Quantifying the exposure of humans and the environment to oil pollution in the Niger Delta using advanced geostatistical techniques.

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Abstract

The Niger Delta is one of the largest oil producing regions of the world. Large numbers and volumes of oil spills have been reported in this region. What has not been quantified is the putative exposure of humans and/or the environment to this hydrocarbon pollution. In this novel study, advanced geostatistical techniques were applied to an extensive database of oil spill incidents from 2007 to 2015. The aims were to (i) identify and analyse spill hotspots along the oil pipeline network and (ii) estimate the exposure of the hydrocarbon pollution to the human population and the environment within the Niger Delta. Over the study period almost 90 million litres of oil were released. Approximately 29% of the human population living in proximity to the pipeline network has been potentially exposed to oil contamination, of which 565,000 people live within high or very high spill intensity sectors. Over 1,000 km^2 of land has been contaminated by oil pollution, with broadleaved forest, mangroves and agricultural land the most heavily impacted land cover types. Proximity to the coast, roads and cities are the strongest spatial factors contributing to spill occurrence, which largely determine the accessibility of sites for pipeline sabotage and oil theft. Overall, the findings demonstrate the high levels of environmental and human exposure to hydrocarbon pollutants in the Niger Delta. These results provide evidence with which to spatially target interventions to reduce future spill incidents and mitigate the impacts of previous spills on human communities and ecosystem health.

Keywords: Oil pipelines, Sabotage, Oil Spills, Pollution hotspots, Risk assessment, Health

1. Introduction

Nigeria is the largest producer of oil in the entire African continent and has the largest natural gas reserve (Kadafa, 2012). The Niger Delta is the main oil and gas producing region located in Southern Nigeria (Figure 1), providing the main source of revenue for the country. However, the Niger Delta is also one of the ten most important marine and wetland ecosystems in the world (Ambituuni et al., 2014). Since 1958, when oil exploration began, many environmental problems have arisen, such as oil pollution of soil and water, degradation of biodiversity and food production and atmospheric pollution from gas flaring; all of which have impacted upon the health and well-being of communities living in the region (Nwilo and Badejo, 2005; Ordinioha and Brisibe, 2013; UNEP, 2016). For example in a recent study, it was found that communities with visible pollution had high levels of emotional distress and disease symptoms (Nriagu et al., 2016). Consequently, the Niger Delta is now recognised as one of the five most oil polluted regions in the world (Kadafa, 2012).

Oil spills can result from poor maintenance, insufficient investment and vandalism of pipeline infrastructure (Aroh et al., 2010; Anifowose et al., 2012). In particular, the rise in the level of destruction of oil pipelines by militant groups such as 'the Niger Delta Avengers' has led to significant economic hardship through reduction in oil exports and substantial environmental damage. It has been estimated that from 1958-2010 approximately 546 million gallons (10.8 million barrels per year) were spilled into the environment (Francis et al., 2004). In addition, from 1986-2003 approximately 20,234 hectares of mangrove forest have been lost to oil production infrastructure (Francis et al., 2004).

Oil spills in Nigeria are reasonably well documented but information on potential impacts on the population and environment is limited. Some suggest oil spills are the main source of contamination in rivers upon which the livelihoods of many people are based. This is because most sabotage occurs at river crossings (Anifowose et al., 2014). Major oil spills include the 1979 Forcados Tank 6 spill where 570,000 barrels leaked into the estuary disturbing the aquatic environment and contiguous swamps (Tolulope, 2004; Ukoli, 2005). Similarly, the 1980 Funiwa Field blowout resulted in 421,000 barrels of oil being spilled into the ocean (Tolulope, 2004; Gabriel, 2004; Ukoli, 2005), damaging 338, 836 acres of mangrove forest (Kadafa, 2012). Other spills include the Oyakam oil spill where 30,000 barrels of oil were spilt. The village of Oshika experienced a spill of 500 barrels in 1979 and an additional 5000 barrels in 1983 from the Ebocha Brass pipeline. This led to a significant impact on adjoining swamps, including losses in crabs, fish and shrimp communities (Ukoli, 2005). Oil spills generally occur on land, or in the swamps, but occasionally at sea (Anejionu et al., 2015; Nwilo and Badejo, 2005).

To mitigate against oil pollution in the region, there is a need to adequately understand the geographical and historical patterns of pipeline spills and offer quantitative explanations for the observed patterns. This forensic approach will support the allocation of scarce resources which support environmental and health protection and security in the region. There are a number of different approaches that may be used to mitigate against the pipeline spills, and spatially targeting interventions towards oil spill hotspot locations can facilitate this process. Oil spills in the Niger Delta typically occur along the pipeline network. There have been some interesting applications of network analysis over time which have focused on road traffic accident hotspots, which may be applicable to other network based scenarios such as pipeline sabotage. For example, Xie and Yan (2008) used Kernel Density Estimation (KDE) to identify traffic accidents in Kentucky, Benedek et al. (2016) examined urban traffic hotspots and the social backgrounds of victims whilst Kuo et al. (2013) used network techniques to optimise police patrol routes ensuring better allocation of resources and effective response to issues of public importance. The spatio-temporal analysis techniques used in these studies were adopted in the presented study in order to identify oil pollution hotspots along the pipeline network, and then quantify the exposure of residents and the environment to oil pollution in the Niger Delta.

The aim of this study, therefore, is to examine the potential for human and environmental exposure to oil pollution by applying hotspot analysis of oil spills along the pipeline network over a 9 year period. Specifically, the objectives were (i) to examine the temporal and spatial patterns of oil spills and their causes; (ii) to identify and characterise oil spill hot spots; (iii) to assess the putative exposure of the human population and the environment to oil spills, and (iv) to characterise the factors responsible for observed patterns.

This investigation presents a novel method for using existing data to statistically determine the extent of oil spills in the region and generate new information on trends, patterns, human and environmental exposure. This will inform the prioritisation of decision-making in areas that require rapid response to protect human and environmental health through remedial approaches.

2. Materials and Method

2.1. Oil Spill Data

Spill records for the Niger Delta covering 2007-2015 were used in this study. These were provided by the National Oil Spill Detection and Response Agency (NOSDRA) in Nigeria, which is the official government agency responsible for maintaining such records (http://www.nosdra.gov.ng/). The data were compiled through a process of Joint Investigation Visits (JIV) by a team consisting of a host community, NOSDRA staff, and representatives of the pipeline operators. The detailed database contains information such as date, time and location (GPS coordinates) of spills (Figure 2), spill duration, oil type, spill volume and the cause of spill. The database is updated daily contingent on how situations persist. If, for example, after an initial visit to a spill site when the volume of spill is recorded the spill continues, then the record will be updated to cater for the additional spill. Correlation analysis was performed between frequency of oil spills occurrence and volume of spills to establish a relationship.

2.2. Pipeline, Population and Landcover Data

The Nigerian pipeline network is divided into the upstream and downstream component. The upstream network is usually the subject of sabotage and spills due to ease of accessibility, while the downstream network is less prone to sabotage due to the logistics required. The pipeline data used for this article was sourced from Shell Petroleum Development Company Nigeria. The data contains information on oil and gas infrastructure including pipelines. The pipeline information was digitised using ArcMap 10.4, after the map was georectified and projected to UTM Zone 32N (Figure 3a).

Gridded population data at a $1km^2$ resolution (Figure 3b) was sourced from the Centre for International Earth Science Information Network (CIESIN), Columbia University, New York (http://www.ciesin.org/). The version of the data used in this article is the 2015 estimate which was released in June 2016 after it was adjusted with UN data (CIESIN, 2016). Landcover data was sourced from the European Space Agency's Global Land Cover Climate Change Initiative (http://www.esa-landcover-cci.org/). This was produced from Medium Resolution Imaging Spectrometer data. The original landcover types were regrouped into 7 classes including agricultural land, broadleaved vegetation, shrubs, mangroves, settlement and water bodies to suit the purpose of this study (Figure 3c). Pipeline, population and land cover data used in this study are summarized in Figure 3.

2.3. Spatial and Statistical Analysis

Charts were initially constructed to summarise the major causes of oil spills (sabotage, operations and others) over time. Proportional symbols maps were then used to visualise changing patterns of oil spills in space (across the Niger Delta) and time (for individual years).

