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Spatial Co-Occurrence of Oil Spills and Gas Flare Hotspots in the Niger Delta, Nigeria

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ABSTRACT

In this study, we conducted spatial analyses to examine the co-occurrence of oil spills and gas flare hotspots within the Niger Delta region. Utilizing Geographic Information Systems (GIS) and statistical methods, such as; Average Nearest Neighbor, Multi-Distance Cluster Analysis, Chi-square test, and Pearson correlation analysis, the research analyzed the distribution, clustering, and associations between oil spill hotspots, gas flare site hotspots, oil spill density, and gas flare density. The findings revealed significant spatial clustering of oil spill and gas flare hotspots, particularly in Imo, Rivers, Bayelsa, Delta, Edo, Akwa-Ibom, and Abia States. Pearson correlation analysis indicated moderate to strong linear relationships between oil spill hotspots, gas flare site hotspots, oil spill density, and gas flare density; suggesting potential spatial co-occurrence or associations between these environmental phenomena. These findings have implications for targeted interventions and regulatory measures aimed at mitigating environmental risks and vulnerabilities in the Niger Delta region, ultimately promoting sustainable development and environmental stewardship in the area.

Keywords: *Oil spills; Gas flares; spatial analysis; Hotspots; spatial clustering*

1.0 INTRODUCTION

The Niger Delta region of Nigeria has long been plagued by environmental challenges stemming from oil extraction activities, including frequent oil spills and widespread gas flaring. Understanding the spatial patterns and potential associations between these environmental hazards is crucial for effective environmental management and mitigation efforts. A geographical overview of the Niger Delta indicates a complicated network of low-lying plains, mangrove forests, and water bodies. This complex environment is home to a wide variety of plants and animals, making it one of the most biodiverse areas in Africa. However, this fragile ecology has suffered due to oil prospecting, growing urbanization, and agricultural growth (Osuoha & Fakutiju, 2017). The region's economy is primarily driven by oil extraction, although traditional means of subsistence coexist alongside contemporary industries in this mixed economy. Even though the area is rich in natural resources, the local populations frequently struggle with poverty, poor infrastructure, and health problems brought on by environmental deterioration (Osei *et al.,* 2004).

The Niger Delta's oil sector has a lengthy history that dates to the start of commercial oil production in the 1950s (Nwosisi *et al.,* 2021). Since then, the area has grown to be one of the main producers of oil in the globe. However, the ecology has suffered greatly as a result of this surge in oil extraction. Oil spills are frequently caused by malfunctioning machinery, deliberate sabotage, and careless operations. These spills harm livelihoods and devastate farmlands in addition to contaminating water sources. Furthermore, damaging pollutants are released into the atmosphere during gas flaring – the burning of natural gas used in the extraction of oil, which exacerbates air pollution and contributes to climate change (Romsom & Mcphail, 2022).

It is crucial to comprehend the spatial distribution and co-occurrence of gas flaring and oil spills in the Niger Delta for a number of reasons. In the first instance, it enables the understanding of the intricate relationships that exist between many environmental stressors, and how those relationships affect ecosystems and public health in concert. Furthermore, the aforementioned knowledge bears noteworthy policy implications as it might facilitate focused measures aimed at reducing environmental risks and enhancing disaster response tactics. Finally, research on spatial co-occurrence aids in the discovery of new patterns and trends, as well as, advances scientific understanding of environmental dynamics.

2.1 Aim of the Study

The aim of this study was to investigate the spatial distribution of oil spills and gas flare hotspots in the Niger Delta region and to analyze patterns of spatial co-occurrence between these environmental stressors. By doing so, the study seeks to provide insights into the interplay of oil industry activities and their environmental impacts, with implications for environmental management and policy-making.

2.2 Objectives of The Study

a. To analyze the spatial distribution of oil spills in the Niger Delta region: By utilizing geographic information systems (GIS) and remote sensing techniques to map and quantify the extent and frequency of oil spills across the Niger Delta.

b. To examine the spatial distribution of gas flare hotspots in the Niger Delta region. This entails identifying areas with significant concentrations of gas combustion activity through satellite imagery analysis and field surveys.

c. To identify patterns of spatial co-occurrence between oil spills and gas flare hotspots: This involves spatial statistical analysis to determine the degree of overlap or proximity between oil spill sites and areas with high levels of gas flaring.

d. To assess the implications of spatial co-occurrence for environmental management and policymaking in the Niger Delta: This aims to evaluate the environmental and socio-economic consequences of the spatial co-occurrence of oil spills and gas flare hotspots, and providing recommendations for effective mitigation strategies and policy interventions.

3.0 Literature Review

Previous research on oil spills in the Niger Delta extensively documented their causes, impacts, and remediation efforts. Studies have often focused on the direct effects of oil spills on soil degradation, water pollution, and biodiversity loss, emphasizing the vulnerability of mangrove forests and aquatic life (Nwilo & Badejo, 2005; Whanda *et al.,* 2016). For instance, Nwilo & Badejo (2005) indicated that the main sources of oil spill on the Niger Delta include vandalisation of the oil pipelines by the local inhabitants; ageing of the pipelines; oil blow outs from the flow stations; cleaning of oil tankers on the high sea and disposal of used oil into the drains by the road side mechanics. Certainly, the most serious source of oil spill is through the vandalisation of pipelines either as a result of civil dissatisfaction with the political process, or as a criminal activity. Socioeconomic impacts have also been a significant focus, with researchers highlighting how spills adversely affect local communities' livelihoods, particularly fishing and agriculture (Ansah *et al*., 2022). A deficiency in long-term research that monitor the ecological and social recovery after spills persists, despite a wealth of evidence.

Gas flaring in the Niger Delta has evolved alongside the region's oil extraction activities. Initially, gas flaring emerged as a convenient solution for oil companies to dispose of associated natural gas, which was considered a byproduct and deemed less economically valuable than crude oil. The practice began in the mid-20th century when oil production intensified in the region, leading to large-scale flaring operations. Research on gas flaring primarily addressed its environmental and health implications. Studies have shown that gas flaring contributed significantly to greenhouse gas emissions, exacerbating climate change (Aniefiok & Udo, 2013). Furthermore, exposure to pollutants from gas flaring has been linked to respiratory issues and other health problems among the local populations (Eyoh & Ekpa, 2017). The cumulative effect of gas flaring on land use and regional climate patterns, on the other hand, has received less attention, suggesting the need for more thorough environmental impact studies (Fawole *et al.,* 2016).

