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Socio-Economic Risk of Oil Pipeline Vandalism in Nigeria and its Remedy Using Satellite Constellations: An Evidence From Bayesian Spatial Modeling

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ABSTRACT

The threat posed by the vandalism of oil pipelines in Nigeria has resulted in a lack of petroleum products for consumers, loss of life, and significant damage to both property and valuable resources due to resulting fires. This situation has also led to the pollution of marine life and has contributed to food shortages. Nigerian government loses about twenty (20) billions of dollars of the activities of pipeline vandals. This exclude the monetary cost of loss of lives, property and the environmental resources. A spatial statistic based on Bayesian principles aids in measuring spatial patterns and offers understanding into the mechanism behind their formation. With advancements in technology, particularly in storage capacity, the acquisition of georeferenced data is prevalent in current domain sets. The Bayesian approach is commonly employed to analyze such datasets and discern spatial patterns. Although the pipeline vandalization is spatially heterogeneous in Nigeria, current regional estimates of this barbaric act hide the epidemic's heterogeneity. A thorough examination of the prevalence of pipeline vandalism using district-level data could assist to developing the prevention strategies. The major aim of this research among others is to examine the spatial clustering of pipeline vandalism in Niger Delta region and assess the effects on the economy of Nigeria. This research proposes a cost-effective technique for resolving the challenge of oil pipeline vandalism using Earth observation systems (small Satellites/CubeSats) in the Low Earth Orbit and statistically monitoring the imagery data via the help of ArcGIS 10.4 software. The result from the ADSACBOPSS (Affordable DSA-CubeSat Based Oil Pipeline Surveillance System) show a high instant technique of preventing petroleum pipeline vandalization using Data obtained from Nigerian National Petroleum Cooperation (NNPC) and GRID[3] open sources. The constellation of these Satellites/CubeSats, has short development time and can provide 24/7 real-time surveillance data throughout its lifetime. The ADSACBOPSS technique is readily available and I recommend that NNPC and Nigerian government in general should buy the idea and invest in the project to effectively stop petroleum pipeline vandalization. Bayesian hierarchical spatial modeling techniques were utilized to tackle the research goals. We noticed a favorable spatial connection in the geopolitical zones and state indicators during the spatial analysis. The application of the Getis–Ord statistic pinpointed three states—Ondo, Delta, and Rivers—as areas with heightened activity, while the South-South and South-West zones were identified as hotspots, with confidence levels of 95% and 90%, respectively, regarding the prevalence of pipeline vandalism.

Keywords: Bayesian modelling, odds ratios; spatial clustering, Pipeline Vandalism

INTRODUCTION

The use of petroleum pipeline has been considered as the major means of conveying petroleum products in Nigeria. This includes fossil fuels, chemicals substances, gases and other essential hydrocarbon fluids which

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serve as valuable and major assets to the economy of a nation like Nigeria. Oil and gas pipelines are the most cost-effective and secure way to transport crude oil. They meet the highest standards for reliability and efficiency. For instance, the estimated deaths per ton-mile for shipped petroleum products are significantly higher using ships (4%), trucks (87%), and rail (2.7%) compared to pipelines. Despite their advantages, the global popularity of transporting hazardous substances through extensive pipelines in recent decades has raised the risk of critical accidents. This risk is particularly associated with pipeline failures and vandalism. (Fidelis, Paki & Agusomu, 2018).

The root cause of pipeline failures is either intentional (by pipeline vandals or unintentional (like device/material failure and corrosion) damages, leading to pipeline failure. This results in irreversible damages which include financial losses and environmental pollution, especially when the leakage is not detected on time (Odulanu, 2015).

