SPATIO-TEMPORAL INFLUENCE OF FLARE STACK PROXIMITY ON THE SPREAD OF AIR POLLUTANTS IN THE BRACED STATES

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ABSTRACT

The study examined the spatio-temporal influence of flare stack proximity on air pollutant dispersion in the BRACED states of the Niger Delta, Nigeria. Field data were collected from six states with intensive oil and gas activities using stratified purposive sampling. Measurements of CO_2, SO_2, and NO_2 were taken at distances of 250 meters, 500 meters, 750 meters, and 1 kilometre from flare stacks, across wet and dry seasons. Results indicated that pollutant concentrations were highest at 250 meters, with CO_2 peaking at 38.7 ± 5.2 ppm, SO_2 at 31.4 ± 4.8 ppm, and NO_2 at 29.9 ± 3.7 ppm, confirming the distance decay model. Concentrations declined significantly with distance, reaching their lowest at 1 kilometre due to atmospheric dilution. Seasonal analysis revealed elevated emissions during the wet season, particularly in September, with higher morning concentrations attributed to thermal inversions and stable atmospheric conditions. MANOVA results showed significant effects of proximity and location on emissions (F = 47.998, p < 0.001), while Tukey post-hoc tests revealed spatial disparities, with Bayelsa and Rivers states recording consistently higher pollutant levels. CO_2 remained dominant at longer distances due to its chemical stability. The study underscores the spatial non-uniformity of air pollution, the significance of climatic variation, and pollutant-specific dispersion dynamics. These findings support the need for buffer zones of at least 750 meters around flare stacks, spatio-temporal air quality monitoring, and gas-specific mitigation strategies to reduce public health risks in oil-producing communities.

INTRODUCTION

Air pollution associated with gas flaring in the Niger Delta region presents a significant environmental and public health concern. The region, which hosts the majority of Nigeria's oil and gas activities, is characterised by extensive emissions of greenhouse gases such as carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen dioxide (NO_2). These pollutants arise largely from petroleum-related operations and contribute to atmospheric degradation, with severe implications for human health, ecological integrity, and environmental sustainability (Akpoghelie *et al.*, 2021; Falih *et al.*, 2024). Despite increasing awareness of the risks associated with these emissions, systematic understanding of their spatio-temporal dynamics remains limited. Previous studies have confirmed the presence of harmful pollutants in oil-producing communities (Raimi & Sawyerr, 2022; Ezennubia & Vilcáez, 2023), yet few have addressed how their concentrations vary with proximity to flare stacks and under differing climatic conditions (Oliveira & Corrêa, 2022; Zangana, 2025). The region's tropical monsoon climate, marked by distinct wet and dry seasons, as well as diurnal shifts in temperature, humidity, wind speed, and rainfall, creates a complex atmospheric environment that influences pollutant dispersion and accumulation (Boyitie *et al.*, 2024).

In addition, the socio-environmental conditions, including high population density and inadequate monitoring infrastructure, further complicate the pollution landscape. The Niger Delta's gas flaring activities pose a significant environmental challenge due to the persistent emission of greenhouse gases. Existing research and policy frameworks fail to address the spatial distribution and temporal variability of these pollutants, which are influenced by flare stack proximity and climatic influences. The lack of spatially disaggregated data and studies that integrate seasonal and diurnal climatic variability limits the predictive accuracy of pollution models and weakens the scientific basis for environmental risk assessments. The underuse of inferential statistical tools in existing analyses also hampers the translation of scientific findings into policy recommendations. Monitoring infrastructure in the Niger Delta is insufficient and fragmented, resulting in sporadic data collection and limited temporal coverage. This study aims to address these gaps by offering a rigorous spatio-temporal assessment of greenhouse gas emissions in relation to flare stack proximity and climatic conditions. The study is designed to fill that gap by evaluating the spatial gradients of greenhouse gas emissions in relation to flare stack proximity and assessing how pollutant proximity changes seasonally and diurnally across selected oil-producing BRACED states in the Niger Delta. By offering a comprehensive spatio-temporal analysis of air pollution in the Niger Delta, the study contributes to a more nuanced understanding of emission behaviour in industrialised tropical environments. The

outcomes will provide essential evidence for the formulation of effective environmental health interventions, emission control policies, and sustainable development strategies aligned with the United Nations Sustainable Development Goals, particularly those related to climate action, good health, and sustainable cities.