Understanding the distribution and effects of environmental stressors require the use of spatial analysis, which has become an essential technique. Research employing Geographic Information Systems (GIS) and remote sensing techniques has yielded valuable insights into the temporal and spatial patterns and trends of oil spills and gas flaring (Deinkuro *et al.,* 2021; Motte *et al.,* 2021; Uchegbulam et al., 2022). These methods have made it easier to identify hotspots and ecosystems that are at risk, which has helped to inform focused intervention plans. Numerous studies have documented the severe environmental consequences of gas flaring in the Niger Delta. Air pollution is a primary concern, as flaring releases toxic pollutants, such as, sulfur dioxide, nitrogen oxides, and particulate matter into the atmosphere. These pollutants contribute to respiratory illnesses, cardiovascular diseases, and other health problems among the local communities living near flaring sites (Nwilo & Badejo, 2005). Water pollution is another significant issue associated with gas flaring, as gases and waste fluids from flaring operations often contaminate water bodies, including rivers, creeks, and groundwater sources. This pollution poses risks to aquatic ecosystems and threatens the livelihoods of fishing communities reliant on these resources for sustenance and income (Ansah *et al.,* 2022). Moreover, gas flaring contributes to climate change by releasing greenhouse gases such as carbon dioxide and methane into the atmosphere. These emissions exacerbate global warming and climate variability, leading to adverse impacts on weather patterns, sea levels, and agricultural productivity in the region and beyond.

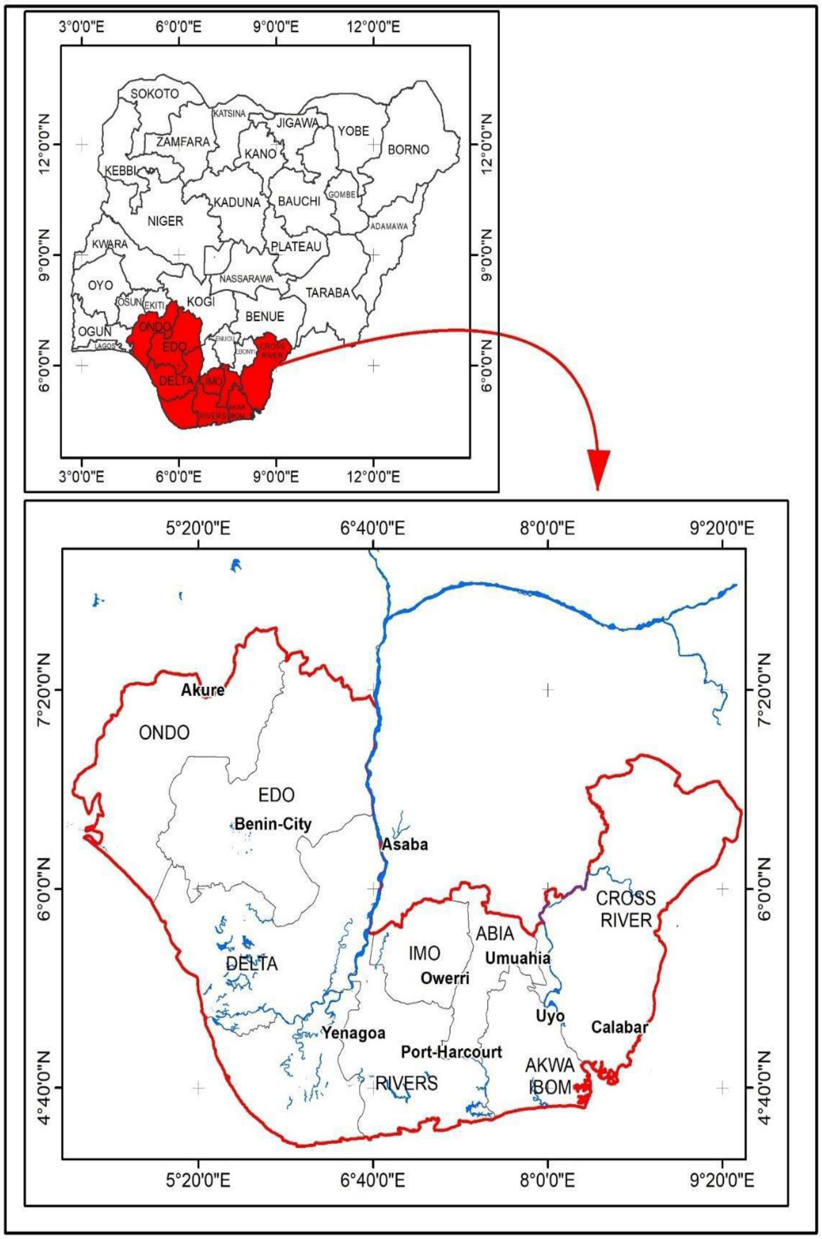

Figure 1: Map showing the Niger Delta Region

4.0 Study Area

The Niger Delta Region (shown in Figure 1) lies in the southern part of Nigeria where the River Niger divides into numerous tributaries ending at the edge of the Atlantic Ocean. It is bordered to the south by the Atlantic Ocean and to the east by Cameroon. It lies between longitude 4º 30' - 9º 50'E and latitude 4º 10' - 8º 0'N (Eyoh & Ekpa, 2017). The region covers nine southern states namely: Cross River, Akwa Ibom, Abia, Imo, River, Bayelsa, Delta, Edo and Ondo State. It has more than 40 ethnic groups with about 250 different dialects. Covering an approximate area of 112,110 square kilometers, the delta is one of the world's largest deltas.

In essence, the Niger Delta is the region where the River Niger's main channel meets base level, and splits into several tributaries to disperse and dispose of the sediment load and water discharge.

5.0 METHOD

A. *Data Collection*

Oil spill data for the Niger Delta was collected from the National Oil Spill Detection and Response Agency (NOSDRA) and World Bank for officially reported spill incidents. Also, data on gas flaring sites in the Niger Delta was derived through ground surveying method. The coordinates of each gas flare sites were obtained during the field survey as well as pictures on some gas flare sites.

