# Counting the cost of the Niger Delta's largest oil spills: satellite remote sensing reveals extensive environmental damage with >1million people in the impact zone.

Christopher B. Obida, George A. Blackburn, James D. Whyatt

and Kirk T. Semple[*]

Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ United Kingdom

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[*] Corresponding author: k.semple@lancaster.ac.uk

# Abstract

The Niger Delta has a long history of oil and gas exploration and production, but this has come with a heavy environmental cost arising from oil spills and other pollution events. Two oil spills in Ogoniland in 2008/9 were by far the largest in terms of both duration (149 days combined) and magnitude (82,939,170 litres combined), but little is understood about the extent of impact of these events because traditional field-based surveys are virtually impossible in this region. In this study, the normalised difference vegetation index, a technique used for measuring plant health, was applied to multi-temporal satellite images to delineate an extensive area of 393 km$^2$ that has experienced vegetation mortality resulting from the oil pollution. These effects persist to present and are exacerbated by continuing subsequent spill events. Independently collected field samples confirmed the high concentrations of hydrocarbon pollutants in the impact area. The extensive tidal river network and mangrove swamps have facilitated the spread of oil, with the delta becoming a sink for the oil that is dispersed but not removed. Over 1 million people live within the area contaminated by oil and have potentially been exposed to pollution through direct and indirect pathways over a prolonged period. The population in the impact area is particularly vulnerable to chronic illness due to its young age structure and pre-existing very low life expectancy. Hence, there is an urgent need to mitigate the impacts of the pollution on environmental and human health. The novelty of this work is that satellite remote sensing allows the impacts of pollution to be monitored across large areas in a geographically remote and challenging environment. The outputs from this study could be used to guide the future spatial targeting of the limited remediation resources that are available, to achieve positive outcomes.

**Keywords**: Oil Spills, NDVI, Spatial Impact, Exposure, Pollution

## 1. Introduction

Oil spills significantly increase the risk of human exposure to harmful substances. Many constituents of crude oil are of particular concern due to potential health problems that may result from exposure (Ugochukwu et al., 2018), including organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs), benzene, toluene, ethylbenzene and xylene (Nduka and Orisakwe, 2010; Philibert et al., 2018), and heavy metals, such as lead, vanadium and cadmium (Chinedu and Chukwuemeka, 2018; Oti, 2016). PAHs are of particular concern because of their persistence in the environment, which can lead to prolonged periods of exposure and chronic illnesses, such as cancers, even at low concentrations (Afshar-Mohajer *et al*., 2018). Similar toxic effects can be induced in other organisms that are exposed to oil pollution and has the potential to have serious consequences on wider ecosystem functioning and ecosystem service provision (Mendelssohn et al., 2012). Hence, in order to minimise these effects, it is crucial to delineate the area impacted by an oil spill, identify the key pathways for oil transport and, importantly, identify which human populations and ecosystems are potentially exposed. This can assist in targeting health services and environmental remedial interventions.

Over the last 7 decades, the Niger Delta has suffered from significant oil spillages with an estimated 7,950,000,000 litres having been released in the region (Kadafa, 2012). Several factors have been identified as the root causes of oil spills in the region including sabotage and operational failures (Obida et al., 2018). Due to the number of oil spills in the region, the Niger Delta has been described as one of the most polluted regions on earth (Chukwubuikem et al., 2014; UNEP, 2014, 2011). The oil spills have led to significant environmental degradation, which has greatly reduced ecosystems services (Opukri and Ibaba, 2008), including the fisheries and agriculture which constitute the major sources of livelihood of the region (UNEP, 2014). Human exposure to oil spills occurs from consumption of contaminated food resulting from bioaccumulation and air pollution from volatilisation of some components, leading to exposure and impacts on human health and mortality (Afshar-Mohajer *et al*., 2018; Alharbi *et al*., 2018; Fu *et al*., 2019).

In 2008/9, two major spill events received global attention, due the exceptionally large volume of oil released into the low-lying Ogoniland region from a 24-inch Trans Niger Delta pipeline operated by Shell Petroleum Development Company (SPDC) Nigeria  (Amnesty International, 2011; Fentiman and Zabbey, 2015). The first spill was reported to have started on 28 August and stopped on 7 November 2008, while the second spill started on 7 December and stopped on 21 February 2009; both spills, therefore, had a combined duration of 149 days (Amnesty International, 2011; Pegg and Zabbey, 2013). In terms of spilled volume, there have been varying estimates and debates between SPDC and other stakeholders, including the impacted local communities. In this study, data was used from recently published official reports to determine the magnitude and temporal profile of spills in this region (UNEP, 2011; 2014). The 2008/9 spills led to the widespread, although previously unquantified, environmental destruction in the Ogoniland region, which provoked a continuous cycle of litigations between the operators SPDC Nigeria and the local communities. A relatively recent landmark ruling by a British court in favour of the community led to a compensation payment of $55 million (Yakubu, 2017; Amnesty International, 2021). However, since the 2008/9 incidents, efforts to quantify the magnitude and extent of the impacts have been very limited, mainly because it is virtually impossible to undertake traditional field-based surveys within this region.

UNEP conducted field-based studies in Ogoniland to ascertain the concentration of pollutants at certain locations (UNEP, 2011) and attempts have been made to assess the ecological and human health risk due to the spills in the region (Chikere et al., 2018; Fentiman and Zabbey, 2015; Lindén and Pålsson, 2013). However, these studies were based on sampling regimes which were very limited in spatial extent. The need for clean-up and remediation of contaminated areas in the Niger Delta and Ogoniland, in particular, has been highlighted (Sam *et al*., 2017; Zabbey *et al*., 2017). Such remedial activities are necessary for reducing human exposure and returning land to agricultural, commercial and residential use. However, it is difficult to develop a detailed remediation plan for this region, partly because of funding constraints but largely due to lack of detailed information on the extent of the spill impact (Ozigis *et al*., 2019), difficult terrain and issues of security and personal safety.

Additionally, information is needed to target the resource-limited health services in the region towards those communities at greatest risk from the pollution (Nriagu et al., 2016). Hence, there is a pressing need to quantify the spatial extent of the environmental impact and the magnitude and distribution of human population exposure resulting from the 2008/9 Ogoniland oil spills and other relatively smaller spills before and after the major incidents.

Plants can act as effective bioindicators of oil pollution as their physiological functioning is sensitive to exposure to oil (Mishra *et al.*, 2012a). The interactions between plants and oil is complex, but can include both physical and chemical effects (Ozigis *et al.*, 2019). The physical impacts typically result from oil coating foliage or root systems, thereby reducing photosynthesis and transpiration, and the uptake and water and nutrients. The chemical impacts occur when toxic substances within oil are absorbed by plants, causing disruption to physiological pathways (Domingues *et al.*, 2018; Emengini *et al.*, 2013a). These deleterious processes affect the health and vigour of vegetation, ultimately leading to death; therefore, readily observable biophysical indicators including reductions in canopy chlorophyll content, leaf area index and above ground biomass can be used to monitor the impacts of oil pollution (Arellano *et al.*, 2015; Duke, 2016; Emengini *et al.*, 2013b; Mishra *et al.,* 2012b).

