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Understanding NO_2 Concentration Dynamics within Tema Metropolitan Area of Ghana Using Generalized Linear Model

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Abstract: The concentration of nitrogen dioxide (NO_2) is worsening across the globe alongside growth in industrial and general anthropogenic activities. Due to its serious health implications with long-term exposure, studies on NO_2 concentration have gained space in the academic literature. In this study, awareness is created on the levels of NO_2 across four (4) locations within the Tema Metropolitan area, with specific interest in selecting locations and periods significantly saturated with NO_2 within the study area. NO_2 was measured using RKI Eagle, an instrument with a built-in sensor for a specific gas measurement. Measurements were taken day and night at sampling points around 100 meters apart in each location. Data collection was performed over a nine (9)-month period. The Generalized Linear model is explored for selecting locations and periods significantly affected by NO_2. From the results, the fourth week (26th–31st) of July 2020, the fourth week (27th–31st) of December 2020, the first week (1st–7th) of January 2021, and the fourth week (24th–31st) of January 2021 recorded severe concentrations of NO_2. Additionally, the lives of residents in the Oil Jetty and the VALVO hospital areas were found to be the most endangered, as they recorded significantly high concentrations of NO_2. In a developing country such as Ghana, this study is useful for monitoring NO_2 concentrations in similar areas to inform decision making and environmental policy formulation.

Keywords: NO_2 concentration; generalized linear model; Ghana; environmental policy; anthropogenic activities

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1. Introduction

High levels of NO_2 concentration are largely associated with industrialization and urbanization [1,2], and the corresponding increase in road vehicles [3]. Although NO_2 is not a carcinogen, there are several studies linking long exposures to NO_2 to high risk of acquiring lung cancer. In one such study by Hummer et al., 2015, titled "Lung cancer and exposure to NO_2 and traffic; a systematic review", consistent evidence of a correlation between NO_2 and cancer was well-established [4]. The danger of long exposure to high concentrations of NO_2 to human health ranges from bronchial and lung cancer [5,6], to deterioration in the management of severe asthmatic conditions in patients [7]. The consensus is reached among public health professionals on the fact that air pollution increases morbidity for respiratory and cardiovascular conditions and usually results in premature death [8–13]. Therefore, many studies pay serious attention to NO_2 concentration levels by way of putting forth policies that attempt to reduce NO_2.

The European Union (EU) is implementing one of such integrated environmental policies to help improve air pollution at national and subnational levels [14]. There is an outstanding issue of variability in urban air-pollution research. Many of these studies [15–17] have concluded that representativeness is challenged by the adoption of fixed-site measurements and limits the possible association between exposure and the exact effects of air pollution on residents. The need for direct, personal level exposure measurement remains a very relevant issue along with measurements of many associated environmental stressors [18].

In essence, air-quality monitoring involves the processes of determining the appropriate number of stations, sampling sites, and measurement methods [18]. That is, placing monitoring stations or sampling points at carefully selected representative locations chosen based on the dispersion patterns of pollutants. Han and Naeher [19] outline the objectives for developing air-quality measurement and monitoring strategies that include facilitating background concentration measurements, monitoring current levels as a baseline for assessment, and checking air quality relative to standards and limit values, plus strategies to determine the exposure and assess the effect of air pollution on health, vegetation, and materials, to observe trends related to emissions and to develop abatement strategies, to inform the public or affected communities on the air quality and raise awareness, to develop warning systems for the prevention of undesired air pollution episodes, and finally to supply data for research investigations.

Generally, air-pollution levels around the Tema industrial area of the Greater Accra Region have seen no reduction in recent years [20]. Designing an optimal air-quality monitoring network around areas of industrial activities such as Tema Ghana will help environmental authorities and policymakers manage and control air-pollution sources [21]. In this work, the selection of NO_2 as a study pollutant was determined by the relationships it stands to have with the various emissions from the industry and its health impacts on people in and around the location. Based on each of the above considerations, this preliminary study aims to measure the NO_2 concentrations in the selected locations, to raise awareness of the urgency to implement mitigation actions. Specifically, the study measured urban ambient NO_2 concentrations and studied the spatial variability of pollutant concentration within four locations in the Tema Metropolis.

