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Quantifying the Contribution of Road Traffic to Total Suspended Particle Pollution in Dong Thap Province, Vietnam

Tran Anh Quan[1] & Nguyen Thi Hong Ngoc[2*]

[1]Faculty of Environment, Hanoi University of Mining and Geology, Hanoi 11909, Vietnam

[2]Faculty of Natural Resources and Environment, Vietnam National University of Agriculture, Hanoi 12400, Vietnam

Abstract

Total suspended particles (TSP) from transportation sources pose a growing environmental and public health concern in rapidly developing regions like Vietnam's Mekong Delta. This study investigated TSP emissions and dispersion patterns in Dong Thap province, an area undergoing significant economic transformation. Using the AERMOD air quality model integrated with R-LINE, we simulated TSP dispersion from 43 major roads divided into 88 segments. The model incorporated high-resolution ERA5 meteorological data from 2021-2023, Vietnam-specific emission factors, and detailed traffic data for eight vehicle categories. The results revealed significant spatial and temporal variations in TSP concentrations. In extreme scenarios, TSP levels in urban centers like Cao Lanh city reached up to 1,100 μg m^{-3} for 1-hour averages and 350 μg m^{-3} for 24-hour averages, substantially exceeding national standards. Annual average TSP concentrations in urban areas approached or potentially exceeded the 100 μg m^{-3} national standard, even when considering only transportation sources. The region's flat terrain facilitated long-range TSP transport, with concentrations up to 100 μg m^{-3} detected beyond provincial borders under extreme scenarios. Atmospheric stability strongly influenced TSP dispersion, with very stable conditions contributing to elevated TSP levels. The study highlights the critical need for targeted air quality management in Dong Thap, particularly in urban areas and along major transportation routes.

Keywords

Aermod, Dong Thap, air pollution, transportation, TSP

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Correspondence to
Nguyen Thi Hong Ngoc
ntnngoc@vnua.edu.vn

Introduction

Dong Thap province, situated in the center of Vietnam's Mekong Delta, exemplifies the complex interplay between rapid economic development and mounting environmental concerns. Renowned for its agricultural productivity, particularly in rice and aquaculture, this gateway to the Long Xuyen Quadrangle has been undergoing a significant transformation. Dong Thap's industrial parks have expanded from one in 1998 to four in 2024, with five more planned by 2030. As the region evolves, the environmental impact of increased transportation activities, especially the emission of total suspended particles (TSP), has emerged as a critical issue demanding urgent attention and comprehensive study. The strategic location of Dong Thap within the greater Mekong subregion has accelerated its economic growth, leading to intensified industrialization and transportation activities. This transition, while economically beneficial, has resulted in a concerning rise in air pollutants, with TSP being of particular significance due to its wide-ranging impacts on human health and the environment (Carruthers *et al*., 2011; Hoinaski *et al*., 2017; Akomolafe *et al*., 2024)

Recent studies across Southeast Asia have highlighted the growing contribution of transportation to air pollution in developing regions. In Vietnam's urban and peri-urban areas, vehicular emissions have been found to account for up to 60% of the total particulate matter in the air (Huu & Ngoc, 2021). The Mekong Delta, including Dong Thap, faces unique air quality challenges due to the rapid expansion of transportation infrastructure and vehicle usage (Nguyen & Phan, 2019; Huy *et al*., 2023). Similar trends have been observed in other Southeast Asian countries, such as Thailand (Reddington *et al*, 2019; Chantaraprachoom *et al*., 2023; Thanatrakolsri & Sirithian, 2024), underscoring the regional nature of this issue.

TSP pollution is crucial due to its comprehensive nature, encompassing a wide range of airborne particles, including those small enough to penetrate deep into the respiratory system. In Dong Thap's mixed rural and increasingly urban landscape, understanding the specific contribution of transportation emissions to TSP levels is vital for effective environmental management and public health protection (Cimorelli, 2005; Phung *et al.*, 2016). Studies have shown significant risks to respiratory and cardiovascular health associated with particulate matter exposure in Asian countries (Carruthers *et al*., 2011; Adeniran *et al*., 2023). Moreover, the economic implications of air pollution are substantial, with global costs estimated in the trillions of dollars annually due to lost productivity and healthcare expenses (Hoinaski *et al*., 2017; Adeniran *et al*., 2023). Atmospheric pollutant dispersion is largely determined by meteorological conditions (He *et al*., 2017; Liu *et al*., 2020). As Vietnam faces intensifying climate change (Thanh, 2023; Tran-Anh *et al*., 2023; Tran-Anh & Ngo-Duc; 2024), the impact of TSP pollution in Dong Thap is likely to become even more significant, underscoring the importance of this research in informing future environmental and public health strategies.