Conceptual Issues: Distance decay, a principle in spatial interaction theory, is crucial in environmental science for understanding the dispersion of pollutants from emission sources (Gao *et al*., 2021). In the Niger Delta region of Nigeria, where gas flaring is a prevalent and poorly regulated practice, distance decay provides a theoretical and empirical lens to examine atmospheric pollutants' distribution. This concept is central to assessing greenhouse gases and hazardous emissions from flare stacks, especially when influenced by climatic factors like wind, temperature, and humidity. Pollutants in the Niger Delta are distributed in spatial gradients influenced by natural and anthropogenic factors. The distance decay model suggests that environmental influence is strongest near the source and weakens with spatial separation (Clark *et al*., 2021). Distance decay is a fundamental concept in understanding pollutant dispersion, but its interaction with climatic variables adds complexity to environmental exposure patterns (Johnson, 2022). In the Niger Delta, where the climate is tropical monsoon with wet and dry seasons, atmospheric conditions like wind speed, temperature, humidity, and rainfall influence the dispersion of pollutants. In the dry season, lower humidity and higher temperatures facilitate upward dispersion, while increased precipitation and lower temperatures limit vertical dispersion and lead to pollutant washout (Lin *et al*., 2024). Diurnal variations, such as temperature inversions in the early morning and late evening, trap pollutants close to the surface and restrict vertical mixing, causing elevated concentrations near flare stacks. The influence of distance decay is temporally sensitive, necessitating the integration of climatic parameters for accurate representation of air pollution behaviour (Long *et al*., 2025).

Distance decay is crucial for effective environmental governance, as it helps policymakers define buffer zones around gas flaring, establish air quality monitoring thresholds, and develop targeted mitigation strategies. Spatially explicit models can guide land use planning, ensuring industrial activities are sited away from ecologically sensitive areas (Zurell *et al*., 2022). Distance decay also impacts public health, as residents near flare stacks are disproportionately exposed to harmful pollutants, leading to increased rates of respiratory and cardiovascular diseases (Arab *et al*., 2024). Health risk assessments can identify high-risk zones, allocate healthcare resources, and support community advocacy. These models provide a scientific basis for environmental injustice (Aker *et al*., 2024). Distance decay is a concept used in environmental studies to reduce pollution exposure and enhance urban resilience. It aligns with the United Nations Sustainable Development Goals, particularly Goals 3 and 13. By integrating spatial analysis into environmental impact assessments and climate adaptation strategies, it contributes to sustainable development and environmental justice in vulnerable regions like the Niger Delta. This approach provides theoretical insight and practical tools for environmental assessment, policy development, and public health planning. In regions with industrial pollution, climatic volatility, and socio-economic vulnerability, distance decay integration is both analytically sound and ethically imperative.

MATERIALS AND METHODS

The study was conducted in six states within the Niger Delta region of Nigeria, namely Bayelsa, Rivers, Delta, Akwa Ibom, Cross River, and Edo, collectively known as the BRACED states (Fig. 1). The BRACED states were purposefully selected due to their prominent role in Nigeria's oil and gas sector, which is a major contributor to greenhouse gas (GHG) emissions, particularly from gas flaring activities. The selection of sites for petroleum exploration and production in various states was based on stratified purposive sampling, identifying locations based on proximity to active flare

sites, industrial zones, and communities with documented exposure to oil and gas-related pollution. Two main categories were defined: high-intensity flaring zones in rural or semi-urban oil-producing communities and medium-intensity zones near industrial operations with less flaring activity (Table 1).
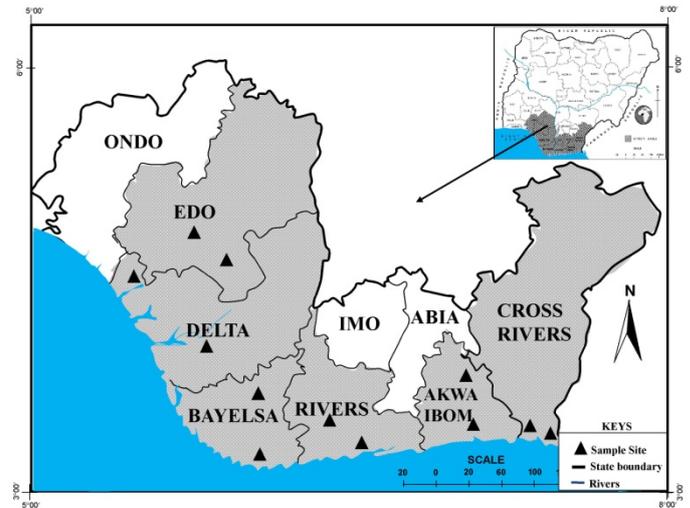