Since the discovery of commercial quantities of crude oil in the Oloibiri oilfield in present-day Bayelsa State in 1956, crude oil has been a crucial contributor to Nigeria's economy, accounting for approximately ninety percent (90%) of the country's gross earnings (Adewole, 2013). While a significant portion of the nation's crude oil is produced onshore, there has been a recent uptick in offshore production (Nwachukwu, 2013). This shift has led to an increase in organized oil theft and vandalism activities in Nigeria. It is estimated that the nation loses around twenty billion dollars annually due to the unjust activities of pipeline vandals, with a total loss of about two hundred and twelve billion dollars' worth of crude oil between 2009 and 2019. **(**Nwachukwu, 2019)**.**

The oil and gas industries have consistently faced challenges from pipeline vandalism, impacting both upstream and downstream operations. According to former Group Managing Director of the Nigerian National Petroleum Corporation (NNPC), Mr. Andrew Yakubu, the pipeline known as system 2B, running from Atlas Cova, Lagos to Ilorin, Kwara State, experienced over seven hundred and seventy-four (774) breaches in a three-month period (specifically from August to October 2012). Notably, Atlas Cova and the Mosimi depot in Ogun State encountered approximately 181 breaches, Mosimi to Ibadan in Oyo State had around 421 breaches, Mosimi to Ore in Ondo State faced about 50 breaches, and Ibadan to Ilorin had approximately 122 breaches—all attributed to vandal activities (Nwachukwu, 2013).

This widespread vandalism has prompted some oil companies to withdraw prematurely from oil-producing regions, consequently impacting the overall economy of Nigeria. Empirical studies have shown that, in many instances, there were incidents of fire outbreaks, resulting in the unfortunate burning of numerous residential structures and the loss of human and aquatic lives. These acts of sabotage have significantly impaired the operational efficiency of oil industries in Nigeria (Fidelis, et al, 2018).

In the past years, The government's primary step to prevent pipeline vandalism and oil theft involved creating legislative frameworks for the petroleum industry. These include acts like the Federal Environment Protection Agency Act, 1990, and the National Oil Spillage Detection and Response Agency Act, 2006, among others. Presently, security personnel rely on tips to manually monitor oil spillage and theft. In vulnerable areas, tall surveillance towers and CCTV on jetties monitor the surroundings. (Nwachukwu, 2013). Yet, this endeavor has proven

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ineffective in alleviating the issue, as security personnel typically arrive at vandalized sites hours after the pipelines have been broken. While some vandals are occasionally apprehended, detained, or prosecuted, these actions have not dissuaded them from making repeated attempts. (Umar & Othman, 2017).

Figure 1: Niger Delta oil polluted soil and stream

Source: NNPC Website (https://www.nnpcgroup.com)

Deliberate hostile actions targeting environmental objects with the sole intention of causing damage constitute vandalism. The primary motive behind such behavior is the intent to harm or destroy property. According to James (2013), vandalism can be interpreted through Marxian perspectives as a force that actively opposes the exploitation inherent in the capitalist system. Vandalism can manifest in various forms, including tactical vandalism, which involves acts of sabotage in the workplace; vindictive behavior, representing a form of revenge; 'playing' vandalism, such as the breaking of window panels; and malicious vandalism, stemming from boredom, exasperation, resentment, or frustration. Each of these perspectives offers distinct insights into the motivations behind acts of vandalism. Theoretical perspectives on vandalism primarily center around two key aspects: the individuals responsible for the acts and the objects targeted. The former involves delving into the psychology of the actors, seeking to uncover the social factors contributing to vandalism. On the other hand, the latter perspective is rooted in environmental psychology, posing inquiries about why specific objects become targets of damage while others remain unharmed. A comprehension of the psychology of vandalism facilitates the identification of a connection between the actor, the object, and the associated rewards. Furthermore, it enables the establishment of a causal link between the intention and benefits of vandalism and the societal costs incurred due to the resulting damage. The contextual framework provides insights into the destruction or deterioration of environmental objects. (Umar & Othman, 2017).

Vandalism can be a consequence of marginalization, characterized by the denial, deprivation, and exclusion from societal resources and the resulting socioeconomic backwardness. This condition leaves individuals or groups with little to no control over their lives and resources. In response, aggrieved individuals may form groups, experiencing stress and emotional outbursts. Marginalized people, feeling deprived of their rightful societal position, may be motivated to inflict damage on public or private properties.

Additionally, societies facing marginalization believe that social policies and practices are less favorable to them, particularly in areas such as education, health services, housing, income, leisure activities, and employment opportunities. According to Ofuoma and Omoruyi (2014), marginalization is closely connected to vandalistic behavior and can lead to a society marked by a breakdown or absence of social norms and values. Through a comparative analysis of marginalized and non-marginalized regions, they determined that destructive behavior among youths is more prevalent in marginalized areas. Umar and Othman (2017) observed that marginalized individuals experience a higher incidence of social problems, emphasizing the need for the government to address their concerns seriously to prevent the escalation of social unrest.

