.5}$ value for provinces/cities. Provinces with high $PM_{2.5}$ exposure include Bac Giang, Bac Ninh, Ha Nam, Hanoi, Hai Duong, Hai Phong, Hung Yen, Phu Tho, Thai Binh, Thai Nguyen and Vinh Phuc. Compared to the 2021 WHO recommendation for annual mean $PM_{2.5}$ value (5 µg/m³), the annual average $PM_{2.5}$ values and population-weighted $PM_{2.5}$ values of all provinces/cities across the nation in 2021 were many times over the recommendation.

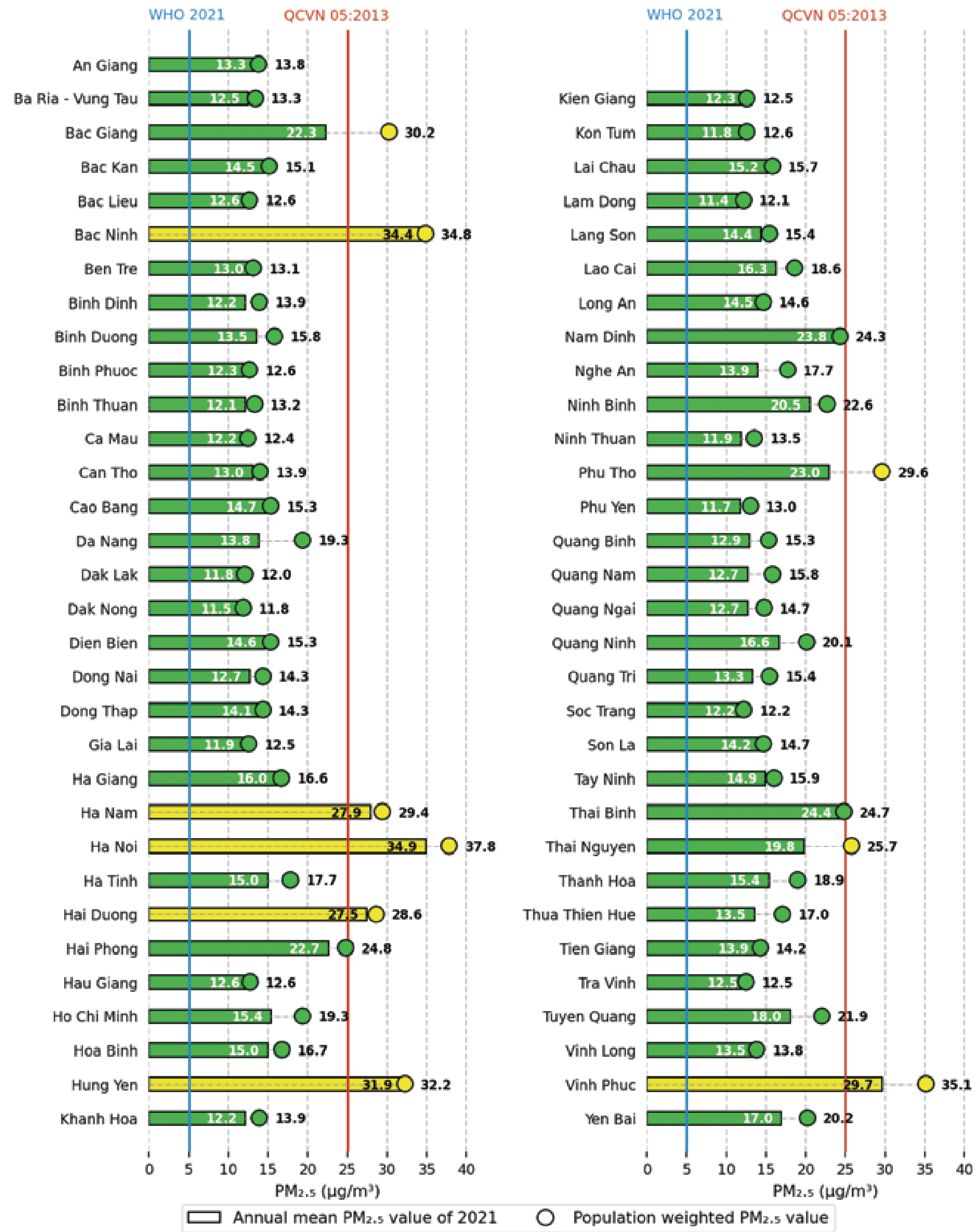


Figure 5. Mean of $PM_{2.5}$ concentration and population-weighted $PM_{2.5}$ concentration by province in 2021

STATUS OF PM$_{2.5}$ BASED ON URBAN CLASSIFICATION

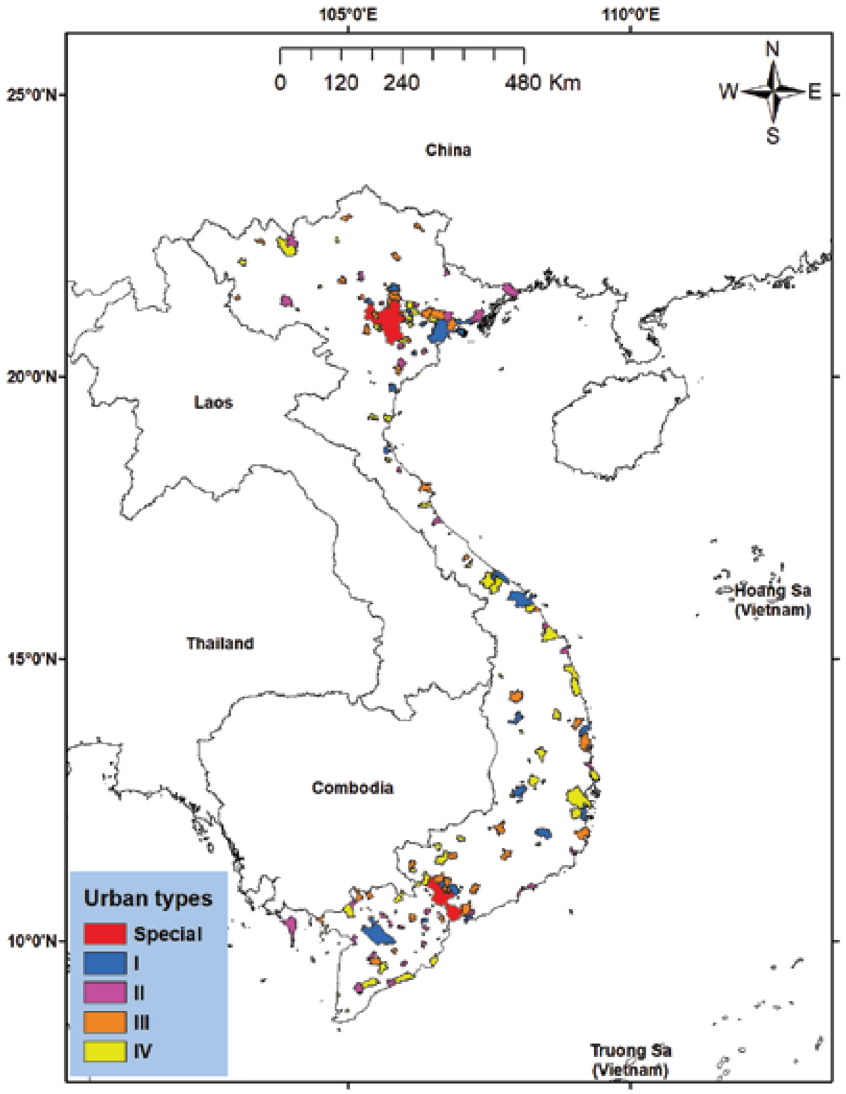


Figure 6.
Urban classification in Vietnam as of December 2021

Urban classification in Vietnam

According to Resolution 1210/2016/UBTVQH13[22], the urban areas in Vietnam are divided into 6 categories including Special, type I, type II, type III, type IV and type V. There are 5 criteria to determine the type of an urban area including: Position, function, role, structure and the level of socio-economic growth; Population size; Population density; Percentage of non-agricultural labor; and the Level of infrastructure and urban landscape development.

In this research, the list of different types of urban areas nationwide are collected based on public sources, specifically Wikipedia[23]. As of December of 2021, there are two cities classified as Special, specifically Hanoi city and Ho Chi Minh city, along with 22 type I, 33 type II, 47 type III, 94 type IV and 674 type V urban areas.

The status of PM$_{2.5}$ based on urban classification

Considering the 5 types of urban areas (from Special to type IV), the percentage of urban areas with annual mean PM$_{2.5}$ in 2021 exceeding the national standard (25 µg/m^3) of each types tended to decline as the level of urbanization decrease, except for type II and type III. One of the two Special urban areas (50%) had annual

[22] Vietnam National Assembly Standing Committee, 2016

[23] Wikipedia. Đô thị Việt Nam.

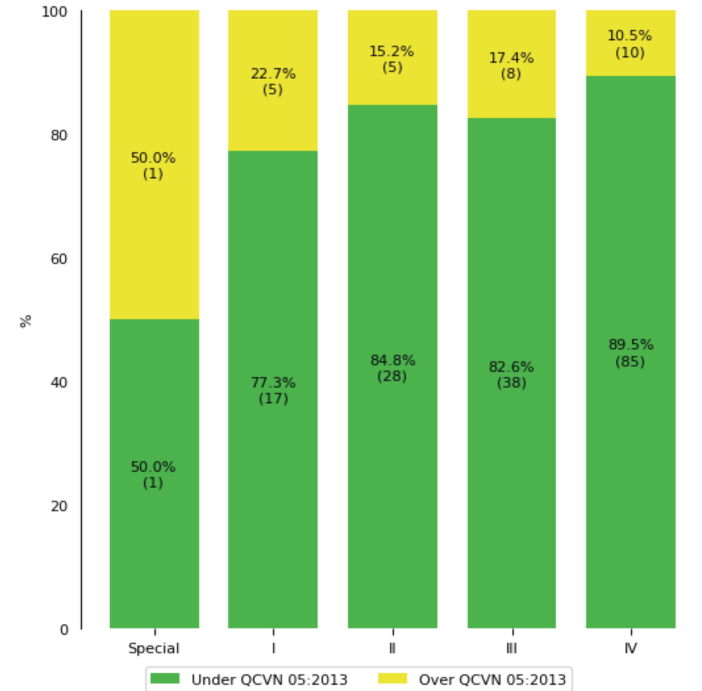


Figure 7. Percentage of urbans with mean of PM$_{2.5}$ concentration in 2021 exceeding Vietnam standards (QCVN 05:2013/BTNMT)

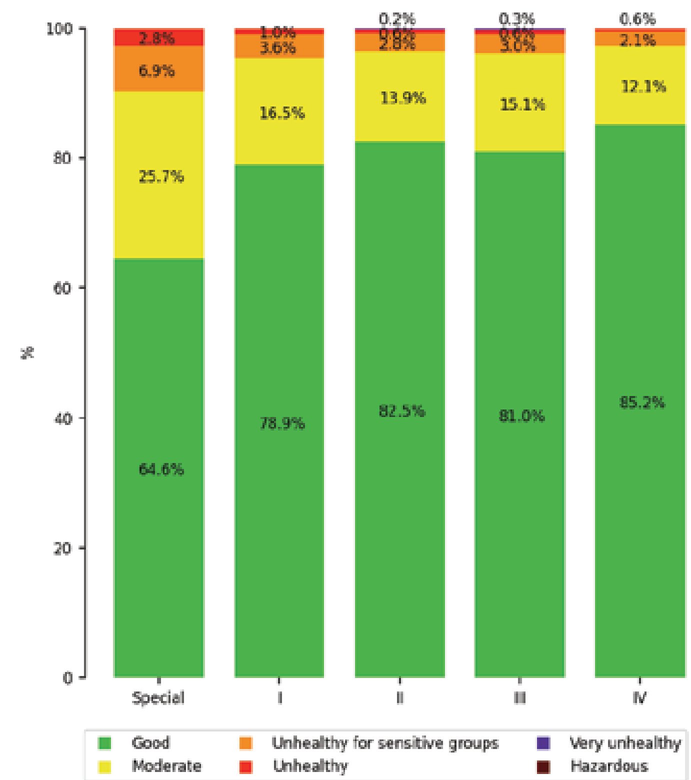


Figure 8. Percentages of days at different air quality levels in different urban types in 2021

mean PM$_{2.5}$ in 2021 exceeding the nation standard. The respective percentages for type I, II, III and IV are 5/22 (22.7%), 5/33 (15.2%), 8/44 (17.4%), and 10/95 (10.5%) (Figure 7). Because of the lack of information, we could not perform the assessment on V type urban areas.

Daily air quality in different urban types

The ratio of days with good and moderate air quality were prominent in all urban types while the ratio of days with poor, unhealthy and very unhealthy AQI levels was substantially less. There were no days with hazardous level of air quality (Figure 8).

The percentage of days with good air quality (green) tended to be inversely proportional to the urbanization level. The higher the urban level, the smaller the percentage of days with good air quality. The percentage of days with good air varied from 64.6% to 85.2%, the highest in type IV urban areas, the lowest in Special urban areas.

The percentage of days with moderate air quality (yellow) ranged from 12.1% to 25.7% for different urban types, with the highest in the Special urban areas, and the lowest in type IV.

The percentage of days with unhealthy air quality for sensitive groups (orange) varied from 2.1% to 6.9%, with the highest in the Special urban areas, and the lowest in type IV.

Unhealthy air quality (red) only occupied 0.6% to 2.8% of the days in 2021 for different urban types, with the highest in the Special type and the lowest in type II, III, and IV.

There were some days in the type II and III urban areas where the air quality was very unhealthy, with the percentage being only 0.2 and 0.3%.

STATUS OF $PM_{2.5}$ IN THE NORTHERN REGION

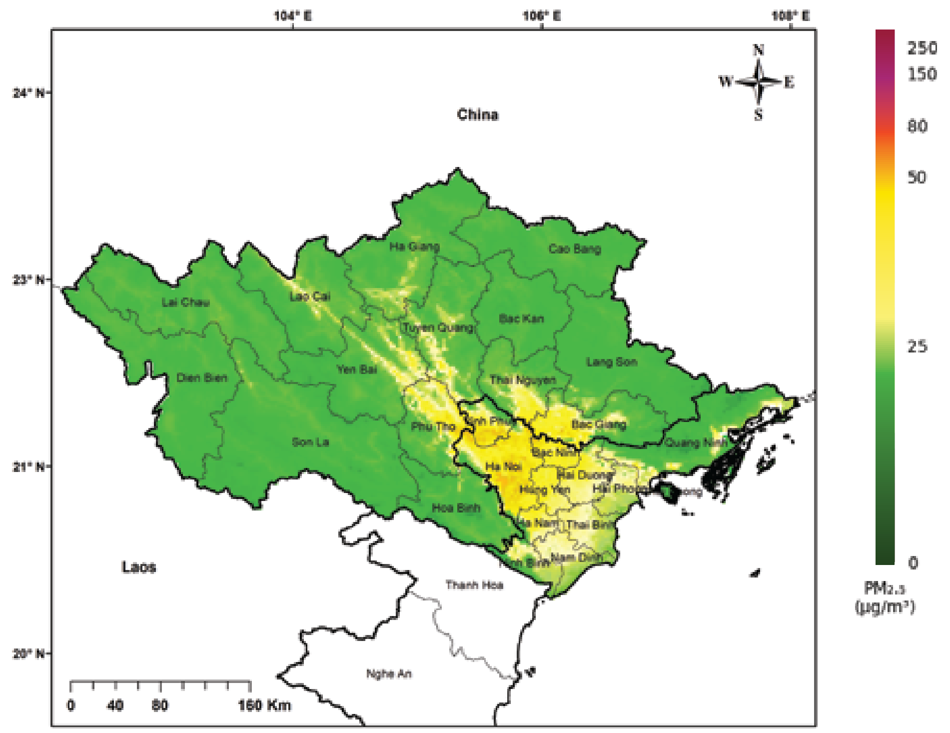


Figure 9. Annual $PM_{2.5}$ concentrations in 2021 in the Northern region

Natural and socio-economic conditions

The North region consists of 25 provinces and cities, divided into 2 socio-economic regions: Northern Midlands and Mountains (14 provinces) and the Red River Delta (11 provinces)[24].

The Red River Delta is a large area located at the lower reaches of the Red river in the North of Vietnam with relatively low and flat terrain. This region has a tropical monsoon climate and accounts for 22.7% of the country's population[25].

The Northern midland and mountainous region includes the Northwest and the Northeast. The Northwest region is in the Northwest direction - Southeast and has a rugged terrain, with many high mountains. The climate here changes by altitude. The Northeast region has a midland and low mountainous terrain, with strong north wind blowing in winter and humid subtropical climate in summer.

The Northern midland and mountainous region has an area of 28.7% and a population of 13.1% of the whole country[26]

Status of $PM_{2.5}$

In the North, $PM_{2.5}$ concentrations in 2021 was high in the provinces of the Red River Delta and the lower provinces in the Northern Midlands and Mountains (Figure 9). Moreover, in some provinces there were variations in $PM_{2.5}$ between different areas (e.g., $PM_{2.5}$ in the West of Bac Giang, bordering Bac Ninh and Thai Nguyen, was higher than the rest of the province).

[24, 25, 26] Institute for Development Strategies, 2018

The average $PM_{2.5}$ concentration per province in 2021 in this region ranged from 14.2 µg/m³ to 34.9 µg/m³. $PM_{2.5}$ exposure at provincial level ranged from 14.7 µg/m³ to 37.8 µg/m³, with the lowest value in Son La and the highest in Hanoi (Figure 10).

76% of provinces in the North had annual mean $PM_{2.5}$ concentrations that met the Vietnam standards (QCVN 05:2013/BTNMT) while the other 24% provinces that exceeded the standards are all located in the Red River Delta (Figure 11). $PM_{2.5}$ concentration of the provinces that met the standards ranged from 14.2 µg/m³ to 24.4 µg/m³, while the $PM_{2.5}$ concentration of the provinces that exceeded the standard varied from 27.5 µg/m³ to 34.9 µg/m³ (Figure 10).

The $PM_{2.5}$ at district level in the Northern region was the lowest in Binh Lieu district, Quang Ninh (13.1 µg/m³) and the highest in Nam Tu Liem district, Hanoi (43 µg/m³) (Figure 12).

The 10 highest $PM_{2.5}$ polluted districts were in Hanoi, Vinh Phuc and Bac Ninh, with $PM_{2.5}$ concentration ranging from 39 µg/m³ to 43 µg/m³ (Table 15.5). The 10 cleanest districts were in some mountainous provinces including Quang Ninh, Son La, Lang Son, Hoa Binh, Yen Bai, $PM_{2.5}$ concentration of which ranged from 13.1 µg/m³ to 13.8 µg/m³. (Table 2).

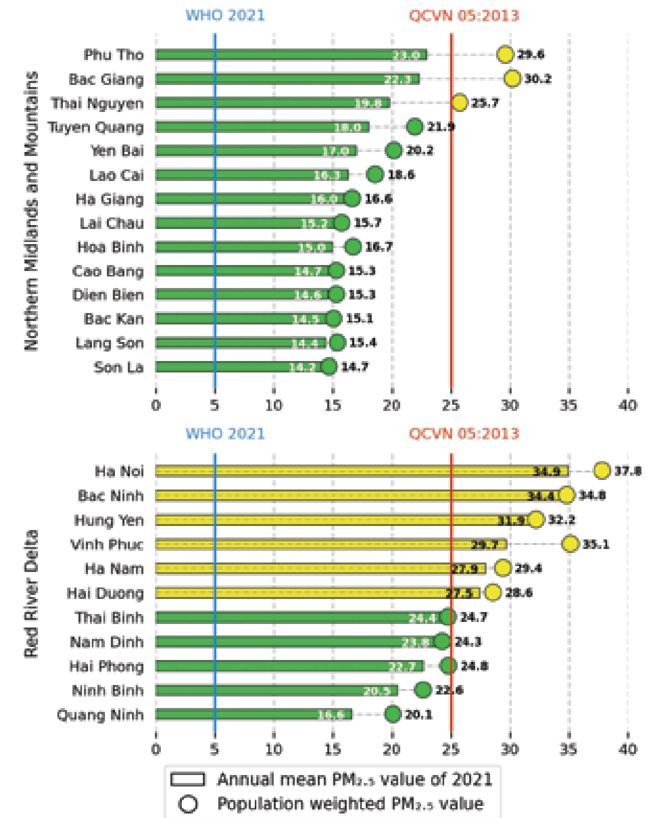


Figure10. Annual $PM_{2.5}$ concentration in 2021 at provincial level in the North, compared to population-weighted $PM_{2.5}$ concentration

Figure 11. Percentage of provinces/cities in the North met the Vietnam standards (QCVN 05:2013/BTNMT)

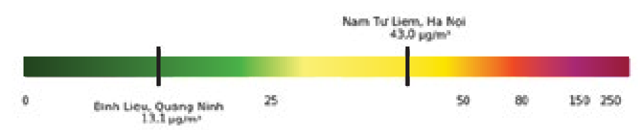


Figure12. Annual mean range of $PM_{2.5}$ concentration in the Northern districts

Districts with high concentration (43.0 µg/m³ – 39.0 µg/m³)		Districts with low concentration (13.1 µg/m³ – 13.8 µg/m³)	
Province/city	District	Province/city	District
Ha Noi	Nam Tu Liem	Quang Ninh	Binh Lieu
Ha Noi	Thanh Xuan	Son La	Sop Cop
Ha Noi	Thanh Oai	Lang Son	Đinh Lap
Ha Noi	Cau Giay	Hoa Binh	Mai Chau
Ha Noi	Ha Đong	Yen Bai	Mu Cang Chai
Vinh Phuc	Vinh Tuong	Son La	Van Ho
Ha Noi	Bac Tu Liem	Yen Bai	Tram Tau
Bac Ninh	Yen Phong	Son La	Moc Chau
Ha Noi	Hoang Mai	Quang Ninh	Ba Che
Ha Noi	Thuong Tin	Son La	Yen Chau

Table 2. The most and least polluted districts in the North in 2021 based on the annual mean

STATUS OF $PM_{2.5}$ IN HA NOI

General information

Hanoi, the cultural center and the capital of Vietnam, has a tropical monsoon climate with four distinct seasons in a year. Hanoi is also the second most populated city in the nation with the population of over 8.33 million in 2021, and population density of 2,480 people/km². As of 2021, Hanoi had 8 functional industrial parks[27].

Status of $PM_{2.5}$

In 2021, 100% of the districts in Hanoi had $PM_{2.5}$ concentration exceeding the Vietnam standard (QCVN 05:2013/BTNMT) and the 2021 WHO recommendation. The annual mean $PM_{2.5}$ values at district level varied from 28.9 µg/m³ to 43.0 µg/m³, which were 8.5% to 10.5% lower compared to 2019 and 3.1 to 7% higher compared to 2020 (Figure 15).

$PM_{2.5}$ concentration in Hanoi was shown to be higher in the inner districts than some of the outer counterparts like Soc Son, My Duc, Thach That, Ba Vi (Figure 20.1). $PM_{2.5}$ also tended to rise in January and December (dry season) and fall in July and August (rain season) (Figure 14).

Compared to last years, $PM_{2.5}$ concentration in 2021 were lower in the period between May and September, which was similar to $PM_{2.5}$ values of 2020 and lower than those of 2019. January of 2021 observed unusually high $PM_{2.5}$ values, nearly doubled the value of the same period in 2020, making the annual mean value of 2021 slightly higher than that of 2020 (Figure 16). These abnormal values could also be observed at most of the on-ground monitoring stations in Hanoi (Appendix B) and the similar situation has also been reported in the Global Air Quality report for 2021[28].

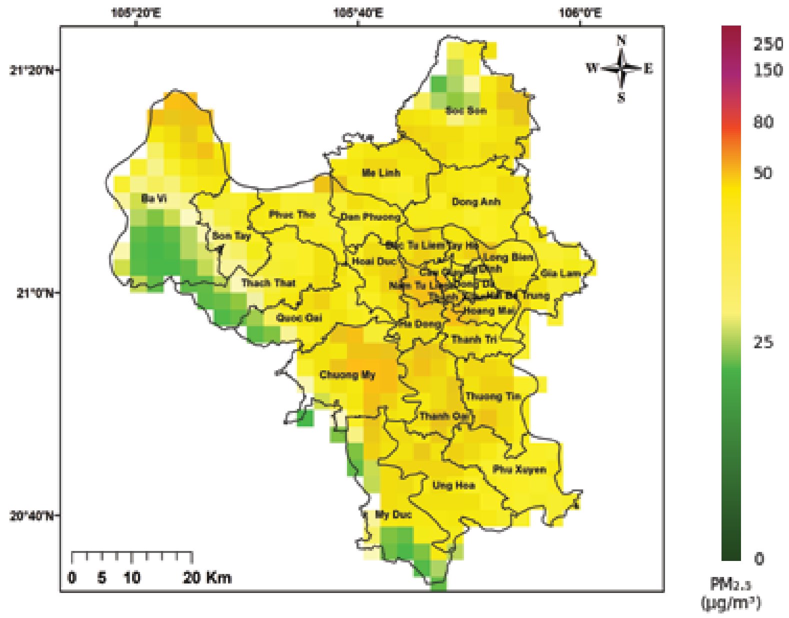


Figure 13. Annual mean $PM_{2.5}$ concentration in 2021 in Hanoi

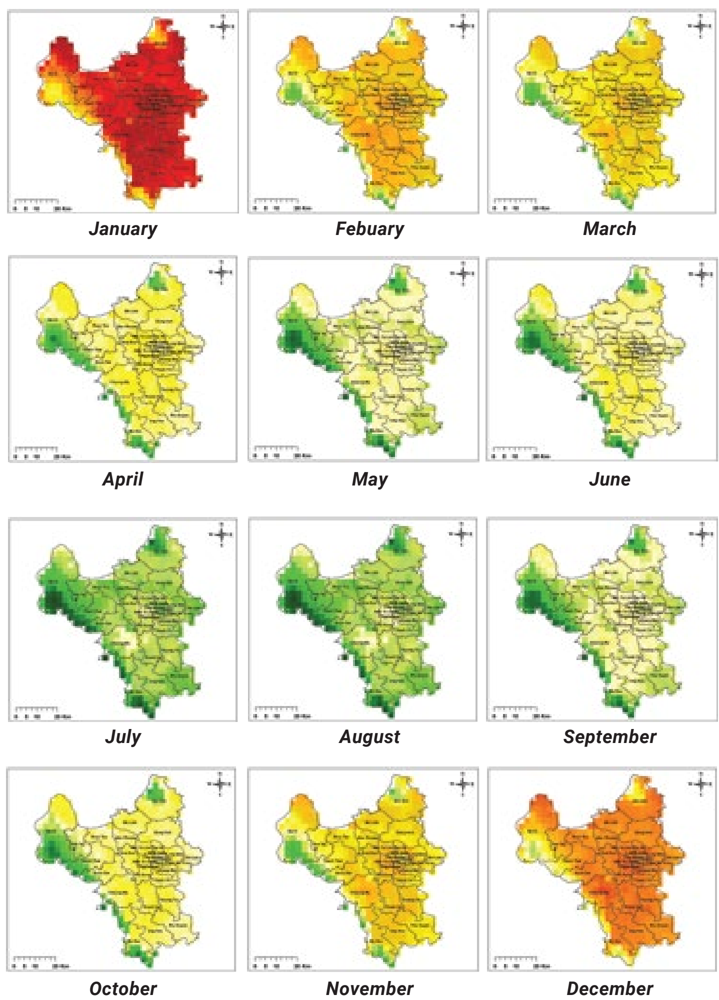


Figure 14. Monthly $PM_{2.5}$ concentration in 2021

Good air quality accounted for 42.2% the number of days in 2021, while moderate air quality accounted for 39.7%. These proportions are similar to 2020 (42.7% and 40.8% for good and moderate quality, respectively), and better than 2019 (20.5% and 58.9%). There was no major difference in the percentage of days with unhealthy air quality for sensitive groups and overall unhealthy quality from 2019 to 2021 (Figure 17).

