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GEOSPATIAL MAPPING OF AMBIENT AIR QUALITY AND VULNERABILITY OF URBAN AREAS IN DAVAO CITY

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Abstract

In the past few decades, the level of air pollutants enhancing ambient air pollution rose due to enhanced industrial production and human activities. However, there is limited number of research on the spatio-temporal variation, interpolation, overlay analysis for vulnerable areas, and formulation of technical findings and policy implications for ambient air pollution. The main objective of the study was to geospatially map the ambient air pollution and susceptibility of urban centers in Davao City. Data were analyzed using the Geographic Information System (GIS). The four parameters; particulate matter 10 (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ground level ozone (O_3) from the five air quality monitoring stations (DC Stations 2, 7, 11, 14, 15) in the city were interpolated and mapped using the Inverse Distance Weighting method. Based on the results, most of the monitoring stations have not exceeded the National Ambient Air Quality Guideline Value (NAAQGV) but greatly exceeded the Global Ambient Air Quality Guideline Value (GAQGV) of WHO. Majority of the city is highly vulnerable to ambient air pollution. Structures around Station 14 or Toril Open Park Area Station are among the most exposed to ambient air pollution, has the highest number of affected structures, and is classified as highly vulnerable to ambient air pollution. With this, the results suggest that policies that guarantee clean ambient air must be strongly enforced in the community due to the problem of ambient air pollution.

Keywords: Ambient Air Pollution, GIS, Spatio-temporal, Davao City, Philippines.

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INTRODUCTION

Ambient air pollution is a significant environmental problem (Laumbach et al. 2015) and detrimental to human health (Mackenzie & Turrentine 2021). In recent years, industrial production and anthropogenic activities increased the concentration of air pollutants (Rahaman et al. 2022), exacerbating ambient air pollution (Mannucci & Franchini 2017). Intensified human activities and boosting the use of fossil fuels due to an increase in vehicle volume contribute to the increasing levels of exhaust emissions and air pollution in emerging megacities (Zhou et al. 2018). A wide range of air pollutants is associated with air pollution (Nafrah et al. 2018) such as ozone (O_3) (Zhang et al. 2019), carbon monoxide (CO) (Ruan et al. 2021), nitrogen dioxide (NO_2) (Meng et al. 2021), sulfur dioxide (SO_2) (Geravandi 2015), particulate matter ($PM_{2.5}$ and PM_{10}) (Kowalska & Kocot 2016). Exposure to ambient air pollutants can cause non-communicable human diseases (Linou et al. 2018), occurrence and aggravation of respiratory and cardiovascular diseases, cancers (Lamichhane et al. 2017), reproductive and developmental effects (Kioumourtzoglou et al. 2019), and decreased life expectancy (Waidyatillake et al. 2020). The spatial variation of air pollutants can be determined and presented using Geographic Information System (GIS) (Shakeel et al. 2015). The Philippines is one of the fastest-urbanizing countries in East Asia (Baker & Watanabe 2017). Meanwhile, Davao City is one of the highest and most competitive industrialized cities in the country (Palo 2022). Additionally, the city was considered a first (1st) class highly urbanized city on the island of Mindanao (NEDA-Region XI 2022). It has the third-highest population in the country, with 1.78 million as of 2021 (Philippine Statistic Authority 2021) and is slowly becoming one economic pillar of the country as more investments and development projects pour in (Manila Standard 2021). With the prevailing industrialization and urbanization in the city, ambient air pollution may be high, and people are susceptible to these high levels of air pollution. However, literature is scarce on the spatio-temporal variation, interpolation, overlay analysis for vulnerable areas, and formulation of technical findings and policy implications for ambient air pollution in the aforementioned city. The general objective of the present study was to geospatially map the ambient air pollution and vulnerability of urban centers in Davao City. Moreover, the specific objectives of the study were (i) determine the spatial variation pollutants through interpolation and overlay analysis using GIS; (ii) assess the temporal distribution of air pollution concentration; (iii) analyze the vulnerable areas in urban centers; and, (iv) formulate technical findings and policy implications. The study was anchored on the study of Kumar et al. (2016) and Atmospheric Diffusion Theory (Seinfeld 1983), which mathematically describes the spatiotemporal distribution of air contaminants.

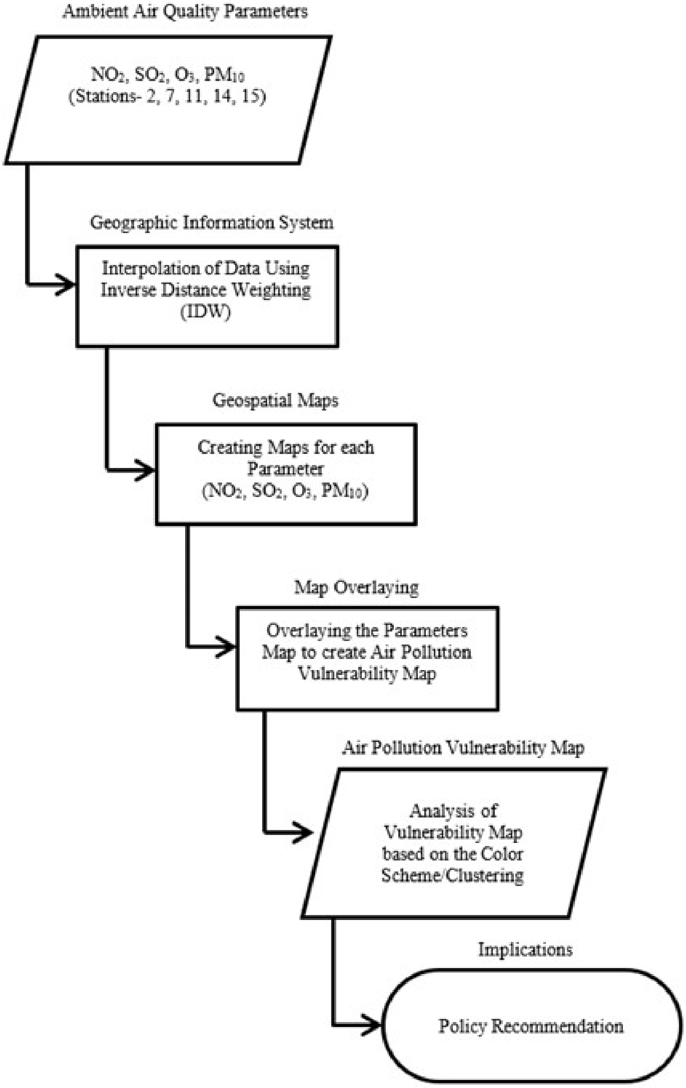

Figure 1. The conceptual framework of the study.

MATERIAL AND METHODS

Research design

This study utilized a descriptive quantitative-non-experimental. The GIS is composed of spatial data that are basically quantitative since it is made up of coordinate pairs, which are mathematically changeable numbers (Gregory & Ell 2007). Spatial analysis make use of this to summarize the patterns within spatial data or to inquire how attribute values are structured in space. As a non-experimental study, it enables the analysis or examination of variables or phenomena that the researcher/s cannot control (IvyPanda 2020).

Research locale

The area of study was Davao City which lies 7.207573, 125.395874 (7° 12' 27.2628" North, 125° 23' 45.1464" East) latitude and longitude, and divided into three (3) congressional districts, which are then further divided into 11 administrative districts with a total of 182 barangays. The city has six (6) air quality monitoring network sampling sites supervised and monitored by DENR-EMB to monitor air quality located in Ilang, Davao International Airport, Barangay 12-B, Davao Memorial Park, Toril, and Calinan. These sites monitor PM_{10}, $PM_{2.5}$, NO_2, SO_2, and O_3. In this study only Stations 02, 07, 11, 14, 15 were used due to the unavailability of data in Station 16 located in Calinan.