Remote sensing techniques which involve gathering environmental information from a distance using sensors on board airborne or spaceborne platforms have the potential for effective monitoring of vegetation. Plant biophysical indicators can be assessed remotely using well established spectral vegetation indices such as the normalised difference vegetation index (NDVI) derived from remotely-sensed imagery (Díaz and Blackburn, 2003; Emengini *et al.*, 2013a; Kross *et al.*, 2015). Hence, remotely-sensed imagery offers capabilities for detecting oil pollution indirectly via changes to vegetation biophysical characteristics in large and challenging environments. For example, spectral indices derived from a time series of Landsat images were used to assess the long term impacts of crude oil on mangroves in a coastal region of Brazil (Domingues Pavanelli and Loch, 2018). Similarly, Ozigis et al. (2019) used random forest classification techniques with a range of Landsat-derived vegetation indices to distinguish between oil impacted and non-impacted vegetation in the

Niger Delta (Ozigis *et al.,* 2019). Therefore, with their large spatial coverage and repeat sampling capability, satellite imagery offers a valuable means of monitoring the impacts of oil spills on vegetation which is a crucial first step towards identifying areas of risk and ultimately mitigating human exposure.

This study aims to quantify the spatial extent and temporal dynamics of the impact on vegetation of the large 2008/9 Ogoniland oil spills and other small spills in the region, then use this to estimate the size of the human population within the impact zone. This study also examines the relationship between the spill extent and UNEP's detailed field-based pollution measurements at selected locations to potentially provide inference on unmeasured locations. In order to achieve this the following objectives were addressed: (a) to determine the spatial extent of the impact caused by the 2008/9 Ogoniland spills and other small spills in the study area and assess the role of river channels in pollution distribution; (b) to analyse the spatial variation of measured pollutant concentrations in relation to temporal NDVI changes within the delineated impact area, and (c) to quantify the human population living within the delineated impact area, who are at risk of being affected by the pollution.

## 2. Materials and Methods

### 2.1. Study area

Ogoniland lies in the Southeast of Rivers State and is estimated to cover some 1,000 km$^2$ of the Niger Delta (UNEP, 2014). It is characteristically a mangrove swamp creek system with an estimated population of 1.2 million at 2016, based on the 2006 official census and projected growth rates (https://www.citypopulation.de/php/nigeria-admin.php?adm1id=NGA033). The region is administratively divided into four local government areas (LGAs) namely Tai, Eleme, Khana and Gokana (Lindén and Pålsson, 2013), which lie east of the state capital Port Harcourt. The region has been identified as one of the most polluted regions of the Niger Delta (Obida et al., 2018), with spills impacting upon its delicate biodiversity and affecting the livelihoods of its residents, which are mainly based on fishing and farming. Bodo, located in Gokana, was the epicentre of the large 2008/9 Ogoniland oil spills (Figure 1).

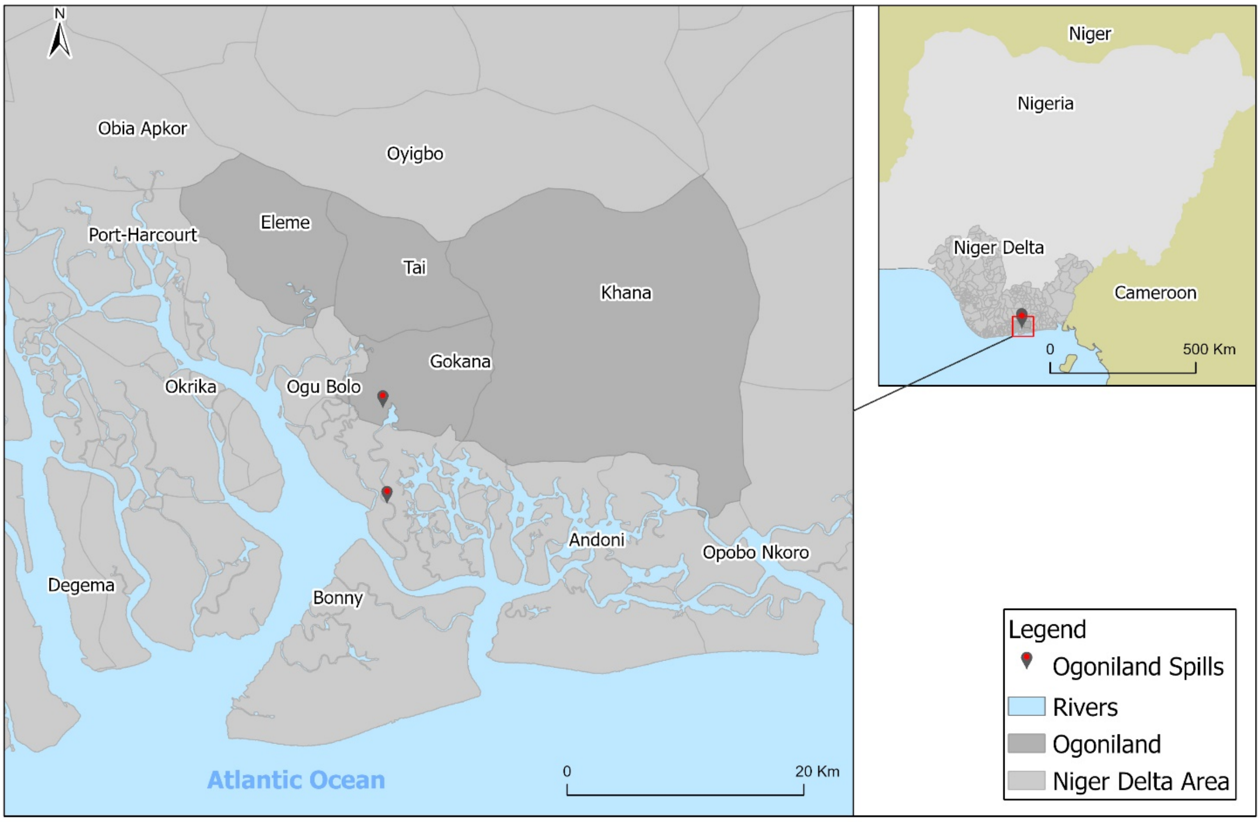

**Figure 1**. The Niger Delta, with inset maps of Ogoniland showing location of the 2008/9 oil spills and Nigeria showing the position of the Niger Delta.

## 2.2. Assessing oil spill occurrences and spatial extent of impact

The Niger Delta is a challenging environment for field-based investigations, due to the physical inaccessibility and security threats, making it impossible to assess the spatial extent of oil spill impacts using traditional survey and sampling techniques. Hence, remote sensing provides the most effective method for achieving the aim of the study. This study therefore used a well-established remote sensing technique the NDVI to delineate areas of vegetation death or damage resulting from oil spill events. Additional spatial data pertaining to environmental measurements of petroleum hydrocarbons, oil spill locations and human population distribution, were also used to assess the environmental impacts of oil pollution and potential human exposure. A summary of all data used is shown in Table S1.

### *2.2.1 Oil spill data*

Data on the location and volume of oil spills covering the period 2006 -2019 were sourced from the National Oil Spill Detection and Response Agency (NOSDRA), which is the official government agency responsible for the management of oil spills in Nigeria. The data is freely and publicly available (NOSDRA, 2019). Spill locations falling within the study area were extracted and the spill volume data from these sites were used in the subsequent analysis.