Fig. 1. Map showing The BRACED states of the Niger Delta

Table 1. Classification of flare sites

States	Locations	Classification of Flare
Akwa Ibom	Uyo	High Intensity
	Eket	Medium Intensity
Bayelsa	Brass	High Intensity
	Yenagoa	Medium Intensity
Cross Rivers	Calabar	High Intensity
	Ikang	Medium Intensity
Delta	Forcados	High Intensity
	Warri	Medium Intensity
Edo	Ologbo	High Intensity
	Okada	Medium Intensity
Rivers	Bonny	High Intensity
	Port Harcourt	Medium Intensity

Source: Authors Computation (2024)

The study aimed to understand the spatial and temporal dynamics of greenhouse gas (GHG) emissions in the Niger Delta, focusing on flaring proximity. A mix of onshore and nearshore oil production areas was selected, ensuring accessibility and security for researchers. The selection was based on the concentration of flaring operations and reported air pollution impacts in these regions. The study adopted a mixed-methods design, integrating quantitative environmental measurements with geospatial and statistical analyses. The explanatory research design, structured around geospatial sampling, environmental monitoring, and statistical modelling, facilitated the investigation of the relationship between flare stack proximity and meteorological variability across selected oil-producing states in the Niger Delta. The design was guided by previous air quality studies in flaring zones (Pratt *et al*., 2022; Tran *et al*., 2024). To examine the spatial distribution of GHG emissions (CO_2, SO_2, and NO_2), direct measurements were carried out at predefined distances of 250 meters, 500 meters, 750 meters, and 1 kilometre from identified flare stacks. Direct measurements were taken at predefined distances, using a stratified random sampling technique. Portable air quality monitoring instruments, calibrated electrochemical gas sensors, were used to capture pollutant concentrations. The sensors were deployed along transects radiating from each flare stack to obtain real-time data. Air pollutant concentrations were measured twice daily for both dry (February) and wet (September) seasons to account for temporal variability. Data collection spanned a three-month period for each season, with February chosen for its low precipitation, increased atmospheric stability, and high flare visibility, while September was chosen for its high rainfall, increased humidity, and atmospheric

cleansing, which typically reduce surface-level pollutant concentrations. An additional third month was included as a transitional phase to enhance temporal comparability and verify consistency across early and late seasonal conditions. This approach provided a representative temporal framework to observe seasonal effects on pollutant distribution without meteorological interference. The study collected data during two specific timeframes: morning hours between 7:00 and 9:00 AM and evening hours between 5:00 and 7:00 PM. These times were chosen to ensure atmospheric stability and minimal convective turbulence, enhancing the reliability of surface-level greenhouse gas (GHG) concentration measurements. Morning hours were chosen due to lower ambient temperatures and reduced vertical mixing, allowing for more accurate capture of emissions close to the ground before they are dispersed by increased solar radiation and thermal updrafts later in the day. Early morning periods often represent peak hours for human activity, reflecting emission levels under active conditions. Evening measurements were conducted during the transition from daytime heating to nocturnal cooling, characterized by declining atmospheric instability and surface temperature inversions, trapping pollutants near the ground. These periods optimized the accuracy and consistency of GHG data by reducing diurnal variability and atmospheric noise, which are commonly observed during midday hours due to higher solar radiation and wind-induced dispersion (Delkash, 2021; Tinsley, 2022). The instruments were kept at a fixed height of 1.5 meters above ground level to replicate human breathing zones, as recommended by the Nigerian Meteorological Agency. The study excluded meteorological parameters to avoid potential covariates and to ensure a more direct interpretation of proximity-related emission patterns. The Niger Delta region's high intra-regional meteorological uniformity during the study periods allowed for a more direct interpretation of emission patterns, avoiding the introduction of multiple covariates.

The study used Euclidean distance modelling to analyse emissions at different distances, and quantitative data was analysed using IBM SPSS version 27. Descriptive statistics were computed for pollutant concentrations at each distance and season. Inferential statistical methods were applied to test the study hypotheses, including a Multivariate Analysis of Variance (MANOVA) to assess the influence of flare stack proximity and geographic location on greenhouse gas emissions. A Tukey HSD post-hoc test was used to determine the significance of differences in emissions across locations and distances. Instruments were pre-calibrated using standard gases and cross-checked against known concentration levels before field deployment. Environmental sampling was conducted in adherence to ethical guidelines, with access to flare sites secured through collaboration with local agencies and oil companies. Community consultations were held to inform residents about the study's objectives and obtain consent for sampling within their environments. The methods employed are consistent with international best practices for atmospheric studies and align with analytical requirements.

