Oil Spill Trajectory Simulations for the Niger Delta Region of Nigeria

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Abstract. The consequences of oil spills due to exploration and exploitation activities in the Niger Delta region of Nigeria have continued to pose detrimental effects to human health and the environment. This study examines the advection effects of oil spills using the Gnome oil spill trajectory tool to forecast oil slick movement and to assess the harmful environmental consequences associated with shoreline impacts. Oil spill data were obtained from the Department of Petroleum Resources, Nigeria, and used to simulate the spread of the spills over 12 consecutive months. The results for June, July, and December revealed the worst-case scenarios due to the high volatility of Nigerian crude, with the oil reaching the shoreline after 48 and 72 hours of simulation, respectively. The results predicted rapid spreading due to the higher API (American Petroleum Institute) grade of Nigerian crude oil. Response measures are therefore needed to address the spill at an earlier stage to avert escalation.

Keywords: Oil slick movement; Shoreline; Environmental Impacts; Advection; Gnome.

INTRODUCTION

The environmental impacts of oil spills remain a widespread problem that governments, industry operators, and local communities must address in oil – and gas-producing areas worldwide. The consequences of oil spills can be severe, negatively impacting human life and the environment. Oil production activities have many positive impacts, particularly as a source of income, but also have negative consequences, resulting in severe environmental degradation that poses serious threats to the environment and human life. According to authors [1], oil production activities have led to severe ecological degradation by polluting onshore and offshore areas through the introduction of oil slicks. The Niger Delta region of Nigeria is one of the world's major oil-producing regions and a major contributor to global economic development. However, the unaddressed environmental consequences of these activities have compromised the ecosystem's resilience, resulting in reduced quality of life for residents in those areas [2].

Crude oil, a naturally occurring resource, has had a positive impact by playing a vital role as a major contributor to economic development and a source of revenue for most countries worldwide. However, the process of exploiting the resource has negative environmental impacts. The environment has long played a vital role in livelihoods, and human beings tend to exploit the resources it provides, which, when not properly utilised, can have disastrous environmental impacts on human life [3].

Oil spills in the Niger Delta region are a daily occurrence, subjecting the people living in the polluted areas to homelessness at times, to drinking non-potable water, and to farmland used to grow food being overshadowed by oil slicks. On several occasions, the consequences of these problems have led to loss of human life as the vast majority of people living in that area depend solely on the natural environment for their survival [4]. No matter the amount of oil spilt, the damage could persist for a very long time. Groundwater in Africa is said to be less contaminated and suitable for consumption, unlike surface water, which is exposed to oil slicks and chemicals [5]. However, one of the most significant adverse impacts of oil and gas activities is contamination of both surface fresh water and groundwater by oil. Oil gleam appears even in areas without recorded oil spills or where exploitation activities ceased long ago. Spilt crude oil or produced water discharged from oil wells contaminates the water, pollutes the aquifer, and renders it unsafe for consumption. People living particularly in the oil-producing region of the Niger Delta are subjected to hardship because they depend solely on flowing rivers and near-surface underground aquifers for their daily domestic activities and consumption [6].

To ascertain the extent of oil slick movement, several oil spill trajectory models were developed, such as Gnome and oil map and are used to determine the response and movement of the slick on the offshore, thus allowing the forecasting of the probable trends and impacts at the time of the spill incidence and when it reaches the shoreline [7]. In this research, the authors will use the GNOME (General NOAA Operational Modelling Environment) trajectory tool to run several simulations. Accordingly, they will review previous studies that used the tool to compare their findings with this study and to understand better understand how researchers have applied GNOME to determine oil slick movement. Several studies using the Gnome tool have shown that it allows for precise predictions of the oil route. Recent work by authors [8] reported that the Gnome software has an edge over most oil spill trajectory tools and is considered an accurate tool for forecasting an oil spill route with high precision when an adapted location map is used.

This research aims to investigate the trajectories of oil slicks and the environmental damage caused by oil exploration and exploitation activities. The study will ascertain these consequences by collecting available data on the quantity of oil spilt in the Niger Delta region of Nigeria, analysing the data, and using the GNOME oil spill trajectory model to simulate the extent of oil movement.