This research explores a critical but underexamined aspect of air pollution dynamics in transitioning economies within the Mekong Delta. Unlike previous studies, which have focused on major cities or industrial hubs (Tran *et al*., 2022; Dung *et al*., 2023; Ha *et al*., 2023), this study examined transportation-related TSP emissions within Dong Thap's unique environmental context. The necessity of this research is further emphasized by current limitations in air quality monitoring across the province. Reports from the Department of Natural Resources and Environment indicate a rise in air quality standard violations, particularly in urban areas and along major transportation routes. However, the current monitoring system, which relies on manual sampling at limited locations, is insufficient for accurately assessing the impact of transportation emissions on TSP levels.

The study aimed to establish foundational knowledge for developing targeted strategies to mitigate TSP emissions from transportation sources in Dong Thap. By identifying key transportation-related sources and simulating particle dispersion, this research will provide crucial insights for policymakers and environmental managers. Findings from this study will also provide a robust foundation for policy implementation at the provincial level. By analyzing TSP sources and dispersion patterns, this paper aimed to provide a clearer understanding of the current situation and offer practical steps toward cleaner air and better public health in the region.

Methods

Study area

This study focused on Dong Thap province, a key agricultural region in Vietnam's Mekong Delta (**Figure 1a**). Covering 3,374km^2 with 1.7 million inhabitants, Dong Thap is characterized by a low-lying terrain of 1-2 meters above sea level and extensive river networks. The study area encompassed 12 administrative units with two cities, Cao Lanh and Sa Dec, representing a mix of agricultural, residential, and emerging industrial zones, providing a comprehensive view of the region's diverse landscape and development patterns.

Modeling framework

Our study used the United States Environmental Protection Agency (EPA) AERMOD model (EPA, 2023) to assess the impact of transportation emissions on air quality in Dong Thap province. We utilized AERMOD View version 12.01, which is the certified graphical user interface for the US EPA’s AERMOD version 23132 (Lakes Environmental, 2023). This model is a state-of-the-art Gaussian plume model designed for complex terrain and multiple emission sources (Huang & Guo, 2019; Shaikh *et al*., 2020; Salva *et al*., 2021). We also incorporated R-LINE version 1.2, a specialized near-road air quality model, which was integrated within the AERMOD model (EPA, 2019). This integration combined AERMOD's advanced algorithms for broad spatial analysis with R-LINE's recent improvements in horizontal and vertical dispersion, which are essential for evaluating transportation corridors. The use of AERMOD is well-established in Vietnam, especially in regions where in-situ measurement data is limited, and the model has demonstrated reliable performance (Tran *et al*., 2022; Dung *et al*., 2023; Ha *et al*., 2023).

Emission source characteristics

Our study modeled 43 major roads in Dong Thap province, prioritizing those with the highest traffic density and critical roles in regional connectivity and economic development. These included 8 national highways, 17 provincial roads, and 18 urban routes (**Figure 1a**). The network was divided into 88 segments with 1,204 nodes for accurate representation (**Figure 1b**). Road dimensions were estimated using Google Earth satellite imagery.

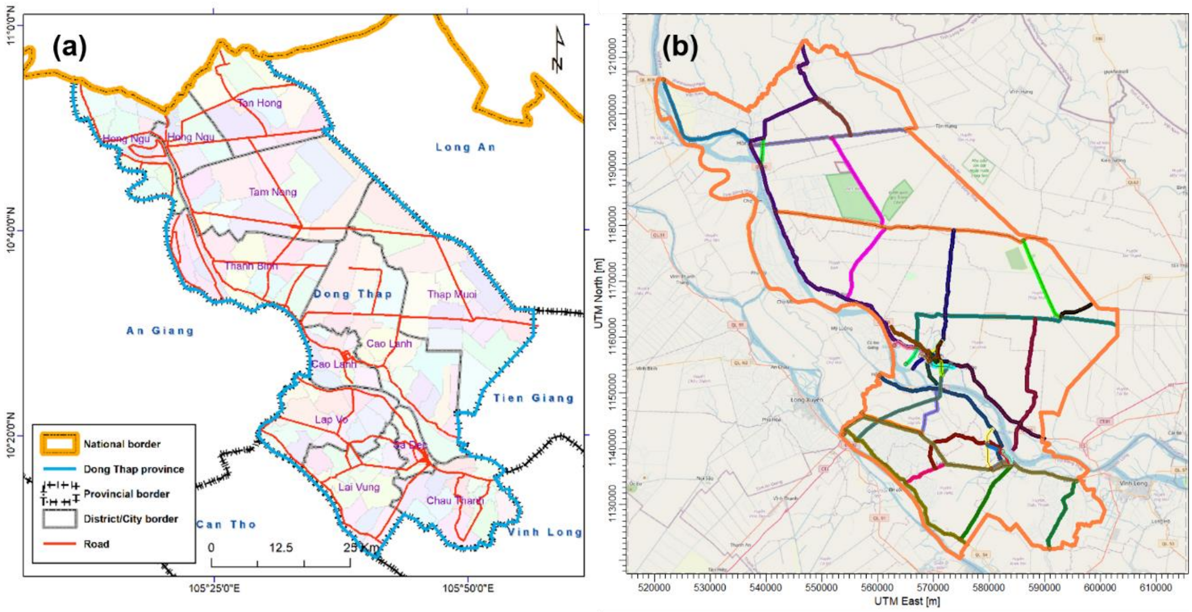

Figure 1. (a) Administrative map of Dong Thap province, with red lines indicating the 43 roads analyzed in this study; (b) Simulation domain defined in the AERMOD model, showing the 88 divided road segments overlaid on an OpenStreetMap base layer.