Similar to [20], the generalized linear model (GLM) is employed in the assessment of the variation characteristics of NO_2 concentrations within four selected communities in the Tema Metropolitan area. The main aim of this study is to select locations and periods with high concentrations of NO_2. The current study is novel both in geographical location and the scope of the statistical techniques used in the selection of significant periods and locations. This study contributes to the empirical literature by providing the results of data analyzed from a sub-Saharan country. It also fills an important gap by making the public aware of the extent of exposure of people in the selected locations to pollution of NO_2. It is therefore expected that this paper will form the basis for a well-coordinated air-pollution prevention and control plan for the Republic of Ghana.

2. Materials and Methods

2.1. Study Area

Tema is about 30 to 40 kilometers from Accra, the capital of Ghana. Tema is a host to many heavy industrial firms, including Ghana's main seaport, Tema Oil Refinery (TOR), Volta Aluminium Company (VALCO), and Volta River Authority (VRA) Header Station. It is estimated to be home to over 1 million residents. The key communities along the industrial route include Abonkor, Manhean, and Bankuman, all within 10 km of each other. Figure 1 shows the earth picture of the area within which sampling sites were chosen. The basis for setting the four sampling sites and the emission source around sampling sites is because they are the major areas along the right of way of the gas pipeline construction and are the area of influence of all industrial activities within the area.

2.2. Measurement of NO_2

NO_2 was measured using RKI Eagle, an instrument with a built-in sensor for a specific gas measurement, in this case, a standard toxic sensor for $NO_{x.}$ Since the monitoring was performed on the right of way of a gas pipeline, it was ideal to use RKI Eagle, which is well-known for monitoring of high exposures. Because of the industrial setting and the movement of heavy-duty equipment and trucks at the times of construction, it was ideal to use such equipment in monitoring NO_2 concentration. If equipment that measures low levels of NO_2 concentration was to be used, extremely high values would have been recorded.

A sample hose was connected to the instrument's quick-connect inlet fitting. A hydrophobic filter and probe tip were then connected to the sample hose's quick-connect fitting. The instrument was then aired to accumulate time-weighted average (TWA) before readings were taken. The instrument performs direct simultaneous measurements of the gases. The baseline value is the average of four-week NO_2 concentration values prior to data collection for this study. Monitoring and readings taken twice a day (day and night) at sampling points about 100 m apart in a selected location. Monitoring was conducted once every week, within a sampling period of 24 h per location, for a total of 36 weeks. Daytime averages were calculated using a 8 to 12 h interval, while the time interval for nighttime was strictly 12 h. NO_2 concentration classification was based on Ghana Standard (GHA) [22], International Financial Corporation guidelines (IFC) [23,24], and baseline values.

2.3. Statistical Analysis

The generalized linear model (GLM) was explored in the selection of communities and periods affected by NO_2. In theory, GLM is an extension of linear regression [20,25–27]. The distribution of the predictor variables is not restricted to the normal distribution alone as it is with the linear regression. The distribution of the predictor variables are now allowed to belong to the exponential family of distributions that includes the normal distribution. The assessment of model goodness-of-fit is therefore similar to that of the linear regression, but in the case of GLMs, standardization of residuals instead of residuals is required. Specifically, the NO_2 concentration model is expressed as a linear function of regressors.

$$\eta_i = \beta_0 + X_{ij}\beta_j + \ldots + X_{ij}\beta_j = X'_{ij}\beta \quad (1)$$

where $i = 1, 2, 3, \ldots, n$ (total weeks observed), $j = 1, 2$ (independent variables; weeks, location) on which the expected value μ_i of Y_i (NO_2 concentration) depends. An invertible link function $g(\mu_i) = \eta_i$, is also inherent, which transforms the expectation of the response to the linear predictor. The inverse of the link function is referred to as the mean function. All data processing and statistical analyses were performed in R 3.5.2 (http://www.R-project.org/, accessed on 28 June 2021).

Figure 1. Location of Study Area (Source: Google Earth, accessed in January 2021).

