



IDENTIFICATION AND MONITORING OF OIL PIPELINE SPILL FIRES USING SPACE APPLICATIONS

**A dissertation submitted in partial fulfilment of the requirements for the
degree of Master of Philosophy in Space Studies**

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February 2018

SL18-01M

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Abstract

Oil pipeline spills in the Niger Delta cause a great deal of environmental damage to sensitive ecosystems and losses of many millions of dollars to the Nigerian economy every year. These spills occur along the routes of pipeline infrastructure and other oil facilities like flowlines, trunk lines, flow stations, barges, well heads etc. The causes of these spill events include: operational or maintenance error, ageing oil facilities, as well as acts of deliberate sabotage of the pipeline equipment which often result in explosions and fire outbreaks. In this project, we have investigated whether satellite observations could be used to detect these oil pipeline fires. The Nigerian National Oil Spill Detection and Response Agency (NOSDRA) database contains a total of 10 072 oil spill reports from 2007 to 2015. The space-based approach we considered in this dissertation included the use of data gathered by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua satellites, which recorded 85 129 active fire hotspots in the Niger Delta from 2007 to 2015. Since the oil spill reports serve as validation data for these oil spill fires, we explored the capability of the MODIS instrument to study the spatio-temporal correlation between spills and fire events by attempting to investigate whether the largest spills by volume that resulted in fires could be detected from space in near-real time. Although the NOSDRA oil spill reports are plagued with several irregularities from the Joint Investigation Visits by the joint task force who visit spill sites, our approach in this dissertation automated the filtering process of the raw database to meet our research goal and objective. This study confirms that, indeed, fires resulting from oil spills are detectable using the MODIS fire products. For 43 of the largest spill events, we were able to establish a spatio-temporal correlation of spill incident reports with MODIS fires clearly associated with the oil pipeline infrastructure. Our study also shed light on the spatial and temporal characteristics of non-pipeline fires in the study area.

Acknowledgements

My wholehearted and profound appreciation go to Professor Peter Martinez and Associate Professor Frank Eckardt, who co-supervised this dissertation. Thank you very much Professor Martinez for suggesting this project. I have learnt a lot from your constructive criticism and patience that provided direction in all the phases of this dissertation.

I am grateful to Jewel, my wife, for all her support and prayers. Her words of encouragement provided inspiration to ensure this project was completed.

I also appreciate Mr Nicholas Lindenberg of the Geographical Information Science Laboratory at the University of Cape Town for his mentorship and advice.

Finally, I appreciate the joint support and encouragement received from Dr Joseph Okop and Dr Isaac Inyang.

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1 INTRODUCTION

1.1 Oil transportation through pipelines

The transportation of crude oil through pipeline systems may be thought to be a modern technique, but its uses can be dated as far back as 2500 years when it was first recorded in ancient China. At that time, crude oil was being transported through bamboo pipes, which were used for the boiling of seawater in salt production (see Figure 1.1). The evolution of pipeline uses continued beyond 400 BC when bamboo pipes were coated with wax for the production of gas for illumination in the city of Peking in China (Kuhn, 2004). Subsequent to the bamboo pipeline era in China, pipelines were made from wood and laid underground in 1861 for the transportation of crude oil in the United States (Hopkins, 2011). The first modern oil pipeline was constructed by S.F. Karns following the discovery of oil in Pennsylvania in the United States (Williamson et al., 1966). With new discoveries made possible by the emerging capabilities of engineers, the initial problems associated with pressure and prevention of leaks had been overcome to allow pipelines to become an integral part of the modern-day societal infrastructure.



Figure 1.1 Early 20th century photo of gravity-driven bamboo pipelines used to transport brine and natural gas in China. It was reported that bamboo pipelines covering a distance of up to 95 km were in operation until the 1950s in China. Source: Kuhn (2004)

Petroleum products have to be moved from production and processing sites to places of economic applications and use in order to be of benefit to society. Typically, oil is transported by barges and

tankers on waterways and by road, rail or pipelines over land. Frittelli et al. (2014) considered pipelines as one of the most effective means of transporting petroleum products over long distances on land.

Crude oil transported by pipeline systems plays a crucial role in the world economy. Refined petroleum products are used for transportation, for the generation of electricity, for heating and for the production of feedstocks used in synthetic fabrics, plastics and the pharmaceutical industry (Bashiri Behmiri & Pires Manso, 2013; Ghosh, 2009; He et al., 2010). Apart from the fact that pipelines are used for the transportation of large quantities of petroleum products over long distances, they also provide economic benefits to the country or countries concerned, both during construction of the pipeline infrastructure and in its operations, where they provide direct demand for labour, services and capital infrastructure to the local community.

It is estimated that there are currently 3 500 000 km of oil pipelines in use world-wide (Hopkins, 2011). Globally, an additional 180 000 km of crude oil pipelines are being planned and/or under construction. Walker et al. (1995) noted that pipelines are part of the national infrastructure of a country for the oil and gas sector and are critical to a nation's energy security and economic development. It is expected that crude oil pipelines will provide market stimulus locally within the country and internationally among the trading countries. This means that in a friendly trading atmosphere, the crude oil pipeline system has a potential for economic returns on investment.

1.2 Pipeline oil spillage

Generally, pipelines are susceptible to leaks from natural and technical causes. Natural causes include earthquakes (in places with high seismicity), landslides, or floods, while technical causes include accidents originating from maintenance errors (i.e. poor maintenance culture) or arising through the negligence of the oil companies who take ownership of the pipeline equipment. For example, an earthquake of magnitude 6.9 that struck Ecuador on the 5th of March 1987 caused up to 40 km damage to the Trans Ecuadorian oil pipeline. A total of 100 000 barrels of oil was spilled polluting the surrounding environment. In 1994, over 34 500 barrels of crude oil were spilled both onshore and offshore Texas in the USA due to the impact of a massive flood from the San Jacinto River, where an estimated 545 people suffered from petroleum burns and serious inhalation injuries (Girgin & Krausmann, 2016). An example of accidental spills due to operation or maintenance error is the spill from the Guanabara Bay oil pipeline off Brazil in 2000, which released 9282 barrels of oil into the sea (United Nations Environmental Programme, 2001). Figure 1.2 shows the fifteen largest spills recorded worldwide from 1967 to 2010.

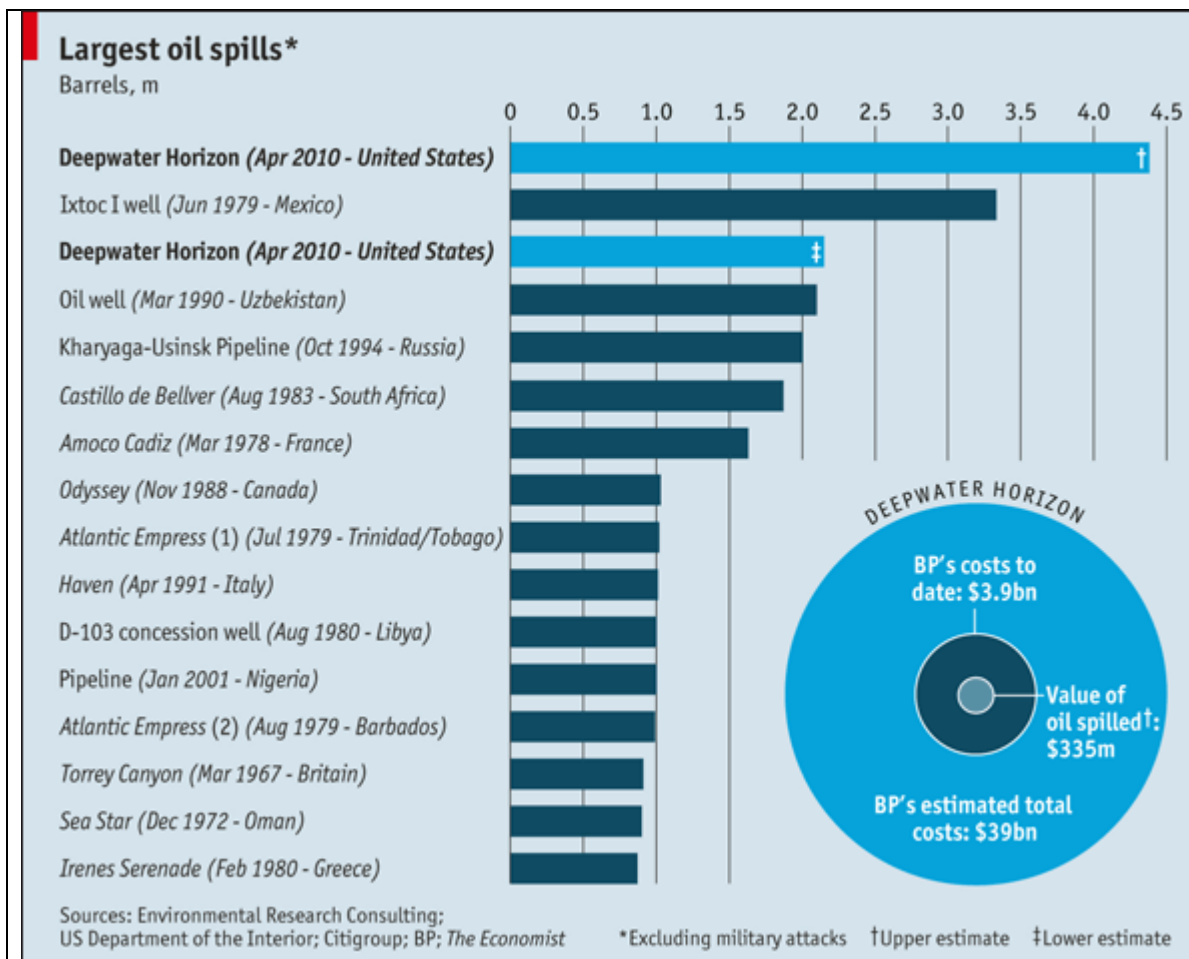


Figure 1.2 The fifteen world largest oil spills in the world 1967 to 2010.
Source of image: Jones (2010)

Large oil spills can be extremely costly to the oil companies whose infrastructure becomes, for whatever reason, the source of a spill. The largest spill event to date, the Deepwater Horizon spill of potentially almost 4.5 million barrels in April 2010 (Figure 1.2), provides an interesting example. Although the value of the spilled oil was “only” US\$ 335 million, the estimated cost to BP may be as high as US\$ 39 billion (Figure 1.2).

In addition to the natural and technical operational causes discussed above, oil pipeline spills can also be caused by theft and deliberate acts of sabotage. These causes are collectively referred to as third-party interference, especially in the event of malicious damage (Anifowose et al., 2012). The case of the Trans-Alaskan pipeline in 2001 is an example of deliberate pipeline damage (in that instance caused by a drunk man who shot a hole in the pipeline), where 6143 barrels of oil were reportedly spilled (Winner, 2012). Suárez (2015) reported oil spills due to pipeline attacks in Columbia. It is also reported that some pipeline attacks occurred in remote and ecologically sensitive places that are hard to reach for maintenance and repairs. Repairs on such equipment may

also be hindered by the host communities and rebels (Shell Petroleum Development Company, 2005; Albers, 2003). Deliberate attacks on oil pipelines and associated infrastructure have been reported in Iraq, Saudi Arabia and Nigeria. In Iraq, significant attacks were recorded along Turkish and Syrians pipeline terminals on the Mediterranean via Baiji in the north of Iraq (Serebryakov, 2009). Most of these attacks were between 2003 and 2007, after the start of the second Gulf War.

Coastal ecosystems are vulnerable to the impact of oil pipeline attacks. The work of Mendelssohn et al. (2012) provided an extensive review of effects of oil spills on the marine ecosystem and coasts worldwide. Oil seepage enters such water bodies through natural seeps, accidents on pipeline vessels, run-off from the terrestrial environment, and deliberate or illicit dumping (Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, 2007), (see Wiese & Robertson, 2004; Camphuysen & Heubeck, 2001).

Generally, discharges of oil into the marine environment are regarded as non-compliant with the “International Convention for the Prevention of Pollution from Ships” (MARPOL). Basically, run-off and seepage are amongst the largest causes of oil spills into marine habitats worldwide (GESAMP, 2007). Research on oil spillage into the marine habitats and the related consequences to humans, the marine environment, and aquatic species abound in the literature (Anifowose et al., 2012; Wiese & Robertson, 2004; Camphuysen & Heubeck, 2001).

1.3 Fires associated with oil pipeline spills

Pipeline oil spills caused by natural and technical phenomena, and acts of deliberate sabotage, often result in fire scenarios. The severity of oil pipeline explosions, the volume of such spills, the environmental conditions (i.e. the type and abundance of vegetation) or types of habitats (i.e. savannahs) and the hydrocarbon constituents of spills are critical factors which determine whether a pipeline spill will result in a fire or not (Mealy et al., 2014; Mealy et al., 2012; Julius et al., 2011; National Institute of Justice, 2001; Steinhaus et al., 2007; Mckendrick & Mitchell, 1978). Steinhaus et al. (2007) described the burning behaviour of an oil spill fire to be characteristically distinguished from other fires with respect to its hydrocarbon sources which defines its higher emission rate, radiative power, and larger plumes compared with other sources of fires. Hydrocarbons burn more than other fire sources due to the fuel load. The analysis of natural causes of wildfires in the United States from 1986 to 2012 showed that more wildfires were caused from oil pipeline explosions due to earthquakes in Louisiana, Texas and Oklahoma than other natural causes of fires in other states. These three states are known for pipeline oil spills due to oil operations (Girgin & Krausmann, 2016). Oil spill fires from pipeline explosions due to accidents at the oil facilities have also been reported (Anifowose et al., 2012). In addition, Taylor (2011) provided a review of pipeline fires resulting from deliberate attacks on oil pipeline equipment. Mealy et al. (2012) explained how accidents from industrial oil spill sites can result in a fire scenario and differentiated such fires from those caused by acts of arson.

According to the online source Wikipedia (2017), the following countries were listed as having pipeline oil spill fire cases which resulted in fatal injuries¹ between 1962 to 2014: Canada, USA, Nigeria, Mexico, China, Malaysia, Belgium, and Kenya.

Although gas flares are not directly contributory to wildfires, they are a global concern for their effect on global warming and climate action. Volkova et al. (2014) noted that the reduction of fuel and hydrocarbon constituents potentially reduce wildfire effects. The effect of wildfires on global warming was explained by Westerling et al. (2006), in the study that compared large forest wildfires in the Western United States over 15 years period with ordinary land-used fires, and discovered increased in summer temperature with forest wildfires than with land-used fires.

1.4 Detection of oil pipeline spills with satellite remote sensing

Oil pipelines can be monitored using visual inspections for those infrastructures that are easily accessible. In the Niger Delta of Nigeria, human direct inspection of oil pipelines with the aim of validating oil spill occurrences in a process known as the Joint Investigation Visit (JIV)² is routinely carried out for the safety of the pipeline equipment and the host communities where the oil facilities are situated. Fingas & Brown (2014) reported that the more common approach to oil spill detection and surveillance involves routine inspection visits, taking videos and photographs of oil pipeline sites. However, the remotely sited facilities are difficult to access and hence require remote sensing technology such as satellite sensors for detecting spill incidents (Chalgham et al., 2016). Suárez (2015) reported that such remotely sited oil pipelines are hard to reach for maintenance and repairs. Satellite remote sensing, therefore, offers a promising technique for detecting oil pipeline spills.

Infrared detectors (i.e. within the thermal infrared range) have been widely used in the detection of oil spills on seas, but with limitations on land due to the background vegetation that confounds the thermal contrast necessary for detection (Fingas & Brown, 2011). In the same vein, (Jha et al., 2008) ultraviolet sensors have been used to detect oil spills in marine habitats due to the difference in surface reflection of water versus oil. For a similar reason as with infrared, it has limited land application (an ultraviolet sensor requires clear skies and daylight). Singha et al. (2013) reported

¹ Countries are arranged in decreasing order of casualties.

² The Joint Investigation Visit (JIV) in Nigeria is made up of government agencies, representatives from the host community, oil company and security operative. The team investigates oil spill events in situ and such spill events are recorded in a database

that synthetic aperture radar (SAR) has been used to detect oil spills in marine habitats with a degree of success depending on the roughness of the water. The degree of roughness of the water surface produces image brightness variations through backscattering property of the SAR sensor. Singha et al. (2013) reported that side-looking airborne radar (SLAR) and synthetic aperture radar have been used on aircraft to detect pipeline deformation, with a secondary application in the actual leak detection. Such microwave sensors can detect and monitor oil spills regardless of weather conditions during day and night (Brekke & Solberg, 2005). However, SAR is more frequently used on seas than on land because the latter does not have the same backscattering properties as the former.

As discussed earlier, oil pipeline spills, often with fire cases, significantly affect surrounding areas (i.e. vegetation, soil, water, etc.). For this reason, several authors have investigated the use of multispectral sensors (like MODIS, Landsat, etc.) including hyperspectral sensors for the detection and monitoring of oil spills on land (Fingas & Brown, 2011; Lunetta et al., 2006; Brekke & Solberg, 2005). Such remote sensing data have been used to monitor vegetation with respect to oil spills for compliance monitoring, crop or vegetation condition, yield density, crop classification, and mapping of various locations (Fretwell et al., 2011).

1.4.1 Spill extent

Remote sensing allows an assessment of the extent of oil spills. Oil does not appear to have a particular spectral signature that permits easy identification against the background of possible interference (Fingas & Brown, 2014), but infrared cameras can detect oil in daytime since it absorbs sunlight and reflects thermal energy. This provides a strong possibility for multispectral sensors (like MODIS and Landsat) and hyperspectral sensors to detect spills, especially when such spills are significantly high in volumes. Adamu et al. (2015) used Landsat data collected between 1986 and 2003 to investigate vegetation stress resulting from oil spills. Their study pointed out the advantage of using historical data as a means of studying temporal variations to investigate the spectral response of an area contaminated by an oil spill.

The 250 m spatial resolution of the MODIS instrument on the Terra and Aqua satellites has been well used for oil spill detection in oceans (Pisano et al., 2015; Grimaldi et al., 2009), and for land cover change detection (Lunetta et al., 2006). Research towards its uses for direct oil spill detection on land is still in progress.



Figure 1.3 Image of the Deepwater Horizon spill as observed by NASA's Terra satellite with the MODIS sensor on 24th May 2010.

Source: NASA (2010)

In Figure 1.2, we highlighted the case of the Deepwater Horizon spill, as one of the largest global spills where an estimated five million barrels spilled into the Ocean. Figure 1.3 shows that such an extensive of oil spill can be detected using 250 m spatial resolution of MODIS sensors.

The 250 m spatial resolution of MODIS instrument may provide significant milestones for land spill monitoring for large spill volumes. Its current usage for deriving a vegetation index is an additional advantage for detecting and monitoring vegetation stress due to oil seepage and other anthropogenic activities (Lunetta et al., 2006). Obida et al. (2017) studied the spatial extent of spills by quantifying spill intensity (i.e. low, medium and high) as areas of impact of hydrocarbon pollution caused by pipeline oil seepage on the following land cover indices: broadleaved trees, mangroves, cropland, water, shrubs settlements and grassland.

Spill size often gives information about the extent of damage to vegetation and hence the size of fires and heat that will be released from such spills (Mealy et al., 2014; Mealy et al., 2012; Julius et al., 2011).

1.4.2 Detection of active fires

The MODIS sensors onboard the Aqua and Terra satellites have been a useful global resource in meeting the needs of the changing world since these satellites were first launched. The MODIS instrument has 36 spectral bands which are specifically equipped to study land cover and ocean dynamics. Although MODIS has a low spatial resolution, its temporal resolution is high enough to detect changes in the landscape over a period of time, and also to detect active fires and fire scars. Xin et al. (2013) report on real-time fire detection using MODIS active fire products, while Hawbaker et al. (2008) studied the fire detection rate of Terra and Aqua over the United States of America. Additionally, the MODIS instrument has been used for validation of anthropogenic sources of thermal emissions in Siberia (Csiszar et al., 2006).

MODIS is not only limited to active fire detection globally but is also capable of estimating burn scars. It has been used to estimate burn areas in the presence of smoke and for the validation of fire hotspots when the time of active burning is not taken into account (Dacamara et al., 2012; Chuvieco et al., 2008).

Sensor	Satellite	Spatial Resolution	Temporal Resolution	Swath Width	Channels and bands for fire detection
AVHRR	NOAA	1.1 km	2 times in 24 hrs	2400 km	3a(1.6 μ m(Night)) 3b(3.9 μ m(Day)) 4 (11 μ m)
MODIS	Aqua/Terra	1 km at nadir	4 times in 24 hrs (2-day and 2-night)	2330 km	21 and 22 (3.9 μ m) 31 (10.8 μ m)

Table 1.1 Characteristics of the Advanced Very High-Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS).

Source: Morisette et al. (2005)

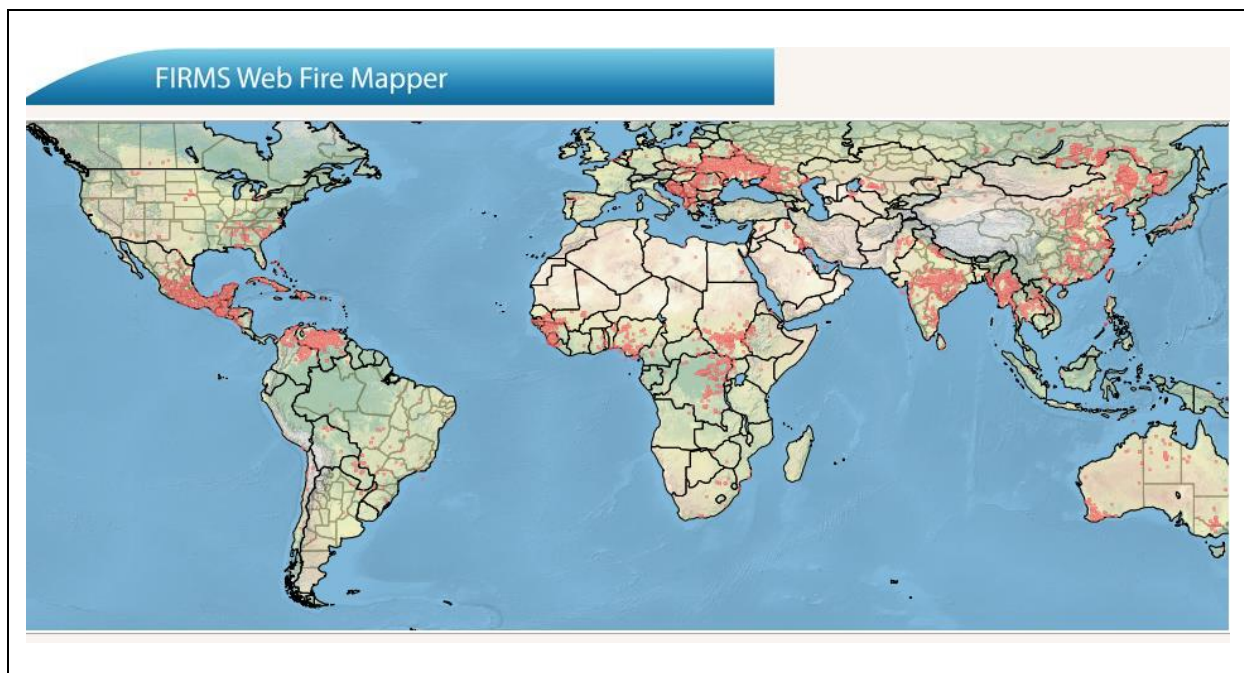


Figure 1.4 MODIS active global fires at near-real-time as shown on the global fire map.
Source: NASA (2016)

The MODIS instrument onboard the Terra and Aqua satellites provides data for the global Fire Information for Resource Management System (FIRMS), which shows near-real-time fires for the entire globe in Figure 1.4. Nigeria remains one of the dominant countries producing a high volume of fires which are detectable by MODIS sensors.

1.5 The rationale and scope of this research

The Niger Delta of Nigeria is highly vulnerable to oil spills, which are often accompanied by explosions and wildfires. The following causes are responsible for these spill events: maintenance and operational error, equipment ageing and acts of deliberate sabotage of the pipelines and other oil equipment. Past research efforts have only focused on spill events without investigating the accompanying fires. Meanwhile, the oil facilities owners (oil companies), governments, local communities and global health and ecological organizations all have a stake in ensuring that spills are prevented, detected and repaired as quickly and often as possible to avoid fires. Several authors have studied the changes to the vegetation, soil and water caused by the spills (Bashir et al., 2016; Egberongbe et al., 2006; Lindén & Pålsson, 2013). However very few authors have investigated fires in respect to oil spills in Nigeria (Anifowose, et al., 2012; Osuji & Ukale, 2005). Anifowose et al. (2012) studied the number of fires from routine oil spill reports from 1990 – 2008 without investigating their locations and the essence of damage, while Osuji & Ukale (2005) examined the chemistry of fire damage that leads to land pollution.

While changes in vegetation indices like Normalized Differential Vegetation Index (NDVI) provide basic information about the health of the affected vegetation vis-à-vis the healthy vegetation, such detection is not at near-real-time. The effect of oil spills on vegetation is a slow and gradual process, thus making rapid detection and monitoring of oil spills on vegetation a big challenge. Apart from ocean spills, whose changes are almost instantly evident, changes to vegetation and soil can take much longer to manifest in remote sensing data (Ordinioha & Brisibe, 2013; Mendelsohn et al., 2012). More importantly, of interest is the neglect of the fire scene which occasionally accompanies many spill events. A large number of fire images is available online for the Niger Delta, but without scientific literature accounting for their sources or any database describing their source. This is a major concern. Why are there so many reports on Niger Delta oil spills, with significant environmental damage caused by explosion and fires without corresponding research efforts to investigate those fires? This research is particularly interested in proposing a space-based approach that can be used in near-real-time to detect oil pipeline spill fires.

This study will consider ground oil spills in the hotspots of the Niger Delta and use Earth observation sensors capable of detecting fires associated with oil spills. We chose to use MODIS after a substantial literature review³ (Takahata et al., 2010; Davies et al., 2009; Lee et al., 2002). The conceptual framework for considering MODIS products in this project is defined by its sensor which includes 36 spectral bands designed for effective monitoring of land cover, ocean colour and vegetation index, combined with other dynamics (United States Department of Agriculture, 2010; Gillan, 2002). MODIS fire hotspots are available for users 3 hours after satellite overpass with morning (Terra) and afternoon (Aqua) daily visits. Can Earth observation with an accurate record of fires provide a mechanism for monitoring oil spills? Perhaps we may be able to use this as an early warning signal to detect spill events and to monitor oil pipelines for early warning of sabotage.

1.5.1.1 Aim of research and objectives

Although oil spills are a global phenomenon which takes different contextual dimensions in each country, this research will focus on the hotspots of the spills in the Niger Delta of Nigeria. The purpose of this study is to propose Earth observation applications to detect oil spill events from active fires in the Niger Delta. Therefore, this study aims to identify whether accidental or deliberate oil spill fires may be sufficiently large to be detected by the 250 m resolution MODIS fire products. If so, what is the detection threshold, and the relationship between oil spill events

³ MODIS is largely designed for global Fire Information for Resource Management System (FIRMS).

and fires observed? The key objective of this study is to investigate the spatial and temporal correlation between oil spills and the MODIS active fire products. This work will allow us to produce an inventory of oil pipeline fire hotspots in the Niger Delta that could be useful in many ways. Our ultimate objective is to attempt to develop a tool that could be useful for the detection of oil pipeline fires in near-real-time.

1.6 The structure of this dissertation

In Chapter two, we will present a comprehensive list of literature describing the study location with an emphasis on oil spills from pipelines and related facilities (i.e. flowlines, flow stations, well heads, etc.) with attendant consequences of fires. We will provide a vivid picture of the Nigerian oil landscape with the goal of providing justification for the outlined aims and objectives of this research. Chapter three will describe the sources of data. In Chapter four, we will present the detailed analysis of the data described in Chapter three. In Chapter five, we will investigate the spatio-temporal correlation between spill events and fire events, while Chapter six will aggregate the main components of the research with a view of discussing the main findings as they address the aims and objectives of the research. Lastly, in Chapter seven, we will provide recommendations based on the key scientific results established in this project and propose areas for further future research.

2 DETAILED REVIEW OF THE STUDY LOCATION

2.1 The Nigerian oil economy

According to the World Bank (2017), Nigeria has the largest economy in Africa with a Gross Domestic Product (GDP) of US \$404 billion, ahead of South Africa with a GDP of US \$295 billion in 2016. It is also the largest oil producer in Africa and sixth-largest producer in the World. The main source of its revenue generation is the export of crude oil. For instance, according to the Nigeria National Bureau of Statistics (2017), the returns in term of export trades in crude oil in the second and third quarters of 2014 were US 19.1 billion⁴ (69.8%) and US 17.1 billion (65.2%). On the other hand, exports of Natural Liquefied Gas for the same quarters in 2014 were respectively US 1.8 billion (6.61%) and 1.66 billion (6.4%). Europe is the biggest buyer of Nigerian crude oil, followed by India (Nigeria National Bureau of Statistics, 2017). Fluctuations in the global price of crude oil trigger a proportionate economic reaction in Nigeria. Although Nigeria is a big player in crude oil exportation, it is also unfortunately a big importer of refined petroleum products due to political and social factors. The sharp decline in the price of crude oil in the world market between 2015 and second quarter of 2016 spelt woe to the Nigerian economy as the cash-strapped government could not fulfill its responsibilities to the taxpayers. In addition, many of the civil servants did not receive their monthly salaries for several months.

The Nigerian economy is not only affected by the fluctuations in the global price of crude oil, but also by the effects of vandalism on the petroleum equipment nationwide. Ajibola et al. (2014) studied the economic losses suffered by the Nigerian economy due to pipeline vandalism and theft of oil between 2000 and 2010 and estimated a revenue loss of US \$1.01 billion. Pipelines are also subjected to deliberate acts of sabotage by militant groups. The militant group known as the Niger Delta Avengers has taken responsibility for repeated attacks on oil pipelines in the Niger Delta and has subsequently prevented repairs to such equipment. Moreover, the pipelines are often in remote places, making their repairs difficult (Shell Petroleum Development Company, 2005; Albers, 2003).

⁴ The average exchange rate of the Nigerian Naira 'N' in 2016 was N 300 to 1 US Dollar. The exchange rate in 2017 = N 360

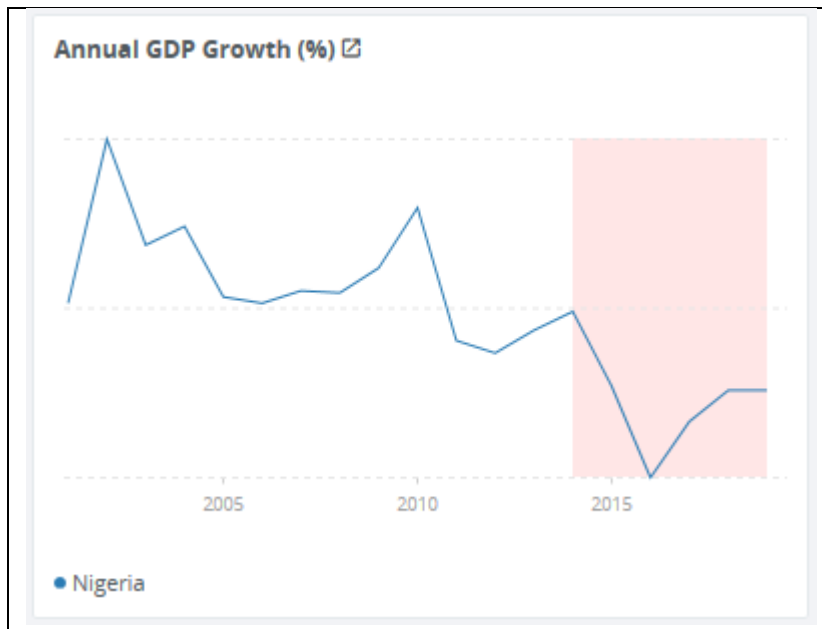


Figure 2.1 Annual GDP growth (%) in Nigeria (2014 – 2019).
Source: World Bank (2017)

2.2 The oil pipeline system in Nigeria

Our study focuses on the oil pipeline system in Nigeria, which is the principal means by which petroleum products are transported in the country. Other oil facilities by which crude oil is borne in Nigeria include flow stations, flow-lines, trunk lines and well heads. Spills from these oil facilities are frequently accompanied by fires and are the focus of this project.

The Nigerian oil pipeline network spans a distance of 7 000 km (Oxford Business Group, 2016). These pipelines are designed to transport petroleum products from points of exploration through depots of refineries to the various consumers. This pipeline system can either run underground or above the surface, depending on the landscape (Ebike et al., 2014). The passage of this network of pipelines across the country has altered the original environmental layout, biodiversity and the general ecosystem of the areas through which these pipelines run (Egberongbe et al., 2006; Nwilo & Badejo, 2005; Ogwu, 2011).

The Nigerian petroleum industry had its origins during the British colonial era. The British colonial government enacted what is known as Mineral Oil Ordinance of 1947, which limited the granting of oil licenses and leases to British companies. It was this regime that granted the ‘British-Dutch’ company known as Shell Petroleum Development Company (SPDC) the right of oil exploration over the whole of Nigeria (Nigerian National Assembly, 2000; Nigerian National Petroleum Corporation, 1969). The company’s exploration activities led to the discovery of the first commercially viable oil deposit in Oloibiri in 1956 in the Niger Delta, which subsequently led to the building of pipeline infrastructure for both offshore exploitation and distribution of crude oil

in Nigeria (Pinto, 1987). The commercial production of crude oil in Oloibiri at this time was to the tune of 5 000 barrels per day. Following Nigerian independence from British colonial rule in 1960, large-scale oil exploration began in 1971, when Nigeria became a member of the Organization of Petroleum Exporting Countries (OPEC) leading to the establishment of the Nigerian National Petroleum Corporation (NNPC) (NNPC, 2014).

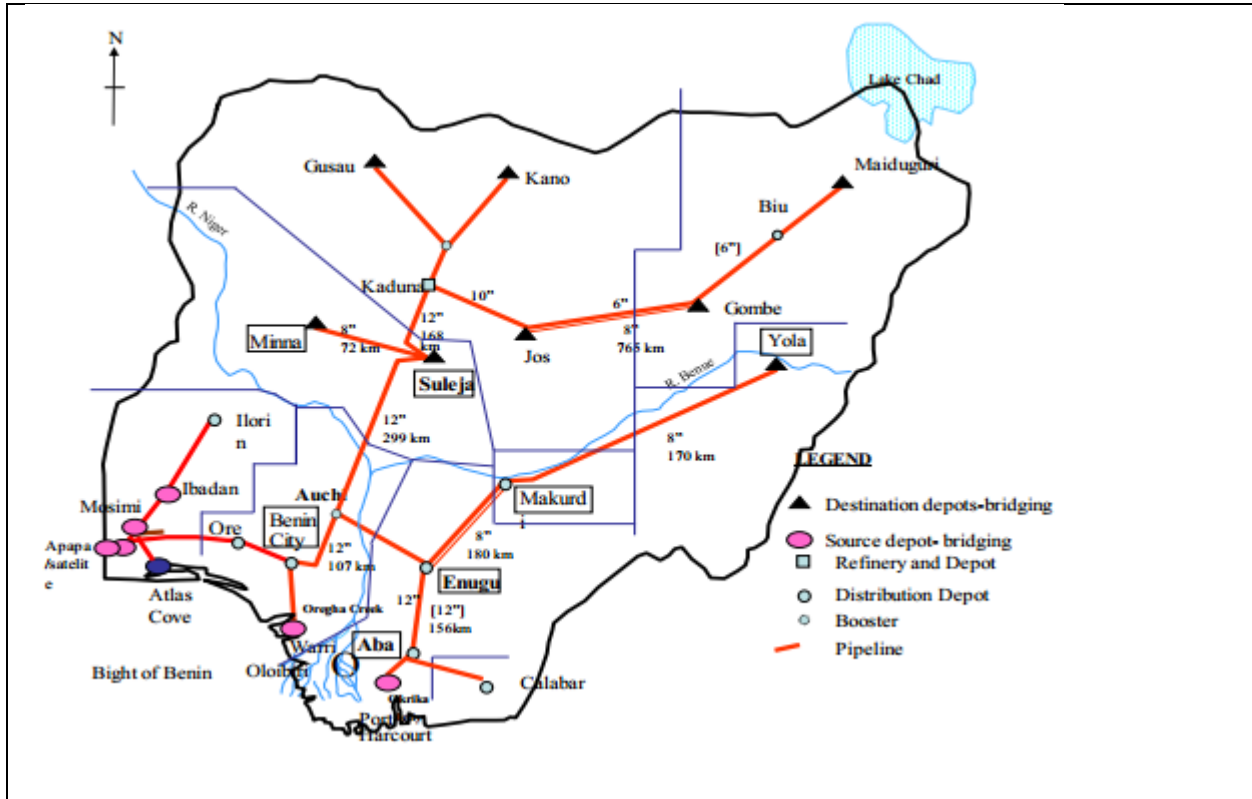


Figure 2.2 The oil pipeline network system in Nigeria.
Source: Anifowose et al. (2014)

Today, more diverse stakeholders and many more oil companies are involved in the oil exploration activities in Nigeria. Niger Delta areas remain the country’s central oil reserve from where oil infrastructure has been developed across the country, with more than 300 oil fields having about 5 284 wells, all connected through a network of pipelines extending some 7 000 km. Other infrastructure includes 11 export terminals, 22 petroleum depots, 10 gas plants, 275 flow stations and 4 refineries. Today, there are four oil refineries in Nigeria, with two in Port Harcourt in River State, one in Warri situated in Delta State in the Niger Delta of Nigeria, and one in Kaduna State, in the northern part of the country (Kadafa, 2012). There are 11 export terminals in Nigeria which are operated by the foreign oil companies in the Niger Delta. Some of these companies include Addax Petroleum, CHEVRON (American), MPN, NAOC, PPMC, SEEPCO, SEPLAT, Shell (British Dutch), Total (French), Agip (Italian) and Exxon Mobil (American). The Nigerian National Petroleum Corporation (NNPC) superintends over all matters of petroleum in Nigeria,

with a 60% stake in joint oil ventures and a Memorandum of Understanding (MOU) that governs the relationship among parties (Pinto, 1987).