B. *Data Analysis*

Geographic Information Systems (GIS) and remote sensing was employed to map and analyze the spatial distribution of oil spills and gas flare hotspots. This included utilizing GIS software, especially, ArcGIS to integrate, visualize, and analyze spatial data on oil spills and gas flares.

C. *Analysis on Spatial Co-Occurrence*

Spatial co-occurrence analysis was conducted to identify patterns and relationships between oil spill locations and gas flare hotspots. This involved:

- Average Nearest Neighbor Analysis and Multi-Distance Cluster Analysis to understand the level of distribution and clustering of oil spill and gas flare sites.

- Density Analysis: to assess areas of high occurrence of oil spills and gas flaring in the region.
- Hotspot and Coldspot Analysis: to derive statistically significant hotspots and coldspots of oil spills and gas flaring.

D. Statistical Analysis

Statistical analysis was integral to interpreting the spatial patterns and assessing the significance of co-occurrence between oil spills and gas flares. The methods include:

- Descriptive Statistics: Calculation of descriptive statistics, such as means and standard deviations, to summarize the spatial distribution and characteristics of oil spills and gas flare hotspots.
- Chi-square tests to examine the independence between the locations of oil spills and gas flares.
- Pearson's correlation analysis to measure the strength and direction of the relationship between the spatial distribution of spills and flares.

6.0 RESULTS AND DISCUSSION

6.1 Visual Analysis and Comparison

As shown in Figure 2, the oil spill locations visually corresponded with gas flare sites (Delta, Bayelsa, Rivers, Imo and Cross River). It would be recalled that both oil spills and gas flaring are often associated with the extraction and production of crude oil (Aigbe *et al.*, 2023). In the Niger Delta, oil exploration and production activities involve the drilling of wells, transportation of crude oil through pipelines, and processing at refineries. Gas flaring often occurs as a byproduct of oil extraction and refining processes. A close proximity of both sites illustrate that the environmental phenomena have a close relationship. This was further investigated using spatial analysis as shown in subsequent figures.

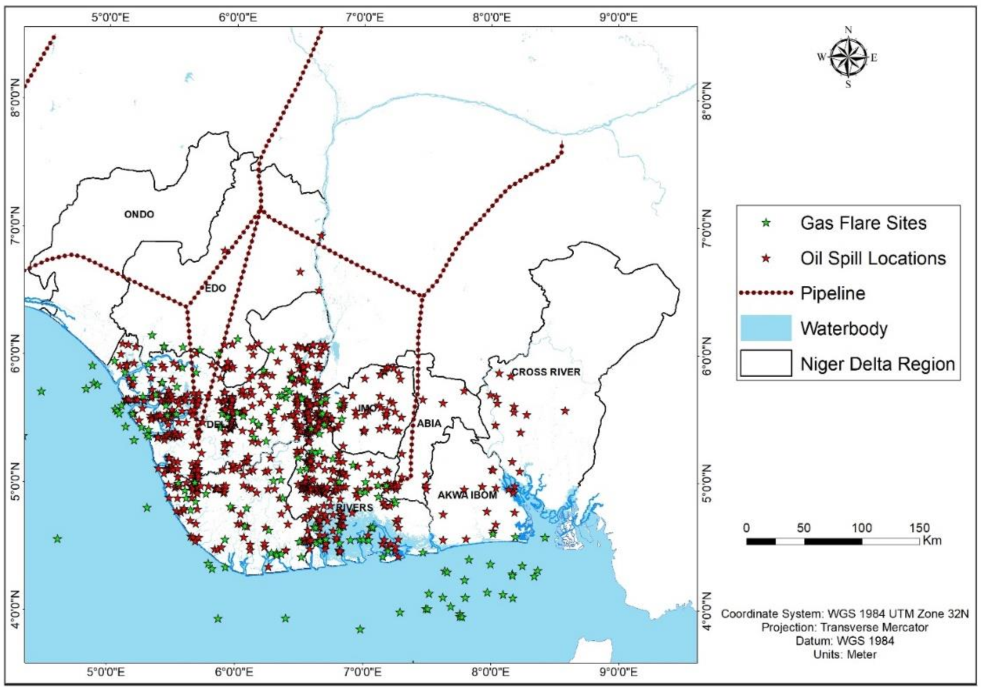

Figure 2: Locations of oil spill and gas flare sites (Author's Analysis, 2024).

6.2 Analysis on Spatial Co-occurrence

6.2.1 Average Neighbor Analysis and Distance Clustering

A measure of the degree of clustering or dispersion of the occurrence of both environmental phenomena was demonstrated through Average Neighborhood and Distance Clustering Analysis. Figures 3a and 3b indicates that both oil spill and gas flaring are clustered within the region. This supports the visual analysis shown in Figure 2.

For gas flare sites, with an NNI of 0.73, the value closer to 1 suggests a relatively higher degree of clustering. This means that gas flare sites tend to be spatially clustered, indicating that they are not randomly distributed across the study area. This clustering reflect the tendency for gas flare sites to be concentrated in specific regions due to factors such as proximity to oil extraction and processing facilities and geological characteristics (Giwa *et al.*, 2016). Similarly, for oil spill sites, although with a slightly lower NNI of 0.52, the value still indicates a tendency towards clustering. While the clustering of oil spill sites may not be as pronounced as those of gas flare sites, the NNI suggests that oil

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spill sites are not randomly distributed either. Instead, they tend to occur in clusters, indicating that certain areas within the study region are more prone to oil spills compared to others.

Multi-Distance Cluster Analysis, often represented using Ripley's K function, provides additional insights into the level of clustering at various distances within a dataset. By examining the clustering tendencies across multiple distance thresholds, the research gained a more comprehensive understanding of spatial patterns. Ripley's K function analysis can reveal the extent of clustering among gas flare sites at different distance thresholds. If the analysis shows consistently high K values across multiple distances, it indicates significant clustering of gas flare sites throughout the study area (Figure 4a). This suggests that gas flare sites are not only clustered at short distances but also exhibit clustering tendencies at longer distances, reflecting broader spatial patterns of concentration. Similarly, analyzing the Ripley's K function for oil spill sites elucidated the level of clustering across various distance thresholds (Figure 4b). If oil spill sites demonstrate elevated K values across multiple distance ranges, it suggests clustering at both local and regional scales. This indicates that oil spills are not only clustered in specific localized areas but also exhibit broader spatial clustering patterns across the study region.