METHODS

The Gnome tool. In this research, the authors used the GNOME oil trajectory tool [9] to conduct the simulations. The National Oceanic and Atmospheric Administration (NOAA) developed GNOME as a user-friendly, freely accessible tool that researchers widely use to predict oil dispersion in water. Therefore, to indicate the extent of the spill, the trajectory tool was configured to operate optimally using information on winds, currents, tides, and spreading. Emergency responders and environmental agencies can deploy the tool to enable swift response and monitoring of oil slicks worldwide. The Gnome is packaged with a weathering algorithm that aids in computing and predicting oil movement under the influence of tides and winds. NOAA developed the tool using three classical methods to evaluate spill extent [9]. The GIS mode enables emergency responders to analyse spill response operations, while the Standard mode excels at forecasting spill routes for a specified location. The Diagnostic mode allows users to simulate real-time spill scenarios. In this research, the authors used the Standard mode to forecast potential oil trajectories under wind and current uncertainties, as stated above.

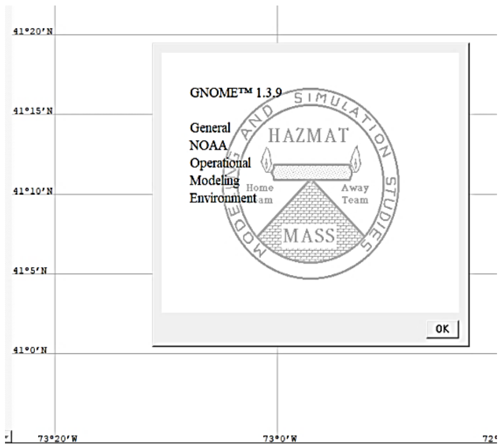


Figure 1 – Gnome operational modelling environment

Now, to achieve the location setup, the geographical location of the Niger Delta region lies between 4° 15' and 4° 50' in latitude and 5° 25' and 7° 37' in longitude, and must be uploaded as shown in Figure 2 below.

After successfully setting up the model workspace, uploading the location file, and defining the time range, the researchers specified the simulations and wind data in the tables below.

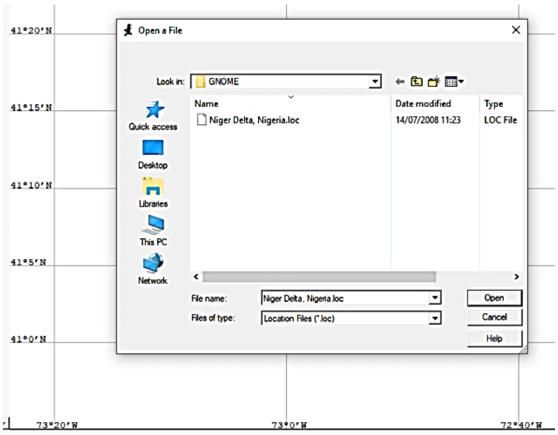


Figure 2 – Workspace for location file

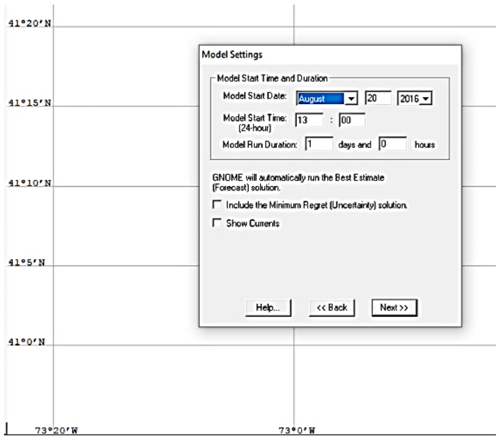


Figure 3 – Model start time and duration setup

Table 1 – Summary of oil spill data [10]

Month	Causes of the Spill (by numbers)							Total number of spills	Quantity (barrels)
	Natural cause	Corrosion	Failed Equipment	Sabotage	Human error	Unknown cause	Mystery		
January	1	3	12	31	1	6	2	56	324.56
February	0	5	10	39	1	8	0	63	515.42
March	0	4	8	41	0	6	4	63	191.68
April	1	5	20	35	0	18	3	82	139.05
May	0	2	9	51	1	18	1	82	332.46
June	3	2	12	61	3	12	1	94	19 445.92
July	0	2	7	32	1	7	5	54	3 256.27
August	0	2	3	16	0	14	3	38	1 338.54
September	0	3	8	33	0	1	3	48	598.13
October	2	4	10	34	0	4	2	56	130.67
November	2	3	2	58	4	5	2	76	1 013.32
December	1	2	4	24	0	9	1	41	5 451.20
Total	10	37	105	455	11	102	27	753	32 756.86

Now, to run the simulation successfully, wind data is required. The table below summarises wind data adapted from [11].