Nigeria is one of the biggest oil producing countries in the world, and Niger delta region of Nigeria is the main areas in Nigeria that has the largest wetland in Africa. The area is believed to contain approximately 37 billion barrels (bb) of oil reserves and 168 trillion cubic feet of gas deposits. Nigeria relies heavily on the oil sector, which contributes over 90% of its foreign exchange earnings, with the majority originating from the Niger Delta region. Despite its significant resources, the Niger Delta is recognized as one of the most environmentally impacted regions globally, largely attributed to inadequately regulated oil activities. Several factors are believed to be responsible for the environmental deterioration in the region, such as gas flaring, industrial pollution, and incidents like oil spillage and pipeline vandalism. These elements have collectively contributed to the environmental degradation of the area over the years. (Raji & Abejide, 2013).

According to (NNPC, 2022), in speaking on the ending menace of pipeline vandalism in Nigeria, first half of 2021, a total of four hundred and forty-one (441) pipeline points were vandalized and one thousand four hundred and eighty-four (1484) points were vandalized in 2019 and 350 pipeline points were vandalized. In the 2020 alone, NNPC spent 53.36 billion in pipeline repairs and management.

Over time, the region has faced a significant challenge in the form of crude oil spillage resulting from pipeline vandalism. The increasing incidents of pipeline vandalism by militant groups have notably impacted the revenue sources of both the government and oil companies operating in the area. The militants assert that their actions aim to liberate the region from environmental neglect. According to statistics, Nigeria is experiencing a loss of well over 300,000 barrels per day (bpd) due to crude oil pipeline vandalism, resulting in losses amounting to billions of dollars. (James, 2013).

Bayesian spatial modeling is a class of statistical modeling which incorporates spatial data (geographically related data) into Bayesian models. It investigates spatial patterns and quantification of spatial uncertainty. The goal of Bayesian spatial statistics is to measure spatial patterns and gain understanding into the pattern-generation process. With current technological advancements, particularly in storage capacity, the acquisition of georeferenced data is prevalent in domain sets. The Bayesian approach is commonly employed to analyze and discern spatial patterns within these datasets. Spatial statistics has been increasingly applied in physical and environmental sciences. To develop an efficient and robust intervention approach for reducing the rate of pipeline vandalism, and to mitigate economic lost in Nigeria, knowledge of the factors responsible and associated with transmission of pipeline products and identification of the sections in the regions/states that need priority for interventions are needed (Chan-Yeung, et al., 2005, Manda, et al., 2012). The latter further requires good understanding of the spatial patterns of pipeline vandalism epidemics at the lower level geographical units of the country (Manda, et al., 2012). As discussed above, the distribution of pipeline vandalism in Nigeria is heterogenous and the reported sectional or regional and national estimates of pipeline vandalism prevalence may mask this heterogeneity within the country. Hence, having dependable data for lower-level geographic units related to pipeline vandalism and potential risk factors is crucial for evaluating these factors and spatial components in targeted interventions. The primary objectives of this study were to model the occurrence of pipeline vandalism regionally, employing a Bayesian hierarchical spatial modeling approach. The advantage of Bayesian hierarchical spatial modeling lies in its capacity to integrate spatial, specifically neighborhood, information concerning the variable of interest (Louzada, et al., 2021).

Space-based observation is an essential resource for big data analysis, as it helps data forecasting/prediction and analysis. Applications of Space-based observation (spatial statistics) vary in complexity and are frequently applied in risk surface detection, healthcare, urban planning, economics, engineering. This complex structure is accommodated in a flexible class of statistical models that are related to observed data and spatial dependencies. Because of these, the Bayesian approach is preferable as it possesses the ability to incorporate information from various sources. In the Bayesian framework, questions are answered through an estimation procedure by combining different sources of information, in such that previous knowledge (the prior) and the acquired information in the data (likelihood) are statistically combined to obtained the posterior and its associated information. Therefore, this research sought to investigate the socio-economic risk of oil pipeline vandalism in Nigeria and its remedy using satellite constellations: an evidence from Bayesian spatial modeling.