Figure 2.3 Oil pipelines are a common feature of the landscape in the Niger Delta of Nigeria. Source: Taylor (2011)

2.3 Pipeline Right-of-Way

Generally, the construction of pipeline systems worldwide has allowed for what is known as “Right-of-Way” as a legal regime that should not be violated. The right-of-way (ROW) is a strip of land, usually between 18 metres and 36 metres wide, containing one or more pipelines (Fung et al., 1998; Nigerian National Assembly, 2000).



Figure 2.4 The standard right-of-way in global pipeline management. Source: Enbridge Inc (2017)

The violation of the ROW regime by any of the parties, (either by members of the community through which the pipeline system is conveyed, or by the petroleum company who claims ownership of the pipeline equipment, or by the government) often results in serious consequences. These consequences can take the form of equipment failure that will result in oil spills, fire outbreaks, pollution of the environment, health risks to the communities concerned, scarcity of a precious commodity in the country and economic losses to the oil industry and the government. In Nigeria, however, the adherence to ROW is a complicated matter. Reports of deliberate pipeline sabotage or illicit oil tapping by the host community abound in the literature (Anifowose et al., 2014; Kadafa, 2012; Paraskova, 2016). Oil spills from these pipelines and other oil facilities (flow stations, well heads, and flow-lines) often lead to explosions and outbreaks of wildfires that result in serious injuries and in many instances loss of lives and properties (Ajibola et al., 2014; Murdock, 2012). Oil spills from pipeline systems are a source of daily fires in the Niger Delta. In cases of such pipeline oil spill fires, women and children are the most affected (Onuoha, 2009).

News about illegal oil refineries in the Niger Delta is a daily affair in the media houses within and outside Nigeria (BBC News, 2012; Thisday, 2017). As recently as September 2016, the Federal Government of Nigeria destroyed seventy-four illegal oil refineries in the Niger Delta (Paraskova, 2016).

2.4 The Niger Delta of Nigeria

The Niger Delta region of Nigeria comprises the areas which are covered by the natural Delta of the Niger River and the areas to the East and West which are also involved in oil production (Anejionu et al., 2015). The natural boundaries of the region can be defined by its geology and hydrology, covering approximately 25 900 square kilometers. Due to political, administrative and developmental reasons, the region was extended to about 75 000 square kilometers, covering all other nearby oil producing areas (Emoyan, 2016). The region comprises nine states of the Federal Republic of Nigeria (Figure 2.5). These states are Abia, Akwa-Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo, and Rivers. Broadly speaking, Nigeria's vegetation is made up of three distinct belts, namely forest, savannah, and mountain vegetation. The forest vegetation can either be mangrove or freshwater swamps, depending on proximity to the coastal areas of salt water. The Niger Delta zone is criss-crossed with rivers, canals, streams, creeks, and rivulets representing the largest mangrove wetland in Africa and third largest in the world, (Oribhabor, 2016). In addition, it is classified as a tropical rainforest comprising four ecological zones, which comprise the lowland rainforest, freshwater, mangrove swamp forest and coastal barrier islands. It is the source of over 80 percent of Nigeria's oil production, contributing about 85 percent of the total foreign exchange earnings of the country (Chinyere & Adewole, 2016).

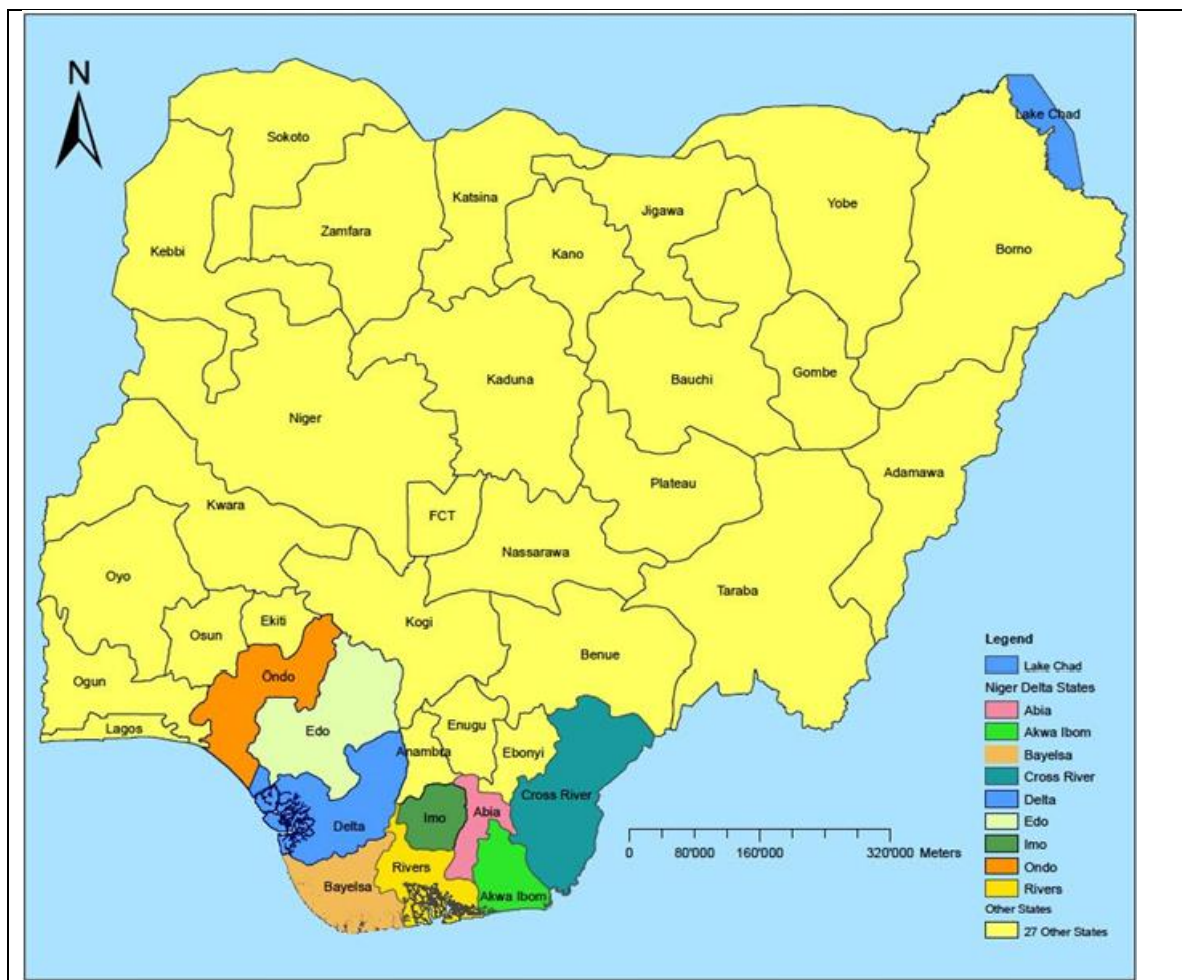


Figure 2.5 Map of Nigeria showing the nine states comprising the Niger Delta. Adapted from Aniefiok et al. (2013)

2.5 Specific documented cases of oil spills in Nigeria

The cases of oil spills in the Niger Delta of Nigeria are too numerous to list individually. Here we provide just a few examples of some of the larger spills to underscore the severity of the problem. In July 1979, there was an oil spill of 570 000 barrels from Forcado tank terminal in Delta State that polluted the Forcado estuary and aquatic environment (Ukoli, 2001). In 1990, 200 000 barrels of crude oil spilled into the Atlantic Ocean due to the failure of offshore equipment causing environmental damage to more than 340 hectares of mangrove habitat (P. C. Nwilo & Badejo, 2005). In 1998, 40 000 barrels of crude oil were spilled from an Exxon Mobil facility in Eket, Uyo State. In 2001, Shell Petroleum Development Company (SPDC) recorded 115 cases of oil spills from company facilities (Shell Petroleum Development Company, 2005). A report from the Department of Petroleum Resources (DPR) recorded 4647 incidents of oil spills between 1976 and 1996, leading to a rough estimate of a loss of 2 369 470 barrels to the surrounding environment (Fatai Egberongbe et al., 2006). An approximate volume of 1 820 410 barrels (77%) of the total

amount were recovered, while 549 060 barrels (23%) were lost to the environment. Egwu (2012) augured that for oil spills to reduce significantly, the government needs to display greater commitment to protecting lives and properties.



Figure 2.6 An aerial view showing illegal oil refineries in the creeks of the Niger Delta.
Source: Taylor (2011)

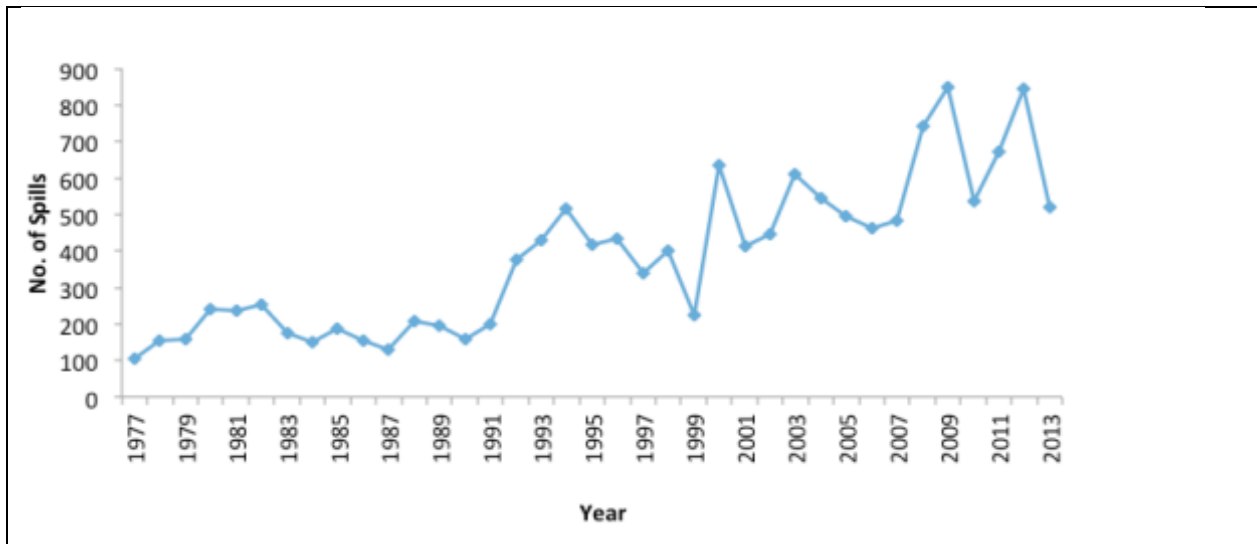


Figure 2.7 Incidence of oil spills in the Niger Delta of Nigeria from 1977-2013.
Source: Elizabeth Ekwugha (2014)

A publication released by the Nigerian National Petroleum Corporation in 2010 highlighted three major causes of oil spillage in Nigeria between 1987 and 2007, as depicted in Table 2.1. These statistics reveal that deliberate sabotage accounts for most of the oil spill incidents, and that it is increasing compared to spills caused by human error or equipment failures.

Year	Equipment Failure	Human Error	Sabotage	Total Oil Spills Recorded
1998	28	12	65	105
1999	19	28	55	102
2000	34	39	40	113
2001	46	15	64	125
2002	39	20	67	126
2003	41	53	63	157
2004	38	32	96	166
2005	49	27	127	203
2006	37	39	187	263
2007	31	29	209	269
Total	362	294	973	1629
Percentage	22.2%	18.1%	59.7%	100%

Table 2.1 Causes of oil spillage in Nigeria from 1998-2007.

Source: Nigerian National Petroleum Corporation (2010)

2.6 Consequences of oil spills in Nigeria

2.6.1 Economic implications

Ajibola et al. (2014) studied the economic losses suffered by the Nigerian economy due to pipeline vandalism between 2000 and 2010 and estimated a revenue loss to maintenance and repairs of pipeline equipment to the tune of \$1.32 billion. Vandalism and sabotage of Nigerian pipelines have led to market volatility and extreme scarcity of the product nationwide (Nwilo & Badejo, 2005; Rim-rukeh, 2015). They are also responsible for the raising of the prices of crude oil in the international market (Le Billon & Cervantes, 2009). Generally, in Nigeria, disruptions of pipelines have led to the scarcity of the refined products (petrol, gas, kerosene and diesel), putting pressure on the prices and making them unaffordable to the common man, especially kerosene which is used for cooking by many people both in the rural and urban areas. Recently, the same has been responsible for the inability of airline companies to scale up their operations in Nigeria due to the scarcity of kerosene in the country. The problem of adulteration of constituent products (like petrol and kerosene) is also a common phenomenon during times of nationwide scarcity (Aprioku, 2003), where the products of such adulteration⁵ are referred to as “Killer fuel” (Anifowose et al., 2012; Ikuabe & Sawyer, 2005).

⁵ It is a common practice in Nigeria to adulterate petroleum products during times of scarcity. The practice generally leads to mechanical failures (Barnett et al., 2011).

During the 2014 fiscal year, the Nigerian government earmarked US \$1 billion to combat oil theft, cleaned the places affected by oil spills, and repaired oil pipeline infrastructure damaged due to vandalism. Following the slump of the prices of crude oil in the international market in 2015, most of the oil companies (i.e. about 116) have reduced their capital budget by almost 24% (in the tune of US \$120 billion) (Odularu, 2008).

2.6.2 Socio-environmental implications

Nigeria was already an agricultural exporting country before the oil boom in the mid-nineteen-seventies. The main exporting crops (cash crops) include cocoa, rubber, palm oil, millet, and groundnut. Joseph Akpokodje and Sheu Salau (2015) reported that the major economic activity of the people in the Niger Delta is basically agriculture with arable land that supports yam, cassava, rubber, plantain, maize, and vegetable crop farming at a subsistence level. The effect of oil spills on such farmlands has given rise to the destruction of crops through spillage and/or fires, often leaving a permanent scar on the environment. Where remediation is possible, it is always accompanied by huge costs (Ajibola et al., 2014). This is further worsened by the high rate of poverty of the people, with poor health and inaccessibility to quality education (Aaron, 2005).

Work by Odoemene (2011) revealed that crude oil spills and exploration activities by the oil companies carried out close to agricultural communities consistently expose the people in those communities to health hazards (UNDP, 2006), contamination of sources of drinking water and destruction of freshwater aquatic species, including fishes and the general ecosystem. Anifowose et al. (2012) studied the effects of oil spills in the Niger Delta of Nigeria with specific reference to socio-environmental factors. Deliberate attacks and vandalism of the pipelines have caused the loss of many lives from fire explosions and the loss of properties worth billions of US dollars close to the pipeline network.

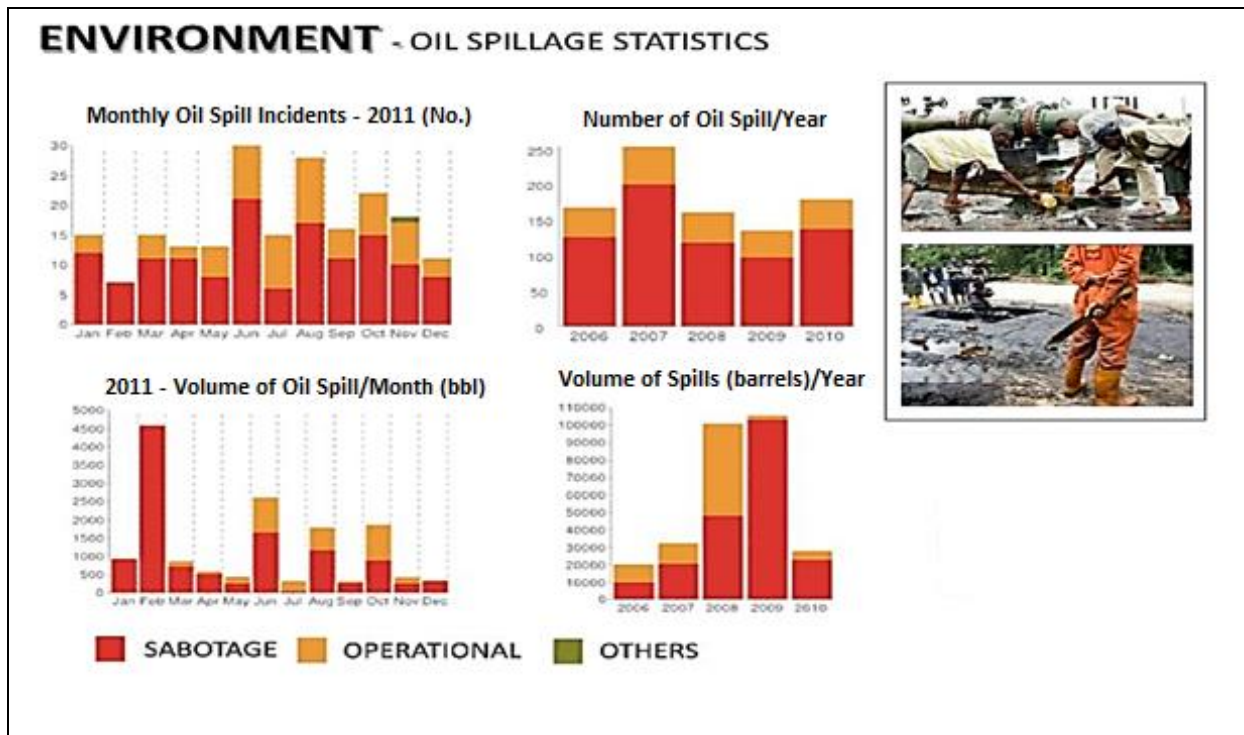


Figure 2.8 Major causes of oil spillage by volume in the Niger Delta.
 Source: Fadojutimi (2012).

Oil exploration and spills in oil-producing areas and along oil-bearing pipelines have exposed communities in these areas to environmental risks such as damage caused to the vegetation, disruption to the biodiversity and oftentimes internal displacement of the rural populace due to the degradation of the environment (Kingston, 2002). The impacts of hydrocarbon spills into the environment affecting vegetation, contaminating water bodies and coastal waters and the entire mangrove and freshwater swamp system in the Niger Delta have been studied by various authors (Allen, 2012; Aaron, 2005; James et al., 2007).



Figure 2.9 Environmental pollution caused by an oil spill in the Niger Delta.
Source: Arts Activism Education Research (2011)



Figure 2.10 Fire explosion caused by an oil spill in the swamp habitat of the Niger Delta.
Source: Taylor (2011)

2.7 The fire culture in Nigeria

The northern part of Nigeria is made up of the Sahel, Sudan, and Guinea savannahs, while the southern part consists of rainforest, freshwater swamps and mangrove ecosystems. Oguntala (1984) reported that the Nigerian savannahs are most susceptible to wildfires during the dry season while the rainforest zones experience bush burning in preparation for agricultural activities (i.e. in preparation for the planting season between January – April, depending on the vegetation belts). A few regional studies on vegetation fires are available (Ogunbadewa, 2015; Soaga et al., 2013; Augustine et al., 2009), but there is no comprehensive documentation of such fire events in the Niger Delta (International Forest News, 2006). In Nigeria, wildland fires rarely occur in the rainforest vegetation belts during the rainy season (Akani et al., 2013; Aweto, 2000), while in the Niger Delta zone, although it is predominantly mangrove swamps, wildfires are a regular

occurrence due to pipeline oil leaks and explosions (Adedoyin, 2004). Generally, during the dry season across the entire country, many cases of fires in the urban areas and commercial complexes are experienced each year ((Oladokun & Emmanuel, 2014), and such fires have attracted the attention of the news media, the Federal Fire Service and the National Emergency Management Agency. The highly dense built area pattern and lack of regulatory enforcement by government agencies to ensure land developers adhere to international ethics and the use of fire alarm and fire suppression systems are among major reasons for such urban fires.

Crude oil exploration and exploitation by the different oil companies in the Niger Delta contribute significantly to global greenhouse gas emissions. It is estimated that 17.2 billion m³ of natural gas is flared in Nigeria per year, and this adversely affects human populations and the ecosystem in proximity to such industrial sites (Aniefiok & Udoh, 2013; Effiong & Etowa, 2012; Ishisone, 2004). Thus, wildland fires from agriculture and bush burning processes, urban fires, industrial flaring and oil spills are among the major sources of fires in Nigeria. The use of data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Terra and Aqua satellites has been suggested as a tool for the monitoring of fire in Nigeria with the ultimate goal of contributing to the global fire inventory (International Forest News, 2006). The only known research effort in Nigeria on this topic examined MODIS data for the detection of fires for different ecosystems and their geographical distribution in Ondo State⁶ (Ogunbadewa, 2015). This study revealed a preponderance of fire cases associated with petroleum-related activities.

⁶ Ondo State is one of the nine states in Nigeria belonging to the Niger Delta. The area is predominantly known for naturally occurring bitumen, a non-flammable hydrocarbon. However, sizeable well heads are present only in one of the nineteen Local Government Areas in the State and spills are not as frequent as in other Niger Delta areas. Hence Ondo State rarely witnesses militant activities directed against oil infrastructure (Tobor, 2016; Ajayi et al., 2008).

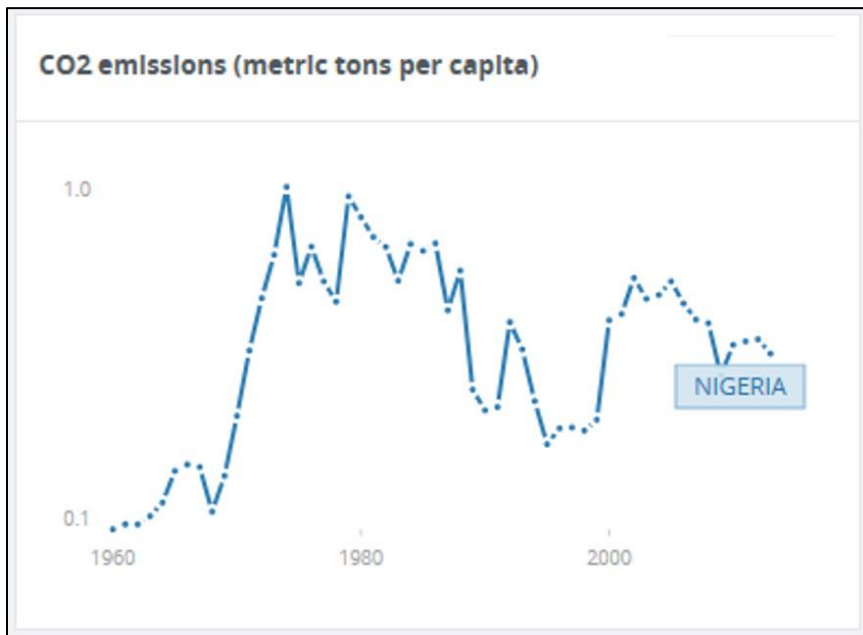


Figure 2.11 The temporal pattern of CO₂ emission in Nigeria from 1960-2013.
Source: World Bank (2017)

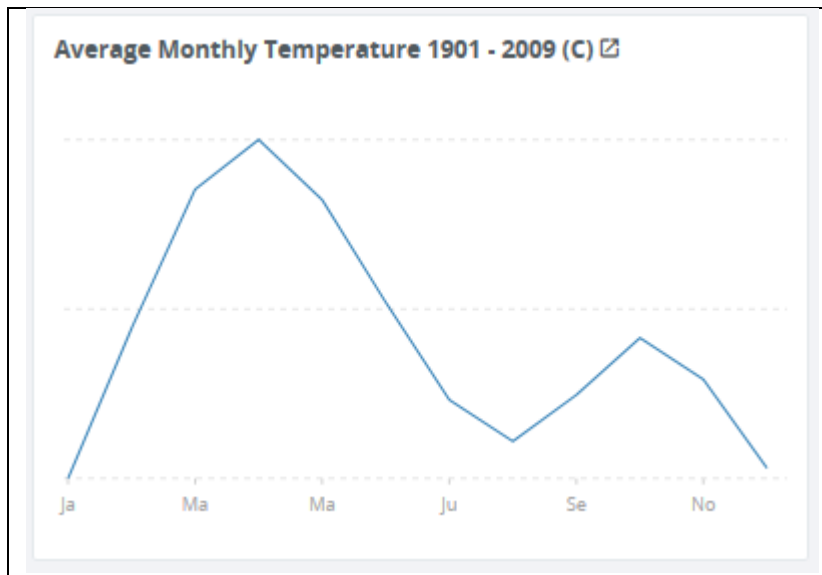


Figure 2.12 The monthly pattern of the average temperature in Nigeria.
Source: World Bank (2017)

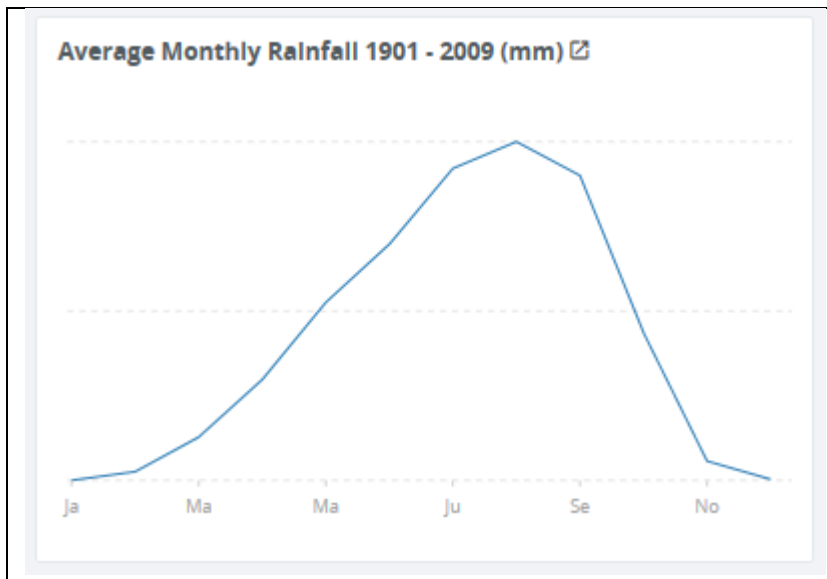


Figure 2.13 The monthly pattern of the average rainfall from in Nigeria from 1901-2009.
Source: World Bank (2017)



Figure 2.14 Gas flares on an offshore facility belonging to Total oil Company.
Source: Taylor (2011)



Figure 2.15 NASA satellite image of the Earth at night. Nigerian oil companies account for the second highest gas flaring by volume globally. The Niger Delta is clearly visible in this image (white arrow). Much of the illumination is produced by gas flaring. Source: Taylor (2011).

2.7.1.1 The cause of pipeline bunkering in the Niger Delta of Nigeria

Pipeline sabotage in the Niger Delta, which plays host to the international oil companies, is explained by Frustration-Aggression-Theory (Dollard et al., 1939). This theory posits that when a source of frustration cannot be challenged, the aggression gets displaced to an alternative target. In this instance, the source of frustration is the lack of development and access to economic benefits of petroleum activities. Communities are unable to address their frustration directly with government and petroleum companies and therefore channel their frustration into acts of aggression against the oil infrastructure.

The expectations of the Niger Delta communities since the discovery of crude oil in 1956 in Oloibiri in the present day Bayelsa State, and subsequently in other Niger Delta States, were to benefit from the oil wealth of the nation, which would mean quality social amenities like a good road system, regular electricity supply, state-of-the-art health facilities and to be gainfully employed by the oil companies (foreign and local) who are taking advantage of their land in oil exploration. Instead, they felt disenfranchised by the Nigerian government in the distribution of benefits of oil wealth to the Nigerian people. Despite pollution of their communities resulting from oil exploration, the government and the oil companies are not passionately motivated for their rehabilitation. Hence, the aggression of these communities towards the oil infrastructure.

Hamilton (2011) found that unemployed Niger Delta youths started illegal refining of crude oil due to the opportunity arising from damaged oil equipment contaminating their environment. These opportunistic acts were subsequently followed by deliberate acts of vandalism to tap oil. Omofonmwan & Odi (2009) suggested that oil spills through sabotage of pipeline equipment will only be comprehensively addressed when the Nigerian government demonstrates its passionate commitment to the protection of lives and properties in the Niger Delta. Anifowose et al. (2012) recommended that one critical way of reducing the frustration and anger of the Niger Delta people is by actively involving them in the oil exploration activities and the downstream oil sector of Nigeria.



Figure 2.16 Pipeline vandalism in the Niger Delta.

Source: Movement for the Emancipation of the Niger Delta (2013)

3 DATA AND THEIR SOURCES

In Chapter 2, we provided a comprehensive overview of the study area of this project, namely the Niger Delta. In this Chapter, we describe the main sources of data for our study and the procedures by which we extracted the subsets of data useful to address the goal of this work. The Chapter is accordingly structured along the following lines. Sections 3.1 & 3.2 describe the oil spill incident reports and the MODIS fire products for the Niger Delta, while Section 3.3 describes the supporting Geographical Information System data layers that we used in this study.

In this regard, the two primary sources of data for the study are:

- (i) oil spill ground data reports from the database of the National Oil Spill Detection and Response Agency (NOSDRA) (see www.oilspillmonitor.ng); and
- (ii) MODIS active fire products obtained from the National Aeronautics and Space Administration (NASA), (see website on <https://firms.modaps.eosdis.nasa.gov/download/>).

3.1 The NOSDRA oil spill database

3.1.1 Detailed description of the data

Cases of oil spill events were recorded in the NOSDRA⁷ oil spill monitor, the official database of oil spills (www.oilspillmonitor.ng) maintained by the National Oil Spill Detection and Response Agency of Nigeria. This is ground data and is referred to in this study as “the NOSDRA data”.

In situ information on oil spill incidents is captured and reported in a process known as a Joint Investigation Visit. The Joint Investigation Visit (JIV) team comprises representatives of the following entities:

- The oil companies, who are the owners of oil infrastructure;
- The affected host community;
- Representatives of relevant enforcement and security agencies;
- The National Oil Spill Detection and Response Agency (NOSDRA);
- The Ministry of the Environment; and
- The Department of Petroleum Resources (DPR).

⁷ NOSDRA is officially responsible to monitor all spill events as they are reported in Nigeria. The majority of oil spill reports are from the Niger Delta area.

During such a visit, the JIV team establishes the cause of a given spill event in a jointly agreed report that contains information such as estimated quantity (volume) of the spill, estimated spill area, the type of habitat where the spill happened, the coordinates of the affected location, and a unique identity number/incident spill number assigned to such spill event. The above information and other key statements are entered by NOSDRA in the spill monitor database. Additionally, observations made by the team are recorded in a joint investigation visit form (see Appendix C). Detailed information captured in the NOSDRA database includes the following:

- (i) Oil spill incident ID/incident number.
- (ii) Status of a spill: the team will make a statement on the status of a spill after the visit. Status of a spill can be one of the following: confirmed, reviewed, invalid and yet to be determined.
- (iii) Zonal office of NOSDRA responsible for a given investigation: Zonal office can be Port Harcourt, Akwa Ibom, Uyo, Warri.
- (iv) Company: the following companies were reported as owners of oil infrastructure in the NOSDRA database: Addax Petroleum, Chevron, MNP Petroleum, Nigerian Agip Oil Company (NAOC), Pipeline and Products Marketing Company (PPMC), which is a subsidiary of Nigerian National Petroleum Corporation (NNPC), Sterling Oil Exploration & Energy Production Company (SEEPCO), Seplat Petroleum Development Company (SEPLAT), Nigerian Petroleum Development Company (NPDC), Niger Delta Petroleum Resources (NDPR), Shell Nigeria Exploration and Production Company (SNEPCO) and Shell Petroleum Development Company (SPDC).
- (v) Incident date: this is the date of oil spill event.
- (vi) Report date: the date when joint investigation team visit was made.
- (vii) Contaminants: contaminants include any of the following: crude oil, gas, condensate, chemical, refined product, and/or other (i.e. Automotive Gas Oil (AGO), Premium Motor Spirit (PMS), Dual Purpose Kerosene (DPK))
- (viii) The estimated quantity of the spill in barrels.
- (ix) Type of facility: this is the oil infrastructure releasing the spill. The following are reported in the database: pipeline, well head, flow line, barge, flow station, trunk line, and/or unknown.
- (x) Spill area habitat: this is the habitat where the spill event occurs. The following are reported in the database: offshore, swamp, land, inland water, seasonal swamp, and/or unknown.
- (xi) Cause of spill: the following causes were documented in the database. Sabotage, equipment failure, corrosion, an operation error, yet to be determined (i.e. the cause of the oil spill is not yet established), and other.
- (xii) Name of oil spill site location.
- (xiii) Coordinates of the spill location.
- (xiv) Local Government Area of the spill location.

- (xv) Estimated spill area.
- (xvi) Description of impact.
- (xvii) State affected by the spill.
- (xviii) Members of the JIV team present during the JIV visit.
- (xix) Clean-up date.
- (xx) Clean-up completed date.
- (xxi) Methods of clean-up.
- (xxii) Post clean-up inspection.

We obtained additional data to substantiate the NOSDRA oil spill reports. Generally, a reported spill event should have JIV (Joint Investigation Visit) form and the site location of the spill occurrence. Unfortunately, not all spill events have a JIV form and spill site location. However, for those events that do, we downloaded the JIV forms, pictures and observations that were taken during the Joint Investigation Visits. It was possible to compare the JIV form and the spill location recorded by NOSDRA and the oil company. In most cases, the oil company has a more detailed description of the JIV form and site location than the information provided by NOSDRA (see <http://www.shell.com.ng/sustainability/environment/oil-spills.html>).

3.1.2 Weaknesses in the NOSDRA database

For this project we analyzed the NOSDRA database for oil spill events recorded between 17th January 2007 and 31st December 2015, making a total of 10 072 events. The NOSDRA oil spill event records are not all complete. Many records were found to be missing one or more of these 22 elements. The missing information included spill coordinates, estimated spill area, the cause of the spill and the spill ID in the database. Missing and inaccurate information in the report of oil spill events in the Niger Delta was attributed to poor information collection, verification, and management practices (Amnesty International, 2013). Additionally, parameters like spill quantities (volumes) and spill areas are based on estimates derived using methodologies that are not always clear or consistent. A report by Amnesty International (2013) noted that many of the JIV forms completed by the JIV team did not include spill volume, spill area, and other key data. The report also shows that explanations were not given regarding the methods used for determining the spill volume. Factors like the area of spill, depth, and porosity of soil are not explained. The interviews conducted by Amnesty International with several people, including NOSDRA's River State Zonal Director, shows that during a JIV, the determination of the volume of a spill is based on a visual estimation of the oil spill area, multiplied by the depth of the spill. On many occasions, a rod is used to gauge the depth of oil. However, an interview with the Managing Director of Shell Petroleum Development Company in London in the Amnesty International report shows that the volume of a spill is relative to the size of the leak point (often a pipeline) and the pressure of flow per unit time. The limitation of these estimated spill volumes is that they provide no information about how oil moves below the soil surface.

Rim-rukeh (2015) conducted a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis for the Joint Investigation Visit process in the Niger Delta. The study summarized the weaknesses of the JIV spill incident reporting process under the following headings:

- Lack of oversight and independence by the JIV investigation team.
- The regulatory bodies lack technical competence.
- The community representative lacks technical competence.
- The oil companies lack transparency.
- Lack of clearly defined technical procedures for investigating the cause of a spill.
- Lack of clearly defined technical procedures for determining the actual volume of the spill.
- Lack of clearly defined technical procedures for assessing damage to the spill area.

By way of determining an independent assessment of the impact of spills as recorded in the JIV process, two spills in Bodo Creek of the Niger Delta, which resulted in extreme damage to the mangrove, land and swamp habitats in 2008, were reviewed by Amnesty International and CHERD using pre-post “spill environmental studies, video footage, and satellite images analyzed by the American Association for the Advancement of Science” (CHERD, 2011). The result of this assessment contrasted significantly with the limited size of the impacted areas reported in the JIV form.

3.1.3 Oil spill incident date

The JIV report form shows that there are two ways of detecting a spill event. A drop in the pressure of the pipeline triggers an alert in the oil company about the start date of the spill, or it can be reported by surveillance contractors who may be members of the host community (Amnesty International, 2013). The NOSDRA database sometimes shows the same spill events with more than one incident date. This suggests that such geographical locations have more than one spill report for a given spill incident. In such cases, we took the spills with greater estimated quantities and higher impacts, since only one location can be represented spatially. Conversely, we also discovered instances of the same entries appearing more than once in the database. Only one of such spill cases was considered. The dates of incidents in the NOSDRA database were not chronologically arranged as the spills occurred but rather as spills were reported. We extracted spill incident reports from the NOSDRA database from 17th of January 2007 to 31st of December 2015, making a total of 10 072 spill events.