Table 2 – Summary of wind data [11]

Months	Wind Speed m/sec
January	3.40
February	3.89
March	3.90
April	3.98
May	3.71
June	3.67
July	3.67
August	3.93
September	3.64
October	3.19
November	2.91
December	2.86

Then, returning to the window, the spill point location has to be initiated before moving to the map window, as shown in the figure below.

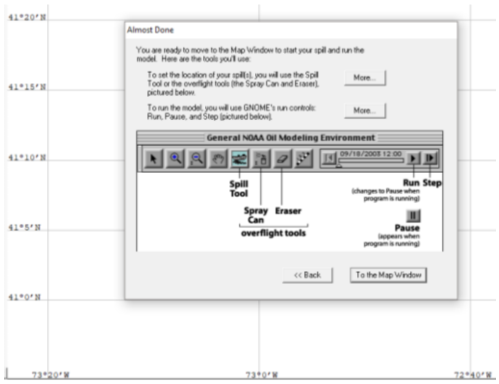


Figure 4 – Spill point locator interface

Gnome Model Setup. The researchers configured the GNOME model software to run the simulations in Standard mode because the study does not involve a real-time scenario. This mode excels at predicting spill routes at specified locations. Using the general Gnome location file database for the region intended for this work's simulations, the tool is set up to run simulations with time steps ranging from 6 hours to 72 hours, because Gnome can only run simulations for up to 3 days in this mode [9]. The researchers then configured the software to operate under conditions of uncertainty, accounting for uncertainties in wind effects and slick size distribution. To predict minimum-regret solutions and fine-tune wind speed during simulations, other meteorological data, such as current, were selected as movers from the Gnome database. The researchers then indicated the spill position on the location map with a black horizontal line to show the actual point of initiation, known as the line source (at any point along the pipe length). The wind characteristics and direction in Nigeria predominantly flow from offshore southwest to the Northeastern part, as reported by the authors [12]. The researchers then selected the simulation start time. GNOME can simulate various pollutant types, including gasoline, kerosene, non-weathering substances, and fuel oil. For this study, the researchers chose the non-weathering pollutant category because it limits rapid evaporation and allows the software to simulate spill extent more effectively [9].

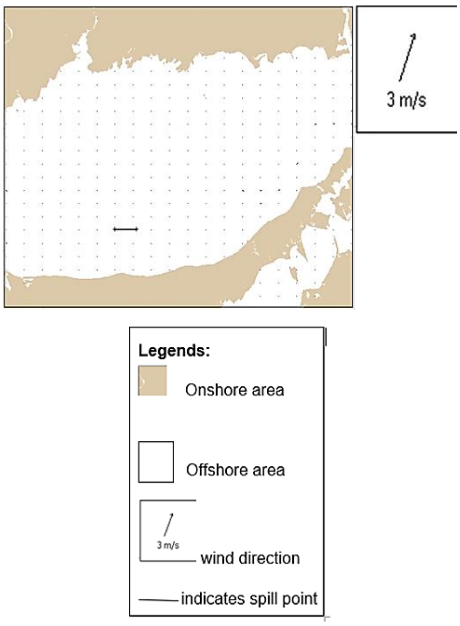


Figure 5 – Spill point (Line Source)

Optimisation. The governing equations guiding the Gnome tool are developed to employ a mixed Eulerian/Lagrangian diffusion law and to forecast how oil spreads. In their work, authors [13] highlighted that the area covered by water is determined by Fay's spreading governing equations, which describe the slick's spreading diameter and are presented below.

Table 3 – Fays' spreading equations (1)

Spreading Phase	1-D Spreading Length (Le)	Axissymmetrical Spreading Radius (R)
Gravity-Inertia	$1.39(\Delta\rho g A t^2)^{1/3}$	$1.14(\Delta\rho g V t^2)^{1/4}$
Gravity-Viscosity	$1.39(\Delta\rho g A^2 t^3 \upsilon^{-1/2})^{1/4}$	$0.98(\Delta\rho g V^2 t^3 \upsilon^{-1/2})^{1/4}$
Surface Tension - Viscosity	$1.43(\sigma^2 t^3 \rho_w^{-2} \upsilon^{-1})^{1/4}$	$1.60(\sigma^2 t^3 \rho_w^{-2} \upsilon^{-1})^{1/4}$

However, authors [13] reported that Fay's Law did not account for wind effects on the spill area. To cater for the wind effects on the spill area, particularly for field measurements, the law is modified by [13] as:

$$A = 2270\left(\frac{\Delta\rho}{\rho_0}\right)^{2/3} V^{2/3} + 40\left(\frac{\Delta\rho}{\rho_0} V U_w\right)^{1/3} t \quad (2)$$

where A – area of oil slick in (m2); V – total volume spilt in (bbl); Uw – wind speed (knots); $\Delta\rho$ = density change (Kg/m3).