RESULT AND DISCUSSION

Table 2 shows spatial variation in greenhouse gas emissions (CO_2, SO_2, and NO_2) at different distances from flare stacks in the Niger Delta region. The study supports distance decay theory, which suggests that pollutant intensity decreases with distance from the source. Maximum concentrations were found at 250 meters, indicating flaring's immediate impact on air quality. At 500 meters, values decreased to 30.5 ± 4.6 ppm, indicating partial air dilution. At 750 meters, levels decreased significantly, indicating distance decay's continued impact. The study found that CO_2, SO_2, and NO_2 concentrations decreased at 1 km, indicating lower pollutant concentrations.

Table 2. GHG Emission from Various observed Distance

Distances	CO_2	SO_2	NO_2
250m	38.9 ± 3.4	39.1 ± 11.7	25.3 ± 6.4
500m	30.5 ± 4.6	25.8 ± 11.8	23.7 ± 11.6
750m	19.0 ± 3.7	19.9 ± 15.1	19.8 ± 12.2
1km	13.1 ± 12	13.7 ± 14.6	13.4 ± 5.6

Source: Fieldwork (2024)

Table 3. Mean Seasonal and daily measurement of GHG emission in the Niger Delta

SO_2 (µg/m³)							
States	**Akwa Ibom**	**Bayelsa**	**Cross Rivers**	**Delta**	**Rivers**	**Edo**	**Average**
September	13.1	25.6	19.8	24.7	26.7	19.7	21.6
February	10.9	23.5	15.2	21.8	24.3	15.6	18.6
Morning (0700 hr)	12.4	25.1	18.3	23.9	25.6	18.2	20.6
Evening (1900 hr)	11.5	24.0	16.7	22.6	25.4	17.1	19.6
CO_2 (µg/m³)							
States	**Akwa Ibom**	**Bayelsa**	**Cross Rivers**	**Delta**	**Rivers**	**Edo**	**Average**
September	22.8	26.5	25.4	26.3	26.8	25.0	25.5
February	23.6	27.1	25.4	26.3	24.1	25.1	25.3
Morning (0700 hr)	25.2	27.6	26.9	27.0	26.6	25.7	26.5
Evening (1900 hr)	21.1	26.1	23.9	25.5	24.3	24.3	24.2
NO_2 (µg/m³)							
States	**Akwa Ibom**	**Bayelsa**	**Cross Rivers**	**Delta**	**Rivers**	**Edo**	**Average**
September	21.5	26.5	23.7	25.2	28.6	21.0	24.4
February	20.6	25.5	22.7	24.1	27.8	16.0	22.8
Morning (0700 hr)	21.3	26.2	23.6	24.9	27.2	19.5	23.8
Evening (1900 hr)	20.8	25.8	22.9	24.4	29.1	17.6	23.4

Source: Fieldwork (2024)

Table 4. Cluster Proximity Analysis of Gases at different distances

	Matrix File Input			
Distances	**250m**		**250m**	
250m	.000	191.727	298.798	386.617
500m	191.727	.000	147.789	235.553
750m	298.798	147.789	.000	122.288
1km	386.617	235.553	122.288	.000

Source: SPSS Computation (2024)

However, unpredictability in pollutant behaviour over long distances was observed. The study suggests stronger spatial zoning laws and environmental monitoring near flare sites to protect populations exposed to higher pollutants. Table 3 shows seasonal and daily measurements of SO_2, CO_2, and NO_2 emissions across six Niger Delta states. SO_2 levels are generally higher in September than in February, possibly due to increased industrial activity or atmospheric conditions. Morning readings are higher, indicating early-day industrial and vehicular activities. CO_2 levels are slightly higher in September, but daily variation is more marked, with morning concentrations significantly higher than evening values.