3.1.4 Critical factors for consideration during spill database filtering

Since this study focuses on fires resulting from oil spill events, we assume when filtering the oil spill database, that consideration should be given to spill volume, spill area and habitat types

(environment). There are published studies on the subject of oil spill fires and their relation with spill volume, spill size, fire size and heat release (Mealy et al., 2012; Mealy et al., 2014; National Institute of Justice, 2001). However, these studies are indoor experimental investigations involving spill volumes on nonporous/smooth surfaces of spill areas. Mohamadi et al., (2016) studied the impact of 163 of oil spill events on vegetation cover using spill volume ≥ 2 barrel and spill area $\geq 10 \text{ m}^2$ in the Niger Delta of Nigeria. The study shows a vegetation cover loss of 73% of the spill area for 104 of the 163 oil spill events of two barrels or more. This means that as little as 2 barrels of a spill can result in environmental damage when such a spill is close to vegetation.

Spill habitat in the study location includes land, inland water, swamp, seasonal swamp, offshore, nearshore and coastland through which the pipelines run (Ebike et al., 2014). In this research project, we classify habitats into land, swamp, inland water, nearshore, offshore and seasonal swamp.

Oil spill fire events in a densely populated grassland will more likely cause a severe fire scenario than a spill in a water habitat. The method employed by Mckendrick & Mitchell (1978) in their study of effects of burning crude oil spill on six different habitats in the US was used to decide the choice of spill events in this research. Mckendrick & Mitchell (1978) examined the closeness of vegetation to the source of the spill. Their study showed that more fire cases were recorded with vegetation closer to the source of a crude oil spill, with greater impact and longer recovery time (in years) after ignition with as little as 2 ml of crude oil.

We refer to a few illustrative examples drawn from the NOSDRA database. In the study location, one of the spill reports shows that 11 barrels of an oil spill from a well head resulted in an explosion impacting an estimated 2.3 ha of land area (JIV, 2014). The spill case was close to mangrove vegetation in a swamp habitat. In another oil spill fire event, 22 barrels of spill impacted an estimated area of 0.02 ha (JIV, 2015). The extent of the impacted area is significantly low because the spill site is away from any sensitive vegetation. A report by Royal Society of London in 1982 investigated Oyakamo pipeline oil spills with a fire explosion leading to the destruction of an estimated 360 km² of swamp habitat (Julius et al., 2011).

Clearly, the surface area of an oil spill is an important indicator of spill volume and of the extent of environmental damage associated with a spill event. However, more than 97% of the spill incidents recorded in the NOSDRA database do not have values for the oil spill area and/or have zero as the value. Where a direct comparison of the JIV form with the NOSDRA data is possible, the values recorded for spill area in the database are often inconsistent with those on the JIV forms. We present a sample of a JIV form in Appendix C where 70 barrels of spill impacted an estimated spill area of 14.99 hectares, while several cases of spill events with over a thousand barrels of volume are listed (obviously incorrectly!) as impacting zero area. This indicates that the spill area estimates are inconsistent with spill volumes and generally unreliable. For this reason, we excluded spill areas in the NOSDRA data and from our analysis.

Of the twenty-two parameters described in Section 3.1.1 in the NOSDRA database, only the

following three elements were more consistently recorded, and hence were used to filter the 10 072 oil spill events:

- incident spill dates, and
- coordinates (latitude, longitude), and a
- spill volume

We produced a Python code to extract all the spill event records containing data for these three elements. The python code is listed in Appendix A.

When we ran this python code on the 10 072 spill events in the NOSDRA data set, we extracted 4422 events which had values for the spill incident date from 17th January 2007 to 31st December 2015, spill coordinates and spill volume. These 4422 spill events were for the whole of Nigeria. Our next step was to isolate the spill events in the Niger Delta.

Since NOSDRA maintains the database of all the oil spill reports in Nigeria (see Section 3.1.1), we were more interested in the spill events that were within the Niger Delta. We described the Niger Delta area by maximum and minimum latitudes⁸ in NOSDRA database from 7.35975°N to 4.4.0302°N. The northern cutoff was defined by the northern most boundary of the States in the Niger Delta. The southern cutoff was chosen to include spill events recorded offshore in the NOSDRA database.

With this description in mind, the Python code can automate the extraction of all spill events in the Niger Delta area.

Through this filtering process a list of 4357⁹ spill events were extracted from the database, comprising all spill events within the Niger Delta domain which represents the study area. These spill events have complete information about spill coordinates, spill incident dates and spill volume.

We then performed Excel filtering on the Niger Delta spill events (i.e. 4357) to exclude all spill events with less than 100 barrels. We extracted a total of 386 events in this process. This means, of the 10 072 events in the NOSDRA database between 17th January 2007 and 31st December 2015, there were 386 spill cases that are ≥ 100 barrels in volume in the Niger Delta. Keeping the objective of this project in mind, we assumed that large spill events can be detected from space

⁸ A similar filtering in longitude was not required because the shape of the coast line in the Niger Delta area defined the longitudinal extent of the study area, which by definition contained all the data of interest.

⁹ NOTE: Of all the 4422 spill events with complete information of spill coordinates, spill dates and spill volume extracted, 4357 spill events (i.e. 98.5% of all spill events) are within the Niger Delta.

when such spills are attended by a fire scenario. We therefore isolated the cases of spill events with quantities ≥ 100 barrels. The filtering process is depicted schematically in Figure 3.1.

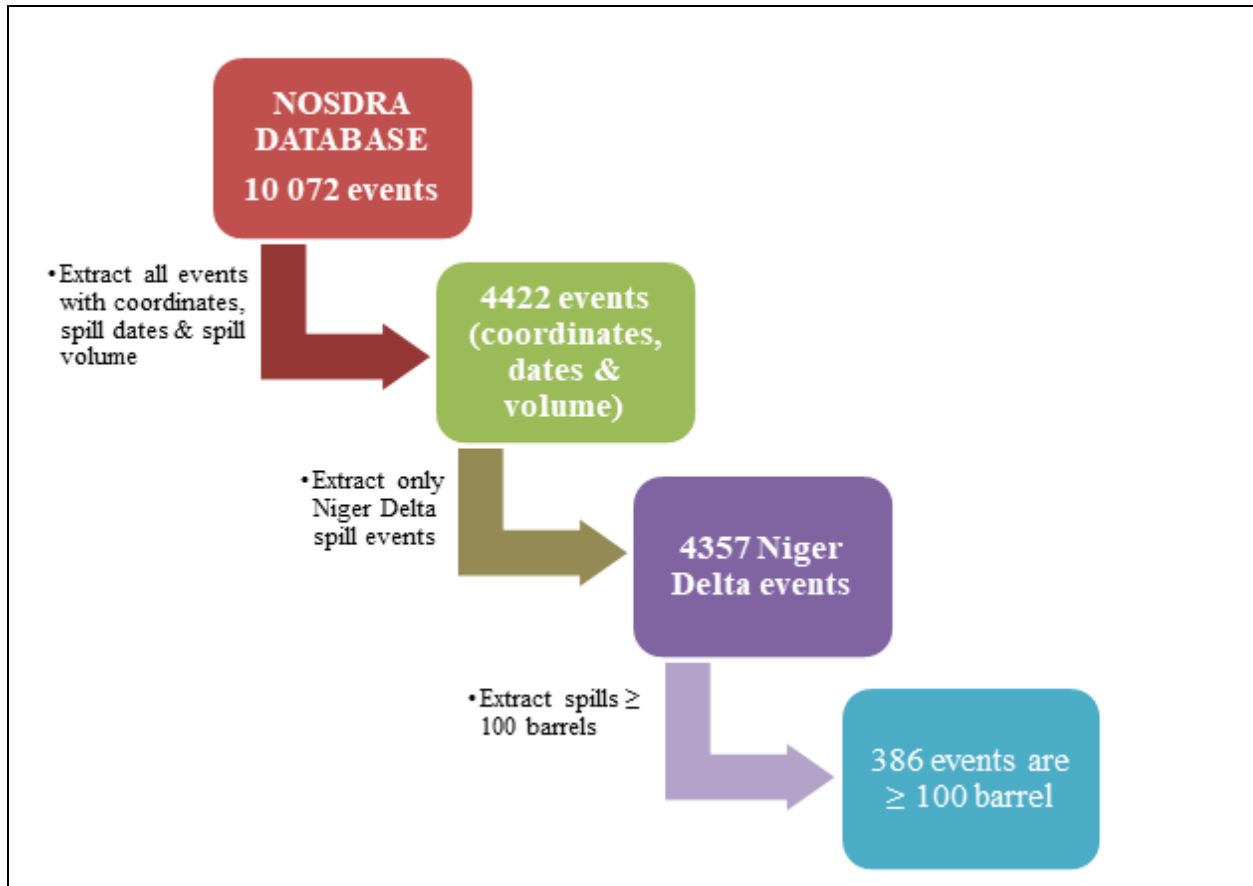


Figure 3.1 Chart showing the filtering process applied to the 10 072 NOSDRA oil spill database (2007- 2015) to identify spills in the Niger Delta ≥ 100 barrels. Filtering steps 1 and 2 of the chart were executed using python while step 3 was accomplished using Excel spreadsheet.

3.1.5 The coordinates of spill locations

Two coordinate reference systems were used to record the geographical locations of the spill events. The locations of almost all the spill events were taken using the World Geodetic System (WGS) reference frame while a few others were taken using the Minna EPSG 4262 reference system. The locations recorded in the Minna EPSG coordinate reference system were changed to WGS 84 coordinates.

For vector and geoprocessing analyses, we projected the default CRS EPSG:4326 – WGS 84 in degree to the nearest UTM zone for Nigeria (i.e. EPSG:32630, WGS 84/UTM zone 30N).

3.2 Satellite data from MODIS fire products

Satellite fire data of the Niger Delta area was obtained from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on the Terra and Aqua satellites. The MODIS instrument on board the Terra satellite detects fires in the morning, while the Aqua satellite detects fires in the afternoon globally (Aulas, 2010; Hall et al., 2002; Hawbaker et al., 2008). MODIS fire products are near-real-time with 250-meter, 500-meter and 1000-meter spatial resolution. The active fire product from MODIS is an initiative of the National Aeronautics and Space Administration, which is used for the Fire Information for Resource Management System (FIRMS).

The acquired MODIS fire data matches the date range of the ground oil spill events in the NOSDRA database (i.e. 2007/01/17 through 2015/01/31). During this period, a total of 85 129 fire events (only in the Niger Delta) were recorded. There are 23 895 Terra events and 61 234 Aqua events in all. MODIS fire products were in shapefiles and text data. The text data contain the location of each fire incident (coordinates), fire acquire date, fire acquire time (time is in UTC), type of satellites (Aqua and/or Terra) and the fire radiative power (FRP).



Figure 3.2 Area of Interest (AOI) of the Niger Delta in Nigeria used for the extraction of MODIS fire data. The Niger Delta of Nigeria drawn as a polygon showing the Area of Interest (AOI). The AOI was created from the global map (see earthdata.nasa.gov/earth-observation-data/near-real-time/firms).

3.2.1 MODIS fire product quality

The MODIS fire products are produced in near-real-time, which is good for identifying active fires and providing spatial and temporal information such that data can be compared between years (NASA, 2017). The MODIS fire database does not provide information about cloud cover, missing data or a unique ID for the fire hotspots, thus affecting the quality of the MODIS fire products. However, the database provides spatial resolutions (250m, 500m and 1000m), and temporal resolution of 1 – 2 days, and availability of data 3 hours after satellite overpass (Justice et al., 2002).

3.3 Pipeline data

In addition to the ground oil spill data from NOSDRA and MODIS fire products from NASA as described earlier, we obtained oil pipeline shapefiles for the study location. The author had trouble accessing Nigerian pipeline data directly from government agencies. However, an independent approach was used to obtain Nigerian pipeline data from Anifowose (2012). A more detailed and comprehensive pipeline description of the pipeline network that shows its distribution within Nigerian districts and across Nigerian boundaries with other West African and Central African countries along the Atlantic ocean was provided by Scott Madry (2016).

Nigerian oil pipelines are buried underground or run above the ground surface, depending on the terrain (Ebike, 2014). Petrou & Gracia (2002) have shown that both buried, and above-surface pipelines can be effectively studied using satellites.

4 DATA ANALYSES

In this Chapter we present the analysis of the oil spill and remote sensing data set that were described in the preceding Chapter. We will seek to establish a relationship between oil spill events, MODIS fire products and the pipeline network as we keep the objective of the research in view. This Chapter is divided into two sections; Section 4.1 describes the analysis of the NOSDRA database while Section 4.2 describes the analysis of MODIS remote sensing fire data products.

In performing spatial analysis for all the data which we described in Chapter 3, we used Quantum Geographical Information System (QGIS) as the main analytical software for all geospatial analyses. QGIS is an open source software with the capability of performing any GIS applications, and is enhanced by a myriad of GIS plugins (<http://www.qgis.org/en/site/>). The QGIS software is available in many languages and offers a flexible GIS platform for diverse users. Additionally, QGIS is written with and supports python scripts, which further enhances its ease of use.

4.1 The NOSDRA oil spill database

4.1.1 Preliminary description of the oil spill database

Using descriptive statistics, we analyzed the NOSDRA database with the aim of obtaining a visual expression of oil spills in the Niger Delta of Nigeria. In Chapter 3 we described the complex nature of the 10 072 oil spill events in the NOSDRA database and the method of filtering the database to identify the 4357 spill events recorded in the Niger Delta with complete date, location and spill volume information. The following preliminary descriptive statistics were generated using the parameters provided in the database to understand oil spill patterns in the study location. In particular, we were interested in:

- (i) The types of oil facilities associated with oil spills (i.e. barges, flowstations, flowlines, floating production storage and offloading (FPSO) facilities, pipelines, trunklines, well heads, and others).
- (ii) The types of habitat associated with oil spills (i.e. inland water, land, near shore, offshore, seasonal swamp, swamp and unknown).

- (iii) The cause(s) of oil spills (i.e. corrosion, equipment failure, operational error, sabotage, yet to be determined (ytd)¹⁰, and others).
- (iv) The type of contaminants (i.e. chemical, condensate, crude oil, gas, refined products and others).
- (v) The relationship between the oil companies who are the owners of the oil facilities and the spill events.

4.1.2 Temporal distribution of oil spill events

We began our analysis of the NOSDRA database by charting the temporal evolution of all the 4357¹¹ Niger Delta events, extracted from the 10 072 records from 2007 to 2015. The result of the analysis is presented in Figure 4.1. The data clearly document the growing occurrence of oil spill incidents in the Niger Delta. Figure 4.2 shows the distribution of spill events for the 386 largest spills extracted from the NOSDRA data. The distribution of the 4357 Niger Delta events is comparable to the filtered 386¹² spill events occurring in the Niger Delta.

The two graphs show a steady increase in the number of oil spill incidents annually in the Niger Delta.

The KML file of these 386 largest spill events is presented in Appendix D.

¹⁰ The cause of the spill has not been ascertained.

¹¹ These are the Niger Delta events with complete information of spill coordinates, spill incident dates and spill volume extracted from the 10 072 spill events in the NOSDRA database.

¹² These 386 spill events are the largest events by volume filtered from the 4357 Niger Delta events. They are spill events with complete information of spill coordinates, spill incident dates and spill volume that are ≥ 100 barrels. They are the Niger Delta events that form the pivot in pursuing the research objective. See Section 3.1.4 for the filtering process.

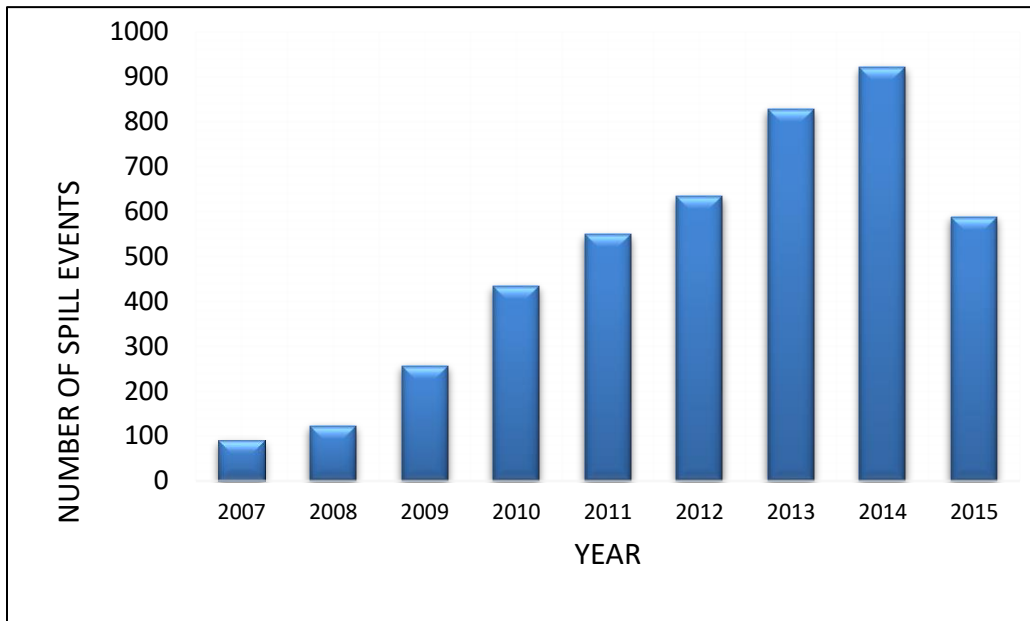


Figure 4.1 The temporal distribution of the 4357 Niger Delta events extracted from the 10 072 records in the NOSDRA database from 2007 – 2015.

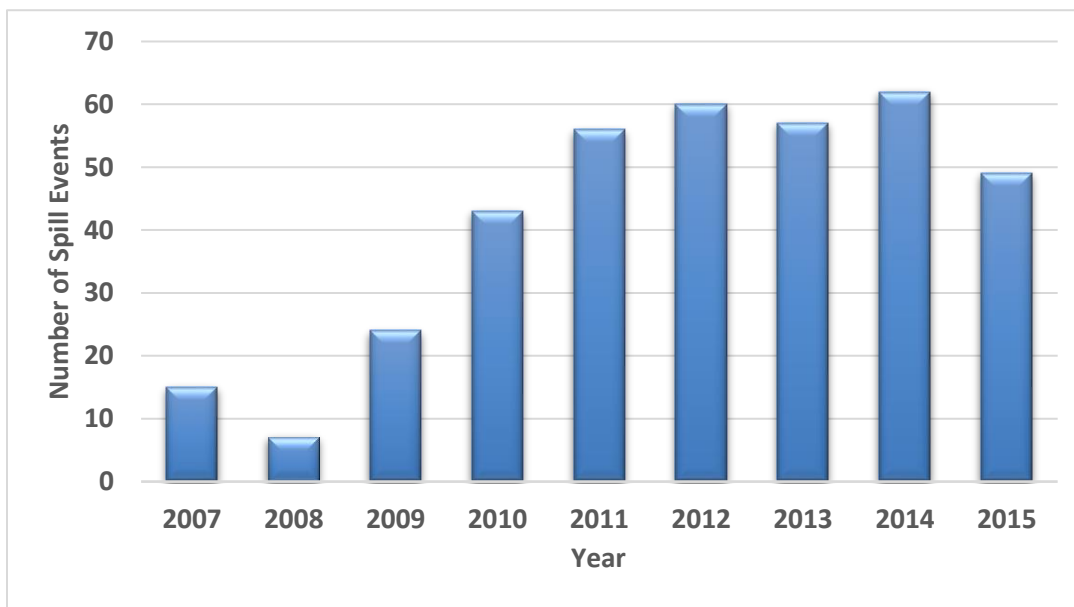


Figure 4.2 The temporal distribution of the 386 largest spill events (≥ 100 barrels) recorded by NOSDRA in the Niger Delta from 2007-2015.

4.1.3 Estimated spill volume versus estimated spill area

As described in Section 3.1.4, 97% of the events in the NOSDRA database do not have values for spill areas. Nonetheless, we modified the python codes to extract all events having numeric values

for spill area and spill volume to be able to establish a correlation between these two variables. There were 1127 observations extracted from 10 072 NOSDRA spill events in the database that contained both spill volumes and spill areas. Many of the extracted values have spill areas of zero. When we filtered out these null values and some obviously incorrect outliers, we arrived at 50 spill events with non-zero spill volumes and areas. When the graph of these 50 observations of spill volume and spill area was plotted, there was no established correlation.

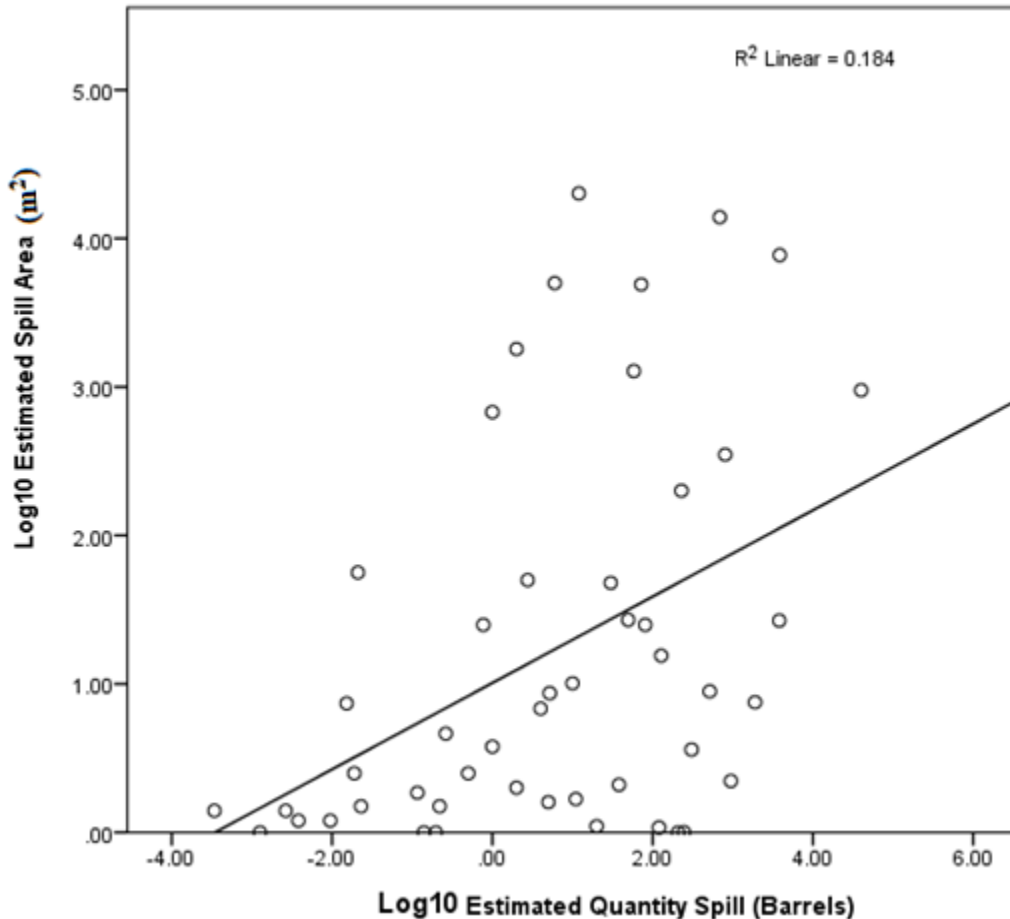


Figure 4.3 Estimated spill area versus spill volume.

From Figure 4.3, it is observed that there is no marked relationship between spill area and spill volume because the data is too bad to show it (i.e. the regression coefficient (R^2) is very low at 18.4%). More than 97% of the entries in the database do not have values or zero value for the spill area. This confirms reviewed work by previous authors who stated that the oil spill reports in the Niger Delta are affected by irregularities and errors (Rim-rukeh, 2015; Amnesty International, 2013; CHERD, 2011).

4.1.4 Spatial plot of the NOSDRA database

For our first spatial analysis of the NOSDRA data, we simply plotted all 4422 events with spill dates, locations and spill volumes using QGIS (Fig 4.4). Spill data in Excel was changed to csv format and projected to QGIS using the WGS coordinate system. The spill layers were plotted on West African oil pipeline layers and the Nigerian political boundary with other West African countries. The plot describes the geospatial distribution of spill events and their spatial pattern in Nigeria (see Figure 4.4).

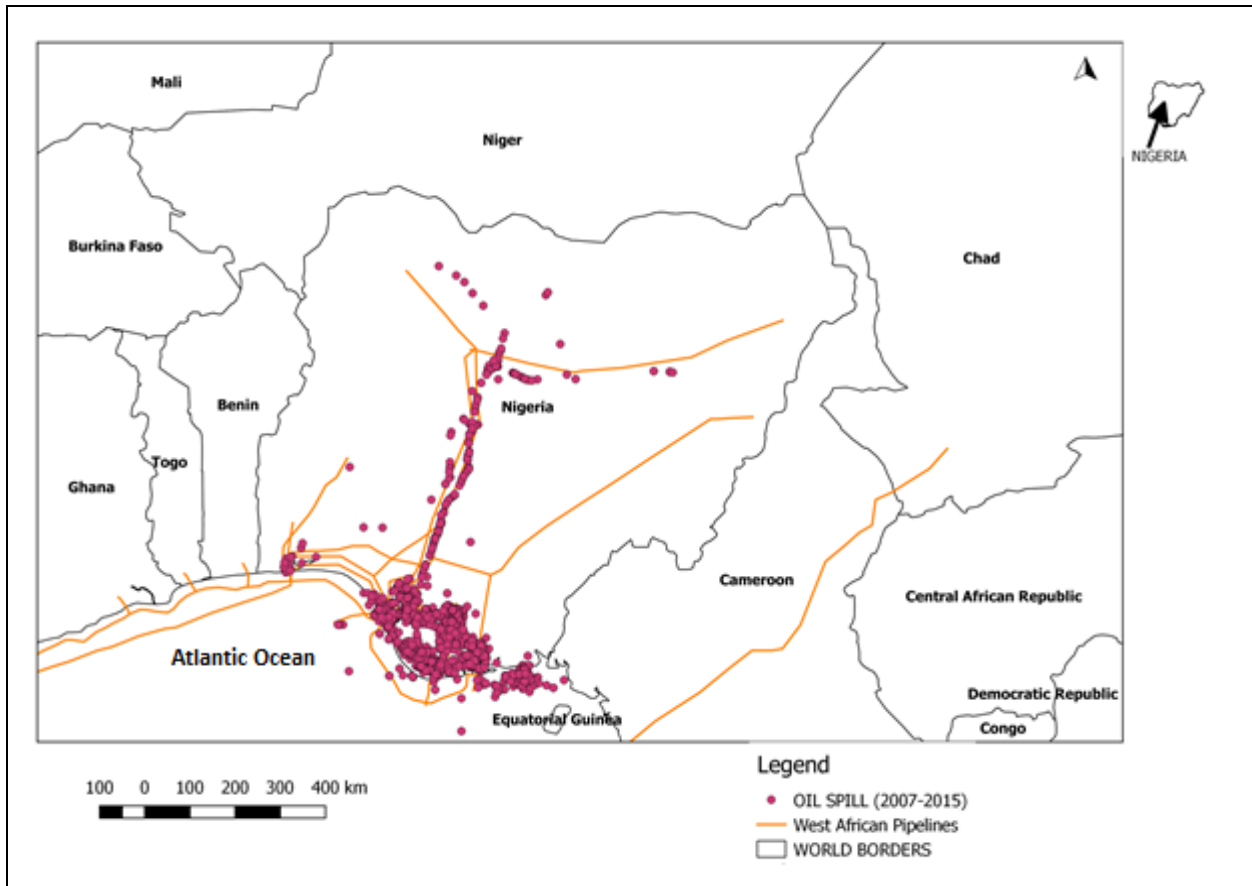


Figure 4.4 The spatial distribution of all 4422 spill events with coordinates, dates and volumes in the NOSDRA database (2007 – 2015).

There are 4422 observations with spill volume, spill dates and coordinates extracted from 10 072 events NOSDRA database. Of these, 4357 spill events were located in the Niger Delta. This implies that only 65 spill events have spill coordinates, spill volume and spill dates, for all non-Niger Delta spills in NOSDRA database. We provide the KML file of the NOSDRA database described in this Section in Appendix D.

Figure 4.4 shows the general locations of spills in Nigeria as they were recorded in NOSDRA database from JIV reports. We overlaid the spills on pipelines to describe their routes along pipeline transport, to observe their locations spatially and to provide reference to the Niger Delta

area, where oil spill activities are prevalent in Nigeria. The Niger Delta is the area with the highest concentration of oil spills and borders the Atlantic Ocean. The pipelines spread out from the Niger Delta to other parts of the country. The pipelines also traverse Nigerian borders to the West and Central African countries. Thus, the Niger Delta is a strategic location where crude oil is distributed to the rest of Nigeria and to other countries.

Fig 4.4 shows that spills extend outside Nigeria's border to the Atlantic through to Cameroun via pipeline routes. Examination of the spills in the Atlantic Ocean shows that they are not GPS coordinate errors, but actual spill events. Studies by several authors indicate that oil spills do happen in the Atlantic Ocean along the Niger Delta. Nwilo & Badejo (2006) recorded 200, 000 barrels of spills in Nigeria from an offshore well in the Atlantic Ocean in January 1980. In the same way, Kadafa (2012) described the occurrences of oil spills as a consequence of oil exploration of the oil companies both onshore and offshore in the Niger Delta. The NOSDRA oil spill monitor described spills in the Atlantic Ocean using the following criteria:

- spill events that were not visited by the JIV
- spill events which could not be quantified (see www.oilspillmonitor.ng for details).

4.1.5 Description of spills in the study location

In this Section, we focus on the 386 spill events with coordinates, date and spill volume ≥ 100 barrels in the Niger Delta. The spatial distribution of spill events in the NOSDRA database (Fig 4.4) confirms that for spills outside the Niger Delta, they are along the pipeline routes in Nigeria. Within the Niger Delta, there is a much higher concentration of spills than in any other parts of Nigeria

As represented by the spill events, the following states experienced the bulk of spill events in the Niger Delta of Nigeria: Abia, Akwa Ibom, Bayelsa, Delta, Cross River, Edo, Imo, Ondo and Rivers. The result of the statistical ranking of the states is provided in Figure 4.6. The plot identifies the states with the largest number of spill events between 2007 – 2015 in the NOSDRA database. The following states show a significant number of spills, Rivers, Bayelsa, Delta and Akwa Ibom when ranked in decreasing order.

The KML file of all the largest events by spill volume described above is provided in the Appendix D.

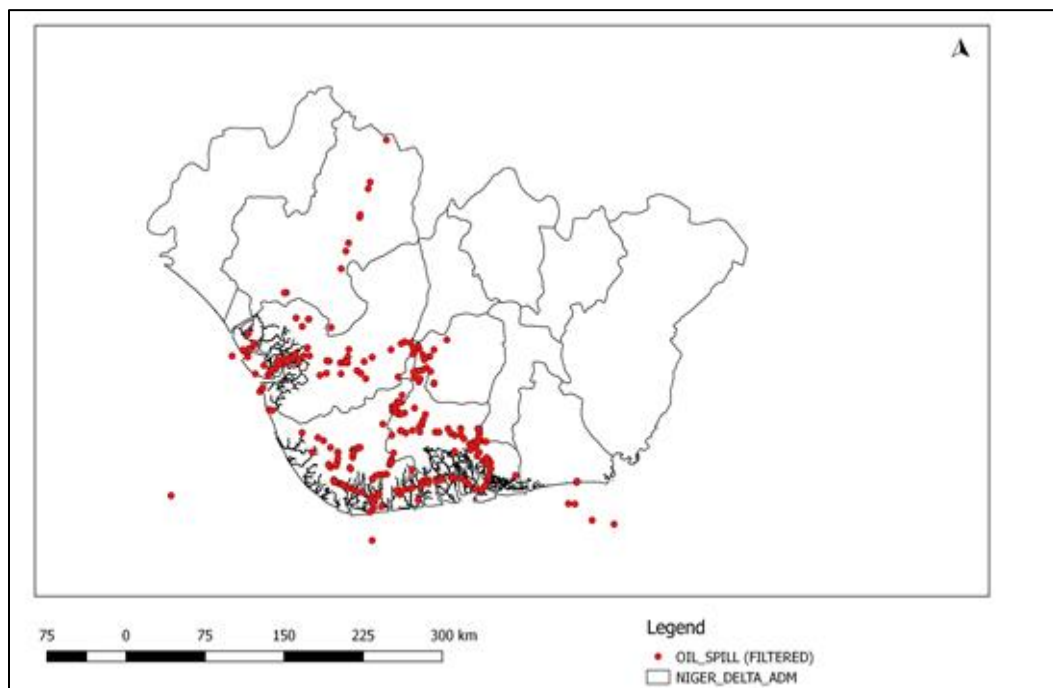


Figure 4.5 The geospatial distribution of largest spill events in the Niger Delta from 2007 – 2015.

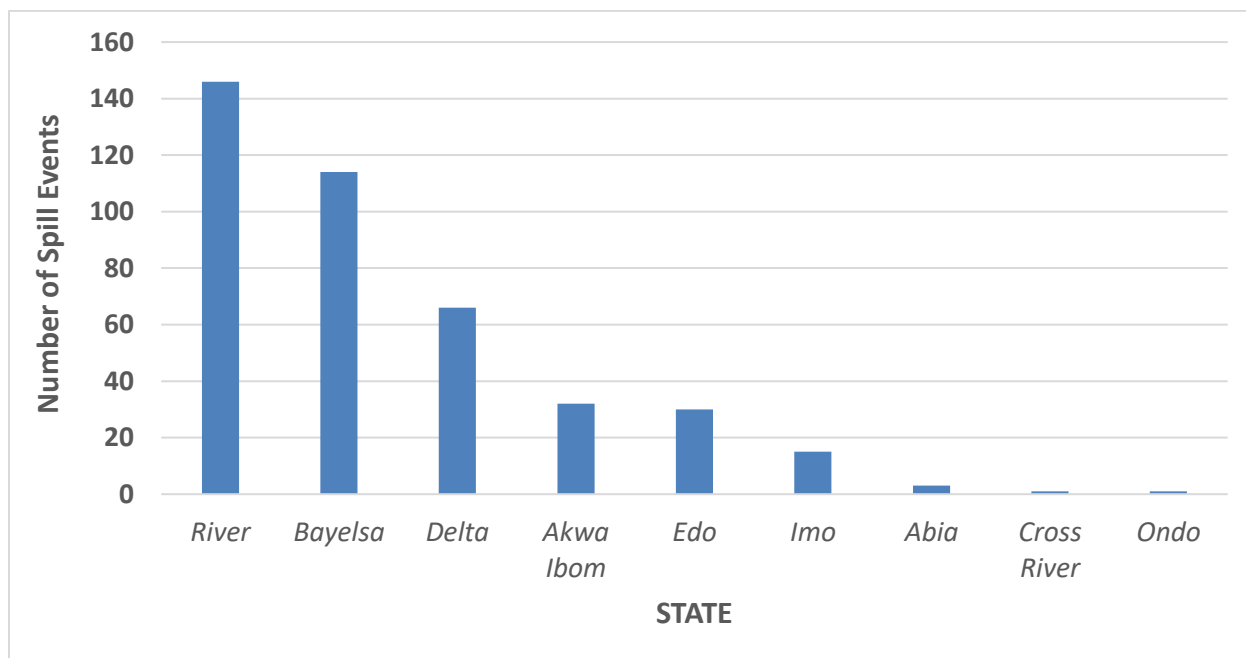


Figure 4.6 Number of oil spill events recorded by states in the Niger Delta.

The knowledge of states with a high occurrence of spills is necessary to increase surveillance and serves as a monitoring mechanism when there is a gradual increase or decrease in oil spill events in the study location.

4.1.5.1 Sources of spill events

In Figure 4.7, we plotted the number of spills against the various oil facilities to provide information on the types of oil equipment which are susceptible to constant spills in the Niger Delta. The following facilities were reported in the NOSDRA database: barge, flowline, FRPO¹³, trunkline, well head and pipeline. However, the NOSDRA records also show parameters like “other” and “unknown.” We queried the NOSDRA officials through email and telephone conversations to provide information about the terms “other” and “unknown” as specified in the database. The officials explained that they only recorded the information provided to them by the task force that visited oil spill sites. They are only the custodians of information provided to them. There were also a few discrepancies noted between the JIV reports and the NOSDRA database. Again, this confirms the earlier findings that oil spill reports in the Niger Delta are flawed with irregularities (Rim-rukeh, 2015).