2.3.2. Getis Ord for Oil Spills Hot Spot Detection

Different researchers have used different methods to identify statistically significant hotspots in spatial data (Anderson, 2009; Benedek et al., 2016; Chicas et al., 2016; Lauren , 2012; Mahboubi et al., 2015). Popular methods include Kernel Density Estimation (KDE), which is well suited for point datasets. It was developed for epidemiological studies but has been widely applied in transport and other related studies (Kuo et al., 2013; Xie and Yan, 2013). Getis-Ord Gi* statistics (Getis and Ord, 1992; Ord and Getis, 1995) were used in this study as the first method to determine statistically significant spills hotspots.

2.3.3. Spatial Analysis along Pipeline Network

Given the very linear distribution of oil spills points along the pipline network, an alternative approach to identifying hotspots was adopted. Xie & Yan, (2008) have previously applied a network-based KDE to estimate accident hotspots along busy roads. Here we adopt the SANET algorithm (Okabe, 2015) to detect spills hotspots along the pipeline network. This geostatistical technique was designed to identify hotspots of traffic accidents on a road network based on point data of individual accident occurrences. In this study we have modified this technique in order to use the quantity of spills rather than point occurrence as the basis of the analysis, since this gives a much better quantification of the magnitude of spill hotspots, from an environmental and health perspective. The SANET algorithm produces line segments with assigned values which are classified relative to the intensity of spills (very high, high, medium, low and none). Used in combination, Getis Ord and SANET are able to provide powerful insights into the areas most affected by oil pollution. Further details of SANET can be found in the supplementary information.

2.4. Potential Human and Environmental Exposure to Hydrocarbon Contamination

To determine potential human and environmental exposure to spills a buffer of 2.5 km, which is the maximum impact radius a pipeline spill is known to have (Shittu, 2014; United States Department of Transport, 2011), was created around pipelines and individual spill events. The impact radius is consequent upon the pressure, type of pipeline and volume of spills, but the buffer used in this study represented the typical potential area of impact. Human exposure was analysed using the classified SANET outputs with total population living in close proximity to very high, high, medium and low spill intensity sections of the pipeline computed from the 1km^2 gridded population data. The percentage of the total population exposed in each Local Government Area (LGA) was also computed. This allowed the ratio of spill volume per head to be computed. In order to measure the extent of environmental contamination, land cover data were combined with spill buffers using an iterative python script to delineate the percentage breakdown of damage per landcover type within each spill zone for the entire period (2007-2015).

2.5. Factors Influencing Oil Spills

Several factors have been identified as potential causes of oil spills. Some scholars have argued that socioeconomic factors such as poverty are the main drivers (Onuoha, 2008; Oviasuyi and Uwadiae, 2010). Others assert poor operational standards on the part of the companies, or political reasons (Anifowose et al., 2008). Here we examine distance-based factors including proximity to the coast, cities, minor and major roads, and security bases

(Trimble, 2016). Euclidean distances from each spill to each influencing factor were computed. Resulting values were exported to SPSS for cluster analysis, to first identify if clusters existed and if so, what the most influential factors were. Initially a non-parametric clustering analysis was applied to the data to identify clusters before applying the K-means clustering analysis for final cluster delineation.

3. Results

3.1. Oil Spill Pollution Trend

Figure 4 shows how the number of pipeline spills has generally increased over the 9 year study period. In addition to the upward trend, sabotage has been identified as the leading cause of oil spills in the region, accounting for over 40% of spills between 2013-2015 as shown in Table 1. The figure also reveals a significant drop in sabotage and spills in 2015; this can be partly explained by uncertainties associated with the 2015 general elections in Nigeria.

In terms of the volume of spills, Table 1 shows that sabotage accounted for 66% of all oil spilled over the 9 year period. The 'other' category denotes spills whose immediate causes are not known or have not been recorded due to the remoteness of the location or security threats posed by local communities affected by spills. Table 1 also shows that a total of almost 90 million litres of oil was spilled into the region over the 9 year period. Although volumes vary on an annual basis, 2011 and 2014 were the worst years with more than a quarter of the total spilled volume for the study period occurring in these two years. A correlation analysis between frequency of oil spill incidence and volume of spills indicates a weak to moderate correlation (R^2 = 0.52). Correlation analysis data is presented in the supplementary information. This is because the volume of oil released from each spill incident varies considerably depending on a number of factors such as pipeline pressure and duration of leakage. Therefore, for example, in 2014 there were 800 spill incidents resulting in over 18 million litres of spilled oil. In contrast, in 2013 there were 1400 spill incidents resulting in 10 million litres of spilled oil.

3.2. Temporal and Spatial Oil Spills Trends

Figure 5 illustrates the spatial and temporal trends of oil spills in the Niger Delta over the study period. The data show that oil spill contamination is more prevalent in the southwest of the region. The spatial distribution of the spills also varies over the 9 year period. Some LGAs, such as Southern Ijaw, Warri South West and Nembe, have experienced oil pollution throughout the time-frame of this investigation. Overall the areas that received the greatest volume of oil spills were the communities in Southern Ijaw, Ogbaegbe and Ibeno.

The network-like pattern of the spills (Figure 2), is determined by the configuration of the pipeline network. The Figure also shows that apart from the outliers in Akure North in the North, and Ibeno in the South East, the vast majority of spills occur in the Central and Southern part of the Niger Delta. This can partly be explained by the existence of oil and gas infrastructures in the region. The linear pattern of spills northwards towards Etsako East is potentially due to sabotage of the crude oil pipeline transporting crude from the Port Harcourt refinery in the South, to Kaduna refinery in the Northern part of Nigeria.

Figure 6 presents pipeline segments that are hotspots of oil spill intensity based on the SANET analysis. Contingent on the kernel density value, the pipeline network has been classified into categories of low, medium and high oil spill intensity. According to this classification, several segments of pipeline have experienced a large number of oil spills. The Southern Ijaw-Nembe-Brass axis (Figure 6.C) of the pipeline is by far the most contaminated area in terms of oil spill intensity. Obgaegbe, located in the Northern Niger Delta region (Figure 6.A) is also an area of high spill activity; with 29 km of affected pipelines. This can partly be explained by the fact the area is known to have many leased oil fields, thus intensive extractive activities. The Gokana-Bonny-Tai area has also been badly affected by oil spills (Figure 6.B) with 23 km of pipeline being heavily affected. This indicates pipeline sabotage is a frequent occurrence in the area. Northwest Port Harcourt and Yenagoa are also areas were many spills have occurred. Unsurprisingly, this area is known for agitation and struggle for resource control, and where one of the notorious groups of militants i.e. Movement for the Emancipation of the Niger Delta (MEND) are based. Ekeremor has been highlighted in a similar way to Southern Ijaw in the southern part of the region (Figure 6.D) because the area is remote and inaccessible, therefor making policing a difficult task.

3.3. Potential Human and Environmental Exposure to Hydrocarbons

Based on the SANET analysis of spill intensities the potential extent of human exposure to hydrocarbons was derived from a 2.5km buffer around the pipeline network (Table 2). This revealed that approximately 29% of the human population living within the buffer is exposed to spills, of which 565,000 people live within high or very high spill intensity sectors. Some LGAs have more than half of their population living within zones impacted by oil pollution (see Supplementary Table S.1). Most notably Uvwie, Tai, Warri South West, and Eleme have in excess of 80% of their population living within contaminated zones. Figure 7 shows the distribution of the percentage of population impacted within each LGA in the Niger Delta, which indicates that the Southern LGAs as the worst affected. However, the volume of oil spilled in these areas varies considerably and this can affect the level of exposure. As shown in Figure 8 exposure expressed as litres of spilled oil per person indicates that many people may be exposed to large volumes of oil in Ibeno, Burutu, Ndokwa and Southern Ijaw. In the most extreme case, on average each person in Ibeno has potentially been exposed to 570 litres of oil through the study period (see Supplementary Table S.1).

The impact of oil spills on different forms of land cover was also evaluated (Table 3). The most contaminated land cover types are the broadleaved tropical rainforest followed by mangroves and crop land. Substantial areas of settlements were directly exposed to spills, while the least affected land cover was grassland as it is an uncommon cover type in the region.