3. Results

3.1. NO_2 Concentration across the Four (4) Locations

The chi-squared test in Table 1 examines whether there exists an association between NO_2 concentration (categorized based on the standard benchmarks (IFC or GHA)) across study locations. NO_2 concentration classification (pollution vs. no pollution) was based on

Ghana Standard (GHA) [22], International Financial Corporation guidelines (IFC) [23,24], and baseline values. Values of NO_2 concentration above the threshold were classified as pollution, while those below were classified as no pollution. The results reveal a general spread of the NO_2 concentration across the locations studied (chi-squared: $p < 0.423$, based on $N0_2$ (IFC); $p < 0.663$, based on NO_2 (Ghana)). The test hereby concludes the existence of no association between NO_2 concentrations. All four locations are equally exposed to NO_2 concentration.

Table 1. NO_2 concentration across the four (4) locations.

Pollutant	Location	No Pollution	Pollution	Chi-Squared
NO_2 (IFC)	Abonkor	9	27	0.423
	Bankuman	4	32	
	Oil_Jetty	5	31	
	Valco_Hosp	6	30	
	Total	24	120	
NO_2 (GHA)	Abonkor	3	33	0.663
	Bankuman	2	34	
	Oil_Jetty	4	32	
	Valco_Hosp	5	31	
	Total	14	130	

3.2. Differences between Baseline and Study Period NO_2 Concentration Levels

A paired sample test was conducted for baseline NO_2 concentrations before the study and for those observed during the study period. Table 2 presents descriptive statistics, while the test result is found in Table 3. The mean baseline NO_2 concentration was found to be 76.489 (0.7222), with the observed mean NO_2 concentration being 342.5 (9.589). According to the IFC guidelines, an average weekly NO_2 value ≤ 200 ($\mu g/m^3$) is acceptable while an average weekly NO_2 value ≤ 150 ($\mu g/m^3$) is acceptable for the Ghana Standards. For these two benchmarks, the average weekly NO_2 value is clearly beyond the limits and gives an indication of an NO_2-polluted environment.

Table 2. Paired Samples Statistics.

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	NO_2_Base	76.489	140	8.5454	0.7222
	NO_2	342.500	140	113.4681	9.5898

Table 3. Paired Samples Test.

		Paired Differences					t	df	Sig. (2-Tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	NO_2_Base-NO_2	−266.01	112.5889	9.5155	−284.83	−247.19	−27.95	139	0.000

The test in Table 3 examines whether differences exist between baseline NO_2 concentration and study period concentration levels. The results of the paired *t*-test indicate that there exists a significant difference between baseline NO_2 concentration levels and study period NO_2 concentration levels (t(df = 139) = 127.956, $p < 10^{-4}$). The level of NO_2 concentration recorded for the four locations over the study period was significantly higher than that seen before. This is evidence of a worsening incidence of NO_2 pollutants within the study area. It does not appear to be getting better week by week.

3.3. Model for NO_2 Concentration

The fitted Gaussian GLM as shown in Table 4, selected the fourth week of July 2020, the fourth week of December 2020 entering the first week of January 2021, and the fourth week of January 2021 as those that recorded significantly high levels of NO_2 pollution in the Tema Metropolitan area. Additionally, of the four (4) communities, Oil Jetty and VALCO hospital are clearly polluted with respect to NO_2 concentration. There were higher NO_2 concentrations there because there was an increase in excavation works, frequent vehicular movement, and the use of heavy machineries in construction activities at the sites while monitoring was ongoing.

Table 4. Significant variables estimates for NO_2 concentration.

	Estimate	Std. Error	t Value	Pr(>|t|)
(Intercept)	6.31944	1.02979	6.13661	0.0000
4 December 2020	3.25	1.39922	2.32273	0.02212
4 July 2020	−5.5	1.39922	−3.93077	0.00015
4 January2021	4	1.39922	2.85874	0.00513
Dec/Jan	−4	1.39922	−2.85874	0.00513
Oil Jetty area	1.02778	0.46641	2.20362	0.02974
Valco Hospital area	1.02778	0.46641	2.20362	0.02974

To ensure that the NO_2 concentration model has the required quality and goodness of fit, model-checking plots as shown in Figure 2 were used. Also, the time series plots of the NO_2 concentration for the sampled sites are shown in Figure 3. From Figure 2, the plot of residual vs. fitted (first plot) tries to assess whether the model is adequately specified. For an accurately specified model, there should be no form of marked trend in plot one [25–27]. From Figure 2, the first plot clearly has no form of marked trends, indicating a well-specified model. The second plot (absolute residual vs. fitted) examines the stability of the variance function, with a suitable model showing a flat trend. As evident in plot two, the relatively stable slope is an indication that errors are stationary and nonincreasing. The normal probability plot (third plot) is used together with the histogram of studentized residuals (fourth plot) to assess the normality assumption and possible outlier effects. From these two plots, the data set can be said to be normal and free from outlier effects.