Bayelsa and Delta in the BRACED states of the Niger Delta have high CO_2 levels, while NO_2 emissions are higher in September than in February, indicating traffic and combustion processes. Rivers State consistently records the highest NO_2 emissions, possibly due to traffic congestion. Industrial activity, vehicular emissions, and seasonality significantly influence air quality in the Niger Delta. Policy interventions, such as emissions control during peak hours, and targeted regulatory efforts during the wet season are needed. Table 4 shows a spatial pattern in pollutant dispersion at distances of 250 meters, 500 meters, 750 meters, and one kilometre from flare stacks. The maximum distance value, 386.617, falls between 250 meters and 1 km, indicating significant variances in gas concentrations.
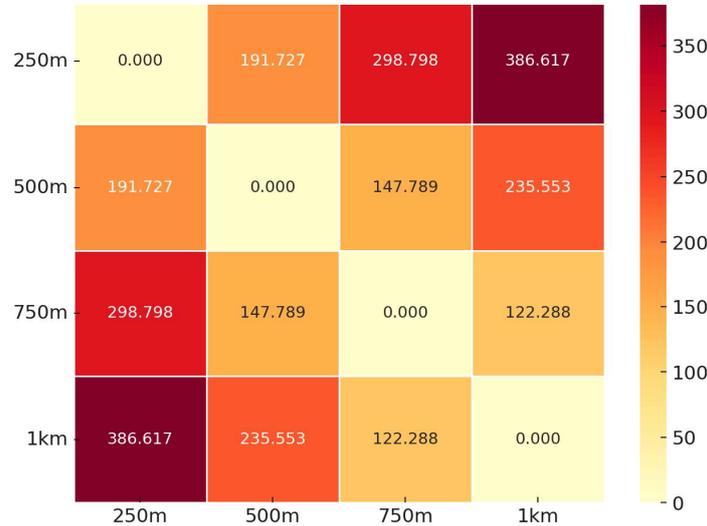

Fig. 2. Cluster proximity matrix of gases at Varying Distances

Table 5. MANOVA on Distance and location variations of GHG emission in the Niger Delta

Tests of Between-Subjects Effects							
Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	@250m	14729.487[a]	17	866.440	21.739	.000	.578
	@500m	6715.893[b]	17	395.053	22.474	.000	.586
	@750m	4240.232[c]	17	249.425	16.014	.000	.502
	@1km	3640.438[d]	17	214.143	19.911	.000	.556
Intercept	@250m	333210.260	1	333210.260	8360.435	.000	.969
	@500m	193630.201	1	193630.201	11015.383	.000	.976
	@750m	104978.202	1	104978.202	6739.767	.000	.961
	@1km	48695.663	1	48695.663	4527.605	.000	.944
Location	@250m	1757.919	5	351.584	8.821	.000	.140
	@500m	2203.691	5	440.738	25.073	.000	.317
	@750m	3103.330	5	620.666	39.848	.000	.425
	@1km	2581.156	5	516.231	47.998	.000	.471
Gases	@250m	12092.655	2	6046.328	151.706	.000	.529
	@500m	2998.385	2	1499.192	85.287	.000	.387
	@750m	18.064	2	9.032	.580	.561	.004
	@1km	2.958	2	1.479	.138	.872	.001
Location * Gases	@250m	878.913	10	87.891	2.205	.018	.076
	@500m	1513.818	10	151.382	8.612	.000	.242
	@750m	1118.838	10	111.884	7.183	.000	.210
	@1km	1056.323	10	105.632	9.821	.000	.267
Error	@250m	10761.015	270	39.856			
	@500m	4746.104	270	17.578			
	@750m	4205.503	270	15.576			
	@1km	2903.926	270	10.755			
Total	@250m	358700.763	288				
	@500m	205092.198	288				
	@750m	113423.938	288				
	@1km	55240.027	288				
Corrected Total	@250m	25490.503	287				
	@500m	11461.998	287				
	@750m	8445.736	287				
	@1km	6544.364	287				
a. R Squared = .578 (Adjusted R Squared = .551)							
b. R Squared = .586 (Adjusted R Squared = .560)							
c. R Squared = .502 (Adjusted R Squared = .471)							
d. R Squared = .556 (Adjusted R Squared = .528)							

Source: SPSS Computation (2024)

The lowest value, 122.288, suggests increased similarity and a potential zone of pollution attenuation. This pattern supports the study's emphasis on the effect of flare stack proximity on air contaminants' dispersion, indicating normal plume dispersion behaviour. The study by Oguntoke and Adeyemi (2017) found that air pollutant concentrations around flare sites in the Niger Delta decrease significantly within the first 500 meters and continue to decrease at a slower pace after that threshold.