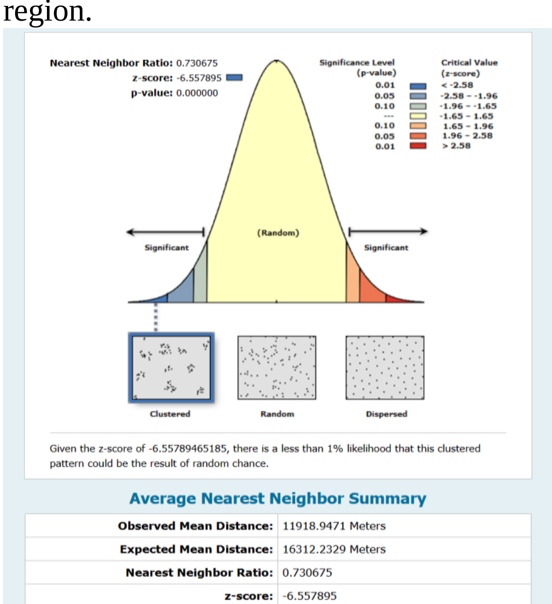

Figure 3a: Analysis on distribution of gas flare sites (Author's Analysis, 2024)

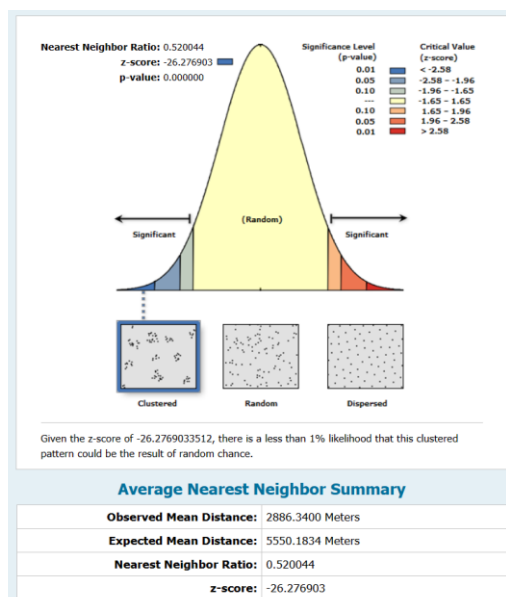

Figure 3b: Analysis on Oil Spill Distribution in Niger Delta (Author's Analysis, 2024)