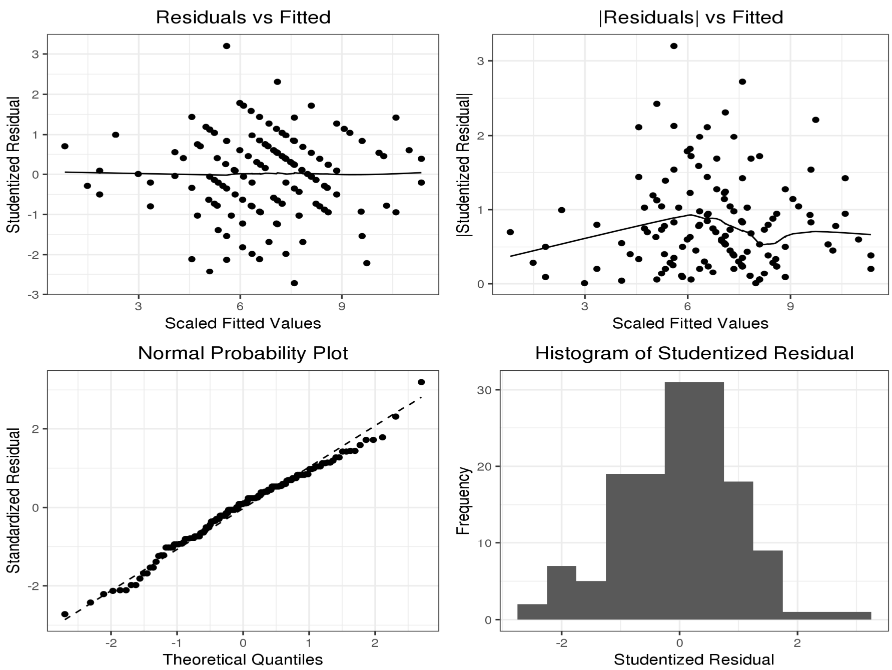

Figure 2. Diagnostic plots of NO_2 concentration based on the Gaussian model.

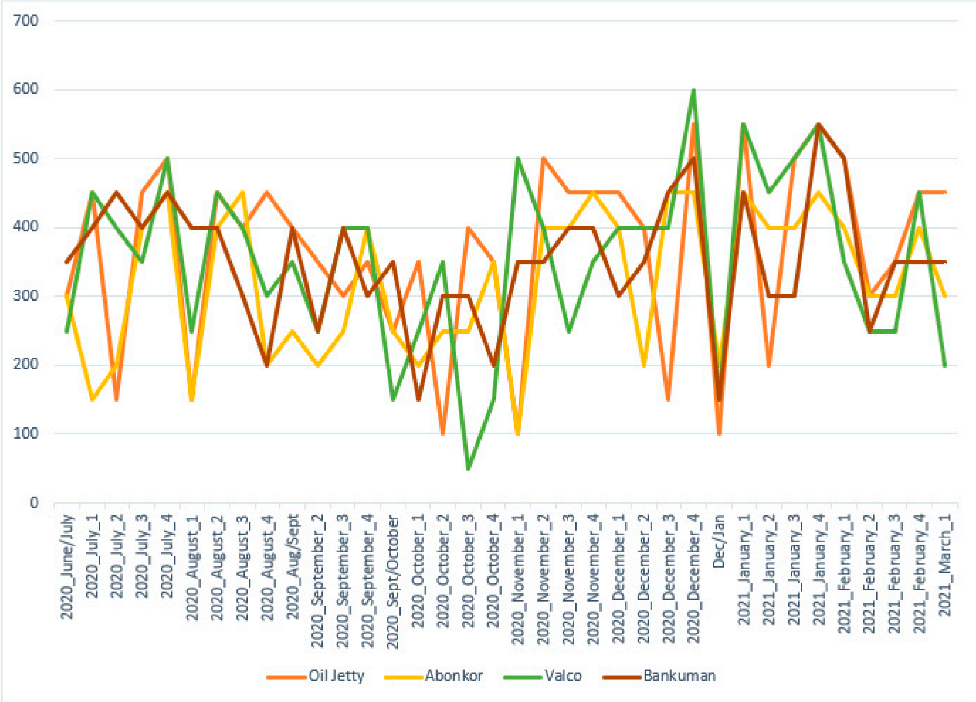

Figure 3. Plot of NO_2 concentration for sampled sites.