RESULTS AND DISCUSSION

The oil spill data were reported monthly, without an indication of the amount of oil spilt per incident, as shown in Table 1. However, in this study, the researchers collected data on the expected quantity spilt per incident and averaged these values to calculate the mean amount per spill, as shown in Table 4.

Table 4 – Calculated average quantities split per incidence

Month	Total Number of Spills	Total quantity split (barrel)	Average quantity/spill (barrel)
January	56	324.56	5.79
February	63	515.42	8.18
March	63	191.68	3.04
April	82	139.05	1.69
May	82	332.46	4.05

Month	Total Number of Spills	Total quantity split (barrel)	Average quantity/spill (barrel)
June	94	19445.92	206.87
July	54	3256.27	60.30
August	38	1338.54	35.22
September	48	598.13	12.46
October	56	130.67	2.33
November	76	1013.32	13.33
December	41	5451.20	132.95

Oil Spill Category Comparison. Comparing the average quantities of the results obtained in table 4 above with that of oil spill categories standard as reported in the work of authors [14] table 5 below, it can be seen in figure 6 below that after analysing and obtaining the averages for the spill incidences from January to December, the result in the chart showed that all incidences falls within the range of minor oil spill category with quantities less than 250 barrels per spill incidence.

Table 5 – Oil spill categories standard

Category	Quantity (barrel)	Environment
Minor	< 25 to < 250	Inland Waters, Onshore, Offshore and Coast Waters
Medium	between 25 and 250 or between 250 and 2500	Inland Waters, Offshore and Coast Waters
Major	>250 excess of 2500	Inland Waters, Onshore, Offshore or Coast Waters
Disaster	>2500	Onshore, Offshore or Coastal Water

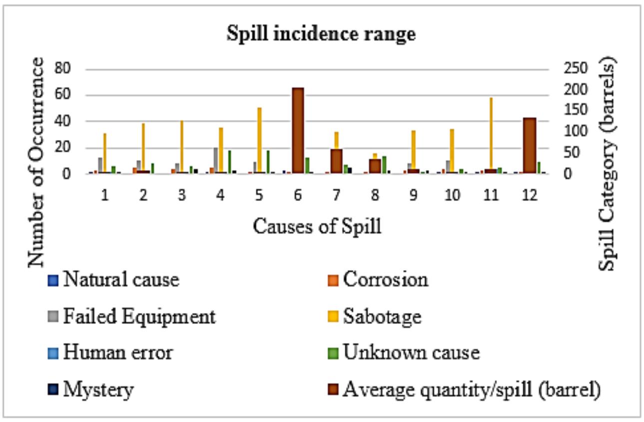


Figure 6 – Comparison of Spill incidence with Spill Category standards

Spill Extent. The extent of the oil spill in the Niger Delta was determined using the collected spill data. Most spill incidents in the Niger Delta occurred for several reasons, as shown in Table 1, and sabotage is the leading cause of oil spills. Records show that 753 spills occurred in 2015, of which 455 were caused by sabotage, while other factors caused the remainder. Figure 6 shows that smaller spill quantities happened in the first and second quarters, except in the sixth month, which accounted for approximately 63% of the total annual spill volume and fell within the catastrophic spill category. In the last two quarters, spill quantities declined, although the data also indicate a sudden increase in the preceding month.