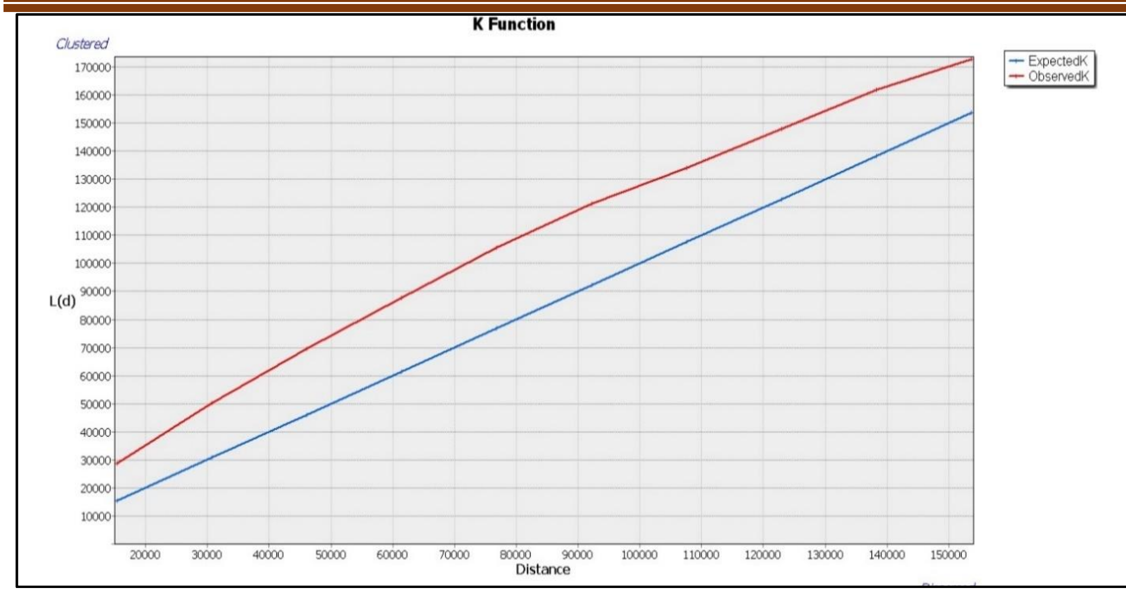

Figure 4(a): Ripley K Function for Gas Flare Sites

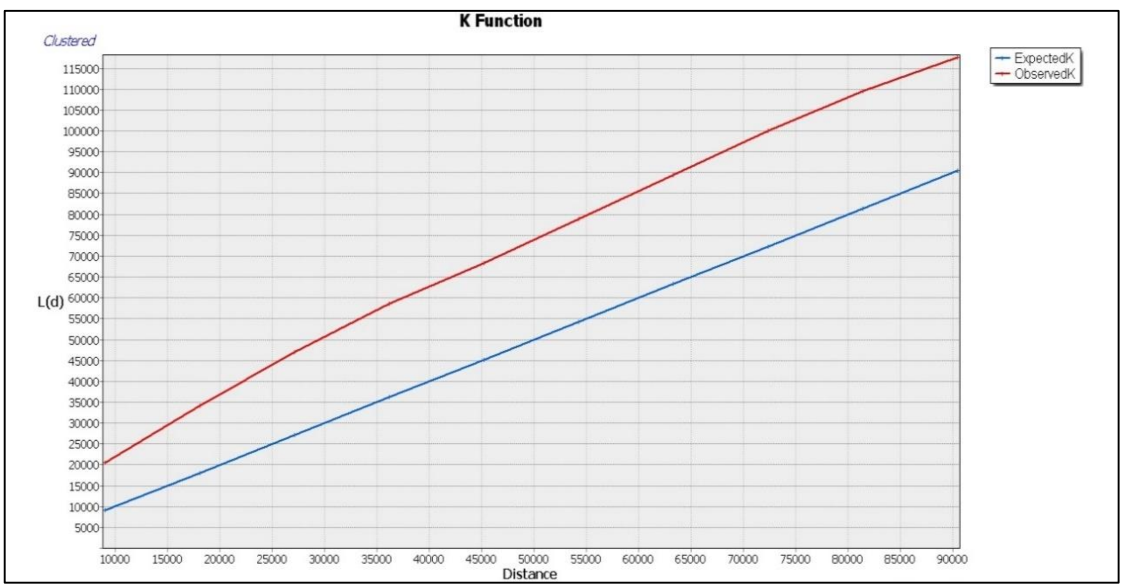

Figure 4(b): Ripley K Function for Oil Spill Sites

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6.2.2 Density Analysis

This was used to examine the concentration or distribution of gas flare sites and oil spill sites features within the Niger Delta. Figures 5 and 6 showed that both phenomena were major occurrence within Delta, Rivers, Imo and Bayelsa States. The inference drawn from this analysis is that these states exhibit high concentrations of both gas flare sites and oil spill sites. This suggested that these areas have a high potential for experiencing the adverse effects associated with gas flaring and oil spills. Such effects may include elevated greenhouse gas emissions from gas flaring and environmental contamination from oil spills. Furthermore, the high occurrence rate of both gas flare and oil spill incidents in these states highlights the significant environmental challenges facing these regions. It indicates a heightened vulnerability to environmental degradation, which can have detrimental impacts on ecosystems, human health, and socio-economic well-being (Nwafor, 2022; Kamel Boulos, 2003; Kolawole et al., 2016; Morakinyo, 2015).

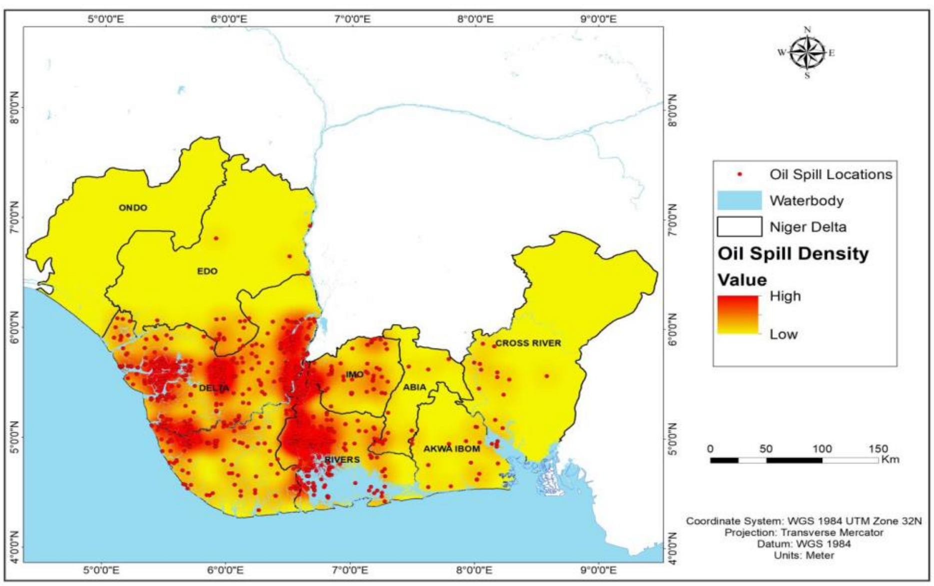

Figure 5: Oil Spill Density in Niger Delta

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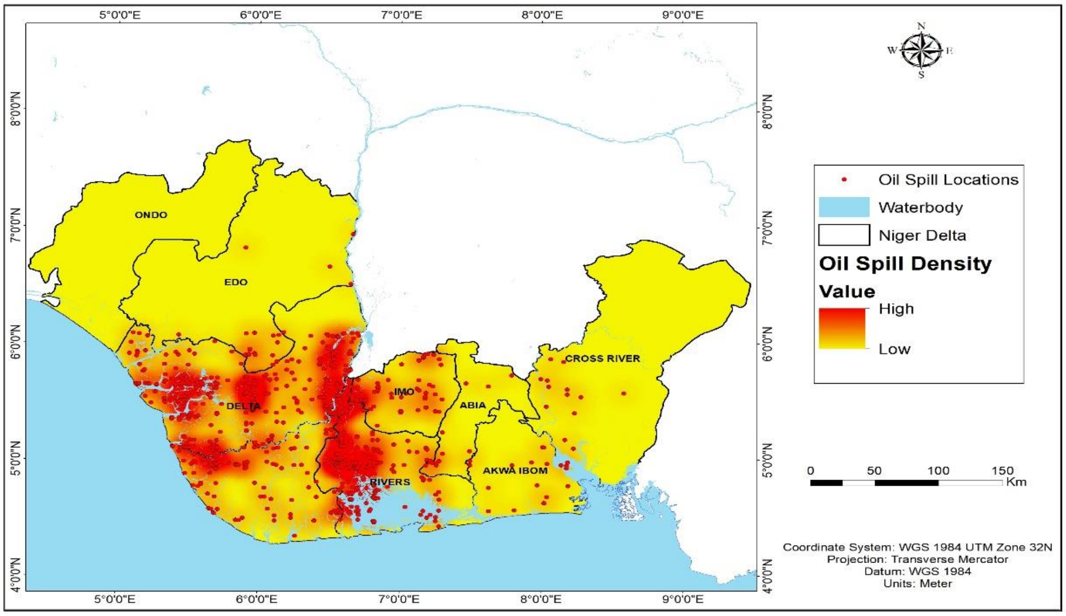