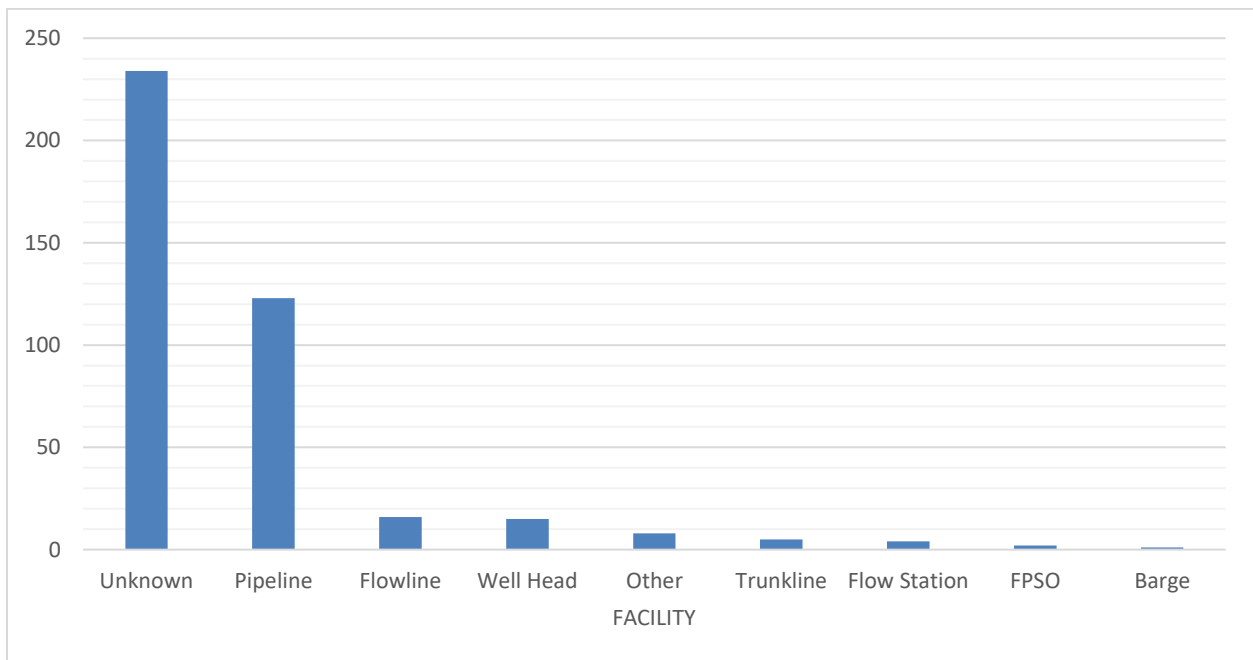


Figure 4.7 The number of spill events associated with different types of oil facilities.

¹³ FRPO means Floating, Production, Storage and Offloading.

Figure 4.7 shows pipeline equipment has the highest incidence of spills, attributed to a given facility. However, it is also noteworthy that, according to NOSDRA database, there were more spill events associated with oil equipment described as “unknown.”

The geospatial distribution of spill locations confirms that the spills are along pipeline routes (see Figure 4.4). The geospatial mapping of the spill events overlaid in Quantum GIS also provided a means of identifying some of the facilities which were marked as “unknown” (see Appendix F for oil spill mapping). However, we did not attempt a systematic reclassification of all the “unknown” facilities as that was outside the scope of the present project.

4.1.5.2 Distribution of spill events by habitat

Since this study focuses on spills that result in fire scenarios, we are therefore concerned about examining the various habitats where spills are prevalent in the Niger Delta. In Section 2.4, we reported that the Niger Delta is criss-crossed with rivers, canals, streams, creeks, and rivulets representing the largest mangrove wetland in Africa and third largest in the world (Oribhabor, 2016).

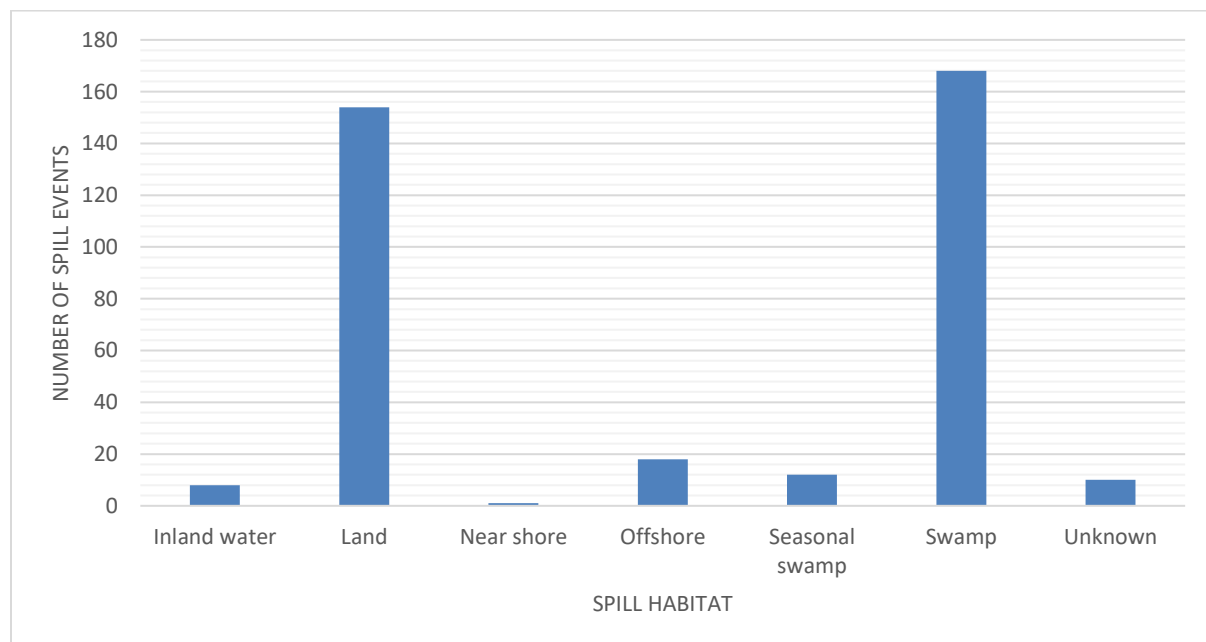


Figure 4.8 The distribution of spill events by habitat.

Figure 4.8 shows that spills are distributed in almost all the different habitat types found in the Niger Delta. Spills are significantly reported in both land and swamp ecosystems. The reports of spills offshore also confirm that the spill events shown in the Atlantic Ocean in Figure 4.4 are not due to an error. In the JIV form (an example of which is provided in Appendix C), the closeness of a spill to a sensitive habitat is an important factor that can lead to serious environmental damage.

An example of such a sensitive habitat is swamp and/or land vegetation, which is an important precursor to a fire scenario in an oil spill explosion.

4.1.5.3 Causes of spill events

The following causes are reportedly responsible for most of the oil spills in the Niger Delta. They are corrosion, equipment failure, operation error, and sabotage. When a spill event is not caused by any of the listed factors, the cause of such a spill is regarded as “other.” However, when the cause of spill could not be established even after JIV’s team visit, such spill event is usually recorded as “yet to be determined.”

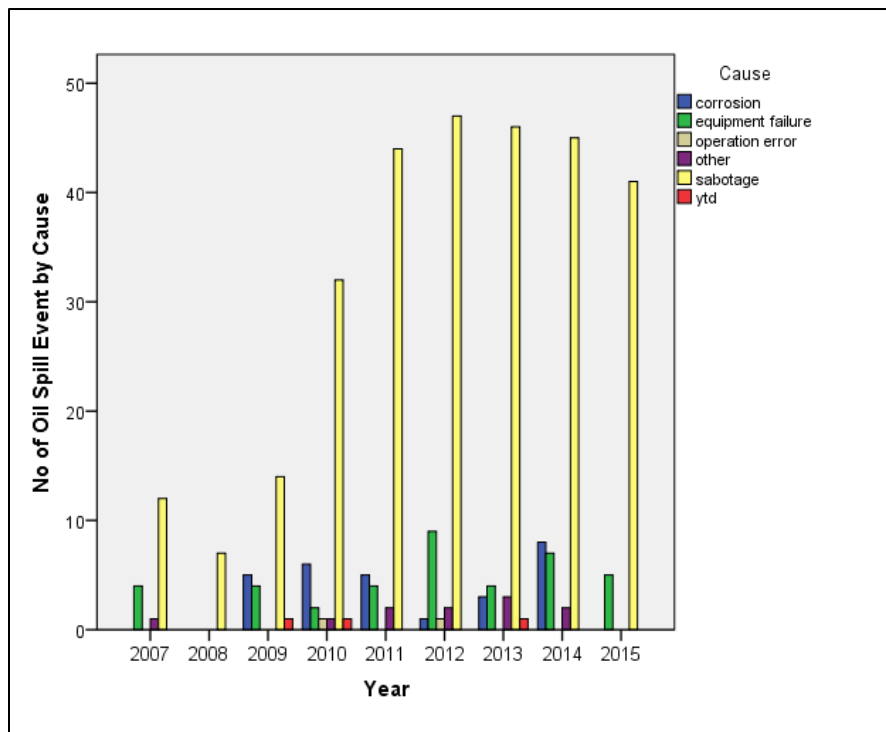


Figure 4.9 The number of spill events per year broken down by their causes.

Figure 4.9 shows the largest 386 oil spill events from 2007 – 2015 expressed by their causes. Sabotage accounts for most of the spills each year in the Niger Delta. The graph also shows a steady increase in spills caused by sabotage from 2007 – 2012.

4.1.5.4 Spill events by contaminants

The oil equipment conveys different products from production sites to target destinations. The following are the different products that are transported by the oil facilities: chemical, condensate, crude oil, gas, refined products (e.g. gasoline, kerosene, diesel, etc.) and others. The spills are always expressed by contaminants due to environmental impacts (Ajibola et al., 2014). Fig 4.10

shows the annual spills (386 largest events) from 2007 - 2015 broken down by the various types of contaminants. Crude oil spill is significant for all cases of spill from 2007 – 2015.

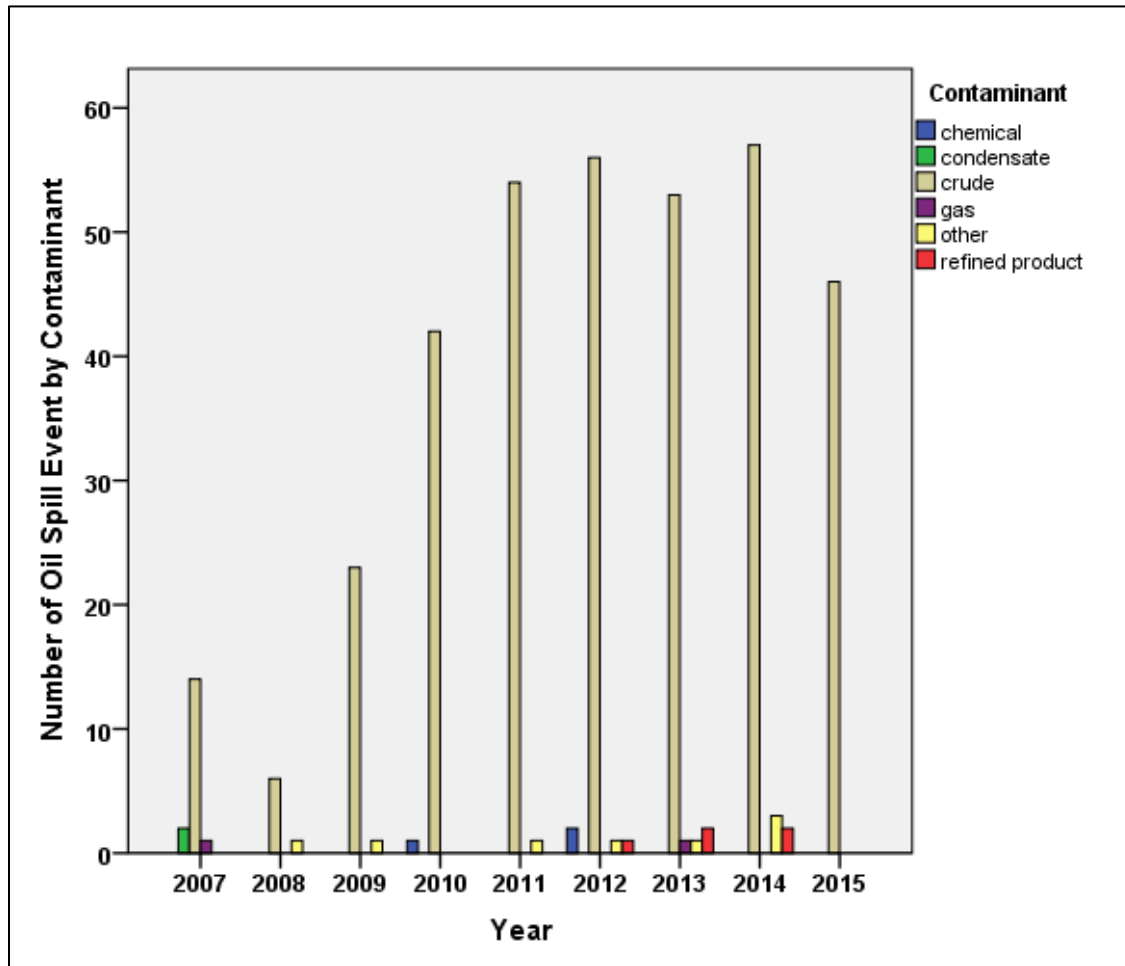


Figure 4.10 Number of spill events per year broken down by contaminants.

4.1.5.5 The spill events experienced by the various oil companies

The spill events, when evaluated by their causes against the oil companies for the years 2007 to 2015, (Figure 4.11) reveals that the Nigerian Agip Oil Companies (NAOC) and Shell Petroleum Development Company (SPDC) experienced a significantly higher number of spills due to sabotage than other oil companies. SPDC was the first licensed foreign oil company and is by far the largest oil company in Nigeria (see www.shell.com.ng).

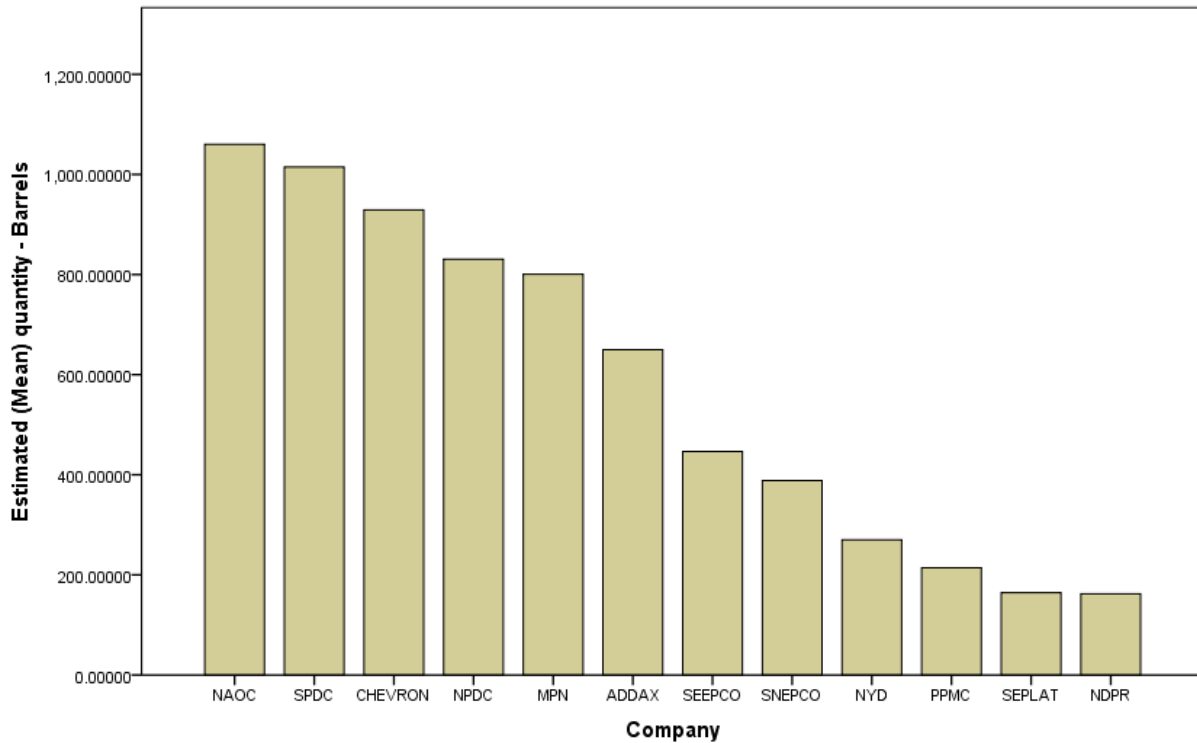


Figure 4.11 Spill volumes from 2007 - 2015 for the various oil companies.

The spill events investigated were those with the highest spill by volume as described in Section 4.1.2 (i.e. 386 extracted spill events). There is no information about the volume of oil production by the oil companies. We only have information about the spill volume. The largest spills by volume in the NOSDRA database are 40 000 and 30260 barrels from Shell Petroleum Development Company (SPDC). In Figure 4.11, we plotted the average spill by volume against each of the oil companies. For these large spill events, Nigerian Agip Oil Company (NAOC) has the largest spill by volume when expressed in the mean.

4.1.5.6 Spill volumes as a function of time

We further investigated the 386 largest spill events in the Niger Delta from 2007 – 2015 to show the temporal evolution of the spills by volume (see Figure 4.12). The relationship compares the number of spill events in the range 100 – 1000 barrels, and those events greater than 1000 barrels. The graph shows that most spill events are below 1000 barrels, with such events reaching peak level between 2011 to 2014. It is worth noting that the two largest spills in the database (i.e. 40 000 barrels and 30 260 barrels) occurred on 2011/12/20 and 2012/06/29 respectively.

The rationale for evaluating the spills by their volume is to address the objective of this research, which we stated earlier (see Section 1.5.1.1). We are probing the source of the Niger Delta fires

which can be detected using MODIS sensor as a possible consequence of the large spills by volume.

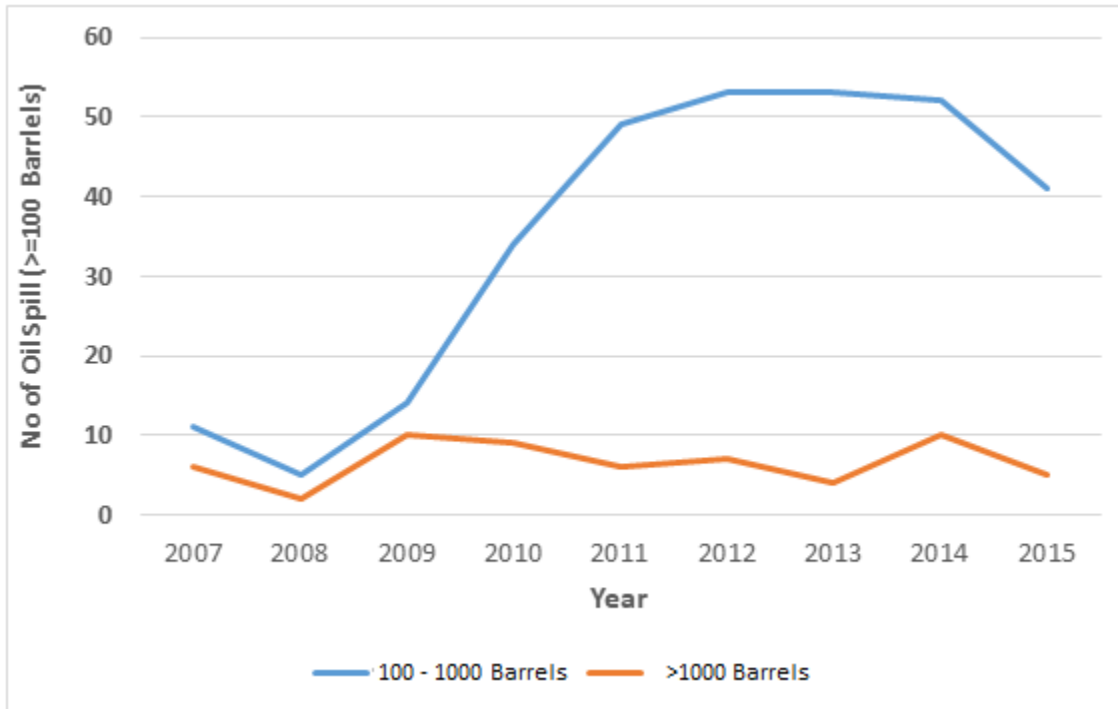


Figure 4.12 Spill events with volumes in the range 100 - 1000 barrels and events with volumes > 1000 barrels from 2007-2015.

4.1.6 The temporal pattern of spill events

We also investigated the temporal pattern on a longer time frame (yearly) and shorter time frame (monthly) to study the general temporal patterns of spills. Earlier in this Section (Figure 4.1 and 4.2), we provided two plots which described:

- (i) all Niger Delta events in the database by their years of occurrence and
- (ii) the largest spill events by volume which are peculiar to the Niger Delta.

These plots described the yearly pattern of spills in the Niger Delta from 2007 to 2015. For both graphs, we observed that spill incidents have been gradually increasing on a yearly basis, and have a similar pattern.

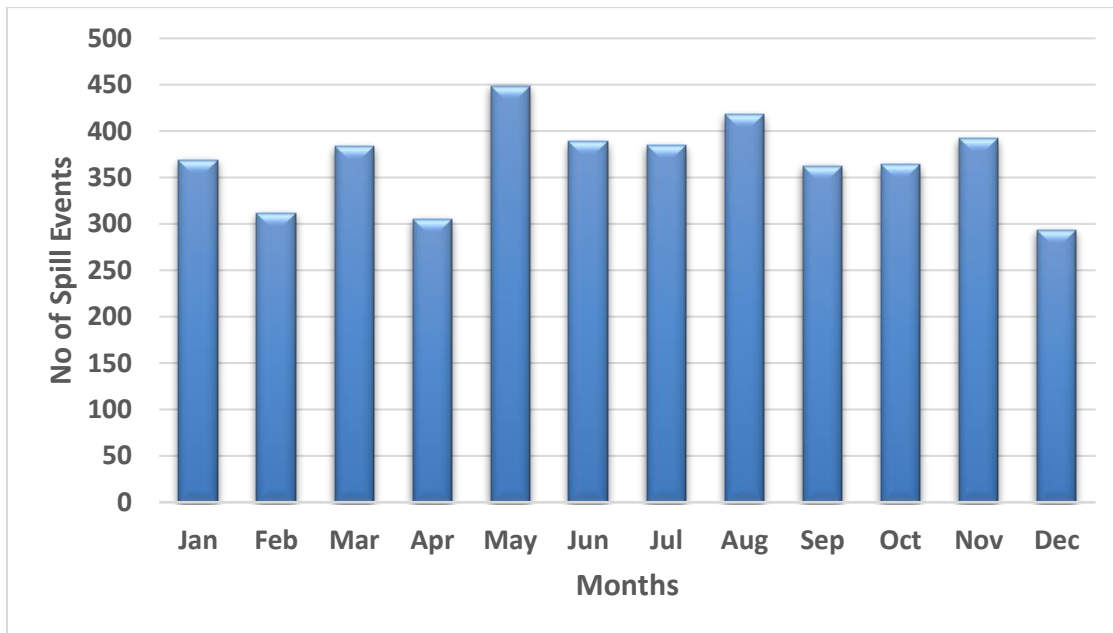


Figure 4.13 Monthly pattern of the 4357 Niger Delta events from 2007 – 2015 as recorded by NOSDRA.

The monthly pattern of the 4357 Niger Delta spill events in the NOSDRA database shows no obvious seasonal fluctuations, suggesting that oil spill events occur with equal probability throughout the year. The yearly pattern has been described in Figure 4.1, which shows a steady increase in the number of spills from 2007 to 2015.

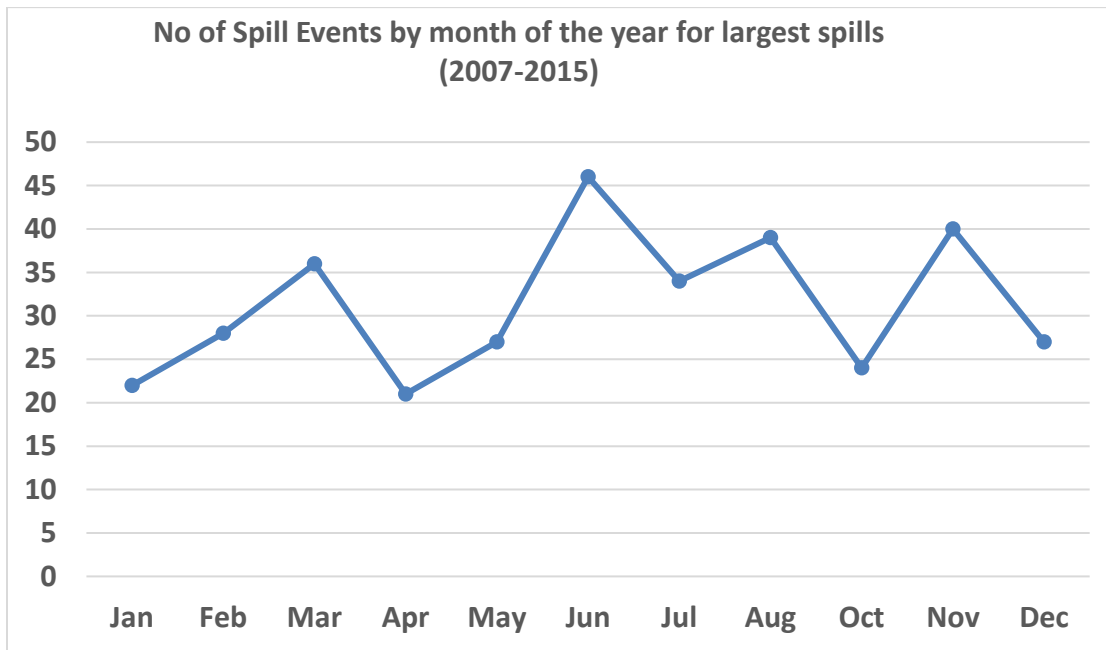


Figure 4.14 Monthly pattern of the largest spills by volume in the Niger Delta.

Figure 4.14 shows the monthly pattern for the 386 largest spills by volume in the Niger Delta. The number of spill cases are higher in June, followed by November. The month of April recorded the lowest number of spill events for largest events by volume in the Niger Delta. The low record of spills in the month of April also holds for Figure 4.13. This indicates that oil spill incidents are generally less common in April.

4.2 The MODIS fire database

In this Section, we present the analysis of the MODIS fire database as it relates to oil spill fires in the study location. The description of MODIS fires and the accompanying parameters are provided in Section 3.2. During the period of January 2007 to December 2015, there were 85 129 MODIS fires recorded in the study area. The spatial plot of the MODIS fire points overlaid on the GIS Niger Delta layer is reported in Figure 4.15.

4.2.1 Extraction of MODIS fires correlated with oil pipeline infrastructure

Unlike the NOSDRA oil spill data, which is by definition correlated with the pipeline infrastructure, MODIS fires are not (see Figure 4.15). Therefore, we devised a method to identify the MODIS fires that were spatially correlated with the pipeline infrastructure.

We projected the MODIS fire layers in csv format to Quantum GIS using the WGS coordinate system. MODIS fire points were overlaid on a GIS pipeline layer to observe the spatial correlation between fires and pipelines (see Panel A in Figure 4.17).

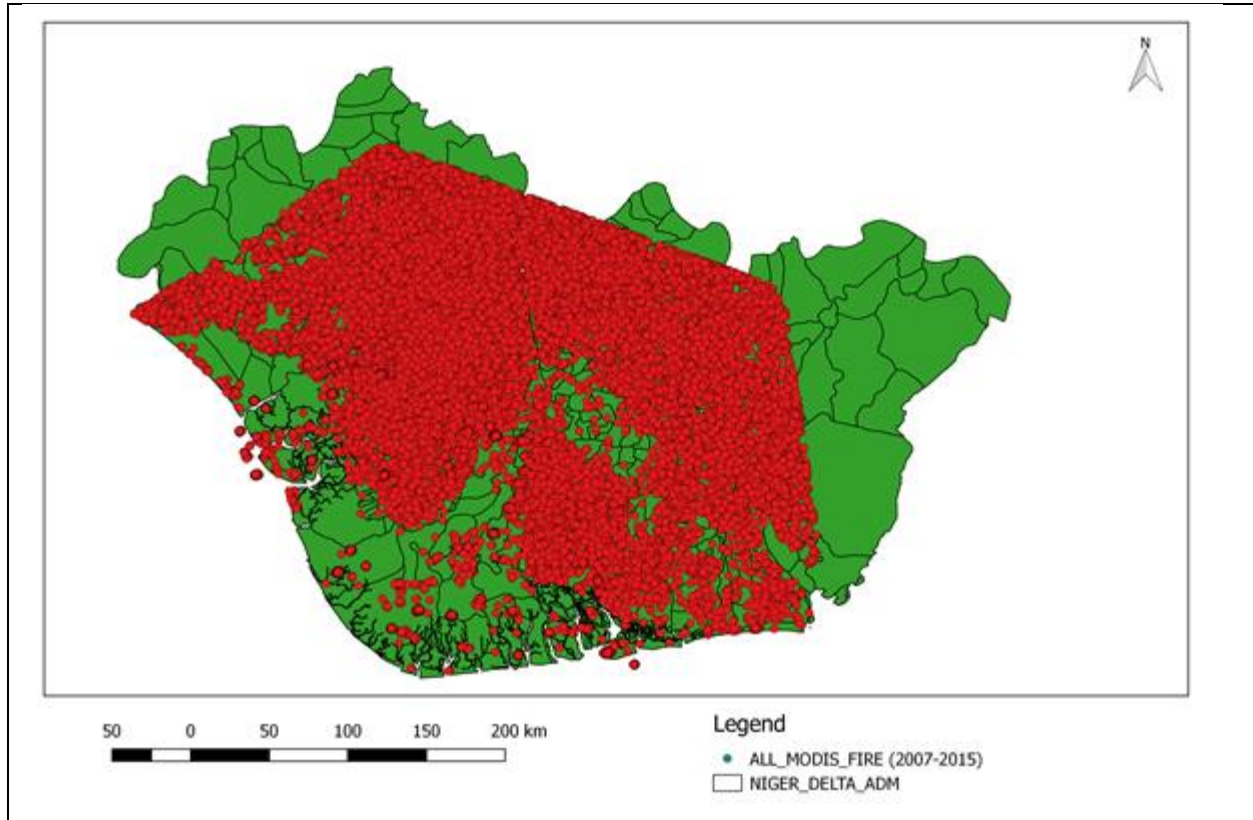


Figure 4.15 Spatial plot of all 85 129 MODIS fire points in the study area.

To describe MODIS fire locations with respect to the pipelines, we used the NNJoin plugin in Quantum GIS to join the nearest fire locations to the pipeline network spatially. Joining fire locations and the pipeline network spatially requires vector analysis, hence the two ‘spatial neighbours’ to be joined must be vector layers and the distance between them must be in meters. Therefore, we projected the default Coordinate Reference System (CRS) EPSG:4326 – WGS84’ (i.e. in degrees) to meter-based UTM coordinates. We used the nearest UTM zone for Nigeria (i.e. EPSG:32630 – WGS 84/UTM zone 30N).

We changed the newly projected WGS 84/UTM to shapefile formats (.shp). In this way, we expressed the MODIS fire locations and pipeline infrastructures in vector formats and the distances between them in meters.

In Section 2.3 we described the ROW in oil pipeline management. For safety reasons, the ROW in an oil pipeline does not allow infringement, and hence a 30-meter distance is allotted to both

sides of the pipeline. In Section 2.6.2, we reviewed the significant impact of spill events on the environment, often causing harm to the surrounding ecosystem, and resulting in the displacement of host communities close to spill locations. Infringement in oil pipeline ROW therefore often results in environmental impact well beyond the 30-meter strip of land in the ROW management. With this in mind, we will consider all MODIS fire locations with 1000 m of the pipeline network as oil pipeline fires.

The method of oil pipeline fire extraction from the 85 129 MODIS fire locations includes the following procedures:

- We described the pipeline network of the Niger Delta area in the attribute table of QGIS
- The following names represent the pipeline network in the Niger Delta
 - (i) Port Harcourt oil pipeline, Bonny to Auchi products pipeline
 - (ii) Ilorin to warm products pipeline, Kaduna to wam products pipeline
 - (iii) Yola to Enugu products pipeline
 - (iv) West Africa gas pipeline, coastal and
 - (v) West Africa gas pipeline, inland

Note: The above-named pipelines are situated in the Niger Delta from where they transport crude oil and other contents to other parts of Nigeria and countries outside Nigeria (see Figure 4.4).

Using the ‘conditional formatting’ feature of QGIS (in the attribute table), we described those pipeline attributes without names (i.e. blank columns) as A, B, D and E.

To extract the MODIS fires close to pipelines, we used the following procedure in QGIS:

- Open the processing interface of NNJoin plugin.
- Select ‘MODIS fire layer’ as input vector layer: the geometry type is described as ‘Point.’
- Select ‘Pipeline layer’ as Join vector layer: the geometry type is described as ‘LineString.’
- We run the algorithm by clicking the ‘OK’ button.
- This produces an output containing new attributes which describe the joint layer of MODIS fire by distance to the nearest pipeline.
- Import the output layers as csv data into Excel.
- Use Excel to extract all MODIS fires within 1000 m distance to the nearest pipeline neighbours by sorting on the distance between the fires and pipelines.

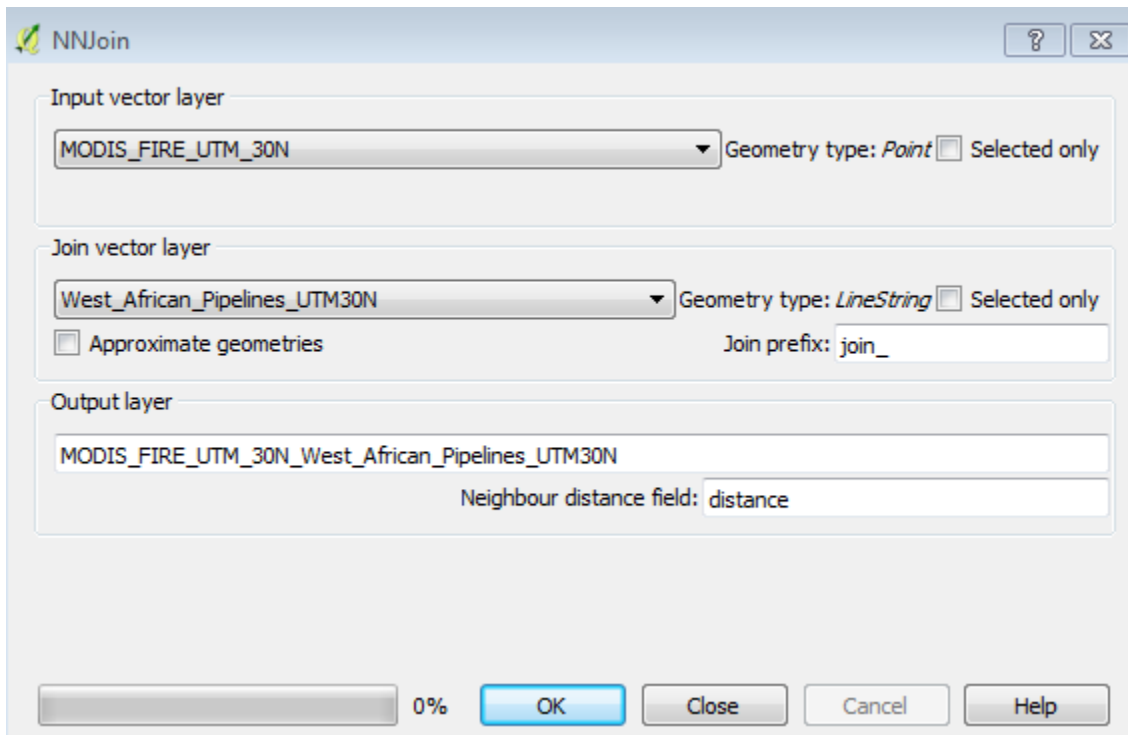


Figure 4.16 QGIS NNJoin plugin interface showing the oil pipeline extraction process.

Figure 4.17 shows the result of spatial vector analysis between MODIS fire locations in UTM 30N (.shp) and the West African pipeline network.

Panel (A) shows the West African Pipeline network overlaid with 85 129 MODIS fires in the study area. Panel (B) shows the extracted MODIS fires within 1000 m of this pipeline network. NNJoin automatically assigned a named distance in meters to each fire point and a named pipeline layer line to generate an output layer which we can rank by distance in Excel to find all fires within 1000 m of the pipeline infrastructure. Thus, we obtained 2192 MODIS fires from a total of 85 129 MODIS fire database that were automatically assigned a named distance to each nearest pipeline.

The KML file of these MODIS fires associated with pipelines is presented in the Appendix D.