Emission sources of $PM_{2.5}$

According to a study by the World Bank[29] on emission inventory in 2015, the main sources of $PM_{2.5}$ in Hanoi include industrial activities (29%), straw burning (26%), road dust (23%), traffic (15%), and other sources (7%). 1/3 of all $PM_{2.5}$ in Hanoi originated within the city, while the other 2/3 came from adjacent areas, the Red River Delta, neighboring countries, long-range transport, and natural sources.

Air quality monitoring

Currently Hanoi has an air quality monitoring network of 39 on-ground stations operated by government agencies (4 stations operated by the VEA and 35 stations operated by Hanoi Department of Natural Resources and Environment); 7 of which are standardized stations and the other 32 are sensors. In addition, the US Embassy has been operating 1 standardized station since 2015 (airnow.gov).

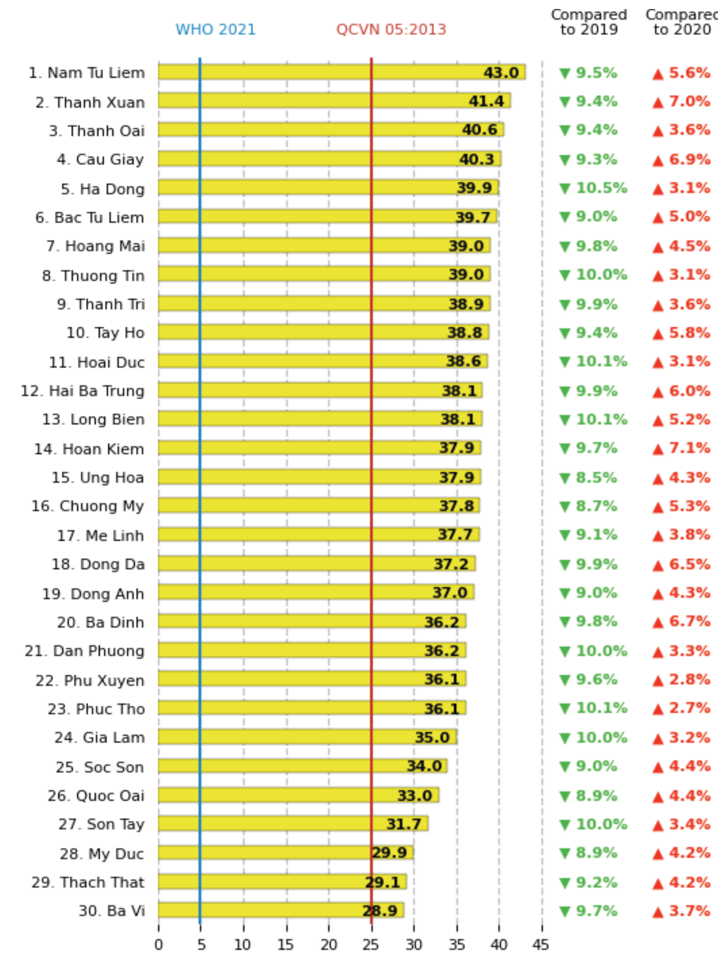


Figure 15. Mean of $PM_{2.5}$ concentration in 2021 in Hanoi by district and compared to 2020 and 2019

Figure 16. Monthly mean of $PM_{2.5}$ concentration in Hanoi

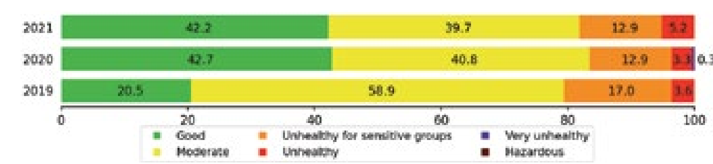


Figure 17. Percentage of days at different levels of air quality in Hanoi

[27] General Statistics Office, 2022

[28] IQAir, 2022

[29] WorldBank, 2021

STATUS OF $PM_{2.5}$ IN BAC NINH

General information

Bac Ninh has the smallest total area of the whole country with 822.7 km². Situated in the Red River Delta, Bac Ninh has a fairly flat terrain with a tropical monsoon climate, which is divided into four seasons. The population of the province is 1.46 million people with the population density of 1,778 people/km². Bac Ninh, as of 2021, had 10 up-and-running industrial parks[30].

Status of $PM_{2.5}$

In 2021, 100% of the districts in Bac Ninh having annual average $PM_{2.5}$ concentrations exceeding the QCVN 05:2013/BTNMT and the 2021 WHO recommendation. Annual mean values at district level ranged from 31.9 µg/m³ to 39.2 µg/m³, 7.8% to 8.7% lower than 2019 and 4.1% to 5.1% higher than 2020 (Figure 20).

$PM_{2.5}$ distribution in Bac Ninh showed little variation between districts (Figure 18). $PM_{2.5}$ concentration reached the highest in January and December (dry season) and lowest in July and August (rain season) (Figure 19).

Compared to the previous years, $PM_{2.5}$ concentration in 2021 was lower in the period from May to September, which was similar to values of 2020 and lower than values of 2019. $PM_{2.5}$ concentration in Bac Ninh in January of 2021 was also abnormally high, similar to Hanoi, with values almost doubled those of the same period of 2020 (Figure 21). These abnormal values could also be observed at some of the on-ground monitoring stations in Bac Ninh (Appendix B).

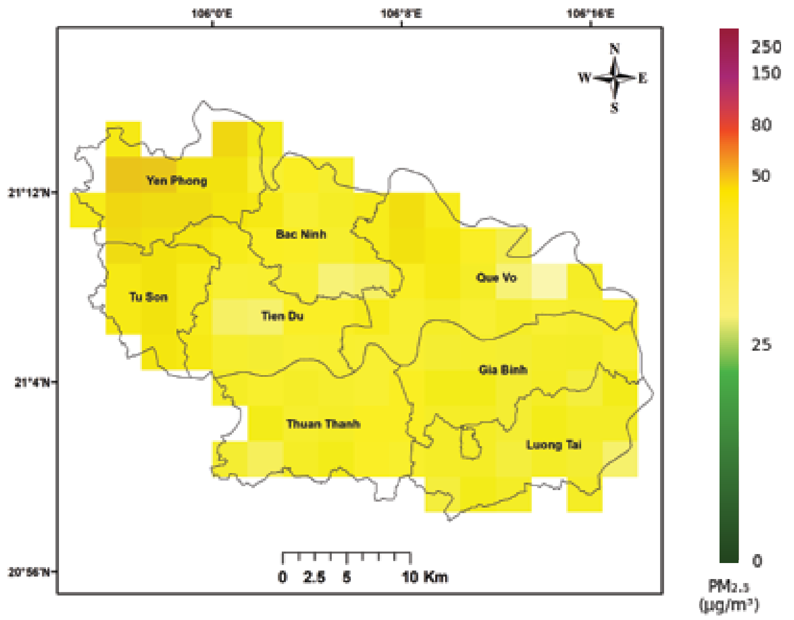


Figure 18. Annual mean $PM_{2.5}$ concentration in 2021 in Bac Ninh

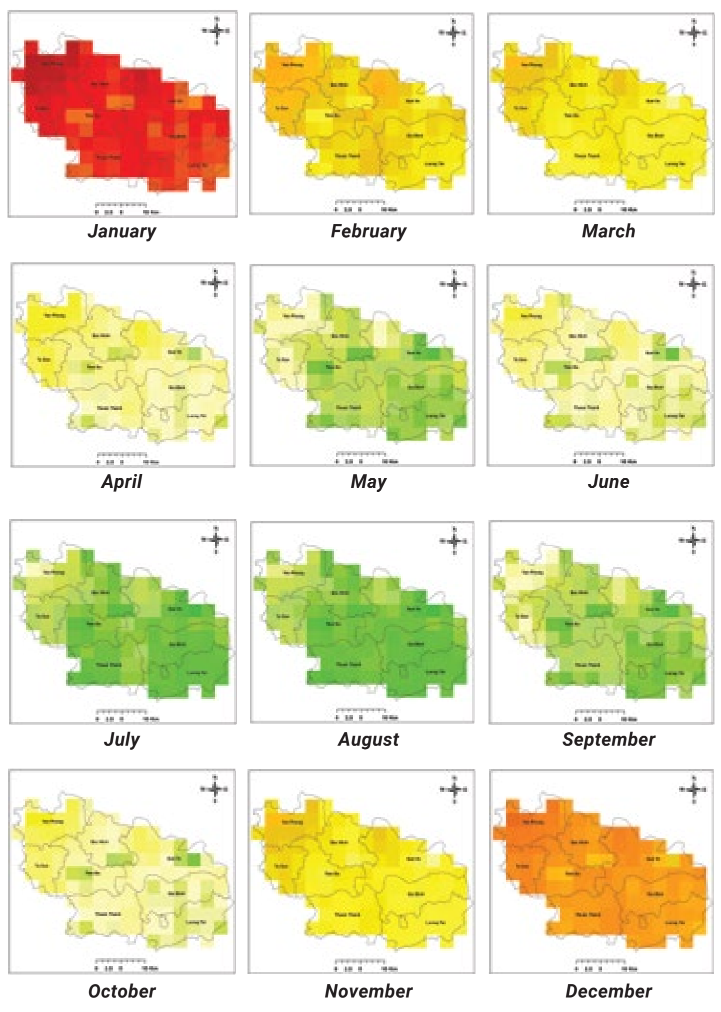


Figure 19. Monthly $PM_{2.5}$ concentration in 2021 in Bac Ninh

The percentage of days in 2021 with good air quality was 44.9%, while the percentage for moderate quality was 37.3%. These proportions were similar to 2020 (44.6% and 39.4% for good and moderate quality, respectively), and better than 2019 (22.7% and 57.5%). The percentages of days with unhealthy air quality for sensitive groups and over unhealthy quality showed little fluctuation throughout the 3 years (Figure 22).

Craft Villages and Industrial Parks

Bac Ninh has 62 craft villages, 30 of which are of traditional crafts and 32 are of modern crafts[31]. Bac Ninh has plans to build overall 16 industrial parks, 10 of which are already operational[32]. According to statistics, across the entire province, there are more than 500 tons of domestic waste, 200 tons of industrial waste, and two tons of medical waste being released into the environment everyday.

Air quality monitoring

As of 2021, Bac Ninh has had 18 standardize stations run by Bac Ninh Department of Natural Resources and Environment. Moreover, a lot of factories and industrial park has also set up pollutant monitoring stations and provided real-time data to government agencies (cem.gov.vn)

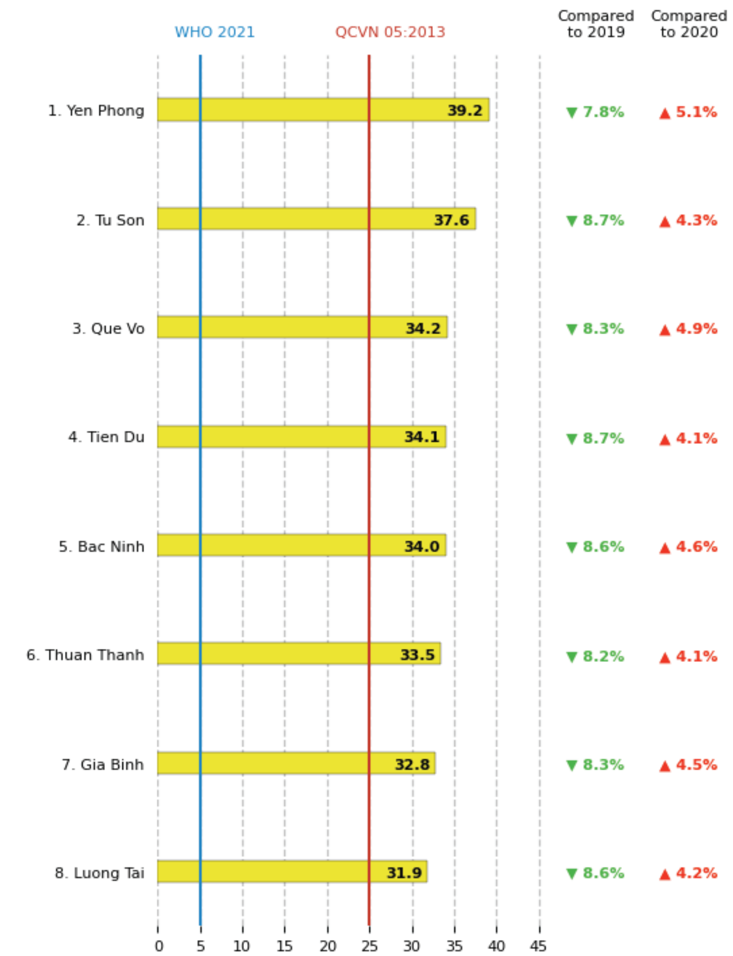
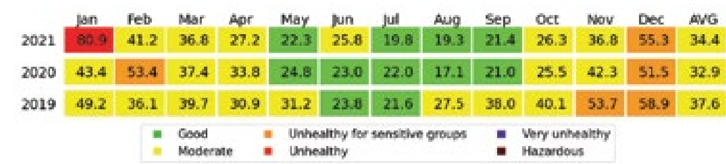


Figure 20. Mean of $PM_{2.5}$ concentration in 2021 in Bac Ninh by district and compared to 2020 and 2019



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AVG
2021	80.9	41.2	36.8	27.2	22.3	25.8	19.8	19.3	21.4	26.3	36.8	55.3	34.4
2020	43.4	53.4	37.4	33.8	24.8	23.0	22.0	17.1	21.0	25.5	42.3	51.5	32.9
2019	49.2	36.1	39.7	30.9	31.2	23.8	21.6	27.5	38.0	40.1	53.7	58.9	37.6

Figure 21. Monthly mean of $PM_{2.5}$ concentration in Bac Ninh

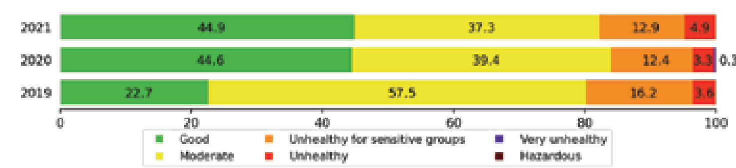


Figure 22. Percentage of days at different levels of air quality in Bac Ninh

[30] General Statistics Office, 2022

[31] Developing craft villages in Bac Ninh

[32] Bac Ninh: Nearly 1,300 enterprises operate in concentrated industrial zones

STATUS OF $PM_{2.5}$ IN THAI BINH

General information

Thai Binh province is located in the southeast of the Red River Delta, with a natural area of 1,584.6 km². Thai Binh has a tropical monsoon climate, which leads to the province receiving a large amount of rain every year (1,700-2,200mm)[33]. As of April 1, 2019, the GRDP of Thai Binh province reached 68,142 billion VND[34]. The population of the province in 2021 reached 1,875.7 thousand people. Thai Binh, up till 2021, had 6 functional industrial parks[35].

Status of $PM_{2.5}$

In 2021, annual $PM_{2.5}$ concentrations of 5/8 districts in Thai Binh exceeded Vietnam standards (QCVN 05:2013/BTNMT). The average $PM_{2.5}$ in 2021 at the district level varied from 20.7 µg/m³ to 28.2 µg/m³, decreased from 7.7% to 9.6% compared to 2019 and increased from 2.2% to 3.9% compared to 2020 (Figure 25).

$PM_{2.5}$ in Thai Binh was high in western districts (Hung Ha, Quynh Phu, Vu Thu and Thai Binh city), low in eastern coastal districts (Thai Thuy, Kien Xuong, Tien Hai) (Figure 23). $PM_{2.5}$ concentration in Thai Binh was high in January (dry season) and low in July and August (rainy season) (Figure 24).

Compared to previous years, the $PM_{2.5}$ concentration in 2021 was low in the period from April to October, which lasted longer comparing to 2020 and 2019. January 2021 observed an abnormally high $PM_{2.5}$ concentration in Thai Binh, nearly twice that of the same period last year (Figure 26).

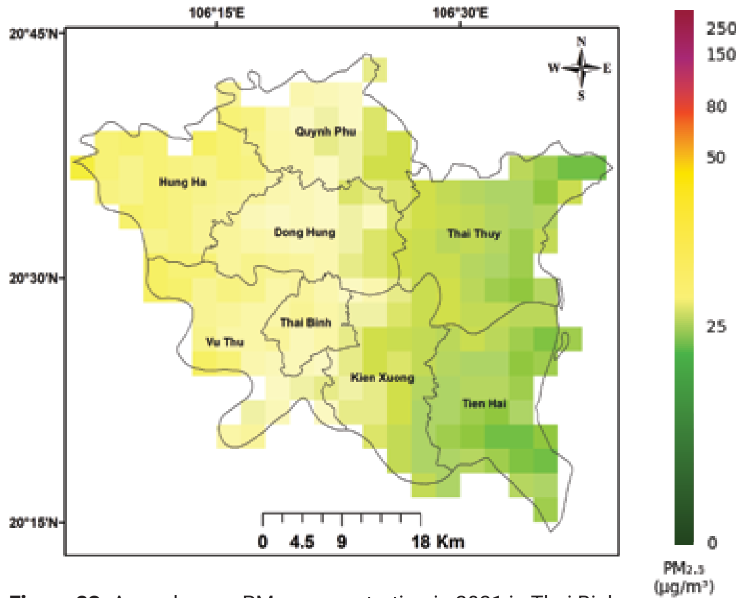


Figure 23. Annual mean $PM_{2.5}$ concentration in 2021 in Thai Binh

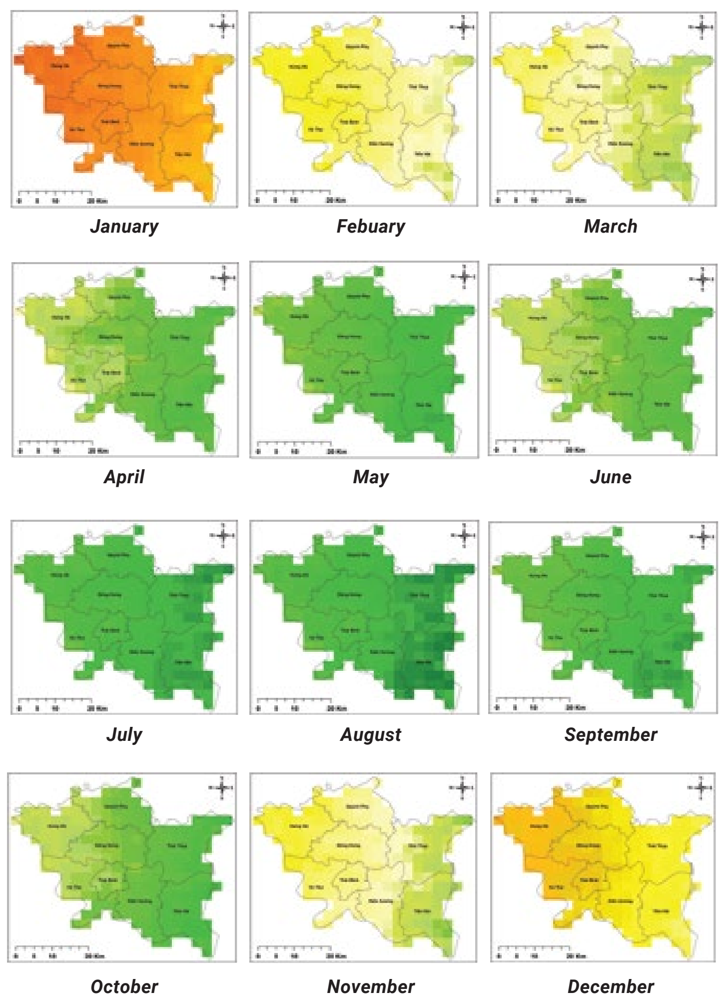


Figure 24. Monthly $PM_{2.5}$ concentration in 2021 in Thai Binh

The ratio of days in 2021 with good air quality accounted for 69.3%, the moderate level accounted for 24.4%, comparable to 2020 (64.7% and 28.9%), and better than 2019 (57.3% and 36.4%). In the years 2019-2021, there were fluctuations between the percentage of days with good and moderate air quality, while the ratio of unhealthy level did not change much (Figure 27).

Industry, craft villages and agriculture

Local air pollution occurs in places such as industrial parks and craft villages. By 2019, Thai Binh had 6 established industrial parks, with 3 new industrial parks in construction[36].

Emission from agriculture is also a major source in Thai Binh. According to calculations by Vietnam National University, Hanoi[37], the amount of CO_2 emitted from burning straw was up to 738.8 thousand tons/year, the amount of CO released into the environment is up to 58.3 thousand tons/year. According to Decree 45/2022/ND-CP, the act of outdoor burning by-products from crops near residential areas, airports, and major traffic routes is subject to a fine of 2.5 - 3 million VND.

Air quality monitoring

As of 2021, Thai Binh has only 1 monitoring station managed by the provincial Department of Natural Resources and Environment (DONRE).

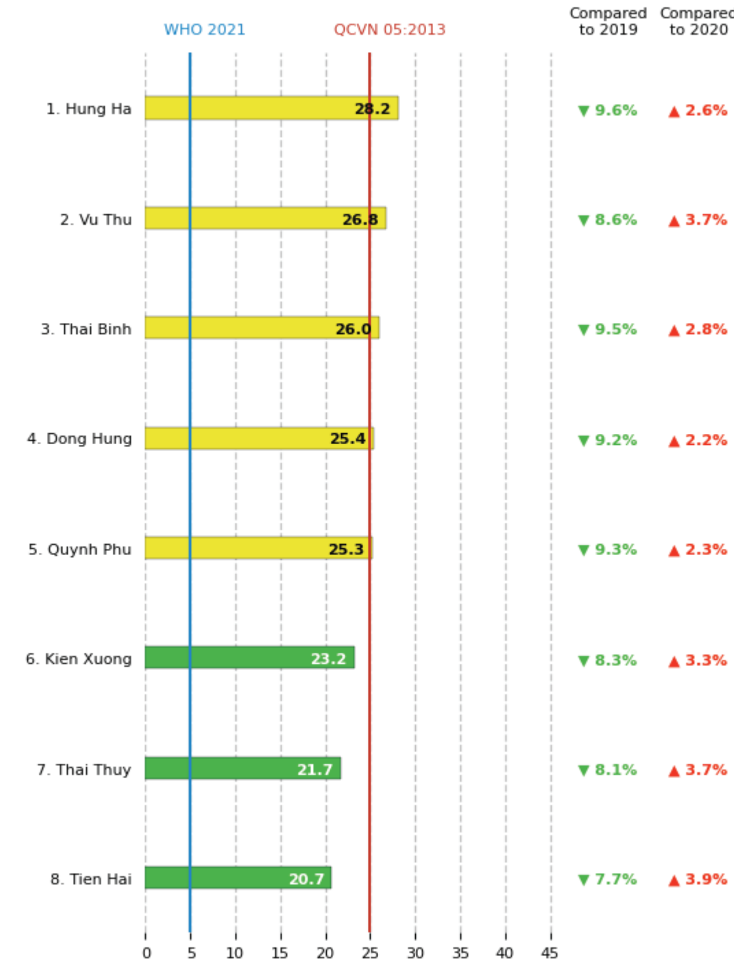


Figure 25. Mean of $PM_{2.5}$ concentration in 2021 in Thai Binh by district and compared to 2020 and 2019

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AVG
2021	56.8	28.8	25.3	19.1	16.3	19.3	14.2	13.7	15.0	18.7	26.4	38.8	24.4
2020	30.7	38.0	27.0	25.7	18.2	16.7	15.3	12.0	14.8	17.9	30.4	37.1	23.6
2019	35.7	25.8	27.0	22.7	22.6	17.8	15.5	19.1	26.7	28.4	38.0	41.3	26.7

Good; Moderate; Unhealthy for sensitive groups; Unhealthy; Very unhealthy; Hazardous

Figure 26. Monthly mean of $PM_{2.5}$ concentration in Thai Binh

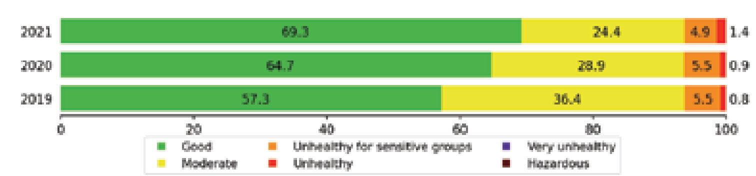


Figure 27. Percentage of days at different levels of air quality in Thai Binh

[33] Thai Binh Statistical Office, 2019

[34] General Statistics Office, 2018

[35] General Statistics Office, 2022

[36] Thai Binh web portal. Industry zones.

[37] Research on building emission coefficients from straw burning activities to apply to emissions inventory and impact assessment on air quality in Hanoi

STATUS OF $PM_{2.5}$ IN THE CENTRAL REGION

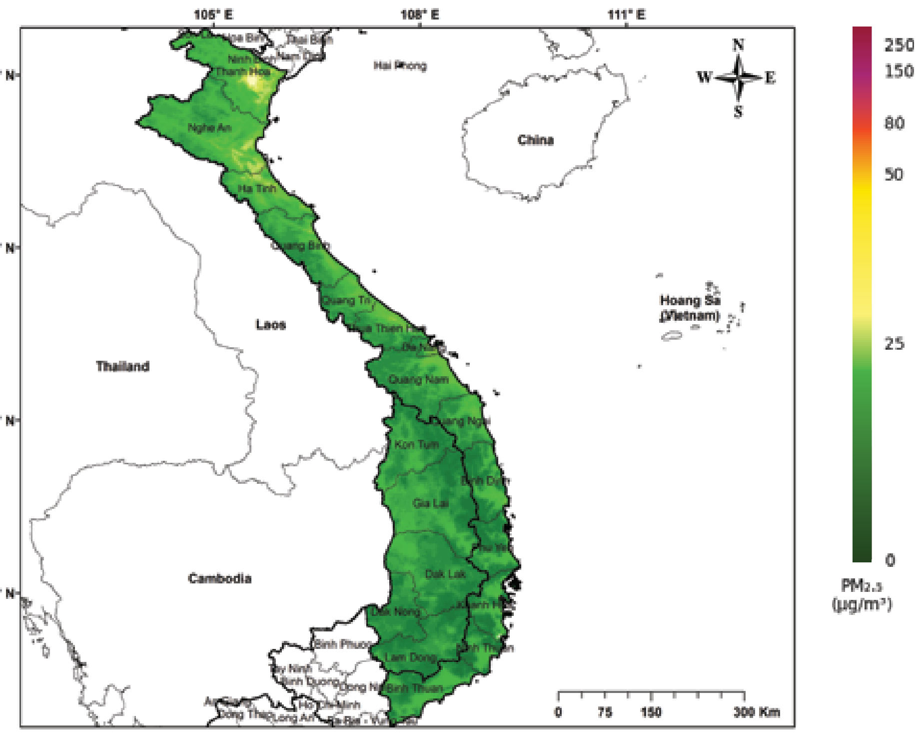


Figure 28. Annual mean $PM_{2.5}$ concentrations in 2021 in the Central region

Natural and socio-economic conditions

The Central region has 19 provinces and cities, divided into 2 regions including North Central and South-Central Coast (14 provinces) and Central Highlands (5 provinces).