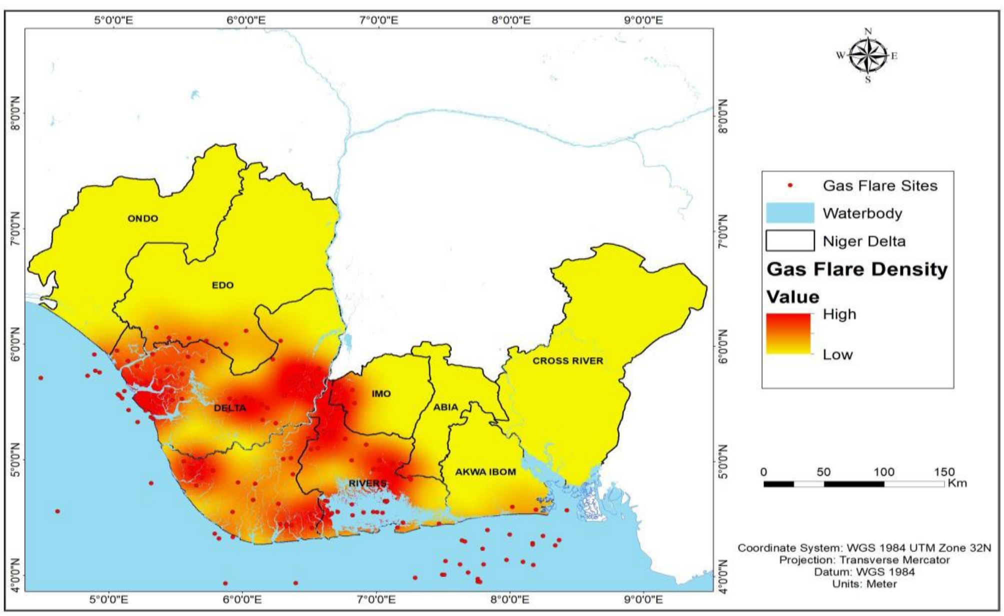

Figure 6: Gas Flare Density in Niger Delta

6.2.3 Hotspot and Coldspot Analysis

In the context of gas flare sites and oil spill sites, hotspot analysis helped to identify spatial clusters of intense gas flaring or frequent oil spills. As shown in figure 7, hotspot areas of oil spill were shown to occur in Imo, Rivers, Bayelsa and Delta States, while in figure 8, regions of gas flare hotspot were indicated in the same locations in addition to Edo, Akwa-Ibom and Abia States. The identification of hotspot areas for both oil spills and gas flaring suggests a concentration of environmental hazards in these regions as shown in the density analysis. It implies that these areas were particularly vulnerable to the adverse effects associated with oil and gas extraction activities, including environmental pollution, ecosystem degradation, and threats to human health and livelihoods (Ite et al., 2024).

Furthermore, the overlap between hotspot areas of oil spills and gas flaring in Imo, Rivers, Bayelsa, and Delta States, as well as, the additional hotspot areas identified for gas flaring in Edo, Akwa-Ibom, and Abia States, highlight the interconnectedness of these environmental issues. It emphasizes the complex relationship between oil production activities, environmental degradation, and socio-economic impacts in these regions.

In terms of co-occurrence, the identification of overlapping hot spot areas for both oil spills and gas flaring in certain regions suggests a significant spatial relationship between these two environmental phenomena. Specifically:

1. **Spatial Co-occurrence**: The co-occurrence of hot spot areas for oil spills and gas flaring indicates that these environmental hazards tend to occur together in the same geographic locations. This spatial relationship often result from shared underlying factors such as proximity to oil extraction and processing facilities, environmental vulnerabilities, and regulatory oversight (Morakinyo *et al.,* 2019; Morakinyo *et al.*, 2022).

2. **Cumulative Environmental Impacts**: The co-occurrence of oil spill and gas flare hotspots implies that certain regions within Imo, Rivers, Bayelsa, Delta, Edo, Akwa-Ibom, and Abia States were subject to cumulative environmental impacts associated with both phenomena. This includes pollution of air, water, and soil, ecosystem degradation, and risks to human health and livelihoods. The combination of oil spills and gas flaring may exacerbate environmental damage and increase the severity of impacts in these co-occurring hotspot areas (Motte *et al.*, 2021).

3. **Integrated Mitigation Strategies**: Addressing the co-occurrence of oil spills and gas flaring requires integrated mitigation strategies that consider the interconnected nature of these environmental hazards. This often involve coordinated efforts to improve regulatory oversight, enhance operational practices, invest in infrastructure upgrades, and promote sustainable development initiatives (Edem, 2020). By addressing both oil spill and gas flare hot spots holistically, stakeholders can more effectively mitigate environmental risks and promote environmental stewardship in the affected regions.