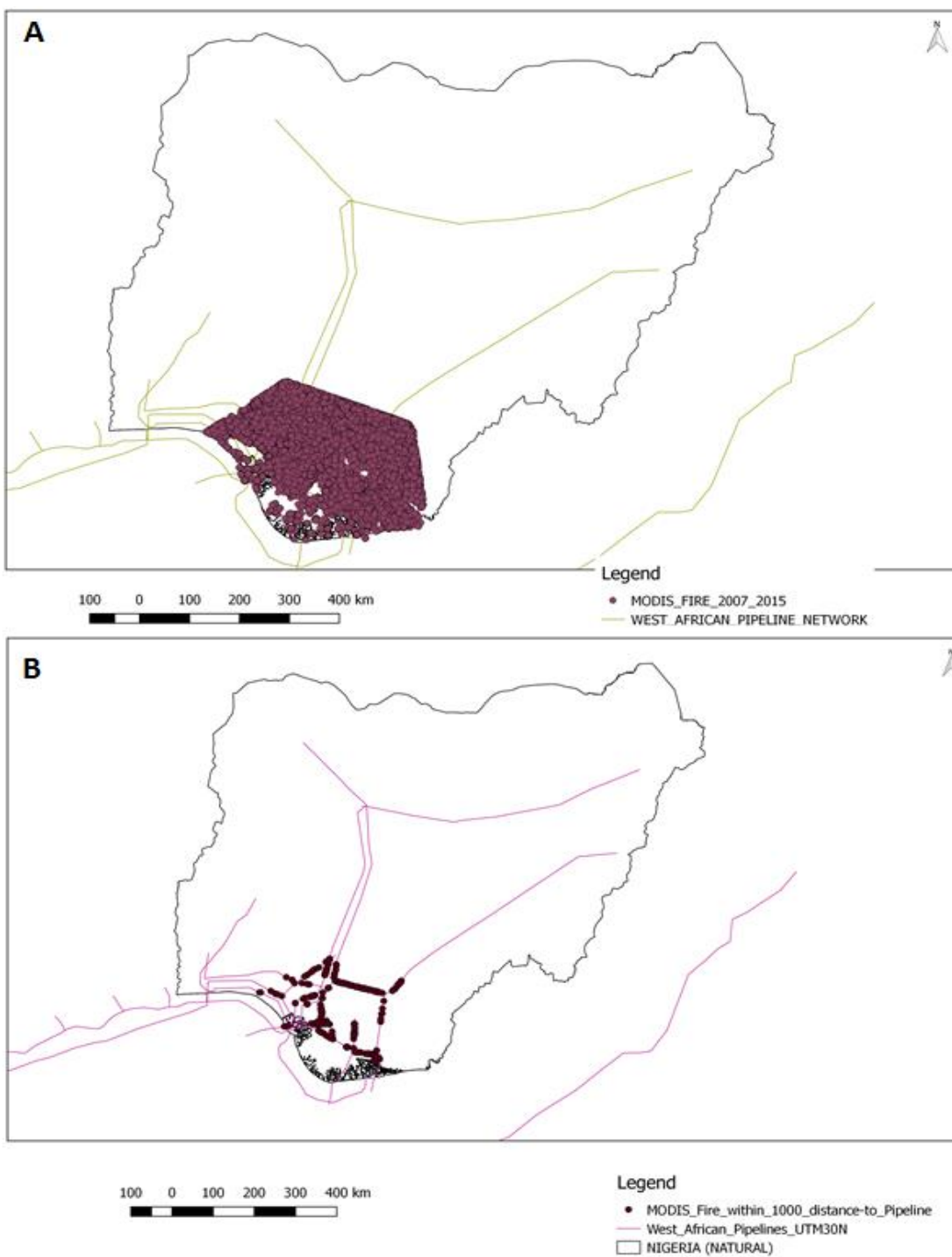


Figure 4.17 Oil pipeline fire extraction from the MODIS fire database. Panel (A) shows all 85 129 MODIS fires in the study area. Panel (B) shows the 2192 MODIS fires that occurred within 1000 m of the pipeline infrastructure.

4.2.2 Extraction of industrial, agricultural, ocean and domestic (built) fires from the MODIS fire database

Although the focus of this study is oil pipeline fires, the sheer number of MODIS fires in the study area is intriguing and it is instructive to classify these fires according to their locations and/or causes.

Due to the very large number of fires recorded by MODIS, we defined fire layers and Niger Delta locations using the vector geoprocessing tools of QGIS to classify the main fires in the study area. As described in Section 4.2.1 for the oil pipeline extraction process, the MODIS fire layers and Niger Delta oil spill locations' latitude-longitude coordinate systems were changed to a meter based (i.e. EPSG:32630 – WGS 84/UTM zone 30N) coordinate system.

Two major steps allow MODIS fires to be classified according to their districts in the Niger Delta. The rationale for this is to investigate the spatial distribution of the MODIS fire layers, and their evolutions in the study area.

- (i) The vector geoprocessing algorithm of Quantum GIS allowed the intersection of MODIS fire layers and Niger Delta districts to produce a new set of geodatabases. Each new geodatabase is a vector file which describes the intersected Niger Delta districts with MODIS fires.
- (ii) The vector analytical algorithm of the Quantum GIS allowed the intersected locations of the Niger Delta as polygons to assign every MODIS fire into each polygon (i.e. district of the Niger Delta). We obtained a new geodatabase describing each polygon¹⁴with a specific count of MODIS fires.

We classified MODIS fires in the polygons using the Graduated style with a natural break. The fires classified by the district provide information about their sources when zoomed in on the Google satellite image (i.e. open layer plugin) on the QGIS interface.

We generated a list of MODIS fires in each district from industrial sites, domestic (built) and agricultural fields. In an Excel spreadsheet, we extracted fires with similar coordinates from MODIS fire database using VLOOPUP function. The KML files of these fires were then examined on Google Earth. We examined the temporal trend of the fires to see if they have histories (i.e. history of fire image) with Google Earth's time slider.

¹⁴ We refer to the polygons as the administrative districts.

The features of the fires that were classified in this project are in line with the few published works available on the different fire sources in the Niger Delta.

(i) Agriculture or bush burning activities

- Such fires are from land clearing and bush burning activities in preparation for the planting season. Aweto (2000) described agricultural fires as a type of fire arising from land preparations for planting season, while Joseph Akpokodje & Sheu Salau (2015) described such fires as having limited impact when compared with fires from oil sources.
- Such fires are usually accompanied by very mild vegetation burnt leaving very insignificant scars.
- Such fires rarely have histories when viewed using the Google Earth Pro time slider. When they do have histories, they usually occur within the same period of January and March (historical images are similar).

(ii) Domestic (built) fires

- The most notable feature is that such fires are within the built areas. These fires are easily recognized since they are within the populated areas. Oladokun & Emmanuel (2014) reported that built area fires from markets, rural and urban settlements are very common in Nigeria, especially during the dry season.

(iii) Industrial Flaring

- Fires from industrial areas. Most of the industrial satellite images observed were from the oil companies. Ekeinde (2010) reported that most of the oil companies in Nigeria are situated in the Niger Delta, while Hassan & Kouhy (2013) stated that the constant gaseous emissions in this region arise from gas flaring by the oil companies.
- Such fires are consistent and have historical imagery on Google Earth's time slider.

We present the historical images of such fires from the Google Earth's time slider in Appendix I.

(iv) Ocean fires

- Fires situated in the ocean. These are fires in the Atlantic Ocean.

(v) Oil pipeline fires.

- Such fires are situated close to pipelines and result in significant vegetation burnt. Paraskova (2016) reported that the major source of fires that penetrate different habitats in the Niger Delta, all year-round, is through oil spill explosions from the oil facilities. See Figure 4.17 for extraction of MODIS fires associated with oil pipelines.

Examples of fires that have historical images when viewed on the Google time sliders are provided in Appendix I.

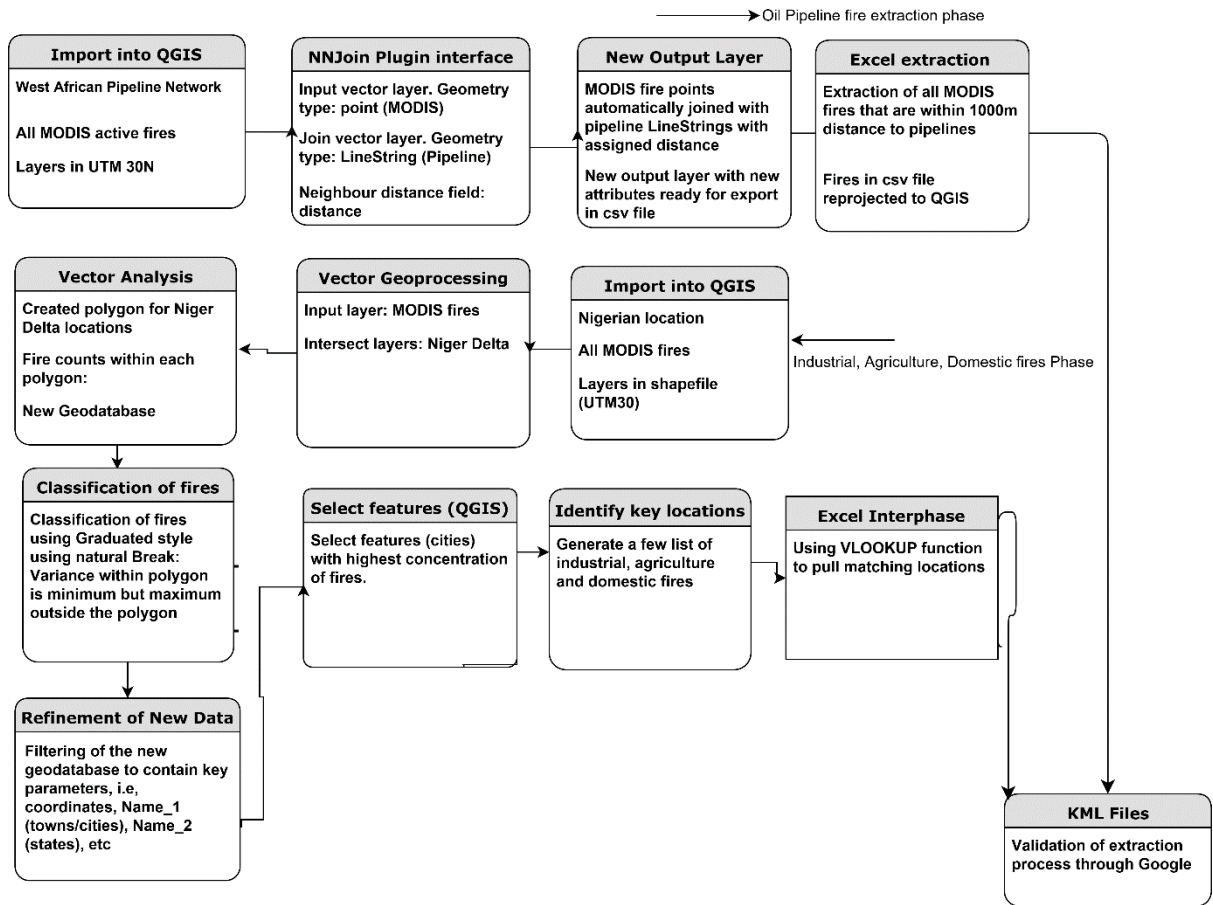


Figure 4.18 Process flow diagram for oil pipeline fire and non-oil pipeline fire extraction from the MODIS database (2007- 2015).

Figures 4.19 and 4.20 present the GIS analysis of the fire extraction sequence which we discussed earlier in this section. The result of the extraction of MODIS fire points intersecting with Niger Delta locations shows that out of a total 85 129 MODIS fires, 68 924 intersected with Niger Delta locations¹⁵. Each vector layer contains a MODIS fire point and Niger Delta locations where they intersect. Figure 4.18 describes the flow chart process for both oil and non-oil pipeline fires which we described in Sections 4.2.1 and 4.2.2 respectively.

¹⁵ The non Niger Delta political districts add up to 16 205 fires which were excluded in our analysis.

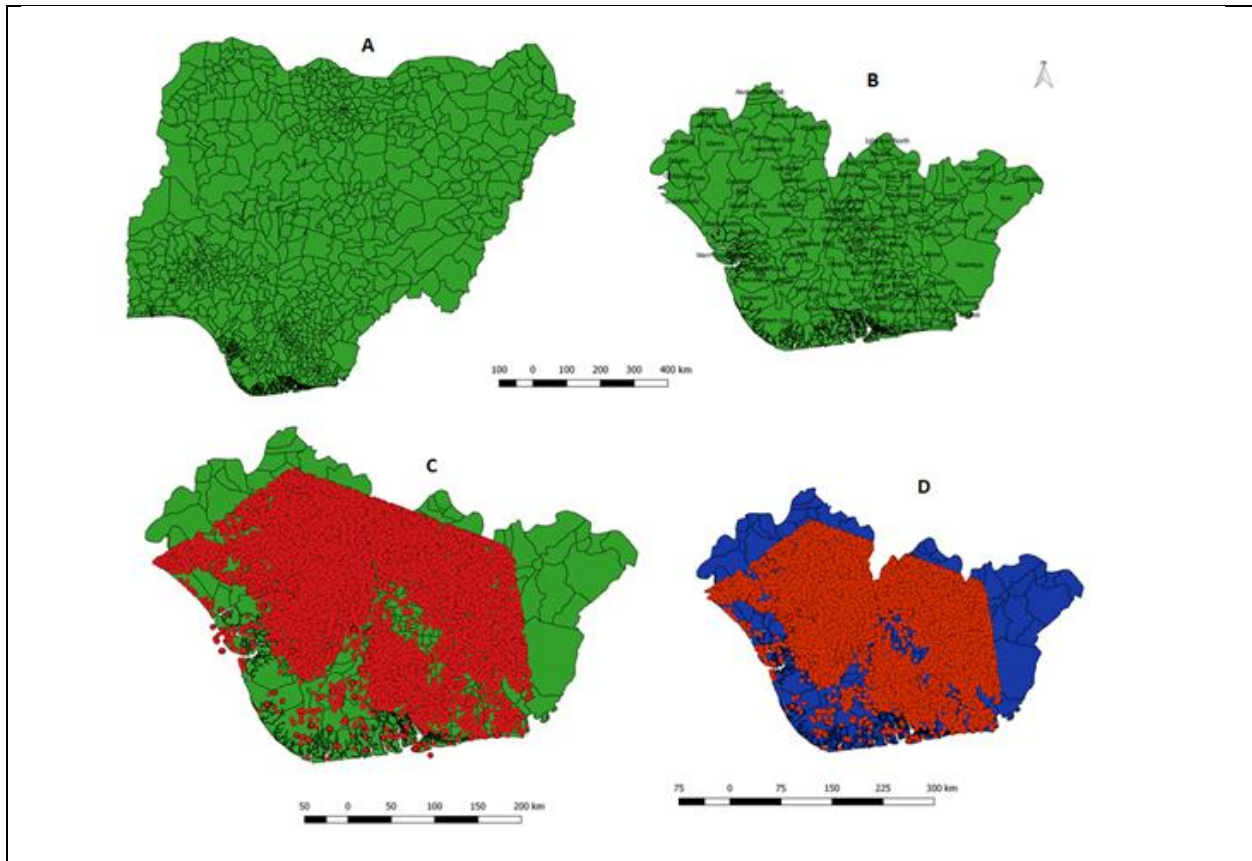


Figure 4.19 The extraction process of the non-oil pipeline fires from the MODIS fire database in QGIS. (A) Map shows Nigerian locations “Name_1” (states) and “Name_2” (towns, cities and local government). (B) The preliminary filtering to define the area of interest. (C) MODIS fires in .shp and UTM 30N and Niger Delta in .shp and UTM 30N. (D) Extracting only MODIS fires that intersected with Niger Delta locations.

Figure 4.19 describes the beginning of the extraction process for the non-oil pipeline fires (industrial, agriculture and domestic) from the MODIS fire database.

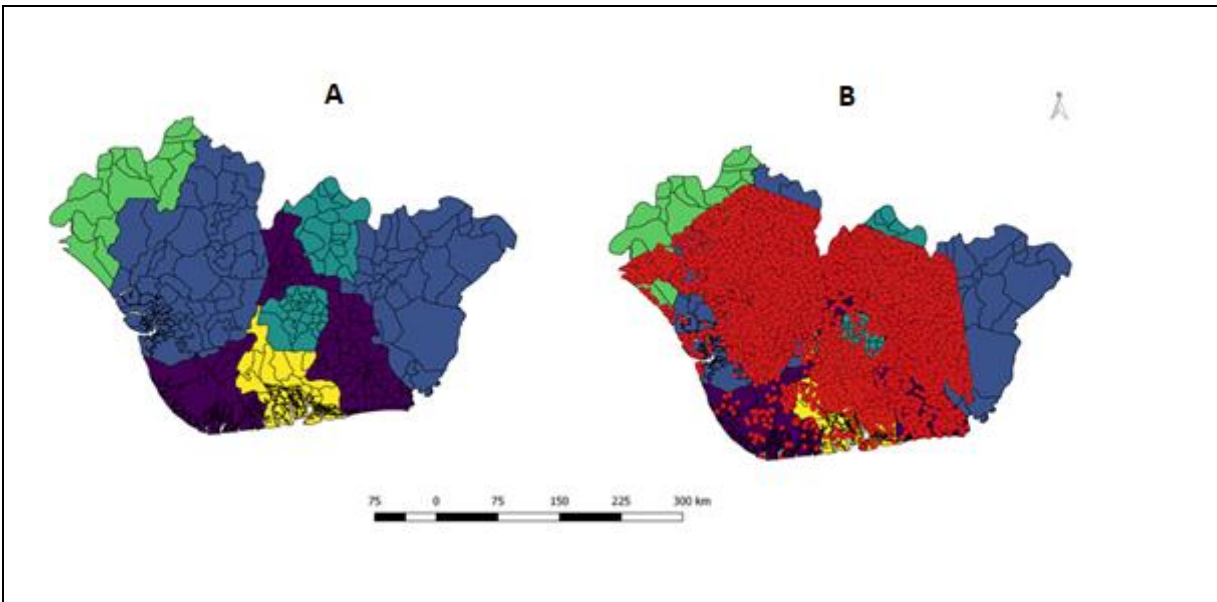


Figure 4.20 Distribution of MODIS fires according to Niger Delta districts.

Figure 4.20 describes the distribution of MODIS fires within each polygon. (A) There were 185 polygons (administrative districts) in the Niger Delta. (B) MODIS fires overlaid on the Niger Delta districts. We present the chart flow of the filtering process of the MODIS fire products from 2007-2015 in Figure 4.21.

S/N	NAME_1 (States)	NAME_2 (Town, Cities) [Polygon]	Fire Counts
1	Edo	Esan South-East	2002
2	Edo	Etsako Central	1255
3	Edo	Etsako West	1366
4	Edo	Ikoba-Okha	1482
5	Edo	Orhionmy Orhionwon	5736
6	Bayelsa	Ekeremor	1201
7	Bayelsa	Ogbia	1568
8	Bayelsa	Southern Ijaw	1264
9	Bayelsa	Nembe	948
10	Delta	Aniocha South	1081
11	Delta	Ndokwa East	1861
12	Delta	Ndokwa West	1799
13	Delta	Sapele	1376
14	Edo	Ovia North-East	2015
15	Edo	Ovia South-West	1248
16	Edo	Owan East	1537
17	Edo	Uhunmwonde	2760
18	Imo	Oguta	3975
19	Imo	Ohaji/Egbema	1035
20	Rivers	Ogba/Egbema/Ndoni	8606
Total Fires			44 115

Table 4.1 The Niger Delta districts with the highest incidence count of MODIS fires from 2007 - 2015.

Table 4.1 shows the top twenty districts from a total of 185 in the Niger Delta with highest fire counts. These districts represent the main fire hotspots in the Niger Delta.

There are 185 NAME_1 ‘towns/cities’ in the new geodatabase of MODIS fires containing 68 924. Twenty-six of these districts have no fire record, while 159 districts have at least 1 recorded fire case to a maximum of 8606.

The fires extracted in this process include non-pipeline fires. Pipeline fires were extracted using proximity to the pipeline as discussed earlier in Section 4.2.1.

Note: All 16 205 fires in the non-Niger Delta districts were not included in our analysis.

MODIS FIRE CLASSIFICATION	NUMBER OF FIRE LOCATIONS
Oil pipeline fires	2192
Industrial flares	2135
Ocean flares	150
Domestic fires	109
Agricultural fires	100
Total fire locations	4686

Table 4.2 The classification of Niger Delta fires.

The KML files of these classifications are presented in Appendix D.

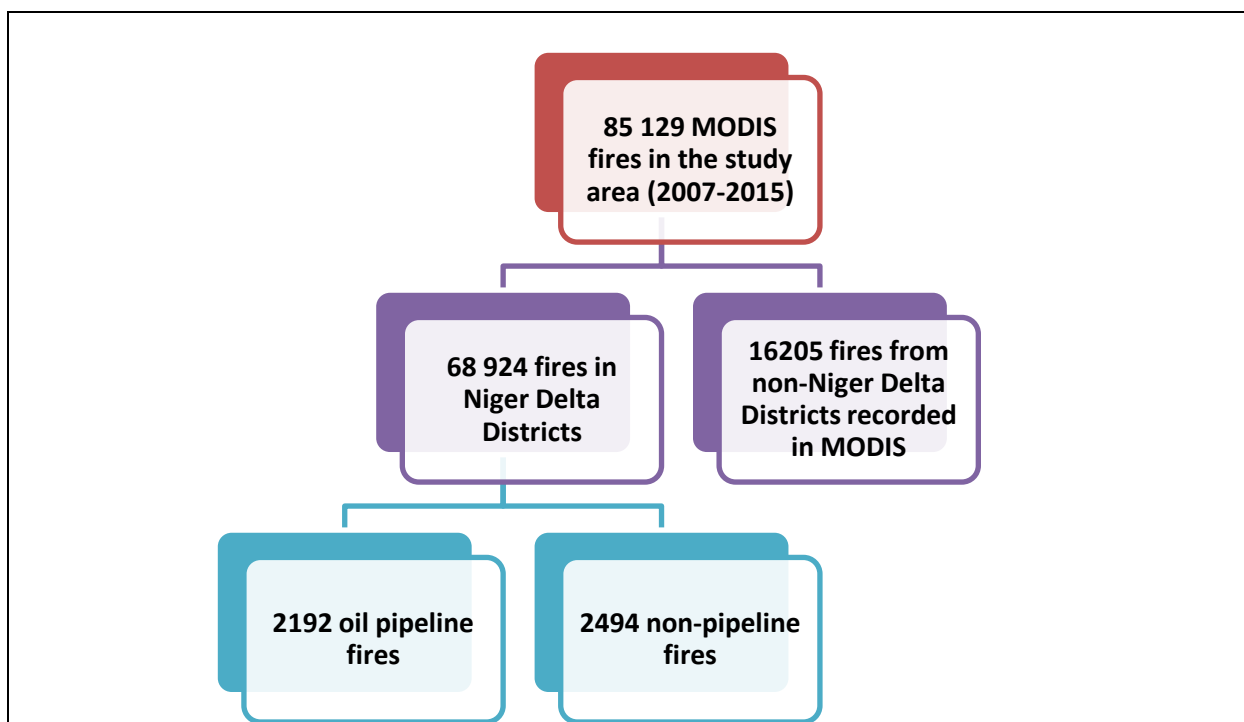


Figure 4.21 Chart flow showing the filtering process to extract MODIS fires in the Niger Delta from 2007-2015.

Note: The non-pipeline fires totaling 2494 events are derived from Table 4.2.

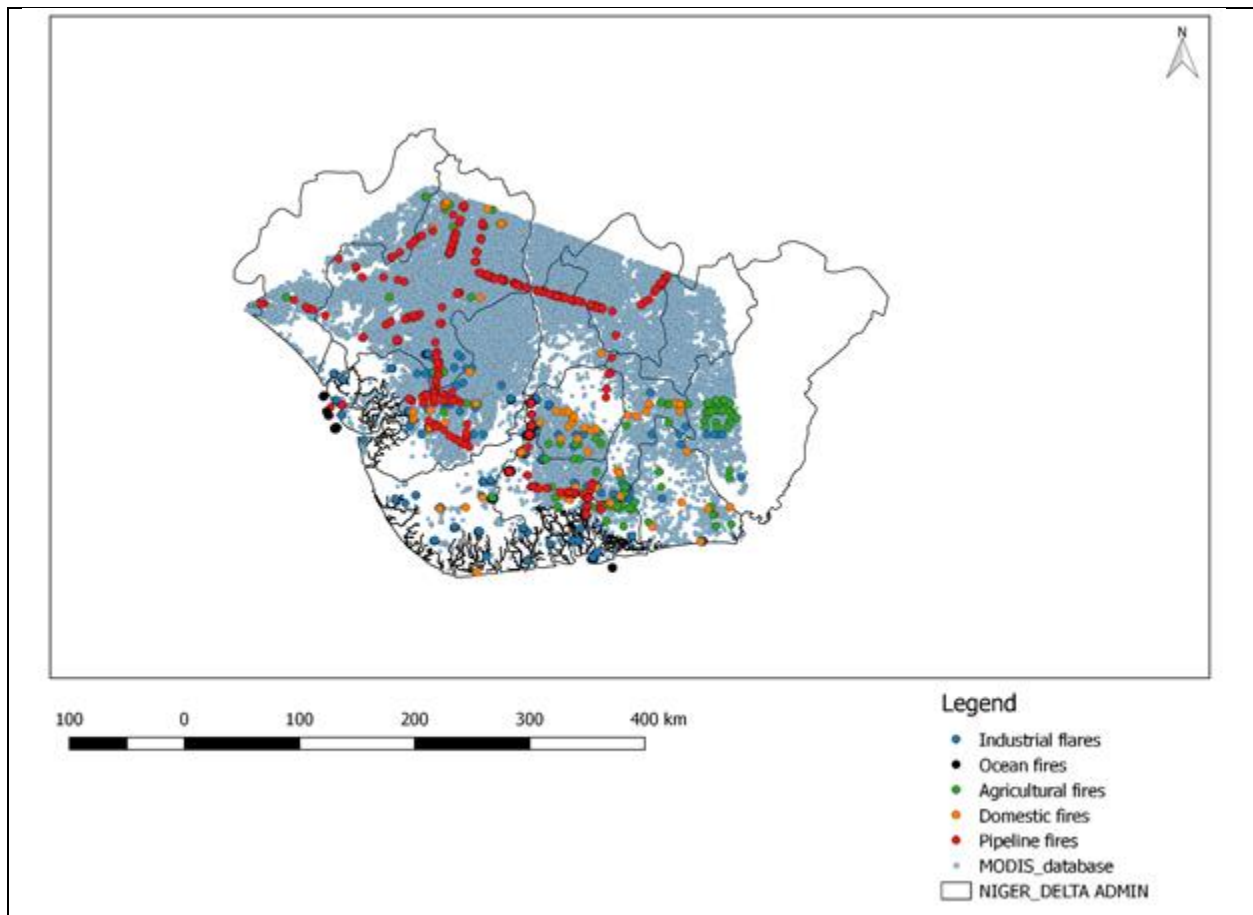


Figure 4.22 The spatial plot of oil pipeline, industrial, domestic, agricultural and ocean fires in the Niger Delta.

Figure 4.22 shows the different types of fires extracted from the MODIS fire database from 2007 – 2015. It describes the spatial location, pattern and distribution of fire activities in the Nigerian Niger Delta. The fires in the Ocean provide a proof to the possibility of fires either from oil explorational activities or theft cases that could not be accounted for by the JIV team (see Section 4.1.4 and Figure 4.4). In addition, Figure 4.22 explains the type of fires that describe the Niger Delta landscape and their geographical locations. More fires are caused from pipeline and industrial sources: and these fires can be detected by MODIS sensors in near real-time.

4.2.3 Temporal pattern of oil pipeline, industrial and agricultural fires

Having extracted the different fire types from the MODIS fire database, we went further to study their temporal patterns. As much as the plots are interpretable, we examined the temporal patterns in a longer time frame (yearly) and in a shorter time frame (monthly).

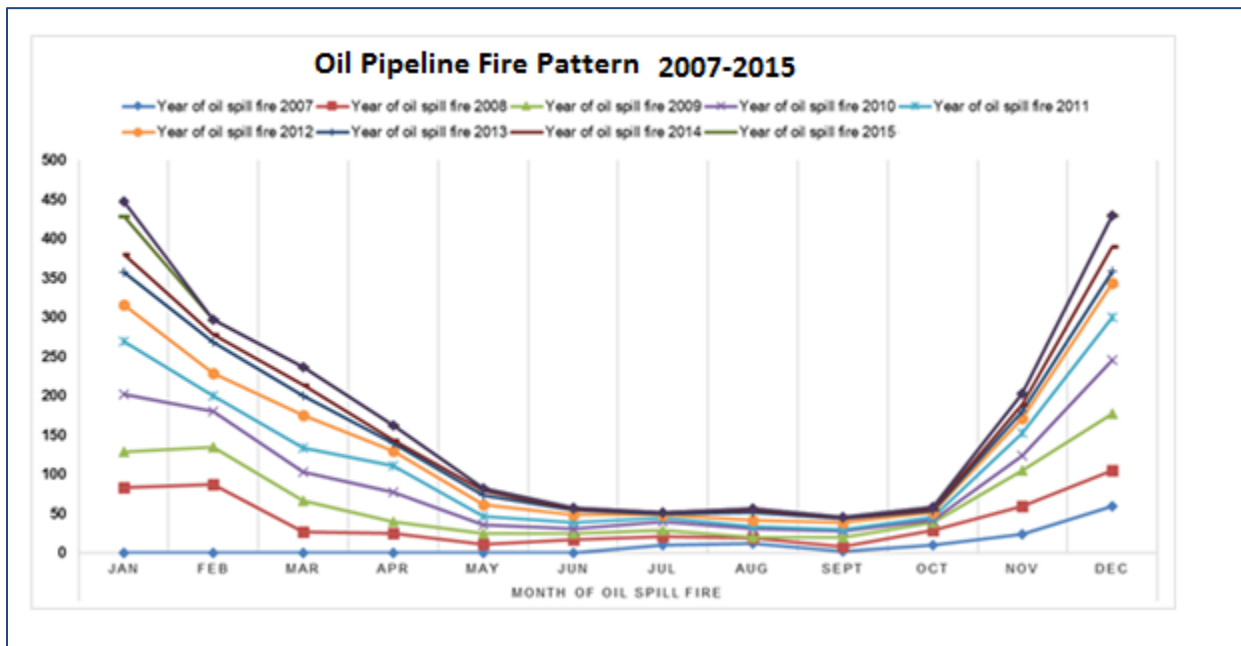


Figure 4.23 The yearly pattern of oil pipeline fires from the MODIS fire database (2007- 2015).

Figure 4.23 shows the yearly pattern of oil pipeline fires (i.e. 2192) for each year from 2007 – 2015. The pipeline fires show a strong seasonal dependence across all the years, with heightened incidence in the dry season during November to March.

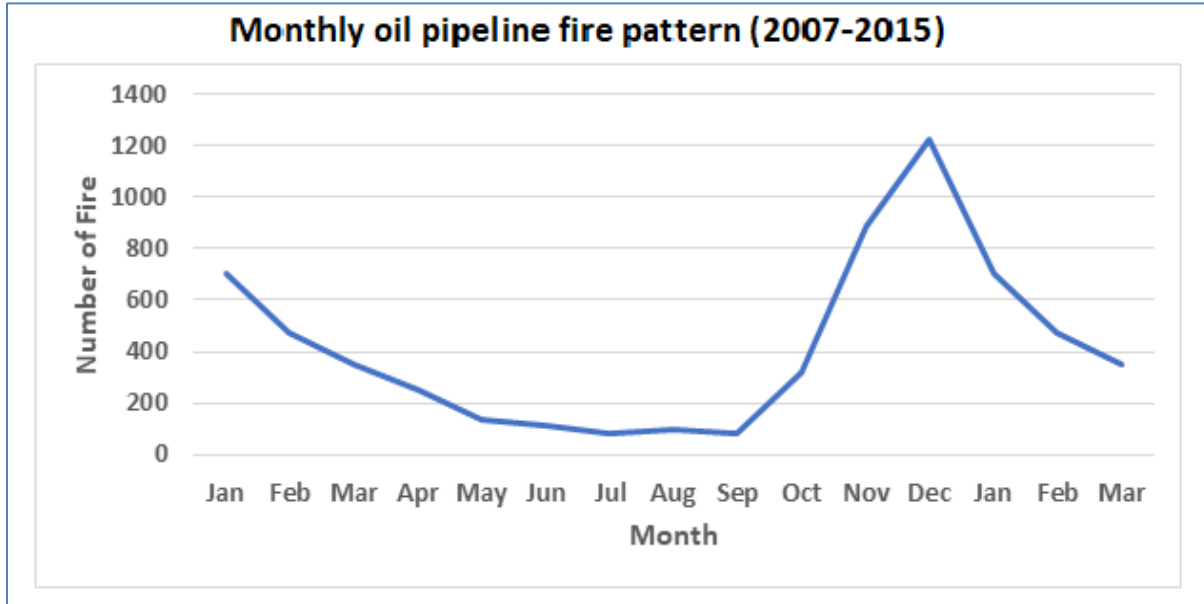


Figure 4.24 The monthly pattern of oil pipeline fires.

In Figure 4.24, we plotted the cumulative monthly occurrence for all years from 2007 – 2015 to support the plot in Figure 4.23. It is clearly seen from the two plots that the peak period for oil pipeline incidences are in the months of November, December, January, February, March, while

the months of June, July, August, September and October represent the off-peak period. The dry season in Nigeria corresponds to the months of November to February. Ogunbadewa (2015) studied the yearly and monthly pattern of active fires in the major ecosystem of Ondo State, and found out a steady increase in the fire counts from 2002 to 2011. This study revealed that the highest fire records were associated with sites with petroleum related activities. It follows therefore that drier vegetation during this period will more effectively fuel fires resulting from oil pipeline spills.

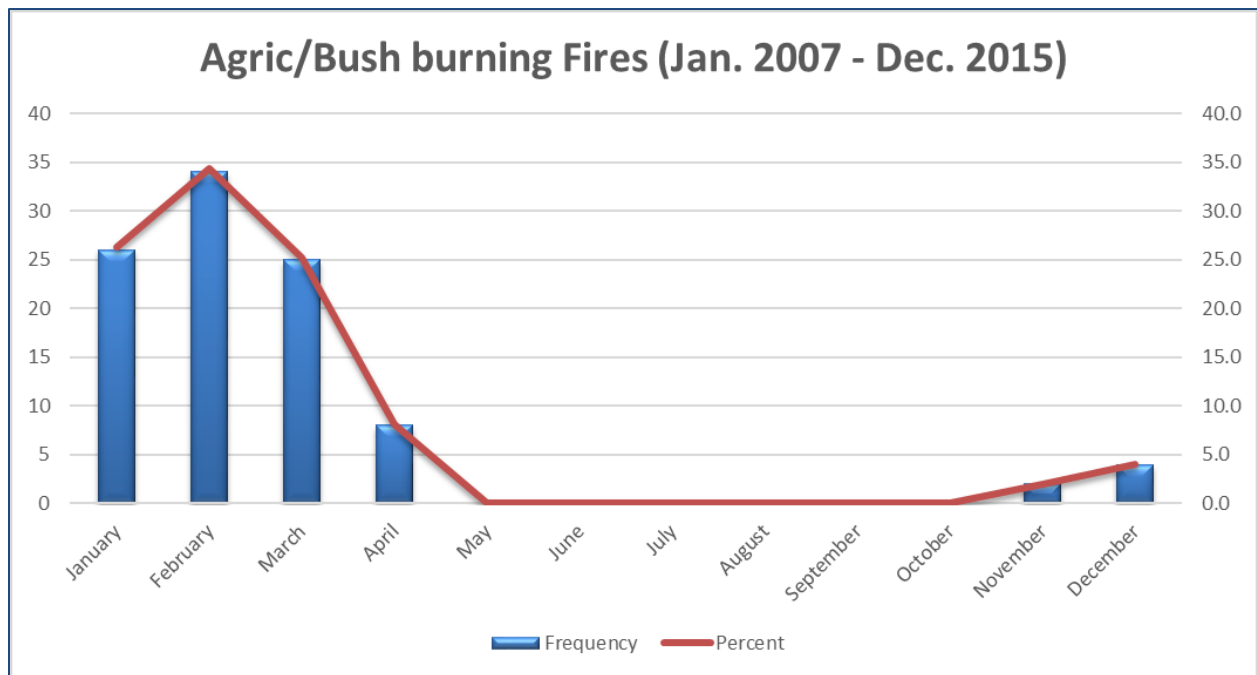


Figure 4.25 The monthly pattern of agricultural fires from the MODIS data.

Figure 4.25 shows the monthly pattern of agricultural fires in the Niger Delta. There is virtually no fire occurrence from May to October. This result corroborates earlier reviewed work, stating that January – March is a period of bush burning activities to prepare the land for the planting season in the rainforest belt of Nigeria. The studies of Aweto (2012) and Aweto (2000) on the succession of the depleted soil organic matter from the previous farming season in the Niger Delta of Nigeria revealed that the burning activities of vegetation during the dry season help to rejuvenate soil fertility, in preparation for the next planting season. This period of bush burning is from November to March.

The yearly plot is presented in Appendix J.



Figure 4.26 The monthly pattern of industrial fires.

Figure 4.26 shows the monthly pattern of industrial fires for each year from 2007 – 2015. These fires generally show a trend with a strong seasonality from September to December each year.