### *2.2.2 Remotely sensed data*

A series of eight Landsat images were acquired for the period 2000 – 2018 inclusive, covering pre-spill and post-spill periods. These include images from the Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM) and Operational Land Imager (OLI) sensors, obtained from the USGS (https://earthexplorer.usgs.gov/). The images used represented all of the cloud-free images available for the site over the study period and excluded ETM images affected by the scan line error. All images were geometrically and atmospherically corrected making them suitable for temporal analysis. The TM and ETM data were corrected to surface reflectance using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) algorithm developed by the National Aeronautics and Space Administration's (NASA) Goddard Space Flight Centre (GSFC) and the University of Maryland (Claverie et al., 2015). The OLI images were corrected to surface reflectance using the Landsat 8 Surface Reflectance Code (LaSRC) algorithm (Vermote et al., 2016).

### *2.2.3. Vegetation indices and image differencing*

The Normalised Difference Vegetation Index (NDVI) (Rouse et al., 1973) was calculated according to Equation 1 for all images in the Landsat time series.

$$NDVI = \frac{\mathrm{NIR-R}}{\mathrm{NIR+R}} \qquad \text{Eq. 1}$$

where NIR is reflectance in the near-infrared waveband and R is the red waveband. It has been demonstrated that NDVI is an effective indicator of physiological stress and biophysical changes caused by the impacts of hydrocarbon pollution on plants (Domingues and Loch, 2018). This is primarily due to an increase in reflectance in the red waveband due to stress-induced leaf chlorosis and a decrease in reflectance in the near-infrared due to wilting and defoliation (Domingues and Loch, 2018; Sanches et al., 2014). In the context of the present study, it is expected that mangrove plants exposed to oil pollution will have lower NDVI values than non-polluted plants and pre-polluted plants.

Image differencing was applied to the 2003 (pre-spill) and 2018 (post-spill) NDVI images to ascertain changes in vegetation (Domingues Pavanelli and Loch, 2018) using the Map Algebra tool in ArcGIS 10.4. This was performed by subtracting NDVI value in a pixel in the post spill image from the corresponding pixel in the pre spill image. The output represents the change in NDVI and is normally distributed data with areas of no change around the mean and areas of significant change found on the histogram tails (Chambers and Wynne, 2002). In order to determine the level of change in NDVI that represented a significant impact on vegetation caused by the spill (as opposed to natural variation), the NDVI difference image was classified into 5 change threshold classes (-0.05, -0.10, -0.15, -0.20, -0.25 and -0.30).  The accuracy with which each change threshold was able to delineate impacted vegetation was quantified by using reference data of impacted and non-impacted locations collected through manual interpretation of high resolution (0.5m) satellite imagery obtained from ArcGIS Imagery (acquired in 2016). To obtain this reference data 200 randomly located points were overlaid on the high-resolution image and an analyst determined from the image whether the point represented a location where vegetation was damaged/destroyed or unaffected. The reference data were then compared to the values (i.e. impacted or non-impacted vegetation) derived from the NDVI change technique for the same 200 point locations, to calculate an overall accuracy metric. This procedure was undertaken for each of the 5 different NDVI change thresholds in order to determine the optimum threshold. The NDVI change threshold of -0.20 (i.e. all areas with a reduction of NDVI of 0.20 or more) presented the highest overall accuracy (85 %) and was therefore adopted as the threshold for delineating the spill impact area.

### *2.2.4 Refining the delineation of the impact area*

Since population growth has led to increasing rates of urbanization within the Niger Delta, some areas with a significant NDVI reduction between 2003 and 2018 could potentially be explained by urban construction displacing vegetation. Therefore, an urban land cover data layer derived from the European Space Agency's prototype high resolution land cover map of Africa (http://2016africalandcover20m.esrin.esa.int/) was used to remove urban areas from the initial delineation of the impact area. To enable further analysis and information extraction the final delineated impact area (as derived from raster image analysis) was converted to polygon features using the raster to polygon tool in ArcGIS 10.4.

### *2.2.5 Assessing the role of rivers in oil dispersion*

The Niger Delta is low lying region with an extensive river network. Rivers therefore play an important role in the distribution of pollutants within the delta system. Hence, a map of the river network, delineated using Sentinel-1 imagery (see Obida *et al.*, 2019), was used to evaluate the potential routes for oil spill dispersion in the study area by investigating the spatial relationships between the river network, the source of the oil spill and the delineated impact area.

## 2.3. Evidence of pollution from field samples, associated impact on vegetation and characterising lethal and sublethal impact zones.

Data from a UNEP environmental assessment were used to investigate the key pollutants associated with the crude oil spill in Ogoniland. An environmental assessment was carried out at the request of the Nigerian government (UNEP, 2011) and involved detailed investigations of soil, ground water, surface water and sediments, with over 4,000 samples analysed in total (Lindén and Pålsson, 2013; UNEP, 2014). The samples were collected in 2011, 2 to 3 years after the major oil spills in 2008/9. The locations used for sample collection were selected randomly from within an area extending from the source of the major spills out to approximately 20 km distant. However, the random spatial sampling strategy was influenced by accessibility issues and there is some bias towards locations accessible from waterways or roads. The UNEP data are also somewhat restricted because it represents a single snapshot of the oil pollution at the time of survey. Nevertheless, the UNEP data do constitute the most detailed and extensive measurements of petroleum hydrocarbons in the Niger Delta obtained in response to the 2008/9 spill events, and therefore, they can fulfil a valuable role within this study for characterizing oil spill impacts. The data used in the present study were sourced from the Hydrocarbon Pollution Remediation Project, a Nigerian government agency tasked with leading the clean-up and remediation work in Ogoniland.

NDVI values were extracted for all of the 8 images in the Landsat time series for 4 locations within the delineated impact area at which field samples had been tested for pollutants by UNEP.. At each location, a window of 4 x 4 pixels (120 $m^2$) centred on the field sampling point were extracted and a mean NDVI value calculated using image analysis software ENVI 5.4. The same procedure was undertaken for four locations outside of the impact area, where field samples were analysed. The temporal changes in NDVI for the locations within and outside the impact area were compared, alongside the values for total petroleum hydrocarbons (TPHs) determined from the field samples (UNEP, 2011).

### *2.3.1. Characterising lethal and sublethal impact zones*

The results of the analysis above (reported later in section 3.3.) revealed that areas with high pollutant levels were associated with persistently low NDVI values that indicated vegetation mortality. Hence, the impact area delineated from the Landsat image analysis (resulting from section 2.2.4) represents an impact area of oil pollution that was lethal for mangrove vegetation (subsequently termed ‘lethal zone’). It has been established that in mangrove swamps the area affected by oil spills at a sublethal level (i.e. where significant physiological stress is induced short of death) can be up to 15 times the size of the observed lethal impact zone (Duke, 2016). It is difficult to detect the sublethal zone from satellite images as changes in NDVI that are smaller than those caused by mangrove mortality can be influenced by a wide range of factors such as natural stress, disturbance and senescence, which vary over a range of spatial and temporal scales. Hence, to approximate the sublethal zone of the impact area, all remaining mangrove areas within an LGA containing lethal zones were used. This resulted in sublethal zones that were a maximum of approximately 2-3 times the lethal zone in each LGA, which is well within the 15 times observed by Duke (2016). It indicates that sublethal effects of the 2008/9 oil spills are likely to have been observed across the entirety of the mangroves in the study area.