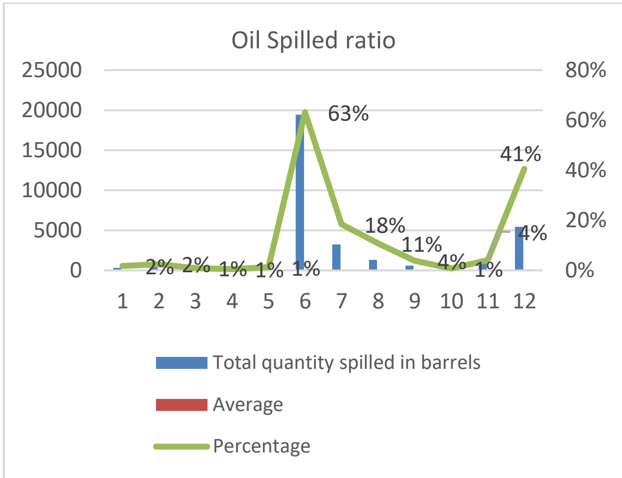


Figure 7 – Percentage Spill ratio vs Spill extent released

Spill Frequency. To ascertain the frequency of spill occurrences from 1978 to 1982, the work of authors [14] was compared with that of this study for recent years from 2010 to 2015. The figure below shows that larger quantities have been spilt in the past than in recent years. An apparent disparity exists between the two scenarios: the past incidents were in the disastrous category, and all occurred due to either equipment failure or a blowout. In recent years, more oil spills have been recorded than in the past, and it was found that almost 75% of the spills were minor, mainly due to militancy-related sabotage affecting the oil-producing states of the Niger Delta. Although oil spills are inevitable, effective policy implementation and the sensitisation of vandals can significantly reduce them in the Niger Delta, compared to current levels.

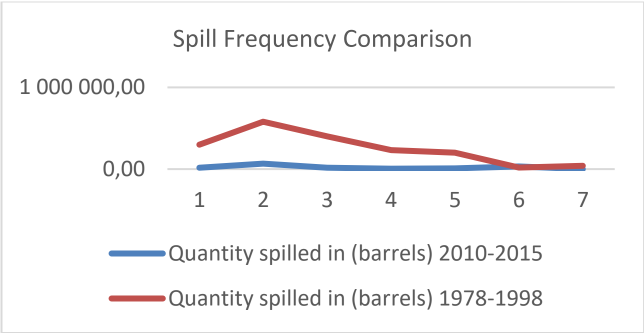
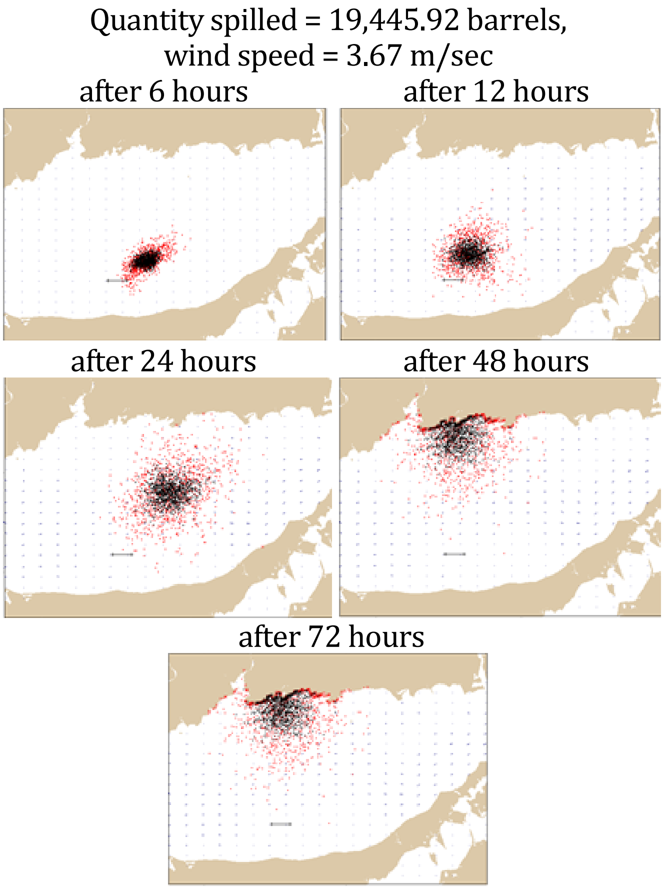
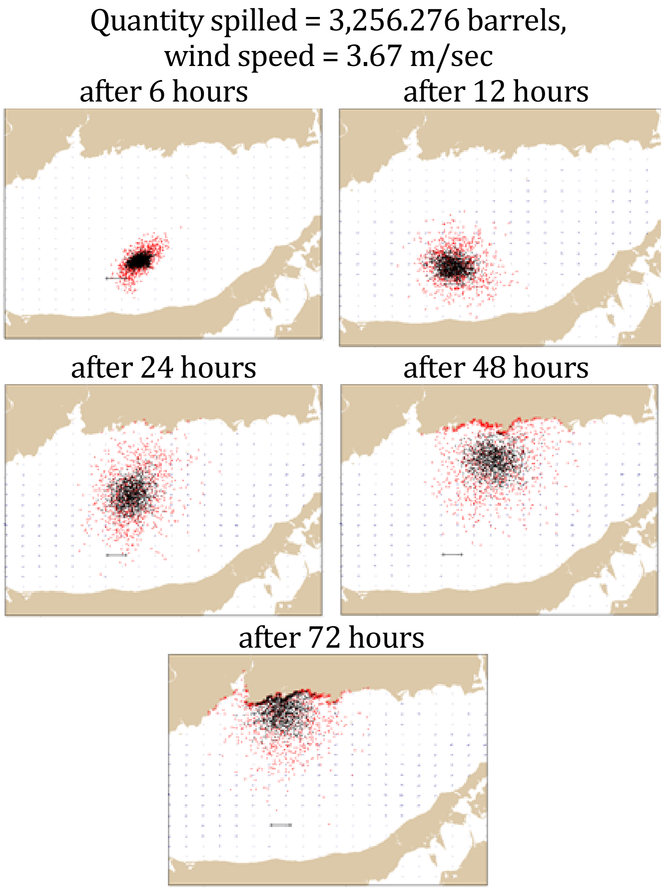