3.4. Spatial Factors Contributing to Oil Spills

Figure 9 shows the results of the cluster analysis based on the distances of spills from the coast, cities, security, minor and major roads. A total of 4 clusters were identified and Table 4 shows the spatial factors influencing each cluster, and volumes of oil based on cluster configurations. Proximity to the combination of all of the spatial factors tested accounted for the cluster of spills which released the largest volume of oil. The individual spatial factor which accounted for the largest spill volume was proximity to coast. The results show that proximity to security locations is not a significant factor individually or in most of the clusters except in the first one where all factors were influential.

4. Discussion

The causes and impacts of oil spills in the Niger Delta have long been a concern for government and industry. Social, economic and political drivers in the region have resulted in different causes of spills, leading to associated environmental and health impacts. Analysis of the oil spill data from 2007–2015 reveals that sabotage as the leading cause. This contradicts the notion that oil companies have been largely responsible for pollution incidents (Oviasuyi and Uwadiae, 2010), a claim always denied by the industry. However, operational failures are the next major cause of spills in the region and these are mostly attributed to the practices and production activities of the companies. The companies have been accused of failing to meet acceptable standards of maintenance and sluggish response times to oil spill incidents (Eweje, 2006). In the present study, operational spills account for 30% of total spills (Table 1), presumably, as argued by Fatoba et al (2015), the result of ageing pipelines and corrosion. Overall, nearly 90 million litres of oil have been spilled over the 9 year study period, enough to cause significant damage to human health, community well-being and the environment (Nriagu et al., 2016; Ordinioha and Brisibe, 2013). Regrettably, the region has a poor clean up and remediation record, hence the impact of accumulated spills on the environment is highly significant. For example, the 2004 oil spill that occurred in Ogoniland (part of Niger Delta) is only now being considered for clean up and remediation some 13 years later (UNEP, 2016). The clean-up action stems from UNEP's 2011 report on the Shell facility incident, demanded by the Nigerian government, which led to substantial environmental damage (UNEP, 2011). In addition, the landmark judicial victory of the community against Shell in a London court is seen as a likely catalyst for future action (The Guardian, 2015). While bioremediation may potentially be a cost effective alternative to remediation, past studies show it may be effective in reducing soil toxicity and reduces effects on plant growth, aromatic fractions in light oils may be responsible for acute toxicity in soils (Dorn and Salanitro, 2000).

The novel network-based hotspot analysis presented here has revealed the severity of the oil contamination problem in the Niger Delta states of Bayelsa, Rivers, Delta and Akwa Ibom. Most of the areas affected are around the coastline and creeks. This can be partly explained by the remoteness of these coastal fringes, which in turn makes policing more difficult. In addition, coastal locations provide ease of transit for oil that has been illegally extracted from pipelines so these locations are favoured by criminals. The inland urbanised area of Ogbaegbe has also been highlighted as an oil spill hotspot. It is common to have pipelines in and around cities which make them vulnerable to attacks, and spills from such attacks expose more people to contaminants due to higher population densities. The prevalence of hotspots in the study area demonstrates that the problem of oil spills remains a live issue in the region; recently, the key perpetrators are the militant group the Niger Delta Avengers (Onuoha, 2016).

The human and environmental exposures were quantitatively assessed based on the outcomes of network-based hotspot analysis. Exposure estimates were based on populations living within low, medium, high and very high spill intensity sectors of the pipeline network. Well over half a million people live in high or very high spill intensity areas. The implication is that this group of people are more likely to be exposed to oil contamination and have a higher likelihood of negative impacts on their health such as irritation, cancer, genetic disorder, and organ failure (Shittu, 2014). There are also considerable health concerns for the nearly 1 million people living within the medium and low spill intensity parts of the pipeline network; this is because it is well known that exposure to even trace levels of oil and it constituents can causes health problems (Nduka and Orisakwe, 2010; Shittu, 2014). The implications for the Niger Delta overall are quite revealing, with 29% of the population living within a spill impact radius; this undoubtedly has the potential to have enormous consequences for the health of the Niger Delta population. Oil can have both short and long term effects on the environment and human health. Crude oil, commonly spilled in the Niger Delta, contains chemicals such as polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs – benzene, toluene, ethylbenzene and xylenes) (Mohamadi et al., 2015). Crude oil also contains heavy metals, which potentially have a range of effects on human health (Ndidi et al., 2015; Olobaniyi and Omo-irabor, 2016). Therefore, to properly address and remediate the significant volume of spilled oil, there is the need for the application of detailed hydrocarbon fingerprinting for source identification and characterisation (Wang and Fingas, 2003). Generally, areas around hotspots are presumed to be more contaminated; therefore, increasing the likelihood of exposure. Human exposure may occur through direct ingestion and contact with skin or indirectly through bioaccumulation in crop plants (Omodanisi et al., 2014). In this study, it was shown that 22% of the land area contaminated by oil spills is arable land (Table 4), offering a significant exposure route to humans. The persistence of oil after a spill in the environment, especially in sediments, suggests that remedial interventions will be required to remove the contaminant. For example, unresolved complex mixtures of petroleum residues were found in West Falmouth sediment extracts 30 years after the spill (Reddy et al., 2002). A study on human health impacts of oil spills in the Niger Delta would be an excellent extension to our work, possibly through focussed case studies in hot spot areas that have been identified by our analysis.

Mangroves and broadleaved tropical rainforest are the most polluted land cover types in the region. These classes of land cover serve as significant carbon sinks and play a key role in global climate change mitigation, so disruption form oil spills at the scale observed in this study can have major implications beyond the region. Mangroves and rainforests are known to provide other significant ecosystems services in the context of hydrological and nutrient cycling but they also provide valuable habitat for the wide range of floral and faunal species, many of which are endemics within the Niger Delta (Mendoza-Cant et al., 2011; Ndidi et al., 2015). The magnitude of the impacts of oil spills on mangroves and rainforests that have been revealed in the present study demonstrate the severe and ongoing threat that is being presented to sustainability of these sensitive ecosystems.

With 66 km^2 of water bodies being affected by oil spills in the region there potential for a substantial increase in the mobility of pollution as oil can easily spread across the surface of water and be moved under the action of the incoming and outgoing tides. Most people in the Niger Delta, especially in rural areas, depend on streams for domestic use (eg. washing and cooking), thereby increasing the potential for exposure to carcinogenic chemicals within oil such as PAHs (Aroh et al., 2010). PAHs have no safe level hence even very low concentrations can cause impacts to human health (Kendal and Strugnell, 2009). For example, certain kinds of cancers such as lung and skin cancers have been reported to be more prevalent in Port Harcourt due to the concentration of PAHs in ambient air compared to Ibadan in Southwest Nigeria (Ana et al., 2010). Skin contact, consumption, and breathing dangerous constituents can result in acute (short term) and chronic (long term) effects. Acute symptoms include respiratory symptoms such as shortened breath and throat irritation, ocular (eye) symptoms such as soreness and redness. Neurological symptoms include dizziness, irritability, weakness and confusion (Adekola and Fischbacher-Smith, 2016). Longer term effects include respiratory effects like the chronic obstructive lung disease, carcinogenic effects such as leukaemia, skin and lung cancers (Ordinioha and Brisibe, 2013). Furthermore, the people of the Niger Delta who are exposed to oil contamination are more often from rural communities, usually without access to facilities and healthcare. They continue their activities without caution even in the face of health risks from polluted rivers as shown in the supplementary information.

The level of oil contamination of water and arable land identified in this study means that no meaningful activities such as farming and fishing can be undertaken safely in affected areas (Nduka and Orisakwe, 2010). This has wider impacts in the region considering land ownership and availability remains a problem due to continuous destruction of the land as revealed by Wam (2012). This results in people travelling longer distances for their livelihoods due to the reduction in the productive capacity of the land and water bodies (Nriagu et al., 2016; Okoli and Orinya, 2013). It has been reported that background radiation levels of oil contaminated areas in the Niger Delta are 45% higher than normal, suggesting that surface water and crops are being contaminated above the maximum allowable limit at any particular time (Avwiri et al., 2007).