Traffic data for the provincial and urban routes were collected through direct vehicle counts, while highway data came from official Department of Transportation records. The inventory was conducted during peak hours in July and August 2023. Vehicles were classified into eight categories: motorcycles, tractors, large and small buses, and four types of trucks (large, heavy, medium, and light). Emission factors were based on Vietnam-specific data from Tung *et al*. (2011) and national official technical guidance (MONRE, 2024), ensuring relevance to the Mekong Delta context. Transportation emissions were modeled as line sources, assuming uniform TSP emission levels per square meter of road in the same segment.

Meteorological data assimilation

We utilized the ERA5 reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) for the period January 2021 to December 2023. This high-resolution (0.25° x 0.25° grid) hourly data encompassed critical parameters including wind vectors, cloud cover, radiation fluxes, temperature profiles, precipitation, and atmospheric pressure (retrieved from https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview). The integration of ERA5 data, known for its advanced data assimilation system, provided a robust representation of the atmospheric state. Upper air data from the Ca Mau radiosonde station complemented the surface observations, offering crucial vertical profile information for the model's planetary boundary layer calculations. The modeling experiment covered a full three years cycle (1,095 days), resulting in 26,280 hourly simulations. This temporal resolution allowed for the capture of diurnal and seasonal variations in pollutant dispersion patterns.

Atmospheric Stability Categories

Atmospheric stability plays a crucial role in pollutant dispersion, and we used the Pasquill stability categories to characterize the conditions based on the ERA5 dataset (Pasquill, 1961). These categories, ranging from very unstable (A) to very stable (F), were determined using wind speed, solar radiation (for daytime), and cloud cover (at night) (**Table 1**). During the day, strong solar radiation and low wind speeds indicated unstable conditions (Categories A or B), which promoted vertical mixing. At night, stability was influenced by cloud cover and wind speed – clear skies and low winds led to very stable conditions (Category F), while increased cloud cover and higher winds resulted in more moderate stability (Categories D or E).

Model domain and geospatial data processing

The model domain covered a 100km x 100km area centered on Dong Thap province. We applied a Cartesian grid with 500 x 500 cells, each with 200m spacing, aligned with the model domain. Terrain data were extracted from the high-resolution (30m) Shuttle Radar Topography Mission (SRTM) digital elevation model and resampled using the Kriging interpolation technique to match the 200m grid resolution (**Figure 2a**). Land use classification utilized a

Table 1. Pasquill stability classes (Pasquill, 1961)

Wind speed at ground level U (m s^{-1})	Daytime				Night time (Solar elevation < 0)
	Solar radiation Q (0.01 kWm^{-2})				
	60 < Q	30~59	15~29	1~14	
U < 2.0	A	A-B	B	D	F
2.0-2.9	A-B	B	C	D	E
3.0-3.9	B	B-C	C	D	D
4.0-5.9	C	C-D	D	D	D
U > 6.0	C	D	D	D	D

A: Extremely unstable; B: Moderately unstable; C: Slightly unstable; D: Neutral; E: Slightly stable; F: Very stable hydrid approach, combining the Global Land Cover dataset (100m resolution) with high-resolution Google Maps satellite imagery. This method, processed through the AERMET View Land User Creator tool, generated a refined 30m resolution land use dataset (**Figure 2b**). The resulting 12-sector surface parameter scheme provided a detailed representation of surface roughness, the Bowen ratio, and albedo – important inputs for the AERMOD meteorological preprocessor.

Analysis approach

The dispersion of TSP from transportation routes was analyzed under three distinct scenarios. First, the highest concentration case identified the peak TSP value at each grid point throughout the 26,280 hourly simulations, representing the worst-case pollution events. Second, the 99^{th} percentile concentration case captured extremely rare but significant high-concentration occurrences, providing insight into infrequent yet potentially hazardous air quality episodes. Finally, the three-year average (2021-2023) provided insight into seasonal variations in TSP pollution trends. To isolate and emphasize the impact of transportation-related TSP on the environment, the simulations were conducted in a hypothetical "blank" environment, excluding other potential pollution sources.

Results and Discussion

Assessment of ERA5 meteorological data

ERA5 wind data were compared to the Can Tho station data, the closest national meteorological station. Both datasets, converted to daily averages and eight directional sectors, displayed similar wind roses for 2021-2023 (**Figure 3**). While ERA5 reliably represented regional wind patterns, it showed lower frequencies of strong winds than the station, possibly due to local effects not captured by ERA5's grid-based data.