MATERIALS AND METHODS

This research utilizes secondary data for the purpose of achieving its objectives. The secondary data are gotten from Nigerian National Petroleum Cooperation (NNPC) website and GRID^3 (http://grid3.gov.ng) open sources. R-statistical software (version R-3.3.3) was used in the analysis.

Spatial Clustering

Spatial clustering is a technique used in Bayesian spatial modeling to identify group of locations having high or low similarities. It is used to find areas with similarities in terms of demographics, infrastructures, or other characteristics. Spatial analysis was conducted to identify the geographical clustering of pipeline vandalism prevalence in Nigeria. In this analysis, the regional or states boundaries were geo-referenced. Then, for the Ground Terminal Chips GNC using ArcGIS software version 10.4, choropleth maps were created for visualization. The global spatial autocorrelation of pipeline vandalism was investigated using the global Moran’s I statistic. This statistic was utilized to evaluate the existence, direction, and intensity of spatial autocorrelation in pipeline vandalism across Nigeria. The Moran's I statistic indicates positive spatial autocorrelation when values in neighboring regions exhibit spatial clustering. Conversely, if adjacent regions or states display disparate values or spatial dispersion, it implies negative spatial autocorrelation. When deviations in some neighboring pairs align in the same direction and others in the opposite direction, the statistic approaches zero.

To distinguish between a hotspot (flash points) and a coldspot within a spatial cluster, the geostatistical Kriging principle, specifically the Getis–Ord G_i local statistic, can be employed as an alternative to the local Moran's I index. In this research, we utilized the Getis–Ord G_i statistic to identify districts with the highest prevalence of pipeline vandalism (hotspots) and those with the lowest prevalence (coldspots). Unlike the local Moran's I statistic, the Getis–Ord G_i statistic calculated for each district is easily expressed in terms of z-scores from the standard normal distribution, providing a clearer indication of statistical significance. However, multiple confidence intervals can be depicted on a map, enhancing its statistical appeal.

Spatial statistics Modeling Overview

The primary focus is on estimating the uncertainties surrounding both b and g, and generating forecasts for the latent variable z. In a Bayesian framework, for the prior distribution on ***b***, *t*, *s*2, and *a* are either elicited depending on the available information or are assigned vague priors, allowing the data to decide.

$$f(\psi, \alpha, \varphi, \emptyset, | y) = \frac{f(\alpha)f(\phi)f(\boldsymbol{\beta}|\Sigma)f\left(\gamma\middle|\psi, \Sigma(\alpha)\right)f\left(\alpha\middle|\theta_i^{-1}, \beta, \gamma, \phi\right)}{\int f(\alpha)f(\phi)f(\beta|\Sigma)f\left(\gamma\middle|\psi, \Sigma(\alpha)\right)f\left(\alpha\middle|\theta_i^{-1}, \beta, \gamma, \phi\right)dy} \quad (1)$$

The above Bayes expression is updated with the marginal posterior distribution for the spatial aspect which is given as:

$$f(\alpha|y) = \int f(\beta|\Sigma)f\left(\gamma\middle|\psi, \Sigma(\alpha)\right)f\left(\alpha\middle|\theta_i^{-1}, \beta, \gamma, \phi\right)d\beta d\phi d\alpha \quad (2)$$

$$f(\boldsymbol{\beta}|y) = \int f(\beta|\Sigma)f\left(\gamma\middle|\psi, \Sigma(\alpha)\right)f\left(\alpha\middle|\theta_i^{-1}, \beta, \gamma, \phi\right)d\gamma d\phi d\alpha \quad (3)$$

Where $\alpha, \phi, \boldsymbol{\beta}\ and\ \gamma$ are hyperparameters which are subjectively chosen by the researcher in the course of the analysis.

Because of the computational burden associated with Markov Chain Molte Carlo (MCMC) method with Gaussian Markov Random Field (GMRF), the researchers intend to use Integrated Nested Laplace Approximation (INLA) installed in R-software in the course of statistical analysis (Debusho and Bedaso, 2023).