The implication of this level of contamination is severe because people around these areas rely on the environment, therefore the spills end up affecting human health and community well-being many in ways. For example, a study found unusually high concentrations of ascorbic acid in vegetables grown on contaminated land compared with the ones grown on uncontaminated sites (Ordinioha and Brisibe, 2013). In the same study the authors found an unusually high concentration of heavy metals in streams in contaminated areas compared to WHO standards (Ordinioha and Brisibe, 2013). Further, oil pollution has been shown to reduce crop yields due to reduction in soil fertility (Anifowose et al., 2014), as well as destroying crops and vegetation with economic value, such as trees. As most people in the rural areas of the Niger Delta depend on fishing and subsistence farming, the prevalence of food poverty is already problematic and is even more acute in spill contaminated lands (Ordinioha and Sawyer, 2009).

Several factors have been used to explain the causes of oil spills in the Niger Delta (Anifowose et al., 2012; Nwilo and Badejo, 2005). The spatial factors identified in this study include proximity to coast, major and minor roads, cities and security installations. Although all have been influential proximity to coast, cities and roads appear to be the most significant factors. Coastal areas are more prone to spills because of their remoteness and associated low level of security, meaning that acts of oil theft and pipeline sabotage are easier to commit unhindered. In addition, most coastal areas provide an easy means of transit for stolen oil products with little or no interference from security operatives, through the use of vessels that can transport relatively large volumes. This study has demonstrated that more than 20% of oil contamination (by volume) resulted from spills close to the coast. Roads connect cities and are also in cities therefore, these two factors are intertwined; they are responsible for over 11 million litres of total oil spill. This brings to light the level of security presence in the Niger Delta (Onuoha, 2016). More than 50% of security units in the Niger Delta are located over 50 km from identified oil spill hotspots. Such distances cast a doubt on the effectiveness of policing and protection of pipelines. The problem has been made worse by the crisis in the North Eastern part of Nigeria, which has resulted in overstretching already inadequate security. It is quite evident therefore, that current levels of security provision in the Niger Delta are not adequate for protection of oil and gas installations. On the whole, the findings presented in this study give a starting point for a wider discussion among various stakeholders: Federal and State Governments, companies and local communities on the possibilities of mitigating the problems arising from the release of oil into the Niger Delta.

5. Conclusion

By analysing the extensive oil spill database, sabotage was identified as the leading cause of oil spills in the study area; operational failures were also identified as a key factor contributing to the problem. With a considerable number of spills classified as 'others', it means the level of response and efficiency of government agencies concerned need to be improved, as those spills with lack of proper documentation contribute to the many uncertainties in terms of impact in the sector. The danger from a lack of early detection or even any detection at all becomes apparent. Therefore, there is a need for the development of alternative cost effective means of oil spill detection, such as employing remote sensing.

Secondly, by using the innovative SANET tool, oil spills hotspots were identified in the study area. This key finding can potentially provide the baseline for implementation of further oil spill monitoring and prevention measures. Thirdly, this study presents new information on the level of putative human and environmental exposure to oil contamination for the entire region, which before now has been largely speculative. Moreover, this novel study provides a spatial framework for any mitigation measures to be employed towards reducing potential human health and environmental implications of oil spills. This paper provides a step-change improvement to rapidly support decision making for security operations, environmental protection and the health for exposed communities in the Niger Delta.

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Figures

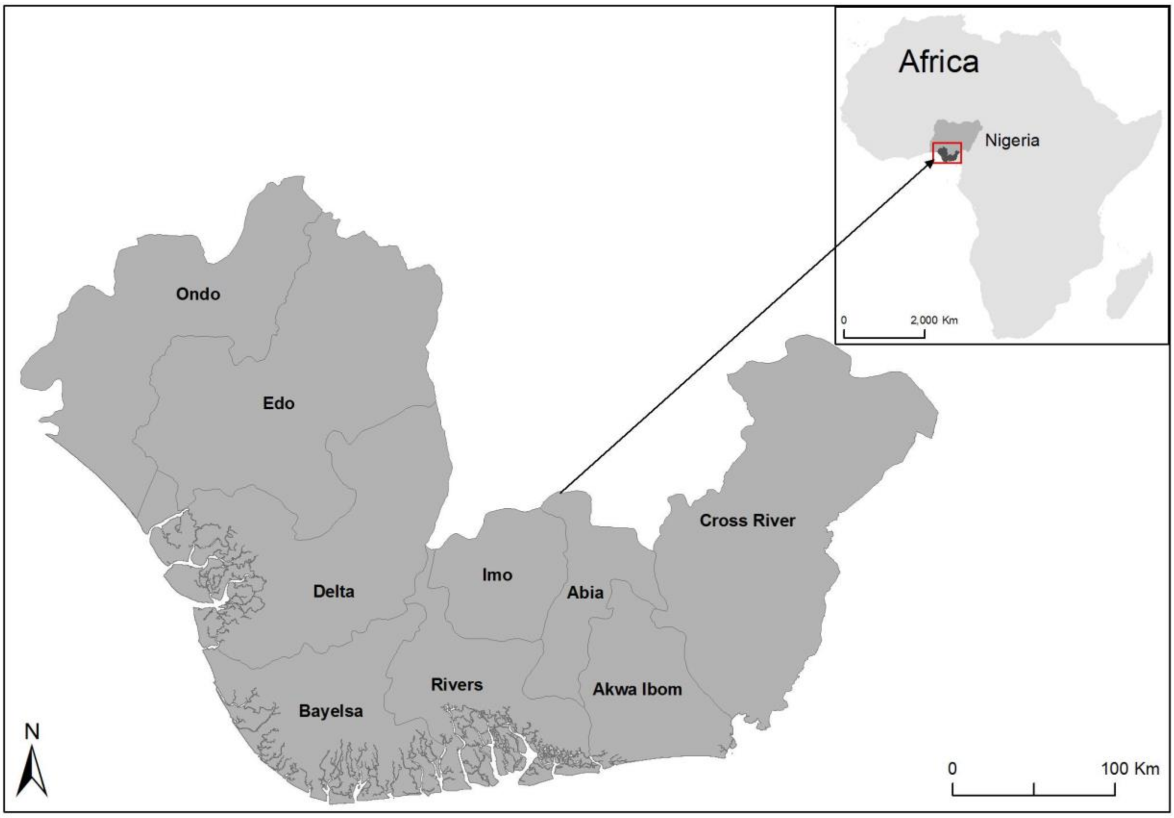


Figure 1. Niger Delta states with inset map showing Africa and the locations of Nigeria and the Niger Delta.