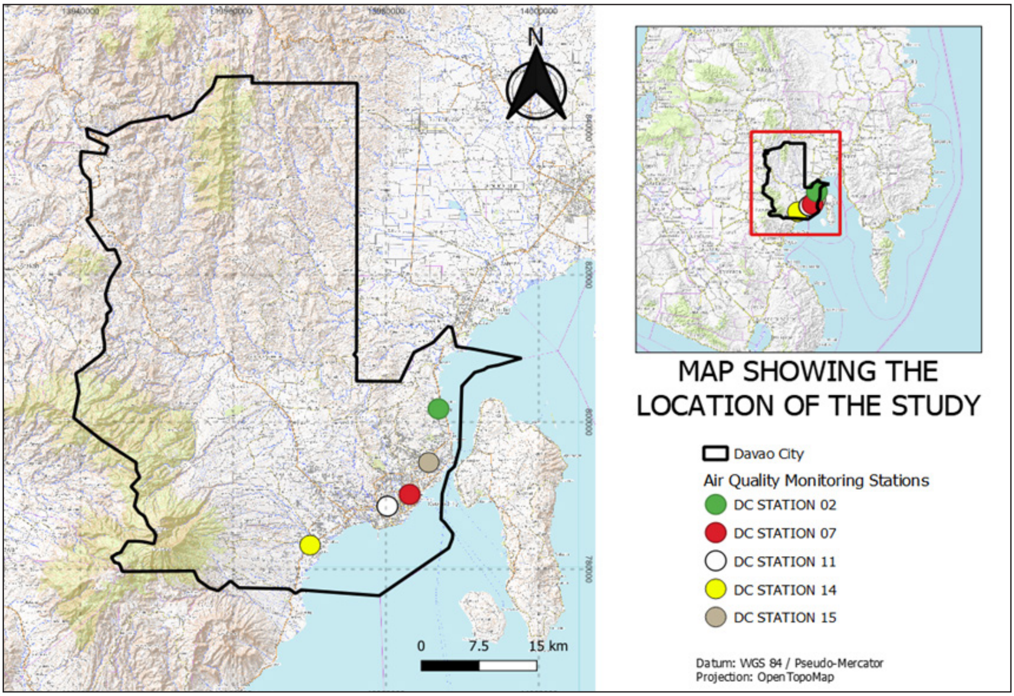

Figure 2. Map showing the location of the study.

Research instrument

In conducting the study, the following instruments were utilized.

1. Global Positioning System (GPS). This was used to determine the coordinates of the monitoring stations.
2. Quantum Geographic Information System (QGIS). This was used in the study, specifically in making maps. In this software, the interpolation of air quality data from the monitoring stations was done.
3. Geospatial Tool: Inverse Distance Weighting (IDW). This was used in the interpolation and the formula is presented below:

$$y_0 = \frac{\sum_{i=1}^{n} \left(\frac{1}{d_i^p}\right) y_i}{\sum_{i=1}^{n} \left(\frac{1}{d_i^p}\right)}$$

Where:

y_0= value predicted for location 0,
y_i= values known for a location i,
d_i=the gap b/w location I and location 0,
n= total number of samples points, and
p=power function

4. Microsoft Excel. This was used to tabulate and arrange the data needed in the interpolation.

Data gathering procedure

The following steps were followed in the gathering of necessary data for the study:

1. Approval to Conduct the Study. The researchers asked permission from the research committee to conduct the study by writing formal letters addressed to the adviser, panel members and statistician.
2. Collection of Secondary Data. The secondary data on the concentrations of pollutants from different monitoring stations was formally requested from the Environmental Management Bureau XI (EMB-XI).
3. Tabulation. The collected secondary data on concentrations of pollutants were then tabulated and arranged accordingly.
4. Interpolation of Data to GIS. Once the data were tabulated, they were then input into the Quantum Geographic Information System (QGIS) software and interpolated using the Inverse Distance Weighting (IDW) to create the maps for each parameter.
5. Map overlaying. The created maps on different pollutants were overlayed to create vulnerability maps for each station.
6. Vulnerability Map Analysis. Interpretation of findings was completed in a descriptive and implicative manner. The analysis was followed by the formulation of conclusions and recommendations of the study.

Statistical treatment of data

The researchers calculated and analyzed the data that were gathered in this study using the statistical tools listed below.

1. Average. This was used to calculate the annual average of pollutant concentration.
2. Standard Deviation. This was used for the clustering of vulnerable areas on the vulnerability maps.
3. Spatial Statistics. This was used to analyze and understand a given vector dataset. This included the mean, standard deviation, sum, minimum value (min), maximum value (max), amount of sample (n), covariance (cv), number of unique values, range, and median.

Ethical provision

In the collection of secondary data, a letter of request was sent to the EMB-XI. The collected data was kept private and was not subjected for mass distribution in accordance with the Data Privacy Act of 2012. Appropriate disclaimers and confidential declarations were followed and stated in compliance with the data privacy policies. Before being published, the study was also checked for plagiarism and reviewed by the experts. The researchers were guided by a research adviser who supervised and suggested empirical concepts and ideas for the betterment of the study. The role of the adviser guided and ensured that the researchers were conducting the study in a scientific manner.

Scope and delimitation

The study only covers the five (5) monitoring stations: DC Station 2, 7, 11, 14, and 15. DC Station 16 was excluded from the discussion, because the sampling site only monitored particulate matter. This monitoring station had no data on the air pollutants such as SO_2, NO_2, and O_3 and the involvement of this station would result in inconsistent analysis. In station 15, there were no data available for O_3, thus, excluding it from the analysis of this parameter. The annual data on the concentration of air pollutants used in the study were from 2017-2019 because these years had tested for uniform parameters. Ununiformed parameters testing happened in 2016, 2020, and 2021 because of equipment communication errors, malfunctioned spectrophotometers, and COVID-19 restrictions.

RESULTS AND DISCUSSION

Spatial variability of pollutants

Particulate matter 10 (PM_{10})

Presented in Figure 3 is the spatial variation of PM_{10} in Davao City. As visualized, Station 4 had the highest concentration, followed by Stations 2, 1, 5, and 3, having the value of 57.510 µg/Ncm, 46.650 µg/Ncm, 45.521 µg/Ncm, 42.076 µg/Ncm, and 33.440 µg/Ncm, respectively. Station 4 with the highest concentration value, primarily represents road vehicle, residential, and commercial emissions (EMB XI 2017). On the other hand, the Station 3 with the lowest concentration is represented by cluster industries, residential, and bus garages (EMB XI 2018). The production of PM_{10} is primarily from fuel combustion, and diesel produces a significant proportion of PM_{10} (California Air Resources Board 2023). Moreover, the commercial, household, and institutional sector includes combustion, which also produces a tremendous amount of PM_{10} (European Environment Agency 2014). This high concentration or levels of PM_{10} pose a threat to humans because this can irritate the eyes and throat and exacerbate respiratory and cardiovascular diseases (Environmental Protection Agency 2022).

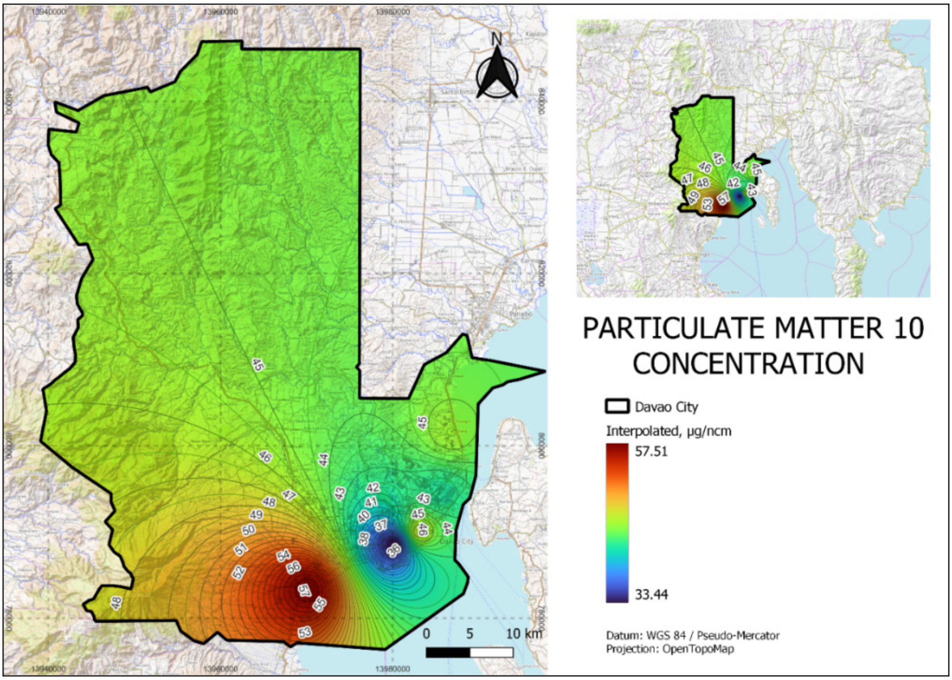

Figure 3. Particulate Matter 10 (PM_{10}) concentration.