Figure 4 compares the measured and ERA5 wind speeds and temperatures. ERA5 wind speeds correlated well (R = 0.87, RMSE = 0.57 m s^{-1}), although there was increased scatter at low speeds and systematic biases. ERA5 temperature data aligned closely with the measurements. Overall, ERA5 provided reliable wind speed and temperature data for air pollutant dispersion modeling in Dong Thap.

Prevailing Wind Patterns in Dong Thap Province

The wind patterns in Dong Thap province, located in the Mekong Delta, exhibited distinct seasonal variations driven by the Southeast Asian monsoon system. Data from 2021 to 2023 highlighted prevailing winds from the west-northwest (WNW) to southwest (SW), consistent with broader regional trends in the lower Mekong Basin (**Figure 5**). Wind speeds typically ranged from 0.5 to 5.7 m s^{-1}, with the majority (80.4%) falling between 0.5 and 3.6 m s^{-1}. Specifically, 44.6% of winds occurred in the 0.5-2.1 m s^{-1} range, 35.8% in the 2.1-3.6 m s^{-1} range, and 16.8% in the 3.6-5.7 m s^{-1} range. Stronger winds above 5.7 m s^{-1} accounted for only 1.5%, while calm conditions (<0.5 m s^{-1}) occurred just 2.07% of the time, indicating predominantly mild winds. Seasonal variations were shaped by the monsoon system. During the southwest monsoon (May–October), winds primarily originated from the west and southwest, carrying warm, moist air from the Indian Ocean and Gulf of Thailand, driving the rainy season. Wind speeds were generally higher (2.1-5.7 m s^{-1}) due to the pressure gradient between the Tibetan Plateau low and the Mascarene high in the southern Indian Ocean. Conversely, the northeast monsoon (November-April) brought cooler, drier air from the Siberian high, marking the dry season. Winds shifted to the northeast and weakened (0.5-2.1 m s^{-1}). Transition periods in April-May and October-November featured variable wind directions and speeds as dominant weather systems shifted.

Simulation and dispersion of extreme TSP concentration events

In Dong Thap, the wind rose patterns revealed distinct variations between the rainy and dry seasons, reflecting the region's monsoonal influence (**Figure 5**). During the rainy season, the prevailing winds were predominantly from the southeast, aligning with the southwest

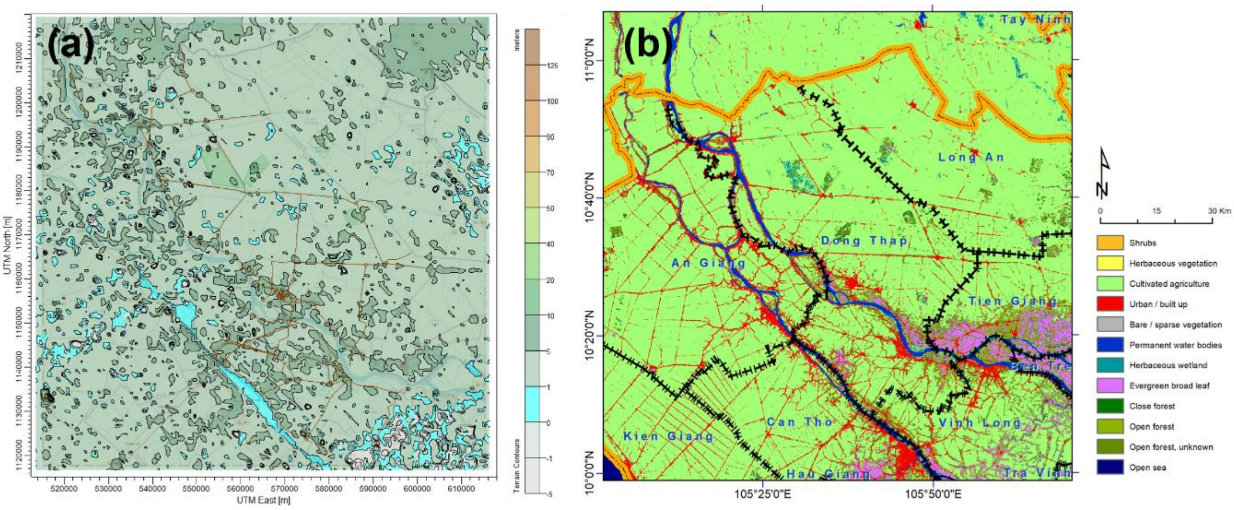

Figure 2. (a) SRTM topographic map and (b) the land cover map of the study domain