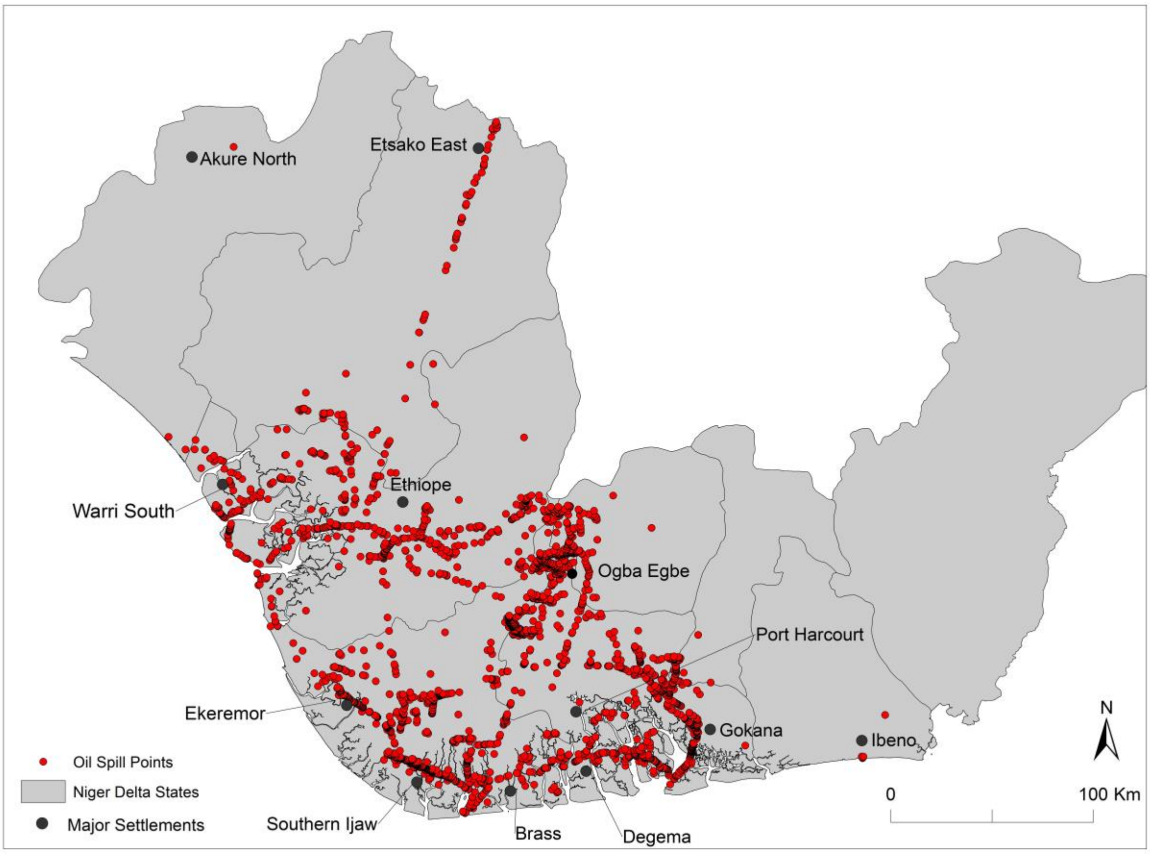
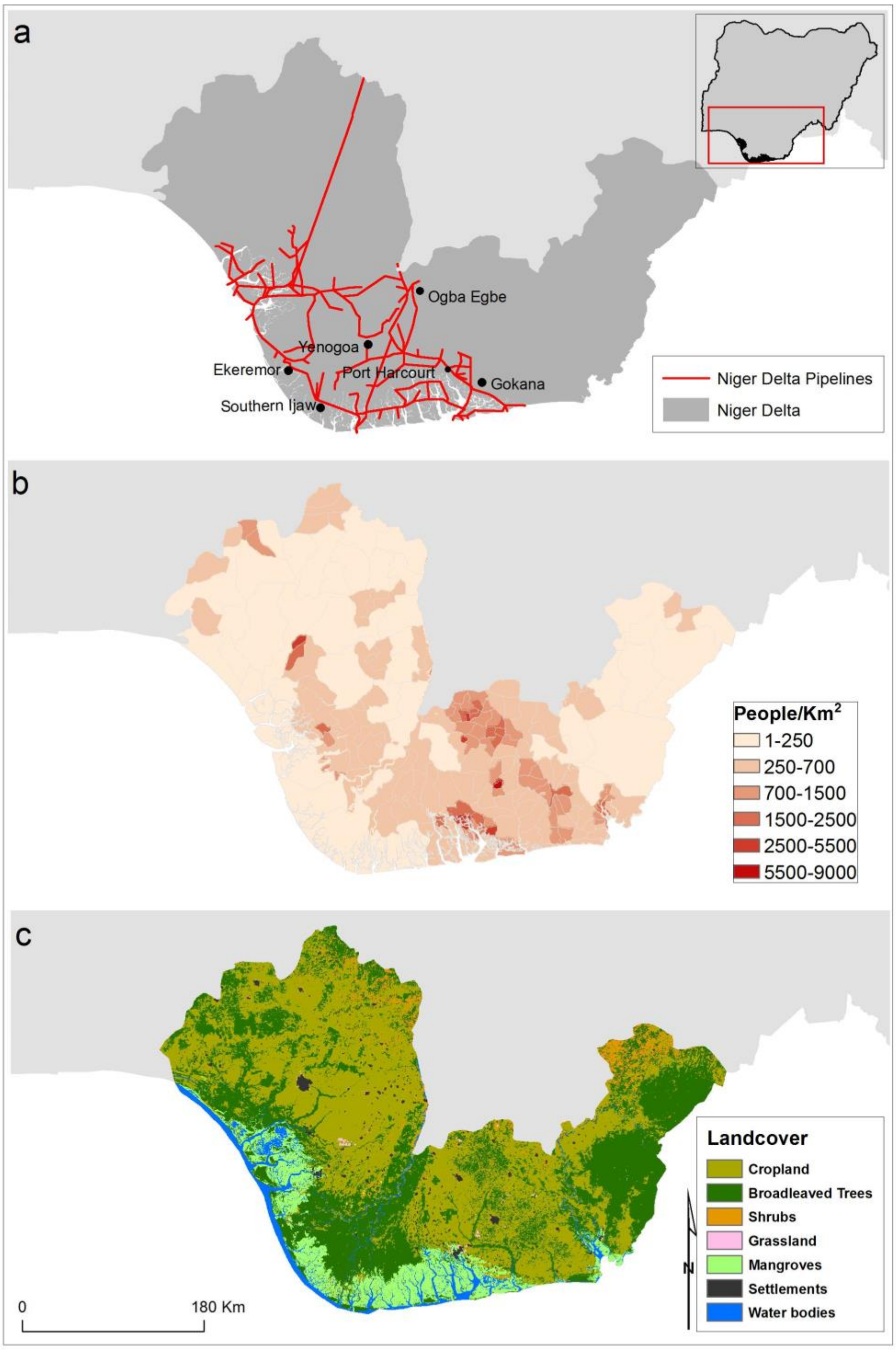


Figure 2. Spatial distribution of pipeline oil spills in the Niger Delta from 2007-2015



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604 **Figure 3**. a: Niger Delta pipeline network showing major towns, b: Niger Delta CIESIN
605 population data and, c: European Space Agency Climate Change Initiative landcover data for
606 the Niger Delta (Source, CIESIN; ESA CCI, 2016).

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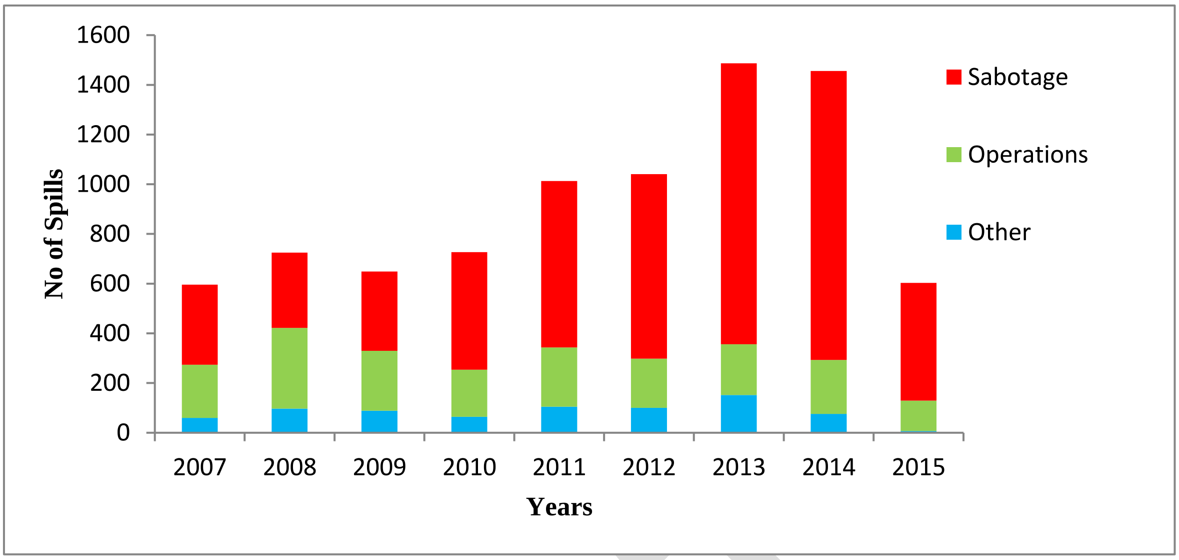

Figure 4. Oil spills by cause for the Niger Delta (2007-2015). Source: NOSDRA.