Furthermore, it damages the respiratory and cardiovascular systems, and the reproductive and central neurological systems, and even causes cancer (Manisalidis et al. 2020). Exposure to PM_{10} has numerous health effects, including coughing, wheezing, asthma attacks, bronchitis, high blood pressure, heart attacks, strokes, and early death (Marlborough District Council 2018).

Sulfur dioxide (SO_2)

The spatial variation of SO_2 in the urban centers of Davao City is shown in Figure 4. Station 5 had the highest concentration having a value of 11.297 µg/Ncm, and followed by Stations 3, 2, 4, and 1, having 1.062 µg/Ncm, 0.959 µg/Ncm, 0.804 µg/Ncm, and 0.713 µg/Ncm, respectively.

The Station 5 represents industrial, road vehicles, aircraft, watercraft, residential and commercial emissions (EMB XI 2017). The primary producer of this pollutant is the burning of fossil fuels by power plants and other industrial facilities (Environmental Protection Agency 2022). Moreover, diesel engines are another primary source, including old buses and trucks, locomotives, ships, and off-road diesel equipment (American Lung Association 2022). A high concentration of SO_2 is harmful since it has a deleterious impact on health and the environment (Mabahwi et al. 2014). Breathing difficulties, coughing, throat irritation, and pain after taking a deep breath are possible side effects (National Park Service 2018). Moreover, the severe effects of atmospheric sulfur dioxide on human health include asthma attacks, pulmonary edema, eye irritation, cardiovascular disorders, breathing difficulties, and increased death rates (Khaniabadi et al. 2017).

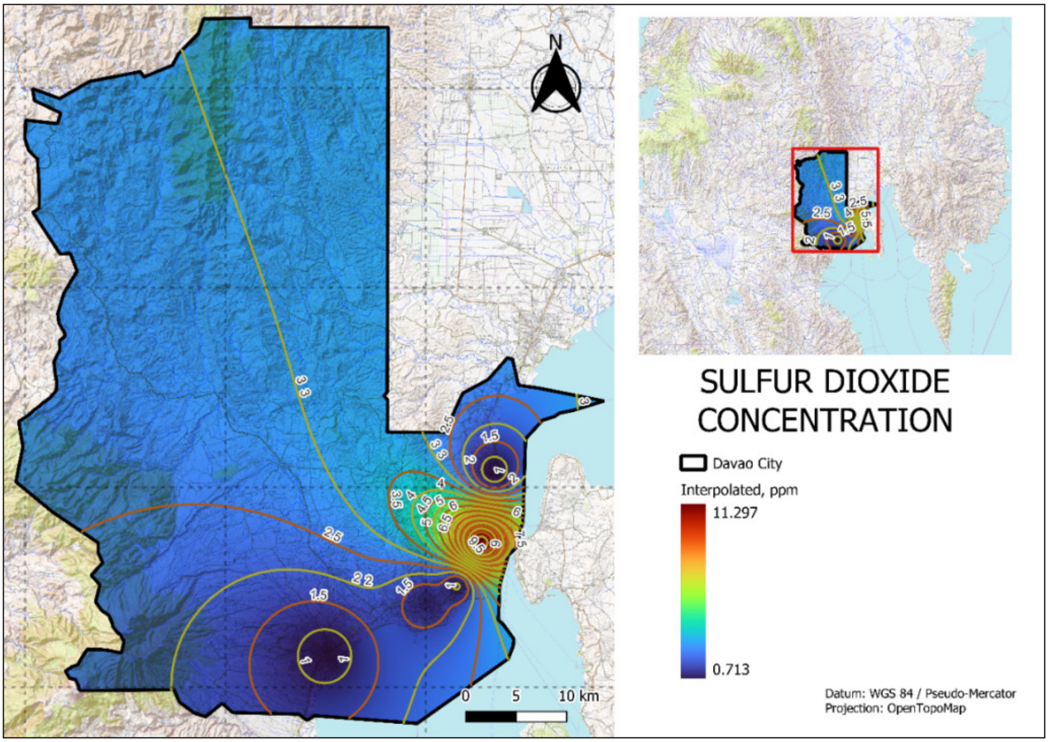

Figure 4. Sulfur dioxide (SO_2) concentration.

Nitrogen dioxide (NO_2)

Illustrated in Figure 5 is the spatial variation of nitrogen dioxide. Map showed that Station 4 again had the highest concentration having 15.925 µg/Ncm, followed by Stations 5, 2, 1, and 3, having 15.402 µg/Ncm, 14.688 µg/Ncm, 10.207 µg/Ncm, and 10.062 µg/Ncm, respectively. Station 4 is located a few kilometers away from power plants, factories, and gasoline plants and is located in one of the busiest districts in the city, with an average daily traffic of 32,719 from 2017-2019. This is one possible reason why the associated concentration values around Station 4 remain close to their actual value of 15.925 µg/Ncm. The spatial variation depends on various factors, including climatic conditions like wind speed, relative humidity, and air temperature (Guo et al. 2019). Station 5 also had a high concentration of the given parameter because of its location within the airport, meaning most of its collected specimens are emissions from aircraft jet engines, which consist of different compounds such as carbon dioxide and nitrogen dioxide (U.S. Department of Transportation 2017). Strong winds around an aircraft and the airport, as it lands, contribute to how nitrogen dioxide is distributed to nearby areas. Another variation seen in the map is how the values were moving away from station 3 increases. This is because there is less pollution within the station, but in the areas around it since most of the specimens collected by the station are from outside sources. The higher concentration of NO_2 constitutes a threat to human health. It has been demonstrated that short-term exposure to NO_2 is linearly associated with an increased risk of death from cardiovascular and respiratory causes (Meng et al. 2021). Prolonged exposure to high levels of NO_2 may also raise the risk of respiratory infections and chronic lung disease. People who already have asthma are typically more vulnerable to the negative health consequences of NO_2 than youngsters and the elderly (Merseens 2020).

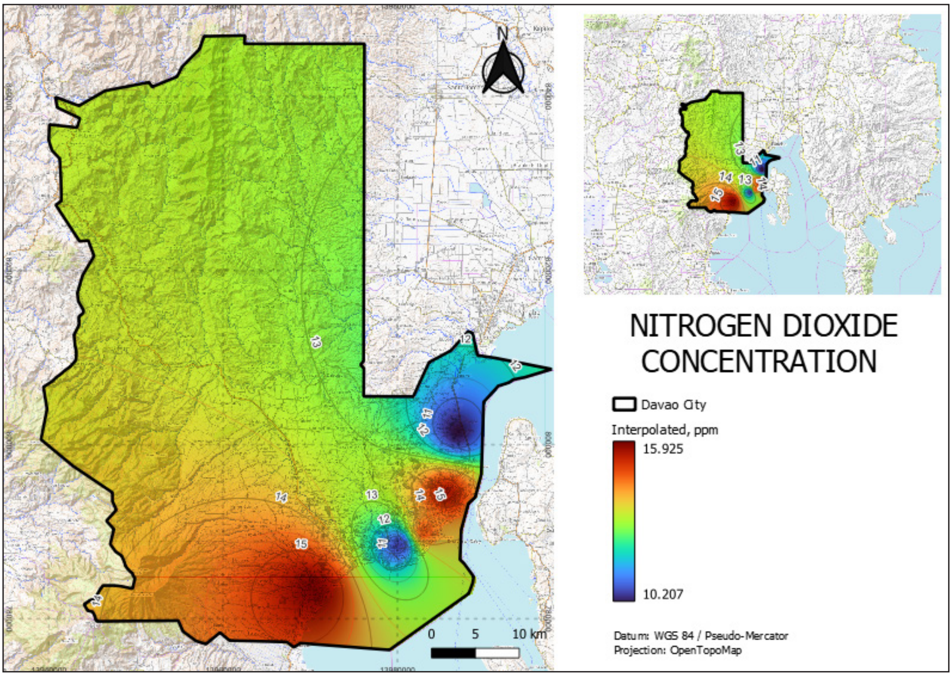

Figure 5. Nitrogen dioxide (NO_2) concentration.