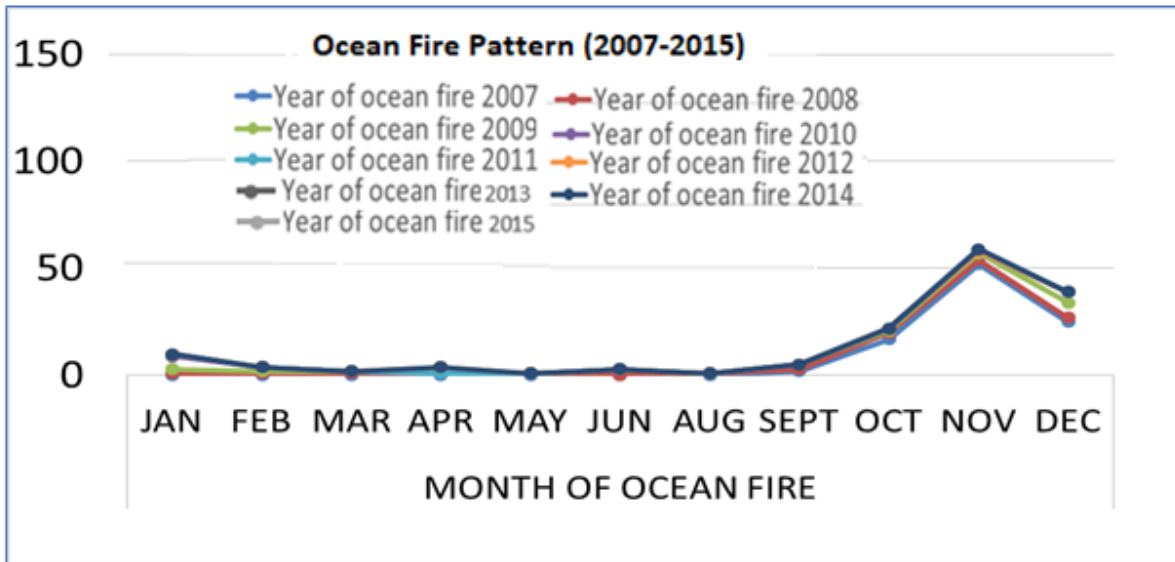


Figure 4.27 The monthly pattern of ocean fires.

Figure 4.27 shows the monthly incidence of ocean fires in the Niger Delta region. We are not sure of the sources of fires in the ocean. However, the spatial plot of oil spills (see Figure 4.4) indicates

that a significant number of spills do occur in the ocean. It is also evident from the distribution of spills according to their sources of habitat, which we presented in Figure 4.8, that oil spills are recorded offshore. For example, in 1990, 200 000 barrels of crude oil spilled into the Atlantic Ocean due to the failure of offshore equipment, causing environmental damage to more than 340 hectares of mangrove habitat (P. C. Nwilo & Badejo, 2005). A spill of this magnitude to the ocean can be accompanied by fire. We can conclude that offshore fires are closely linked with activities of oil exploration in the ocean.

4.2.4 Collective temporal pattern of all MODIS fires

In Section 4.2.3, we only considered the temporal analysis of the different fire types extracted from MODIS fire database. In this section, we will examine the collective temporal pattern of MODIS fires from all sources, yearly and monthly (Figure 4.28).

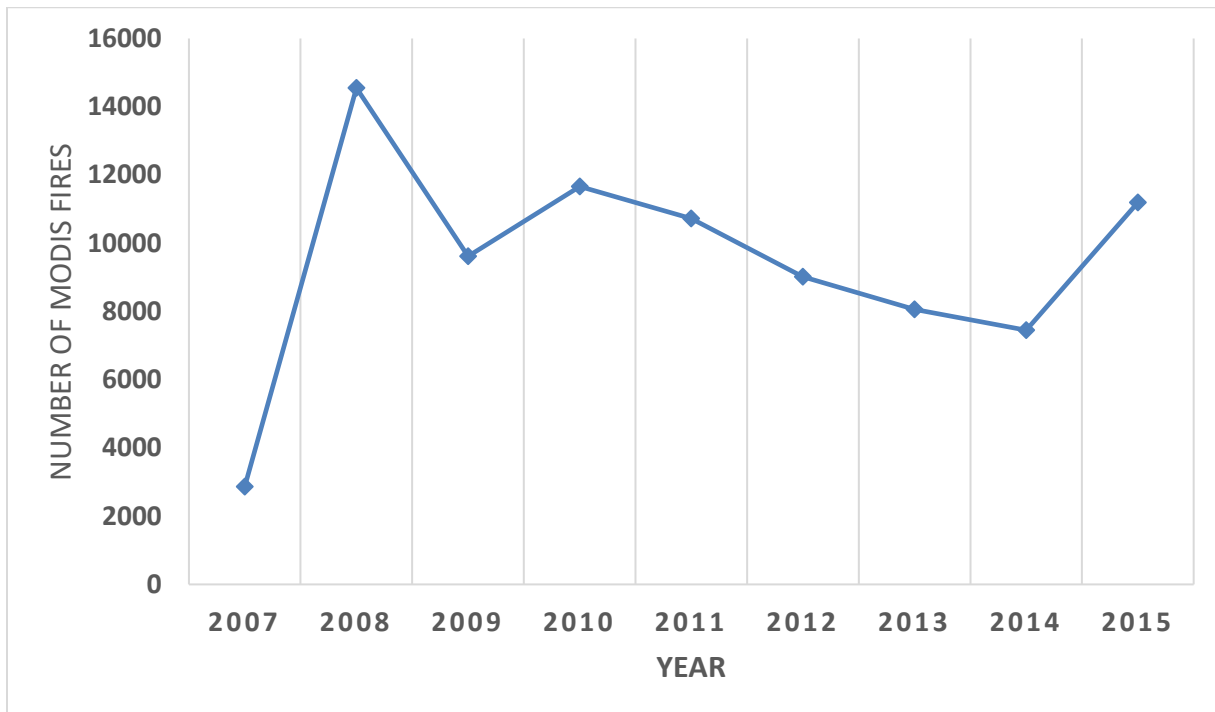


Figure 4.28 The yearly pattern of all MODIS fires from 2007 – 2015 in the Niger Delta.

The yearly pattern of MODIS fires is different from the yearly pattern of oil spill events. While oil spill events gradually increase with years (i.e. Figure 4.1), MODIS fires are fairly steady from 2009 – 2014, with the total number of fires per year averaging 9000-10000 events. This could mean that fires seemed to be relatively constrained by some factors (e.g. rainfall and/or any other weather-related factors) between 2009 - 2014.

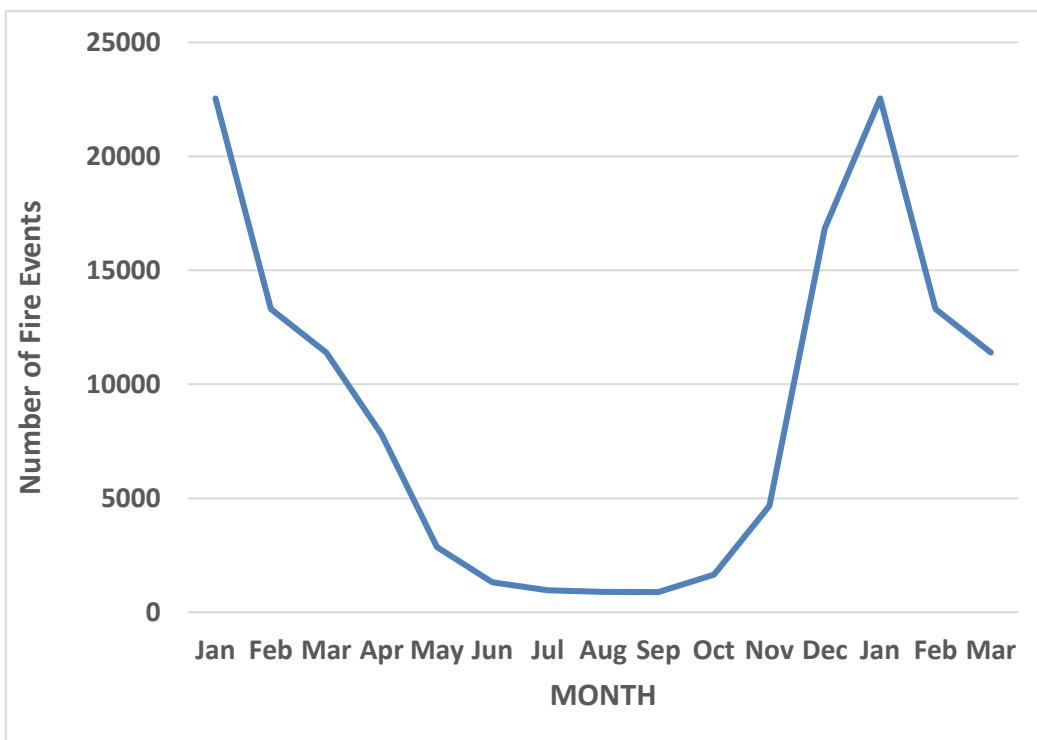


Figure 4.29 The monthly pattern of MODIS fires in the Niger Delta from 2007 – 2015.

The monthly pattern of MODIS fire database is similar to the oil pipeline fire plot (see Figure 4.23). The peak fire season months, November to February are the dry season and the months of May to October are the rainy season in Nigeria.

4.2.5 MODIS measures of fire radiative power

In Section 3.2, we described the MODIS fire database and its parameters. In this Section, we will examine the MODIS fire radiative power (FRP) with respect to the different fire types which we classified earlier. By definition, the fire radiative power is the rate of emission of a fire, which is determined by the type of fuel and the amount of fuel consumed (Freeborn et. al., 2014).

Since the fire radiative power is determined by the fuel load, our goal in this Section is to investigate whether the MODIS FRP can be used to discriminate among the various types of fires.

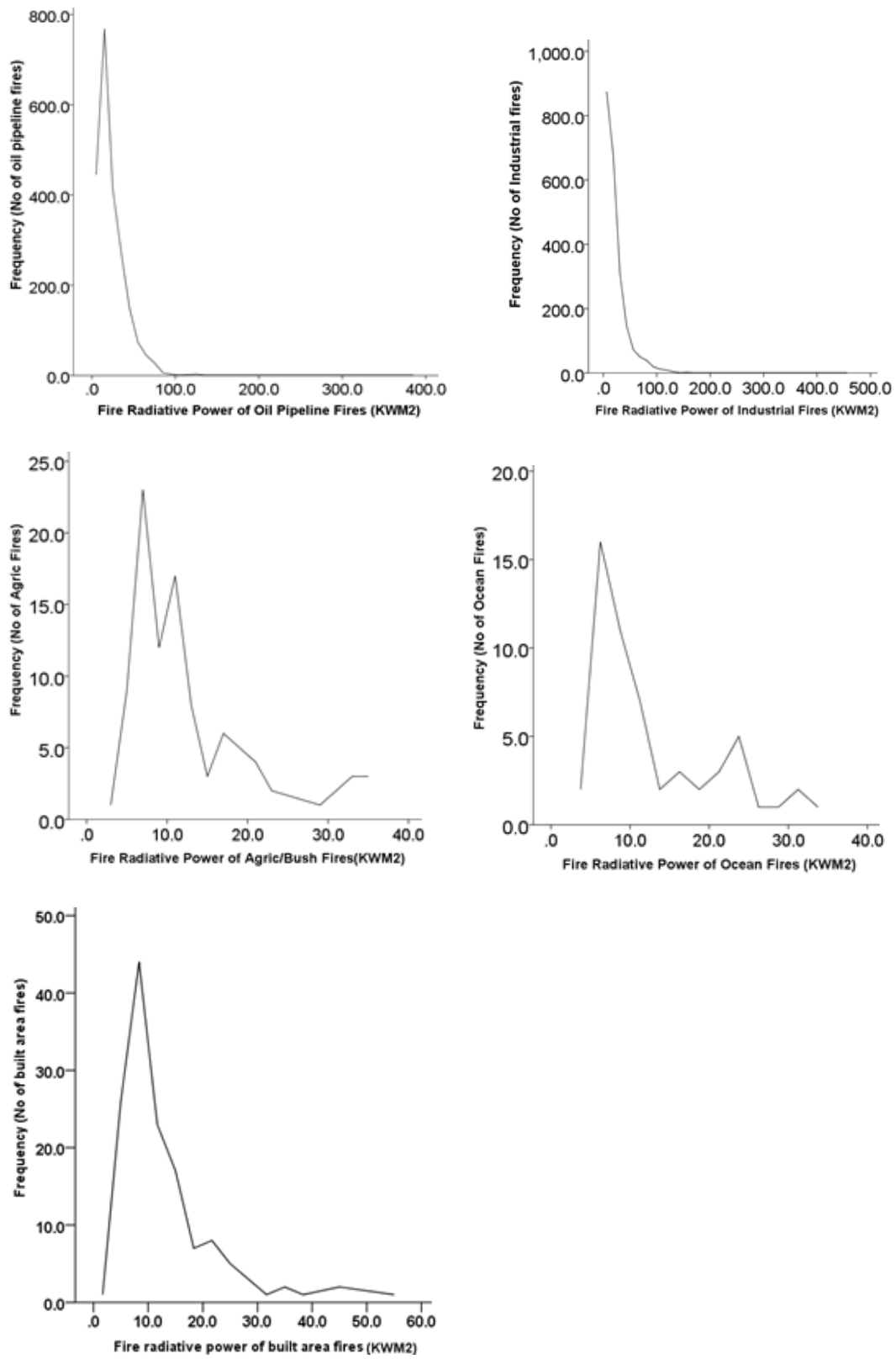


Figure 4.30 Comparing the fire radiative power of five classes of fires obtained from the MODIS database.

Fire radiative power is often studied to ascertain the length of time certain fire sources can last during active burning, including factors like emission and fire intensity, which often give information about the sources of fires (Gumbrecht et al., 2002). Reviewed work on the fire radiative power shows that each research effort is tailored toward a particular goal. Smith & Wooster (2005) reported that the MODIS sensor has been used to classify different fire types by the smoke plume they produced. In their study, two types of classification were considered based on whether fires ‘burn into’ the wind (i.e. backfire) or the fires ‘burn in’ the wind direction (headfire). Backfires have higher heat intensity than headfires. However, to simulate these methods required additional information like azimuth angle of satellite, differences in the size of the pixel across each swath and wind data, etc. Van Der Werf et al. (2010) investigated the uses of fire radiative power of the MODIS sensor to study the burning behaviour and the characteristics of land cover burning (i.e. biomass).

Ichoku et al. (2008) stated that there is no standard value for comparing the fire radiative power of a fire, but a comparison can be made between the values of the FRP of different fires and between different satellite sensors. For example, Wooster et al. (2003) compared the fire radiative power of land cover burning with products derived from BIRD and MODIS instruments. The fire products of the two sensors were used to analyze a fire that occurred in Australia in January 2002. They found out that the FRP of the ‘fire pixel’ from the two sensors was comparatively within $\pm 15\%$ threshold, at similar spatial extent (i.e. the calculations assumed similar spatial extent for MODIS and BIRD). However, many of the fires with heat lower intensity could not be detected by MODIS due to its lower spatial resolution (Ruecker et al., 2012), and at such, its FRP for these fires was 46% compared with BIRD.

In essence, the FRP is used to differentiate fires on the basis of differences in the intensity, fuel load and the rate of emission of these fires. In the same way, the FRP is used to show contrast between different sensors. According to Wooster (2012), the FRP is useful in the characterization of biomass burning within an ecosystem, and is expressed as a measure of the output, due to the fuel load, fuel consumption and the heat intensity.

For each fire type we extracted (Table 4.2), we statistically analyzed the fire radiative power of the MODIS sensor to obtain an expression which we can compare (Figure 4.30). The FRP plots for oil pipeline fires and industrial fires show a similar pattern, while plots for ocean fires, built area fires, and agricultural fires are different, which can be used to distinguish oil and industrial fires from other fire types. The difference is due to very high fire radiative power values of industrial and oil pipeline fires. The high values of FRP for oil pipeline and industrial fires indicate more heat intensity, probably due to more fuel load than agricultural, domestic and ocean fires. This is in agreement with Steinhaus et al. (2007), who described the burning behaviour of spill fires to be characteristically distinguished from other fires with respect to its hydrocarbon source which defines its higher emission rate, radiative power, and larger plumes compared with other sources of fires. As long as fuel remains, an oil spill fire burns horizontally by taking advantage of the substrate to burn at a higher rate (Steinhaus et al., 2007)

5 SPATIO-TEMPORAL CORRELATION BETWEEN MODIS FIRE EVENTS AND OIL SPILL EVENTS

In Chapter 4, we analysed the NOSDRA oil spill reports and the MODIS fires separately. In this Chapter, we aim at establishing the spatio-temporal correlation, if any, that exists between the largest spill events (i.e. 386) and the MODIS fire products (i.e. 85 129) from 2007 – 2015. Two critical parameters from each of the MODIS fire reports and oil spill reports will form our focal point: the dates of the respective events and their locations.

5.1 Dates of occurrence

The oil spill date is the determining factor since we cannot expect a fire incident without a spill case first. The JIV visit to the spill site is triggered after a report of the spill is received (see Section 3.1.3). We stated two methods of establishing the oil spill incident date in Section 3.1.3, which are (a) a drop in the pressure of the pipeline triggers an alert to the oil companies, and (b) a report through surveillance contractors, who may be members of the host community (Amnesty International, 2013).

With the way spill incident dates are recorded in the NOSDRA data, we wrote a python script (see Appendix A for the source code) that considered each of the NOSDRA records (referring to the 386 largest spill events) and searched for MODIS fire events which have dates within ± 3 days of the NOSDRA report date.

5.2 Location of spill event and MODIS fires

Our python code also considered the locations of all matching records from Section 5.1 above in the same script. We used the Vincenty formula to calculate the geographical distance between the NOSDRA spill event locations and MODIS fire locations.

The Vincenty formula allows the calculation of the distance between two geographical locations with extreme accuracy up to 1 mm or even better (see <https://pypi.python.org/pypi/vincenty/0.1.4>).

In order to correlate a spill event with a given MODIS fire, we require the separation of the two event locations to be ≤ 1 km.

5.3 Spill events close to sensitive habitats

The tendency for spill events to result in wildfires depends on the closeness of such spills to vegetation, which can act as an addition to the fuel oil load in case such spills result in a fire. Hence, the greater propensity for such fires to be detected by the MODIS sensor. We described factors that can contribute to a fire scenario in Section 3.1.4 to include sensitive habitat. We also presented a chart of the different habitats in the Niger Delta in Figure 4.8. Although not all NOSDRA spill events have JIV forms (as discussed earlier in Section 3), for those spill events with JIV forms, we checked for fire records and the nearness of such spill events to a sensitive habitat¹⁶. Our check included verifying the spill volume if a spill of less than 100 barrels resulted in a fire case in a sensitive habitat. We looked for such spill events in the MODIS database to establish a correlation of spill events with MODIS fires in sensitive habitats.

5.4 Spatio-temporal correlation between MODIS fires and oil spill events

The list of spatially and temporally correlated MODIS fires and oil spills from 2007 to 2015 is presented in this Section (see Table 5.1). The result of the automated extraction that shows a close correlation between oil spills and MODIS fires was found for 40 events. Nineteen of those events have the same dates for MODIS fires and oil spills, while the other twenty-one occurred within the ± 3 days window. The python code can be modified to accommodate different spatio-temporal windows (i.e. < 1 km, or less or greater than ± 3 days) between the NOSDRA reports and MODIS fires to obtain varying outputs.

Our findings for spill events with spill volume less than 100 barrels (Section 5.3) which resulted in fires and are close to a sensitive habitat revealed that three spill events in the JIV forms were found in the MODIS fire database. Two of the events have the same dates while the third event is within the one-week¹⁷ window. This means that MODIS can detect a fire from a spill volume that is less than 100 barrels (i.e. 49.5 bbl, 70 bbl and 22 bbl), but somewhat close to vegetation.

The KML files of these events are presented in Appendix D.

¹⁶ The JIV form contains a description of the spill source with respect to distance to a sensitive habitat that can be impacted by the oil spill event. This research considered this factor as a potential platform for wildfire spread due to abundance of vegetation cover in such a habitat.

¹⁷ The one week window is interpreted as ± 3 days from spill date. The spill day is an inclusive range making a total of seven days. For details explanation, see Appendix A.

Table 5.1 Spatio-temporal correlated oil spill and MODIS fire events

OIL SPILL COORDINATES		MODIS FIRE COORDINATES		Spatial Distance (m)	Spill volume (bbl)	FRP	Spill incident date	Fire incident date	Habitat	Facility	JIV Fire Report
Latitude	longitude	latitude	longitude								
5.62631	6.79525	5.626	6.795	30.0	160.0	33.6	2007/01/28	2007/01/28	swamp	unknown	Fire report
5.31414	5.33581	5.314	5.335	80.3	200.0	5.7	2008/02/11	2008/02/11	land	unknown	Fire report
5.44625	6.62140	5.446	6.621	42.8	150.0	46.3	2008/11/27	2008/11/27	land	unknown	Fire report
4.96668	6.51384	4.966	6.513	96.5	170.0	13.6	2009/06/05	2009/06/05	land	unknown	Fire report
5.54839	6.71206	5.548	6.712	35.9	295.0	65.4	2009/09/09	2009/09/05	land	unknown	Fire report
4.68511	5.89694	4.686	5.895	126.7	1500.0	70.6	2009/11/11	2009/11/11	swamp	unknown	Fire report
5.10467	6.52025	5.104	6.52	58.9	800.0	61.3	2010/03/03	2010/03/02	swamp	unknown	No report
4.82211	6.14161	4.822	6.141	58.2	1500.0	45.7	2010/04/25	2010/04/24	swamp	unknown	No report
4.82494	6.15083	4.824	6.15	101.1	150.0	6.8	2010/05/12	2010/05/12	swamp	unknown	No report
4.82350	6.14597	4.823	6.145	82.0	227.0	36	2010/05/16	2010/05/14	swamp	unknown	No report
5.10119	6.50856	5.101	6.508	54.6	300.0	15.9	2010/08/19	2010/08/16	land	unknown	No report
5.38883	6.67942	5.388	6.679	86.1	220.0	36.9	2010/09/02	2010/09/02	land	unknown	No report
5.63269	6.67081	5.632	6.67	95.2	335.0	40.4	2010/09/22	2010/09/19	land	unknown	No report
4.54294	5.95828	4.542	5.958	94.8	193.0	18.2	2010/12/30	2010/12/30	swamp	unknown	No report
5.41861	5.82219	5.418	5.822	59.9	144.6	5.3	2011/03/10	2011/03/10	swamp	flowline	Fire report
4.39583	6.65978	4.395	6.659	82.9	49.5	7.1	2011/08/02	2011/08/02	swamp	unknown	Fire report
5.01969	6.35900	5.019	6.359	67.4	134.3	11.5	2011/10/04	2011/10/04	swamp	unknown	No report
4.53181	6.74572	4.531	6.745	94.2	130.0	6.2	2011/10/10	2011/10/05	swamp	unknown	No report
4.94678	6.55508	4.946	6.555	62.5	1500.0	51.4	2011/12/27	2011/12/30	land	unknown	No report
4.97619	7.02500	4.976	7.025	8.9	2755.0	45.7	2012/02/20	2012/02/20	land	unknown	Fire report
5.25536	6.52369	5.255	6.523	77.0	176.0	7.3	2012/03/26	2012/03/20	land	unknown	No report
4.98122	7.16992	4.981	7.17	15.3	200.2	19	2012/06/08	2012/06/08	land	unknown	No report
4.80769	6.10194	4.807	6.101	102.5	111.0	3.8	2012/11/10	2012/11/07	land	unknown	Fire report
4.92692	6.97467	4.926	6.974	109.0	312.0	7.5	2012/12/20	2012/12/20	land	unknown	Fire report
5.53672	5.89494	5.536	5.894	103.3	110.0	21.3	2012/12/29	2012/12/29	land	unknown	No report
4.65231	6.08433	4.652	6.084	45.8	125.8	16.9	2013/04/25	2013/04/23	swamp	unknown	Fire report
4.89467	7.17706	4.894	7.177	54.1	124.0	7.3	2013/04/29	2013/04/29	land	unknown	No report
5.62578	5.16431	5.625	5.164	88.6	768.0	42.4	2013/06/28	2013/06/25	Unknown	unknown	No report
4.58703	7.25647	4.587	7.256	42.4	196.0	6	2013/07/28	2013/07/21	swamp	unknown	No report
5.05358	6.70292	5.053	6.702	98.2	236.0	25.3	2014/01/25	2014/01/22	land	pipeline	No report
4.66136	6.07861	4.661	6.078	70.7	646.0	57.4	2014/03/15	2014/03/13	swamp	pipeline	Fire report
4.43569	6.32200	4.435	6.322	48.0	30260.0	75.3	2014/06/29	2014/06/24	swamp	flowline	Fire report
4.45256	6.32575	4.452	6.325	85.2	294.0	13.8	2014/08/09	2014/08/09	swamp	flowstation	No report
5.56325	5.59481	5.563	5.594	77.6	5000.0	59.6	2014/11/25	2014/11/19	swamp	pipeline	No report
5.19550	6.75211	5.195	6.752	42.8	220.0	4.9	2015/01/05	2015/01/03	Unknown	pipeline	No report
4.57294	7.25381	4.572	7.253	113.8	189.0	10.8	2015/02/18	2015/02/15	swamp	pipeline	Fire report
5.40514	6.48964	5.405	6.489	56.2	150.4	13.7	2015/06/04	2015/06/04	land	well head	Fire report
5.45969	6.69692	5.459	6.696	103.8	687.0	44.1	2015/06/22	2015/06/22	land	other	No report
5.48289	6.20264	5.482	6.202	101.6	1815.0	47.9	2015/06/29	2015/06/28	land	well head	No report
4.546361	7.037698	4.546	7.037	77.3	70	7.9	2015/01/25	2015/01/25	land	well head	Fire report
4.69999	7.24618	4.699	7.246	96.9	144	48.8	2015/08/19	2015/08/19	land	pipeline	Fire report
5.52901	6.05069	5.529	6.05	71.2	127.8	42	2011/08/02	2011/08/02	land	trunkline	Fire report
4.45219	7.17919	4.452	7.179	13.1	22	7.1	2015/12/01	2015/11/28	land	pipeline	Fire report

5.5 Relationship between oil spill volume and fire radiative power

For all spatiotemporal correlated events obtained in Table 5.1, we analyzed whether a relationship exists between the spill volume and the fire radiative power recorded by the MODIS sensor.

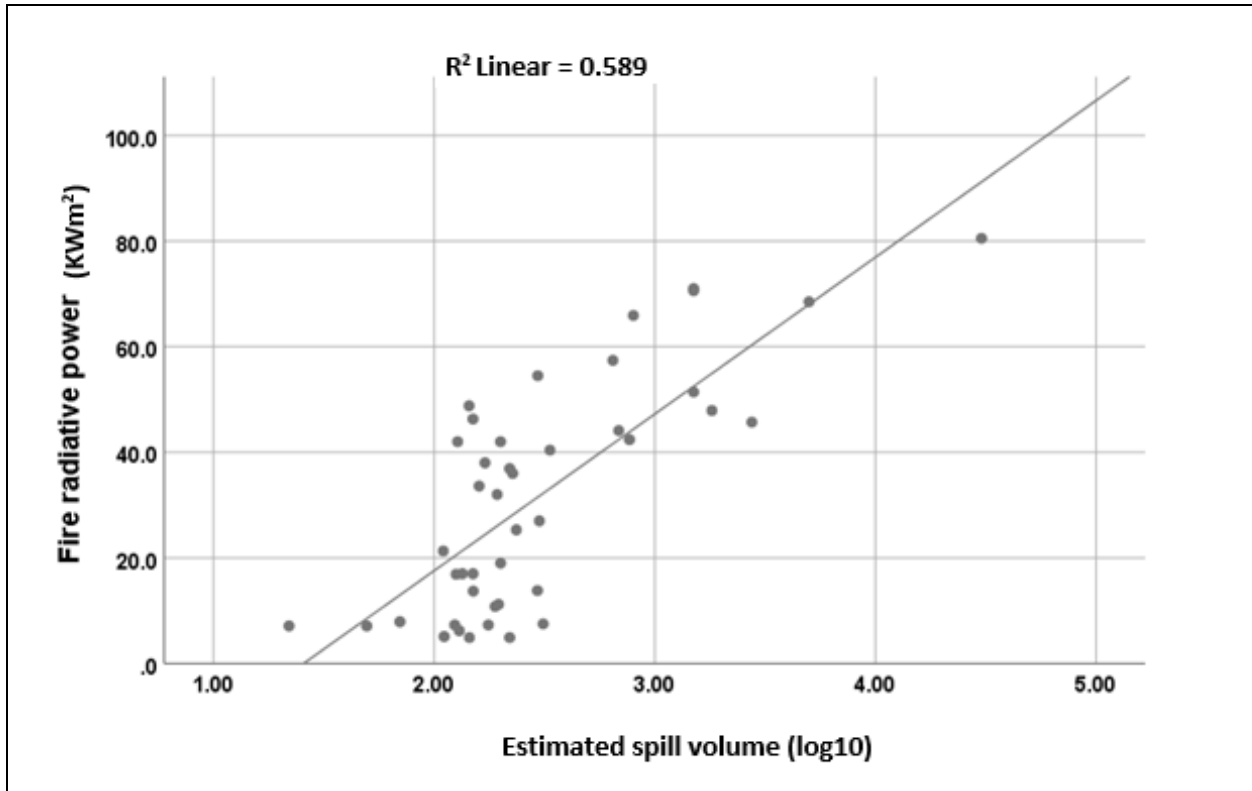


Figure 5.1 Spill volume against fire radiative power for the spatio-temporally correlated spill events and MODIS fire events.

Figure 5.1 shows a plot describing the relationship between spill volume and the corresponding fire radiative power of MODIS. The fitted line shows a coefficient of determination R^2 of 58.9% between spill volume and FRP. We observed from the plot that some spill events resulted in higher fire radiative power of MODIS, while few others were not. This might be due to the satellite over-passed during active burning (see Section 6.6 for discussion).

5.6 The geospatial pattern of the spatio-temporal correlation between oil spills and MODIS fires

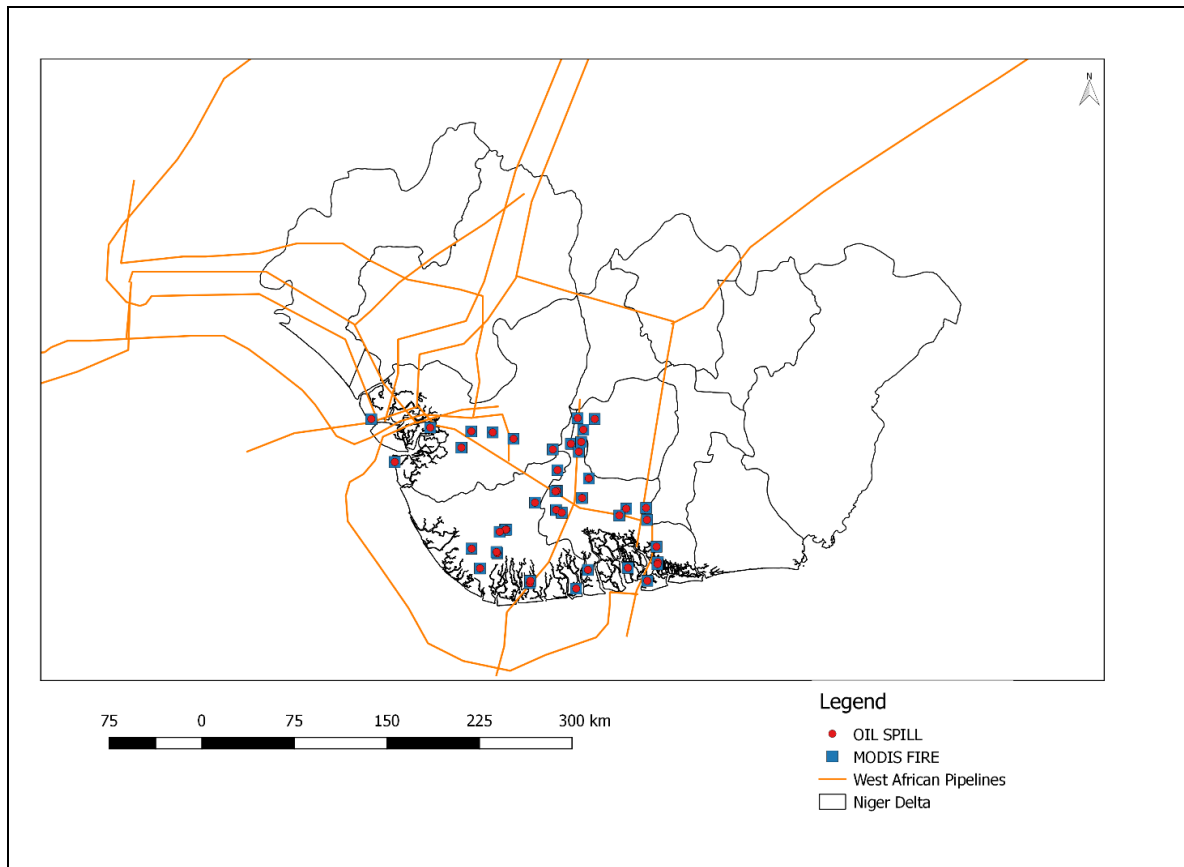


Figure 5.2 Spatial pattern of the MODIS fires and spill events.

In Figure 5.2, we present the spatial pattern of the spatio-temporally correlated events (i.e. the events listed in Table 5.1) to show their spatial locations with respect to the pipelines. Significant numbers of the correlated events are closely located to the pipelines. We recall from Figure 4.7 that the oil facilities are not limited to the pipeline infrastructures, but also included flowlines, trunk lines, flow stations, barges, etc. as the Niger Delta is the hub of oil exploration from where it is distributed to other parts of Nigeria and beyond the Nigerian border. The oil facilities marked as unknown in Table 5.1 were clearly identified through visual inspection of satellite imageries (see Appendix F).

We provide a heat map which shows the spatial concentration between spills and fires on the pipelines in the Niger Delta in Appendix E.

5.7 Maps of spills and MODIS fire images that are spatio-temporally correlated

In this Section, we present maps of spills and fire events that are spatio-temporally correlated. Where possible, the JIV photographs will be presented in addition to satellite imagery.

5.7.1 Spill and fire mapping

- (i) **Case 1:** Spatio-temporally correlated spill event and MODIS fire at the location 4.92692 (latitude) and 6.97467 (longitude).

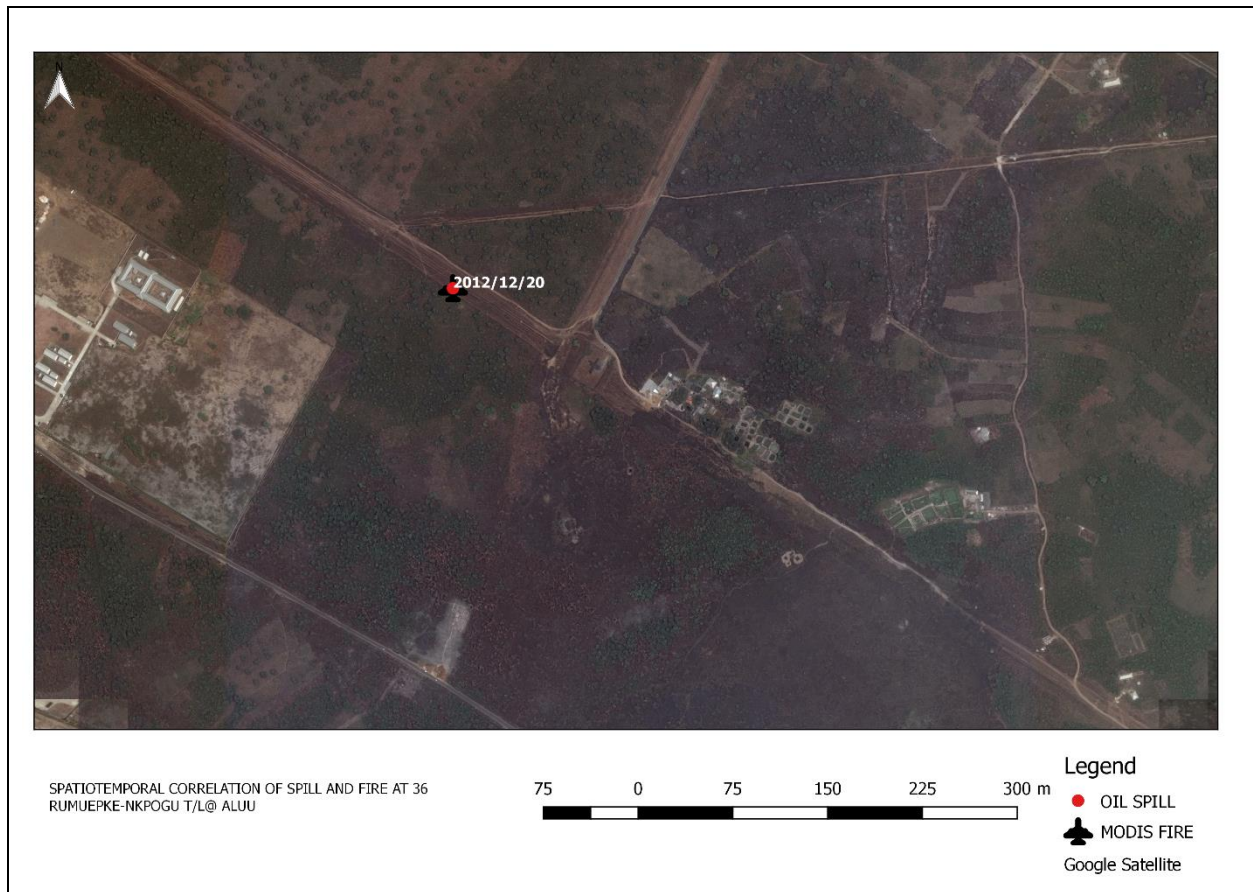


Figure 5.3 Satellite imagery of a spill event and MODIS fire spatio-temporally correlated on 20th December 2012.