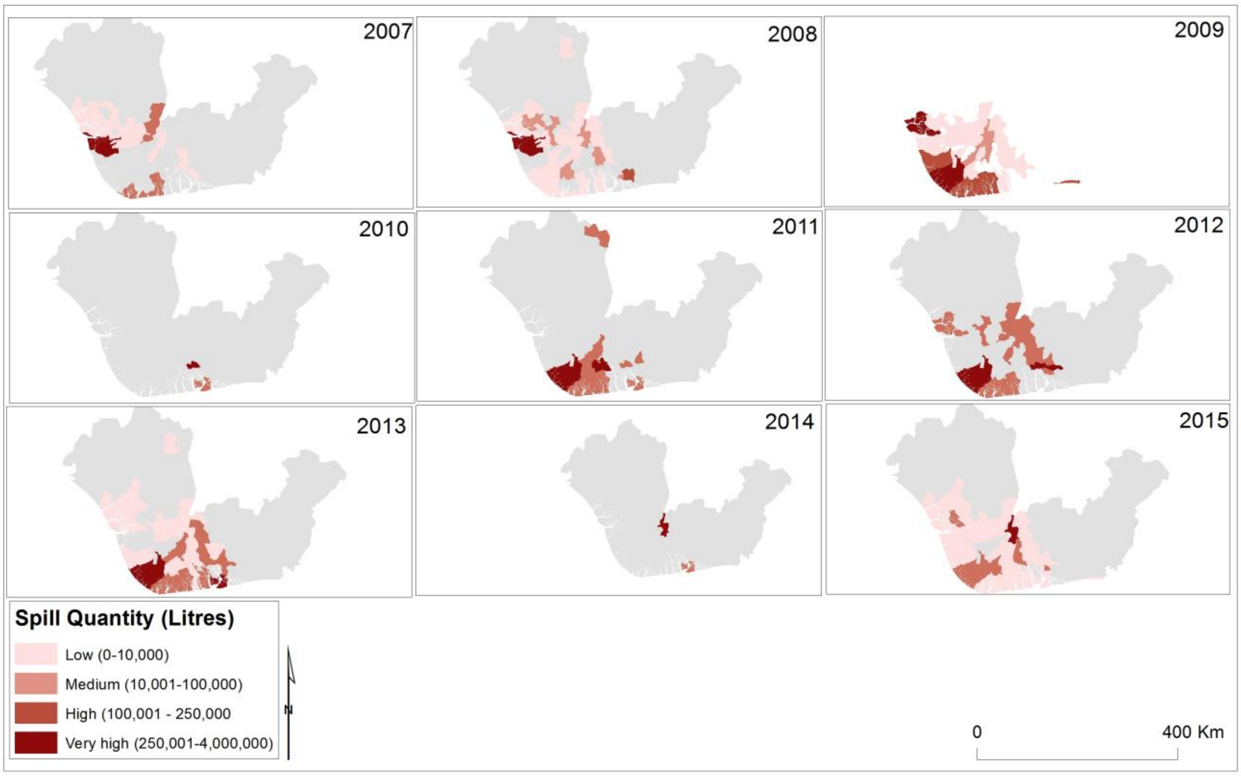

Figure 5 . Temporal and spatial trends of oil spills by volume per Local Government Area (LGA) from 2007-2015

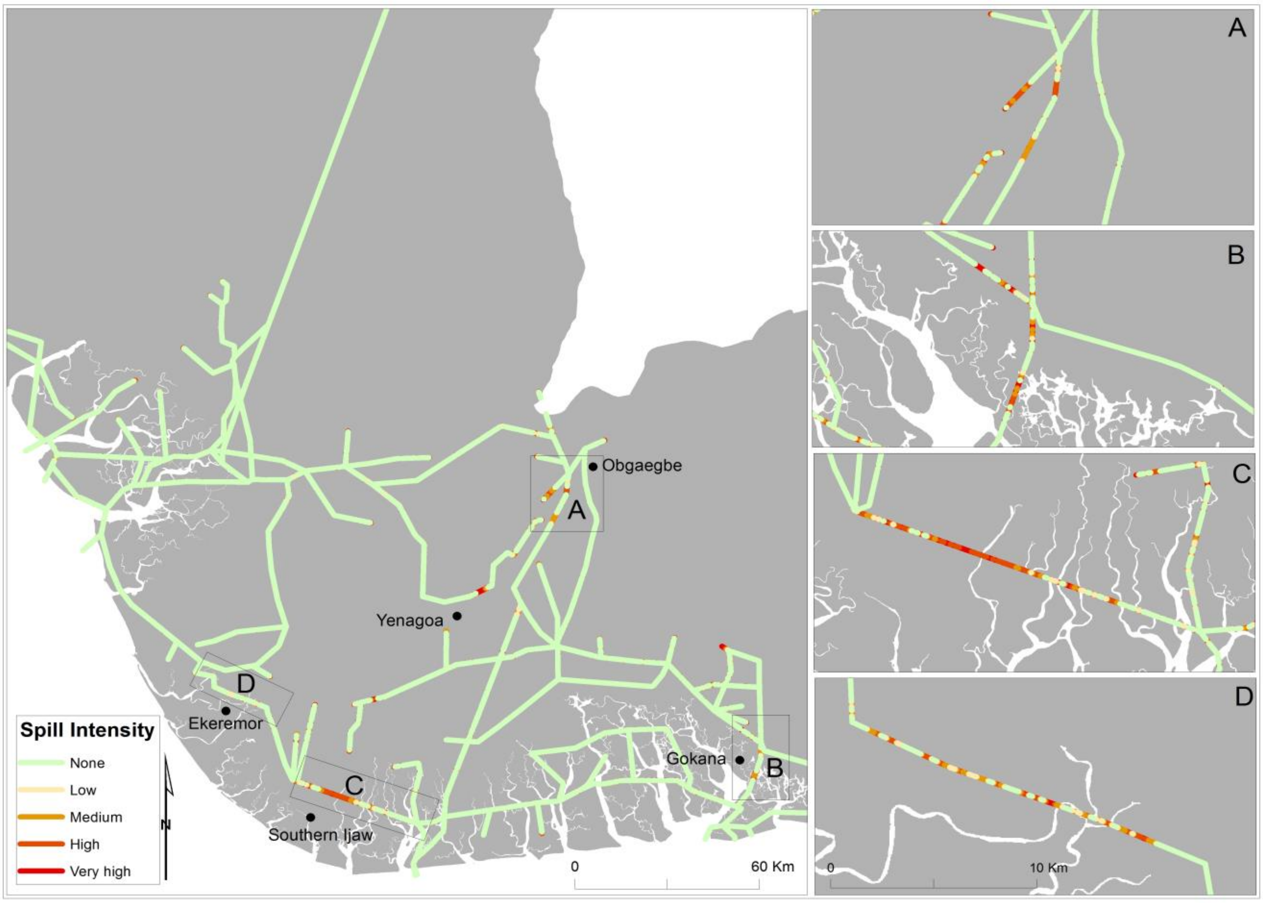

Figure 6 . Oil spills hotspots in the Niger Delta based on the Network Kernel Density estimation (NKD) method applied by the SANET tool.

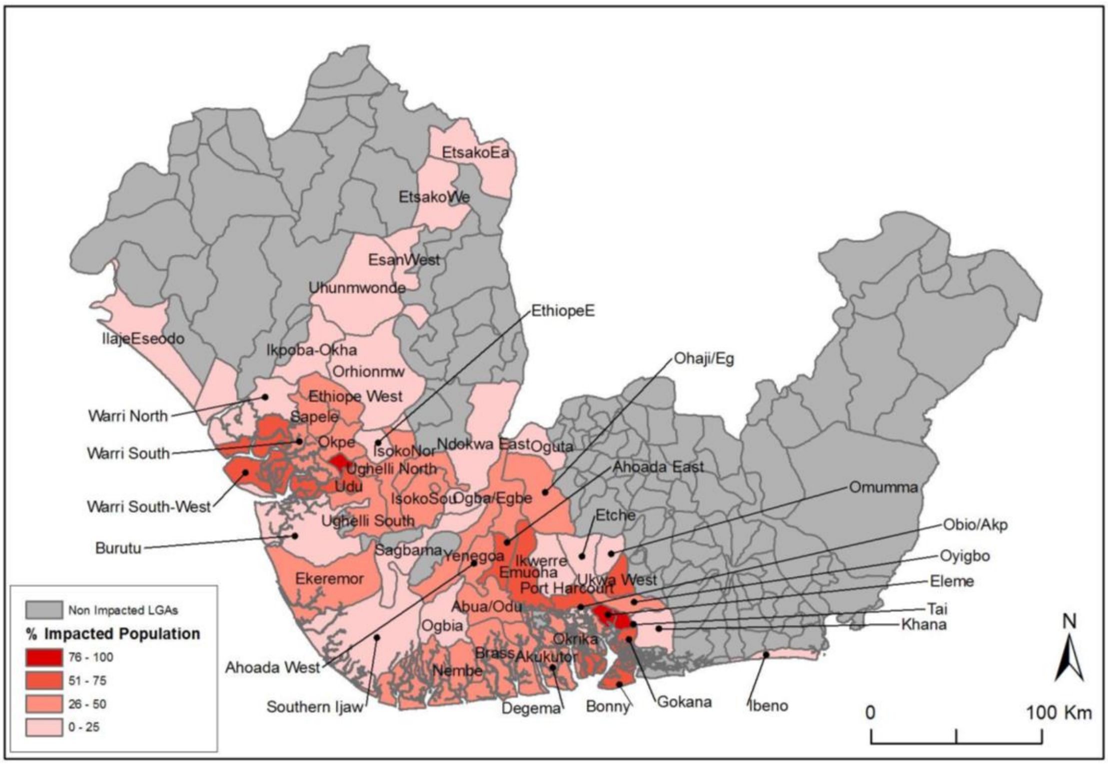

Figure 7. Oil spill impacted LGAs by percentage of affected population in the Niger Delta.