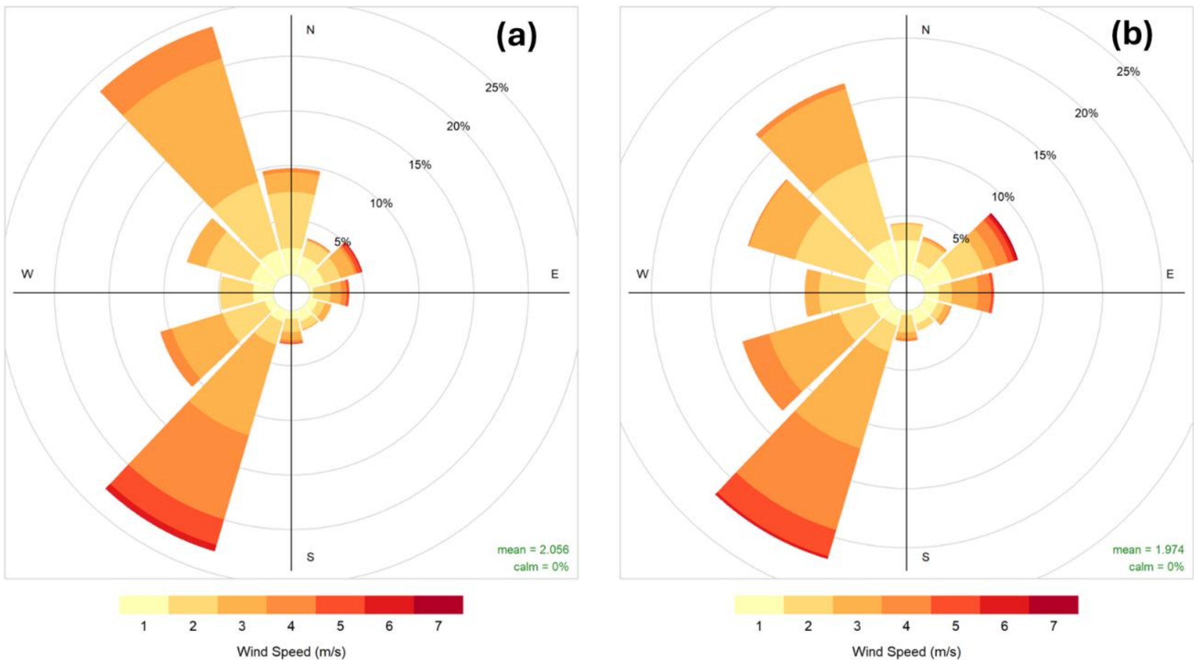

Figure 3. Comparison of wind roses from (a) Can Tho station data and (b) ERA5 data (2021-2023)

monsoon, which brought moisture-laden air from the sea, contributing to higher rainfall in the region. Wind speeds during this season tended to be more robust, with frequent occurrences in the 5.70-8.80 m s^{-1} range, supporting the intensity of the monsoon rains. In contrast, the dry season was characterized by a shift in wind direction, with more frequent winds from the northeast, associated with the northeast monsoon. This shift brought drier and cooler air from inland regions. Wind speeds during the dry season were generally moderate, often in the 3.60-5.70 m s^{-1} range, which were less intense than during the rainy season.

The AERMOD air quality model revealed critical patterns of TSP dispersion from the transportation network in Dong Thap province, with significant implications for air quality management (**Figure 6**). In the most severe 1-hour average scenario, TSP concentrations peaked in Cao Lanh city, exceeding 1100 µg m^{-3} – nearly triple the national standard (350 µg

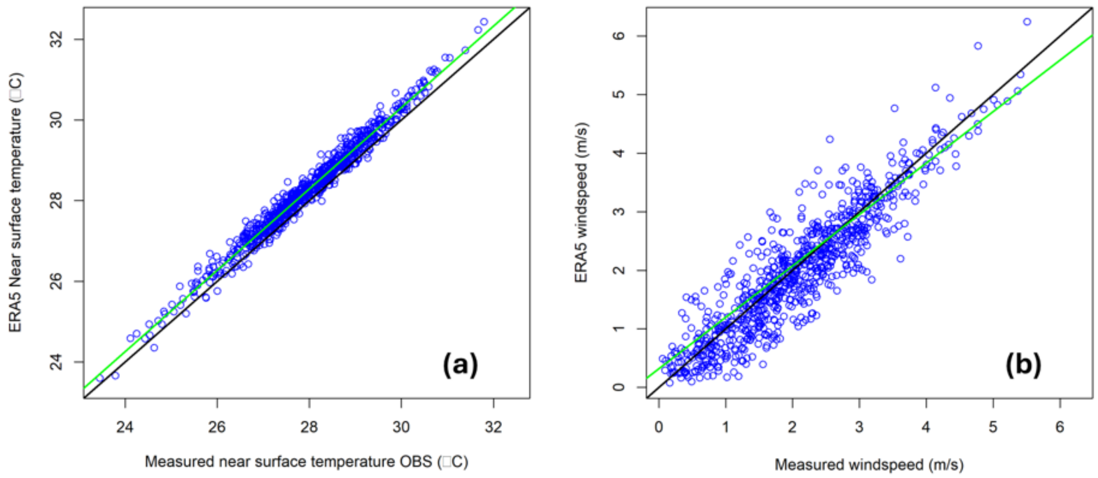

Figure 4. Comparison of measured and ERA5 data for (a) surface temperatures and (b) wind speeds at Can Tho station (2021-2023). The black line represents the 1:1 reference, while the green line shows the regression fit between measured and ERA5 data.