Forecasting Assessment

The HIV prevalence data were modeled using the integrated nested Laplace approximation (INLA) numerical method for fitting Bayesian hierarchical spatial models. To establish spatial relationships between districts, a spatial weight matrix was employed, and Queen's contiguity was utilized to define neighborhoods. Neighboring districts are those that share boundaries or a common vertex. This was defined using the nb2listw function from the spdep R package. The inla(.) function from the R-INLA package was used to perform the Bayesian analysis. The fitted models were compared using the deviance information criterion (DIC), the effective number of parameters (pD), the mean deviance (¯D) and the widely applicable information criterion (WAIC). The model having the lowest DIC, pD, ¯D and WAIC is adjoined as the best-fit model.

Data Analysis

This section looks at the data analysis and it is further subdivided as shown below.

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RESULTS AND DISCUSSION

The data used for the purpose of analysis are mainly secondary sources obtained from an existing source. With the help of ArcGIS 10.4 software used at Defence Space Administration's Geospatial Data Laboratory (Figure 2), is Nigerian Raster Data showing the Network of oil pipeline distribution in Nigeria. The Lagend equally stipulate and identify the locations of the Refineries, Boosters, Major cities deport pump houses, Marine Stations, River lines etc.

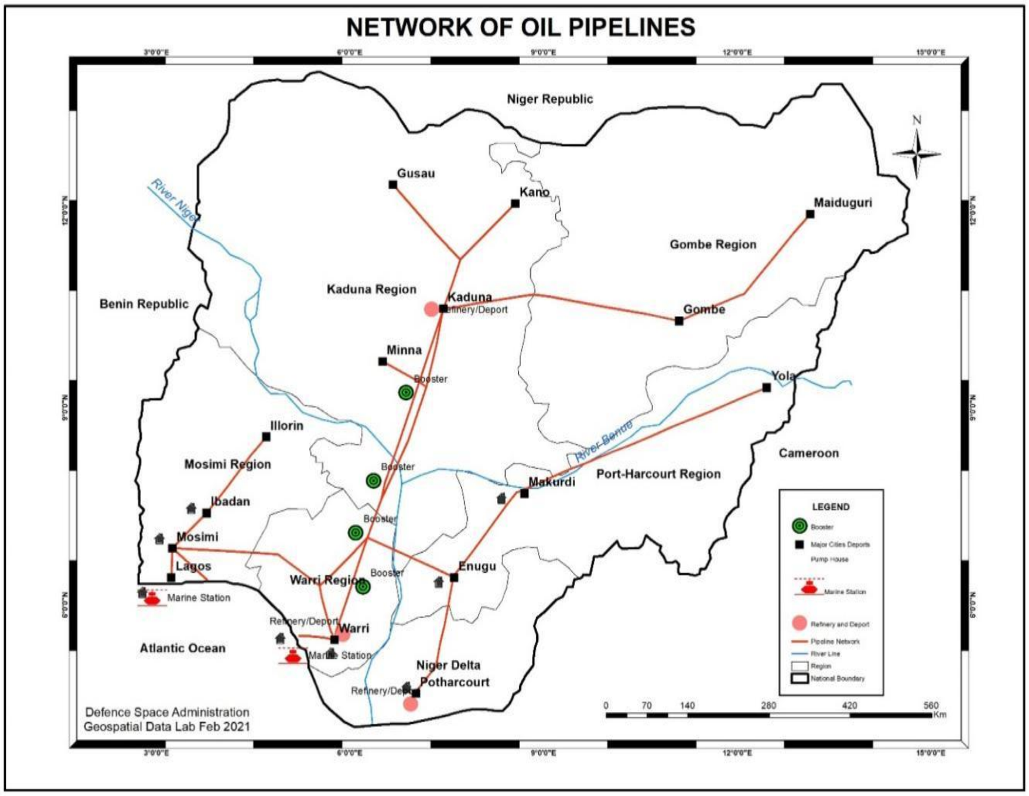

Figure 1: Map showing the Network of oil pipeline in Nigeria

Source: Defense Space Administration's Geospatial Data Laboratory

The Map was gotten as Raster Data and was georeferenced and digitized before it was converted to Vector data for easy analysis at Defence Space Administration Geospatial Data Laboratory with the help of an ArcGIS 10.4 software.