Ground level ozone (O_3)

Demonstrated in Figure 6 is the spatial variation of O_3 in Davao City. The map showed that Station 2 had the highest concentration value, followed by Stations 1, 4, and 3 having 7.832 µg/Ncm, 6.661 µg/Ncm, 1.306 µg/Ncm, and 0.785 µg/Ncm, respectively. Ground-level ozone is mainly produced by emissions from the photochemical reaction between NO_2 and volatile organic compounds (VOCs) (Guo et al. 2019) from emissions produced by vehicles, power plants, refineries, and factories (Ellenburg 2021). Station 2, with the highest concentration value, is surrounded by various commercial establishments such as malls, recreational and entertainment facilities, and schools (EMB XI 2017) while being located meters away from one of the primary roads of the city with and with an average daily traffic of 26,142 from 2017-2019. A higher concentration of this pollutant harms human health because it can cause congestion, coughing, throat irritation, chest pain, asthma, emphysema, and bronchitis (Soni et al. 2021).

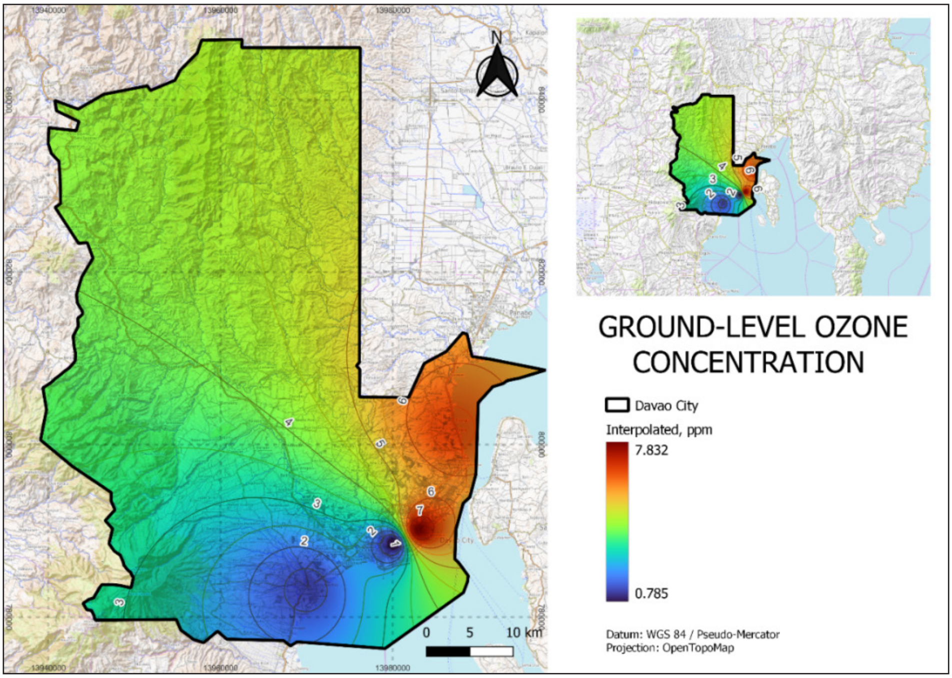

Figure 6. Ground level ozone (O_3) concentration.

Temporal distribution of air pollution in Davao City

Particulate matter 10 (PM_{10})

Presented in Table 1 is the trend of concentration of particulate matter 10 across the three years considered in the study.

In 2017, Station 4 had the highest concentration value, followed by Stations 2, 1, 3, and 5, having 62.381 µg/Ncm, 58.995 µg/Ncm, 55.645 µg/Ncm, 40.840 µg/Ncm, and 40.705 µg/Ncm, respectively. In 2018, Station 4 again had the highest concentration value having 64.422 µg/Ncm, and was followed by Stations 1, 2, 5, and 3 having 50.090 µg/Ncm, 47.227 µg/Ncm, 46.742 µg/Ncm, and 35.068 µg/Ncm, respectively. While in 2019, when the COVID-19 outbreak happened, station 4 still had the highest concentration having 45.730 µg/Ncm, and was followed by Stations 5, 2, 1, and 3, having 36.780 µg/Ncm, 33.730 µg/Ncm, 30.830 µg/Ncm, 24.410 µg/Ncm, respectively. Stations 1, 2, and 3 behaved in descending from 2017 to 2019, but stations 4 and 5 ascended the value from 2017 to 2018 but descended in 2019. This decline in values can be attributed to the stringent restrictions placed during the Covid-19 pandemic, which significantly decreased industrial production and car emissions (Otmani et al. 2020). Furthermore, the three-year annual average of PM_{10} concentration in five (5) stations is shown in Figure 7.

Table 1. Average and long-term guideline value of PM_{10}.

Stations	2017 (µg/Ncm)	2018 (µg/Ncm)	2019 (µg/Ncm)	Average (µg/Ncm)	Long-term guideline value (15 µg/Ncm)
1	55.645	50.090	30.830	45.521	Exceeded
2	58.995	47.227	33.730	46.650	Exceeded
3	40.840	35.068	24.410	33.440	Exceeded
4	62.381	64.422	45.730	57.510	Exceeded
5	40.705	46.742	36.780	42.076	Exceeded

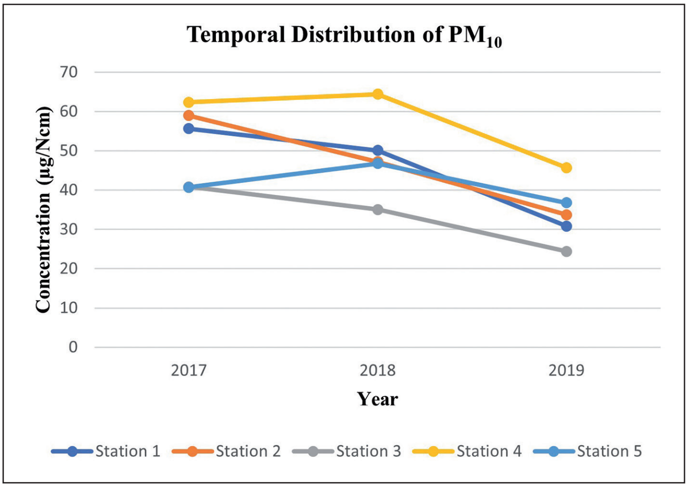

Figure 7. Trend of PM_{10} concentration.

By calculating the three-year annual average of concentration of the five stations, the result showed that Station 4 had the highest three-year average concentration having 57.510 µg/Ncm. Station 2 was next to Station 4, having 46.650 µg/Ncm, followed by Stations 1, 5, and 3 having 45.521 µg/Ncm, 42.076 µg/Ncm, and 33.440 µg/Ncm, respectively. Using the new GAQGV of WHO for the long-term guideline level, the five stations exceeded the guideline value of 15 µg/Ncm. This exceedance of the five stations poses a threat since a higher rate of PM_{10} is mainly associated with mortality and respiratory illnesses (Gautam 2014), which requires intermediate interventions (Balogun & Tella 2022). Moreover, the prevalence of respiratory and cardiovascular conditions revealed a substantial relationship between bronchial asthma and PM10 concentrations (Al-Hemoud et al. 2017).

Sulfur dioxide (SO_2)

Presented in Table 2 is the trend of concentration of SO_2 in terms of averages. The result showed that in 2017, Station 5 had the highest annual average having 19.989 μg/Ncm, while Stations 1, 2, 3, and 4 had the lowest concentration, and all of them had 0.001 μg/Ncm annual concentration. In 2018, Station 5 again had the highest annual concentration at 4.621 μg/Ncm, but this is lower than the concentration in 2017. Additionally, this station was followed by Stations 2, 1, 3, and 4, having 0.808 μg/Ncm, 0.349 μg/Ncm, 0.314 μg/Ncm, and 0.001 μg/Ncm, respectively. Surprisingly, in 2019, all of the said stations had increased their annual averages. Station 5 again had the highest annual concentration having 9.820 μg/Ncm and followed by Stations 3, 4, 2, and 1, having 3.050 μg/Ncm, 2.410 μg/Ncm, 2.070 μg/Ncm, and 1.790 μg/Ncm, respectively.

Table 2. Average and long-term guideline value of SO_2.