4. Discussion

To enable us to accurately select NO_2 concentrations across the weeks and locations within the selected areas, a Gaussian generalized linear model (GLM) was used. Other studies [28] explored the Land Use Regression (LUR) model to analyze the characteristics of NO_2 concentrations with data from selected locations and administrative units of urban and nonurban regions in South Korea. In [20], GLMs were explored to select areas and periods affected by dust pollution. The findings of this current study support the fact that areas with high dust pollution have a high risk of NO_2 concentration, especially around construction and industrial sites. Whereas Sarpong et al. [20] revealed the oil jetty area and the VALCO hospital area had very high concentrations of dust pollution, this current study has revealed that the lives of residents in the Oil Jetty area and VALVO hospital area are found to be the most endangered [20], as they recorded significantly high concentrations of NO_2 pollutants. The VALVO hospital area is a heavily industrial area, with various industrial activities resulting in release of harmful gases. The Oil Jetty area is an anchorage and mooring area, and usually fumes from vessels and other automobiles contribute to NO_2 emissions there.

Many previous studies have examined the concentrations of NO_2 from various angles. For instance, [29,30] compared the accuracy of satellite images and observations based on variations in R^2 values. In the absence of such exhaustive data, this study tries to report findings based on observed measurements from four different geographical locations, creating awareness and calling for urgent attention from all relevant stakeholders. A key strength of this current study is its attempt to provide accurate information on NO_2 concentrations in defined locations. It will promote decision making that reflects specific location dynamics (e.g., mapping out an appropriate response strategy). In [28], prediction of NO_2 concentrations was performed by region, leading to low accuracy as a result of a limited number of sampling sites with the required density of NO_2.

Fortunately, for this study, Tema is a heavily industrialized city in Ghana, hence possessing the propensity to have sampling sites with the required density of NO_2. With all four study locations located in Tema, NO_2 concentrations across all locations were high, with the Oil Jetty area and VALVO hospital area being heavily endangered with significantly higher concentrations of NO_2, largely due to their direct contact with industrial pipes and heavy factory deposits [20]. The industries responsible for the pollution phenomenon along these areas are Tema Oil Refinery (TOR), Volta Aluminum Company (VALCO), a cement-producing company and the port and harbor operations.

One major weakness of the current study is the absence of exhaustive environmental variables from the same city, which could have been classified and examined to assess their contribution to NO_2 concentration. Road-related variables such as road length [1,31], road type [32–35], and others, could have improved the generalizability of our findings. The authors are advanced in proceeding to collect data on an exhaustive list of variables for further research within the Tema industrial area and the Greater Accra region of Ghana. Additionally, our equipment was sometimes carried away by strong winds and bad weather conditions, which may have disrupted the monitoring process. Finally, the monitoring sites considered in this study by the random process covered communities along an ongoing gas pipeline construction project with unfriendly conditions, such as excavation, usage of machines and vehicles that use fossil fuels in their operation and unpaved access roads. This led to extremely high values of NO_2 concentrations.

5. Conclusions

In this study, generalized linear models (GLM) are employed in the assessment of the variation characteristics of NO_2 concentrations within our selected communities in the Tema Metropolitan area. One shortcoming of this current study is the absence of long-run data, with more environmental variables, and over more communities. That notwithstanding, this study has been able to accurately select some time periods as well as areas (the Oil Jetty and VALCO hospital) that are the most affected by NO_2 concentrations. One vital implication of the study is that residents living in and around the Oil Jetty and VALCO hospital areas should take steps to engage city managers in measures related to limiting the extent of exposure to NO_2. This study will also be very useful in decision making in developing countries such as Ghana, where data and literature are usually lacking on environmental pollutants.

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