The said Raster Data was gotten from Nigerian National Petroleum Cooperation (NNPC) website before the transformation from Raster to Vector data via georeferencing and digitization with the help of ArcGIS 10.4 software.

In the above (Figure 3) showing the distribution of illegal activities on petroleum pipeline of map of Nigeria comprises of deports, refineries and pumping stations was vectorized at DSA Geospatial Laboratory using ArcGIS 10.4 Software, Vandalized Location coordinates were collected using GPS so as to locate the areas along the pipeline network that is vandalized either by natural causes or by man. Findings shows that the vandalism is more in the southern part of Nigeria. The data was collected from Nigerian National Petroleum Cooperation (NNPC).

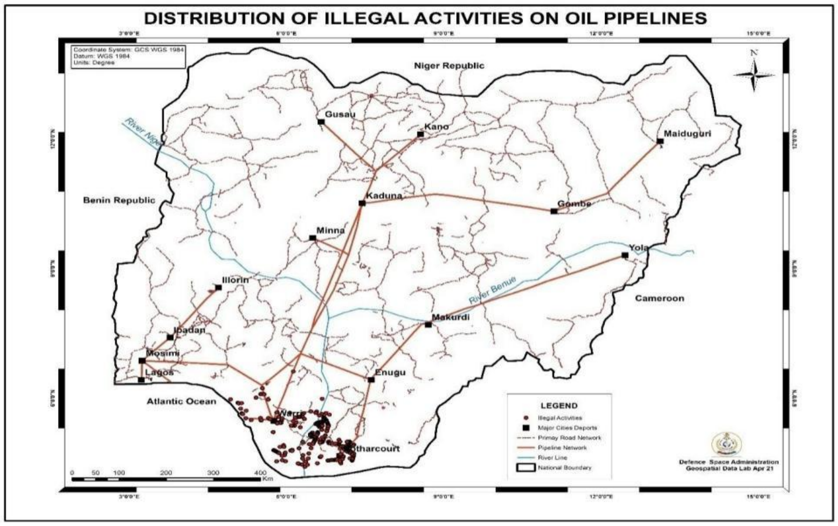

Figure 2: Map showing the Distribution of Illegal activities on oil pipelines

Source: Defense Space Administration's Geospatial Data Laboratory

The operational principles of the ground segment will mirror those of a car airbag system. In the design of this system, the elastic strength of the materials employed in oil pipelines will be utilized to program crash/vibration sensors, denoted as Ground Terminal Chips (GTC). These sensors are configured so that when the resistance threshold of the pipeline is surpassed, the transceiver instantly transmits the GPS coordinates of that specific location to the satellite constellation. Subsequently, the satellite constellation relays this information to the Ground Station (GS), serving as an alert mechanism for security personnel, signaling potential illicit activities occurring at that particular location.