Stations	2017 (μg/Ncm)	2018 (μg/Ncm)	2019 (μg/Ncm)	Average (μg/Ncm)	Long-term guideline value (40 μg/Ncm)
1	0.001	0.349	1.790	0.713	Not exceeded
2	0.001	0.808	2.070	0.959	Not exceeded
3	0.001	0.314	3.050	1.062	Not exceeded
4	0.001	0.001	2.410	0.804	Not exceeded
5	19.989	4.621	9.820	11.297	Not exceeded

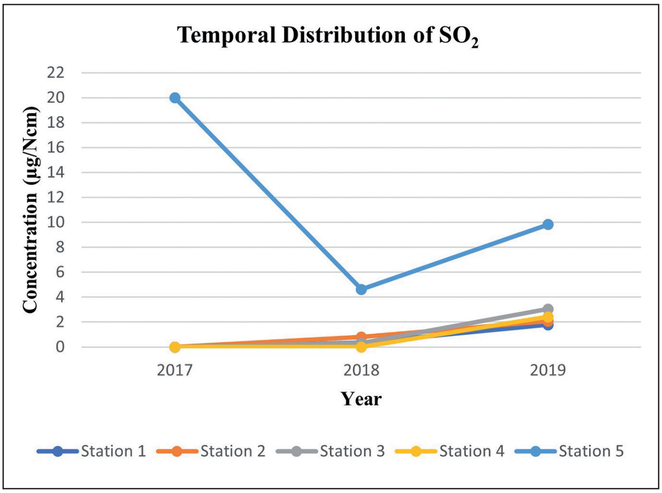

Figure 8. Trend of SO_2 concentration.

This increase in SO_2 concentration has adverse health effects on the human cardiovascular, nervous, and respiratory systems and causes type 2 diabetes (Khalaf et al. 2022). Furthermore, a high concentration of SO_2 can result in a life-threatening build-up of fluid in the lungs (pulmonary edema), and a single exposure to the said high concentration could cause a chronic illness like asthma (Canadian Centre for Occupational Health and Safety 2022). As demonstrated in Figure 8, the three-year annual average of the concentration of SO_2, data showed that Station 5 had the highest average having 11.297 µg/Ncm. This is followed by Stations 3, 2, 4, and 1, having 1.062 µg/Ncm, 0.959 µg/Ncm, 0.804 µg/Ncm, and 0.713 µg/Ncm, respectively. Furthermore, using the long-term guideline value of WHO, all five (5) monitoring stations have not exceeded the guideline value of 40 µg/Ncm.

Nitrogen Dioxide (NO_2)

Table 3 demonstrated the trend of concentration of NO_2 from the five monitoring stations. The data showed that in 2017, Station 5 had the highest annual concentration having 17.403 µg/Ncm, and this was followed by Stations 4, 2, 3, and 1, having 14.930 µg/Ncm, 10.649 µg/Ncm, 9.411 µg/Ncm, and 7.959 µg/Ncm, respectively. In 2018, all of the said stations behaved in an increasingly manner. In this year, Station 5 again had the highest annual concentration 17.712 µg/Ncm and followed by Station 2 (17.465 µg/Ncm), Station 4 (15.595 µg/Ncm), Station 1 (12.953 µg/Ncm), and Station 3 (9.586 µg/Ncm). In 2019, both Stations 3 and 4 continued to increase while Stations 1, 2, and 5 decreased slightly. Station 4 had the highest annual concentration for this year, having 17.250 µg/Ncm, and Station 1 had the lowest annual concentration, with 9.710 µg/Ncm.

Table 3. Average and long-term guideline value of NO_2.

Stations	2017 (µg/Ncm)	2018 (µg/Ncm)	2019 (µg/Ncm)	Average (µg/Ncm)	Long-term guideline value (10 µg/Ncm)
1	7.959	12.953	9.710	10.207	Exceeded
2	10.649	17.465	15.950	14.688	Exceeded
3	9.411	9.586	11.190	10.062	Exceeded
4	14.930	15.595	17.250	15.925	Exceeded
5	17.403	17.712	11.090	15.402	Exceeded

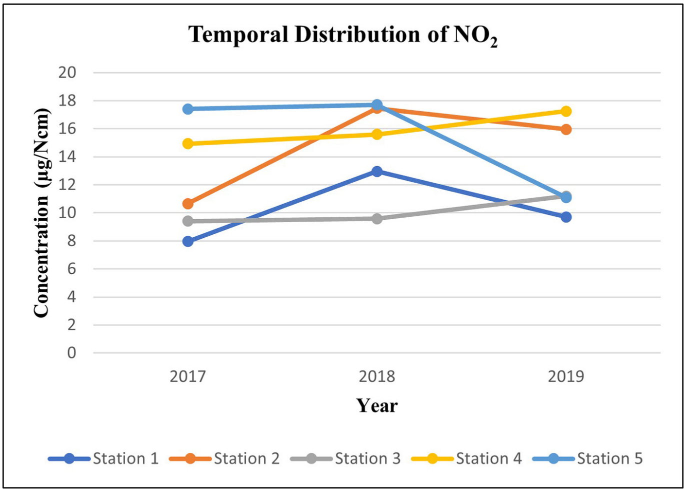

Figure 9. Trend of NO_2 concentration.

In determining the three-year annual average concentration of the five stations, Figure 9 showed that Station 4 had the highest concentration in three years, having an average of 15.925 µg/Ncm, while Station 3 had the lowest three-year average concentration having 10.062 µg/Ncm. Furthermore, using the long-term guideline value of WHO for NO_2, the five monitoring stations have exceeded the long-term guideline of 10 µg/Ncm. Human health will be in danger if this WHO limit is exceeded. A high concentration of NO_2 can cause respiratory irritation, aggravate pre-existing conditions such as asthma, and cause sufferers to be admitted to the hospital (Taylor 2019). In exact words, the consequences of NO_2 on health are typically more dangerous for youngsters, the elderly, and those with asthma (Environmental Protection Agency 2022). Road traffic has the highest nitrogen dioxide concentrations; as a result, those who live close to busy roadways are most affected by pollution (Merseens 2020). Accordingly, short-term and long-term exposure to nitrogen dioxide (NO_2) has been linked to significant human health effects, such as increases in all-cause mortality and respiratory and cardiovascular effects (Faustini et al. 2014).

Ground level ozone (O_3)

Among the five (5) stations, only Stations 1, 2, 3, and 4 had the data for O_3. Illustrated in Table 4 is the trend of concentration of the said parameter. In 2017, Station 2 had the highest annual average of 20.352 µg/Ncm. This was followed by Stations 1, 4, and 3 having 15.663 µg/Ncm, 0.577 µg/Ncm, and 0.378 µg/Ncm, respectively. In 2018, Stations 1 and 2 drastically decreased from 15.663 µg/Ncm and 20.352 µg/Ncm to 2.469 µg/Ncm and 0.855 µg/Ncm, respectively. Correspondingly, only Stations 3 and 4 had increased their values from 0.378 µg/Ncm to 0.577 µg/Ncm to 0.437 µg/Ncm and 1.070 µg/Ncm. In the same year, Station 1 had the highest annual concentration, and Station 3 had the lowest concentration. In 2019, only Station 1 had decreased the value, and the remaining stations behaved increasingly. Station 2 had the highest annual concentration, and Station 3 had the lowest for this year. This continuous increase in O_3 concentration is a key component contributing to the rise in health dangers to people (Zhou et al. 2022). Children are more prone and at high risk to this pollutant because their lungs are still growing, and they are more likely to be outdoors while ozone levels are high, which increases their exposure (Liu et al. 2024). Chronic exposure to O_3 may affect lung function and increase the risk of developing lung cancer, emphysema, and asthma (Li et al. 2019).

Presented in Figure 10 the three-year annual average of O_3 concentration. The figure showed that Station 2 had the highest average having 7.832 µg/Ncm, and this was followed by Stations 1, 4, and 3 have an average of 6.661 µg/Ncm, 1.306 µg/Ncm, and 0.785 µg/Ncm, respectively. Using the GAQGV of WHO, data showed that these monitoring stations had not exceeded the long-term guideline value.

Table 4. Average and long-term guideline value of O_3.