Overview: Part of spill impact on 8" Isimiri-Imo Gate pipeline right of way at Obiakpu. Picture was taken during Joint Investigation of 22nd December 2012.

Figure 5.4 Photograph of the contaminated environment taken during the JIV in the vicinity of the spill on 22th December 2012.

Source: Oil spill data in Nigeria <http://www.shell.com.ng/sustainability/environment/oil-spills.html>



Figure 5.5 The JIV photograph of the spill source due to sabotage of the Isimiri-Imo pipeline at Obiakpu on 22th December 2012.

Source: Oil spill data in Nigeria <http://www.shell.com.ng/sustainability/environment/oil-spills.html>

- (ii) **Case 2:** Spatio-temporally correlated spill event and MODIS fire at the location 5.62631 (latitude) and 6.79525 (longitude).

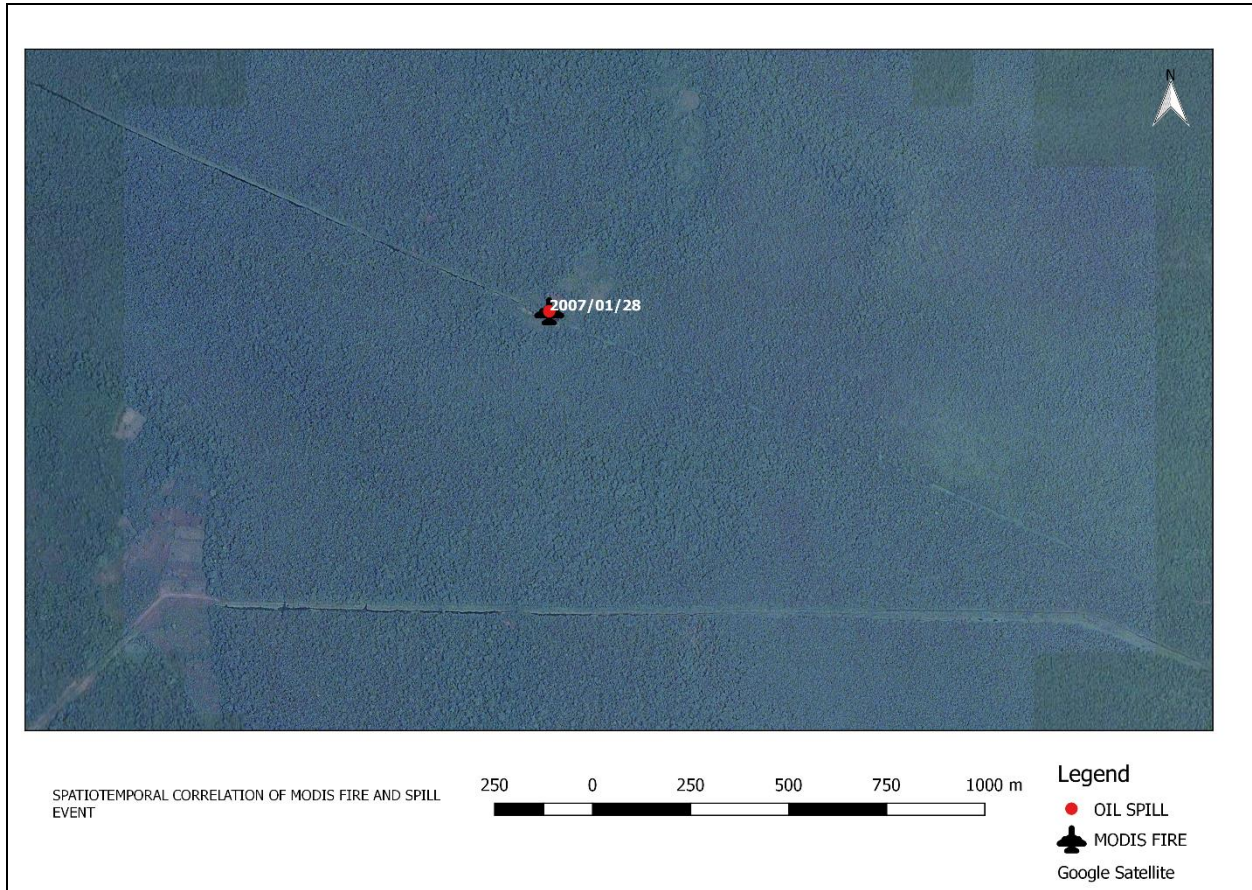


Figure 5.6 Satellite imagery of spill and MODIS fire spatio-temporally correlated on 28th January 2007.

- (iii) **Case 3:** Spatio-temporally correlated spill event and MODIS fire at the location 4.68511 (latitude) and 5.89694 (longitude).



Figure 5.7 Satellite imagery of the spatio-temporally correlated spill and MODIS fire on 11th November 2009.

- (iv) **Case 4:** Spatio-temporally correlated spill event and MODIS fire at the location 5.52901 (latitude) and 6.050 (longitude).

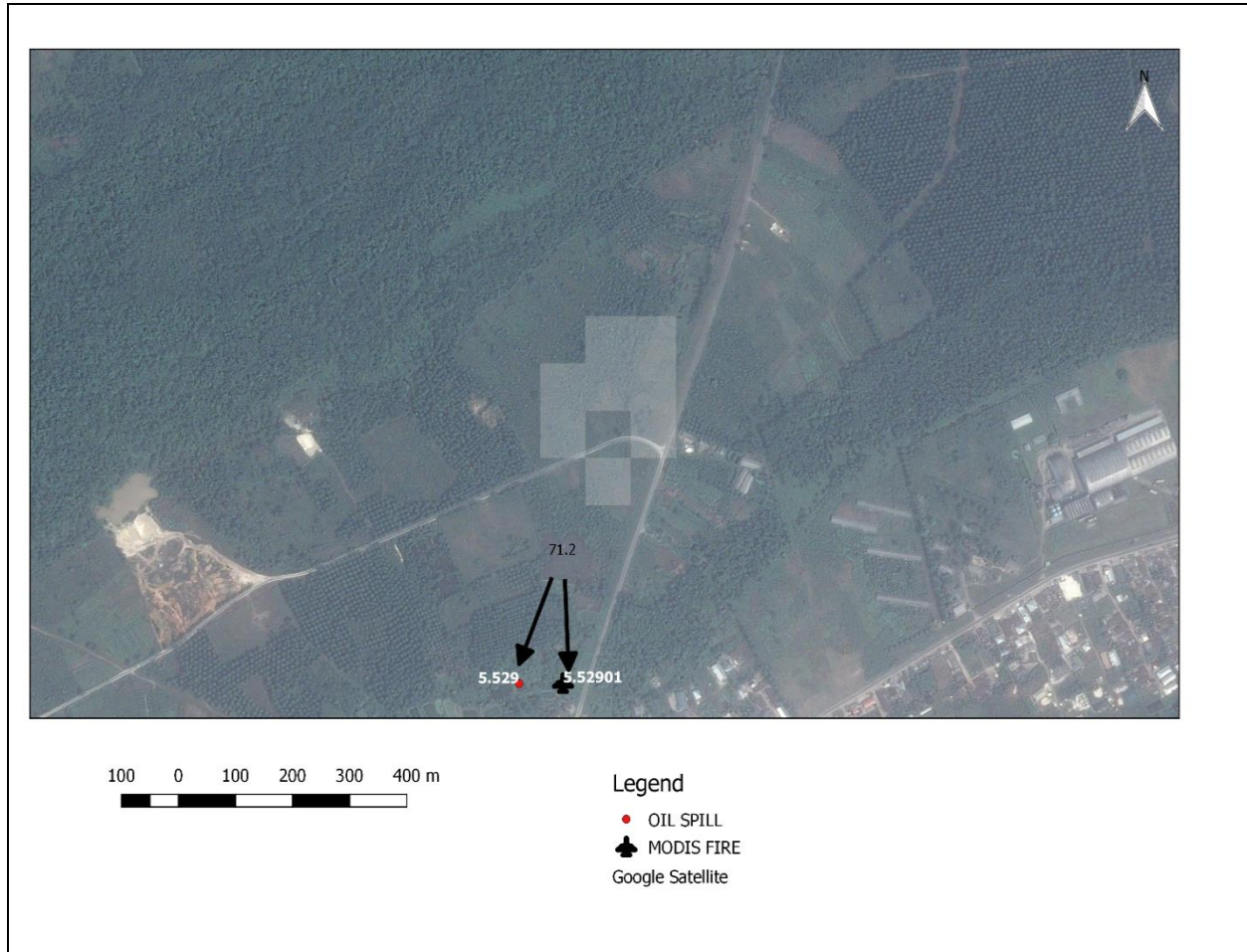


Figure 5.8 Satellite imagery of the spatiotemporally correlated spill event and MODIS fire on 2nd August 2011. The spill event-location and MODIS fire location were separated by 71.2 m. The JIV inspectors probably did not want to walk in the oil!



Overview: Part of spill impact on 12" Imo River-Ogale Pipeline at Komkom. Picture taken during Joint Investigation on 4th August, 2011

Figure 5.9 Available JIV picture of the fire damage taken during the JIV on 2nd August 2011. Source: Oil spill data in Nigeria <http://www.shell.com.ng/sustainability/environment/oil-spills.html>



Figure 5.10 Photograph taken by the JIV showing the source of the spill.
Source: Oil spill data in Nigeria <http://www.shell.com.ng/sustainability/environment/oil-spills.html>

- (v) **Case 5:** Spatio-temporally correlated spill event and MODIS fire at the location 4.45219 (latitude) and 7.179 (longitude).

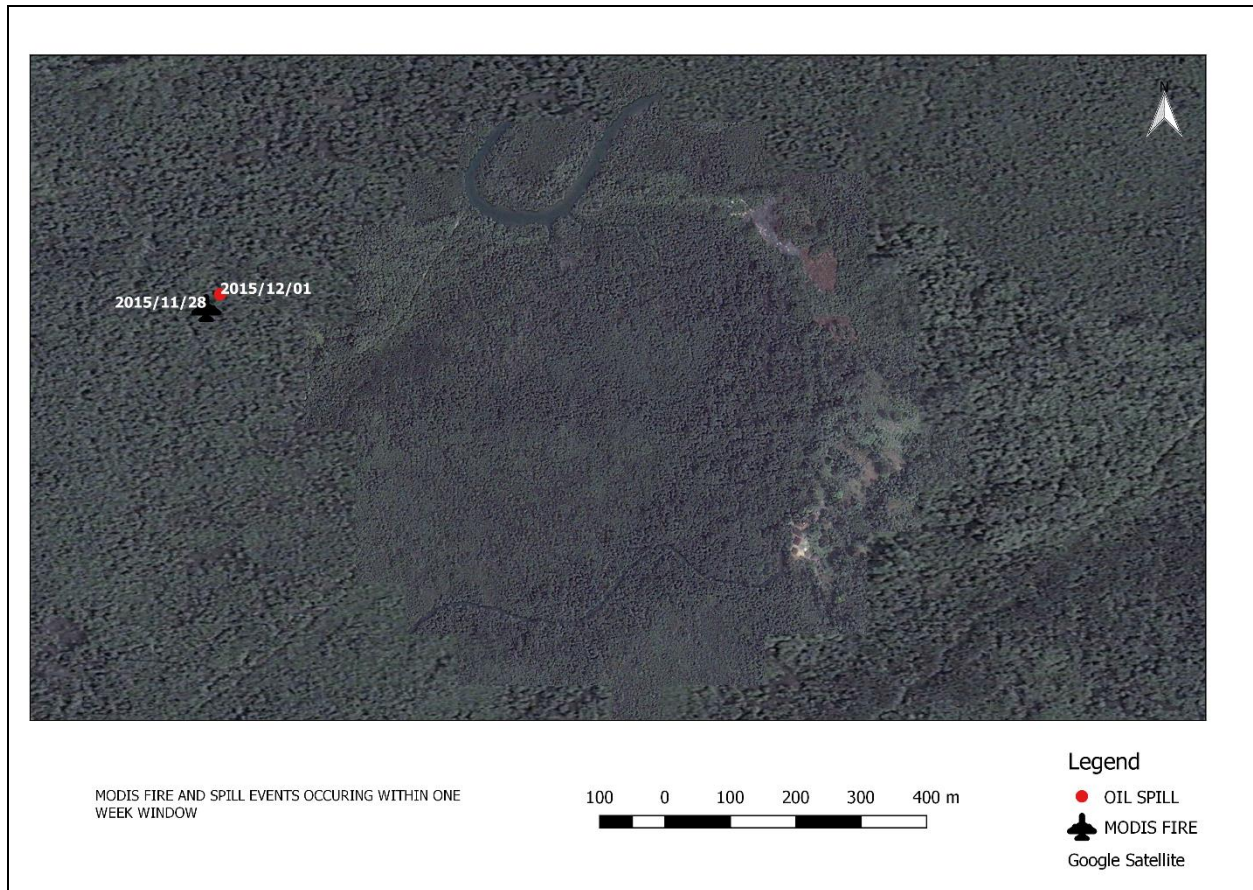


Figure 5.11 Satellite imagery of a spatiotemporally correlated MODIS fire and spill event separated by two days.

This MODIS fire was observed on Saturday 28th November 2015, while the spill was recorded by NOSDRA on Tuesday 1st December 2015, and the actual JIV visit was made on Thursday 17th December 2015 (see the picture taken during JIV visit in Figure 5.12). This was a small spill (22 barrels). It is likely that the spill and fire both occurred during the weekend, but the spill was only recorded by NOSDRA on the following Tuesday.



Figure 5.12 Available JIV picture of fire damage taken during the JIV on 17th December 2015.
 Source: Oil spill data in Nigeria <http://www.shell.com.ng/sustainability/environment/oil-spills.html>.

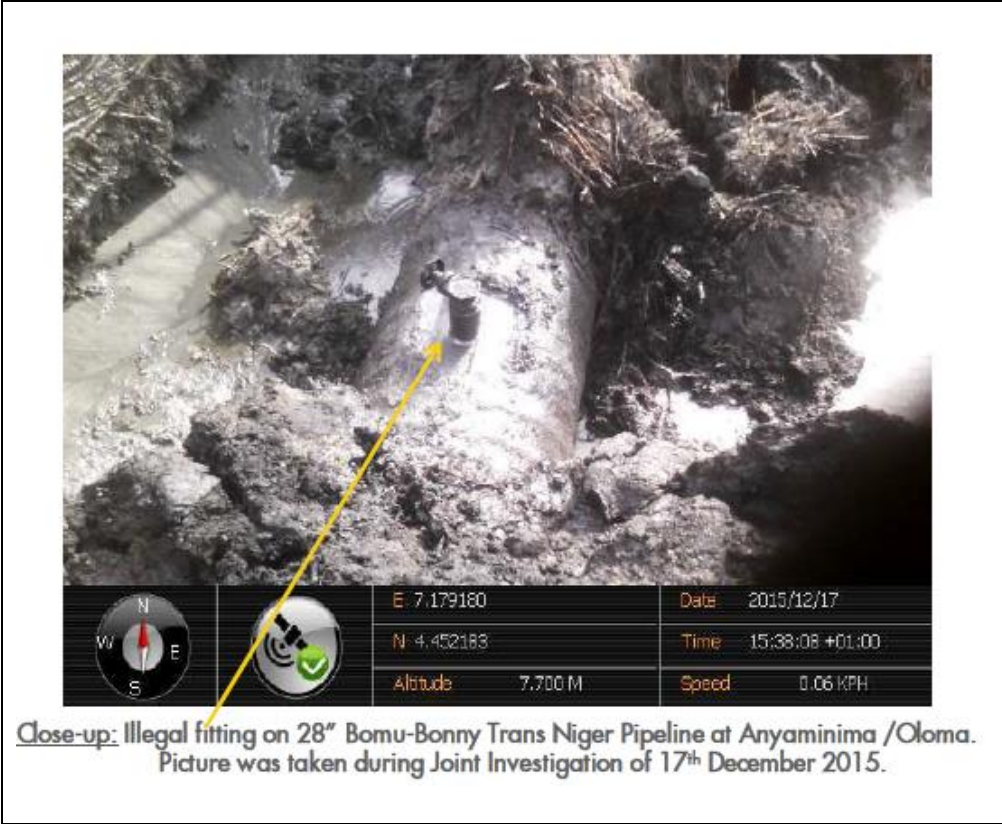


Figure 5.13 Additional JIV picture showing the source of the spill.

6 THE MAIN FINDINGS OF THIS STUDY

In this Chapter, we present all our major findings in this work.

6.1 Limitation and validation of MODIS and spill database

Limitations of spill reports

Detailed information about the oil spill database has been provided in Section 3.1.4 of Chapter 3. The exclusion of the estimated area of spills (see Section 4.1.3) and other parameters from our analysis in this research is an affirmation of the earlier studies which revealed several deficiencies in the Joint Investigation Visit reports in the NOSDRA database (Akpofure Rim-Rukeh, 2015; Amnesty International, 2013; CHERD, 2011). Despite these weaknesses in the spill database, on its own, it has provided enough validation and ground truthing for spill events in Nigeria with emphasis to the study area (i.e. Niger Delta). The ground oil spill reports have been used to support remote sensing detection of spill events (Fingas & Brown, 2014). Also, the spill events have shown consistent agreement with the Nigerian pipeline network (Figure 4.4). The Google Earth Pro validation is provided in the KML file in Appendix D.

Limitations of MODIS fire reports

One intrinsic limitation of the MODIS fire data is its susceptibility to heavy cloud cover. The land form pattern of the Niger Delta coast, the rainfall pattern, the high humidity and precipitation are major factors that predispose this area to cloud cover (Adejuwon, 2012). Despite the cloud cover, this research has shown that MODIS can be a useful tool for detecting and monitoring oil spill fires. In Appendix G, we present the satellite image of real-time active fires of MODIS on 28th November 2015. The satellite image shows the capability of MODIS in detecting some fires despite heavy cloud cover in the study area. Although the MODIS fire reports do not provide information about missing data, such data (i.e. fire images) may be viewed through NASA's Worldview, satellite imagery portal (Davies et al., 2009).

The spatial resolution of the MODIS fire product used for fire detection in this research is in the range 250 m to 1000 m (Justice et al., 2015). This study reveals that such resolution is inadequate for oil spill detection on its own, but we show that when such spills are attended with fires, the MODIS sensor can be effective in detecting such spills on land (see Section 5.4). However, the 250 m spatial resolution of the MODIS instrument has been used with success for oil spill detection in oceans (Pisano et al., 2015; Grimaldi et al., 2009), and in combination with NDVI to detect spill-induced land cover change (Lunetta et al., 2006).

The ground spill reports provided validation for the fire database of MODIS, being a pathfinder for the fire scenarios investigated in this research. Morissette et al. (2005) defined validation as the

principle behind the assessment of the quality of satellite products (i.e. data) with a reference to independent data sources.

The spatial correlation of MODIS fires with spills (Section 5.4) and the pipeline network (Figure 5.2), including Google Earth Pro validation (see Appendix D), are presented in this work.

6.2 The temporal pattern of spill reports and the MODIS fire reports

The temporal plots (i.e. yearly and monthly patterns) we present in this research represent the Nigerian seasonality and define the oil spill and fire activities in the Niger Delta. In general, the temporal relationship in months and years give information about their pattern of occurrences with respect to their sources (see Section 4.2.3 and Appendix J). When we compared the plot that described the monthly pattern of the largest spills by volume in the Niger Delta (i.e. 386 spill events) in Figure 4.14 with that of the oil pipeline fires (i.e. 2192 MODIS fire events) in Figure 4.24, we observed a similar pattern from October – March. This means that oil spills (especially the spills of large volume) and oil pipeline fires are more likely in the dry season from October – March. The location of these spills and the oil pipeline fires in this season provide the areas of focus for monitoring and predicting spills and pipeline fires occurrences in the study location.

In like manner, the monthly plots for spills (see Figures 4.13 and 4.14) and the monthly plots for MODIS fires revealed that spill and fire activities are usually low in the rainy season. The month of April is the beginning of the annual rainy season in the study location.

6.3 Fire inventories from the MODIS fire database

In this research, we classified the 85 129 MODIS fire reports according to their sources. The classes of fires considered in this study include oil pipeline fires, industrial flares, domestic or built area fires, ocean fires and agricultural fires (Table 4.2 and Figure 4.22). We have described the fire situation of the Niger Delta. The industrial flares, domestic and ocean fires extracted from MODIS database in this report are a testimony to the background information we provided earlier in Chapters 1 and 2. Oladokun & Emmanuel (2014) and Oladokun & Ishola (2010) reported that the built area fires from markets, rural and urban settlements are very common in Nigeria, especially during the dry season. The highly dense built areas and lack of regulatory enforcement by government agencies to ensure that land developers adhere to good town planning and international construction ethics are among major reasons for such domestic fires. The Niger Delta area is the hub of oil and gas exploration with an unprecedented rate of flaring of natural gas by industry (Aniefiok & Udoh, 2013; Effiong & Etowa, 2012; Ishisone, 2004).

This work provides an incentive for using a remote sensing tool like MODIS active fire products in probing the sources of fires in the study area. Lin et al. (2012) investigated the gaseous emission on a global scale with MODIS active fire products and found that India, Brazil, and Nigeria are the top three countries contributing more than 25% of Aqua active fires in the world.

6.4 Spatio-temporal correlation between NOSDRA reports and MODIS fire reports

In this study, we established a spatio-temporal correlation between the oil spills (i.e. 386 spill events) and the MODIS active fire hotspots for a total of 43 events. This shows that MODIS active fire products can be used for oil spill fire detection in near-real-time. Twenty-two of these spill events correlated precisely in time with MODIS fire hotspots while twenty-one events occurred within a one-week window (i.e. ± 3 days) of the recorded spill incident dates (see Section 5.4 for details). Of these twenty-one MODIS events, 19 occurred earlier than the spill reported dates while only two occurred after spill incident dates. It might be difficult to explain this, but according to the JIV form, a visit to spill site is only conducted after a report of spill and fire scenario (see Section 5.1).

For example, in Figure 5.11, we presented a case of a MODIS fire which occurred on a Saturday (2015/11/28), while the spill event was recorded on the following Tuesday (2015/12/01) (see Figure 5.11). It is, therefore, justifiable to assume that the spill must have occurred earlier, and resulted in a fire that was observed by MODIS before reports of ground-based observers reached NOSDRA. For other fire hotspots in the MODIS database when compared with spill reports, the difference in time might be due to satellite over-passed during active burning. Gumbrecht et al. (2002) reported that the spatial extent and timing of burning might not be determined accurately with hotspot data due to the satellite sensor over-pass during the period of active burning in addition to cloud cover.

6.5 Oil pipeline fire detection in near-real-time

In this study, we employed GIS techniques in extracting MODIS fires with proximity to the pipelines. The smallest size of a fire that can be detected by the MODIS sensor under favourable conditions (i.e. the angle of scan, the biomass, the direction of the wind, the position of the sun, etc.) and cloud-free is 30 m by 30 m (Frazier, 2017). However, the MODIS sensor is better than other sensors (e.g. ATSR, VIRS and AVHRR) not primarily designed for active fire detection because there is no limit to its detection of the hottest fires (Justice et al., 2002). The oil pipeline fires extracted in this work considered the ROW management practices (see Sections 2.3, 4.2.1 and Figure 4.17). The oil pipeline fires extracted from the MODIS active hotspots are at near-real-time: and provide georeferenced locations in the Niger Delta, and information about their distance

to the network of pipelines within this region. Thus, regardless of the cause of spills which result in fire incidences (i.e. maintenance or operational error, or due to deliberate sabotage), fires from oil pipelines can be detected and monitored with the 250 m spatial resolution of the MODIS sensor in near-real-time.

In Appendix H, we present a case of an illegal oil refinery in one of the key States of the Niger Delta. Usually, such an illegal refinery is situated in a remote place but not too far from an oil facility. Since such an illegal oil refinery will result in fires, a remote sensing tool like the MODIS instrument maybe be useful in spotting such activity when such fires are large enough. A better remote sensing tool like VIIRS with an improved spatial resolution of 375 m has been mentioned to detect visible fires both day and night (Cao et al., 2014). It is likely for such a sensor to deliver better results than MODIS.

6.6 Volume of spills against the fire radiative power

Earlier in Chapter 1, we highlighted that the MODIS instrument had been used for spill detection in the ocean (Pisano et al., 2015; Grimaldi et al., 2009), although, the same success has not been recorded on land. Our result revealed that even though MODIS cannot detect oil spills on land, its can nevertheless be used for the detection of large spill events (≥ 100 barrels) which result in fire scenarios (see Section 5.4 and Table 5.1). The spatio-temporal correlated events also show 3 spills with volume < 100 bbl (i.e. 49.5 bbl, 70 bbl and 22 bbl) that were correlated with MODIS fires. This indicates that small spills that resulted in fires can also be detected using MODIS. Such small spills are located close to a sensitive habitat like vegetation (see Appendix C). Vegetation becomes a precursor for fire occurrence in such spills. This confirms literatures earlier reviewed describing spill fire comparatively with spill volume, spill size, fire size, heat release and spill habitat (Ebike et al., 2014; Mealy et al., 2014; Mealy et al., 2012; Julius et al., 2011; National Institute of Justice, 2001; Mckendrick & Mitchell 1978).

The plot of the fire radiative power against the average volume of spills shows that some spill events result in higher fire radiative power while others do not. The fitted line of regression coefficient between spill volume and FRP is 58.9% (see Figure 5.1). We expect all the large spill events to result in higher radiative power since FRP is defined as the rate of fire emission which is determined by the amount of fuel consumption. For the large spill events not having higher FRP, this may be due to the difference in time when the satellite over-passed during active burning. Gumbrecht et al. (2002) reported that the spatial extent, timing of burning and other key data might not be determined accurately with hotspot data due to the satellite sensor over-pass during the period of active burning in addition to cloud cover.

6.7 The fire radiative power of MODIS fires

In this research, we defined the burning behaviour of MODIS fire records from 2007 – 2015 by classifying each type of fire using the FRP values of the MODIS fire products (Figure 4.30). The statistical analysis of the different fire types shows that oil pipeline fires and industrial fires have higher values for fire radiative power than agricultural, ocean and domestic fires. This agreed with Steinhaus et al. (2007), who described the burning behaviour of spill fires to be characteristically distinguished from other fires with respect to its hydrocarbon source, which defines its higher emission rate, radiative power and larger plumes comparative with other sources of fires. Hydrocarbon burns more due to the fuel load. As long as fuel remains, an oil spill fire burns horizontally by taking advantage of the substrate to burn at a higher rate (Steinhaus et al., 2007).

The burning behaviour and characteristics of land cover burning (i.e. biomass) have been studied using the fire radiative power from the MODIS sensor (Randerson et al., 2012; Van Der Werf et al., 2010). The FRP values of the MODIS give information about the sources of the fire hotspots; thus, it can be used to differentiate oil spill fires from other types of fires.

Google Earth Pro provides the means of ground truthing the classification method of the fires and differentiating oil pipeline fires from industrial fires.

6.8 The Right-of-Way in oil pipeline management in Nigeria

We discussed the ROW in oil pipeline management in Section 2.3. Figure 2.4 shows a typical example of how pipeline infrastructure is protected in ROW management worldwide. The ROW protects oil pipeline infrastructure by a ‘strip of land’ usually 30 m wide on either side of the pipeline (Enbridge Inc 2017). In countries where oil pipelines are used for oil transportation, ROW is legislated, including Nigeria (Nigerian National Assembly 2000; Fung et al., 1998; NNPC, 1995).

As explained in Chapter 1, pipeline spills are caused by maintenance or operational error, equipment failure due to old age and deliberate sabotage of the pipeline equipment by rebels, which often results in explosions and outbreaks of fires (Paraskova 2016; Anifowose et al., 2014; Ajibola 2014; Kadafa 2012; Murdock 2014). It is observed that the ROW protection of the pipeline equipment with a distance of 30 m will be difficult to manage in Nigeria owing to the environmental damage caused by the big spills. Our discussion in Section 2.5 shows that there can be as much as 570 000 barrels of spill into the ocean. Similarly, there was a case of spill event on 2nd November 2014 that resulted in a fire explosion and destroyed an estimated 2.3 ha of land area (JIV, 2014). It is clear that such a magnitude of oil spill fire will extend beyond the 30 m boundary described in the ROW.

In this research, the extraction from MODIS fire layers which are nearest to the pipeline network layers (see Sections 4.2.1) considered a distance of 1000 m. The extracted pipeline fires (i.e. 2192 fires nearest to the pipeline) from MODIS active fires are likely to be fire anomalies from oil

explosions and pipeline wildfires which may be caused by the various reasons mentioned earlier. The assumption is that spills and fires from pipeline sources will extend environmental damage beyond the 30 m ROW band to up to 1000 m distance, depending on the spill volume (see Section 5.3) and sensitivity to the nearest habitat. The spill reports from the oil spill database show the description of spills when such spill events are within the ROW of the pipeline (see the description of ROW in the photographs taken during the JIV visit to the spill sites in Figures 5.4 and 5.12).

In addition to this assumption, in Section 6.5, we described the smallest size of a fire that can be detected by MODIS as 30 m by 30 m while there is no upper limit to the size of fire it can detect. This justifies our method of extracting the oil pipeline fires. The current 30 m distance for pipeline protection in the ROW needs to be reviewed especially in the study area. In view of this, as it stands, the ROW in oil pipeline management needs to be reviewed, especially in countries where oil pipeline fires are a problem.

7 CONCLUSIONS AND RECOMMENDATIONS

The occurrence of oil spills in the Niger Delta of Nigeria has shown a steady increase from 2007 to 2015. During this time, a total of 10 072 spill events were recorded. The major cause of spills has been sabotage of the pipeline equipment and other equipment like flowlines, flow stations, trunk lines, barges, wellheads. It has been noted that although other causes of such spills from the oil infrastructure could include operational or maintenance error, equipment failure, the main cause, however, is due to acts of deliberate sabotage or illicit tapping of oil pipelines as revealed in this study; many such spills are attended with fires. Our efforts in this perspective research have produced a novel approach for identifying and monitoring such spill events from the vantage point of space.

We took advantage of the occasional fire scenario which results from the spills to investigate how these spills can be detected and monitored in near-real-time with Earth observation satellites. In the past, the idea of oil spill fire monitoring in the Niger Delta has not attracted research effort, but we have facilitated this through this study. Our strategy involved using MODIS fire products correlated with spill events over the same period using their dates of occurrence and locations to investigate their commonality in space and time. Over the same period of spill events (2007 - 2015), MODIS recorded a total of 85 129 fires in the Niger Delta. Our spatio-temporal correlation of the big spill events by volume showed that MODIS fire products could provide near-real-time detection and monitoring of oil spill fires.

Our study confirmed the presence of numerous irregularities in the Joint Investigation Visit reports which form the basis of the NOSDRA oil spill database. These irregularities include missing or obviously incorrect values for many of the fields in the spill records. Especially relevant for this study was the fact that most spill records have missing values or zero values for the spill area. Fortunately, many records did have spill volume values in barrels. For this reason, we decided to filter the oil spill data to select only those records containing the spill date, spill coordinates and spill volume.

The NOSDRA oil spill database contained 10 072 spill events recorded from 2007 – 2015. To perform the filtering process, we developed a series of python codes. By running our python codes, we extracted 4422 events with spill dates, spill volumes and spill coordinates for the whole of Nigeria. We then refined our python codes to select only spill events in the Niger Delta (i.e. 4357). This further filtering process yielded 386 largest spill events in the Niger Delta.

Our study reveals that we can rely on the capabilities of the MODIS sensors which include morning and afternoon revisits provided by the Terra and Aqua satellites with a spatial resolution of 250 m to monitor active oil spill fires. The MODIS fire products are available within three hours. For determining spatio-temporal correlations between oil spill events and MODIS fire hotspots, we

developed python codes to automate the process. We used the Vincenty formula as the tool for calculating the geographical distance between spill locations and MODIS fires with high accuracy. The Vincenty formula library is available in python as an open source library that supports diverse users.

In addition to spatio-temporal study between oil spill events and MODIS fire products, we also performed the direct extraction from the MODIS database all fires that are close (and therefore related) to oil pipeline infrastructure spatially. Other sources of fires which we identified from MODIS fire records (domestic fires, agricultural fires, and ocean fires), excluding industrial fire when contrasted with oil pipeline fires regarding the fire radiative power of MODIS sensor, oil pipeline fires have higher values of FRP. This means that we can rely on the MODIS sensor to detect and monitor fires from pipeline sources in the Niger Delta.

Regardless of the causes of oil spill fire events, whether deliberate or unintentional acts in the Niger Delta, we have shown that Earth observation through the MODIS instrument can detect such fires in near-real-time.

As we conclude this dissertation, we recommend the following schemes and tools we developed in this project for near-real-time oil pipeline spill fires monitor in the Niger Delta.

- The use of active fire products from the MODIS instrument which is freely available as global resource material for the Nigerian government in addressing the problem of oil spill fires. It is alarming to discover that from 2007-2015 where the total spills recorded in Nigeria was 10 072, MODIS fire products, on the other hand, recorded as many as 85 129 events (the Niger Delta area). The MODIS products allow detection and monitoring of oil pipeline fires in near-real-time. The MODIS fire products can, therefore, serve as an early warning signal for oil pipeline spills. Efforts should, therefore, be directed toward improving real-time detection of spills from the perspective of fire scenes. Apart from monitoring these spills, the damage caused by the fires to the Niger Delta people and their environment can be greatly mitigated.
- To manage the problem of oil spill fires in the study location, we wrote python scripts (see Appendix A) which automate the filtering process of the official oil spill database of the National Oil Spill Detection and Response Agency (NOSDRA). The python codes serve as a device of checking some of the irregularities and errors commonly found in the NOSDRA database and the JIV form.
- In addition to automating the process of filtering the NOSDRA database by the python codes, we develop another python codes that can automate spatial-temporal investigation of oil spill database and MODIS fire products. It, therefore, means, that on the availability of MODIS fire products at least three hours after satellite over-pass, the location and source of oil spill fires can be determined automatically. The source code of the python scripts is available in Appendix A.

- The method used to study oil pipeline fires in this project considered a distance to the fire that is within 1000 m to the pipeline and relates to the ROW of pipeline management. The current in-use 30 m distance to the pipeline as a way of protecting the pipeline in the ROW in the study area is not sustainable given the environmental damage which usually extends beyond the 30 m distance. This study recommends that the ROW of pipeline management is too narrow, and reviewing this will save the environment and the host community which most of the time are the receiving end. The global ROW of pipeline management needs review especially in countries where the current regime is violated. In Nigeria, it will require a coalition among all the parties involved (i.e. the government, the oil companies, host community and the landowner if different from the host community), to solve this problem. Although, it is beyond the scope of this study, however, the restiveness of the Niger Delta militants who take responsibility for many of the spills can be managed through dialogue among the warring parties while the oil companies adhere to international standards to prevent spills as much as possible.

Although this study has justified the research objective and motivation, the project is however not exhaustive, there are always areas of consideration for future work. The following areas have been identified for future research.

- This study establishes a correlation between spill volume (largest volume in barrels) and the fire radiative power up to 58.9% level of regression coefficient (see Section 5.5). However, not all the large spills by volume resulted in higher fire radiative power. Assuming the values were accurately determined by the JIV team, the spills that show lower fire radiative power as described in Section 6.6 could be that the satellite must have over-passed during the active burning of the fires, in addition to cloud cover. We need to account for such loss of heat or missing data to accurately determine the relationship between spill volume and FRP of MODIS fire products.
- Since the means of validating as well as differentiating the MODIS fire products in our study into fire types is the FRP, it will be interesting to study the more improved sensors that are dedicated for global fire detection like SEVIRI, VIIRS, SLSTR in comparison with MODIS sensor used for this project. The study will provide further information in the choice of better sensors that can be used in the study location.
- Recent studies have shown that the Visible Infrared Radiometer Suite (VIIRS) sensor has more capability than MODIS and can, therefore, produce better results. VIIRS is an improved sensor with a spatial resolution of 375 m including night detection performance, and the ability to detect fires with relatively small areas (Cao et al., 2014). Such a sensor delivers many more fire counts over the same area than MODIS. We could not use VIIRS data in this study because it was launched in October 2011 and data was only available from 2013.

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Appendices

Appendix A: Python scripts

Python codes used in filtering raw NOSDRA database to extract records with spill date, spill quantity and spill coordinates.

```
import pandas as pd
import numpy as np
import os
os.chdir(r"C:\Users\prime\Dropbox\DESKSTOP")
dd = pd.read_excel("Oil Spill Data_2017.xlsx")
dd = dd[["Spill_date", "Estimated_quantity", "Latitude", "Longitude"]]
dd.columns = ["Date", "Quantity", "Latitude", "Longitude"]
dd["Date"] = pd.to_datetime(dd.Date);
dd["Quantity"] = pd.to_numeric(dd.Quantity, 'coerce', 'float')
dd["Latitude"] = pd.to_numeric(dd.Latitude, 'coerce', 'float')
dd["Longitude"] = pd.to_numeric(dd.Longitude, 'coerce', 'float')
dd = dd.loc[(4.06717 <= dd.Latitude) & (dd.Latitude <= 6.0945)]
dd = dd.dropna(axis=0, how="any")
dd = dd.drop_duplicates()
writer = pd.ExcelWriter(r"Oil Spill Data_2017 (preprocessed).xlsx",
engine='xlsxwriter')
dd.to_excel(writer)
writer.save()
```

Python script codes used for spatiotemporal analysis of the 386 oil spill events and MODIS fire records in the Niger Delta.