The proximity values between 250 and 500 meters and 500 and 750 meters show moderate dissimilarity, suggesting the need for minimum buffer zones around flare locations, especially in highly populated areas. This pattern, combined with meteorological conditions, underscores the importance of strategic environmental monitoring and policy implementation in gas-flaring locations. The heatmap graphically represents the proximity matrix of gaseous concentrations across different distances (Fig. 2).

Table 6. Multiple Comparisons of Distances of flare stack and locations

Tukey HSD

Dependent Variable	(I) Location	(J) Location	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
@250m	Akwa ibom	Delta	-5.58*	1.289	.000	-9.28	-1.88
		Rivers	-6.67*	1.289	.000	-10.37	-2.97
	Bayelsa	Akwa ibom	6.57*	1.289	.000	2.87	10.27
		Edo	4.61*	1.289	.005	.91	8.31
	Edo	Bayelsa	-4.61*	1.289	.005	-8.31	-.91
		Rivers	-4.72*	1.289	.004	-8.41	-1.02
@500m	Akwa ibom	Bayelsa	-6.97*	.856	.000	-9.43	-4.52
		Cross Rivers	-3.65*	.856	.000	-6.11	-1.19
		Delta	-6.02*	.856	.000	-8.47	-3.56
		Rivers	-5.87*	.856	.000	-8.33	-3.42
	Bayelsa	Akwa ibom	6.97*	.856	.000	4.52	9.43
		Cross Rivers	3.32*	.856	.002	.87	5.78
		Edo	6.66*	.856	.000	4.21	9.12
	Cross Riv	Akwa ibom	3.65*	.856	.000	1.19	6.11
		Bayelsa	-3.32*	.856	.002	-5.78	-.87
		Delta	-2.37	.856	.066	-4.82	.09
		Edo	3.34*	.856	.002	.88	5.79
	Delta	Akwa ibom	6.02*	.856	.000	3.56	8.47
		Edo	5.70*	.856	.000	3.25	8.16
	Edo	Bayelsa	-6.66*	.856	.000	-9.12	-4.21
		Cross Rivers	-3.34*	.856	.002	-5.79	-.88
		Delta	-5.70*	.856	.000	-8.16	-3.25
		Rivers	-5.56*	.856	.000	-8.02	-3.10
@750m	Akwa ibom	Bayelsa	-7.49*	.806	.000	-9.80	-5.17
		Cross Rivers	-3.41*	.806	.000	-5.72	-1.10
		Delta	-6.19*	.806	.000	-8.50	-3.88
		Rivers	-9.53*	.806	.000	-11.85	-7.22
	Bayelsa	Akwa ibom	7.49*	.806	.000	5.17	9.80
		Cross Riv	4.08*	.806	.000	1.76	6.39
		Edo	5.54*	.806	.000	3.23	7.85
	Cross Riv	Akwa ibom	3.41*	.806	.000	1.10	5.72
		Bayelsa	-4.08*	.806	.000	-6.39	-1.76
		Delta	-2.78*	.806	.008	-5.09	-.47
		Rivers	-6.13*	.806	.000	-8.44	-3.81
	Delta	Akwa ibom	6.19*	.806	.000	3.88	8.50
		Cross Rivers	2.78*	.806	.008	.47	5.09
		Edo	4.24*	.806	.000	1.93	6.55
		Rivers	-3.34*	.806	.001	-5.66	-1.03
	Edo	Bayelsa	-5.54*	.806	.000	-7.85	-3.23
		Delta	-4.24*	.806	.000	-6.55	-1.93
		Rivers	-7.59*	.806	.000	-9.90	-5.27
@1km	Akwa ibom	Bayelsa	-7.20*	.669	.000	-9.12	-5.28
		Cross Rivers	-2.66*	.669	.001	-4.58	-.74
		Delta	-6.13*	.669	.000	-8.05	-4.21
		Edo	-2.39*	.669	.006	-4.31	-.46
		Rivers	-8.47*	.669	.000	-10.39	-6.55
	Bayelsa	Akwa ibom	7.20*	.669	.000	5.28	9.12
		Cross Rivers	4.54*	.669	.000	2.62	6.46
		Edo	4.81*	.669	.000	2.89	6.74
	Cross Riv	Akwa ibom	2.66*	.669	.001	.74	4.58
		Bayelsa	-4.54*	.669	.000	-6.46	-2.62
		Delta	-3.47*	.669	.000	-5.39	-1.55
		Rivers	-5.80*	.669	.000	-7.73	-3.88
	Delta	Akwa ibom	6.13*	.669	.000	4.21	8.05
		Bayelsa	-1.07	.669	.600	-2.99	.85
		Cross Rivers	3.47*	.669	.000	1.55	5.39
		Edo	3.74*	.669	.000	1.82	5.67
		Rivers	-2.34*	.669	.007	-4.26	-.42
	Edo	Akwa ibom	2.39*	.669	.006	.46	4.31
		Bayelsa	-4.81*	.669	.000	-6.74	-2.89
		Delta	-3.74*	.669	.000	-5.67	-1.82
		Rivers	-6.08*	.669	.000	-8.00	-4.16