### 2.4 Quantifying the human population within the impact area

Population data were used to quantify the number of people residing in the area impacted by the 2008/9 Ogoniland spills. Gridded population data at 100 m resolution were sourced from the WorldPop portal (https://www.worldpop.org/). This detailed data product was generated by integrating census data, satellite imagery from a range of sources, settlement and urban area map layers and machine learning algorithms to generate high resolution gridded outputs (Paula et al., 2016; Tatem et al., 2013). General population data and demographic data based on age structure at 5-year intervals were acquired from the same source, as a gridded product. The population data were integrated with the delineated impact area in ArcGIS 10.4 and the Zonal Statistic as Table tool was used to calculate the sum of raster cell values (persons per pixel) within the areas affected by oil pollution. The total populations within the lethal and sublethal zones of the impact area were identified, along with their demographic profiles by gender.

## 3. Results

### 3.1 Oil spill events

The combined 2008/9 Ogoniland oil spills are by far the largest in the region, likely due to the long period of time it took for them to be stopped and the large diameter of the Trans Niger Delta Pipeline which was the source of the spill and transports an average of 19,080,000 litres of crude oil daily. The 2008/9 spills, in addition to a total of >9,540,000 litres of smaller spills in the area, have resulted in an astounding 92,479,170 litres of crude oil released within the study area between 2006 – 2019. Figure S1 shows the temporal distribution of oil spills in the Niger Delta region from 2006 – 2019.

### 3.2 Spatial extent of the oil spill impact

Based on the analysis of the 2003 and 2018 Landsat data, 393 km$^2$ of vegetation was impacted by the oil spill (lethal zone) (Figure 2). The vegetation affected is primarily mangrove swamp, the predominant land cover type in the region, plus some adjoining low-lying estuarine and riparian vegetation. Figure 2 indicates that there is a large area of impact around the spill site at Bodo, which is expected since areas closer to a spill site should experience higher concentrations of pollutants, particularly as the hydrophobicity some petroleum hydrocarbons result in oil sorbing to sediment particles, particularly sedimentary organic matter. However, there is little impact inland of the spill site, to the north east, which is beyond the spatial extent of the river and creek network and mangrove swamp; yet, in almost all other directions from the spill site, impacts have been observed across a very large geographical area. Figure 2 also shows that all impacted areas are either adjacent/connected to the river network or within/connected to the mangrove swamp.

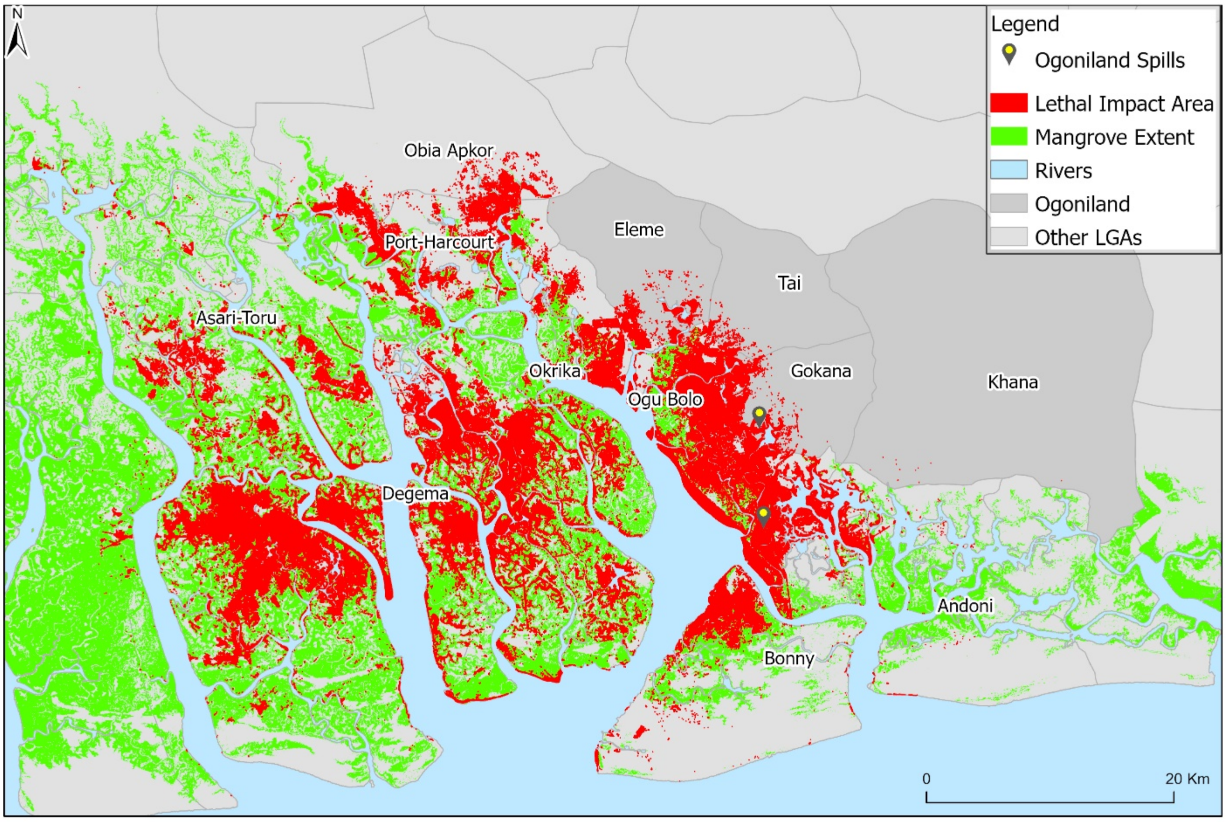

**Figure 2.** Area impacted (lethal zone) by the 2008/9 Ogoniland oil spills, based on NDVI image differencing between 2003 and 2018, indicating areas of significant NDVI reduction and location of the spill incident.

### 3.3. Evidence of pollution from field samples and associated vegetation damage within and outside the impact area

Table 1 shows the temporal variations in NDVI values across 8 sites and their corresponding TPH levels as measured from field samples. Sites 1 to 4 are within the impact area all show substantial and persistent reductions in NDVI after the 2008/9 spills along with very high TPH values. In contrast, sites 5 to 8 are well outside the impact area and all have similar NDVI values before and after the spills and much lower TPH values. These observations are an indication that crude oil has killed vegetation within the impact area (lethal zone) and, as it persists in the mangrove swamp sedimentary environment for a prolonged period of time, this has prevented any observable recovery of the vegetation, 10 years after the major spills. For example, Figure 3 shows evidence of a thick oil slick persisting within a river 5 years after the large Ogoniland spill events, with extensive vegetation damage in areas adjacent to the river network. Figure 4 demonstrates how higher concentrations of pollutants have been observed in field samples obtained within the delineated impact area (lethal zone) as compared to those outside the impact area.