The North-Central Coast and South-Central Coast have a descending terrain from west to east, from mountainous areas to midland hills, down to plains, coastal sand dunes, and then to coastal islands. This region has the harshest climate conditions in the country. Each year, there are many natural disasters including storms, floods, Laos winds, and droughts, which are mainly caused by the geological location and topographical structure of the region. The North-Central Coast and South-Central Coast have an area of 95,847.5 km² (28.9% of the country's area), with a population of 20.58 million people (20.8% of the country's population)[38].

The Central Highlands bares a plateau topography, which includes Kon Tum, Gia Lai, Dak Lak, Dak Nong and Lam Dong province. The climate in the Central Highlands is divided into two seasons: the rainy season from May to the end of October and the dry season from November to April, with March and April being the hottest and driest months. The Central Highlands has an area of 54,548.3 km² (16.4% of the country's area) and a population of 6,033.8 thousand people (6.1% of the country's population)[39].

[38, 39] General Statistics Office, 2022

Status of $PM_{2.5}$

In the Central region, the concentration of $PM_{2.5}$ in 2021 was mostly low, with no major difference between provinces. Higher concentration of $PM_{2.5}$ was observed in some areas in Thanh Hoa, Nghe An, Ha Tinh and coastal provinces (Figure 28).

The average concentration of $PM_{2.5}$ in 2021 per province ranged from 11.4 µg/m³ to 15.4 µg/m³, the lowest in Lam Dong and the highest in Thanh Hoa. $PM_{2.5}$ exposure levels ranged from 12.1 µg/m³ to 19.3 µg/m³, the lowest in Lam Dong and the highest in Da Nang (Figure 29).

Annual mean $PM_{2.5}$ concentration of 100% of the provinces met Vietnam standards (QCVN05:2013/BTNMT – 25 µg/m³) but still exceeded the WHO threshold (5 ug/m³) (Figure 30).

$PM_{2.5}$ of the districts was low in Khanh Son, Khanh Hoa (11 µg/m³) and high in Thieu Hoa, Thanh Hoa (23.1 µg/m³) (Figure 31).

The 10 district with the highest $PM_{2.5}$ levels were located in Thanh Hoa, Nghe An, Ha Tinh and Da Nang provinces with the $PM_{2.5}$ concentration ranged from 20.3 µg/m³ to 23.1 µg/m³. The 10 districts with the lowest annual $PM_{2.5}$ concentrations were located in the Central Highland provinces, with the values ranged from 11.0 to 11.2 µg/m³ (Table 3).

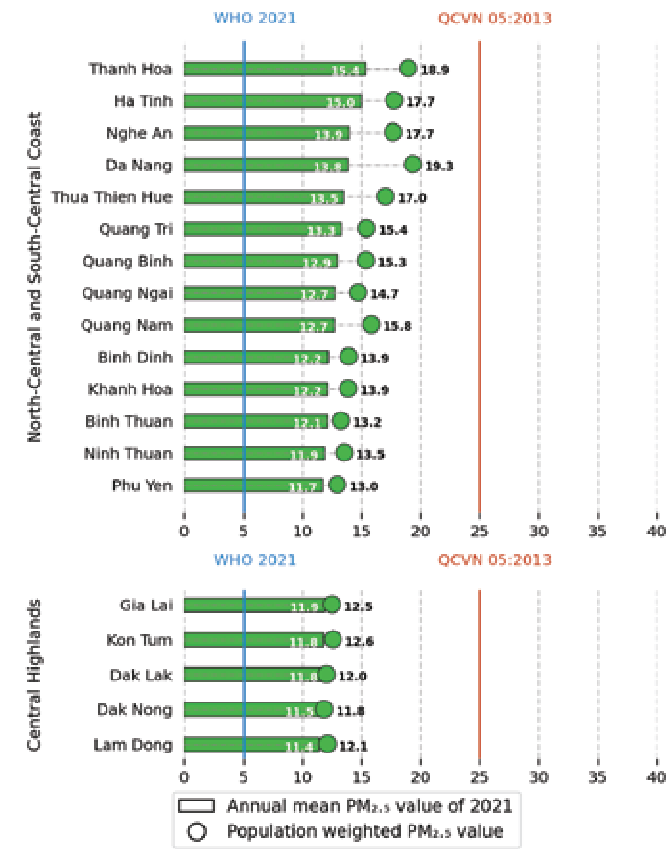


Figure 29. Annual mean $PM_{2.5}$ concentration in 2021 at provincial level in the Central, compared to population-weighted $PM_{2.5}$ concentration

Figure 30. Percentage of provinces/cities in the Central met the Vietnam standards (QCVN 05:2013/BTNMT)

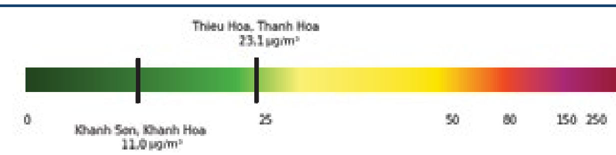


Figure 31. Annual mean range of $PM_{2.5}$ concentration in the Central districts

Table 3.
The most and least polluted districts in the Central in 2021 based on the annual mean

Districts with high concentration (23.1 µg/m³ – 20.3 µg/m³)

Province/city	District
Thanh Hoa	Thieu Haa
Thanh Hoa	Yen Đinh
Thanh Hoa	Tho Xuan
Thanh Hoa	Dong Son
Nghe An	Vinh
Thanh Hoa	Trieu Son
Thanh Hoa	Thanh Hoa (city)
Da Nang	Hai Chau
Da Nang	Thanh Khe
Ha Tinh	Ha Tinh

Districts with low concentration (11.0 µg/m³ – 11.2 µg/m³)

Province/city	District
Khanh Hoa	Khanh Son
Gia Lai	KBang
Lam Dong	Lac Duong
Binh Dinh	Van Canh
Phu Yen	Đong Xuan
Binh Dinh	Vinh Thanh
Gia Lai	Kong Chro
Dak Nong	Dak Glong
Binh Đinh	An Lao
Lâm Dong	Bao Lam

STATUS OF $PM_{2.5}$ IN NGHE AN

General information

Nghe An, located in the North Central region, is the largest province in Vietnam with 16,486.5 km^2. The province has a population of more than 3.4 million people (comprises of 47 ethnic groups)[40]. Its administrative structure includes its capital – Vinh city, along with 03 towns and 17 districts. Located in the Northeast of the Truong Son mountains, Nghe An has a diverse topography with a complex system of hills and rivers. The province has a tropical monsoon climate with two distinct summer and winter. Nghe An, in 2021, had 5 operating industrial parks[41].

Status of $PM_{2.5}$

In 2021, 100% of districts/cities in Nghe An met the Vietnam standard (QCVN 05:2013/BTNMT). The average $PM_{2.5}$ in 2021 at district level varied from 12.3 µg/m^3 to 21.1 ug/m^3, decreased from 7.0% to 9.1% compared to 2019 and increased from 1% to 4.3% compared to 2020 (Figure 34).

The annual $PM_{2.5}$ in Nghe An was high in the Southeast districts (Hung Nguyen, Vinh, Cua Lo...), and low in the Northwest mountainous districts (Ky Son, Que Phong, Tuong Duong...) (Figure 32). $PM_{2.5}$ concentration was high in January and December and low in April and October (Figure 33).

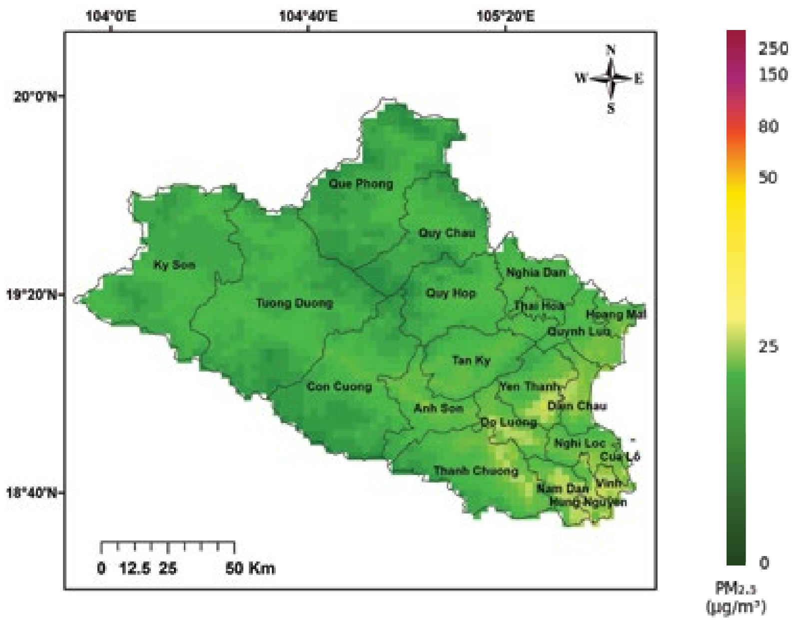


Figure 32. Annual mean $PM_{2.5}$ concentration in 2021 in Nghe An

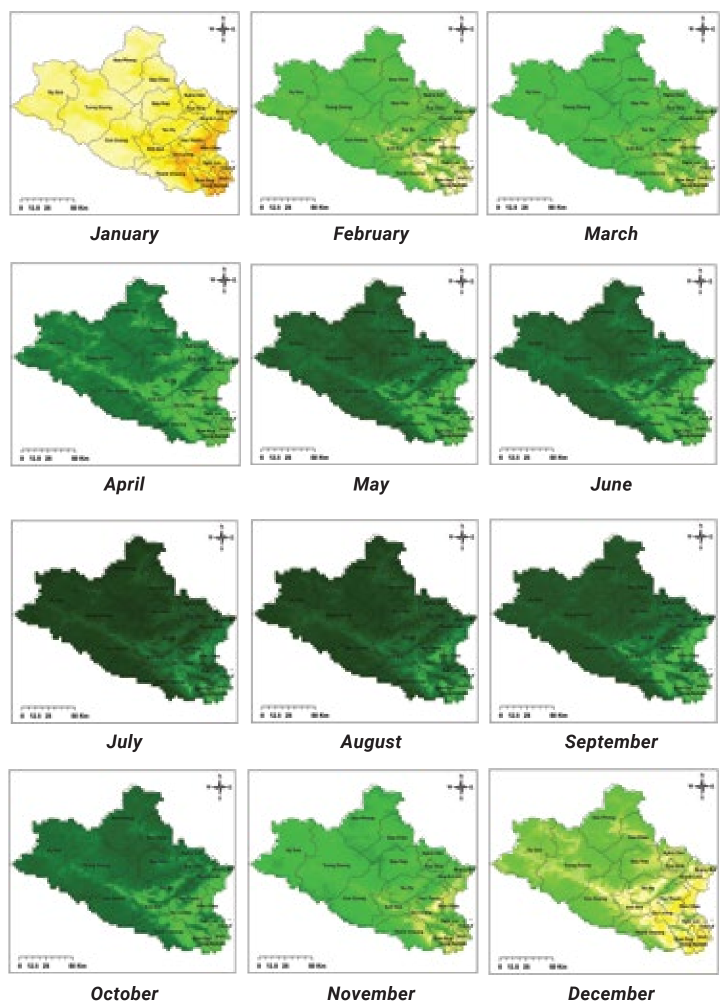


Figure 33. Monthly $PM_{2.5}$ concentration in 2021 in Nghe An

Compared to previous years, January 2021 had an unusually high $PM_{2.5}$ value, nearly twice that of the same period last year (Figure 35).

The percentage of days at a good level in 2021 accounted for 89%, the moderate level was 10.4%, a slight decrease compared to 2020 (91.5% and 7.7%) and 2019 (91.5% and 8.5%). The 2021 and 2020 year had the percentage of days with unhealthy air quality of 0.6% and 0.8%, respectively (Figure 36).

Forest burning

According to the Global Forest Watch's statistics in 2021[42], Nghe An "led the country" in terms of deforestation and forest fire rates in Vietnam with 203 thousand hectares, compared to the national average of 48.7 thousand hectares. In 2020, there were 48 forest fires, 21 of which damaged 122.38 hectares.

Smoke from wildfires can travel great distances, causing spikes in air pollution in the regions it passes. Fires that last long can cause increased air pollution over a long period of time. Large fires that recur in a region every year will increase annual exposure in that region.

Air quality monitoring

As of 2021, Nghe An has 1 station managed by MONRE and 1 station managed by DONRE.

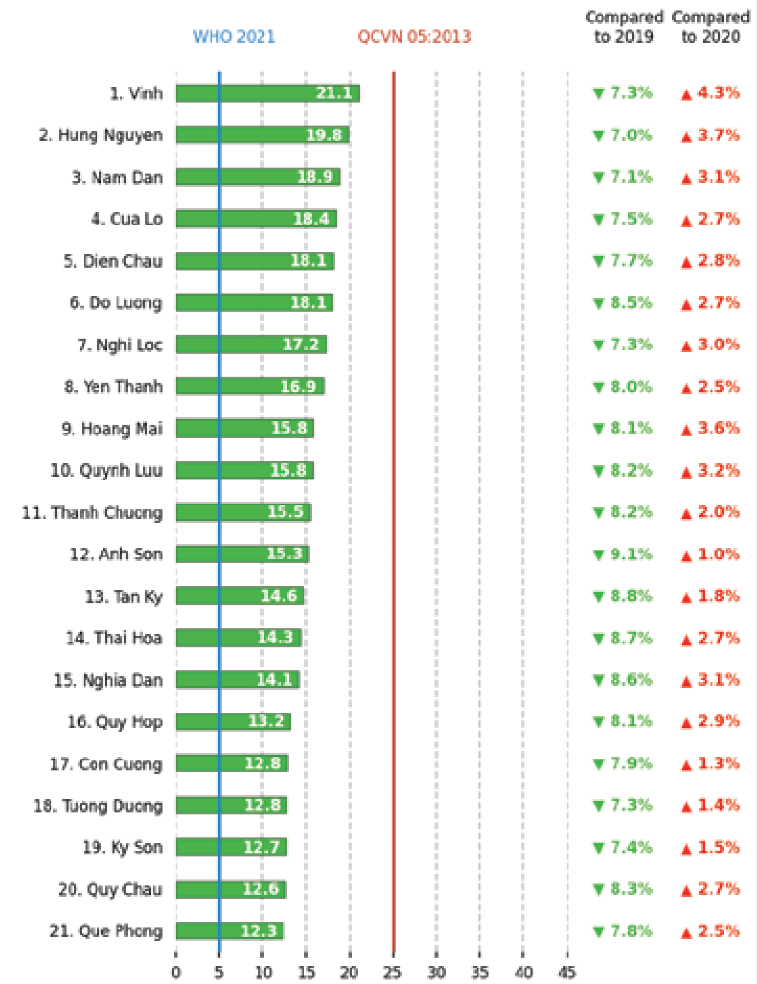


Figure 34. Mean of $PM_{2.5}$ concentration in 2021 in Nghe An by district and compared to 2020 and 2019

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AVG
2021	31.1	17.0	15.1	11.6	9.9	10.3	7.8	8.2	9.2	10.8	14.9	21.4	13.9
2020	17.2	20.7	14.8	14.8	10.8	9.7	9.4	7.5	9.3	10.2	17.5	22.1	13.7
2019	19.0	13.3	15.1	13.3	13.0	10.1	9.2	11.8	15.9	16.1	21.6	23.4	15.1

Good; Moderate; Unhealthy for sensitive groups; Unhealthy; Very unhealthy; Hazardous

Figure 35. Monthly mean of $PM_{2.5}$ concentration in Nghe An

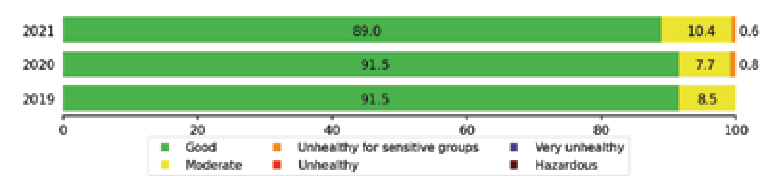


Figure 36. Percentage of days at different levels of air quality in Nghe An

[40] Institute for Development Strategies, 2018

[41] General Statistics Office, 2022

[42] Global Forest Watch

STATUS OF $PM_{2.5}$ IN THE SOUTH

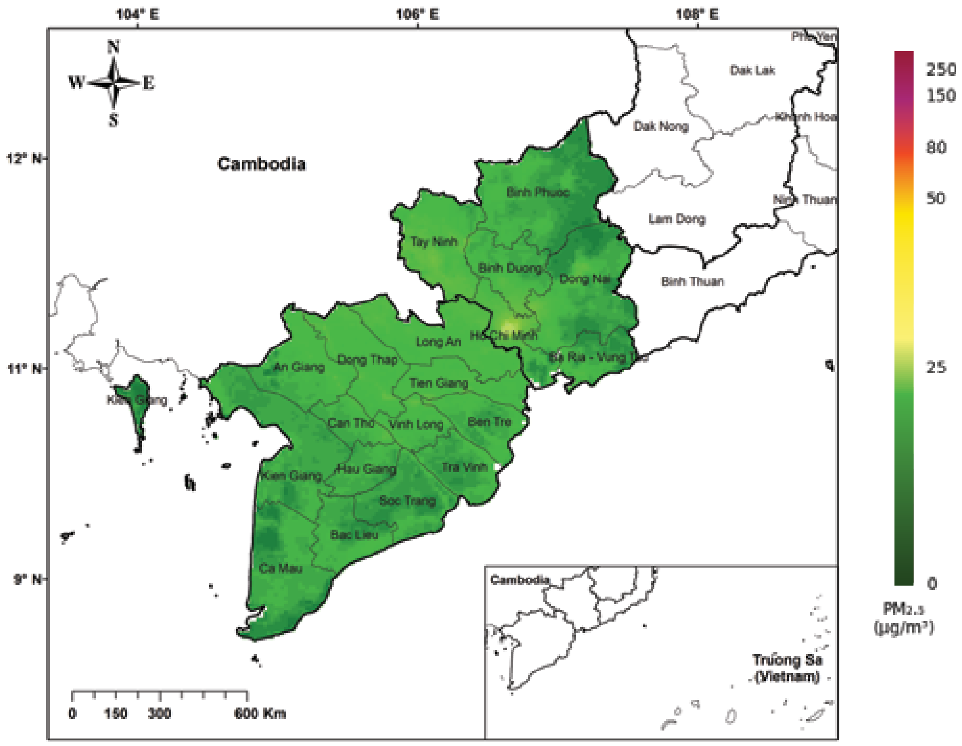


Figure 37. Annual mean $PM_{2.5}$ concentrations in 2021 in the Southern region

Natural and socio-economic conditions

The South has 19 provinces and cities, divided into 2 regions, including the Southeast (6 provinces/cities) and the Mekong River Delta (13 provinces/cities)[43].

The Southeast is composed of large plains and small hills. Therefore, it is very suitable for the development of agricultural industries, urban industry and convenient transportation. The Southeast is characterized by tropical monsoon and sub-equatorial climate, with diverse humid tropical weather, long radiation time and high average and accumulative temperature. The diurnal temperature variation between different months is low. The climate is divided into two seasons, the dry season (May - November) and the rainy season (December - April). The rainfall is quite large in the rainy season, the annual average fluctuates between 1500mm and 2000mm [44]. The Southeast has an area of 7.1% and a population of 18.5% of the whole country[45].

The Mekong River Delta has an area of 40,547.2 km², with an average height of less than 2 meters above sea level, has many rivers and ponds. This area has a sub-equatorial climate (a lot of rainfall and heat), favorable for the development of agriculture, especially for the development of wet rice cultivation and food crops. The climate has two seasons – rainy season (May-October) and a dry season (November-March)[46]. The Mekong Delta has an area of 12.3% and a population of 17.6% of the whole country[47]

[43, 44, 46] Institute for Development Strategies, 2018

[45, 47] General Statistics Office, 2022

Status of $PM_{2.5}$

In the South, $PM_{2.5}$ concentrations in 2021 were low and there was no clear difference between different areas (Figure 37).

The average $PM_{2.5}$ concentration in provinces in 2021 ranged from 12.2 µg/m³ to 15.4 µg/m³. $PM_{2.5}$ exposure ranged from 12.2 µg/m³ to 19.3 µg/m³, the lowest in Soc Trang and the highest in Ho Chi Minh City (Figure 38).

Annual mean $PM_{2.5}$ concentration of 100% of the provinces in the South met the Vietnam standards (QCVN05:2013/BTNMT), but still exceeded the WHO recommendations (Figure 39).

$PM_{2.5}$ concentration of southern districts was low in Phu Quoc and Kien Giang (11.4 µg/m³) and high in District 10, Ho Chi Minh City (21.3 µg/m³) (Figure 40).

The 10 districts with the highest $PM_{2.5}$ concentration were located in Ho Chi Minh City, with the values varied from 20.5 µg/m³ to 21.3 µg/m³. The 10 districts with the lowest $PM_{2.5}$ concentration were scattered in the provinces of Kien Giang, Ca Mau, Binh Phuoc, Soc Trang, Dong Nai, Bac Lieu, Ba Ria - Vung Tau, with values ranged from 11.4 µg/m³ – 12.0 µg/m³ (Table 4).

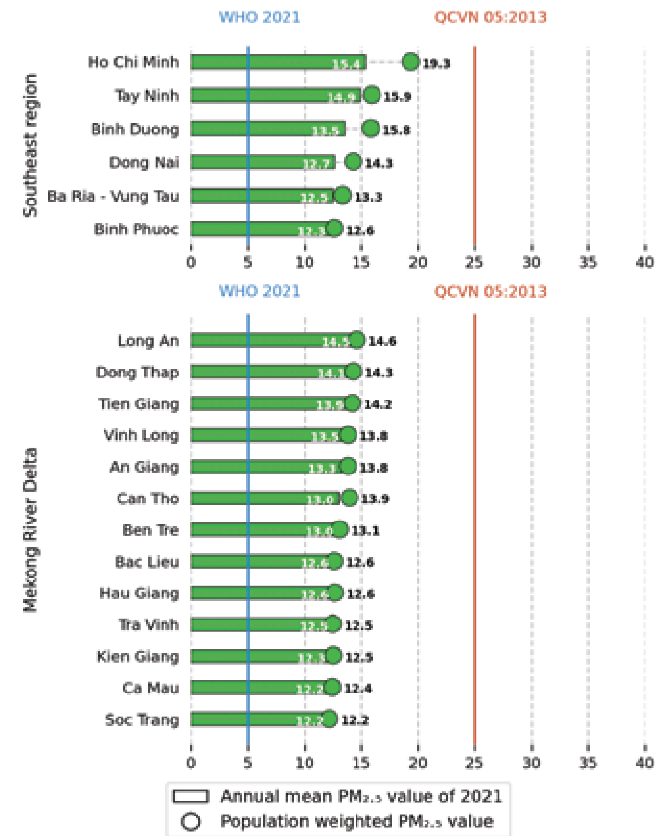


Figure 38. Annual mean $PM_{2.5}$ concentration in 2021 at provincial level in the South, compared to population-weighted $PM_{2.5}$ concentration

Figure 39. Percentage of provinces/cities in the South met the Vietnam standards (QCVN 05:2013/BTNMT)

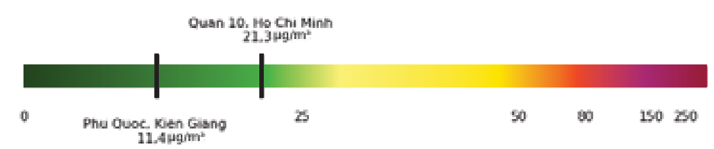


Figure 40. Annual mean range of $PM_{2.5}$ concentration in the Southern districts

Table 4. The most and least polluted districts in the South in 2021 based on the annual mean

Districts with high concentration (21.3 µg/m³ – 20.5 µg/m³)

Province/city	District
Ho Chi Minh	District 10
Ho Chi Minh	Tan Binh
Ho Chi Minh	District 11
Ho Chi Minh	District 3
Ho Chi Minh	Phu Nhuan
Ho Chi Minh	Tan Phu
Ho Chi Minh	District 5
Ho Chi Minh	District 1
Ho Chi Minh	District 6
Ho Chi Minh	District 4

Districts with low concentration (11.4 µg/m³ – 12.0 µg/m³)

Province/city	District
Kien Giang	Phu Quoc
Ca Mau	Ngoc Hien
Binh Phuoc	Bu Dang
Soc Trang	Thanh Tri
Ca Mau	U Minh
Dong Nai	Cam My
Kien Giang	Kien Hai
Bac Lieu	Vinh Loi
Binh Phuoc	Bu Gia Map
Ba Ria - Vung Tau	Xuyen Moc

STATUS OF $PM_{2.5}$ IN HO CHI MINH CITY

General information

Ho Chi Minh City is located in the South of Vietnam, in the tropical monsoon climate region, which is dividable into two distinct rainy and dry seasons. The city has a total area of more than 2095 square kilometers, with a population of 9.16 million people and population density of 4,375 people/km^2 [48]. In 2021, the gross regional domestic product (GRDP) reached 1,298,791 billion VND, which was a 6.78% decrease compared to 2019[49]. Up till 2021, Ho Chi Minh City had 17 functional industrial parks[50].

Status of $PM_{2.5}$

In 2021, $PM_{2.5}$ concentrations of 100% of districts of Ho Chi Minh City were below of Vietnam standard (QCVN 05:2013/BTNMT). The average concentration at district level varied from 12.9 µg/m³ to 21.3 µg/m³, decreased from 7.3% to 10.1% compared to 2019 and increased from 0.4% to 2.8% compared to 2020 (Figure 43).

Average concentration in 2021 was high in central districts and low in the outer districts such as Cu Chi and Can Gio (Figure 41). $PM_{2.5}$ was higher in November, December, January, February and March than in the other months of the year (Figure 42). The same trend was also observed at multiple dust sampling points (Hien et al., 2019). Compared to previous years, January 2021 had an unusually high $PM_{2.5}$ value, nearly twice as much as the same period last year. This made the average concentration of 2021 slightly higher than 2020 (Figure 44).