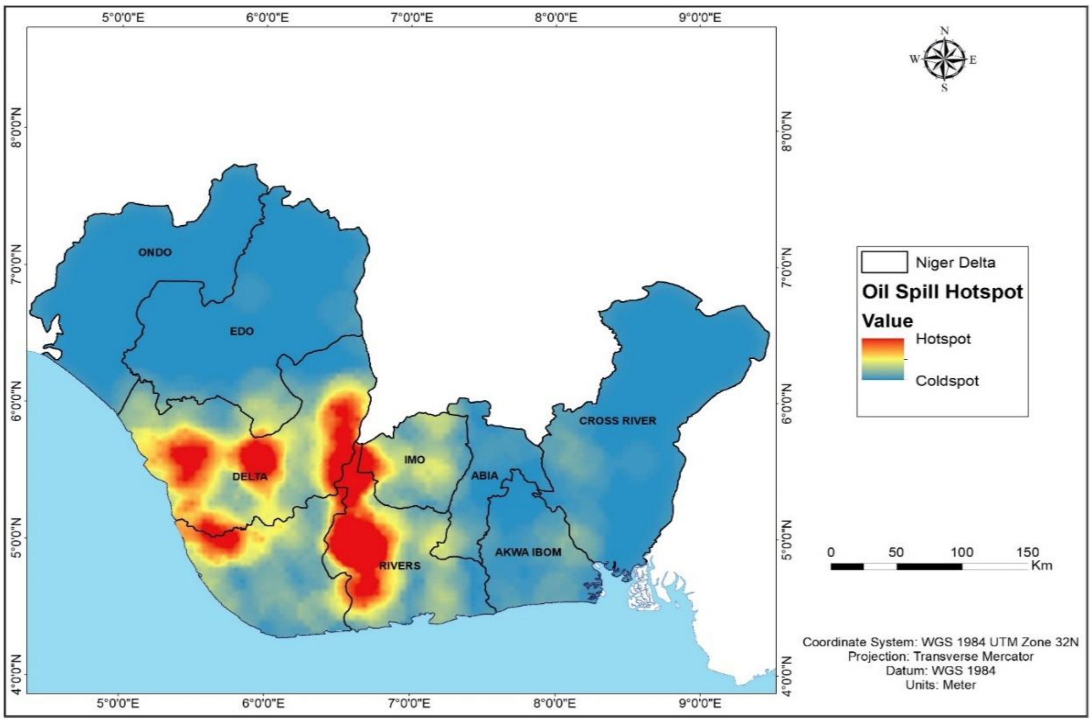

Figure 7: Oil spill Hotspot Analysis

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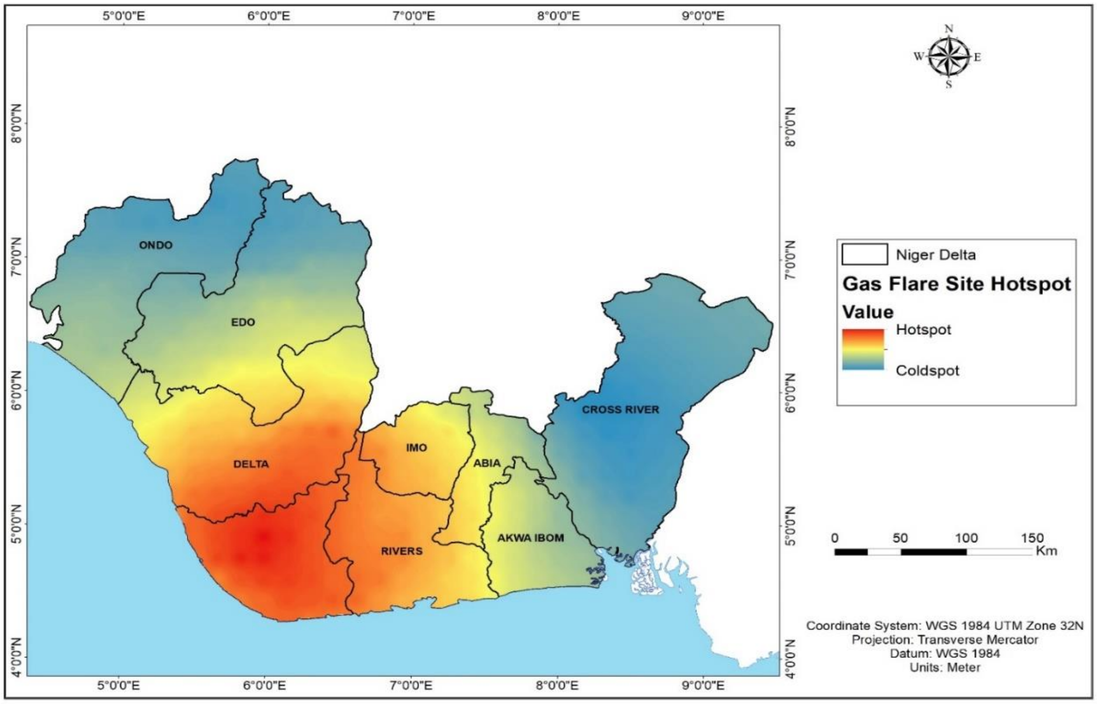

Figure 8: Gas Flare Sites Hotspot in Niger Delta

6.3 Statistical Analysis

6.3.1 Descriptive Statistics

The use of descriptive statistics between density and hotspot occurrences provided insights into the distribution, variability, and central tendency of oil spill hotspots, gas flare site hotspots, oil spill density, and gas flare density within the study area. As shown in Table 1, the average number of oil spill hotspots per observation was 0.31, indicating that, on average, each observation records about 0.31 oil spill hotspots. Similarly, the average number of gas flare site hotspots per observation was 1.96. Also, a higher standard deviation indicates greater variability in the data. For instance, the standard deviation for gas flare site hotspots was higher (4.18) compared to oil spill hotspots (2.82), suggesting that the variability in the number of gas flare site hotspots across observations was greater.

A higher mean for gas flare site hotspots (1.96) compared to oil spill hotspots (0.31) suggests that, on average, there are more gas flare site hotspots recorded per observation. This implied that gas flare sites were more widespread or occurred in higher concentrations across the study area compared to oil spill hotspots. Also, the variability in standard deviation suggests that gas flare site hotspots exhibit more pronounced spatial clustering compared to oil spill hotspots.

Table 1: Descriptive Statistics

	Mean	Std. Deviation	N
Oil Spill Hotspot	.306	2.81	897
Gas Flare Site Hotspot	1.96	4.179	897
Oil Spill Density	.0084	.0144	897
Gas Flare Density	.0011	.0015	897

6.3.2 Chi Square Test for Examining Co-occurrence

1. **Chi-Square Value (χ^2)**: This value indicates the strength of association between the two categorical variables. Higher Chi-square values suggest a stronger association (Table 2).
2. **Degrees of Freedom (df)**: Degrees of freedom represent the number of categories or levels of each variable minus 1.
3. **Asymptotic Significance (Sig.)**: This value, often denoted as p-value, indicates the probability of observing the association between the variables under the null hypothesis of no association. A p-value less than the chosen significance level (commonly 0.05) suggests that the association is statistically significant.

Table 2: Chi square test

	Oil Spill Hotspot	Gas Flare Site Hotspot	Oil Spill Density	Gas Flare Density
Chi-Square	16926.425	19.237	48041.049	87402.939
df	731	878	609	478
Asymp. Sig.	.000	1.000	.000	.000

6.3.2.1 Oil Spill Hotspot and Oil Spill Density:

- The significant Chi-square values for Oil Spill Hotspot and Oil Spill Density suggest that there is a statistically significant association between the occurrence of oil spills and their density within the study area.
- This implies that areas with a higher concentration of oil spill hotspots are also likely to have a higher density of oil spills. In other words, regions where oil spills occur frequently tend to have a higher number of oil spill incidents overall.
- This association could have various implications, such as identifying areas with heightened environmental risk or guiding resource allocation for oil spill response and mitigation efforts.