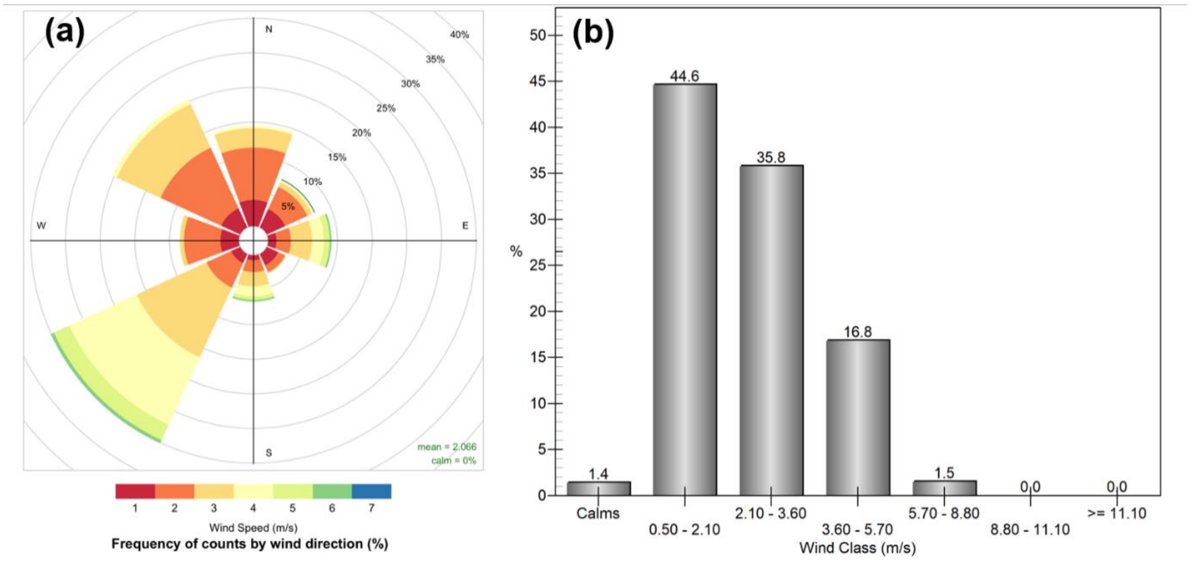

Figure 5. (a) Wind rose and (b) wind speed distribution in Dong Thap province during the 2021-2023 period using the ERA5 reanalysis dataset

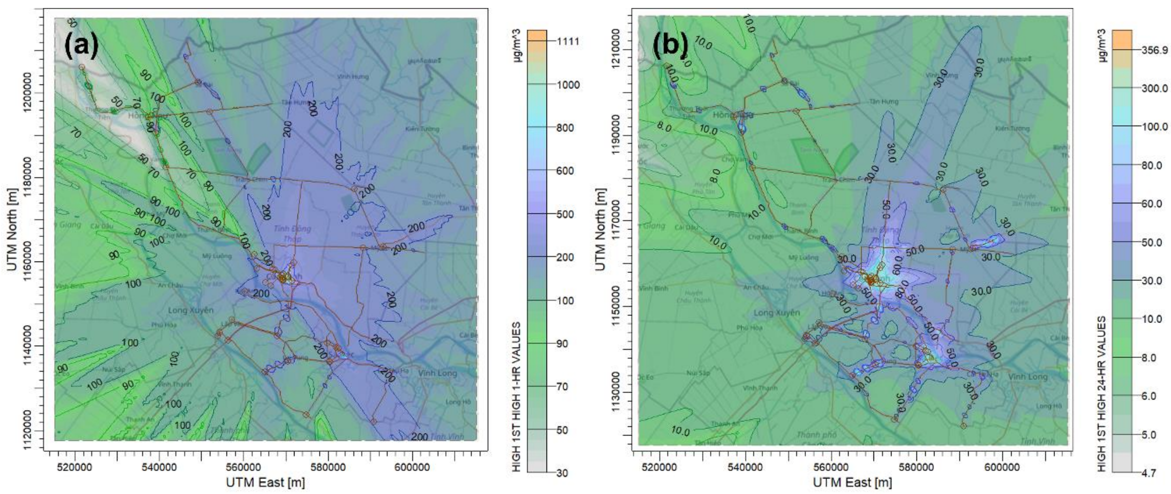

Figure 6. The most extreme TSP dispersion events from transportation sources: (a) 1-hour average and (b) 24-hour average

m^{-3}, QCVN 05/2023/BTNMT) (MONRE, 2023). This extreme concentration rapidly diminished to below 200 µg m^{-3} outside the urban core, highlighting the localized nature of pollution hotspots. The 24-hour average scenario, while less severe, still showed concerning levels along major roads, reaching over 350 µg m^{-3}, almost double the limitation of 200 µg m^{-3} set in QCVN 05/2023/BTNMT. However, air pollution was predominantly a concern in Cao Lanh city even in the worst-case scenario, with other districts not showing significant pollution potential. Notably, the prevailing southwest monsoon winds drove higher TSP concentrations towards the northeast, with levels up to 100 µg m^{-3} detected beyond Dong Thap's borders under the 1-hour highest concentration scenario and 30 µg m^{-3} under the 24-hour highest concentration scenario. This long-range transport, facilitated by the region's flat terrain, underscores the need for inter-provincial air quality management strategies and highlights the far-reaching impacts of local emission sources on regional air quality.