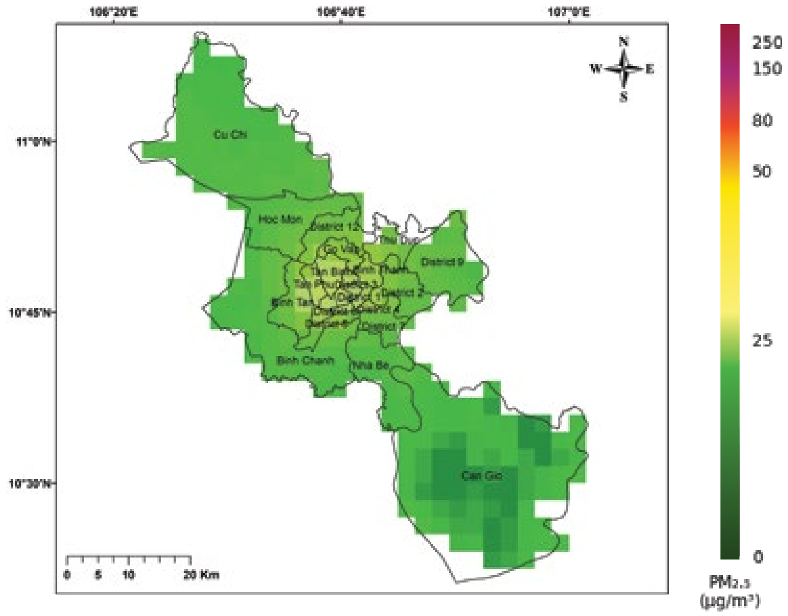


Figure 41. Annual mean $PM_{2.5}$ concentration in 2021 in Ho Chi Minh city

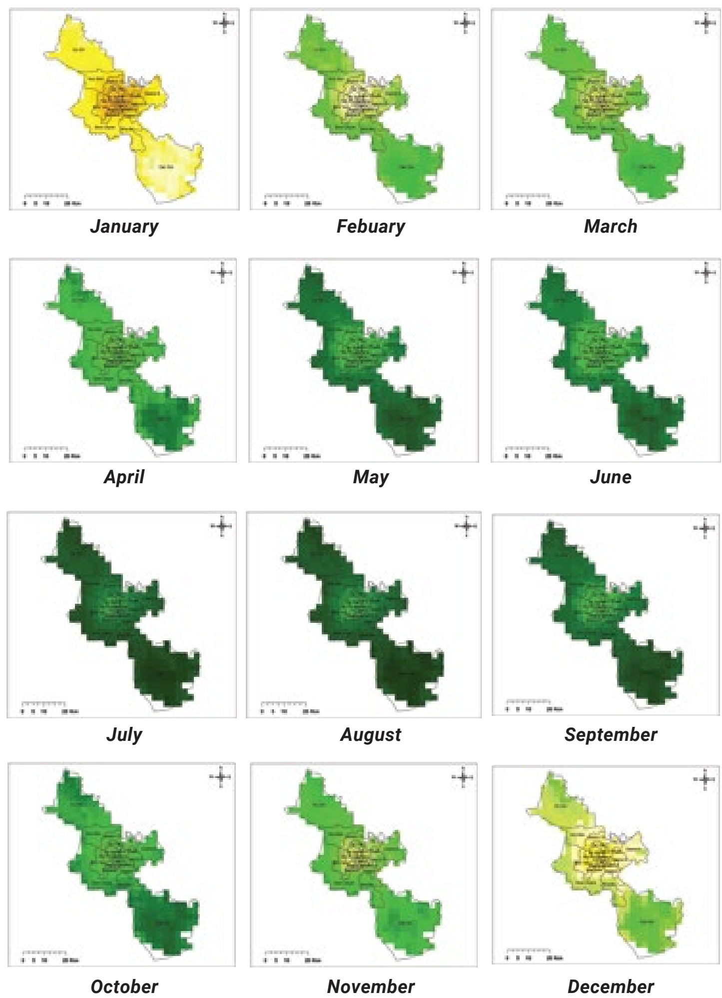


Figure 42. Monthly $PM_{2.5}$ concentration in 2021 in Ho Chi Minh city

This unusual high value could also be observed at the monitoring station in Ho Chi Minh City (Appendix B) and in the World Air Quality Report 2021[51].

The ratio of the number of days in 2021 with good air quality accounted for 87.1%, the moderate level accounted for 11.8%, similar to 2020 (89% and 10.5%) and 2019 (86.6% and 13.4%). In the years 2019-2021, there was not much variation of the percentage of days with unhealthy air quality (Figure 45).

$PM_{2.5}$ emission sources

According to emission inventory results of Ho Chi Minh City in 2017[52], total $PM_{2.5}$ emissions in Ho Chi Minh City were 4,029 thousand tons/year. In which, the traffic source contributed the highest, corresponding to 1,813 tons/year, accounting for about 45% (road traffic is the main source of traffic emissions, accounting for 75.13% of the total traffic emissions). Point source emissions ranked second with 1,289 tons/year accounting for about 32% (textile and food were the two most contributing industries). In addition, area source emission contributed the lowest (927 tons/year), accounting for 23% with households and restaurants being the two main sources.

Air quality monitoring

Ho Chi Minh City has 1 standard air quality monitoring station, installed and operated by the US Embassy since 2016 (airnow.gov). From 2021, a standard monitoring station managed by MONRE will be put into operation. In addition, Ho Chi Minh City has 7 stations managed and operated by research institutions, universities.

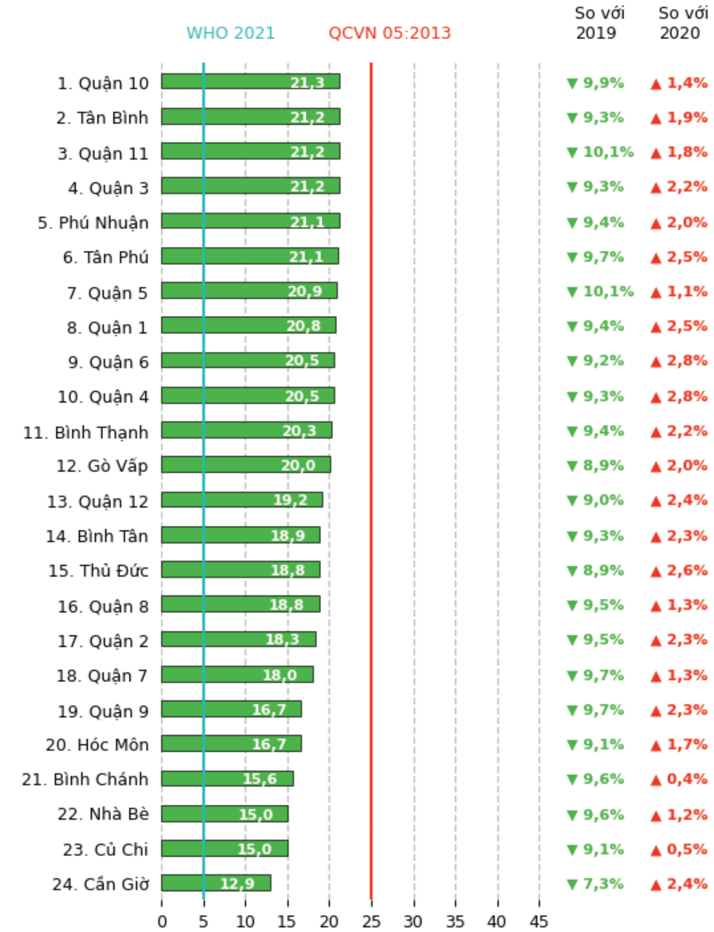


Figure 43. Mean of $PM_{2.5}$ concentration in 2021 in Ho Chi Minh City by district and compared to 2020 and 2019

Figure 44. Monthly mean of $PM_{2.5}$ concentration in Ho Chi Minh city

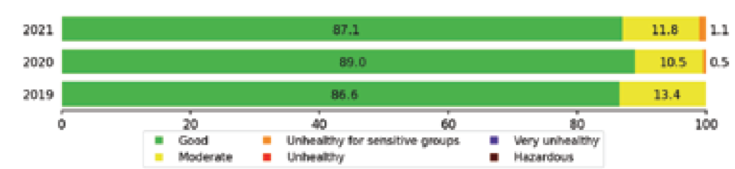


Figure 45. Percentage of days at different levels of air quality in Ho Chi Minh city

[48, 50] General Statistics Office, 2022

[49] Ho Chi Minh Provincial Statistics Office, 2021

[51] IQAir, 2022

[52] Bang et al., 2019

THE TRENDS OF $PM_{2.5}$ IN THE PERIOD OF SOCIAL DISTANCE DUE TO THE COVID-19 PANDEMIC

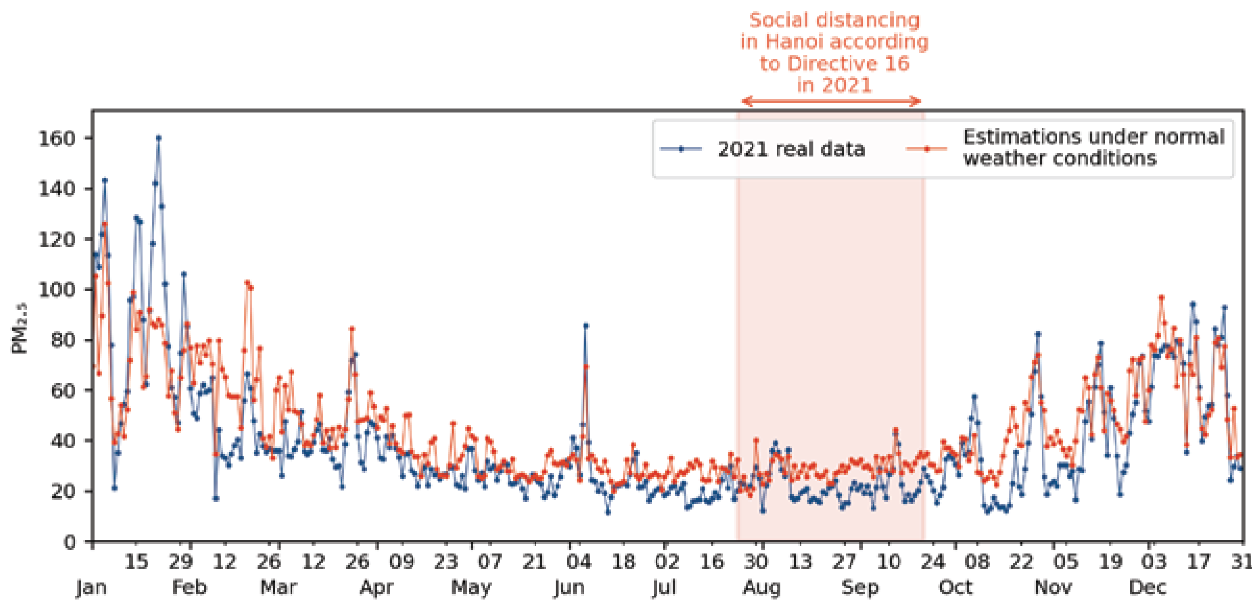


Figure 46. Daily $PM_{2.5}$ concentration measured and estimated under normal conditions in 2021 at the UWYO meteorological station on Nguyen Khang street, Hanoi.

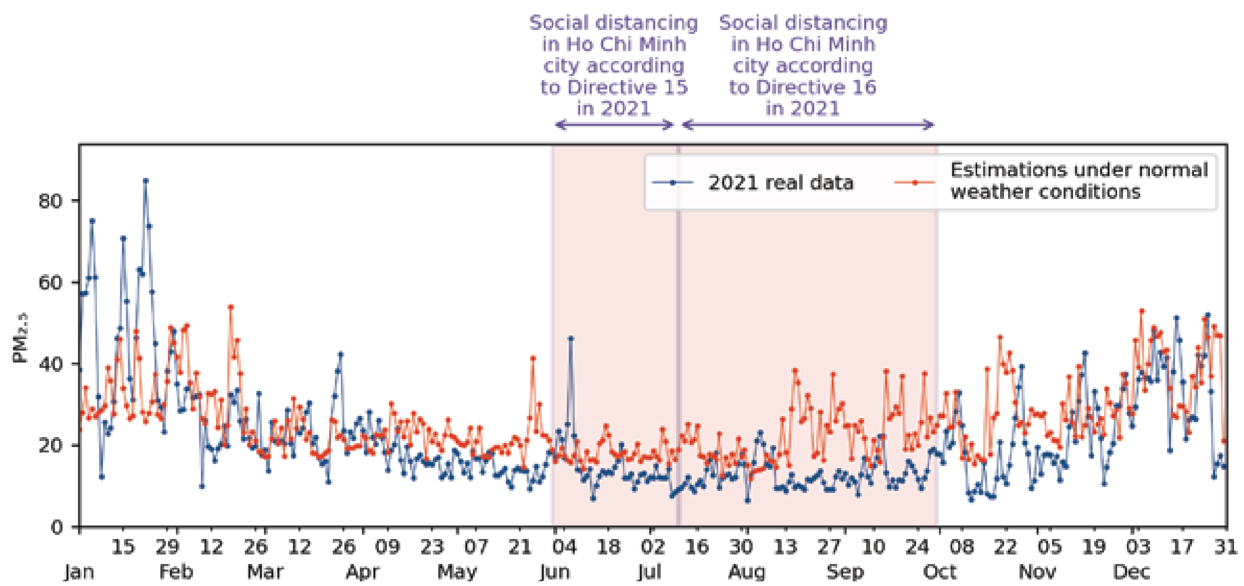


Figure 47. Daily $PM_{2.5}$ concentration measured and estimated under normal conditions in 2021 at the UWYO meteorological station at Tan Son Nhat airport in Ho Chi Minh city.

The outbreaks of COVID-19 in Vietnam 2021

In 2021, Vietnam has recorded two major outbreaks of COVID-19 (the 3rd and 4th outbreaks since the beginning of the pandemic)[53]. Phase 3 started from January 28th to April 26th, 2021, in which there were 1,301 cases and no deaths, with first hotspot in Hai Duong and spread to 13 provinces/cities. Phase 4 took place from April 27th to October 10th, 2021, with 35,445 recorded deaths in 52 provinces/cities.

Until the end of May 2021, the virus has spread to 30 provinces/cities. Some of the hotspots were Bac Ninh, Bac Giang, which had subsided by the end of June 2021.

Ho Chi Minh started recording scattered new cases since April 2021. On May 31st, 2021, the city decided to apply social distancing according to Directive 15/CT-TTg over the whole city and Directive 16/CT-TTg in some areas. On July 9th, 2021, Ho Chi Minh decided to apply Directive 16/CT-TTg on the whole city. At the same time, in some provinces of the key economic area of the South such as Binh Duong, Dong Nai, Long An and in the Central and Mekong River Delta regions, the virus was also starting to spread.

In Hanoi, up till September 16th, 2021, the city has gone through 4 periods of social distancing according to Directive 16/CT-TTg. Overall, after more than 5 months of Phase 4, the pandemic was considered under control nationwide on October 10th, 2021.

Estimating $PM_{2.5}$ concentration under normal weather conditions

$PM_{2.5}$ concentration are constantly under the influence of many factors, one of which is the

weather. Estimations for $PM_{2.5}$ concentration under normal weather conditions ($PM_{2.5}$ under the effects of weather elements only – including temperature, humidity, atmospheric pressure, wind speed and direction and vision) were made and compared with real $PM_{2.5}$ data (real $PM_{2.5}$, affected by weather elements as well as other factors), calculated from the MEM. The discrepancy between these two sets of values would represent the effects of other factors

[53] National Steering Committee for COVID-19 Prevention and Control, 2022

(non-weather) on $PM_{2.5}$ concentration. Details of this procedure are described in Appendix A6.

Status of $PM_{2.5}$

In Hanoi, there were notable differences between real and estimated $PM_{2.5}$ values (real values were lower by 17.6%) from April to July, before quarantine. During social distancing according to Directive 16, real $PM_{2.5}$ values continued to be lower than the estimated-under-normal-condition counterpart (22.8%) (Figure 46). This trend carried on throughout October and November, after quarantine, where real $PM_{2.5}$ was seen 20% lower than estimated $PM_{2.5}$. After that, the real and estimated data started to converge in December. Due to the strict social distancing rules applied on the city, traffic and various production activities have been reduced, which might have led to a decrease in $PM_{2.5}$ emission sources and ultimately $PM_{2.5}$ concentration in the area.

Similarly, in the social distancing periods of 2020 in Hanoi, the decline of $PM_{2.5}$ in the atmosphere was also observed and studied by multiple research teams. One study of Mai et al.[54] pointed out that $PM_{2.5}$ measured during quarantine in 2020 at on-ground stations run by Hanoi EPA showed a 7-10% decline compared to before (after de-weathering the $PM_{2.5}$ data). Another study of Thuy et al.[55] also looked at data from different monitoring stations and concluded that $PM_{2.5}$ during the distancing period in April 2020 dropped by 10% at stations in residential areas and 9% at stations placed at traffic points.

In Ho Chi Minh city, during social distancing according to Directive 16, real $PM_{2.5}$ values were 41.4% lower compared to those of normal-condition estimations (Figure 47). Earlier in the distancing period according to Directive 15 and even before that, in the months April and May, there was a considerable discrepancy between real and estimated $PM_{2.5}$ values (real values were 27.3% lower). This trend continued in the months after quarantine, in October and November with a 25.7% difference between real and estimated values. The impacts of COVID-19 on Ho Chi Minh city was more severe, with a larger spread, more casualties and subsequently longer social distancing period across the city. This has caused a larger decrease in $PM_{2.5}$ sources and distribution than that of Hanoi.

Some studies that focused on Ho Chi Minh city during quarantine also pointed out similar declines in other pollutants in this period. Truong et al.[56] through a similar approach to separate the effects of the weather on the pollutants, noticed that the real NO_2 values measured during social distancing in April of 2020 reduced by 26% compared to the normal-condition-estimated NO_2 values.

[54] Mai et al, 2021 [55] Le et al, 2021 [56] Truong et al, 2022

ASSESSMENT OF $PM_{2.5}$'S IMPACTS ON PUBLIC HEALTH

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NUMBER OF PREMATURE DEATHS DUE TO $PM_{2.5}$ OVER-EXPOSURE COMPARED TO HYPOTHETICAL CASE IN VIETNAM

The number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation: 5 µg/m³

1) In 2019 (Scenario 1): The total number of premature deaths attributed to $PM_{2.5}$ exposure in 2019 was 56,808 cases, accounting for approximately 9.9% of the total number of deaths by natural causes in Vietnam.

The Red River Delta was the most affected region with the total number of attributable deaths reaching over 18,632 cases, followed by the North-Central and South-Central Coast region with more than 11,161 cases. This number of the Mekong River Delta was 9,406 cases. The number of deaths attributable to $PM_{2.5}$ in the Southeast region was 7,378 cases. The Central Highlands was least affected with 1,795 premature deaths due to exposure to $PM_{2.5}$ (Figure 48).

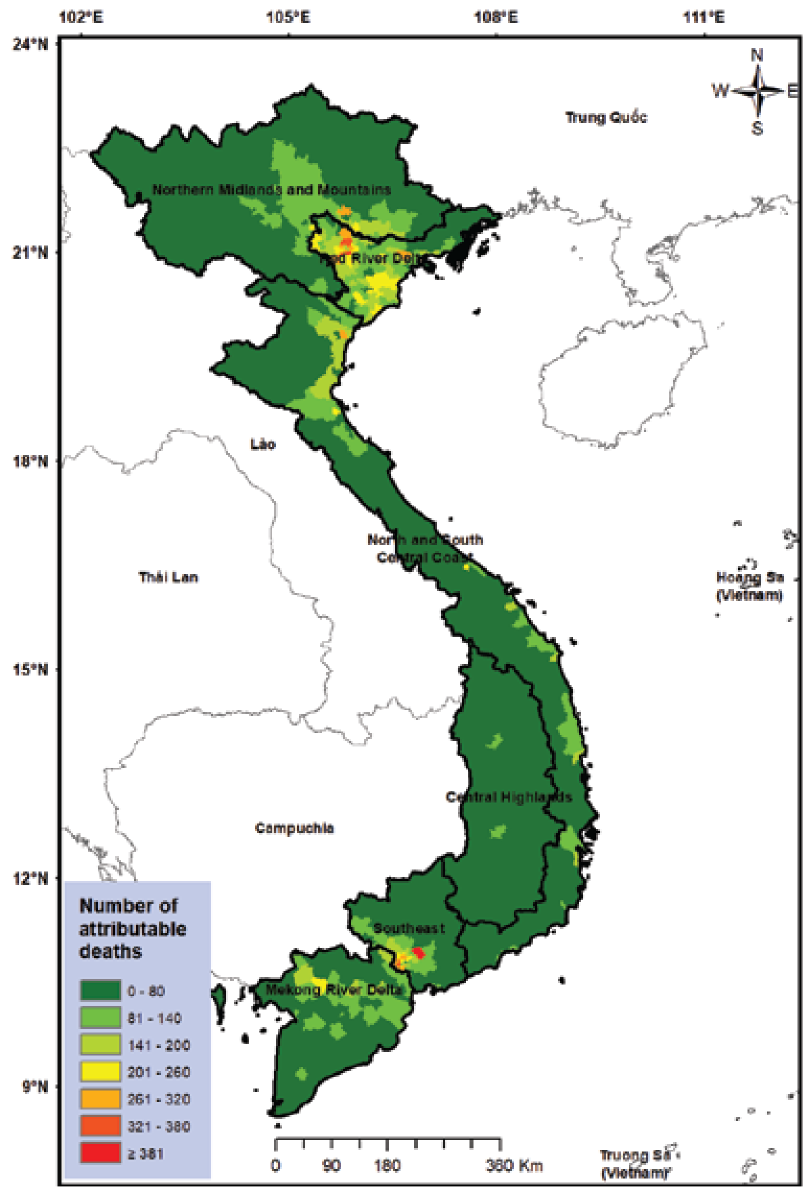


Figure 48. The number of premature deaths attributable to $PM_{2.5}$ exposure in Vietnam in 2019 (Scenario 1)

2) Changes in the proportion of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation if Vietnam had applied the emission control measures (Scenario 2)

In this Scenario, the number of premature deaths in Vietnam in 2019 reduced to 52,993 cases, accounting for only 9.2% of the total number of deaths by natural causes in Vietnam.

The statistics of each region in this Scenario are as follows: the number of attributable deaths in the Red River Delta was 17,475 cases, and the North-Central and South-Central Coast region was 10,412 cases. The number of attributable deaths in the Central Highland would be 1,637 cases (Figure 49).

3) The changes in premature death rate due to emission source control would range from 4.7% to 9.6% of the total deaths attributable to $PM_{2.5}$ in 2019. Dak Lak could reduce by 9.6%, followed by Khanh Hoa (9.3%) and Phu Yen (9.2%) in 2019 (Figure 50). Therefore, the North-Est provinces adjacent to the South-East regions had the largest changes in the burden of disease.

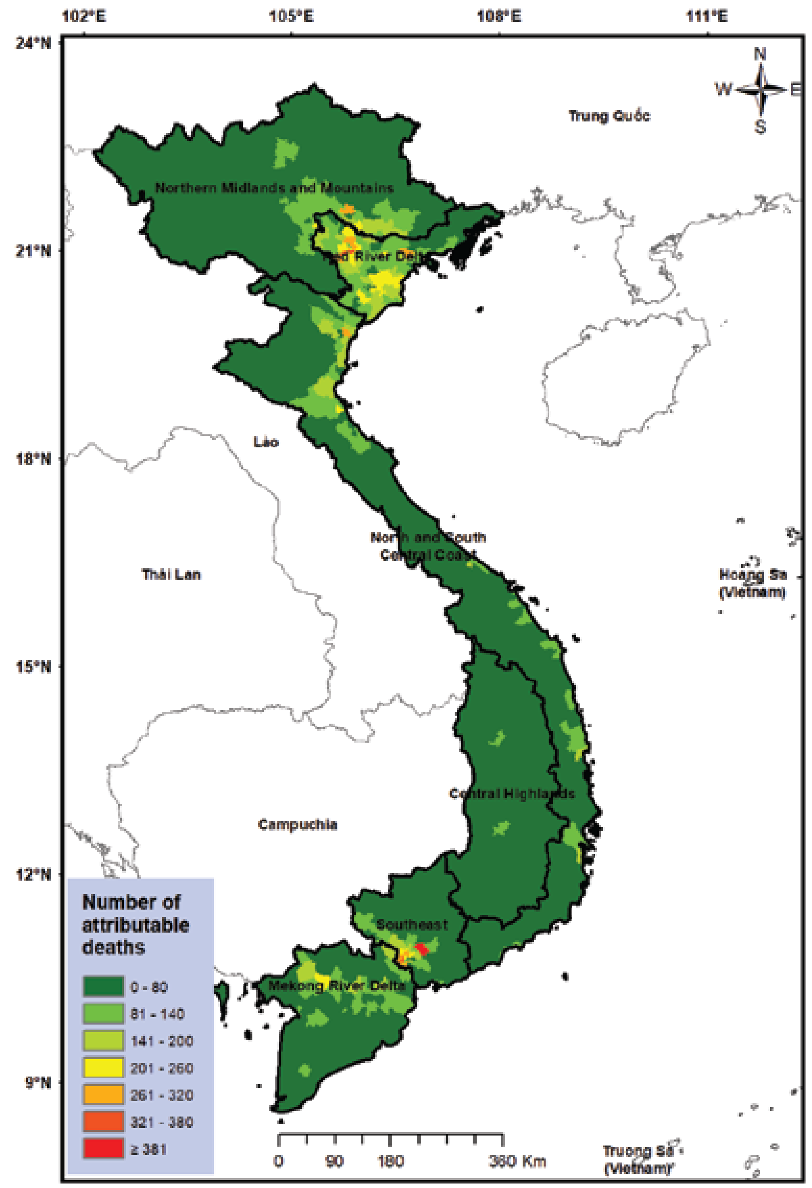


Figure 49. The number of premature deaths attributable to $PM_{2.5}$ exposure in Vietnam in 2019 (Scenario 2)

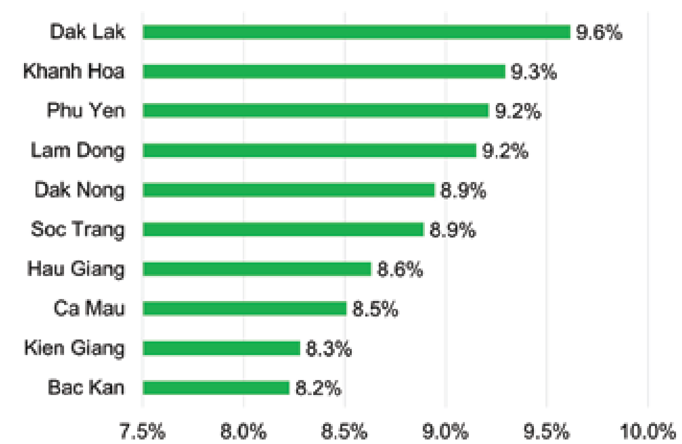


Figure 50. List of 10 provinces with highest reduction rate of attributable deaths due to excess $PM_{2.5}$ exposure in scenario 2 compared to scenario 1 in Vietnam in 2019

ASSESSING IMPACT OF $PM_{2.5}$ ON PUBLIC HEALTH (NORTHERN REGION)

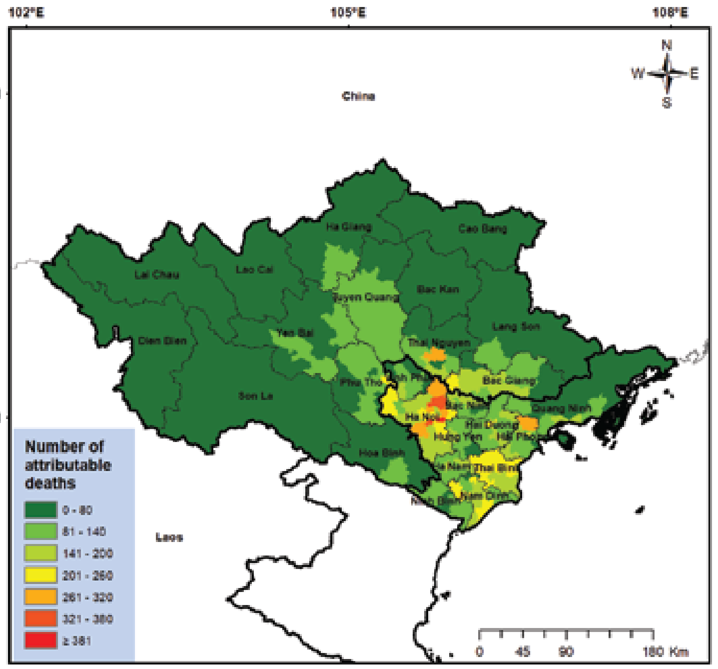


Figure 51. Number of attributable deaths due to excessive level of $PM_{2.5}$ exposure, compared to WHO, in the Northern Midlands and Mountains and Red River Delta in 2019

The number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in the Northern Midlands and Mountains region

1.1) In 2019: Bac Giang and Phu Tho had the highest numbers of attributable deaths in 2019, with 1,419 and 1,372 cases, followed by Thai Nguyen, Lang Son, Hoa Binh, Son La, Tuyen Quang with 988, 568, 561, 554, and 542 cases, respectively (Figure 51).

Bac Kan and Lai Chau had the lowest number of attributable deaths in 2019 with 202 and 207 cases (Figure 51).