Based on observed means. The error term is Mean Square (Error) = 10.755.

*. The mean difference is significant at the .05 level.

Source: SPSS Computation (2024)

The study also highlights the importance of integrating spatial distance with climatic variability to better understand pollutant behaviour in flaring zones. The proximity matrix reveals that pollutant concentration variations are not uniform and can be influenced by topographic variables, wind patterns, and flare stack height. This data supports the hypothesis that pollutants cluster at different distances, suggesting a threshold for uniform dispersion. Warmer colours indicate greater dissimilarity. The proximity between 750m and 1km is lowest, shown by the lighter hue, while the distance between 250m and 1km shows the darkest colour, reflecting the highest dissimilarity. This gradient confirms a consistent spatial pattern in gas dispersion, where profiles become increasingly distinct with proximity to the emission source. Table 5 presents the results of a multivariate analysis of variance (MANOVA) found significant variations in greenhouse gas (GHG) emissions across the BRACED states of the Niger Delta due to distance from flare stacks and geographic location. The corrected model explained a substantial proportion of the variance in GHG emissions, supporting the hypothesis that proximity to flare stacks has a strong spatial influence on pollutant concentrations. Location also had a significant impact, with F-values ranging from 8.821 at 250 meters to 47.998 at 1 kilometre. Spatial heterogeneity increased with distance, aligning with Hu et al.'s (202) findings on Spatial-temporal heterogeneity of air pollution. The study reveals significant interaction effects between location and gases, indicating that spatial variation in emissions is dependent on the type of greenhouse gas being assessed. This interaction effect is crucial for understanding localized impacts of flaring activities and validating the need for gas-specific mitigation strategies. The gases factor is highly significant at shorter distances, but non-significant at 750 meters and 1 kilometre. This suggests that concentration profiles of gases like SO_2, CO_2, and NO_2 converge with distance, likely due to atmospheric mixing and dilution. The study also confirms the spatial non-uniformity of air pollution, providing a nuanced understanding of environmental risk exposure across different communities and distances from gas flaring points.

HSD post-hoc test comparing the concentration levels of sulphur dioxide (SO_2), carbon dioxide (CO_2), and nitrogen dioxide (NO_2) at different distances from flare stacks in the Niger Delta revealed significant differences in pollutant concentrations. At 250 meters, SO_2 concentrations were lower than CO_2 and NO_2, suggesting that CO_2 and NO_2 dominate the immediate vicinity. This aligns with flare stack emission profiles, where incomplete combustion of hydrocarbons often results in higher volumes of CO_2 and NO_2. At 500 meters, CO_2 exhibited higher concentrations than both NO_2 and SO_2, suggesting differential dispersion rates and atmospheric behaviours among gases, influenced by their physical properties and prevailing meteorological conditions. The study reveals that the influence of flare stack emissions varies with proximity, and gas type. CO_2, being more stable and less reactive, persists over longer distances compared to NO_2 and SO_2, which are more chemically active. The concentration gradients show that short-range exposure is more heavily impacted by chemically reactive gases, while stable gases dominate at greater distances due to slower dispersion rates. This is consistent with previous studies indicating unequal dispersion of gaseous pollutants around flare sites. The findings emphasize the need for tailored environmental management strategies that consider pollutant-specific risks and dispersion characteristics, as well as the role of atmospheric chemistry and wind field dynamics in determining the fate and distribution of these pollutants. The study found that the proximity of flare stacks significantly affects the distribution of air pollutants in the Niger Delta. The highest concentrations of CO_2, SO_2, and NO_2 were consistently recorded within 250 meters of flare stacks, confirming the principle of distance decay in pollutant dispersion. Concentrations decreased with distance, reaching their lowest values at 1 kilometre, where atmospheric processes like turbulent mixing, wind shear, and secondary emission sources introduced greater variability. The study also found higher pollutant levels during the wet season, particularly in September, and in states with intense oil and gas operations. The study found that distance from flare sites and location significantly affect greenhouse gas concentrations.