Stations	2017 (µg/Ncm)	2018 (µg/Ncm)	2019 (µg/Ncm)	Average (µg/Ncm)	Long-term guideline value (60 µg/Ncm)
1	15.663	2.469	1.850	6.661	Not exceeded
2	20.352	0.855	2.290	7.832	Not exceeded
3	0.378	0.437	1.540	0.785	Not exceeded
4	0.577	1.070	2.270	1.306	Not exceeded

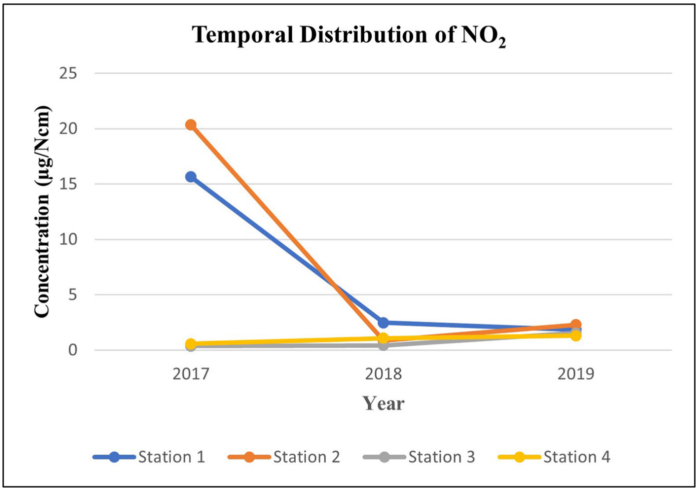

Figure 10. Trend of O_3 concentration.

Vulnerability of urban centers

Presented in Figure 11 the ambient air vulnerability of Davao City. By overlaying the concentration maps of the four parameters, it was discovered that stations 4 and 5 were categorized as very highly vulnerable. In contrast, station 2 was categorized as highly vulnerable, station 1 was moderately vulnerable, and station 3 was lowly vulnerable.

Table 5. Number of affected structures within 1 km buffer.

Stations	Affected structures within 1km buffer
1	3.078
2	5.547
3	2.268
4	8.018
5	5.017

Utilizing buffer analysis is a way to estimate and centralize the impacts of different pollutions on an area's overall air quality (Koas 2010). GIS map overlaying also aids in identifying potential pollution "hot spots" across the city (Mavroulidou 2003). People and establishments located near stations with high concentrations of air pollutants tend to be highly vulnerable and more exposed to ambient air pollution. Sensitivity among individuals varies depending on various socio-economic factors such as housing conditions, occupation and ventilation in establishments (Rangwala 2022).

The Ambient Air Pollution Vulnerability of Station 1 shown in Figure 12. The station is shown to have a moderate vulnerability to ambient air pollution and had the least affected structures within its 1 km buffer. The station also had the lowest concentrations of sulfur and nitrogen dioxide among the five stations in the study. The closest major roadway to the station is Daang Maharlika Highway, which caters to around 27.075 vehicles daily from 2017-2019 with a volume-capacity ratio of 0.29, which indicates relatively free-flowing traffic in the area (Department of Public Works and Highways 2013). Another factor to the moderate vulnerability in the area was that the station is surrounded by industrial factories and establishments, which contribute to their high concentration levels of PM_{10} and O_3.

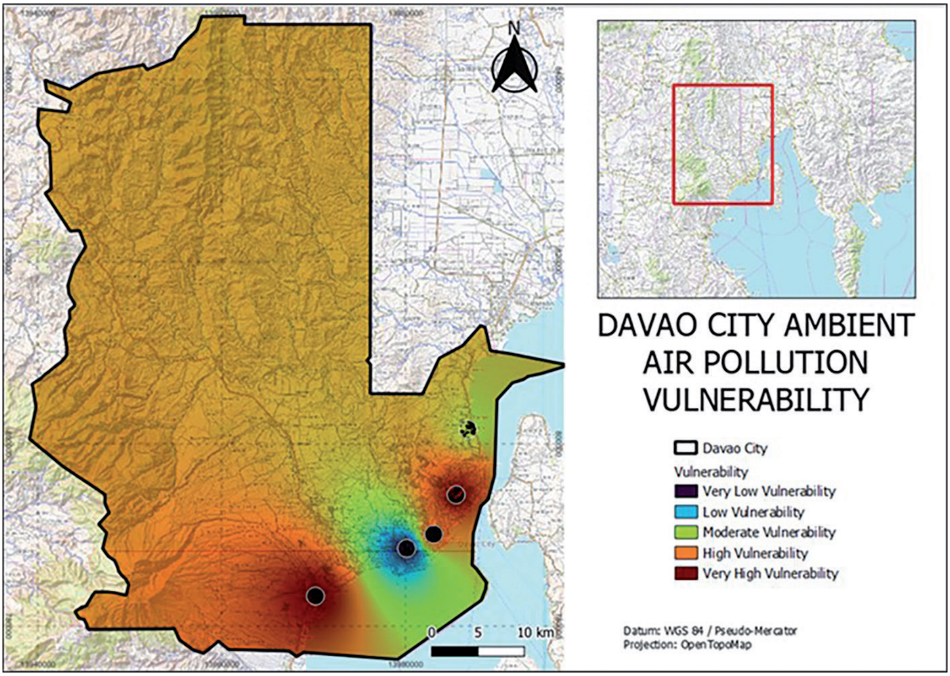

Figure 11. Davao city ambient air overlaid vulnerability map.

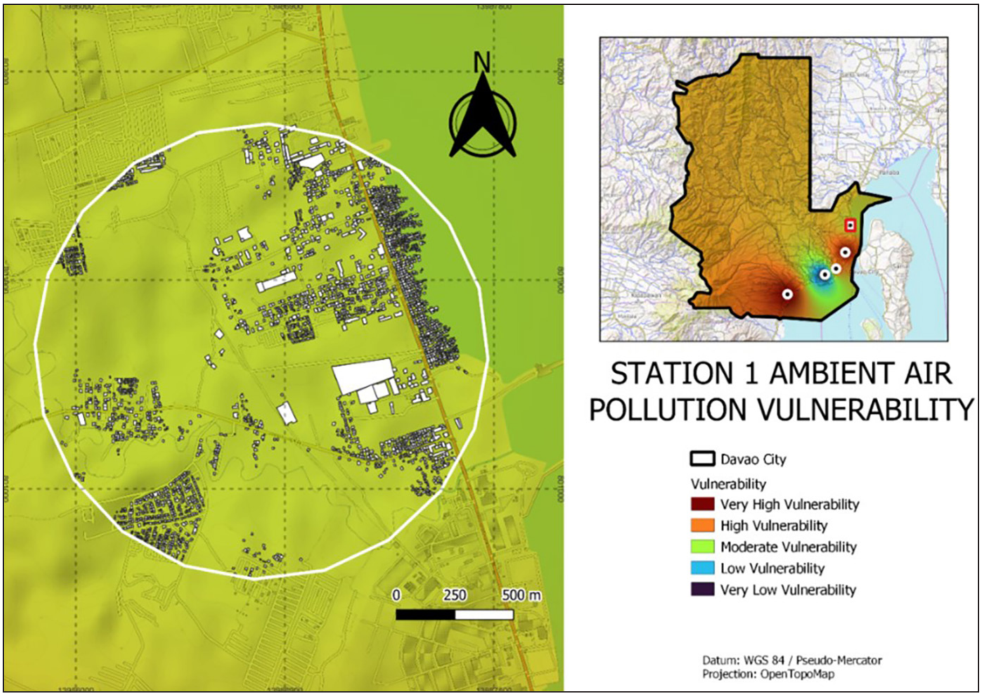

Figure 12. Ambient air pollution vulnerability map of station 1 (overlaid).

Presented in Figure 13 is the ambient air pollution vulnerability of Station 2 or Barangay 12-B station. It indicates a high vulnerability to ambient air pollution with 5.547 affected structures within its 1 km buffer: the second highest among the five stations. The area around station 2 is one of the busiest urbanized areas in the city. It is located close to one of the most crowded malls in the city, schools, a variety of economic establishments, convention center, and high-rise office buildings with an annual average daily traffic of 26.142 from 2017-2019. These vehicular emissions contributed to the high concentrations of PM_{10}. Many of these establishments utilize multiple air conditioning units, which produces nitrogen dioxide, ground-level ozone and other gases which are emitted as greenhouse gases into the atmosphere (Zafar 2021).