The 99th percentile concentrations (**Figure 7**) indicated a less severe but still concerning situation in the downtown region of Cao Lanh city. The AERMOD results, which provided hourly estimates, showed that the 99th percentile TSP concentration could reach up to 660 µg m^{-3} and 220 µg m^{-3} for 1-hour and 24-hour averages, respectively. The significant difference between the highest and 99th percentile scenarios suggests that while extreme pollution events are rare, they can be much more severe than typical high-concentration days. The 1-hour average map highlighted areas prone to short-term TSP concentration peaks, while the 24-hour average map indicated zones with sustained exposure to elevated particulate matter levels.

The simulation results showed that extreme TSP concentrations occurred most frequently at night under clear skies and light winds, classified as Class F in the Gifford stability system (**Table 1**). These very stable conditions suppressed vertical mixing, trapping pollutants near the surface and leading to higher concentrations in specific areas, such as Cao Lanh city. **Figure 8** compares the distribution of atmospheric stability classes in Dong Thap province during the rainy and dry seasons (2021-2023). Very stable conditions (Class F) were more frequent in the dry season (12%) than in the rainy season (9%), while very unstable conditions (Class A) occurred more often in the rainy season (8%) than in the dry season (3%). This seasonal difference suggests that higher stability in the dry season contributes to increased pollutant accumulation due to limited dispersion, whereas greater atmospheric instability in the rainy season enhances dispersion, reducing pollutant concentrations.

Spatial distribution of annual average TSP

The spatial distribution of annual average TSP dispersed from the transportation network in Dong Thap province during 2021-2023 is presented in **Figure 9**. This scenario illustrated the areas most affected by vehicle emissions throughout the year. Higher concentrations were found near major roads and highways, indicating the significant impact of vehicular emissions on air quality. Compared to the national standard of 100 µg m-^{3} for the annual average TSP in ambient air, Cao Lanh and Sa Dec cities were potentially negatively affected. At distances of about 1,000m from the road system, TSP levels from transportation dropped significantly to below 30 µg m-^{3}, well under the standard. However, this simulation only considered the impacts from transportation and did not account for other emission sources such as construction, agriculture, and industry. While the TSP impact from transportation alone was below the limitation, it still contributed to overall environmental pollution and could potentially lead to exceedances when combined with other sources. In the annual average case, it was also evident that areas downwind of the prevailing wind directions were more heavily impacted by traffic-related dust and emissions, highlighting the importance of considering wind patterns in urban planning and air quality management strategies.

Conclusions

The findings revealed significant spatial and temporal variations in TSP concentrations from transportation. The most concentrated areas were along the boundaries of roads. In extreme scenarios, TSP levels in Cao Lanh city reached up to 1,100 µg m^{-3} for 1-hour averages and 350 µg m^{-3} for 24-hour averages, substantially exceeding national standards. The 99th percentile

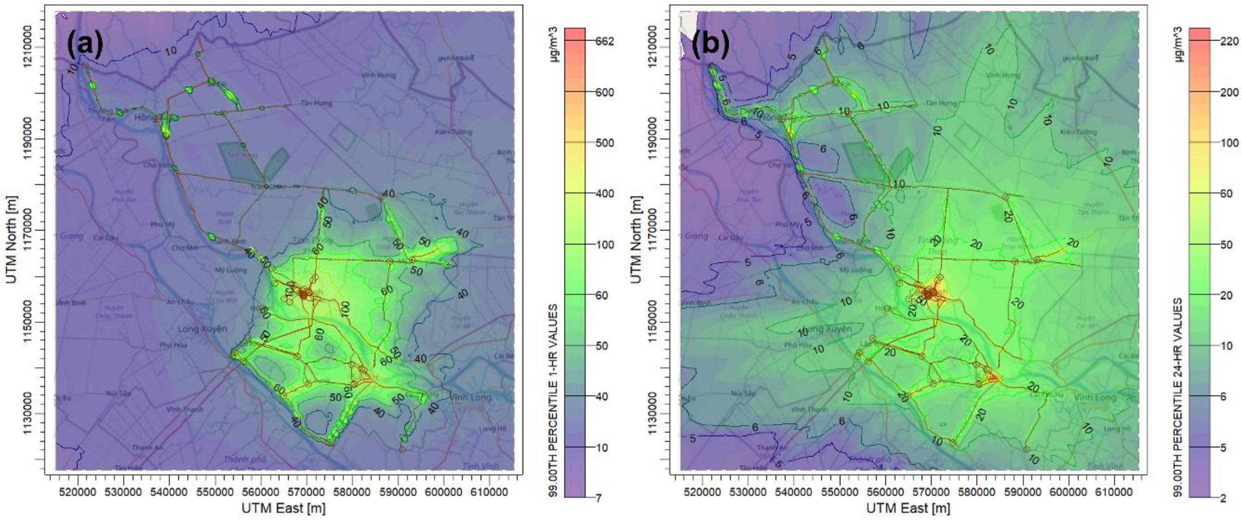

Figure 7. The 99th percentile TSP dispersion events from transportation sources: (a) 1-hour average and (b) 24-hour average.