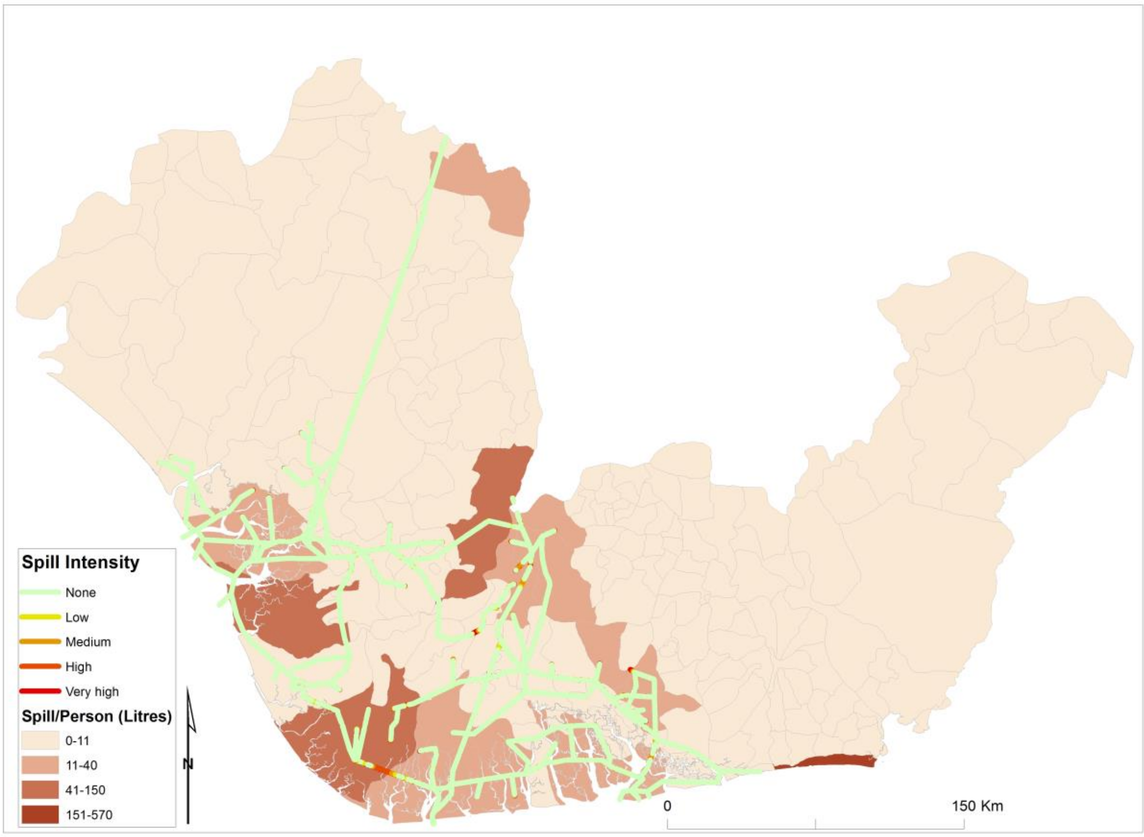

Figure 8. Pipeline spill intensity overlain on volume of potential oil exposure per person.

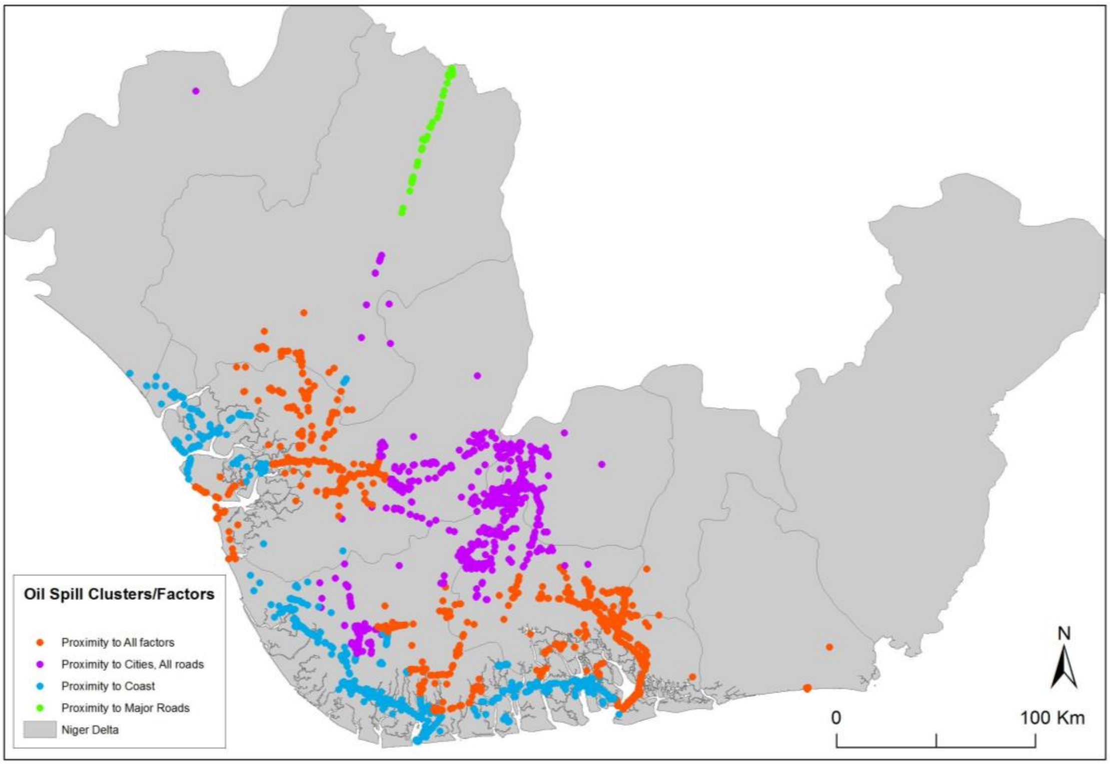

Figure 9. Spill clusters computed from identified proximity based influencing factors (coast, major roads, minor roads, security and cities).

Tables

Table 1. Volume of oil spilled (Litres) attributed to different causes from 2007-2015. Source: NOSDRA

Year	Sabotage	Operations	Other	Total	%
2007	8,998,188	2,092,804	294,216	11,385,208	13.0
2008	8,634,108	1,835,652	120,868	10,590,628	10.0
2009	3,762,652	2,348,152	379,824	6,490,628	7.2
2010	4,444,400	1,263,292	1,046,320	6,754,012	8.0
2011	4,492,780	7,428,052	154,652	12,075,484	14.0
2012	5,783,624	544,644	115,456	6,443,724	7.2
2013	8,973,588	788,184	47,888	9,809,660	11.0
2014	7,370,160	11,141,996	41,328	18,553,484	21.0
2015	7,026,416	243,376	225,336	7,495,128	8.6
Total (over entire period)	**59,485,916**	**27,686,152**	**2,425,888**	**89,597,956**	
% (over entire period)	66.4	30.9	2.7		100

Table 2. Length of pipeline affected and population exposed to oil for each level of spill intensity.