**Table 1.** Extracted temporal NDVI values at 8 sample locations, with NDVI values within the impact area (lethal zone) showing a significant reduction after the 2008/9 spills and corresponding high TPH values (sediments) in comparison to samples outside the impact area with little or no change in temporal NDVI and low TPH values (sediment) (UNEP, 2011).

| Areas and sites | | Dec 2000 | Jan 2003 | Dec 2014 | Jan 2015 | Dec 2015 | Apr 2016 | Jan 2018 | Dec 2018 | TPH (mg/kg) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pre-spill | | Post-spill | | | | | | |
| Inside impact area | Site 1 | 0.42 | 0.44 | 0.13 | 0.21 | 0.12 | 0.16 | 0.04 | 0.02 | 12,100 |
| | Site 2 | 0.30 | 0.33 | 0.09 | 0.15 | 0.10 | 0.12 | 0.05 | 0.01 | 8,630 |
| | Site 3 | 0.41 | 0.42 | 0.17 | 0.20 | 0.14 | 0.20 | 0.10 | 0.07 | 6,470 |
| | Site 4 | 0.32 | 0.34 | 0.27 | 0.31 | 0.20 | 0.34 | 0.17 | 0.18 | 4,520 |
| Outside impact area | Site 5 | 0.59 | 0.47 | 0.44 | 0.41 | 0.37 | 0.43 | 0.31 | 0.42 | 92.60 |
| | Site 6 | 0.52 | 0.49 | 0.47 | 0.49 | 0.41 | 0.54 | 0.33 | 0.48 | 72.90 |
| | Site 7 | 0.61 | 0.55 | 0.49 | 0.56 | 0.49 | 0.61 | 0.42 | 0.54 | 1.56 |
| | Site 8 | 0.53 | 0.49 | 0.46 | 0.49 | 0.40 | 0.51 | 0.34 | 0.46 | 24.50 |

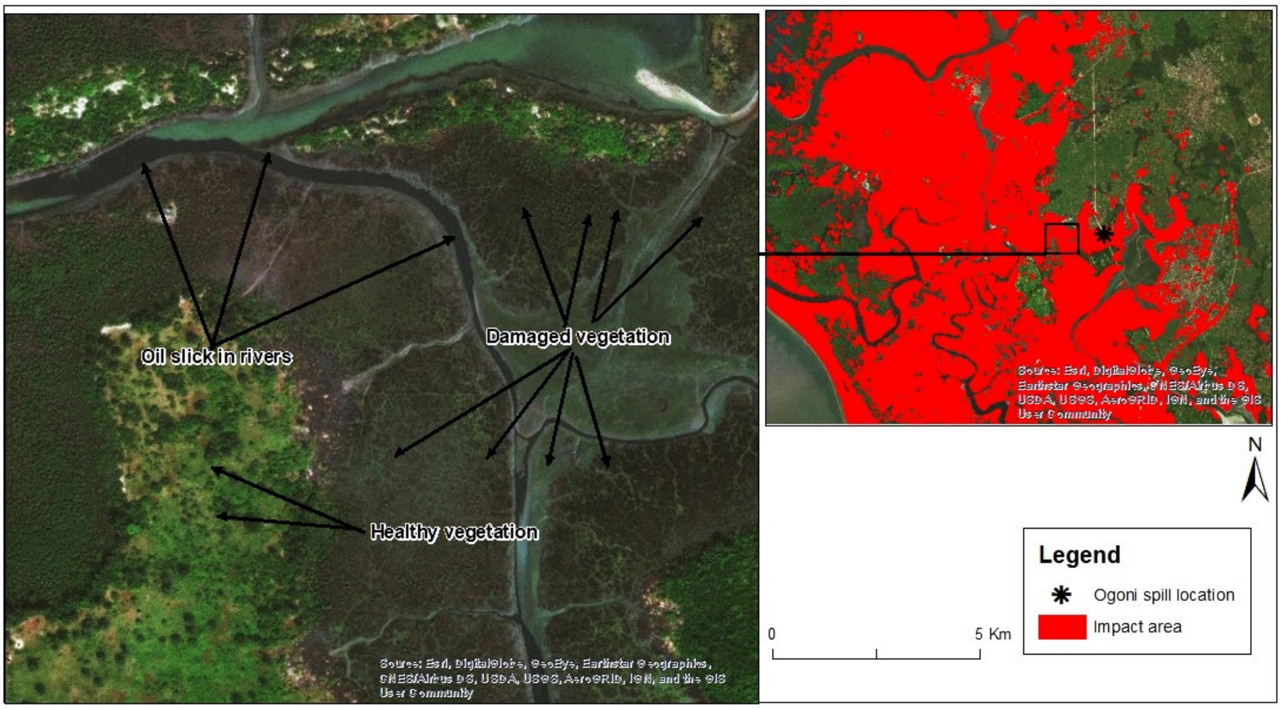

**Figure 3.** Visible thick oil slicks in river channels and damaged vegetation close to the Ogoniland oil spill site, captured by a high-resolution satellite image acquired 5 years after the 2008/9 incidents.

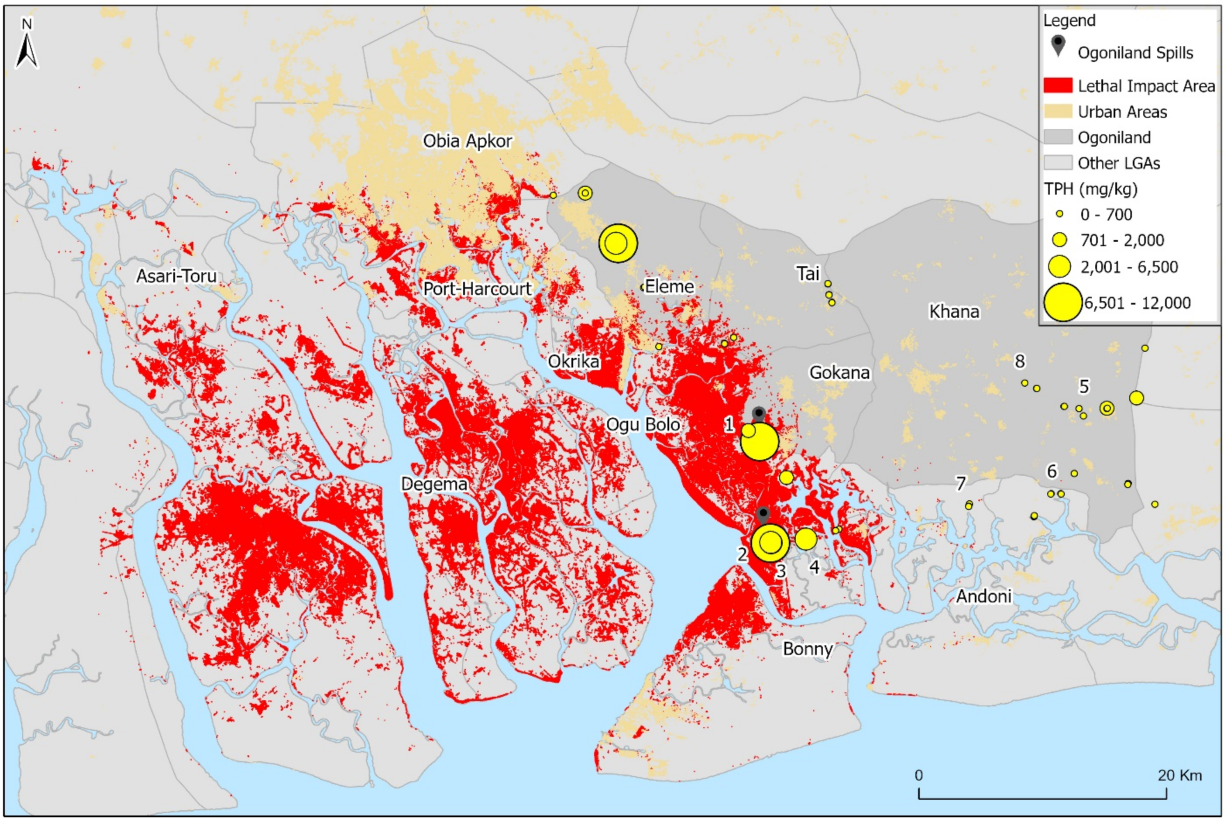

**Figure 4.** Distribution of UNEP's sediment samples and results from TPH measurements, showing substantially higher concentrations of pollutants within the delineated impact area (lethal zone) (sites 1 - 4) compared to samples outside the impact area (sites 5-8).