1.2) Changes in the proportion of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in the Northeast region if Vietnam had applied emission source control measures (Scenario 2)

The changes in premature deaths due to excessive $PM_{2.5}$ exposure in the provinces of this region would vary from 4.7% to 8.2% of the total premature deaths due to $PM_{2.5}$ in 2019.

Bac Kan would have the highest percentage of decrease in attributable deaths in 2019 in this Scenario compared to reality (8.2%), followed by Lang Son and Cao Bang. The smallest percentages of decrease in this scenario would belong to Lai Chau and Dien Bien, with 4.8% and 4.7% of the actual numbers of deaths attributable to $PM_{2.5}$ in 2019 (Figure 52).

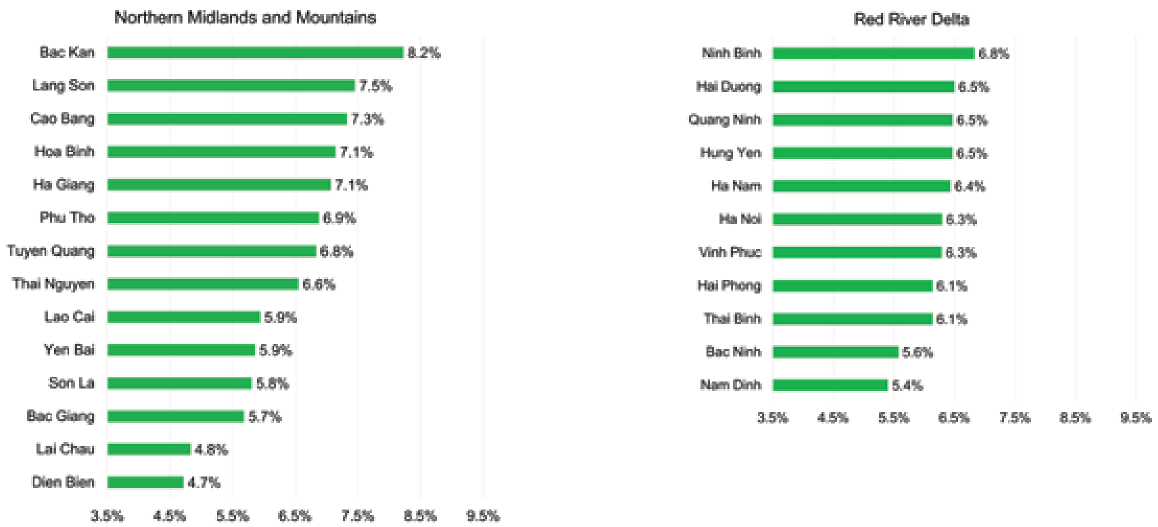


Figure 52. Reduction rate of attributable deaths due to excessive $PM_{2.5}$ exposure in Scenario 2 compared to Scenario 1 in the Northern Midlands and Mountains and Red River Delta in 2019

The number of attributable deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in the Red River Delta

2.1) In 2019: The numbers of premature deaths due to excessive $PM_{2.5}$ exposure in Quang Ninh, Ninh Binh and Ha Nam in 2019 were 678, 743 and 751 cases. This number in Hanoi city was 6,726 cases, 3.8 times higher than the next province in terms of ranking, which is Hai Phong with 1,761 cases (Figure 51).

2.2) Changes in the proportion of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in the Red River Delta if Vietnam had applied emission source control measures (Scenario 2)

The percentage of decrease in attributable deaths in this scenario compared to reality in 2019 in the Red River Delta would range from 5.4 – 6.8% compared to the total deaths attributable to $PM_{2.5}$ in 2019 for each province (Figure 52). Some of the highest percentages of decrease belong to Ninh Binh (6.8%) and Hai Duong (6.5%).

The number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in Hanoi in 2019

3.1) Ha Noi had the highest number of attributable deaths in Vietnam in 2019, ranging from 113 – 444 cases depending on the district (Figure 54).

Populous districts such as Dong Anh, Ha Dong, and especially Hoang Mai, have high number of premature death, all exceeding 300 cases. Son Tay had the smallest number of attributable deaths with 113 cases (Figure 53).

3.2) Changes in the proportion of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in Hanoi in 2019 if Vietnam had applied emission source control measures (Scenario 2)

The percentage of decrease in attributable deaths would vary from 5.6 to 6.8% of the number of attributable deaths in 2019 (Figure 54). Ha Dong had the largest percentage of decline while Ung Hoa and Chuong My district was having the changes (Figure 54).

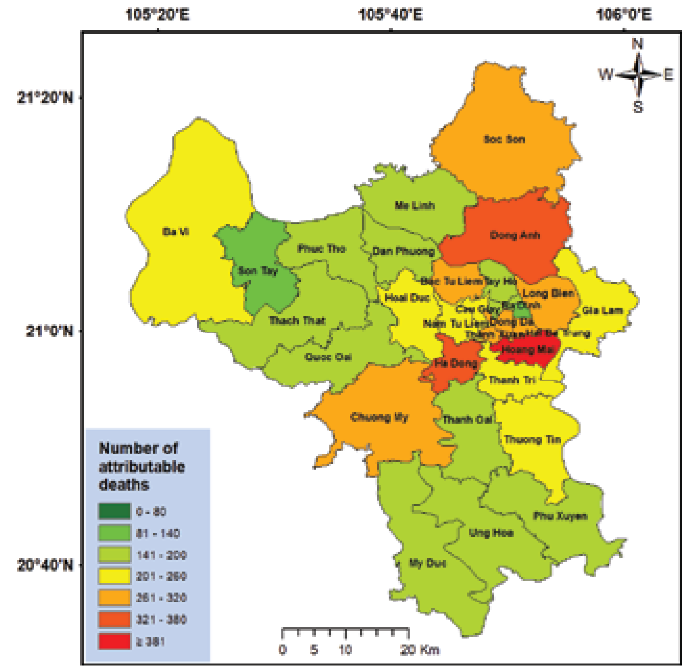


Figure 53. The number of attributable deaths due to excessive level of $PM_{2.5}$ exposure, compared to WHO, in Hanoi in 2019

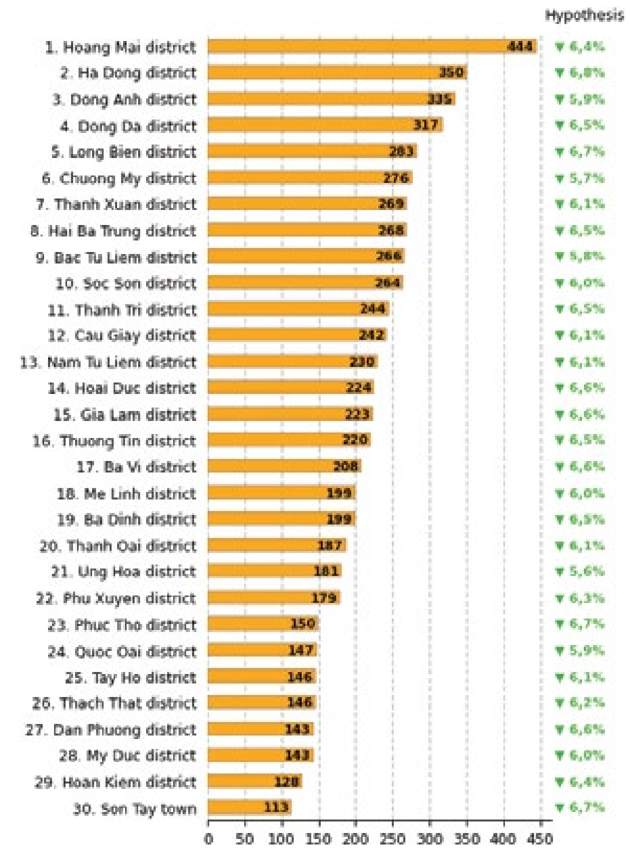


Figure 54. Reduction rate of attributable deaths due to excessive $PM_{2.5}$ exposure in scenario 2 compared to scenario 1 in Hanoi in 2019

ASSESSING IMPACT OF $PM_{2.5}$ ON PUBLIC HEALTH (BAC NINH & THAI BINH)

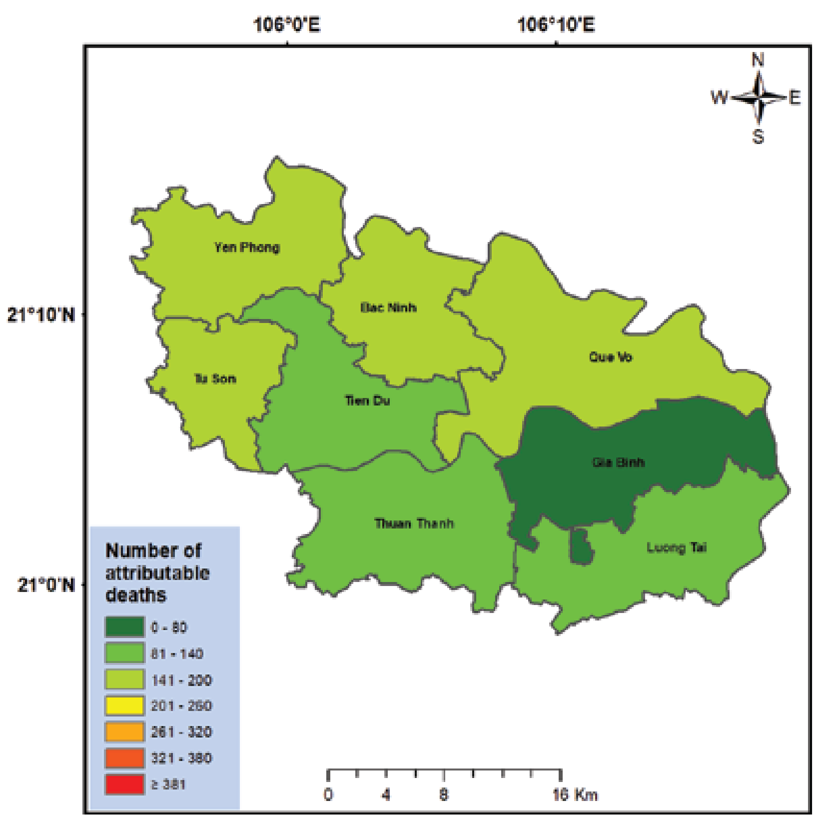


Figure 55. The number of attributable deaths due to excessive level of $PM_{2.5}$ exposure, compared to WHO, in Bac Ninh in 2019

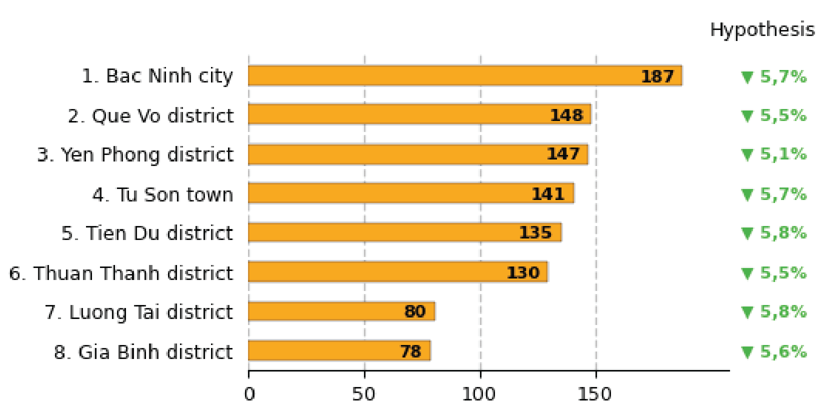


Figure 56. Reduction rate of attributable deaths due to excessive $PM_{2.5}$ exposure in scenario 2 compared to scenario 1 in Bac Ninh in 2019

Bac Ninh

1.1) The total number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in Bac Ninh province was 1,047 cases in 2019. The number of deaths attributable to $PM_{2.5}$ was highest in Bac Ninh city with 187 cases, followed by Que Vo district with 148 cases, Yen Phong district with 147 cases. Gia Binh and Luong Tai have the lowest numbers of $PM_{2.5}$ attributable deaths, with 78 and 80 cases respectively (Figure 55).

1.2) Changes in the proportion of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in Bac Ninh if Vietnam had applied emission source control measures (Scenario 2)

The number of deaths attributable to $PM_{2.5}$ in Bac Ninh in 2019 dropped to 989 cases and the percentages of decrease would have ranged from 5.1 to 5.8% compared to the total of $PM_{2.5}$ attributable deaths. Tien Du and Luong Tai would have higher decreases in attributable deaths proportion, compared to other districts. The percentage of decrease in Bac Ninh city would be 5.7% of the total number of attributable deaths here in 2019 (Figure 56).

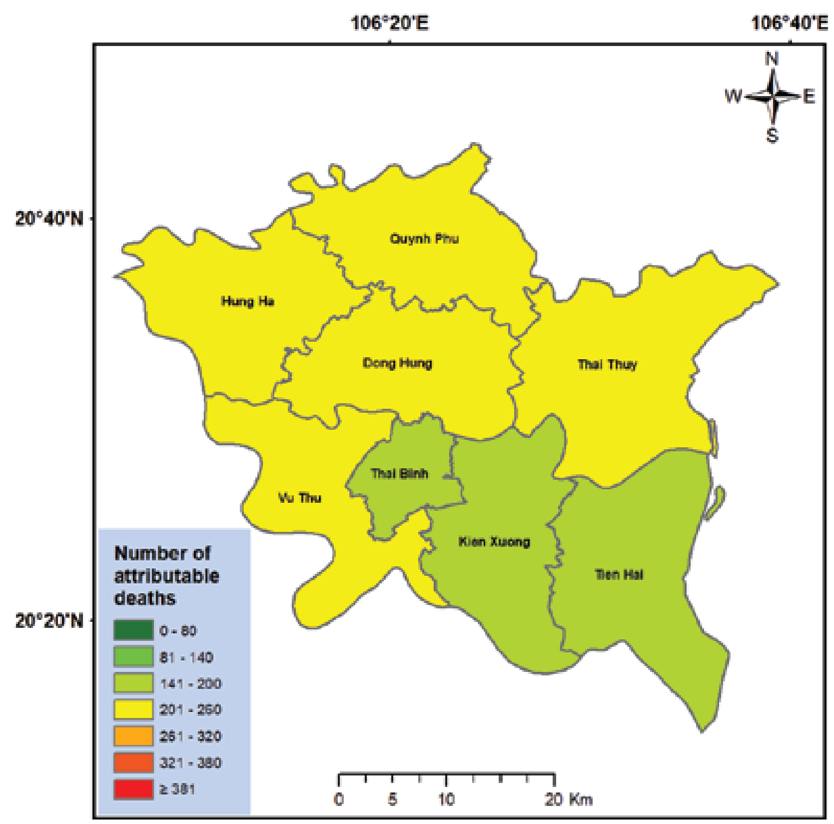


Figure 57. The number of attributable deaths due to excessive level of $PM_{2.5}$ exposure, compared to WHO, in Thai Binh in 2019

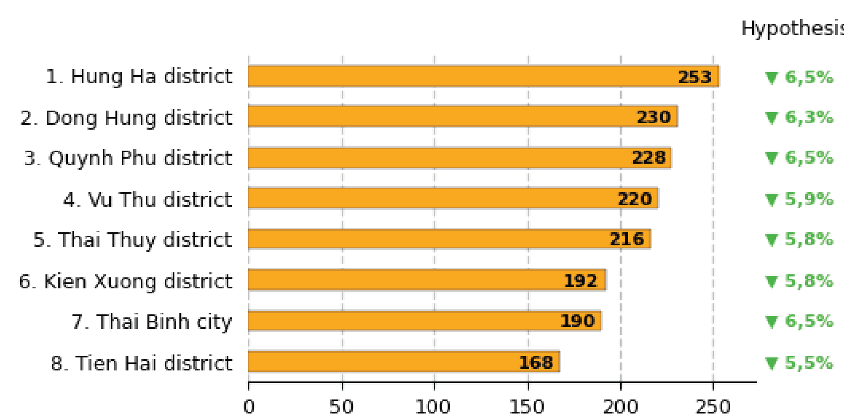


Figure 58. Reduction rate of attributable deaths due to excessive $PM_{2.5}$ exposure in scenario 2 compared to scenario 1 in Thai Binh in 2019

The number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in Thai Binh province

2.1) In 2019: The total number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in Thai Binh province was 1,697 cases. These numbers in each district ranged from 168 cases (Tien Hai district) – 253 cases (Hung Ha district) (Figure 57). In addition, Dong Hung, Quynh Phu, Vu Thu, and Thai Thuy recorded 230, 228, 220 and 216 attributable deaths, respectively.

2.2) The change of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in Thai Binh province if Vietnam had applied emission source control measures (Scenario 2) would have been 6.1%. The number of attributable deaths between districts, though did not vary noticeably, had a tendency of decreasing from the Northwest to the Southeast of the province (Figure 57). The reduction rate of attributable death would have ranged from 5.5 – 6.5% (Figure 58).

ASSESSING IMPACT OF $PM_{2.5}$ ON PUBLIC HEALTH (CENTRAL REGION)

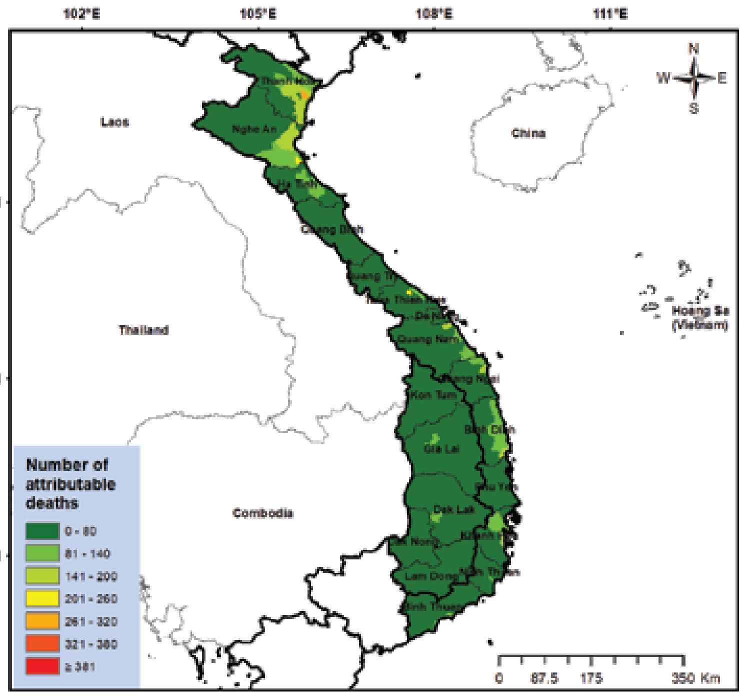


Figure 59. The number of attributable deaths due to excessive level of $PM_{2.5}$ exposure, compared to WHO, in North-Central and South-Central Coast and Central Highlands in 2019

The North-Central and South-Central Coast region

1.1) In 2019: the total number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in the North-Central and South-Central Coast region was 11,162 cases. Almost all of the provinces in this region had the number of deaths attributable to $PM_{2.5}$ in 2019 smaller than 700 cases. For Binh Dinh, Ha Tinh and Quang Nam, the numbers ranged from 700-900 cases and for Nghe An, Thanh Hoa, the numbers were 1,930 and 2,730 cases, respectively (Figure 59).

1.2) If control measures had been applied to emission sources, the number of deaths attributable to $PM_{2.5}$ in the North-Central and South-Central Coast region would have decreased to 10,413 cases (Scenario 2).

Khanh Hoa and Phu Yen would decrease by 9.3% and 9.2% number of deaths in 2019. These numbers in Quang Tri and Ha Tinh would be 5.2% and 5.4% (Figure 60).

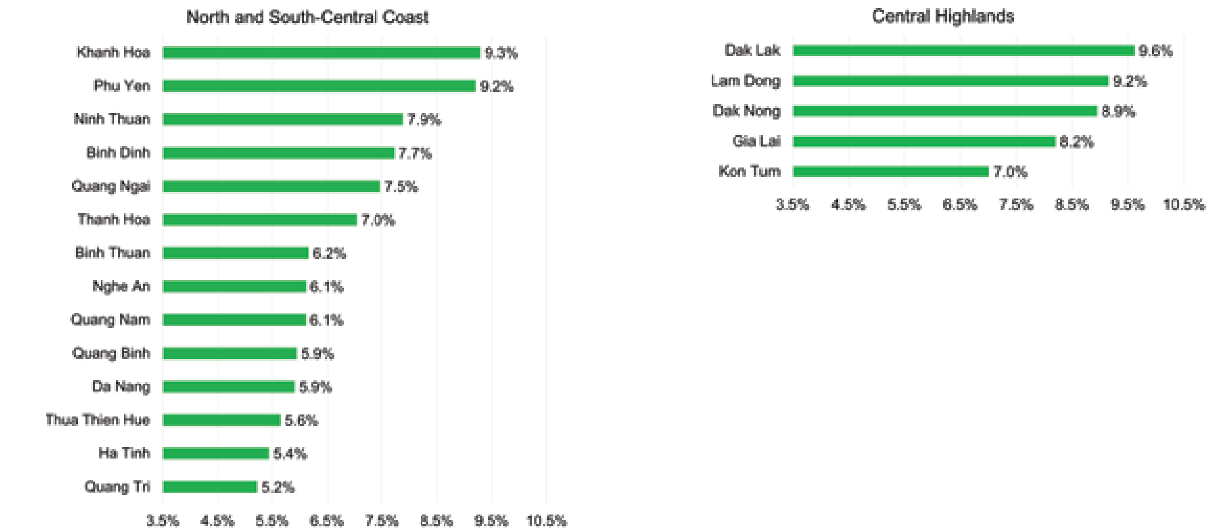


Figure 60. Reduction rate of attributable deaths due to excessive $PM_{2.5}$ exposure in scenario 2 compared to scenario 1 in North-Central and South-Central Coast and Central Highlands in 2019

The Central Highland

2.1) The total number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in the Central Highland was 1,796 cases. The number of deaths attributable to $PM_{2.5}$ in the provinces of this region in 2019 are 580 cases in Dak Lak, 478 cases in Gia Lai and 406 cases in Lam Dong. Kon Tum had the lowest number of attributable deaths with 162 cases (Figure 59).

2.2) If control measures were applied to emission sources, the number of deaths attributable to $PM_{2.5}$ in the Central Highland in 2019 would have decreased to 1,637 cases. The number of avoidable deaths in the whole region would decrease by 8.8% compared to that in this region in 2019. Particularly, Dak Lak would be able to avoid 9.6% number of deaths associated with $PM_{2.5}$ exposure while for Lam Dong it would be 9.2% in 2019 (Figure 60).

Nghe An

3.1) In 2019: The total number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in Nghe An was 1,930 cases. (Figure 61). The highest number of deaths attributable to PM2.5 was in Vinh city with 241 cases, almost 10 times higher than the lowest district Quynh Chau (27 cases) (Figure 61). Dien Chau district and Yen Thanh district had the number of attributable deaths of 191 and 174 cases, respectively.

3.2) If control measures were applied to emission sources, the number of deaths attributable to $PM_{2.5}$ in the Central Highland in 2019 would decrease to 1,812 cases. The percentage of decrease per district would vary from 5.1 – 7.4% and there is no apparent trend based on the geography of the province (Figure 62). Areas with large reductions in the number of attributable deaths would have been Thai Hoa with a 7.2% decrease, Nghia Dan district, Que Phong district, Tan Ky district, all with a 7.1% decrease. Socio-economically active areas like Vinh would decrease by 5.2% of the total attributable deaths in 2019 while the number for Hoang Mai and Nghi Loc would be 6.3% and 5.5%, respectively.

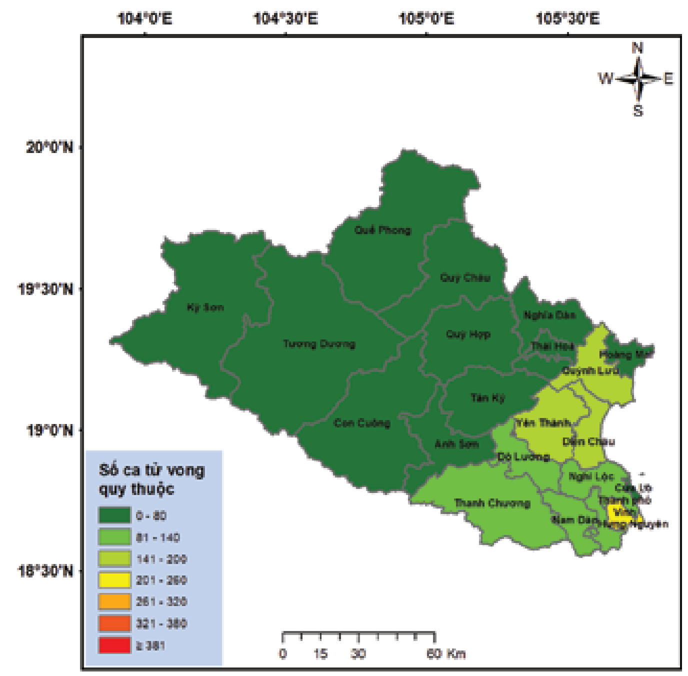


Figure 61. The number of attributable deaths due to excessive level of $PM_{2.5}$ exposure, compared to WHO, in Nghe An in 2019

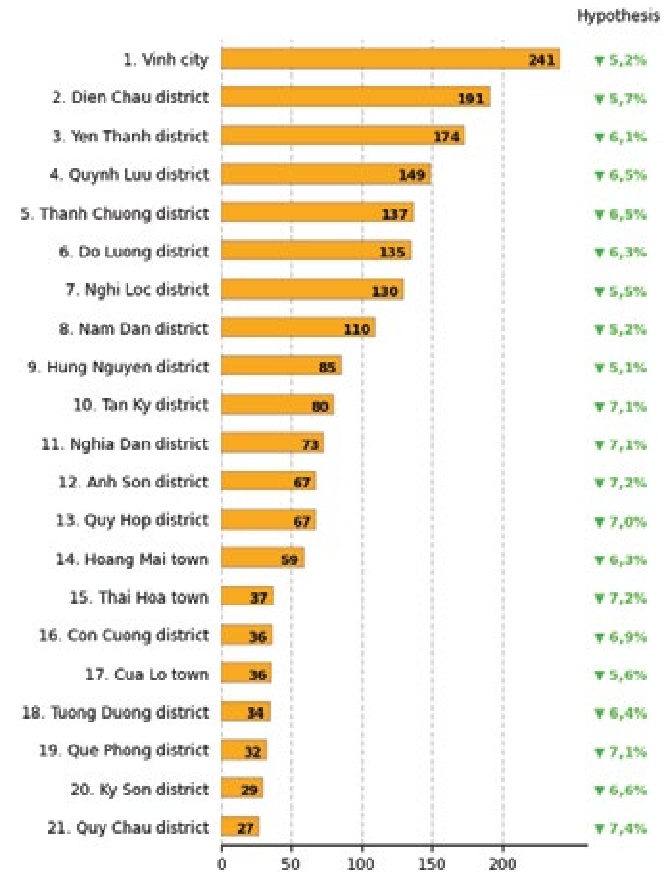


Figure 62. Reduction rate of attributable deaths due to excessive $PM_{2.5}$ exposure in scenario 2 compared to scenario 1 in Nghe An in 2019

ASSESSING IMPACT OF $PM_{2.5}$ ON PUBLIC HEALTH (SOUTHERN REGION)

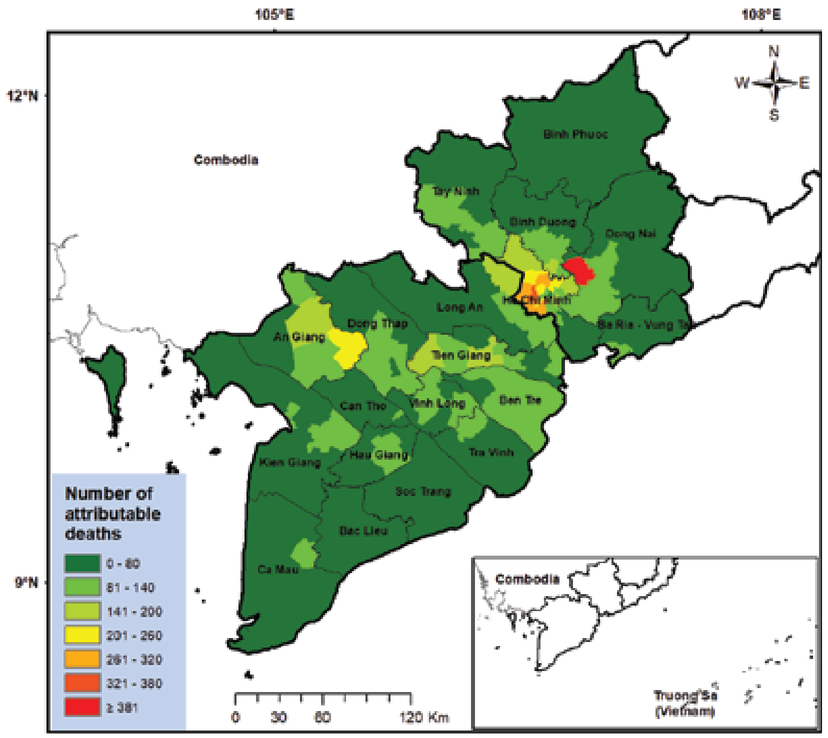


Figure 63. The number of attributable deaths due to excessive level of $PM_{2.5}$ exposure, compared to WHO, in Southeast region and Mekong River Delta in 2019

Southeast Region

1.1) In 2019: The total number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in the Southeast region was 7,378 case. Dong Nai and Ho Chi Minh had the total number of premature deaths due to $PM_{2.5}$ of 1,103 and 4,130 cases, respectively. Binh Phuoc and Ba Ria Vung Tau were the provinces with the lowest number of premature deaths due to $PM_{2.5}$ in the region with 299 and 411 cases, respectively (Figure 63).