Spill Intensity	Length (km)	Population	Percentage
None	1964	3,670,810	71
Low	176	512,188	10
Medium	151	396,059	8
High	140	287,314	6
Very high	113	278,015	5
Total	**2,544**	**5,114,386**	**100**

Table 3. Land cover types impacted by spills.

Land cover	**Area(km^2)**	**Percentage**
Broadleaved Forest	483	41
Mangroves	310	27
Cropland	265	22
Water	66	6
Shrubs	21	2
Settlements	16	1
Grassland	3	<1
Total	**1,164**	**100**

Table 4. Spatial factors contributing to oil spills.

Cluster	Contributory factors	Volume (Litres)	Percentage	No of Spills
1	Proximity to all factors	27,822,764	54	1438
2	Proximity to cities and roads	11,448,020	23	2079
3	Proximity to coast	11,162,332	22	2247
4	Proximity to major roads	296,512	1	45
	Total	**50,729,628**	**100**	**5809**

Supplementary Information

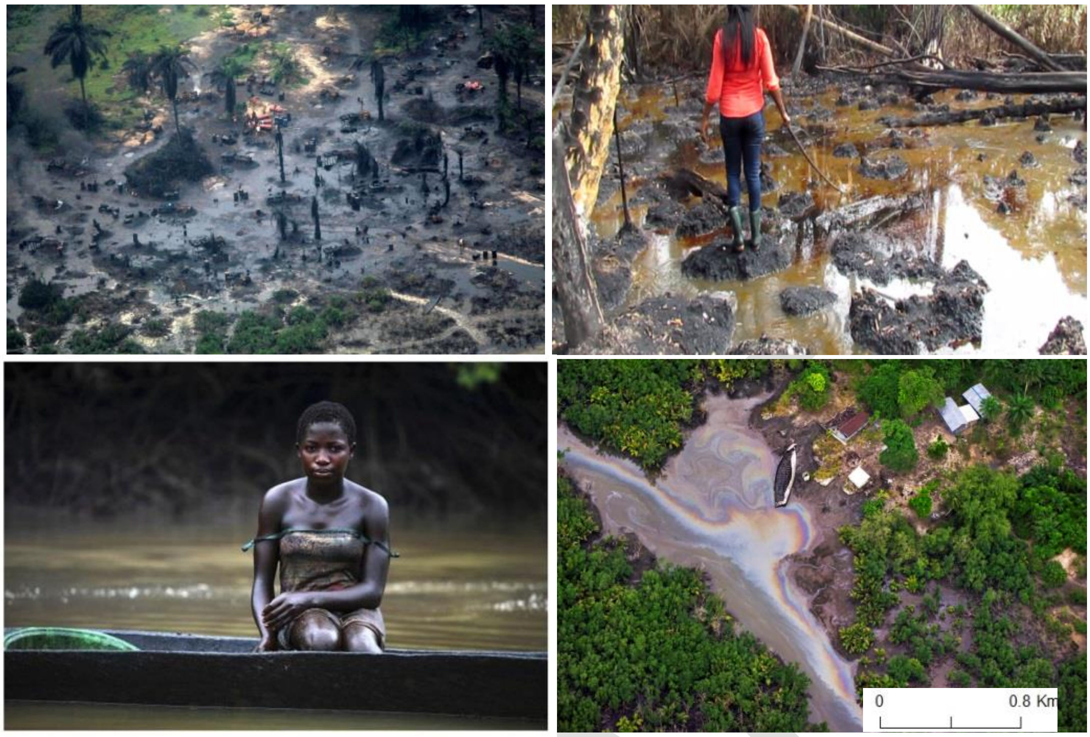

Figure S.1. Oil spill contamination of rivers, vegetation and swamps at varied locations of the Niger Delta. (Source: NOSDRA, 2013; UNEP, 2016).

Table S.1. Population exposure to oil pollution.

LGA	Volume (litres)	Total Population	Impacted Population	% Population Impacted	Litre/Person
Ibeno	5523939	86840	9682	11	570
Burutu	5774993	272964	39092	14	147
Ndokwa East	1021923	144387	15565	11	65
Southern Ijaw	5957657	412951	95661	23	62
Ogbia	2260407	234078	56793	24	39
Brass	1687149	223275	58609	26	28
EtsakoEa	294267	191433	12505	7	23
Ogba/Egbe	3823528	371328	173506	47	22
Warri South-West	1516073	149217	75558	51	20
Nembe	1582700	163479	79981	49	19
Bonny	2776266	257501	148996	58	18
Oyigbo	1278965	180811	77599	43	16
Oguta	218649	186514	15622	8	14
Ohaji/Eg	920424	242616	69095	28	13
Degema	1237255	304599	95385	31	12
Ukwa West	709063	112152	56130	50	12
Etche	370147	328241	31625	10	11
Warri South	2022794	374243	179256	48	11
Tai	1350417	166894	139418	84	9
Abua/Odu	1231162	364780	133789	37	9
Warri North	276020	177856	34190	19	8

Ahoada West	1000133	319466	126859	40	7
Yenegoa	1386399	453435	178468	39	7
Akukutor	464999	202840	62031	31	7
Omumma	25111	133174	3589	3	7
Ikwerre	394965	257388	62392	24	6
Emuoha	780008	266939	144019	54	5
Ughelli North	652523	412694	127778	31	5
Ahoada East	572171	214655	131367	61	4
Ekeremor	470227	347873	134869	39	3
Khana	246000	390350	71864	18	3
Obio/Akp	1115488	609968	353500	58	3
Ikpoba-Okha	92059	459662	30789	7	2
Gokana	408990	275556	190687	69	2
IsokoSou	231622	302912	117209	39	1
Sagbama	18040	246639	9574	4	1
Eleme	335758	241364	203245	84	1
Ughelli South	114713	278572	75393	27	1
Orhionmw	29177	244840	22123	9	1
Okpe	106322	185957	86283	46	1
Ethiope West	131206	261924	109067	42	1
Sapele	66334	223937	79846	36	<1
Udu	81912	179115	102897	57	<1
IsokoNor	51837	186773	71392	38	<1
Uhunmwonde	8323	157468	16056	10	<1
Uvwie	43936	230137	207091	90	<1

Okrika	5456	254657	65749	26	<1
EtsakoWe	1940	249758	35219	14	<1
Port Harcourt	1426	590547	98302	17	<1
EsanWest	360	160185	38602	24	<1
EthiopeE	0.82	259074	3216	1	0
IlajeEseodo	1	364919	4233	1	0
	50,671,257	**13,908,936**	**4,561,768**		

Table S.2. Frequency and volume of spills used for correlation analysis.

Years	Number of Spills	Spill Volume (Litres)
2006	119	5871242
2007	596	11037216
2008	725	10266922
2009	649	6292240
2010	727	6547574
2011	1013	11706393
2012	1041	6246770
2013	1487	9509825
2014	1456	17986392
2015	603	7266037
2016	92	638334

Spatial Analysis Along Network (SANET)

SANET is a toolbox developed by a research group in Japan initially for analysis of network based events especially on road traffic accidents (Okabe, 2015). In estimating the network kernel density (NKD), SANET applies the basic kernel function as used by Xie and Yan (2013), however in contrast to this function which use Quartic or Gaussian variables in the calculation of its kernel function, SANET uses a function given by (Okabe et al., 2009) as:

$$k_y(x) = \begin{cases} k(x) & for - h \leq x \leq 2d - h \\ k(x) - \frac{2-n}{n} k(2d - x), & for\ 2d - h \leq x \leq d \\ \frac{2}{n} k(x) & for\ f \leq x \leq h \end{cases}$$

Given $k(x)$ is the kernel function, x is the point on the network (spill point), y is the midpoint of the kernel function, q is the degree of the node, h is the bandwidth in metres and d is the shortest distance from y to x in meters. The density at a particular point of interest is computed using the formula:

$$D(O) = \int_{-h}^{2d-h} k(-y)dy + \int_{2d-h}^{d} \left[k(-y) - \left(\frac{2-q}{q}\right) k(-2d + y)\right] dy + \int_{d}^{h} (q-1)\frac{2}{q}\ k(-y)dy$$

Where $D(O)$ is the density at source. This produces line segments with assigned values which are classified relative to risk levels (high, medium and low).