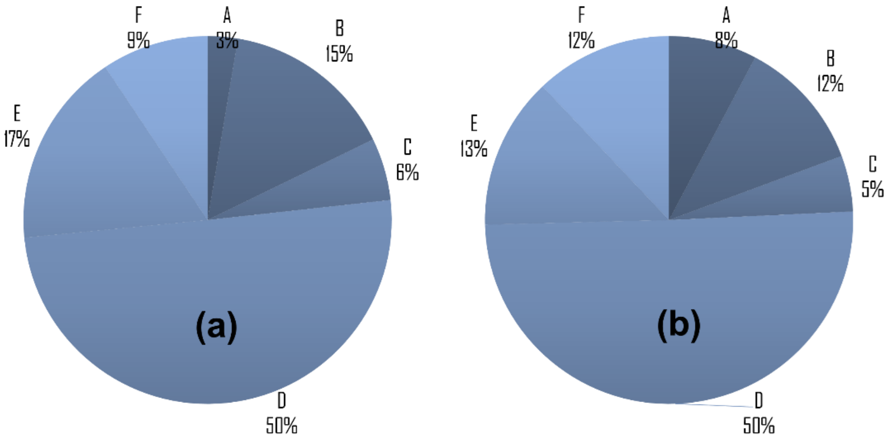

Figure 8. Ratio of atmospheric stability classes in Dong Thap Province during the (a) rainy and (b) dry seasons

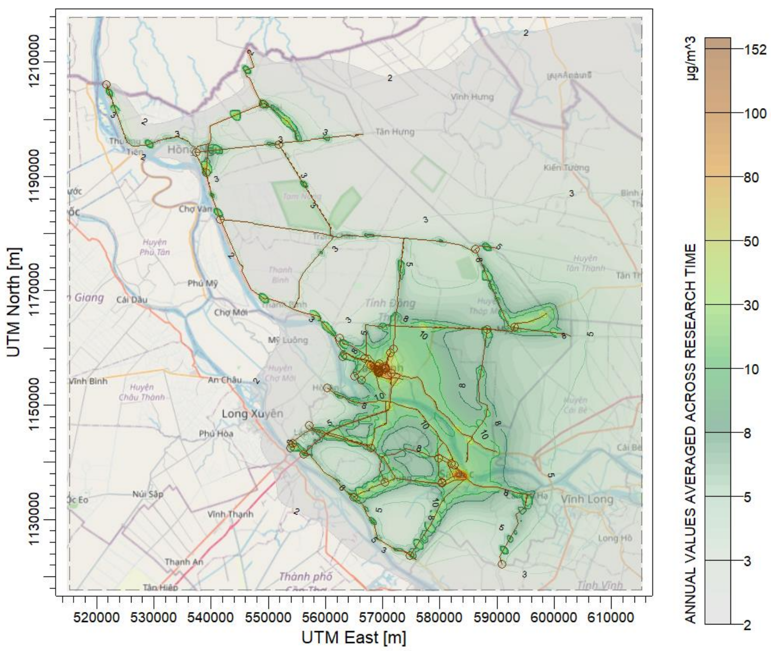

Figure 9. Annual average of TSP dispersion from transportation from 2021-2023

scenarios showed lower but still concerning levels. Cao Lanh and Sa Dec cities were identified as the areas most affected by transportation-related TSP emissions. The annual average TSP concentrations in these urban centers approached or potentially exceeded the national standard of 100 μg m^{-3}, even when considering only transportation sources. Dong Thap's flat terrain allowed for long-range transport of TSP, with concentrations up to 100 μg m^{-3} detected beyond Dong Thap's borders under extreme 1-hour scenarios. The prevailing southwest monsoon winds during the rainy season drove higher TSP concentrations towards the northeast, affecting areas downwind of major emission sources. The dispersion of TSP was strongly influenced by atmospheric stability. Very stable conditions (Class F), which are more common during the dry season, contributed to elevated TSP levels by limiting vertical mixing. Conversely, the more unstable conditions during the rainy season promoted greater dispersion and lower pollutant concentrations.

This study highlights the critical need for targeted air quality management in Dong Thap, particularly in urban areas and along major transportation routes, where transportation emissions alone significantly contribute to air pollution. To gain a more complete understanding of the region's air quality, follow-up studies should include other emission sources and pollutants.

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