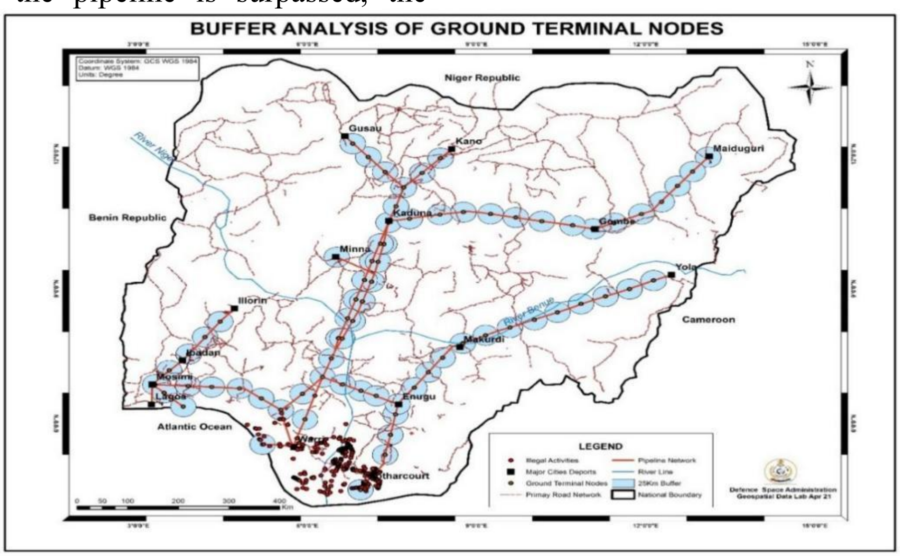

Figure 4: Map showing 50meters radius Buffer analysis of GTC

Source: Defense Space Administration's Geospatial Data Laboratory

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At the ground Station, the ArcGIS 10.4 software helps to indicate the map and possible location in the country where the vandalism is about to take place, and as such makes it possible for the analyst to give the coordinate of the particular area to the security authorities (police station) very close to the area so as to immediately locate the area in question and put an immediate stop to the pipeline vandal.

Figure 5 is a Map illustration produced at Defence Space Administration Geospatial Data Laboratory using ArcGIS 10.4 indicating a particular Ground terminal Chip GTC of 50km radius covering a particular pipeline vandal at a given area along the petroleum pipeline network. Immediately the resistance threshold of the pipeline is exceeded through the process of the vandal, the transceiver automatically transmits the GPS coordinates of that location to the satellite constellation, which will then relay the data to the Ground Station (GS) to alert the security (police station) that there is an illegal activity going on at that particular location, and the image will be of the one at Figure 5 showing the data of the coordinates of the distribution of polices in Nigeria.

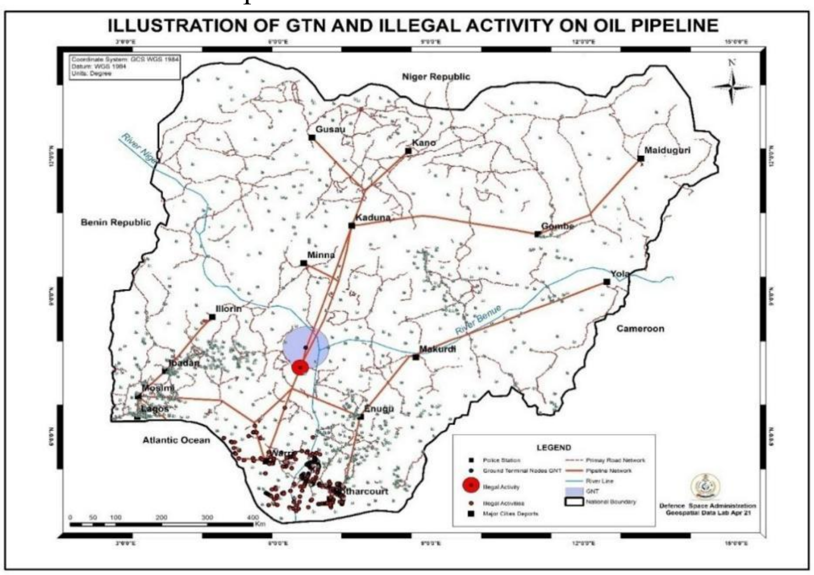

Figure 5: Map illustration of GTC under 50km buffer and Illegal activities on Pipeline
Source: Defence Space Administration's Geospatial Data Laboratory

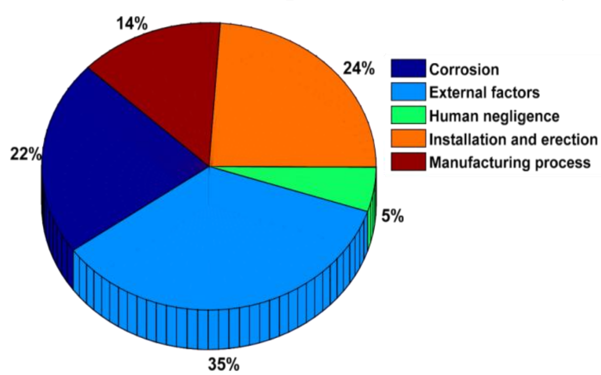

Figure 6: A pie chart of the statistics of the sources of pipeline failure

Source:NNPC Website (https://www.nnpcgroup.com)

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Based on these statistics, incidents of pipeline leakage are hard to entirely avoid as the sources of failures are diverse. However, in order to reduce if not stop the External factor which include vandalization of pipeline by human and hence reduce the loss rate, injuries and other serious societal and environmental consequences due to the pipeline failures, an ADSACBOPSS (Affordable DSA-CubeSat The Surveillance System for Oil Pipelines (SOPSS) ensures ongoing and daily monitoring of oil pipeline networks to safeguard against vandalism. This system covers an extensive network of oil pipelines spanning up to 5000 km throughout Nigeria.