1.2) If control measures had been applied to emission sources, the number of deaths attributable to $PM_{2.5}$ in the Southeast region in 2019 would have decreased by 6.3% to 7.2% (Figure 64) of the total number of attributable deaths in 2019. Specifically, the percentage of decrease for Binh Duong would be 7.2% and for Dong Nai would be 7.0%. The percentage of decrease in the number of deaths attributable to $PM_{2.5}$ for Ho Chi Minh city would be 6.9%.

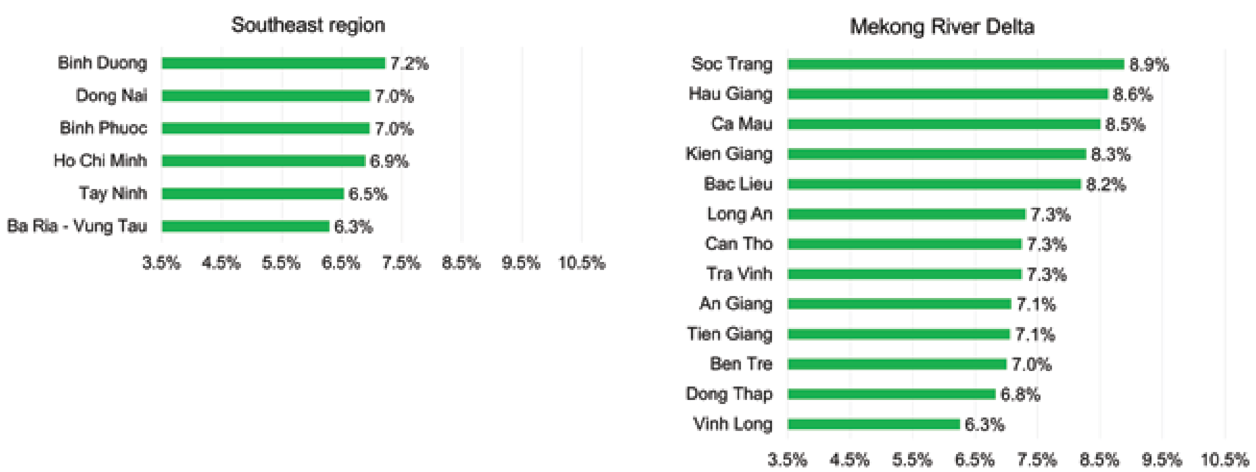


Figure 64. Reduction rate of attributable deaths due to excessive $PM_{2.5}$ exposure in scenario 2 compared to scenario 1 in Southeast region and Mekong River Delta in 2019

Mekong River Delta

2.1) The total number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in the Mekong River Delta was 9,406 cases. An Giang and Tien Giang had the highest numbers of premature deaths due to excessive $PM_{2.5}$ exposure with 1,460 and 1,144 cases, respectively. Hau Giang, on the other hand, had the lowest number of cases (330 cases) (Figure 63).

2.2) If control measures had been applied to emission sources, the number of deaths attributable to $PM_{2.5}$ in the Mekong River Delta in 2019 would have decreased by 6.3% to 8.9% per province. Soc Trang province would be able to avoid 8.9% of the province's total number of deaths attributable to $PM_{2.5}$, followed by Hau Giang with 8.6% of its total cases. The province with the smallest percentage of decrease would be Vinh Long (6.3%) (Figure 64). For Can Tho city the percentage of decrease would be 7.3% of the province's total number of attributable deaths in 2019.

Ho Chi Minh City

3.1) The total number of premature deaths due to higher $PM_{2.5}$ exposure than the WHO recommendation in Ho Chi Minh city was 4,130 cases in 2019, ranking second in Vietnam. The inner districts had higher numbers of premature deaths, with the highest number of cases in Binh Tan with 370 cases, followed by Go Vap district, Binh Chanh district and District 12 (ranging from 280 to 320 cases). Can Gio district had the smallest number of attributable deaths in 2019 in the city (24 cases) (Figure 65).

3.2) If control measures had been applied to emission sources, the number of deaths attributable to $PM_{2.5}$ in the Mekong River Delta in 2019 would have decreased by 6.9%. The largest percentage of decrease would be 7.7% in Nha Be district, followed by Binh Chanh district with a 7.6% decrease and District 9 with 7.4% (Figure 66).

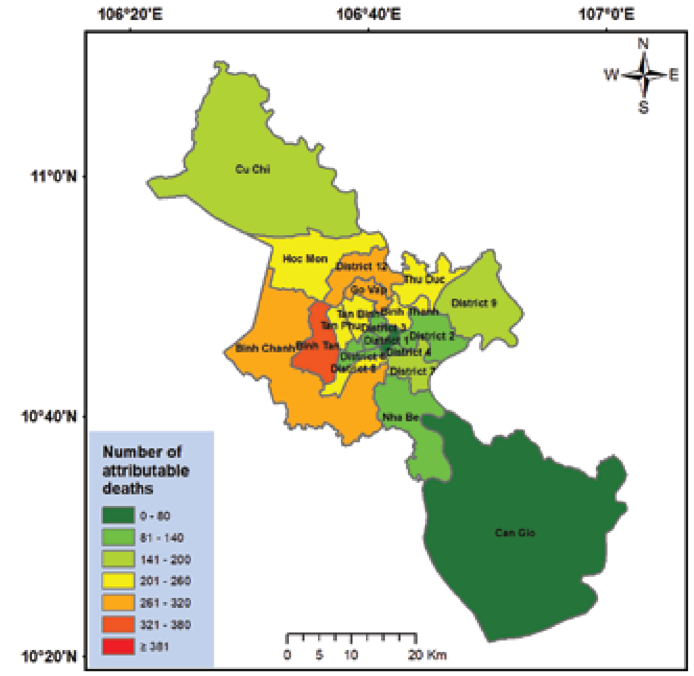


Figure 65. The number of attributable deaths due to excessive level of $PM_{2.5}$ exposure, compared to WHO, in Ho Chi Minh in 2019

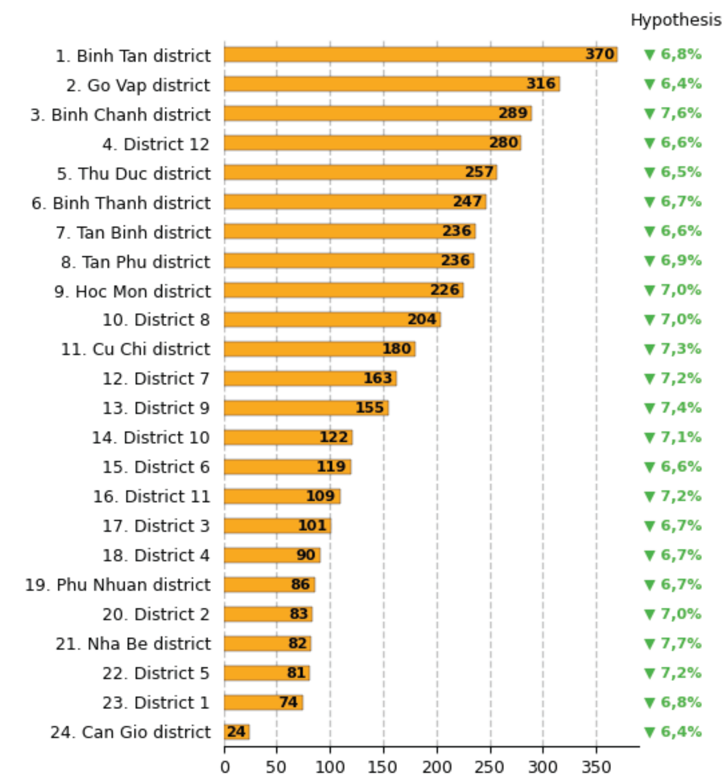
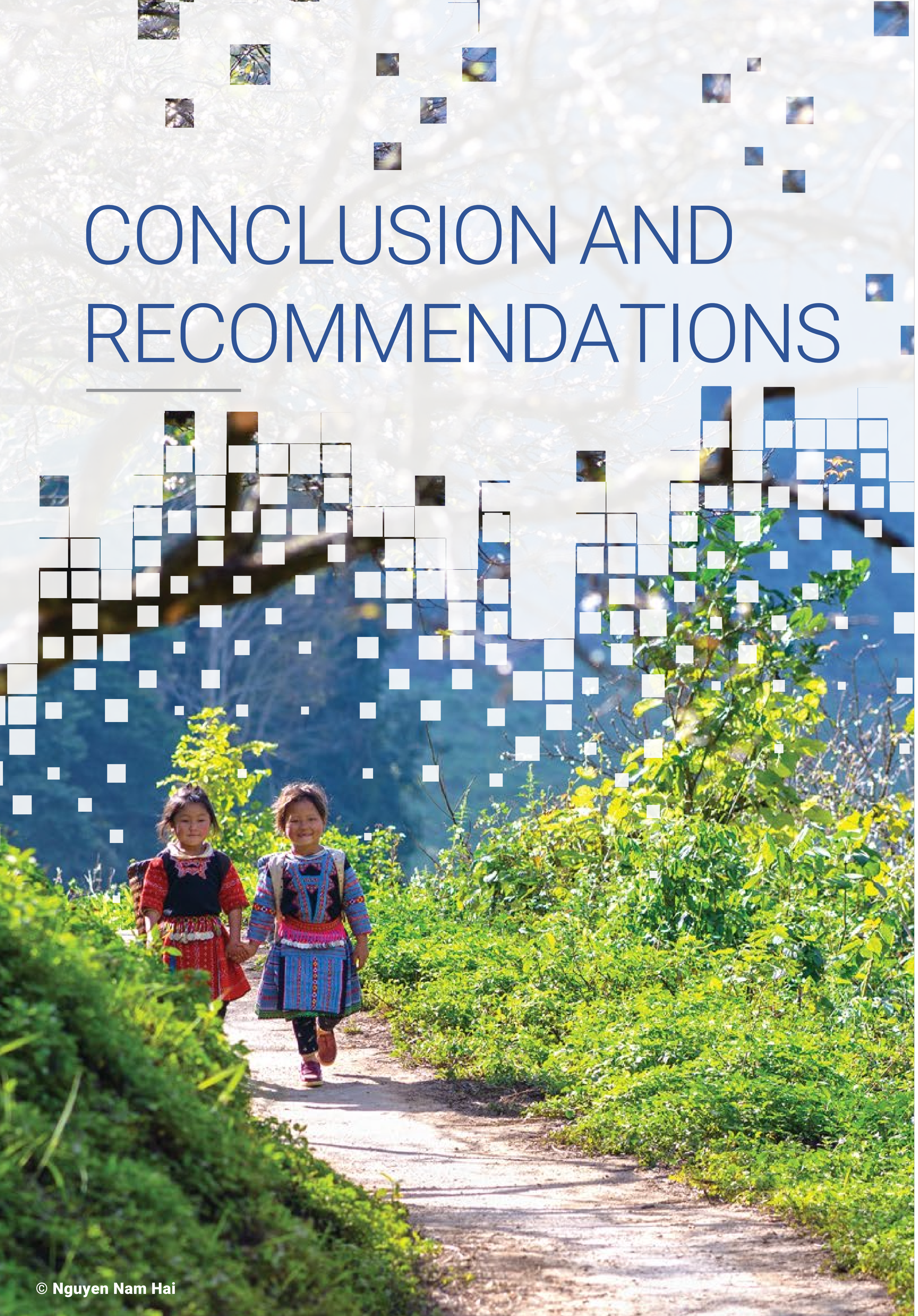


Figure 66. The rate of reduction of premature deaths due to excessive $PM_{2.5}$ exposure in 2019 in Ho Chi Minh city (comparison between the hypothetical case and the actual case)

CONCLUSION AND RECOMMENDATIONS



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CONCLUSIONS

The current status of $PM_{2.5}$

Nationwide

The annual mean of $PM_{2.5}$ concentration in 2021 tended to decrease compared to 2019 and slightly increased compared to 2020 due to the unusually high values in January 2021. Areas with high $PM_{2.5}$ concentration are mainly located in the Red River Delta region (Hanoi and neighboring provinces).

In 2021, there were 06/63 provinces and cities with annual mean $PM_{2.5}$ exceeding Vietnam standards (QCVN 05:2013/BTNMT), including Hanoi, Bac Ninh, Hung Yen, Vinh Phuc, Ha Nam and Hai Duong. $PM_{2.5}$ exposure (population weight $PM_{2.5}$) was higher than the average value of PM2.5 in all provinces/cities. Compared to the WHO recommendations in 2021 (5 μg/m^3), the $PM_{2.5}$ concentration in all provinces and cities nationwide in 2021 were many times higher, which poses great threats to the overall public heath.

Region

76% of provinces in the Northern region had annual average $PM_{2.5}$ concentrations that met the Vietnam standards. Average $PM_{2.5}$ concentration values per district in this region ranged from 13.1 μg/m^3 to 43 μg/m^3.

100% of provinces in the Central region had annual average $PM_{2.5}$ concentrations that met the Vietnam standards (25 μg/m^3), at the same time exceeded the WHO 2021 threshold (5 μg/m^3). $PM_{2.5}$ was high in the North Central provinces, low in the Central Highlands and South-Central Coast. Average $PM_{2.5}$ concentration values per district in this region ranged from 11.0 μg/m^3 to 23.1 μg/m^3.

100% of provinces in the South had annual average $PM_{2.5}$ concentrations that met the Vietnam standards (25 μg/m^3) while exceeded the WHO 2021 threshold (5 μg/m^3). $PM_{2.5}$ was high Ho Chi Minh city and neighboring provinces, low in the southwestern provinces. Average $PM_{2.5}$ concentration values per district in this region ranged from 11.4 μg/m^3 to 21.3 μg/m^3.

Province/city

In Hanoi and Bac Ninh, annual mean $PM_{2.5}$ concentrations at all the districts exceeded the Vietnam standards and WHO recommendations in 2021. The percentages of days in 2021 with good and moderate air quality were dominant. The percentage of days with good air quality was 42.2% and 49.7%, for Hanoi and Bac Ninh, respectively, and moderate level was 39.7% and 37.3%. $PM_{2.5}$ was high in December and January and low in July and August.

In Thai Binh, annual mean $PM_{2.5}$ concentrations at 5/8 districts (62.5%) exceeded the Vietnam standards and WHO recommendations in 2021. The percentage of days in 2021 with good air quality was 69.3% and moderate air quality accounted for 24.4% of the number of days. This percentages were equivalent to those of 2020 and more ideal than those of 2019.

In Nghe An, annual mean $PM_{2.5}$ concentrations at all districts were lower than the Vietnam standards but higher than WHO's recommendations in 2021. The ratio of days in 2021 with good air quality accounted for 89% the number of days in 2021.

In Ho Chi Minh City, annual mean $PM_{2.5}$ concentrations at all districts exceeded the Vietnam standards and WHO recommendations in 2021. $PM_{2.5}$ was high in central districts, low in remote districts such as Cu Chi and Can Gio. The percentage of days in 2021 at good level accounted for 87.1%, and moderate level was 11.8%. $PM_{2.5}$ was high in December, January, February and March and low in the remaining months.

Urban areas

The ratio of urban areas with annual mean $PM_{2.5}$ in 2021 exceeding the Vietnam standards tended to decrease according to the level of urban levels, the highest in special urbans, the lowest in type III urbans. The ratio of good and moderate days prevailed in all urban types, the ratio of days with poor AQI level was less.

COVID-19

In Hanoi, during the period of social distancing from July 24 to September 21, the measured $PM_{2.5}$ concentration decreased by 22.8% compared to estimations under normal weather conditions (without factors like social distancing). In the period before and after the social distancing, the concentration also tended to decrease.

In Ho Chi Minh City, during the period of social distancing from July 24 to September 21, the measured $PM_{2.5}$ concentration dropped by 41.4% compared to normal weather conditions. In the periods before and after the social distancing, $PM_{2.5}$ tended to decrease 27.3% and 25.7% respectively.

The health impact of $PM_{2.5}$

Our results showed that in Vietnam, the number of premature deaths in 2019 due to higher $PM_{2.5}$ exposure than the WHO recommended level was approximately 56,808 cases nationwide, accounting for about 9.9% of the total number of deaths due to natural causes in Vietnam.

Between different socio-economic regions, the number of deaths attributable to excessive $PM_{2.5}$ exposure in 2019 was higher in the Red River Delta, North Central Coast and South-Central Coast. The Central Highlands region had the lowest number of $PM_{2.5}$ attributable deaths.

Hanoi and Ho Chi Minh City had the highest number of deaths due to excessive $PM_{2.5}$ exposure in the country in 2019.

If Vietnam had applied emission control measures, the total number of deaths due to exceedance of $PM_{2.5}$ exposure would have reduced by 6.7% of the total number of deaths due to $PM_{2.5}$ in 2019 nationwide.

RECOMMENDATIONS

For state units and organizations (Ministry of Natural Resources and Environment, Ministry of Health)

Use the $PM_{2.5}$ concentration maps in air quality monitoring for a general picture of the current status of the air environment at the national, regional, provincial and city levels each year. The $PM_{2.5}$ maps can provide information on $PM_{2.5}$ nationwide, especially in areas that lack monitoring stations. These maps can also show more clearly the regions, provinces and cities facing air quality problems, thereby helping legislators to prioritize the implementation of measures to monitor and control $PM_{2.5}$ pollution in specific areas. The results and data of this research will complement the data and methods for the national and provincial air environmental reporting; providing information on the current status to support provinces/cities to develop Provincial Air Quality Management Plans according to Official Letter 3051/BTNMT-TCMT, helping them to set specific objectives to improve air quality and control the effectiveness of the measures being taken.

Prioritize air quality monitoring and management in the order of $PM_{2.5}$ status of provinces and cities. Some provinces and cities, which are at high risk of $PM_{2.5}$ pollution, need drastic, timely, and effective measures and policies to monitor and manage air quality. Meanwhile, provinces and cities with low risk of $PM_{2.5}$ pollution still need to maintain air quality monitoring and controlling mechanisms but at a rational level to save resources.

Invest in air quality management by region and level of urbanization. The results of our research showed that the risk of $PM_{2.5}$ pollution tended to increase as the level of urbanization increase. High ranked urban areas are all areas with strong economic and social development, leading to potential adverse impacts on the air environment if not properly monitored and managed.

Improve the national standard air quality monitoring network, giving priority to provinces and regions with air pollution as recommended earlier in this report. In this research, the $PM_{2.5}$ maps were built based on data from national monitoring stations. The quantity and quality of this data source are essential to ensure the quality of the model. A mechanism for sharing data and QA/QC information at the stations is recommended to improve the quality of $PM_{2.5}$ modelling and $PM_{2.5}$ monitoring, as well as to support scientific research and education - communication about air pollution in general.

Periodically review and improve the national technical regulations on air quality and emission sources. According to the results presented this study, all provinces and cities have annual mean of $PM_{2.5}$ concentrations exceeded WHO recommendations - a level at which $PM_{2.5}$ is considered to have little to no adverse health effects. The Vietnam standards (QCVN 05:2013/BTNMT) currently applies a threshold for the annual mean $PM_{2.5}$ of 25 µg/m³, which is way higher than the WHO recommendations (5 µg/m³ since 2021 and 10 µg/m³ up till 2020). In addition to the ambient air pollution, indoor air pollution also is a pressing problem around the world, especially in low-and-middle-income countries. However, Vietnam currently has no regulations and standards for indoor air quality. Therefore, it is recommended to periodically review existing standards, provide an appropriate roadmap to improve standards of air quality and emissions from industries, waste incinerators, and at the same time promulgate standards for indoor air quality.

Perform health impact assessment annually. The results of the health impact assessment play an important role in developing plans and interventions. The results of this study also showed that if the pollution level was controlled in 2019, the number of premature deaths from $PM_{2.5}$ could be reduced. However, $PM_{2.5}$ concentrations in all provinces were still higher than the recommended level of WHO (set at 5 μg/m^3), and many provinces were still higher than the standard level of Vietnam – QCVN05:2013 (set at 25 μg/m^3). Therefore, it is necessary to conduct periodic health impact assessments to evaluate the effectiveness of the policies being implemented.

Improve the systems for deaths and illnesses statistics in health facilities. In this research, we use estimated data from the death data published by the General Statistics Office, and the national survey on accidents and injuries in Vietnam in 2010. Therefore, the estimate was made with the assumption that the population structure and deaths did not change over the years. To overcome this shortcoming, it is necessary to conduct evaluation based on actual data in the community. However, according to recent study by Tran Thi Hong et al (2018), the data recorded in the A6 book can only be about 89% complete.

Engage in interdisciplinary collaboration to improve the health of the community due to air pollution. In the health impact assessment, the input indicators came from a variety of sources, including air quality measurement agencies, health facilities and agencies that perform population statistics. In addition, some other agencies or organizations need to use these results to implement appropriate interventions.

For research institutes, universities

Invest in statistical modeling and machine learning studies for air pollution nationwide, regionally, and city/province to provide accurate air quality data. In this research, we have used a statistical machine learning model to estimate the $PM_{2.5}$ on a national scale. However, the quality of our $PM_{2.5}$ dataset were only above average due to the complexity of the problem as well as the uncertainties in the input data. Investing in research in standardizing and updating data as well as more modern models to estimate $PM_{2.5}$ will increase the accuracy and reliability of the estimations which can translate into further analyses.

Promote in-depth research on the health impact of air pollution. At present, there are many models of health impact assessment in the world. However, these models are not specific to Vietnam because they were built from studies conducted in other countries. Therefore, it is necessary to carry out studies based on specific data for Vietnam.

Promote research to identify the source contributors of $PM_{2.5}$ and other air pollutants. In 2021, 06/63 provinces and cities were polluted with $PM_{2.5}$ and many other provinces and cities were at risk considering the Vietnam standards. However, the results on emission sources were only made and published in some provinces and cities. This causes difficulties in determining the sources of pollution and construct appropriate and effective policies in controlling emission sources and enhancing air quality.

Consult with government agencies on the process and results of the health impact assessment. This is necessary to ensure the quality of the data as well as the correct interpretation of the output. This will also serve as notification and interest engagement towards government officials so that they can be aware of the research process and possible results to use in policy development and management activities.

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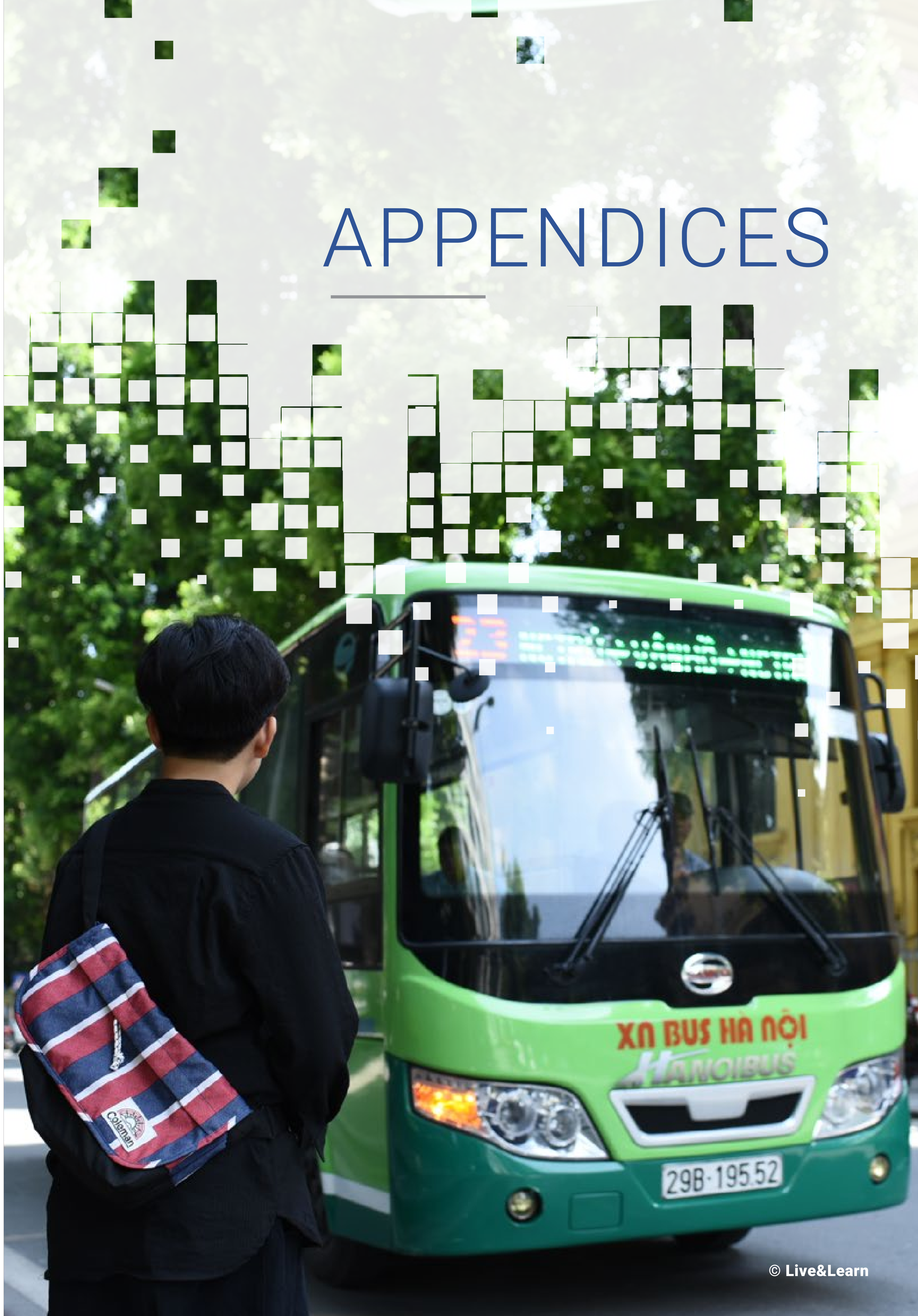
APPENDICES



APPENDIX A. RESEARCH METHODOLOGIES IN ASSESING $PM_{2.5}$ POLLUTION

A1. Method of analyzing the Status of $PM_{2.5}$ pollution

To analyze the Status of $PM_{2.5}$ pollution in 2021 in Vietnam, the report used daily $PM_{2.5}$ concentration maps in Vietnam with spatial resolution of 3x3 km in the period 2019-2021. The maps were estimated using the Mixed Effects Model (MEM) and multi-source data including ground monitoring stations data, satellite aerosol images (AOD), meteorological data, land use data from 2012 to 2021. The maps have been validated by comparing with observations at the ground stations (Appendix B).