Figure 8 – Comparison of Spill Frequencies with Spill Variations

Simulations. This section presents the trajectory simulations conducted in this study. The study uses the oil spill data listed in Table 1 to run the simulations in the GNOME software and presents both worst- and best-case scenarios below.

a) Worst-case scenario: results of this kind showed that the spilt oil spreads farther from where the spill initiated and escalates, reaching the shoreline, where it finally sinks into the shore within a short period beyond containment.





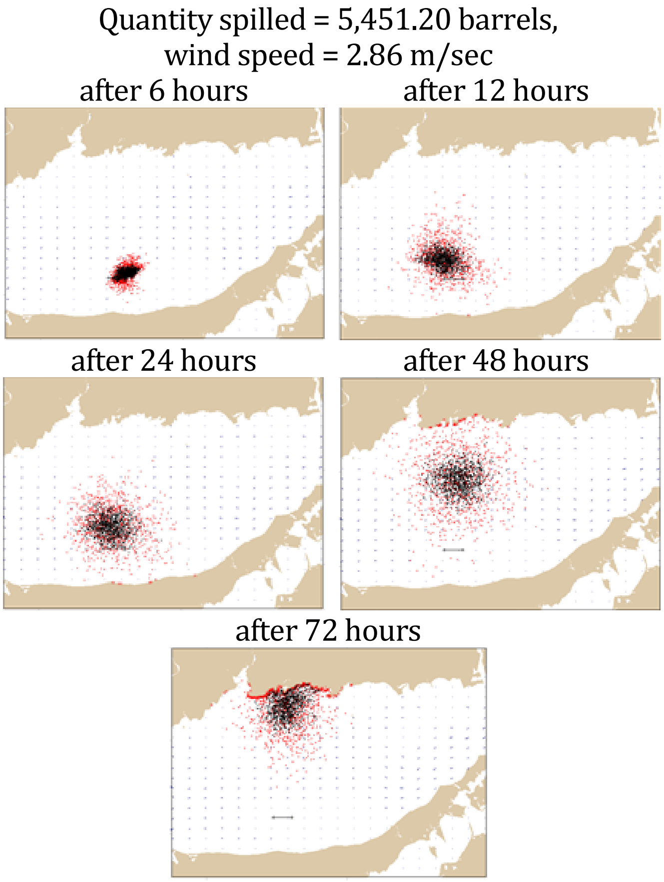


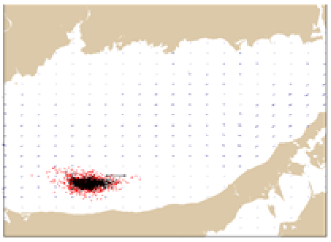
Figure 9 – Worst-case Scenarios

It is pertinent to note that the black spots indicate spilt oil, while the red spots indicate uncertainties due to wind effects, and the same applies to all the results in this work.

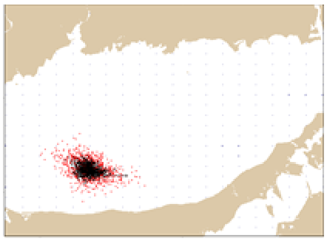
b) Best-case scenario: results from this situation showed floating oil that can be easily contained and prevented from spreading further using containment methods.