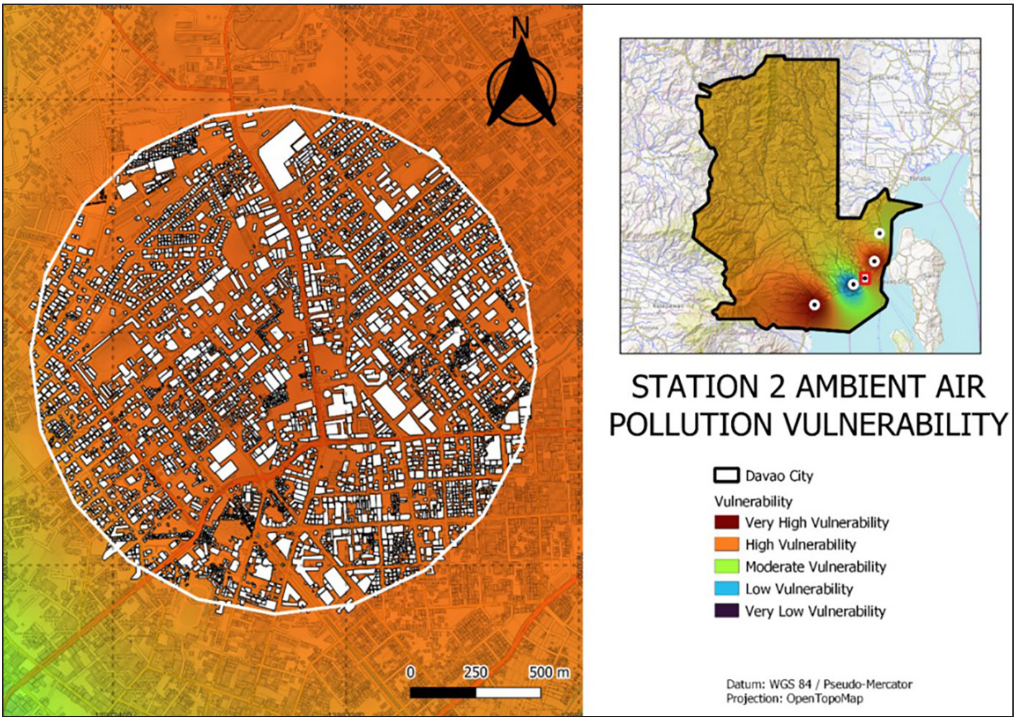

Figure 13. Ambient air pollution vulnerability map of station 2 (Overlaid).

Figure 14 shows the vulnerability of Station 3 or the Davao Memorial Park Phase II Station to ambient air pollution. Among all five stations in the city, only this particular station is at minimal or very low vulnerability to ambient air pollution. Station 3 only had 2.268 structures in its 1 km buffer, most of which were residential houses in neighboring settlements. Others include clusters of industrial establishments and bus garages along Maa Road and vehicular emissions from McArthur Highway. The area is less industrialized compared to the other stations. Industrial and commercial activities contribute significantly to the degradation of ambient air pollution in a given area (US et al. 2022). Station 11 is mainly surrounded by residential establishments. It had the lowest pollutant concentrations among the five stations, except sulfur dioxide.

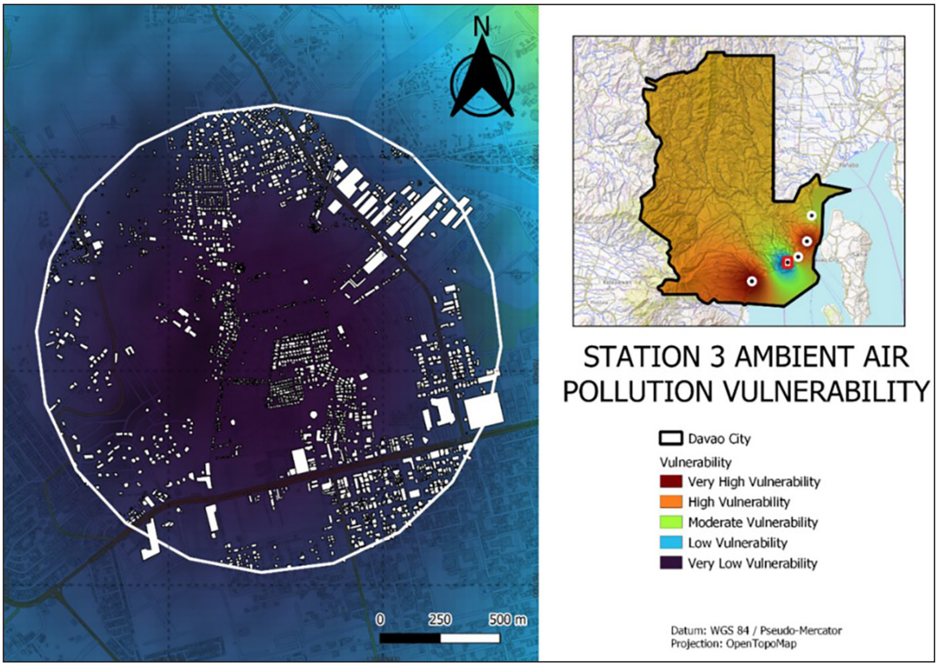

Figure 14. Ambient air pollution vulnerability map of station 3 (overlaid).

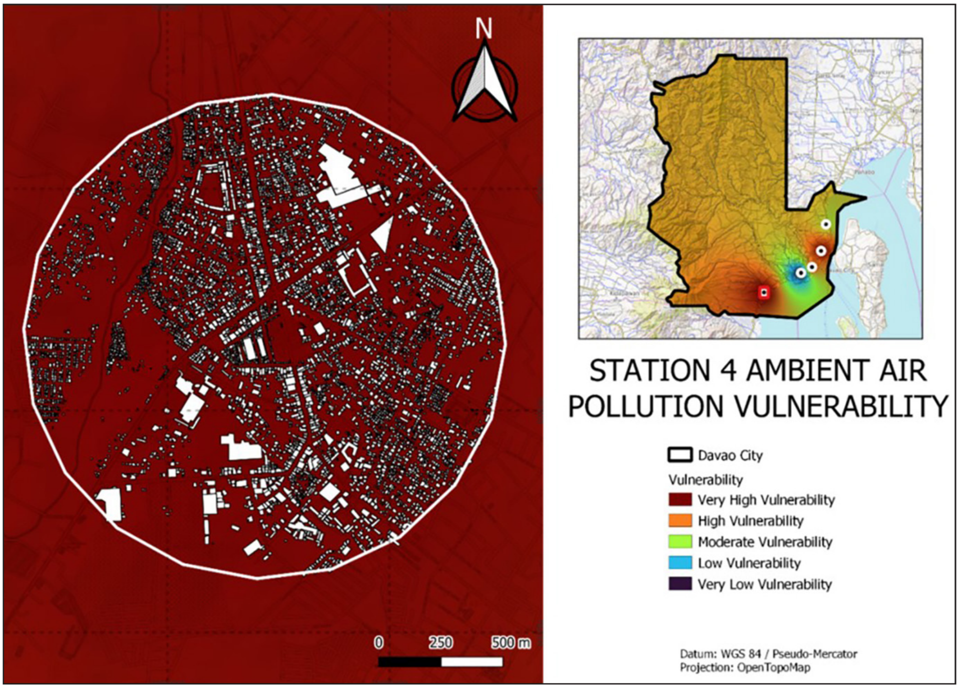

Figure 15. Ambient air pollution vulnerability map of station 4 (overlaid).

The ambient air pollution vulnerability of Station 4 or the Toril Open Park station is presented in Figure 15. It shows that the area is very highly vulnerable to air pollution and had the highest number of affected structures. with 8.018 delineated structures. The station is close to a shopping mall, wet market and various commercial and industrial establishments. It is also located in one of the busiest districts in the city with average daily traffic of 32.719 from 2017-2019. Many residents go to the district to conduct business and other miscellaneous activities. It is also located near a coal-fired power plant, a major producer of air pollutants like mercury, lead, sulfur dioxide, nitrogen oxides, particulates and various heavy metals (US Union of Concerned Scientists 2017). Factors such as vehicular traffic, many commercial and industrial establishments and its proximity to a coal-fired power plant would explain why Station 4 had the highest PM$_{10}$ and NO$_2$ concentrations among the five stations.