### 3.4. Human population living within the impacted area

Table 2 shows for each of the LGAs and the study area as a whole, the total human population and the population living within the lethal and sublethal zones of the oil spill impact area. These results highlight the very large numbers of people that have potentially been exposed to pollutants with over a million people (26% of total population) living within the lethal and sublethal zones of the impact area. Table 2 also reveals that because of the extensive spread of spilled oil from the point of release, large populations in LGAs outside of Ogoniland, such as Bonny, Okrika and Degema, are within the impact area and comprise a large proportion of the overall population that has been potentially exposed to pollution across the study site.

**Table 2.** Human populations living within the oil pollution impact area (lethal and sublethal zones) within the study site and constituent LGAs.

| LGA | Total population | Pop. in lethal zone | Pop. in sublethal zone | % LGA pop. in lethal | % LGA pop. in sublethal |
|---|---|---|---|---|---|
| Eleme | 284,045 | 12,336 | 616 | 4.3 | 0.2 |
| Gokana | 348,367 | 32,349 | 2,237 | 9.3 | 0.6 |
| Khana | 516,367 | 501 | 25,063 | 0.1 | 4.9 |
| Tai | 180,980 | 3,689 | 585 | 2.0 | 0.3 |
| Andoni* | 302,504 | 8,575 | 76,095 | 2.8 | 25.2 |
| Asari* | 316,369 | 10,329 | 87,184 | 3.3 | 27.6 |
| Bonny* | 305,365 | 65,665 | 62,388 | 21.5 | 20.4 |
| Degema* | 356,952 | 61,477 | 185,685 | 17.2 | 52.0 |
| Obio Akpor* | 691,984 | 31,576 | 6,503 | 4.6 | 0.9 |
| Ogu Bolo* | 108,050 | 54,722 | 30,480 | 50.6 | 28.2 |
| Okrika* | 317,574 | 91,290 | 148,081 | 28.7 | 46.6 |
| Port Harcourt* | 772,358 | 116,058 | 61,592 | 15.0 | 8.0 |
| **Total** | **4,500,915** | **488,566** | **686,509** | **10.9** | **15.3** |

* denotes LGA outside of Ogoniland.

Figure 5 shows the population demographics within the impact area (Note: there is no discernible difference in demographics between the lethal and sublethal zones of the impact area). This shows that over 70% of the population in the impact area is less than 30 years old. Indeed, the age distribution reveals that the population is dominated by children and teenagers who are potentially most vulnerable to adverse health effects from cumulative exposure to oil. The age group 30 years and over forms a relatively small proportion of the total population and this is likely connected to the very low average life expectancy of the area which is an estimated 50 years. There is little gender disparity across all age groups.

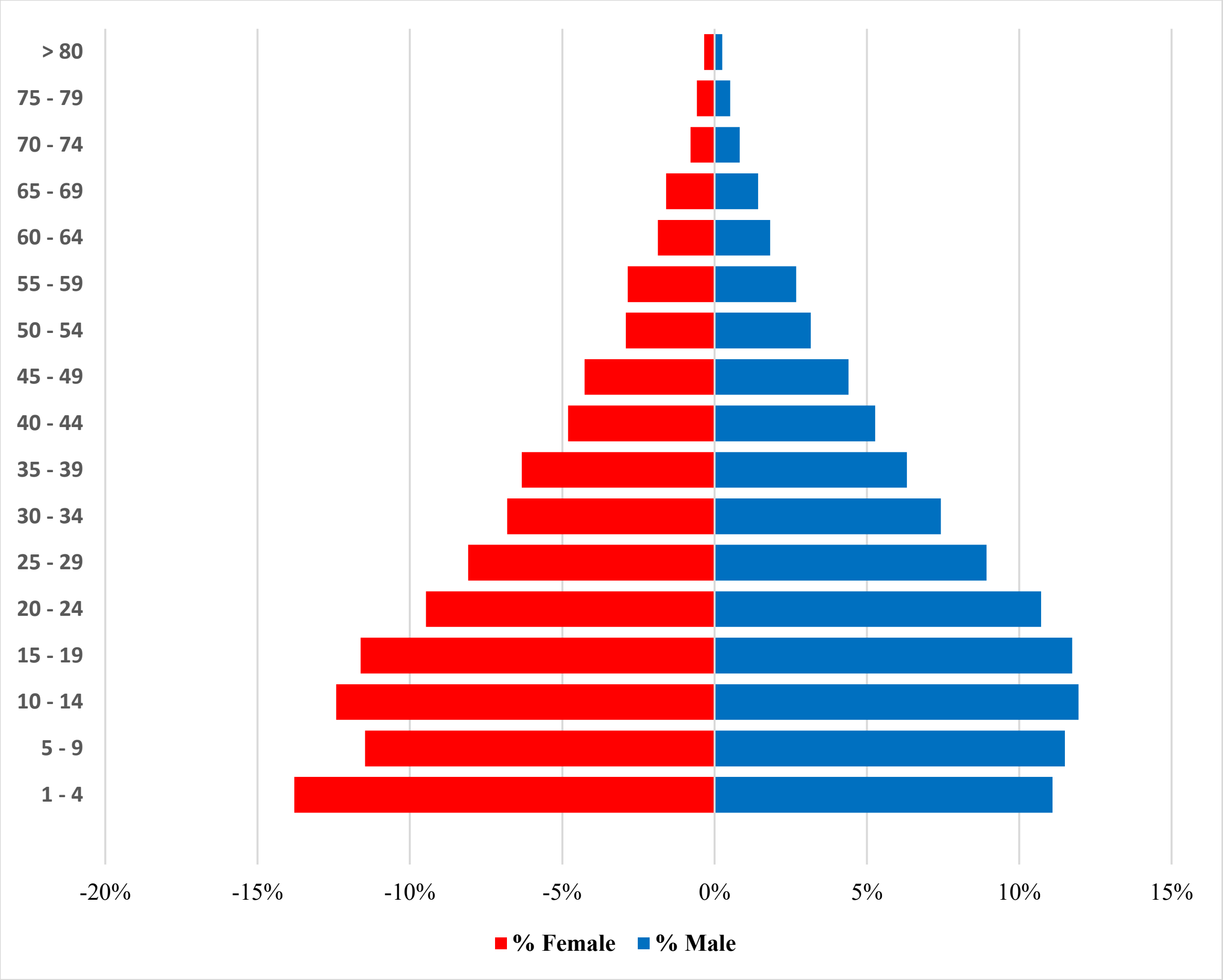

**Figure 5.** Age profile as a percentage of total by gender, of people living within the delineated oil spill impact area, as of 2019.