Quantity spilled = 191.6814 barrels, wind speed = 3.90 m/sec

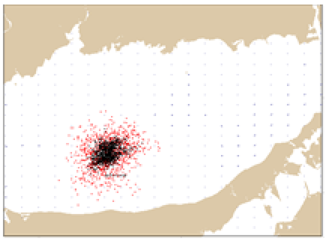
after 6 hours



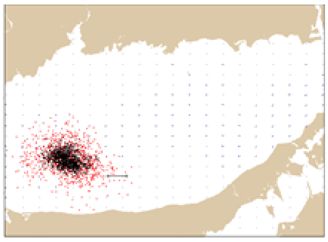
after 12 hours



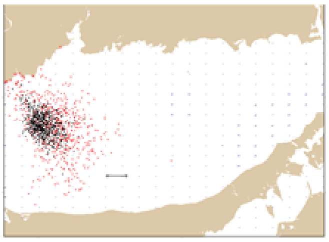
after 24 hours



after 48 hours

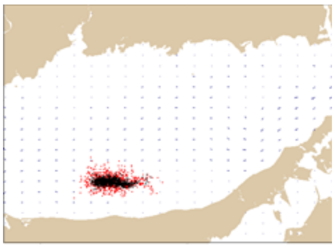


after 72 hours

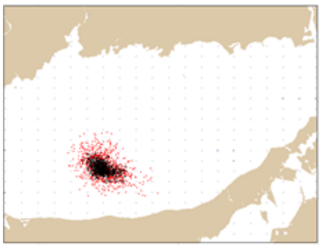


Quantity spilled = 139.0537 barrels, wind speed = 3.98 m/sec

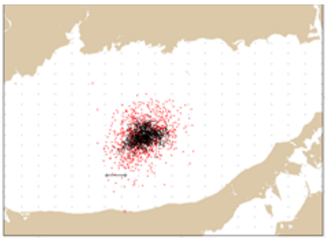
after 6 hours



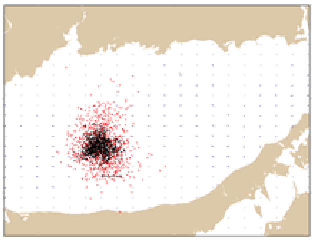
after 12 hours



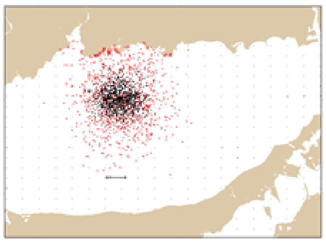
after 24 hours



after 48 hours

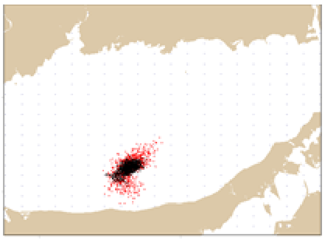


after 72 hours

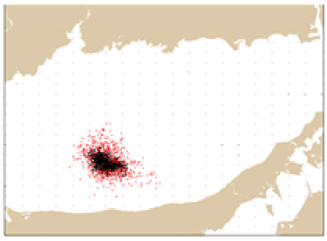


(Quantity spilled = 130.6736 barrels, wind speed = 3.19 m/sec)

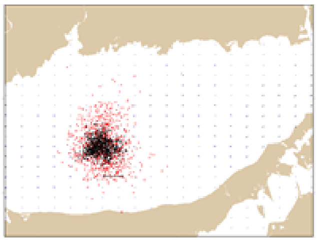
after 6 hours



after 12 hours



after 24 hours



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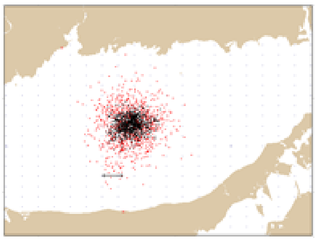

after 72 hours

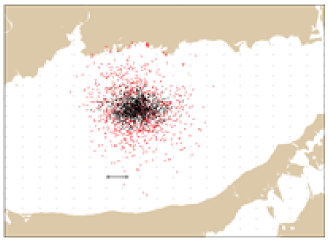

Figure 10 – Best-case scenarios

Discussion of the Trajectory Output. This study ran oil-spill trajectory simulations in GNOME with time steps of 6, 12, 24, 48, and 72 hours. The study simulated the entire year of 2015, from January to December, and set the wind direction to southwest throughout the year, consistent with the predominant wind direction in the Niger Delta region reported by [12]. Different wind speeds were used for each simulation, as indicated in Table 2 above. The results of this study showed two significant trends: worst- and best-case scenarios. This study compared the results with spill category standards and with similar studies conducted using the GNOME software in different parts of the world.