This code defines NOSDRA function which describes incident date of NOSDRA as a time function, and at every given date of NOSDRA event, we will consider such “Date1” meaning a

past date (i.e. the negative sign), and at the same time consider such as “Date2” meaning the next date (i.e. positive).

The implication of the code is to consider a maximum of 1-week window between oil spill and MODIS fire due to uncertainty in the NOSDRA date of spill formulation. When we vary the number of days interval in the code, we expect to get different number of output files.

```
import os

import numpy as np

import pandas as pd

from datetime import datetime, timedelta

from vincenty import vincenty

# Set ipython's max row display

pd.set_option('display.max_row', 100)

# Set iPython's max column width to 50

pd.set_option('display.max_columns', 50)

os.chdir("C:/Users/prime/Dropbox/DESKSTOP/iSx_pYTHON")

def getModis():

    md = pd.read_csv("modis-data.csv", sep="\t")

    md["acq_date"] = pd.to_datetime(md.acq_date)

    md = md[["acq_date", "latitude", "longitude", "brightness", "frp"]]

    md.columns = ["Date", "Latitude", "Longitude", "Brightness", "Frp"]

    return md

def getNosdra():

    ns = pd.read_csv("nosdra-data.tab", sep="\t")

    ns["Incident_date"] = pd.to_datetime(ns.Incident_date)

    ns["Date1"] = ns.Incident_date - timedelta(days=3)

    ns["Date2"] = ns.Incident_date + timedelta(days=3)

    ns = ns[["Incident_date", "Date1", "Date2", "Latitude", "Longitude",

"Estimated_quantity",
```

```

    "Type_of_facility", "Company", "Spill_area_habitat", 'Contaminant', 'Cause']]
    ns.columns = ["Date", "PastDate", "NextDate", "Latitude", "Longitude",
"quantity", "Facility", "Company", "Habitat", 'Contaminant', 'Cause']
    return ns#.sort_values("Date")
md = getModis()
ns = getNosdra().sort_values("Date")
ns = ns.set_index(ns.Date)
results = []
sn = 0
for r in np.arange(0, ns.shape[0]):
    row = ns.ix[r]
    location1 = (row.Latitude, row.Longitude)
    #dd = md.loc[(row.PastDate <= md.Date <= row.Date) or (row.Date <=
md.Date <= row.NextDate)]
    dd = md.loc[(((md.Date>=row.PastDate) & (md.Date<=row.Date)) |
((md.Date>=row.Date) & (md.Date<=row.NextDate)))]
    #dd = md.loc[(((md.Date>=row.PastDate) & (md.Date<=row.Date)) |
(md.Date>=row.Date) & (md.Date<=row.NextDate))]
    for m in np.arange(0, dd.shape[0]):
        mdata = dd.iloc[m]
        location2 = (mdata.Latitude, mdata.Longitude)
        distance = vincenty(location1, location2)
        if distance <= 1:
            sn+=1
            rr = {}
            rr["Sn"] = sn
            rr["NoDate"] = row.Date;
            rr["NoLatitude"] = row.Latitude;

```

```

rr["NoLongitude"] = row.Longitude;
rr["MoDate"] = mdata.Date;
rr["MoLatitude"] = mdata.Latitude;
rr["MoLongitude"] = mdata.Longitude;
rr["quantity"] = row.quantity;
rr["Contaminant"] = row.Contaminant;
rr["Cause"] = row.Cause;
rr["Company"] = row.Company;
rr["Facility"] = row.Facility;
rr["Habitat"] = row.Habitat;
rr["Distance"] = distance
rr["Days"] = np.abs((row.Date - mdata.Date).days)
results.append(rr)

rs = pd.DataFrame(results)
sn = rs.Sn

rs = rs[['NoDate', 'NoLatitude', 'NoLongitude', 'MoDate', 'MoLatitude',
'MoLongitude', 'Days', 'Distance', 'Cause', 'quantity', 'Company', 'Contaminant',
'Facility', 'Habitat']]

rs = rs.set_index(sn)

rs.to_csv("gbenga-data-3.csv")

#np.savetxt("gbenga-data.csv", results, delimiter=",")

```

Appendix B: The Vincenty Formulae

The Vincenty formulae were formulated by a Geodesist named Thaddeus Vincenty to calculate the distance between two geolocations on a spheroid. The algorithm is based on the hypothesis that the Earth's surface is spherical-like (i.e. spheroid) which makes it different from the theory of being completely spherical. It is universally used in Geodesy due to its accuracy, which is within 0.5 mm (Vincenty, 1975).

The first process is called a direct method, or a destination point. It considers a particular point of a location as a distance and direction (azimuth) from another point. This is achieved by computation. The second computation is called an inverse method or a distance between two points. It considers the geographical distance and the direction (azimuth) between two locations.

The Vincenty formulae have been developed into a library in Python (see <https://pypi.python.org/pypi/vincenty/0.1.4>), making it an open source tool. The Vincenty formulae library was as tar.gz files and installed. Our approach in the spatio-temporal correlation between spill (386 largest events) and MODIS fires in this study used Vincenty's formulae to calculate their spatial correlation. The first direct method of Vincenty formulae considered the location of a spill as the point of the destination while the second approach calculated the geographical distance between a spill and MODIS fire.

Appendix C: Joint Investigation Visit Form

This Appendix presents a sample of a JIV form, which is usually completed by the representatives of the Joint investigation team when an alert about oil spill is triggered.

This page shows the general information about the location affected by spill and fire scenario.

THE SHELL PETROLEUM DEVELOPMENT COMPANY OF NIGERIA LIMITED.

JOINT INVESTIGATION REPORT FOR INCIDENT NO: 1324519 JIV report S/N: 00824
(Note: As practicable as possible the JIV report is to be signed in the field by all the participating parties)

A. GENERAL INFORMATION:

1. Spill incident Number: 1324519 2. Type of incident* OIL SPILL/FIRE
 3. Name of Location CAWTHORNE CHANNEL 1 WELL 9
 4. Name of nearest community CAPTAINKIRI 5. State: RIVERS 6. LGA DEGEMA
 7. Type of Production facility/Installation WELL HEAD 8. Asset owner/District SWAMP 1

B. INCIDENT INFORMATION:

9. Details of incident

a. Date of incident: 25TH JANUARY, 2015
 b. Start date/time of investigation: 28TH JANUARY, 2015 / 12:25 HOURS
 c. Investigation End date: 28TH JANUARY, 2015 Actual investigation duration, days: ONE (1) DAY
 d. Description of spill point environment

<input type="checkbox"/> Firmed soil	<input type="checkbox"/> Loose soil	<input type="checkbox"/> Recently excavated area
<input type="checkbox"/> Under water	<input type="checkbox"/> Swampy	<input type="checkbox"/> Exposed pipe surface
<input checked="" type="checkbox"/> Well Platform (on Water)		<input type="checkbox"/> Drill Rig

Additional observations around the spill point: **ON ARRIVAL AT SITE, THE JOINT INVESTIGATION TEAM WAS SHOWN BY THE SPDC ASSET OWNER, THE POSITION OF AN UNKNOWN THIRD PARTY CRUDE OIL BARGE (WHICH WAS CONFISCATED BY SECURITY PERSONNEL AND TAKEN AWAY FROM SITE PRIOR TO JIV DATE) THAT WAS OBSERVED BY THE WELL 9 SLOT AS AT TIME OF INCIDENT REPORT. ON CLOSER OBSERVATION OF WELL 9 (CONFIRMED TO BE NON-PRODUCING AT THE TIME, HAVING LAST PRODUCED IN THE YEAR, 2001), ITS VALVES WERE NOTICED BLACKENED DUE TO A FIRE OUTBREAK THAT OCCURRED ON INCIDENT DATE BUT HAD GONE OFF PRIOR TO JIV DATE. BURNT OIL STAINS WERE NOTICED WITHIN THE POSITION OF THE BEAN BOX COVER (LEAK POINT) WHICH HAD BEEN REMOVED AND RE-FABRICATED (AS EXPLAINED BY THE ASSET OWNER) BY UNKNOWN PERSON(S). SOME ILLEGAL ITEMS LEFT (AND OBSERVED ON SITE AT TIME OF INCIDENT) BY UNKNOWN PERSON(S) BUT RECOVERED BY THE ASSET OWNER, PRIOR TO JIV, FROM SITE (TO PREVENT FURTHER USAGE OR REMOVAL BY SUSPECTED CRUDE OIL THIEVES) WERE DISPLAYED AT THE ASSET OWNER'S OFFICE, AND COMPRISED A PEN KNIFE, BURNT HOSE, LIFTING BELT, STEEL HAMMER, RE-FABRICATED BEAN BOX COVER OR CAP WITH CRUDE OIL CONNECTIONS, A TORCH LIGHT AND A BURNT TWINE ROPE. SOIL IMPACTED ON SWAMP AT SITE IS SILTY CLAY WITH ORGANIC MATTER.**

e. Description of leak point (tick as applicable):

<input type="checkbox"/> Drilled hole	<input type="checkbox"/> Hack saw cut	<input type="checkbox"/> Tear ()
<input type="checkbox"/> Complete Rupture	<input type="checkbox"/> Inward dent,	<input type="checkbox"/> Well head tampering
<input type="checkbox"/> Failed Weld-on illegal hot tap valve,	<input type="checkbox"/> Failed Clamp	<input type="checkbox"/> Missing Pipeline/Flowline
<input type="checkbox"/> Crude oil theft (illegal bunkering) point,	<input type="checkbox"/> Third party tampering with Clamp	<input type="checkbox"/> Third party tampering with flange
<input type="checkbox"/> Third party tampering with valve setting,	<input type="checkbox"/> Surge vessel overflow,	<input type="checkbox"/> Accidental 3 rd party equipment OF
<input type="checkbox"/> Corrosion	<input type="checkbox"/> Saver-pit over flow,	<input type="checkbox"/> Cold vent
<input type="checkbox"/> Bulging Outward impact	<input type="checkbox"/> Valve Failure	<input type="checkbox"/> Com unit failure
<input type="checkbox"/> Relief valve failure	<input checked="" type="checkbox"/> Others (specify) BEAN BOX CAP REMOVAL BY UNKNOWN PERSON(S).	

f. Incident caused by:

Third party interference (Sabotage); crude theft; Line theft; Accidental 3rd party damage; Operational Others (including Mystery spills) **BY THE ASSET OWNER) BY UNKNOWN PERSON(S). SOME ILLEGAL ITEMS LEFT (AND OBSERVED ON SITE AT TIME OF INCIDENT) BY UNKNOWN PERSON(S) BUT RECOVERED BY THE ASSET OWNER, PRIOR TO JIV, FROM SITE (TO PREVENT FURTHER USAGE OR REMOVAL BY SUSPECTED CRUDE OIL THIEVES) WERE DISPLAYED AT THE ASSET OWNER'S OFFICE, AND COMPRISED A PEN KNIFE, BURNT HOSE, LIFTING BELT, STEEL HAMMER, RE-FABRICATED BEAN BOX COVER OR CAP WITH CRUDE OIL CONNECTIONS, A TORCH LIGHT AND A BURNT TWINE ROPE. SOIL IMPACTED ON SWAMP AT SITE IS SILTY CLAY WITH ORGANIC MATTER.**

*This can be: a) Oil Spill b) Drilling fluid/Chemical c) Situation d) construction e) Encroachment f) Fire.

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g. Spill point coordinates

Measuring unit (M) <u>Minna Mid belt</u>	
Northing:	Easting:
<u>60485.93</u>	<u>508379.40</u>
<u>[Signature]</u>	<u>[Signature]</u>

C. RISK ASSESSMENT

10. Type of environment:

- Land Swamp Water Seasonal swamp Shoreline/Waterfront

i. Type of environment to which oil has spread:

- Land Swamp Water River (identify) _____

ii. Weather condition

- Rain Sunny Dry Wet Windy Hot Cool

11. Distance from the nearest sensitive habitat

- Government reserved and designated protected area [,m]
 Drinking water source [,m]
 Built up area [,m]
 Farmlands [,m]
 Fish Farm/Pond [,m]
 Fishing net [,m]
 Others (specify) MANGROVE VEGETATION 20 IMPACTED BY SPILL.

12. Containment measures put in place;

- Booms Trench Dyke Natural depression Pit None
 Others: _____

13. Any pictures or video coverage?

[X] [N]

14. Further response/repair initiated as at the time of JIV?

[Y] [N]X

If yes to item 14, give brief description:

NOT APPLICABLE

15. Was there any disruption to the investigation?

[Y] [N]X

If yes to item 15 give brief description:

NOT APPLICABLE

This page gives information about the impacted site and the distance to the nearest sensitive habitat. In this form, the sensitive habitat impacted by the spill is mangrove vegetation. The distance from the spill to this vegetation is 20 m.

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D. TYPE/NUMBERS OF PROPERTIES, IF ANY, FOUND WITHIN THE AREA OF SPREAD OF OIL

16. Structures / Properties

S/N	Type of Structures	Description	Size	Number	Comments
NONE WITHIN AREA OF IMPACT					

17. Crops/Economic Trees

S/N	Type of crops	Young	Medium	Matured	Quantity	Comments
1.	MANGROVE VEGETATION	✓	✓	✓	WITHIN AN IMPACTED AREA OF 7.33Ha.	IMPACTED BY SPILL

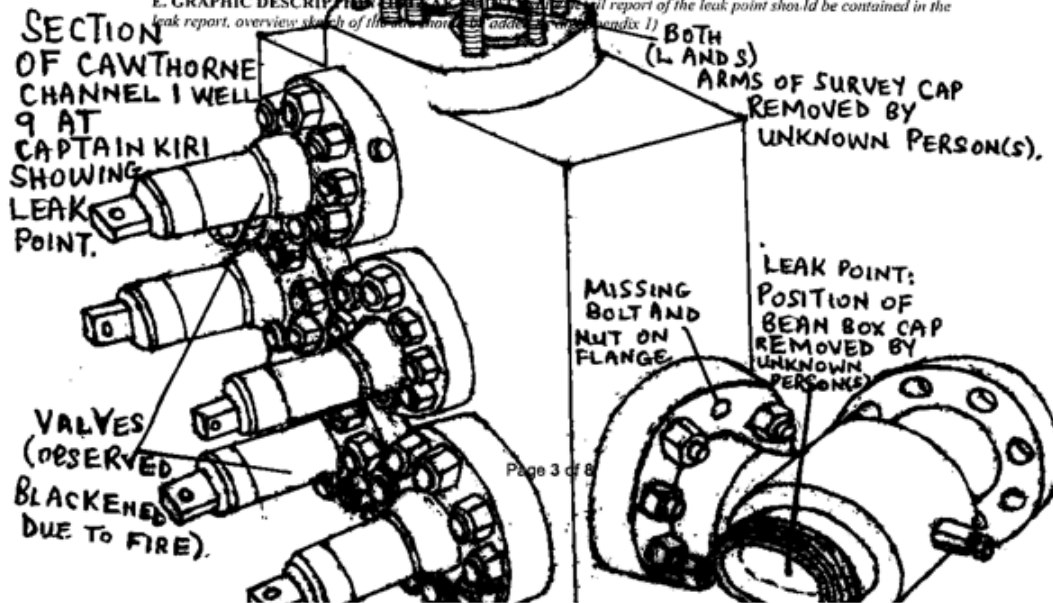
18. Fish/Nets/Ponds

S/N	Fish/Nets/Ponds	Description	Quantity/Size	Comments
NONE WITHIN AREA OF IMPACT				

19. Others (Specify) i.e. Animal Traps

S/N	Others	Description	Quantity/Size	Comments
NONE WITHIN AREA OF IMPACT.				

E. GRAPHIC DESCRIPTION OF LEAK POINT (General report of the leak point should be contained in the leak report, overview sketch of the leak point should be added as Appendix 1)



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G. INCIDENT INFORMATION:

20. Impacted Area Details

- Total calculated area of impact OIL STAINS ON LAND = 7.33HA
OIL STAINS ON WATER = 4.73HA } 14.99HA
OIL SHEEN ON WATER = 2.93HA
- Impact within SPDC R.O.W YES
- Impact outside SPDC R.O.W YES

21. Volume of oil recovered before completion of JIV (V_{rec}):

Recovered oil V_{rec} : NIL Barrels

Controlled recovery/evacuation from source with no impact to environment:

NIL Barrels

22. Net Estimated Spilled Volume V_{est} (bbls)* = 69.29

Estimated Reported Volume** V_{est} (bbls) = 70 BARRELS

*Notes:

- Volume estimation was done using an excel based tool (see attached for details on the calculation)
- Reported spilled volume is an estimate

Write other relevant notes taken into consideration for estimating the spilled in the box below:

IN CONSIDERATION OF THE FIRE INCIDENT ACCOMPANYING THE SPILL, THE NET ESTIMATED SPILLED VOLUME (IN TOTAL) IS INCLUSIVE OF THE ESTIMATED SPILLED VOLUME CONSUMED BY FIRE, AS EXPLAINED IN THE ATTACHED SPILLED VOLUME ESTIMATION DETAILS.

Calculation of the respective estimated volume is to be done on site as far as practicable using the new spill volume estimation software on site; Conversion of m^3 to barrels is Volume (m^3) x 6.29; **Round up estimated volume to next whole number using the following rules:

- Any spill volume in excess of 1 bbl is rounded up to the next whole number.
- Any spill volume in less than 1 bbl is rounded up to the next 0.1 bbl.

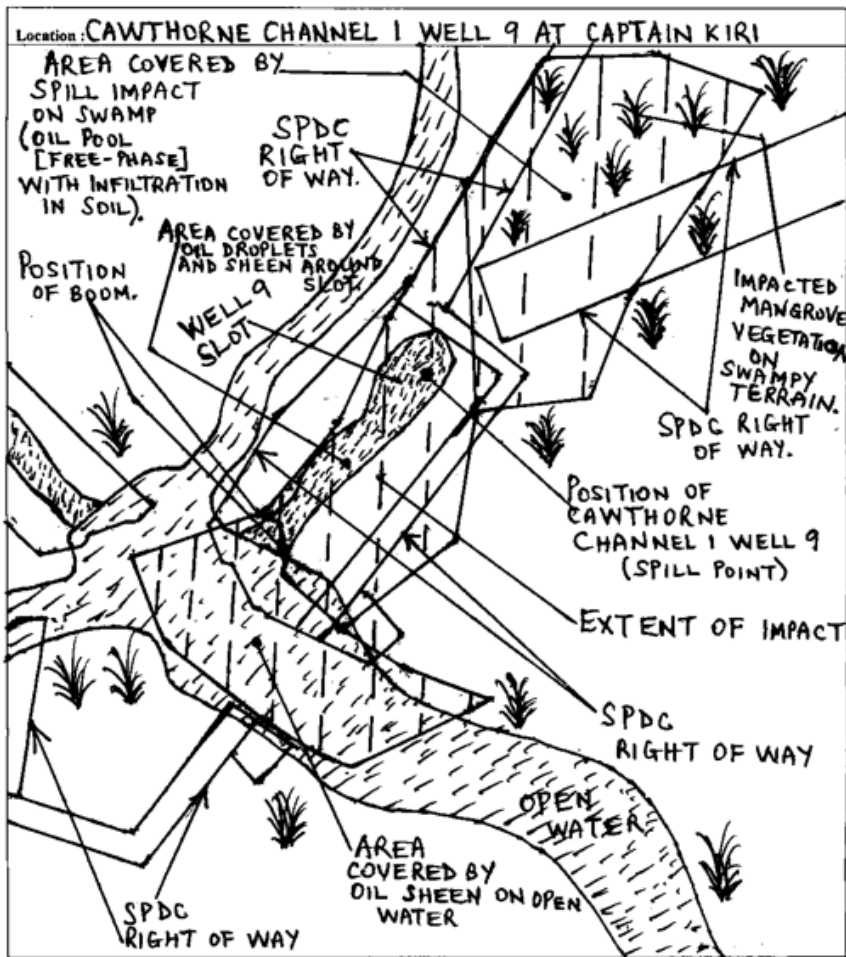
Examples: Calculated volume = 15.3 bbl ----- Reported volume = 16 bbl
 Calculated volume = 0.35 bbl ----- Reported volume = 0.4 bbl
 Calculated volume = 0.01 bbl ----- Reported volume = 0.1 bbl.

Wherever this estimation tool is not applicable please refer to paragraph 6c (Deviations) of the JIV procedure to use appropriate steps for volume estimation; record the calculation in a plain sheet of paper and attach to the JIV report.

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25. Appendix 1: Overview sketch of the site





Overview: Spill impact on Cawthorne Channel1 Well9 Right of Way at Captainkiri. Picture was taken during Overfly of 26th January 2015.



Close-up: Spill point on Cawthorne Channel1 Well9 at Captainkiri. Picture was taken during Joint Investigation of 28th January 2015.

Such a visit by the JIV team is usually followed-up by the description of the affected site using photo imagery. Herein, following the above form which was completed by the joint team, a photo description of the impacted area is presented.

Appendix D: KML FILES

In this Appendix, we provide the KML files for key events that were presented and discussed in Chapters 4 and 5.

Kml files for all oil spill events discussed in section 4.



4422 WITH SPILL
DATES, SPILL VOLUM

Appendix D: 4422 spills with spill dates, spill volume and coordinates extracted from 10 072 oil spill databases.



4357 WITH SPILL
DATES, SPILL VOLUM

Appendix D: 4357 spills filtered from 4422 with spill dates, spill volume and coordinates in the Niger Delta.



386 LARGEST SPILLS
BY VOLUME FOR NIG

Appendix D: 386 largest spills by volume filtered in the Niger Delta.



43 SPILLS
SPATIOTEMPORALLY

Appendix D: 43 spill events spatiotemporally correlated with MODIS events.

Kml files for MODIS events



43 MODIS FIRES
SPATIOTEMPORALLY

Appendix D: 43 MODIS events spatiotemporally correlated with spill events.



OIL PIPELINE FIRES
WITH 1000 M DISTANCE

Kml files for all classified MODIS fire

Appendix D: The oil pipeline fires close to the pipelines by a distance of 1000 m extracted.



INDUSTRIAL
FIRES.kml

Appendix D: Industrial fires extracted from the MODIS database.



AGRICULTURAL
FIRES.kml

Appendix D: Agricultural fires extracted from the MODIS database.



DOMESTIC-BUILT
AREA FIRES.kml

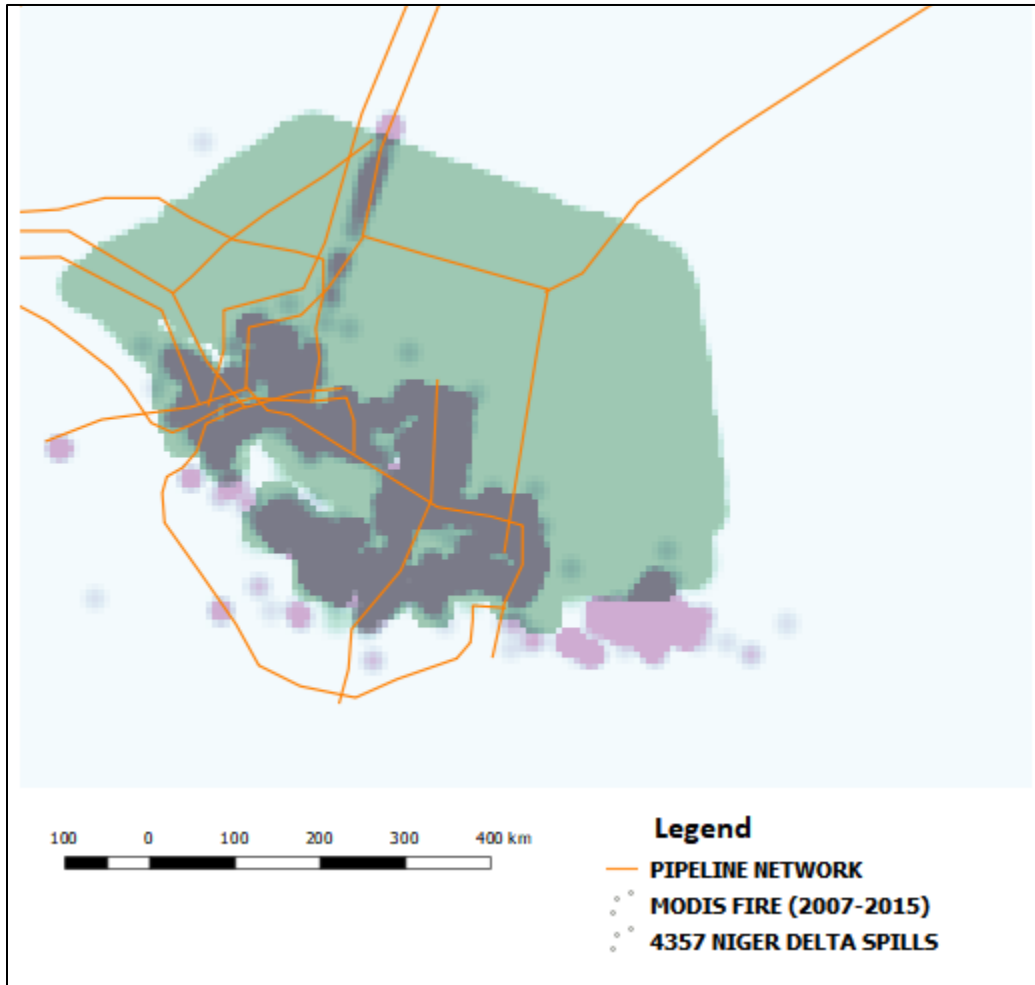
Appendix D: Domestic/built area fires extracted from the MODIS database.



OCEAN FLARES.kml

Appendix D: Ocean fires extracted from the MODIS database.

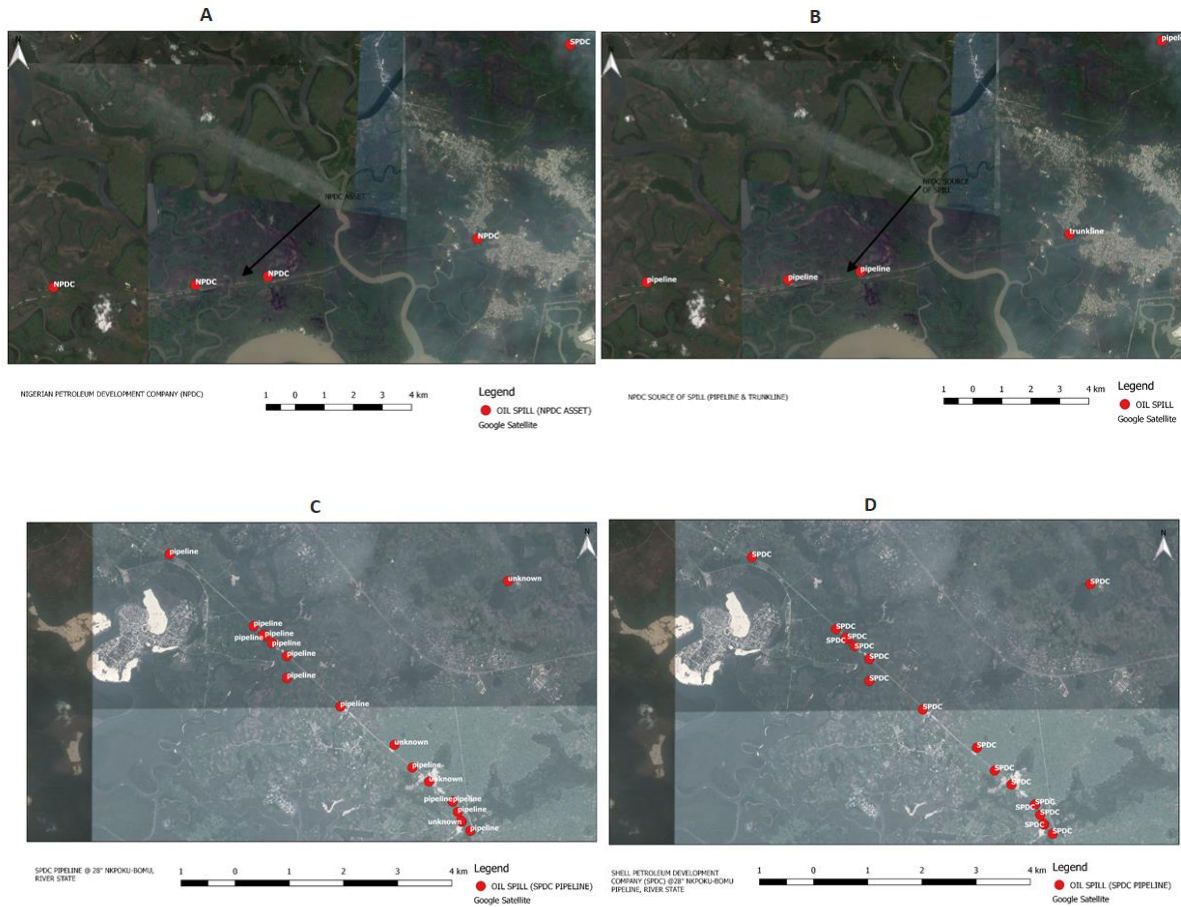
Appendix E: Heat Map



Heat map showing spatial concentration between spills and fires as they relate with the pipelines in the Niger Delta. The darker layers show spatial correlation where the activities of oil spills and fires are both concentrated in the Niger Delta.

Appendix F: Spatial mapping of spill events

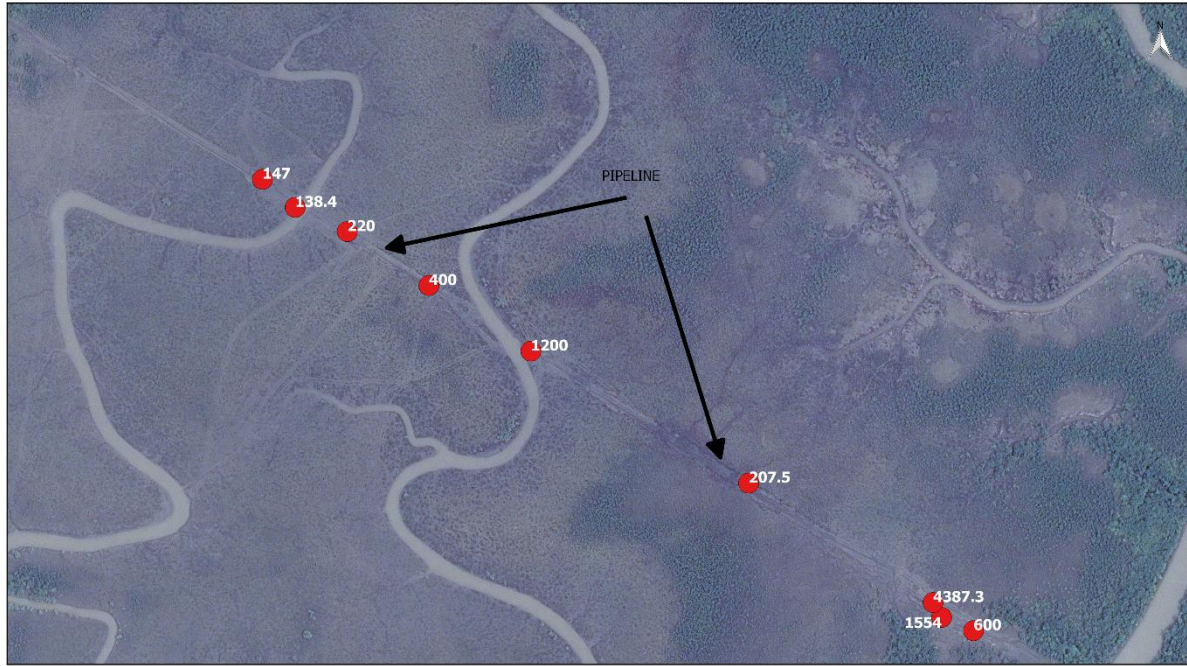
We refer to the mapping of the spill events to show satellite imagery of the spills along the oil pipeline. Some of the spills with oil facilities marked as unknown are easily identified when viewed from satellite images.



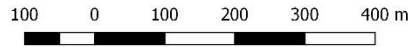
A: Nigerian Petroleum Development Company (NPDC). **B:** NPDC pipeline equipment

C: SPDC pipeline equipment. **D:** Shell Petroleum Development Company

Panel **A** and **D** show the name of the oil companies taking responsibility for oil pipeline spills (NPDC), while panel **B** and **C** described the oil facility as pipeline.



LARGE SPILL EVENTS AT DISTANCE LESS THAN/EQUAL 10m TO THE PIPELINE

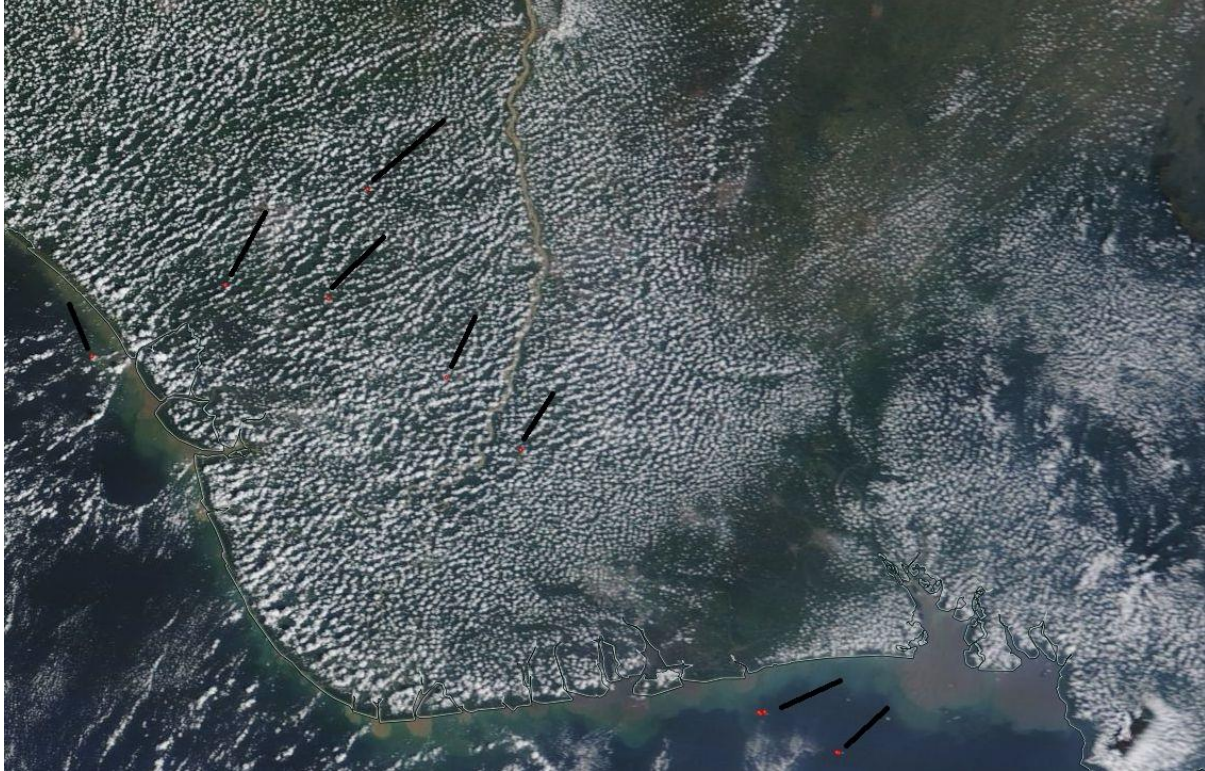


Legend

- OIL SPILL (Large Spill Volume)
- Google Satellite

This image described the process of the spatial mapping of the largest spills by volume, and the spill contamination on vegetation, which can be viewed from Google satellite from QGIS interface. The oil pipeline is own by the Nigerian Agip Oil Company (NAOC).

Appendix G: MODIS visible fire images



Visible MODIS fire active images in the Niger Delta of Nigeria corresponding to the event date '2015/11/28.' MODIS detected active fires despite cloud cover. Source <https://worldview.earthdata.nasa.gov>

Appendix H: An example of illegal refinery in Bayelsa State



An illegal oil refinery close to River Nun in Bayelsa State on November 26th, 2012. Source Akintunde Akinleye (2013).

Appendix I: The historical images of industrial fires from the Google time slider.

We described industrial fires source in the text, as fires with historical images. Examples of such fires are presented in this Appendix. The example shown below is of interest since it is a normal industrial flaring from an oil company.



Actual MODIS fires detected on 13 January 2015.



Historical image from Google time slider on 23rd December 2015



The historical image from Google time slider on 1st February 2013.



The historical image from Google time slider on 9th January 2007.

Appendix J: The statistical analysis of the yearly pattern of agricultural fires.

We present the yearly pattern and months of occurrence of agricultural fires in this Appendix.