Table 1. Summary of DIC, pD, ‾D and WAIC values used to fit the Bayesian spatial model of pipeline vandalism.

Model	DIC	pD ‾	D	WAIC
BSM	6095.72	7405.56	6099.43	6091.41

In Table 1 above, the values of the fitted Bayesian spatial multivariate logistic regression model with spatially structured random effects are displayed. All the characteristics of the forecast assessment used were shown in the table above. Under the Bayesian Spatial Modeling, the forecasting criterion Deviance Information Criteria (DIC) has a value of 6095.72, p^D has a value of 7405.56, D has a value of 6099.43 and WAIC has a value of 6091.41. Therefore, it is evident that WAIC with least value is appropriate in forecasting the occurrence of pipeline vandalism in Nigeria.

Discussion of Findings

The distance between each Ground Terminal Chips is 100 kilometers across the pipeline network in Nigeria. A buffer of 50km radius from each Ground Terminal Chips (GTC) indicates that any activity or vandalization on the pipeline that exceeds the resistance threshold of the pipeline, makes it possible for that particular Ground Terminal Chip GTC under the 50km radius to automatically transmit the GPS coordinate of that location to the satellite constellation, which in turn relay the data to the Ground Station (GS) indicating the GPS coordinate of the particular area where the pipeline vandal is happening at near real time. This makes it possible to track the vandals at real time interval and therefore reducing the waste of crude oil and equally reducing or stopping the polluting of the soil/land as well stopping the pollution of rivers and streams thereby stopping the killing and contamination of aquatic life and in turn increase the economy of the country generally. The system is not complete without mentioning the fact that the Analysts after getting the GPS coordinate of the particular area on the pipeline network under vandal from the satellite constellations, alerts the police station closer to that vandal area to either track the vandals via airplanes, road network if it is motorable or with flying boat depending on the vandal area.

CONCLUSION

A multi-layered security intelligence approach and latest ICT devices should be deployed in fighting this act of economic saboteurs. Also and ultimately, the federal government should have considered the option of outright sale of the pipelines, deports, refineries to private investors with the capacity to manage the resources effectively and the government should restrict itself to the regulation and provision of security possibly by engaging the host communities.

Based on the findings, the following recommendations were made: The Nigerian National Petroleum Cooperation (NNPC), National Oil Spill Detection and Response Agency (NOSDRA) and Nigerian government generally should invest in the project and help stop both oil spillage and the pipeline vandalization issues that has contributed to the nation's economic problems.

The authority should invest in building its own constellation of CubeSats/satellite for earth observation purposes which will not only help in stopping pipeline vandalization, but will equally help in any surveillance purpose that has to do with earth observation for real time data. Example is the ongoing Northeast Banditry and kidnapping in the Northeast and Northwest of Nigeria.

However, the cost of Nigeria's owning its constellation of Cubesat/satellites could be saved by partnering with companies like SecureWatch, SpyMeSat/SkySat, Ikonos, European Space Agency, Planet Lab, Airbus (OneAtlas Data), ImageSat International, Maxar Mutual Communication Group e.t.c. These companies have a constellation of satellites or are in alliance with companies that has constellations of satellites whose missions are strictly on Earth Observation purposes. That way, the Nigerian government or Nigerian National Petroleum Cooperation (NNPC) can collaborate with such companies, tasking their CubeSat/satellites for the images/Data at a cheaper rate compared to building and launching its own constellations of satellites.

Encouraging the engagement of host communities in the oil economy involves fostering open and honest communication, selecting trustworthy leaders at traditional, local, state, and federal levels, and promoting a value reorientation to encourage a culture of constructive dialogue. Implementing these measures is intended to ensure that local communities remain committed to preventing oil pipeline vandalism.

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