Contrary to the map data used in this report, monitoring stations data has been the primary source of data to be analyzed in other air quality reports. Standard monitoring stations, operated by state management organizations, have good quality data but the installation and operating costs for each station are currently too high. These stations are also currently unevenly distributed, and not widely available across the country. Meanwhile, the daily $PM_{2.5}$ concentration map provides information of $PM_{2.5}$ on a large scale, over a long period of time, especially in places where there are no monitoring stations. However, data frequency (daily observation) and data quality are lower than standard monitoring stations (hourly measurement).

In this report, $PM_{2.5}$ concentration maps were aggregated and analyzed according to multiple spatial levels (national, region, province/city, district) and temporal levels (annual, monthly, daily).

At the national scale, the annual mean $PM_{2.5}$ map in 2021 with resolution of 3x3 km was presented to show the general distribution of $PM_{2.5}$ concentrations across the country. Based on those annual mean $PM_{2.5}$ maps from 2019-2021, the annual average $PM_{2.5}$ of each province/city was calculated to analyze the 2021 values comparing to those of 2020, 2019 and the national standard threshold (QCVN 05:2013/BTNMT – 25 μg/m³).

At the regional scale, the report presented in 3 regions (North, Central, South) and 6 socio-economic regions (Northern Midlands and Mountains, Red River Delta, North and South-Central Coast, Central Highlands, Southeast, Mekong River Delta). In each region, its spatial distribution of annual average $PM_{2.5}$ concentrations in 2021 was presented. The $PM_{2.5}$ value by province/city in each region was calculated and compared to the Vietnam standard. In addition, the $PM_{2.5}$ concentration in 2021 by district in each region was also taken into account.

At the province/city scale, the report presented the $PM_{2.5}$ status in 2021 at two special urbans, Hanoi and Ho Chi Minh City and three other provinces: Bac Ninh, Thai Binh and Nghe An. At each province/city, the annual mean $PM_{2.5}$ concentration map and monthly maps in 2021 were presented to consider the pollution distribution and variation trends over time. The $PM_{2.5}$ concentration at districts level was used to ranked districts and compared to corresponding values in 2019, 2020 and the national standard. In addition, based on the daily $PM_{2.5}$ concentrations, the number of days with different levels of air quality in 2021 was also reported.

A2. Method of developing $PM_{2.5}$ map

The daily $PM_{2.5}$ concentration maps in Vietnam were developed based on the Mixed Effect Model using different data collected from 2012 - 2021. The input data including station measurements, satellite products of AOD, meteorological maps for humidity, Planetary boundary layer height (PBLH), and land use maps of traffic, normalized difference vegetation index (NDVI), and terrain.

- Measured $PM_{2.5}$ data was collected from standard stations nationwide under the management of the Northern Center of Environmental Monitoring, US Embassy, Vietnam National University Ho Chi Minh City.
- Satellite AOD data was AOD products of Aqua/Terra MODIS and Suomi NPP VIIRS from 2012-2021, provided freely by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA).
- The meteorological data was outputs of the Weather Research and Forecasting (WRF) model customized and run for Vietnam with the fifth generation ECMWF reanalysis (ERA-5) data used as input of this model.
- The Normalized difference vegetation index (NDVI) maps from Terra MODIS were also collected from NASA during the period from 2012 to 2021.
- Road map was collected from the latest Open Street Map in 2022 which in vector format containing the shapes of road types.
- Terrain map (DEM) was collected from ASTER Global source in 2019 containing information about terrain height.

The steps used to develop the map include pre-processing the station measurements and maps data; enhancing the quality of the satellite AOD; integrating the map data with the station measurements; developing and validating the MEM model; estimating the daily $PM_{2.5}$ values across the nation to make $PM_{2.5}$ maps; aggregating the daily maps into the monthly/annual mean maps of $PM_{2.5}$; evaluating the maps with station measurements and comparing the outputs with the global $PM_{2.5}$ products (Figure 67). In the pre-processing step, station measurements were normalized, cleaned and removed outliers and map data at different resolutions was resampled to the same grid of 3x3km cells. AOD satellite products from MODIS and VIIRS was combined to enhance the quality of AOD data. After pre-processing, the maps and station data are integrated together following a spatial constrain (collecting map data at station locations) and a time constrain (within the same day) to develop the training dataset. A MEM model was built to find out the relationship between input data layers (maps) and $PM_{2.5}$ measurements at the stations according to mathematical functions. The MEM model has the formula:

$$PM_{2.5\,i,j} = \sum_{k=1} \alpha_k X_{k,i,j} + (\alpha + \beta)$$

Where $\boldsymbol{PM_{2.5\,i,j}}$ is the model estimate of $PM_{2.5}$ at day i and spatial location j. $\boldsymbol{X_{k,i,j}}$ is map parameter k (i.e. AOD, meteorology, land use) at day i and location j. The coefficients α, α_k are the fixed components (fixed effect) including slope and intercept of input parameters. The parameter β is the random component (random effect) that varies by day. The model was used to estimate the daily $PM_{2.5}$ maps over Vietnam with the resolution of 3x3km. The daily maps were then aggregated into monthly and annual average maps from 2019 to 2021. Daily, monthly, and annual average maps are compared/evaluated with ground station measurements. In addition, the maps estimated from the MEM model were also compared with the global $PM_{2.5}$ maps obtained from the research of Van Donkelaar et al in the same period[58]. The details of the validating $PM_{2.5}$ map with ground stations are presented in Appendix B. The $PM_{2.5}$ maps developing processes are shown in Figure 67. These maps were used for the analysis of $PM_{2.5}$ status nationally, regionally, by province/city, and urban areas…

Details on our method of estimating $PM_{2.5}$ distribution in Vietnam are available in our Technical report, as well as our scientific paper which is currently in review[59].

[58] Donkelaar et al, 2020 [59] Thanh T.N. Nguyen et al, 2022; Truong X Ngo et al, 2022

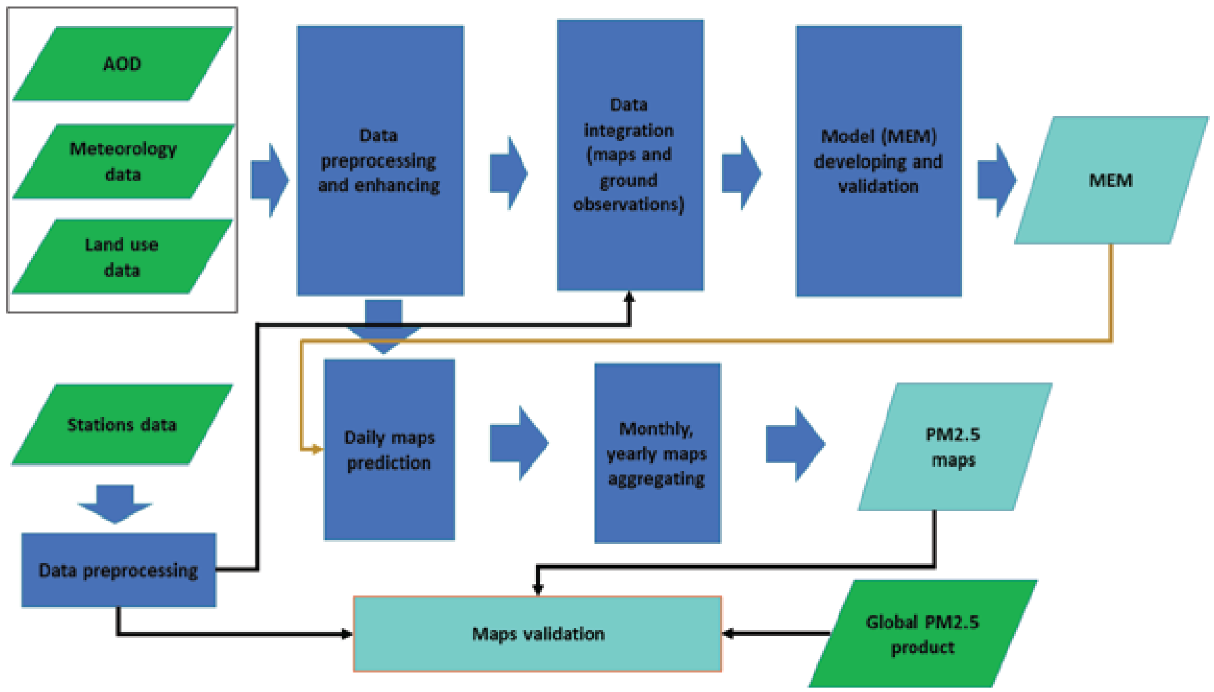


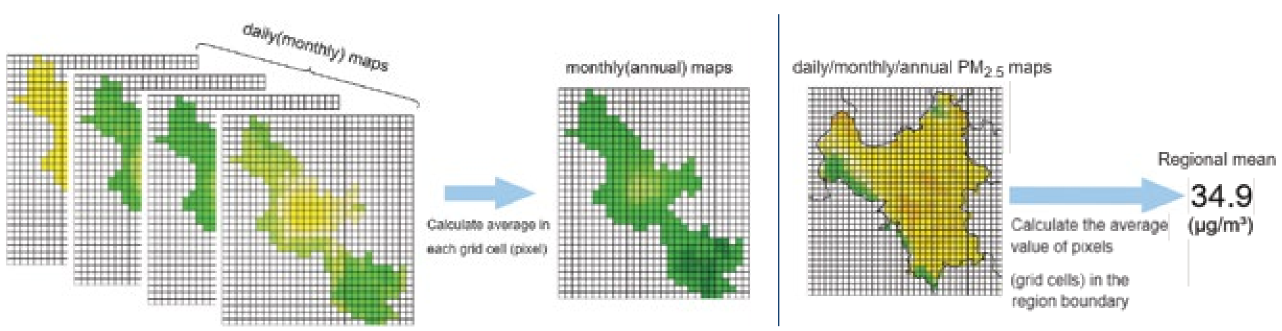
Figure 67. Method of developing $PM_{2.5}$ maps in Vietnam

A3. Method of calculating monthly/annual average and mean of province, city/district

To calculate a monthly average $PM_{2.5}$ maps, the daily maps were aggregated by month. Then, the $PM_{2.5}$ concentration value of each grid cell of a monthly map was averaged from all the corresponding pixel values at the same location in the daily maps in this month (Figure 68a)

The annual average $PM_{2.5}$ map was calculated from 12 monthly maps available in that year. The method of calculating for each pixel is similar to the monthly map (Figure 68a).

The daily, monthly, or annual means of a province/city (district) was averaged all grid cells falling in the boundary of this province/city (district) (Figure 68b)



a) b)

Figure 68. Example of calculate daily (monthly, annual) mean $PM_{2.5}$ maps (a) and province (district) average $PM_{2.5}$ maps (b)

A4. Method of calculating $PM_{2.5}$ exposure (population weighted $PM_{2.5}$)

The $PM_{2.5}$ population-weighted is defined as the average exposure of the population of an area (e.g. country, province, district) to the $PM_{2.5}$ (particles with aerodynamic diameters. less than or equal to 2.5 µm), according to the following formula[60]:

$$PWEL = \frac{\sum P_i . C_i}{\sum P_i}$$

In which:

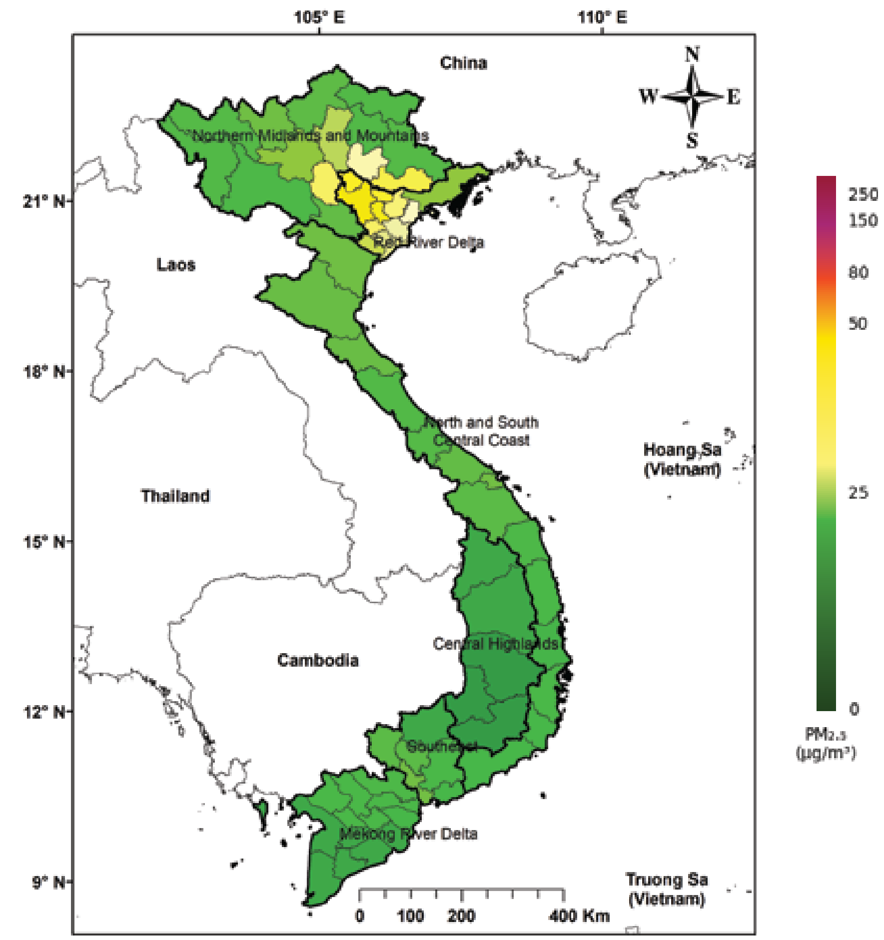


Figure 69. The population-weighted $PM_{2.5}$ at provincial level in 2021

PWEL: population-weighted $PM_{2.5}$

P_i: Number of people in a unit area (i[th] grid cell).

C_i: Annual mean $PM_{2.5}$ concentration in the corresponding unit area (i[th] grid cell)

The indicator at each grid cell is calculated by multiplying the $PM_{2.5}$ concentration (C_i) with the population (P_i) respectively in that grid cell and dividing it by the total population ($\sum P_i$) of the whole area. The PWEL index for a region (province/city, district/district) is calculated as the sum of all indicators of the grid cells located within that region.

[60] Brauer, M., 2017

A5. List of difference urban types

According to Resolution 1210/2016/UBTVQH13 on Urban classification[61], the criteria for different urban types are presented in table 5.

Table 5. Criteria for each urban type according to Resolution 1210/2016/UBTVQH13

Criterion	Special	Type I	Type II	Type III	Type IV	Type V
Location, function, role	Serves as the capital or general center of national and international level in economy, finance, culture, education, training, tourism, health, science and technology, transport hub and exchange in the country. national and international, play a role in promoting the socio-economic development of the whole country	Serves as a national, regional or provincial general center for economy, finance, culture, education, training, tourism, health, science and technology, transport hub and exchange in the country. national and international, has a role in promoting the socio-economic development of an inter-provincial region or the whole country	Serves as a general center or specialized center at regional or provincial level in economy, finance, culture, education, training, tourism, health, science and technology, provincial administrative center, a traffic hub that plays a role in promoting the socio-economic development of a province or an inter-provincial region	Serves as a general or specialized center for economy, finance, culture, education, training, tourism, health, science and technology at provincial level, as a traffic hub, with the role of promoting socio-economic development of the province and inter-provincial regions	Serves as a general or specialized center for economy, finance, culture, education, training, tourism, health, science and technology at provincial level, as a traffic hub, with the role of promoting socio-economic development of the province and inter-provincial regions	Serves as an administrative center or general center at district level or a district-level specialized center for economy, culture, education, training, traffic hub, which plays a role in promoting socio-economic development. of the district or inter-commune cluster
Structure and level of socio-economic develop-ment	Refer to Appendix 1 of this Decree					
Popula-tion size	Whole area: ≥ 5 million people Inner area: ≥ 3 million people	**For central cities:** Whole area: ≥ 1 million people Inner area: ≥ 500 thousand people **For cities that are a part of central cities:** Whole area: ≥ 500 thousand people Inner area: ≥ 200 thousand people	Whole area: ≥ 200 thousand people Inner area: ≥ 100 thousand people	Whole area: ≥ 100 thousand people Inner area: ≥ 50 thousand people	Whole area: ≥ 50 thousand people Inner area (if applicable): ≥ 20 thousand people	Whole area: ≥ 4 thousand people
Popula-tion density	Whole area: ≥ 3000 people/km² Inner area: ≥ 12000 people/km²	Whole area: ≥ 3000 people/km² Inner area: ≥ 12000 people/km²	Whole area: ≥ 2000 people/km² Inner area: ≥ 10000 people/km²	Whole area: ≥ 1800 people/km² Inner area: ≥ 8000 people/km²	Whole area: ≥ 1400 people/km² Inner area: ≥ 7000 people/km²	Whole area: ≥ 1200 people/km² Inner area: ≥ 6000 people/km²
Percent age of non-agri cultural labor	Whole area: ≥ 70% Inner area: ≥ 90%	Whole area: ≥ 65% Inner area: ≥ 85%	Whole area: ≥ 65% Inner area: ≥ 80%	Whole area: ≥ 60% Inner area: ≥ 75%	Whole area: ≥ 55% Inner area: ≥ 70%	Whole area: ≥ 55%
Level of infrastruct ure and urban landscape develop-ment	Refer to Appendix 1 of this Decree					

[61] Vietnam National Assembly Standing Committee, 2016

The urban list was referred from the Wikipedia, a public open source.

Special type: Municipality: Ha Noi, Ho Chi Minh city.

Type I: Municipality: Hai Phong, Da Nang, Can Tho. **Provincial city:** Hue (Thua Thien - Hue), Vinh (Nghe An), Da Lat (Lam Dong), Nha Trang (Khanh Hoa), Quy Nhon (Binh Dinh), Buon Ma Thuot (Dak Lak), Thai Nguyen (Thai Nguyen), Nam Dinh (Nam Dinh), Viet Tri (Phu Tho), Vung Tau (Ba Ria - Vung Tau), Ha Long (Quang Ninh), Thanh Hoa (Thanh Hoa), Bien Hoa (Dong Nai), My Tho (Tien Giang), Thu Dau Mot (Binh Duong), Bac Ninh (Bac Ninh), Hai Duong (Hai Duong), Pleiku (Gia Lai), Long Xuyen (An Giang).

Type II: City: Phan Thiet (Binh Thuan), Ca Mau (Ca Mau), Tuy Hoa (Phu Yen), Uong Bi (Quang Ninh), Thai Binh (Thai Binh), Rach Gia (Kien Giang), Bac Lieu (Bac Lieu), Ninh Binh (Ninh Binh), Dong Hoi (Quang Binh), Phu Quoc (Kien Giang), Vinh Yen (Vinh Phuc), Lao Cai (Lao Cai), Ba Ria (Ba Ria - Vung Tau), Bac Giang (Bac Giang), Phan Rang - Thap Cham (Ninh Thuan), Chau Doc (An Giang), Cam Pha (Quang Ninh), Quang Ngai (Quang Ngai), Tam Ky (Quang Nam), Tra Vinh (Tra Vinh), Sa Dec (Dong Nai), Mong Cai (Quang Ninh), Phu Ly (Ha Nam), Ben Tre (Ben Tre), Ha Tinh (Ha Tinh), Lang Son (Lang Son), Son La (Son La), Tan An (Long An), Vi Thanh (Hau Giang), Cao Lanh (Dong Thap), Vinh Long (Vinh Long), Tuyen Quang (Tuyen Quang), Soc Trang (Soc Trang).

Type III: City: Yen Bai (Yen Bai), Dien Bien Phu (Dien Bien), Hoa Binh (Hoa Binh), Hoi An (Quang Nam), Hung Yen (Hung Yen), Kon Tum (Dak Lak), Dong Ha (Quang Tri), Bao Loc (Lam Dong), Ha Giang (Ha Giang), Cam Ranh (Khanh Hoa), Cao Bang (Cao Bang), Lai Chau (Lai Chau), Tay Ninh (Tay Ninh), Bac Kan (Bac Kan), Tam Diep (Ninh Binh), Song Cong (Thai Nguyen), Sam Son (Thanh Hoa), Phuc Yen (Vinh Phuc), Ha Tien (Kien Giang), Dong Xoai (Binh Phuoc), Chi Linh (Hai Duong), Long Khanh (Dong Nai), Gia Nghia (Dak Nong), Di An (Binh Duong), Nga Bay (Hau Giang), Thuan An (Binh Duong), Hong Ngu (Dong Thap), Tu Son (Bac Ninh), Pho Yen (Thai Nguyen). **Town:** Son Tay (Ha Noi), Cua Lo (Nghe An), Phu Tho (Phu Tho), Bim Son (Thanh Hoa), Go Cong (Tien Giang), La Gi (Binh Thuan), Ben Cat (Binh Duong), Tan Uyen (Binh Duong), Song Cau (Phu Yen), Long My (Hau Giang), Tan Chau (An Giang), Cai Lay (Tien Giang), Quang Yên (Quang Ninh), Ky Anh (Ha Tinh), Binh Minh (Vinh Long), Đong Trieu (Quang Ninh), Phu My (Ba Ria – Vung Tau), An Nhon (Bình Định).

Type IV: Town: Muong Lay (Dien Bien), Quang Tri (Quang Tri), Hong Linh (Ha Tinh), Nghia Lo (Yen Bai), An Khe (Gia Lai), Ayun Pa (Gia Lai), Thai Hoa (Nghe An), Buon Ho (Dak Lak), Binh Long (Binh Phuoc), Phuoc Long (Binh Phuoc), Huong Thuy (Thua Thien Hue), Ninh Hoa (Khanh Hoa), Vinh Chau (Soc Trang), Huong Tra (Thua Thien Hue), Kien Tuong (Long An), Hoang Mai (Nghe An), Ba Don (Quang Binh), Nga Nam (Soc Trang), Dien Ban (Quang Nam), Gia Rai (Nghe An), Duyen Hai (Tra Vinh), My Hao (Hung Yen), Kinh Mon (Hai Duong), Sa Pa (Lao Cai), Duy Tien (Ha Nam), Duc Pho (Quang Ngai), Hoa Thanh (Tay Ninh), Trang Bang (Tay Ninh), Dong Hoa Phu Yen), Hoai Nhon (Binh Dinh), Nghi Son (Thanh Hoa), Chon Thanh (Binh Phuoc). **District:** Tinh Bien (An Giang), Thuan Thanh (Bac Ninh), Dien Khanh (Khanh Hoa), Viet Yen (Bac Giang), Nui Thanh (Quang Nam), Que Vo (Bac Ninh). **Township:** Nui Sap, Phu My, Cho Moi, An Chau, Cai Dau, Tri Ton (An Giang); Thang, Chu, Doi Ngo (Bac Giang); Ba Tri, Binh Dai, Mo Cay (Ben Tre); Phu Phong (Binh Dinh); Phan Ri Cua (Binh Thuan); Nam Can, Song Doc (Ca Mau); Ea Kar, Buon Trap, Phuoc An, Ea Drang, Quang Phu (Dak Lak); Dak Mil, Ea T'ling, Kien Duc (Dak Nong); Long Thanh, Trang Bom (Dong Nai); My An, Lap Vo, My Tho (Dong Thap); Chu Se (Gia Lai); Viet Quang (Ha Giang); Luong Son (Hoa Binh); Nhu Quynh (Hung Yen); Van Gia (Khanh Hoa); Kien Luong (Kien Giang); Plei Kan (Kon Tum); Dong Dang (Lang Son); Lien Nghia (Lam Dong); Ben Luc, Hau Nghia, Duc Hoa, Can Duoc, Can Giuoc (Long An); Thing Long (Nam Dinh); Hoan Lao, Kien Giang (Quang Binh); Cai Rong, Tien Yen, Quang Ha (Quang Ninh); Hat Lot, Moc Chau (Son La); Lam Son - Sao Vang, Ngoc Lac (Thanh Hoa); Diem Dien (Thai Binh); Hung Son (Thai Nguyen); Tieu Can (Tra Vinh).

A6. Method to assess the impact of social distancing due to the COVID-19 epidemic on air quality

The method to assess the impact of social distancing due to the COVID-19 epidemic on $PM_{2.5}$ pollution levels in this report was derived from the study of Truong et al.[62]. This study made the assessment by providing air quality estimates under normal conditions (with natural meteorological conditions and without the effects of social distancing). The estimated data was then compared with the actual data during the social distancing period, to analyze the change in air quality during this period.

The data include:

- Meteorology data measured at UWYO stations located at Nguyen Khang street, Hanoi and Tan Son Nhat airport, Ho Chi Minh city. Indicators include temperature, relative humidity, barometric pressure, wind speed and direction, and visibility. The data were collected between 2019 and 2021, in order to highlight the differences in air quality over different time periods (normal social conditions - 2019, social distancing - 2021). The measured data were aggregated into hourly average and then daily average.
- The daily $PM_{2.5}$ maps with spatial resolution of 3x3km between 2019 and 2021. For each day, the value of the grid cell where UWYO station located was extracted from the maps. Daily $PM_{2.5}$ data were used for modeling and evaluation.

The above datasets were integrated with each other according space (map data and station data were matched at the station locations) and time (daily data of the maps and stations were matched). Each station was developed a separate machine learning model to estimate $PM_{2.5}$ concentration from meteorological parameters. The Random Forest model was used, with the hyper-parameters of all the models being set the same. The 2019 data of each station were used to train the models. Then, the model used meteorological data measured in 2021 to predict the $PM_{2.5}$ under normal weather conditions during the period of 2021. The quality of model at each station is shown in Table 6.

Table 6. Results of model evaluation at UWYO stations in Hanoi and Ho Chi Minh City

UWYO station	R^2	RMSE (µg/m³)	MRE (%)
Nguyen Khang street – Ha Noi	0.96	3.94	6.9
Tan Son Nhat airport – Ho Chi Minh city	0.92	2.86	9.3

[62] Truong et al., 2020

APPENDIX B. $PM_{2.5}$ MAP VALIDATION

B1. Validating the quality of $PM_{2.5}$ concentration maps

The $PM_{2.5}$ maps were compared with $PM_{2.5}$ recorded at 65 ground stations during 2019 - 2021. The integration process of $PM_{2.5}$ maps and ground $PM_{2.5}$ measurements was subject to spatial and temporal constraints:

- Spatial constraints: extracting data on the map at the location where the ground station was located. The measured $PM_{2.5}$ value at station is compared with the extracted $PM_{2.5}$ value of the 3x3km area (grid cell) on the map.
- Time constraints: $PM_{2.5}$ from maps and ground stations were calculated on a daily, monthly, annual averages for comparison.