6.3.2.2 Gas Flare Site Hotspot and Gas Flare Density:

- The non-significant Chi-square values for Gas Flare Site Hotspot and Gas Flare Density indicate that there is no statistically significant association between the occurrence of gas flare sites and their density within the study area.
- This implies that the frequency of gas flare site occurrences does not necessarily correspond to the density of gas flaring activity in the study area. In other words, areas with a higher number of gas flare sites may not always experience a higher intensity of gas flaring. This can be shown in the diverse gas flaring volume for each flare site (Ndidiamaka et al., 2021).

6.3.3 Pearson's Correlation Analysis

As shown in Table 3, the linear relationship between different variables, including oil spill hotspots, gas flare site hotspots, oil spill density, and gas flare density was explored. The table 3 is explained below –

6.3.3.1 Gas Flare Site Hotspot:

- There is a statistically significant positive correlation between gas flare site hotspots and oil spill hotspots, indicated by a Pearson correlation coefficient of 0.581 ($p < 0.01$).
- This suggests that there is a moderate positive linear relationship between the occurrences of gas flare site hotspots and oil spill hotspots within the study area.

6.3.3.2 Oil Spill Density:

- There is a statistically significant strong positive correlation between oil spill density and oil spill hotspots, indicated by a Pearson correlation coefficient of 0.980 ($p < 0.01$).
- Similarly, there is a statistically significant moderate positive correlation between oil spill density and gas flare site hotspots, indicated by a Pearson correlation coefficient of 0.548 ($p < 0.01$).
- These correlations suggest that areas with higher oil spill densities tend to have higher occurrences of both oil spill hotspots and gas flare site hotspots.

6.3.3.3 Gas Flare Density:

- There is a statistically significant moderate positive correlation between gas flare density and oil spill hotspots, gas flare site hotspots, and oil spill density, with Pearson correlation coefficients of 0.631, 0.703, and 0.603, respectively (all $p < 0.01$).
- These correlations indicate that areas with higher gas flare densities tend to have higher occurrences of oil spill hotspots, gas flare site hotspots, and oil spill density.

6.4 Implications for Co-occurrence

1. ***Oil Spill Hotspots and Gas Flare Site Hotspots:***

- The positive correlation coefficient (0.581) between oil spill hotspots and gas flare site hotspots suggests a moderate linear relationship between these two variables.
- This implies that areas with a higher density of oil spill hotspots may also tend to have a higher density of gas flare site hotspots, indicating a potential spatial association or co-occurrence of these environmental phenomena within the study area.

2. ***Oil Spill Density and Gas Flare Density:***

- The positive correlation coefficients between oil spill density and gas flare density, as well as, between oil spill density and gas flare site hotspots, suggest moderate to strong linear relationships between these variables.
- This implies that areas with higher densities of oil spills or gas flares are likely to exhibit higher densities of both types of environmental phenomena, indicating a

potential spatial co-occurrence or association between oil spills and gas flares within the study area.

3. Gas Flare Density and Oil Spill Hotspots/Gas Flare Site Hotspots:

- The positive correlation coefficients between gas flare density and oil spill hotspots, as well as, between gas flare density and gas flare site hotspots, suggest moderate to strong linear relationships between these variables.
- This implies that areas with higher densities of gas flares are likely to have higher occurrences of both oil spill hotspots and gas flare site hotspots, indicating a potential spatial co-occurrence or association between gas flares and oil spills within the study area.

Table 3: Pearson's Correlation Coefficient

Correlations					
		Oil Spill Hotspot	Gas Flare Site Hotspot	Oil Spill Density	Gas Flare Density
Oil Spill Hotspot	Pearson Correlation	--			
	Sum of Squares and Cross-products	7120.446			
	Covariance	7.947			
	N	897			
Gas Flare Site Hotspot	Pearson Correlation	**.581****	--		
	Sig. (2-tailed)	.000			
	Sum of Squares and Cross-products	6133.028	15652.725		
	Covariance	6.845	17.470		
	N	897	897		
Oil Spill Density	Pearson Correlation	**.980****	**.548****	--	
	Sig. (2-tailed)	.000	.000		
	Sum of Squares and Cross-products	35.841	29.702	.188	
	Covariance	.040	.033	.000	
	N	897	897	897	
Gas Flare Density	Pearson Correlation	**.631****	**.703****	**.603****	--
	Sig. (2-tailed)	.000	.000	.000	
	Sum of Squares and Cross-products	2.418	3.995	.012	.002
	Covariance	.003	.004	.000	.000
	N	897	897	897	897
**. Correlation is significant at the 0.01 level (2-tailed).					

6.5 CONCLUSION

In conclusion, the analyses conducted on oil spill hotspots, gas flare site hotspots, oil spill density, and gas flare density within the study area provide valuable insights into the spatial patterns and potential associations between these environmental phenomena in the context of the Niger Delta region. The study revealed significant spatial clustering and distribution of oil spill hotspots and gas flare site hotspots within the Niger Delta region. Areas with higher densities of oil spills and gas flares, as well as, their respective hotspots, were identified, indicating localized environmental risks and vulnerabilities. Pearson correlation analysis suggested moderate to strong linear relationships between oil spill hotspots, gas flare site hotspots, oil spill density, and gas flare density. Significant positive correlations between these variables implied potential spatial co-occurrence or associations, indicating that areas with high densities of oil spills are likely to also have high densities of gas flares, and vice versa. Regions such as Imo, Rivers, Bayelsa, Delta, Edo, Akwa-Ibom, and Abia States were identified as hotspots for both oil spills and gas flares, suggesting elevated environmental risks and vulnerabilities in these areas. The co-occurrence of oil spills and gas flares in these regions pointed out the interconnectedness of environmental challenges and the need for integrated mitigation strategies.

The findings highlighted the importance of targeted interventions and regulatory measures to mitigate the environmental risks associated with oil spills and gas flares in the Niger Delta region. Enhanced monitoring, enforcement, infrastructure improvements, and community engagement initiatives are warranted to address the spatial patterns and co-occurrence of these environmental hazards effectively. While the analyses provided valuable insights, further research utilizing advanced spatial analysis techniques and modeling approaches could enhance understanding of the complex interactions and dynamics between oil spills and gas flares in the study area. Long-term monitoring and assessment efforts are needed to track changes in spatial patterns and environmental impacts over time and inform adaptive management strategies

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