Figure 6 shows the spatial distribution of all oil spills in the study area before, after and including the large 2008/9 spills. Despite the spills, before and after 2008/9, being relatively small in magnitude, they do have a wide spatial distribution with many contributing oil directly into the tidal wetland mangrove system and therefore being available for wide dispersal and contribution to the burgeoning burden of pollutants in this environment. Given the total recorded volume of spills and the calculations of the population within the impact area (lethal and sublethal zones), it was estimated that there was a total environmental loading of approximately 80 litres of oil per person, with potentially grievous health consequences.

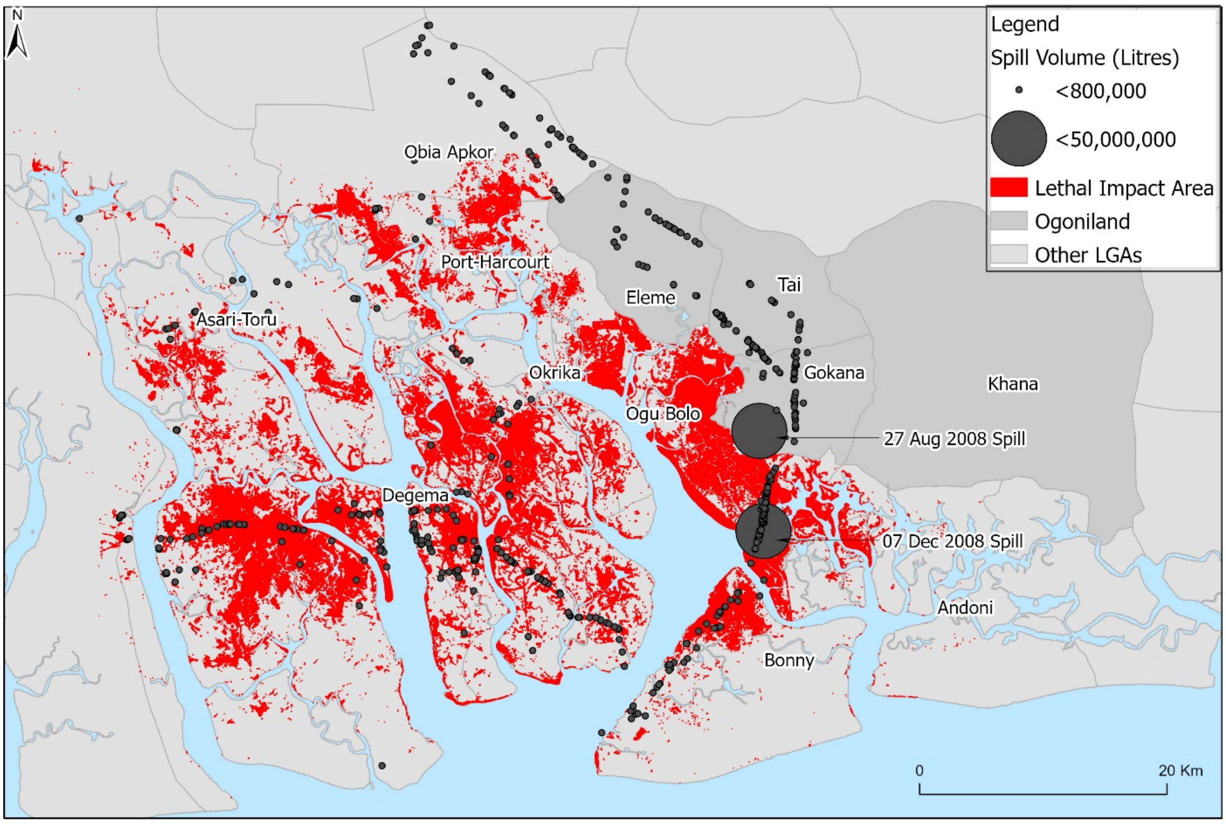

**Figure 6.** Spatial distribution of oil spills before, after and including the 2008/9 Ogoniland oil spills (i.e. 2006 – 2019).

## 4. Discussion

This study has mapped the large area impacted by the 2008/9 Ogoniland oil spills where an estimated 82,939,170 litres of oil were spilled at Bodo and its adjoining creek system. The estimated size of the impact area, comprising lethal (393 km$^2$) and sublethal (730 km$^2$) zones, is in agreement with other studies that have reported extensive environmental damage based on the extent of the resulting pollution (Amnesty International, 2011; Chikere *et al*., 2018). This large area is a direct indication of the widespread impacts of the deleterious physical and chemical effects of crude oil that have resulted in the destruction of mangroves and other low-lying vegetation (Emengini *et al*., 2013a; Ozigis *et al*., 2019). Considering the most recent image used for delineating the impact area was 2018, there is no evidence yet of recovery. Some petroleum hydrocarbons present in crude oil are highly toxic and their persistence in areas such as the Niger Delta is expected as riparian, estuarine and swamp environments have been reported to act as sink for these hydrophobic pollutants (Li et al., 2019). Typical petroleum hydrocarbons, such as PAHs, are not only detrimental to the environment but also to humans due to their prolonged persistence leading to increased exposure and chronic impacts on health (e.g, cancers), even at low concentrations (Alharbi *et al*., 2018).

Movement of water within the river network and beneath mangroves has likely been responsible for spreading oil across the region. Although the general direction of fluvial flows from the catchments feeding the Niger Delta is southwards towards the Atlantic, the study area is predominantly tidal. This facilitates the spread of oil in multiple directions (including westwards away from the spill site and northwards away from the Atlantic coast) across a wide area covered by the interconnected tidal river and creek network and within the tidal mangroves. Moreover, the repetitive tidal cycles are likely to increase the possibilities for deposition of oil through sorption to sediment particles associated with the river network and mangrove swamps where the vegetation induces deposition (Woodroffe, 1992). Thus, rather than the flushing of contaminants which might occur for spills into a typical fluvial system with unidirectional flow, the tidal action means that this area of the Delta is more likely to become a persistent sink for oil that is perhaps reworked and redistributed but not removed (Li *et al.*, 2019).

Destruction of mangroves that means important spawning areas for fish, crabs and other aquatic fauna are impacted. Feeding on the polluted and dead fauna potentially leads to a trail of pollution through the aquatic ecosystem and bioaccumulation of petroleum hydrocarbons in animal tissues along the food chain (Rocha et al., 2018), which can eventually end with human consumption of highly toxic material (Ren et al., 2016). Chronic illness due to prolonged exposure and consumption of potentially polluted food is an important exposure pathway for the local population, with serious health impacts (BBC, 2021). For example, exposure to petroleum hydrocarbons has been linked to reproductive problems, diabetes, cancer, endocrine disturbances and cardiovascular problems (Alharbi et al., 2018).