Table 7. Multiple Comparisons of Distances of flare stack and locations

Tukey HSD							
Dependent Variable	(I) Gases	(J) Gases	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
@250m	SO_2	CO_2	-14.02*	.911	.000	-16.17	-11.87
		NO_2	-13.46*	.911	.000	-15.60	-11.31
@500m	CO_2	NO_2	6.27*	.605	.000	4.84	7.69
		SO_2	7.30*	.605	.000	5.88	8.73
Based on observed means. The error term is Mean Square (Error) = 10.755.							
*. The mean difference is significant at the .05 level.							

Source: SPSS Computation (2024)

Table 4.18 presents the results of a Tukey HSD post-hoc test found significant differences in greenhouse gas (GHG) emission levels across selected locations in the Niger Delta at $p<0.001$. The proximity to flare stacks interacts significantly with geographic heterogeneity, influencing the spatial distribution of air pollutants. At 250 meters, Akwa Ibom and Delta and Rivers States showed substantial differences in emissions, indicating disproportionate burden of pollutant exposure due to high-volume flaring operations. Bayelsa consistently showed higher values, suggesting localized emission accumulation influenced by topographic and meteorological conditions. The study reveals that flare-induced emissions are not uniformly distributed but are spatially concentrated based on proximity and location-specific environmental conditions. At distances of 500 and 750 meters, Akwa Ibom shows significantly lower GHG values compared to Bayelsa, Delta, and Rivers. This pattern of significance supports the findings of Goodluck and Ekwutosi (2022), who documented spatial disparities in ambient air quality across oil-producing communities in the Niger Delta. Bayelsa consistently shows higher mean values than Akwa Ibom and Cross River, while Rivers consistently registers among the highest levels across all distances. Moreover, the statistical differences in mean pollutant levels between locations even at 1 kilometre underscore the enduring influence of local meteorological dynamics and land-use characteristics on air quality. Table 7 presents the results of a Tukey

The greatest dissimilarity occurred between 250 meters and 1 kilometre, while the similarity between 750 meters and 1 kilometre suggests a threshold beyond which dispersion leads to attenuation. This supports the spatial diffusion model of plume behaviour, suggesting the need for buffer zones around flare sites, especially in densely populated areas. The interaction between location and specific gases also showed that dispersion dynamics vary with geography and gas type. Post-hoc analysis reinforced spatial disparities in pollutant levels, with states like Bayelsa and Rivers showing higher emissions across all distances. The study found that CO_2 and NO_2 were more concentrated at 250 meters than SO_2 due to hydrocarbon combustion emissions. At 500 meters, CO_2 became the dominant pollutant due to its stability and lower reactivity. Flare stack proximity significantly influences air pollutant concentrations, with the most significant effects within 500 meters. Temporal and spatial variations further modulate these impacts, emphasizing the need for spatially targeted monitoring and gas-specific regulatory frameworks to mitigate environmental and health risks associated with gas flaring in the Niger Delta.

CONCLUSION

The study has established a strong spatio-temporal relationship between flare stack proximity, climatic variability, and the dispersion

of greenhouse gases in the BRACED states of the Niger Delta. Concentrations of CO_2, SO_2, and NO_2 were consistently highest within 250 meters of flare stacks, decreasing with distance due to atmospheric dilution and meteorological dynamics. Seasonal and diurnal variations, particularly elevated emissions during wet seasons and morning hours, further confirmed the influence of climatic factors. Multivariate analysis revealed significant interactions between distance, geographic location, and gas type, indicating spatial heterogeneity in pollutant distribution. Given these findings, it is recommended that minimum buffer zones of no less than 750 meters be mandated around flare stacks, particularly in densely populated areas. Continuous air quality monitoring should be implemented across seasons and at various distances to capture emission patterns accurately. Regulatory interventions should prioritize emissions control during peak hours and wet seasons when pollutant retention is heightened. Emission-specific strategies are also necessary, given the differing atmospheric behaviours of CO_2, SO_2, and NO_2. These insights have significant implications for environmental policy and public health in oil-producing regions. Localized mitigation efforts must incorporate spatial and temporal dimensions of flare-induced pollution. A regionally adaptive air quality management framework is essential to minimize health risks and support sustainable industrial operations in the Niger Delta.

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