Naturally, when a spill occurs offshore, it immediately undergoes weathering processes, and if the spilt product is a gas or diesel fuel, it might evaporate before it hits the shoreline [15]. Although Nigerian crude is highly volatile and has the characteristics of a light oil, with an API gravity of 320-370 source [16], those qualities make it disperse easily. Now, looking at the results for both the worst- and best-case scenarios, Gnome forecasted clearly that, during the early hours of the spill, between 6 and 24 hours after the incident, the spilt product moved slightly from the initial point of spill to another location, but remained afloat and had not reached the shoreline. However, after running additional simulations by increasing the time steps for both scenarios, the forecasted results for the best-case scenarios showed floating oil trends, while the worst-case results showed oiling at the shore; this implies that larger oil spills are more likely to reach the shoreline sooner than minor spills, depending on the oil type, wind speed, and the environment in which the spill occurred.

Floating Oil. Results for the best-case scenarios which were run with spill data that are within the range of minor spill category as analysed above even after simulating for 48 hours and 72 hours since the oil spilled are in less quantities, it was found that the oil remains afloat but have spread further due to wind effect and the high volatility quality of the Nigerian crude which makes it easier to spread and disperse as it stays longer on the water. Although wind velocity in the Niger Delta is virtually constant, this is why oil slick movement is less pronounced than in areas with strong winds and currents. Comparing the results with the Clair spill incident in the Faroe-Shetland Channel in the United Kingdom, reported by the authors [8], after simulating for 9 hours with a constant wind speed of 5 m/sec, although not a minor spill, the results predicted that the spilt oil did not evaporate and remained afloat. However, with a drastic increase in wind speed from 5 m/sec to 13.5 m/sec, the spilt oil could reach the shoreline in other regions of the Norwegian coastal area if left unattended, and they suggested the need for containment. However, the forecasted results in this work indicate that minor spills in the Niger Delta can be managed for up to 72 hours without escalation by employing physical containment methods such as booms and skimmers.

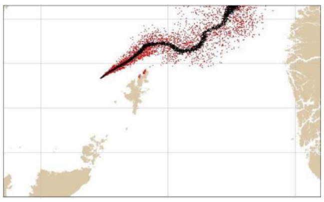

Figure 11 – Forecasted spill route for the Clair spill incidence in the Faroe-Shetland Channel

Shoreline Oiling. The Gnome tool forecasted results for worst-case scenarios and predicted that oil would reach the shoreline after 48 and 72 hours of simulation, respectively. Although a few of the results at 48 hours showed red spots along the coastline, indicating uncertainties in the Gnome software, the tool can still make accurate predictions and compensate for uncertainties in the wind data input. However, the analysis classified larger spill volumes as catastrophic because slick size distribution and wind effects drove the oil toward the shoreline. Therefore, larger quantities when split spread easily owing to the lower specific gravity of Nigerian crude, which makes it less viscous and lighter [16]. In addition, the effects of wind and slick size distribution contribute to the slick's rapid movement toward the shoreline. If left unattended, the oil will penetrate the shores. Even after cleanup, once the shore reaches its maximum retaining capacity, the oil will float back and contaminate the water again authors [17], which is why it is necessary to respond to oil spills at an earlier stage.

Advection Effect of the Spilt Oil. It is evident that whenever an oil spill occurs, the spilt oil undergoes numerous weathering processes. However, the results show that the oil spreads horizontally on the water's surface, despite other processes acting on it. To justify the above statement, authors [18] asserted in their study that horizontal displacement and oil dispersal are the main factors in the movement of oil on water. Therefore, the results of this research clearly demonstrated slick dispersal and demonstrated the effectiveness of the Gnome tool in simulating oil slick movement.

CONCLUSIONS

Oil spills are inevitable so long as the search for and consumption of oil remain realities. Therefore, the only way to eliminate an oil spill is to stop exploitation entirely. However, because society continues to produce oil, governments and industry operators must implement responsive measures to eliminate, or at least reduce, the risk of oil spills in the surrounding environment. Gnome software is one of the best reactive tools for predicting the path of an offshore oil slick. Results from this study have shown the effectiveness of the tool in forecasting trends for the various simulated spill categories and the extent to which they cover in the Niger Delta. The forecasted results will give on-scene responders a first-hand idea of how to respond to such scenarios and avert escalation and further penetration of the oil slick into the shoreline of the Niger Delta region.

This study found that oil spills in the major-to-disastrous categories will reach the shoreline quickly and therefore require immediate response. However, majority of the forecasted results in this study are within the minor and medium spill categories but because these spills are left unattended and not responded at earlier stage, the oil will hit the coast and eventually cause severe harmful impacts comparable to the disastrous incidence and that is why all spills irrespective of the category must be responded to immediately to protect the environment from the damaging consequences of the oil spill.

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