Although mangroves are potentially the most affected vegetation, croplands used for cultivation are also impacted since the people within the Niger Delta engage in subsistence farming (Amnesty International, 2013). This is worsened by the large area affected as highlighted in this study. Bioaccumulation in plants is therefore inevitable considering the extent of the pollution. This happens as a result of contact between the plant root and polluted soil, which can lead to uptake and subsequent transport to other vegetative and reproductive organs of the plant (Jia et al., 2018). Consumption of these crops, fruits and vegetables can lead to high exposure risk to pollutants of concern and constitute grave dangers to human health similar to consumption of polluted animals (Commendatore et al., 2018; Islam et al., 2018).

The impact of oil pollution in this region is further exacerbated by the majority of the population being dependent on the environment for their livelihoods. Since people are largely subsistence farmers, commercial farmers and fishermen, direct dependence on the environment is inevitable, thereby leading to exposure to oil pollutants through established pathways such as dermal contact and inhalation. The population living within the delineated impact area are of particular concern because the levels of the petroleum hydrocarbons are consequentially higher, however, surrounding areas with different land cover types can potentially be equally of concern. This is because chemicals, including petroleum hydrocarbons, can be transported via atmospheric, overland and groundwater flows (Srivastava *et al.*, 2019). Hence, the exposure of people to pollutants may vary considerably depending on individual circumstances and related exposure pathways. While some communities may be exposed by consumption of polluted water or fish caught from such water, others may be exposed by breathing air in the vicinity of polluted sites. The spatial distribution of oil spills may further influence the severity of human exposure to pollutants, with people living in close proximity to spill sites potentially more exposed and impacted. Oil degrades in the environment as it moves further from a point of release, therefore people living further from a spill location are likely to be less exposed to the most toxic petroleum hydrocarbons of oil. Nevertheless, as Figure 6 indicates, for many areas impacted by the large 2009/8 spill events that are distant from the original spill location, smaller spills have made many highly toxic contributions to pollutant loads, likely elevating localised exposure levels.

It has been reported that years after the large 2008/2009 Ogoniland spills, there is evidence of substantial pollution, an indication of persistence and lack of remediation, thereby exposing the population to potentially dangerous health outcomes (Amnesty International, 2011). Indeed, the situation is likely to have been exacerbated by the many much smaller spills (average 11,766 litres) in the area since the large events (Obida *et al.*, 2018). Studies have reported that based on the levels of pollution, breathing the air, eating fish, dermal contact with soil and sediments and drinking water in many parts of Ogoniland can be detrimental to human health (UNEP, 2014). Neurological, hematologic, renal, and respiratory problems are some of the medical issues associated with living in close proximity to petroleum hydrocarbon pollution (Yakubu, 2017). In a recent study in Ogoniland, 100% of respondents reported incidences of coughing and lung problems, chest pains and eyesores, while over 50% reported skin rashes and depression (David and Bodo, 2019). Since over 70% of population within the impact area are below 30 years of age, this increases their vulnerability.

Prolonged periods of exposure of especially the young population leads to more adverse effects evident in shortened life expectancy which is reported to be an estimated 50 years in this region, 20 years below global average (Effiong *et al*., 2012). Since oil pollution has been linked to serious health problems, future detrimental effects on life expectancy could be anticipated in an area where it is already extremely low.

UNEP's detailed measurements of pollutants, as summarised in Table 1, indicate high levels of oil-related pollutants in the delineated impact area (UNEP, 2014, 2011). In some locations the concentrations are so high that human exposure to pollutants is almost inevitable based on proximity to such places. Table 1 shows that sampling locations with higher pollutant concentrations correlate with areas of substantial and enduring levels of NDVI reduction within the impact area. This can be explained by the concentration and persistence of heavier hydrocarbon components in the environment leading to a prolonged and sustained pollutant exposure and impact (Alharbi *et al*., 2018; Kim *et al*., 2019; Ren *et al*., 2016).

The delineated lethal impact area is likely to represent the minimum area across which oil has spread because (i) the areas mapped are where vegetation has been killed or significantly stressed (>0.2 reduction in NDVI), whereas oil pollution may have spread into other (sublethal) areas where less severe vegetation stress has been induced and is not detected using the NDVI differencing technique (Duke, 2016); (ii) when refining the delineation of the impact area, urban areas were removed as the NDVI technique was not appropriate in such locations, but oil may have spread into urban areas via the river network; (iii) the mapping technique identified impacts on vegetation and not aquatic ecosystems which could be more extensive, particularly parts of the river network in between impacted vegetation areas which will have received or conveyed oil. Furthermore, there is some indication that the zone of influence on human health may extend far beyond the area of impact as delineated in this study. There is documented evidence of children, especially infants and unborn babies, pregnant women and people with pre-existing health conditions as being the most vulnerable groups to the potential impact of petroleum hydrocarbon pollution (Abha and Singh, 2012) Hence, the population at risk of adverse health effects may be much larger than those living within the delineated impact area.

Clean up and remediation efforts have been planned in Ogoniland following the UNEP report, which estimated that a 30 year period would be required to reverse the damage to the environment and public health (UNEP, 2011). However, the clean-up efforts have been adversely affected by a combination of financial, political and social factors (UNEP, 2016, 2014). This poor remediation record in the region has caused persistent environmental damage and prolonged exposure of people to hydrocarbon pollutants (Oyibo et al., 2017; Singh and Agarwal, 2018; Ugochukwu et al., 2018). In order to promote recovery from this dire situation an integrated strategy is needed which spatially optimises the deployment of the limited human resources, clean up equipment and supplies (Grubesic *et al.*, 2017). The present study potentially provides a spatial framework for supporting such remediation work, as well as the deployment of health services, by highlighting the areas in greatest need in relation to pollution risk. The satellite image method used in this study provides a more effective means of assessing oil pollution impacts and potential human exposure than can be achieved using traditional field-based methods. Field sampling is expensive, time consuming and logistically difficult in this region due to the challenging environment and security concerns. Hence, field-based methods will always be limited spatially and temporally. The approach used in this study offers an opportunity for assessing the impacts of pollution and monitoring recovery efforts in a comprehensive manner across the entire region.

## 5. Conclusion

In this study, the widespread environmental impact of the Niger Delta's largest oil spills has been quantified using satellite imagery, which revealed a 393 km$^2$ area of vegetation mortality and much wider area sublethal impact. The method used provides a much more spatially comprehensive assessment of the impact than can be achieved using traditional field-based methods, which are virtually impossible in this region due to accessibility and security issues. The results indicated that multi-directional water flows have facilitated the spread of oil across a wide area within the extensive tidal river network and mangrove swamps, with the delta becoming a persistent sink of oil that is redistributed but not removed.

The human population threatened by exposure to hydrocarbon pollutants is high, with >1 million people living directly within the impacted area who may have been subjected to various exposure pathways. Considering the high concentrations of pollutants and persistence of impacts highlighted in this study, there is a high risk of a range of chronic illnesses developing as a result of prolonged periods of exposure. An age structure dominated by children and young people increases the vulnerability of the population to pollutants, in an area which already has an extremely short life expectancy. Clearly, there is a pressing need for clean-up, remediation and health interventions in the region, however, progress has been hindered by financial, social and political factors. Moving forwards, field-based surveys will continue to be wholly inadequate for assessing the response of the sensitive Niger Delta environment to oil spills. However, with the frequent acquisition of satellite imagery that now takes place, remote sensing is a valuable technique for interrogating the impacts of pollution, as well as environmental recovery, over time across large areas in this geographically remote and challenging location.

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