The monthly average from station data was calculated from the daily average if 50% of the daily data in that month was available. Annual average of station data was calculated from monthly average with at least 6 monthly average data available (50%).

Statistical parameters used to compare $PM_{2.5}$ concentrations estimated from the maps and corresponding $PM_{2.5}$ measured at the station include Pearson correlation coefficient r, coefficient of determination R^2, Root Mean Square Error (RMSE) and Mean Relative Error (MRE)[63].

B2. $PM_{2.5}$ maps validation results

In 2021, comparison between daily $PM_{2.5}$ from maps and ground stations had the following results: Pearson r reached 0.77, coefficient R^2 reached 0.6, RMSE reached 16.7 µg/m³, and MRE reached 58.3%. However, these evaluation results varied by station (Appendix B, Figure 70). The stations used to collect data for constructing the MEM and evaluation are most located in Hanoi, Bac Ninh, Quang Ninh, Hai Duong in the North and in Ho Chi Minh City in the South. The evaluation results had shown that the $PM_{2.5}$ maps had high correlation with data at stations in Hanoi and Bac Ninh (almost $R^2 > 0.7$), low correlation with data at stations in Can Tho, Gia Lai, Son La, Ho Chi Minh city ($R^2 < 0.1$). The relative errors (MRE) were low at some stations in Hanoi, Bac Ninh, and Ho Chi Minh (MRE < 30%) and very high at some stations in Quang Ninh, Hai Duong, Nghe An (MRE > 100%). The low validation results may attribute to not only the estimation model's quality but also data quality at those stations, which needs further and deeper investigation.

The monthly $PM_{2.5}$ maps were compared with data at 62 monitoring stations nationwide in 2021. The overall evaluation includes a Pearson r correlation of 0.77, R^2 coefficient of 0.6, RMSE of 13.4 µg/m³, and MRE of 43.1%. The validation results also varied from station to station. The monthly $PM_{2.5}$ map had low absolute errors with RMSE < 5 µg/m³ at different stations located in provinces and cities over the country such as Lang Son, Hai Duong, Hanoi, Bac Ninh, Gia Lai, Ho Chi Minh, Da Nang, ... but high RMSE (> 30 µg/m³) at some stations in Bac Ninh, Hai Duong, and Cao Bang. The map had relatively low MRE (<10%) in Hanoi, Bac Ninh, Ho Chi Minh and high error (MRE > 100%) appears at some stations in Quang Ninh and Hai Duong (Appendix B, Figure 71).

[63] Thanh T.N. Nguyen et al, 2022 ; Truong X Ngo et al., 2022

In Hanoi, Bac Ninh, and Ho Chi Minh, the monthly average $PM_{2.5}$ was compared with monitoring stations during the period of 2019-2021 (Appendix B, Figure 72). In January 2021, the $PM_{2.5}$ concentration was unusually higher than those in the previous year, which can be observed on both $PM_{2.5}$ map data and monitoring stations data.

The annual $PM_{2.5}$ map in 2021 was compared with the annual average $PM_{2.5}$ at 37 monitoring stations nationwide (Appendix B, Figure 73). The overall results includes coefficient of determination R^2 of 0.4, RMSE of 9.78 µg/m³ and MRE of 29.15%. The 2021 annual map tended to underestimate in comparison with corresponding data at stations in Hanoi and Bac Ninh and overestimate at stations in Quang Ninh. Stations in Cao Bang, Lang Son, Thai Nguyen had large errors between estimated and measured $PM_{2.5}$ values. Moderate errors was observed at stations in Quang Ninh, while low errors were occurred at the remained stations .

In addition, the annual and monthly average $PM_{2.5}$ maps in 2019, 2020, 2021 of our research team were compared with the corresponding global maps of Van Donkelaar et al[64]. The method applied by Van Donkelaar et al was used to develop the $PM_{2.5}$ exposure map for the Global Burden of Disease - GBD in 2010, 2013, 2015[65]. Annual and monthly mean datasets of 2019 - 2021 were compared with ground stations. The results showed that our annual and monthly average maps had better quality, which was reflected in the higher coefficient of determination and smaller error (Table 7).

Table 7. Validation results of monthly/annual $PM_{2.5}$ maps with ground stations from our research team and global product

	Year	Number of samples	Our $PM_{2.5}$ maps				The global $PM_{2.5}$ product			
			R^2	Pearson r	RMSE	MRE	R^2	Pearson r	RMSE	MRE
Monthly maps	2019	65	0.81	0.9	7.68	26.14	0.69	0.83	9.3	29.78
	2020	321	0.62	0.79	10.67	34.55	0.44	0.66	13.11	48.06
	2021	447	0.6	0.77	13.43	43.14	Not published			
Annual Maps	2019	5	0.9	0.95	4.32	10.98	0.75	0.87	4.72	14.21
	2020	29	0.5	0.71	8.79	30.76	0.49	0.7	9.42	37.19
	2021	37	0.4	0.63	9.78	29.15	Not published			

Our $PM_{2.5}$ concentration map nationwide[66] was applied to assess the impact of $PM_{2.5}$ on public health[67] and developed an environmental performance index for provinces[68]. These results are being reviewed[69] and have been published in ISI journals (SCIE Q1)[70].

[64] Donkelaar et al., 2021
[65] Donkelaar et al., 2021
[66, 69] Thanh T.N. Nguyen et al, 2022 ; Truong X Ngo et al., 2022
[67] N.T.T.Nguyen et al., 2022
[68] T. T. A. Nguyen, 2022
[70] N.T.T.Nguyen et al., 2022; T. T. A. Nguyen, 2022

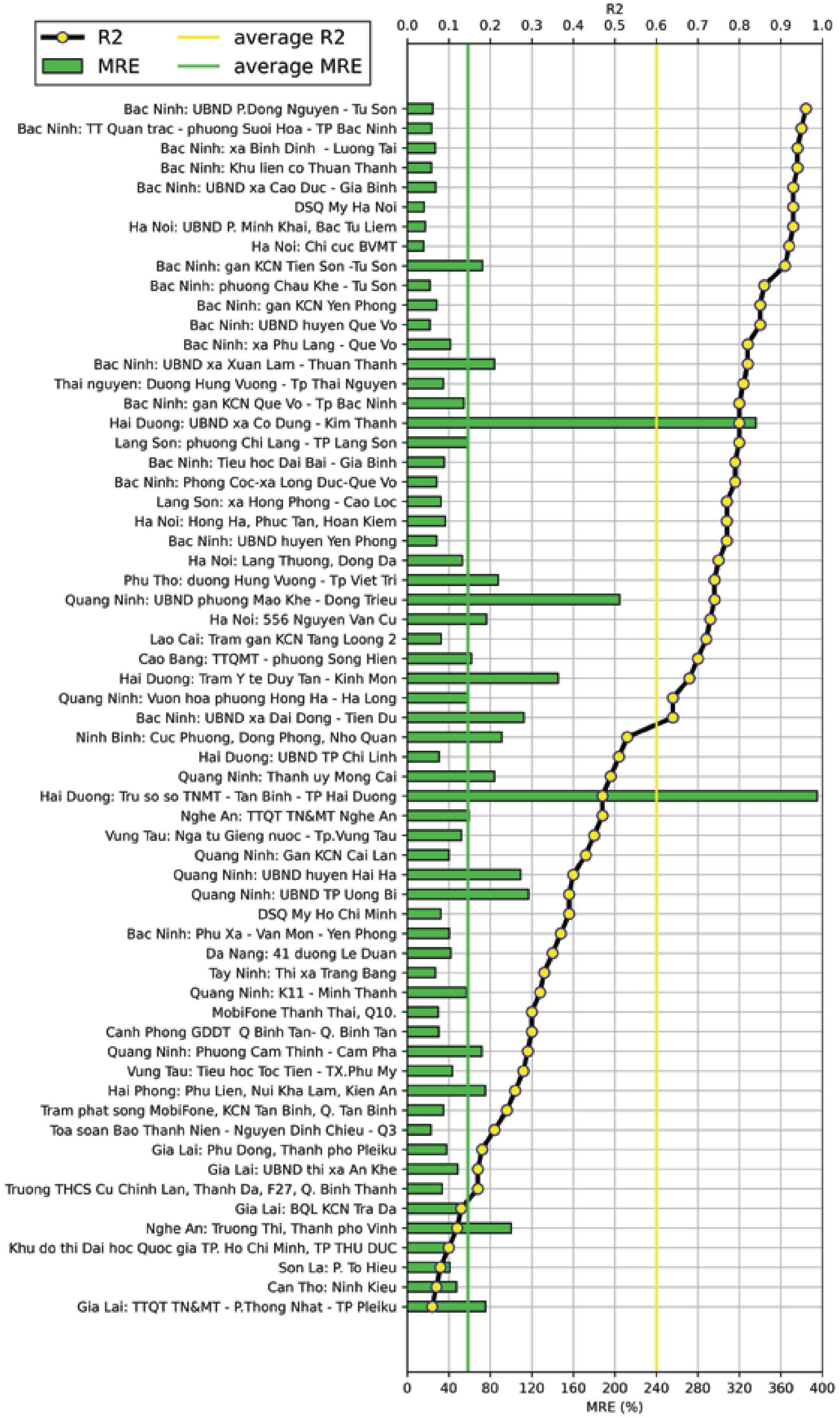


Figure 70. Validation results of daily $PM_{2.5}$ maps at each station in Vietnam in 2021

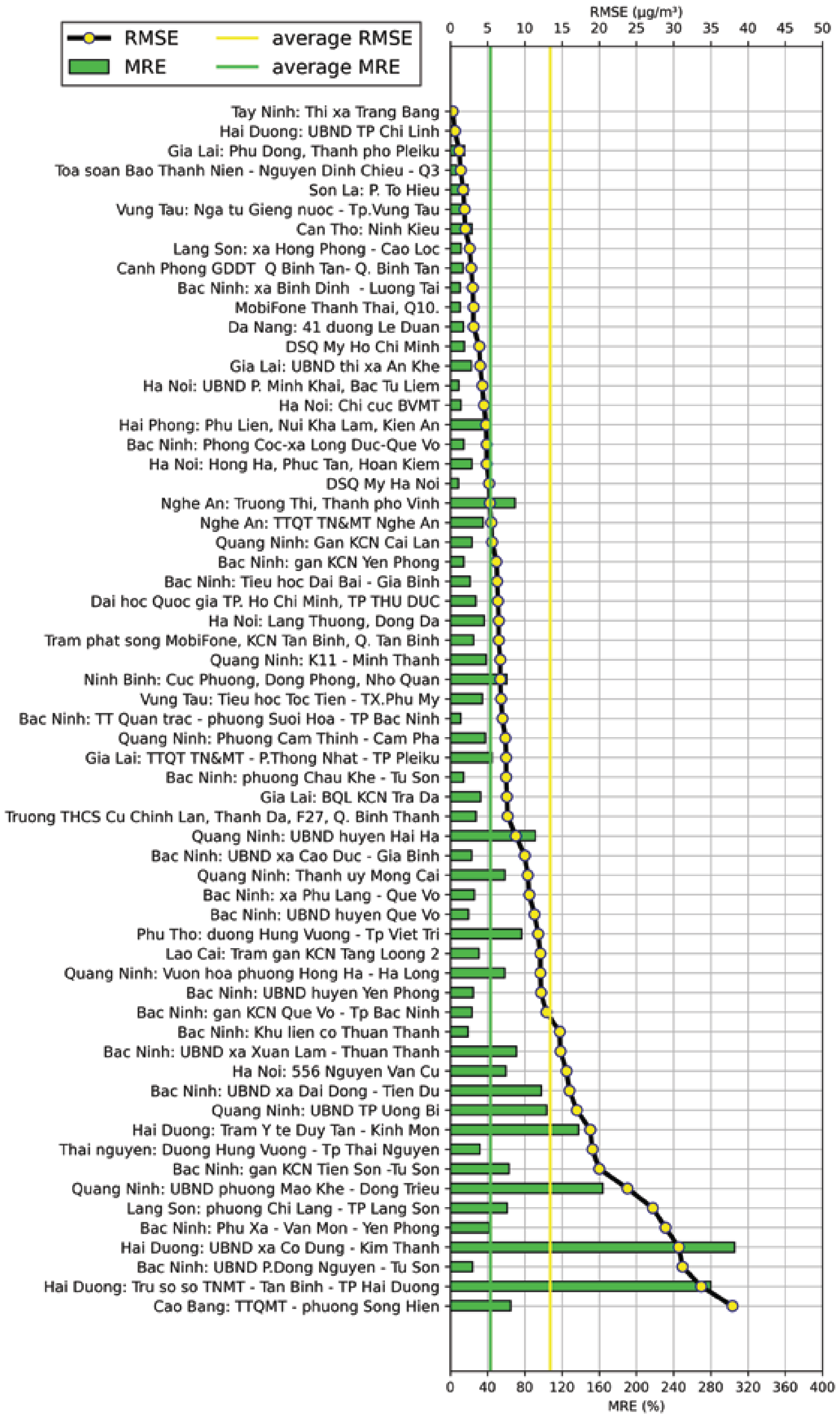


Figure 71. Validation results of monthly $PM_{2.5}$ maps at each station in Vietnam in 2021

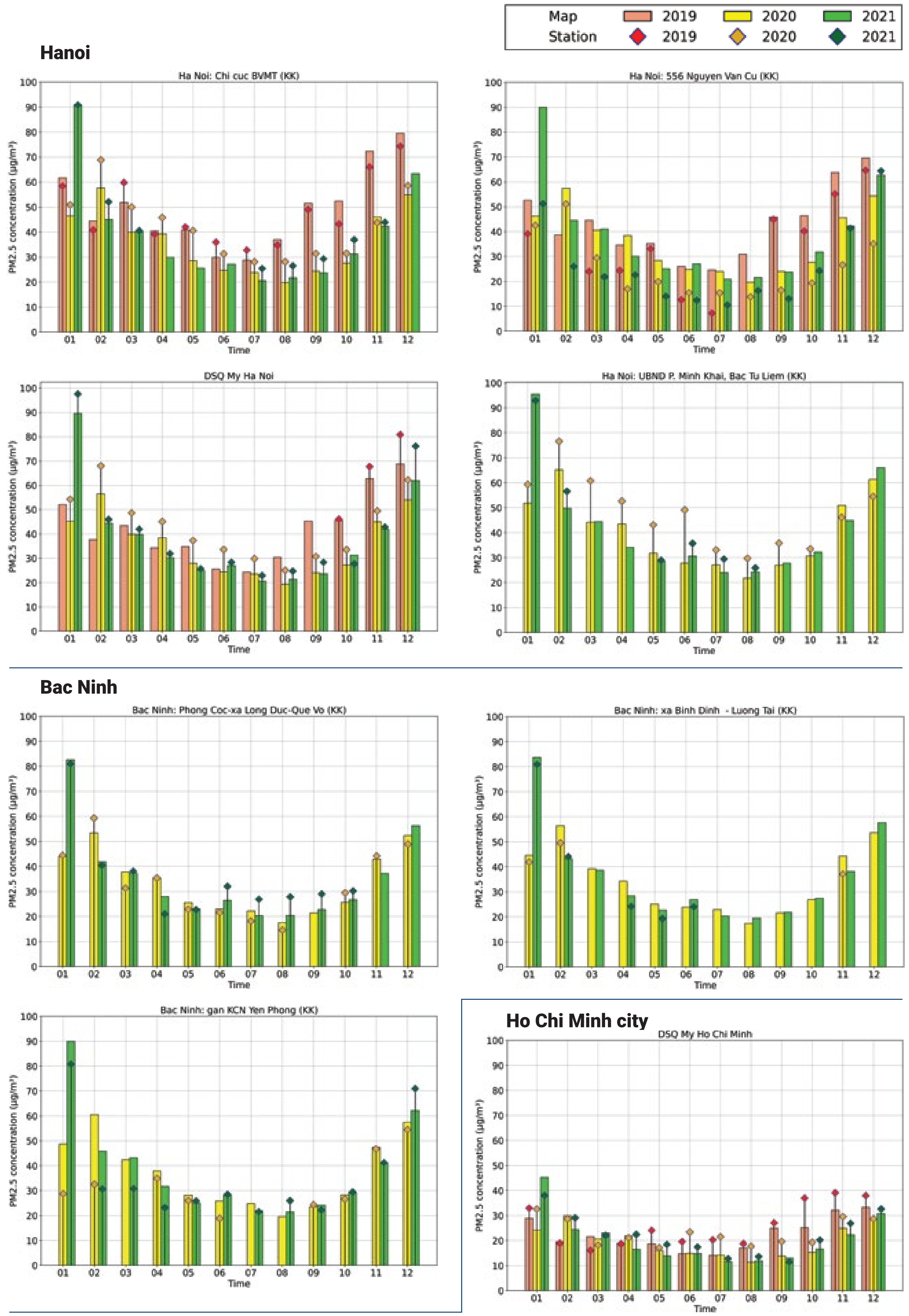


Figure 72. Comparison results of monthly $PM_{2.5}$ maps with stations in some provinces/cities in 2021

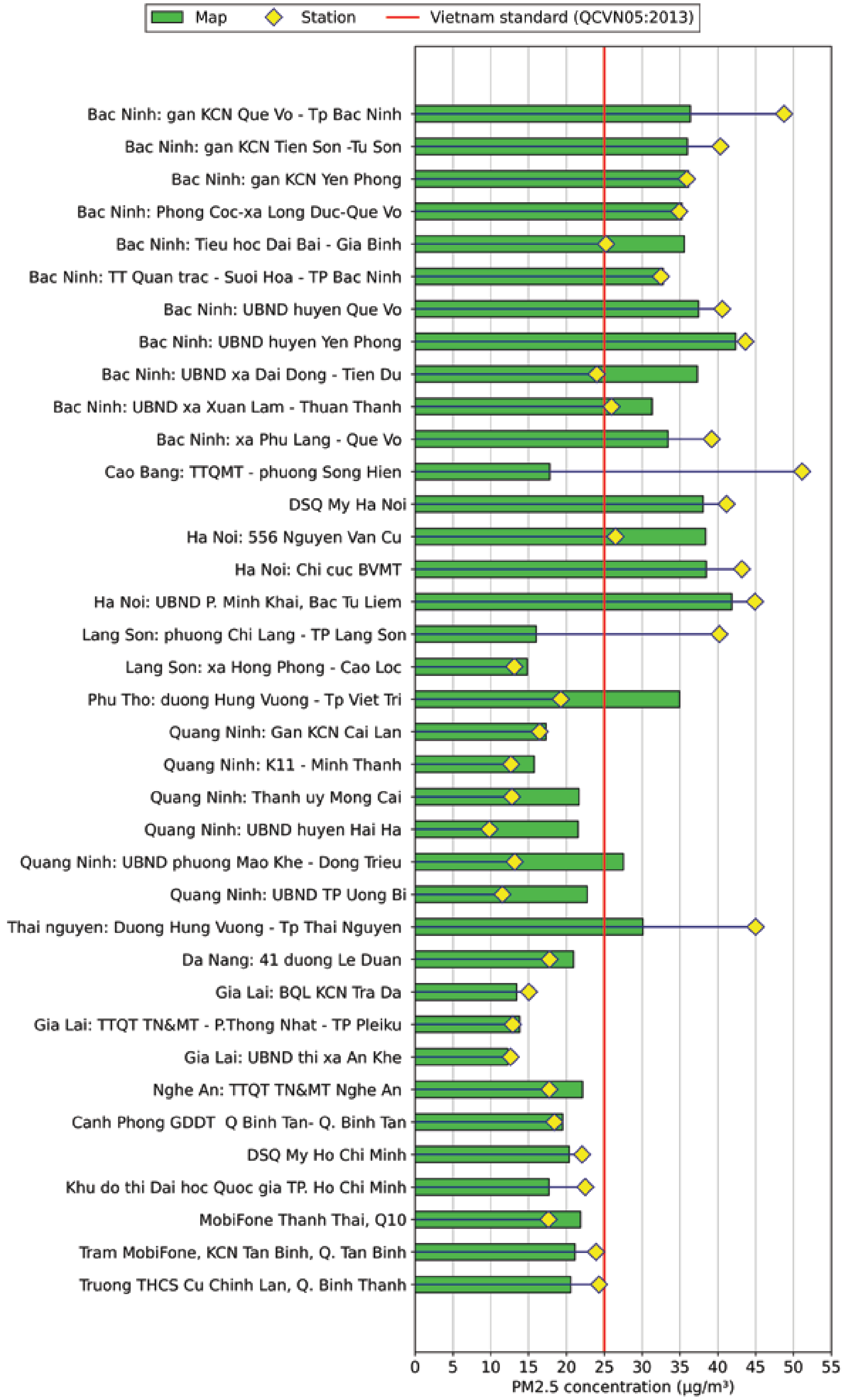


Figure 73. Comparison results of annual $PM_{2.5}$ map at each station in Vietnam in 2021

APPENDIX C. $PM_{2.5}$ CONCENTRATION/EXPOSURE IN SEVERAL PROVINCES/CITIES

Table 8. $PM_{2.5}$ mean/population weighted of provinces/cities in Vietnam in 2021

Region	Province	Annual mean in 2021	$PM_{2.5}$ exposure (Population Weighted)
Northern Midlands and Mountains	Phu Tho	23.0	29.6
	Bac Giang	22.3	30.2
	Thai Nguyen	19.8	25.7
	Tuyen Quang	18.0	21.9
	Yen Bai	17.0	20.2
	Lao Cai	16.3	18.6
	Ha Giang	16.0	16.6
	Lai Chau	15.2	15.7
	Hoa Binh	15.0	16.7
	Cao Bang	14.7	15.3
	Đien Bien	14.6	15.3
	Bac Kan	14.5	15.1
	Lang Son	14.4	15.4
	Son La	14.2	14.7
Red River Delta	Ha Noi	34.9	37.8
	Bac Ninh	34.4	34.8
	Hung Yen	31.9	32.2
	Vinh Phuc	29.7	35.1
	Ha Nam	27.9	29.4
	Hai Duong	27.5	28.6
	Thai Binh	24.4	24.7
	Nam Đinh	23.8	24.3
	Hai Phong	22.7	24.8
	Ninh Binh	20.5	22.6
	Quang Ninh	16.6	20.1
Central Highlands	Gia Lai	11.9	12.5
	Kon Tum	11.8	12.6
	Dak Lak	11.8	12.0
	Dak Nong	11.5	11.8
	Lam Đong	11.4	12.1

Region	Province	Annual mean in 2021	$PM_{2.5}$ exposure (Population Weighted)
North and South-Central Coast	Thanh Hoa	15.4	18.9
	Ha Tinh	15.0	17.7
	Nghe An	13.9	17.7
	Đa Nang	13.8	19.3
	Thua Thien Hue	13.5	17.0
	Quang Tri	13.3	15.4
	Quang Binh	12.9	15.3
	Quang Ngai	12.7	14.7
	Quang Nam	12.7	15.8
	Binh Dịnh	12.2	13.9
	Khanh Hoa	12.2	13.9
	Binh Thuan	12.1	13.2
	Ninh Thuan	11.9	13.5
	Phu Yen	11.7	13.0
Southeast	Ho Chi Minh	15.4	19.3
	Tay Ninh	14.9	15.9
	Binh Duong	13.5	15.8
	Dong Nai	12.7	14.3
	Ba Ria - Vung Tau	12.5	13.3
	Binh Phuoc	12.3	12.6
	Long An	14.5	14.6
	Dong Thap	14.1	14.3
	Tien Giang	13.9	14.2
	Vinh Long	13.5	13.8
	An Giang	13.3	13.8
Mekong River Delta	Can Tho	13.0	13.9
	Ben Tre	13.0	13.1
	Bac Lieu	12.6	12.6
	Hau Giang	12.6	12.6
	Tra Vinh	12.5	12.5
	Kien Giang	12.3	12.5
	Ca Mau	12.2	12.4
	Soc Trang	12.2	12.2

Table 9. $PM_{2.5}$ mean/population weighted of districts in some provinces/cities in 2021

Province /City	District	Annual mean in 2021	$PM_{2.5}$ exposure (Population Weighted)
Hanoi	Ung Hoa	37.9	37.9
	Bac Tu Liem	39.7	39.7
	Ba Dinh	36.2	36.1
	Ba Vi	28.9	33.0
	Cau Giay	40.3	40.0
	Chuong My	37.8	38.7
	Dong Da	37.2	37.1
	Dan Phuong	36.2	35.9
	Dong Anh	37.0	36.8
	Gia Lam	35.0	35.5
	Ha Dong	39.9	40.7
	Hai Ba Trung	38.1	38.2
	Hoai Đuc	38.6	39.2
	Hoan Kiem	37.9	37.1
	Hoang Mai	39.0	39.7
	Long Bien	38.1	37.7
	My Đuc	29.9	33.9
	Me Linh	37.7	37.7
	Nam Tu Liem	43.0	42.9
	Phu Xuyen	36.1	35.9
	Phuc Tho	36.1	35.9
	Quoc Oai	33.0	36.1
	Soc Son	34.0	37.4
	Son Tay	31.7	33.8
	Tay Ho	38.8	39.0
	Thach That	29.1	34.3
	Thanh Oai	40.6	40.9
	Thanh Tri	38.9	39.7
	Thanh Xuan	41.4	41.2
	Thuong Tin	39.0	39.0
Bac Ninh	Bac Ninh	34.0	34.3
	Gia Binh	32.8	32.8
	Luong Tai	31.9	31.9
	Que Vo	34.2	34.5
	Tu Son	37.6	37.5
	Thuan Thanh	33.5	33.6
	Tien Du	34.1	34.2
	Yen Phong	39.2	39.2
Thai Binh	Dong Hung	25.4	25.5
	Hung Ha	28.2	28.2
	Kien Xuong	23.2	23.3
	Quynh Phu	25.3	25.2
	Thai Binh	26.0	26.1
	Thai Thuy	21.7	21.6
	Tien Hai	20.7	20.8
	Vu Thu	26.8	26.7
Nghe An	Anh Son	15.3	16.2
	Cua Lo	18.4	18.4
	Con Cuong	12.8	13.6
	Dien Chau	18.1	19.1
	Do Luong	181	19.0
	Hoang Mai	15.8	16.7
	Hung Nguyen	19.8	20.5
	Ky Son	12.7	12.8
	Nam Dan	18.9	20.2
	Nghi Loc	17.2	18.2
	Nghia Dan	14.1	14.3
	Que Phong	12.3	12.7
	Quy Chau	12.6	13.1
	Quy Hop	13.2	13.9
	Quynh Luu	15.8	17.4
	Tan Ky	14.6	15.1
	Thai Hoa	14.3	14.5
	Thanh Chuong	15.5	17.8
	Tuong Duong	12.8	13.2
	Vinh	21.1	21.5
	Yen Thanh	16.9	19.1
Ho Chi Minh city	Binh Chanh	15.6	16.3
	Binh Tan	18.9	19.6
	Binh Thanh	20.3	20.5
	Can Gio	12.9	13.2
	Cu Chi	15.0	15.2
	Gò Vap	20.0	20.1
	Hoc Mon	16.7	17.4
	Nha Be	15.0	15.3
	Phu Nhuan	21.1	21.2
	Dictrict 1	20.8	20.9
	Dictrict 10	21.3	21.3
	Dictrict 11	21.2	21.2
	Dictrict 12	19.2	19.3
	Dictrict 2	18.3	18.5
	Dictrict 3	21.2	21.2
	Dictrict 4	20.5	20.5
	Dictrict 5	20.9	20.9
	Dictrict 6	20.5	20.5
	Dictrict 7	18.0	18.3
	Dictrict 8	18.8	19.5
	Dictrict 9	16.7	17.2
	Tan Binh	21.2	21.5
	Tan Phu	21.1	21.3
	Thu Duc	18.8	18.7