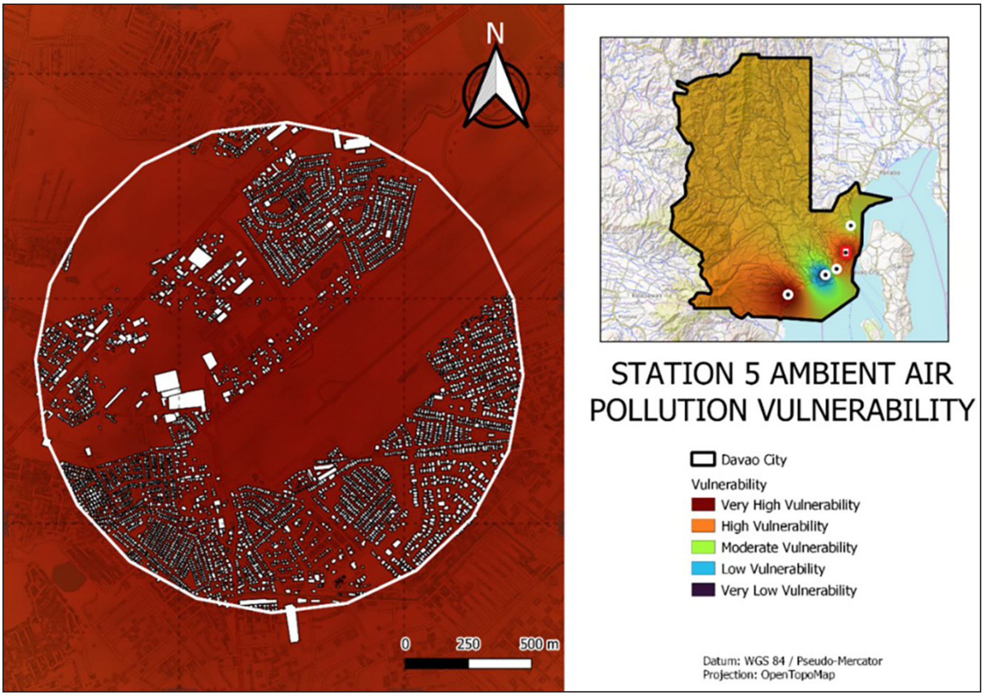

Figure 16. Ambient air pollution vulnerability map of station 5 (overlaid).

The ambient air pollution vulnerability of Station 5 or the Davao International Airport is shown in Figure 16.

AGL Open Area station is very highly vulnerable to ambient air pollution. This station has 5.107 affected structures within the 1 km buffer zone, most of which are residential. One factor that would explain the higher concentrations of air pollutants is the monitoring frequency. Unlike other stations, where the ambient air quality and air pollutant concentrations are only manually monitored once every six days. Station 5 uses a stationary device that measures air pollutant concentrations continuously (EMB 2019); meaning it collects data daily. Another factor in its very high vulnerability is that the station covers all aircraft emissions from the airport that is considered the third busiest airport in the country (Casamayor 2019), accommodating 29 domestic and two international flights daily (Cudis 2022). Passenger air travel is also considered the highest and fastest-growing contributor to individual air emissions producing a high amount of sulfur and nitrogen dioxide (Environmental and Energy Study Institute 2019).

Policy implications

Technical findings were found and policy implications or suggestions were formulated after overlaying the maps of the parameters. Policy implications help to indicate how the results of the study will be applied in practice (Cooley 2016). In this study the policy implications and suggestions are shown in Table 6.

Table 6. Technical findings and policy implication.

Technical Findings	Policy Implications
1. For PM_{10}. Station 4 had the highest concentration and the five stations had all exceeded the GAQGV of WHO.	Introduce stricter emissions limits for industries, power plants and other major PM_{10} sources. Enforce regulations to minimize dust from construction activities, including covering materials, watering roads and using dust suppression technologies. Strengthen the ordinance of no waste burning. Incentivize renewable energy adoption to reduce PM_{10} emissions from coal and other fossil fuels. Promote tree planting and urban green spaces to act as natural air filters.
2. For SO_2. Station 5 had the highest concentration and all of the said stations had increased the annual concentration.	Promote the adoption of renewable energy sources such as wind, solar and hydroelectric power to replace fossil fuels. Frequently monitor the emissions of industrial facilities. Incentivize energy efficiency measures to reduce overall fuel consumption. Set strict SO_2 emission limits for industries, particularly in sectors like oil refining, smelting and cement production. Invest in the restoration of ecosystems damaged by SO_2 and related pollutants, including reforestation and soil remediation projects. Expand green spaces in urban areas to absorb air pollutants and improve overall air quality.
3. For NO_2. Stations 4 and 5 had the highest concentration. Most of the stations had increased the annual concentration and all the stations had exceeded the GAQGV of WHO.	Monitor emissions from manufacturing plantations, industries and power plants. Promote energy efficiency measures to reduce overall demand. Phase out older, high-emission vehicles through scrappage schemes or low-emission zones. Expand urban green spaces, including trees and vegetation to absorb NO_2 and improve air quality. Design urban areas to reduce commuting distances and encourage sustainable transport options.

Technical Findings	Policy Implications
4. For O_3. Station 2 had the highest concentration and most of the stations had increased the annual concentration.	Check and monitor the level of emission of different power plants, industries and manufacturing plants. Procuring electronic tricycles or e-trikes to reduce emissions from motorized vehicles. Encouraging the residents to use public transportation instead of individual cars to reduce emissions. Encourage retrofitting or phasing out older, high-emission vehicles. Provide subsidies and tax incentives for EVs and hybrid vehicles. Promote afforestation and urban green spaces to improve air quality as trees can absorb VOCs.
5. Stations 4 and 5 were categorized as very highly vulnerable. Station 2 was categorized as highly vulnerable.	Strengthen implementation of existing policies on air pollution control and consistent monitoring of air pollutant concentration. Implement stricter air quality standards tailored to the region's specific vulnerabilities, aligned with WHO guidelines or more stringent levels if necessary. Enforce strict limits on industrial emissions, vehicular pollution and other major sources contributing to air pollution in these areas. Introduce or reinforce permitting systems for industries and activities with regular inspections and penalties for non-compliance. Implement vehicle retrofitting programs, phase out high-emission vehicles. and promote electric and hybrid vehicles. Provide subsidies or incentives for adopting cleaner cooking fuels or stoves in households that rely on biomass or coal.
6. Station 4 had the highest number of affected structures.	Encourage residents to walk if their preferred destination is located within the district to reduce vehicular emissions and traffic levels in short-distance travels. Develop regional air quality management plans targeting all major sources of pollution. Establish low-emission zones in urban centers to limit access for high-polluting vehicles. Invest in efficient, affordable public transportation to reduce reliance on private vehicles. Monitor and address the health impacts of air pollution, focusing on vulnerable populations like children, the elderly and those with pre-existing conditions. Expand urban green spaces and tree cover to mitigate pollution and improve air quality. Promote compact, mixed-use urban development to reduce commuting distances and encourage sustainable mobility.

CONCLUSIONS

This study concluded that all of monitoring stations in the city had greatly exceeded the GAAQGV set by the WHO for PM_{10} and NO_2. This indicates that a wide portion of Davao City is highly vulnerable to ambient air pollution. Nonetheless, concentrations of SO_2 and O_3 are within the threshold values set by the WHO. Moreover, most of the stations had increasing concentrations of the four pollutants. The vulnerability maps revealed that 23.928 structures are affected within the 1km buffer of the monitoring stations. There are 13.035 (54.48%) structures considered to be very highly vulnerable, 5.547 (23.18%): highly vulnerable, 3.078 (12.86%) are moderately vulnerable and 2.268 (9.48%) are very lowly vulnerable. A big part of the city was classified as highly vulnerable. Only the areas located around Station 3 were classified as lowly vulnerable and Station 1 as moderately vulnerable. Structures around Station 4 or Toril Open Park Area Station were some of the most affected by ambient air pollution in the city. It had the highest number of affected structures and is classified as highly vulnerable to ambient air pollution. Results indicate that implementing policies that ensure clean and ambient air must be strongly implemented in the community to address the problem of ambient air pollution.

RECOMMENDATIONS

The researchers recommend to the barangay officials to strengthen and expand the programs that would help mitigate ambient air pollution in the community; such as tree planting activities and procuring electronic tricycles or e-trikes to reduce emissions from motorized vehicles. Residents may take measures to help curb the problem of ambient air pollution. Environmental Management Bureau should install additional Ambient Air Quality Sampling Equipment across the city to assess the air quality and pollutant concentration on a broader scope. The scientific community and future researchers may examine the seasonal variations of pollutants and compare results with other cities.

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