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A Theoretical Approach for Designing a Decision Support System for Effective Emergency Response in Oil Spill Management

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ABSTRACT

The study is based on the design of a comprehensive Decision Support System (DSS) to effectively respond to emergencies in the offshore Niger Delta region, using the case study of the December 20, 2011, Bonga Oil Spill incident. Although there has been a positive change in the preparedness of oil spill responses, the current response logistics is still problematic, which affects efficiency and environmental impact. This study provides solutions to the critical gaps in the current decision support systems by proposing a multi-faceted DSS framework, which integrates advanced modeling techniques: the Blowout and Spill Occurrence Model (BLOSOM) and the Oil Spill Cleanup Operations Model (OSCOM). The trajectory of oil spills under different environmental conditions was simulated, predictive modeling of resource allocation, and the use of visualization tools to assess the effectiveness of response was carried out. By using Nigeria-specific information, the research helps to improve rapid decision-making, lessen the environmental effects, and reduce community conflicts. This powerful DSS framework can make a considerable enhancement to the oil spill response plans in Nigeria.

INTRODUCTION

As the world continues to rely on oil, its exploration, production and transportation will persist. But the deleterious environmental, health and socio-economic consequences of hydrocarbon exploitation, particularly during an oil spill, cannot be overlooked. Oil spills can also occur onshore, offshore, or at shorelines and are one of the most devastating forms of environmental challenges, especially for marine and coastal ecosystems (El Moussaoui and Idelhakkar 2023). Significant spills such as the Deepwater Horizon spill in the Gulf of Mexico (2010, ~4.9 million barrels) and the Bonga field spill offshore Nigeria (2011, ~40,000 barrels) have been reported (National Research Council, 2013; NOSDRA, 2012). They are caused when tanks fail, pipelines rupture, tankers crash, blow out occurs due to human error or pipeline vandalism for oil theft (which is predominant in Nigeria). An incident of oil spills can become a transboundary issue if it affects areas outside of the country's territorial waters and Exclusive Economic Zone (EEZ).

Oil Weathering Processes

Crude oil that is released in an accident creates a slick that is influenced by diffusive (concentration difference) and advective (wind, currents, waves) processes (Walker *et al.* 2015). Oil-weathering processes (OWPs) result in alterations to the physicochemical properties (oil density and viscosity) over a long duration, as hydrocarbons are not considered to be conservative pollutants (Mishra and Kumar, 2015). The most important OWPs are spreading, evaporation, dispersion, emulsification and dissolution as presented in Figure 1. These processes occur over longer periods, including photo-oxidation, biodegradation and sedimentation (Keramea *et al*., 2021). Surface tension (smaller values spread farther), specific gravity (most oil spills float, but can increase as the oil evaporates), and viscosity (resistance to flow) all influence the spread of an oil spill (EPA, 1999).

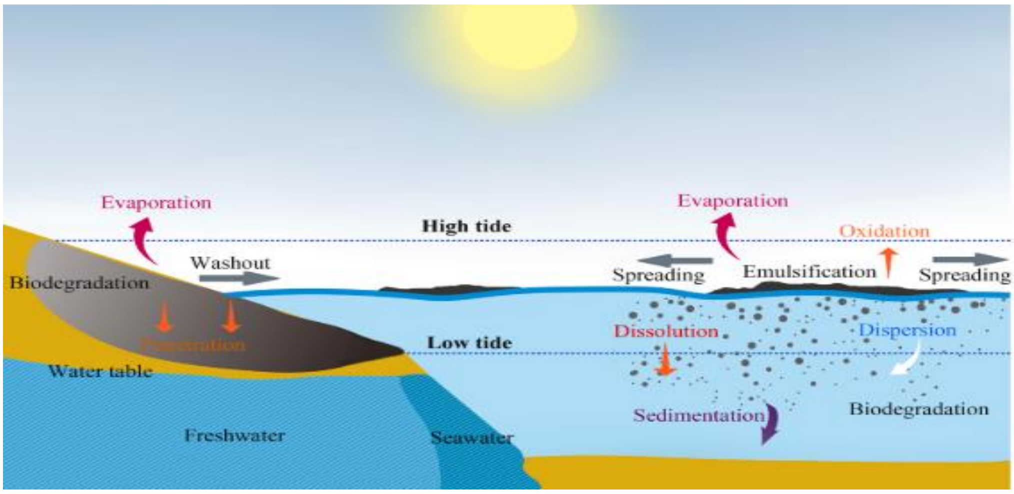

Figure 1: Schematic diagram of typical oil weathering processes at sea and oil-shoreline interaction (ITOPF, 2014)

Need for decision support systems (DSS)

There is a need for a DSS to tackle the issues of coordination, communication, resource allocation, and deployment of equipment when responding to oil spills in a timely and efficient manner. A DSS is an integrated, interactive computer system which assists decision making by providing user-friendly interfaces, data and knowledge of experts (Fabbri, 1998). The successful DSS has five main components: risk assessment (Sardi *et al*., 2019), spill detection (Mera *et al*., 2017), spill modelling (Nelson and Grubesic, 2018; Afenyo *et al*., 2016; Spaulding, 2016), countermeasure selection (Yang *et al*., 2021) and optimization of response operations (Chen *et al*., 2019).

Some studies have focused on the different aspects of DSS for the responses to oil spills: Ye *et al*. (2021) proposed an emergency response system from dynamic simulation and particle swarm optimization, presented in Figure 2, without considering oil transportation processes. Limited consideration of wave fields and biogeochemical conditions in oil-spill modeling was also identified by Keramea *et al*. (2023), who reviewed met-ocean forcings in oil-spill modeling. Ma *et al*. (2021), however, merged BLOSOM and OSCOM and focused on the Gulf of Mexico rather than Nigeria (Ma *et al*., 2020). Liubartseva *et al*. (2016) presented WITOIL for the Mediterranean Sea without involving logistics. DSS-OSM has been developed for use in Canada, but the application is not specific to Nigeria (Li *et al*., 2022). In Malaysia, Pourvakhshouri *et al*. (2006) have created a knowledge-based system without considering logistics. Grubesic *et al*. (2019) took a different approach to resource allocation, one that did not include modelling of the trajectories. Amir-Heidari and Raie (2019) have proposed a DSS without any solutions for logistics in the Persian Gulf. The identified gaps are that some studies optimize allocation but do not consider oil fate and transport, some do not consider logistics in focus on fate or transport, and lastly, for integrated approaches, they are site-specific and have no relation to Nigeria. A multi-factorial Nigeria-specific DSS that addresses the limitations is therefore developed in this research by incorporating: Dynamic environmental parameters – oil fate and transport models

(BLOSOM). Optimization of resource deployment (OSCOM). Analytical tools (Minitab). The case study for validation is the Bonga oil spill (20th December 2011).

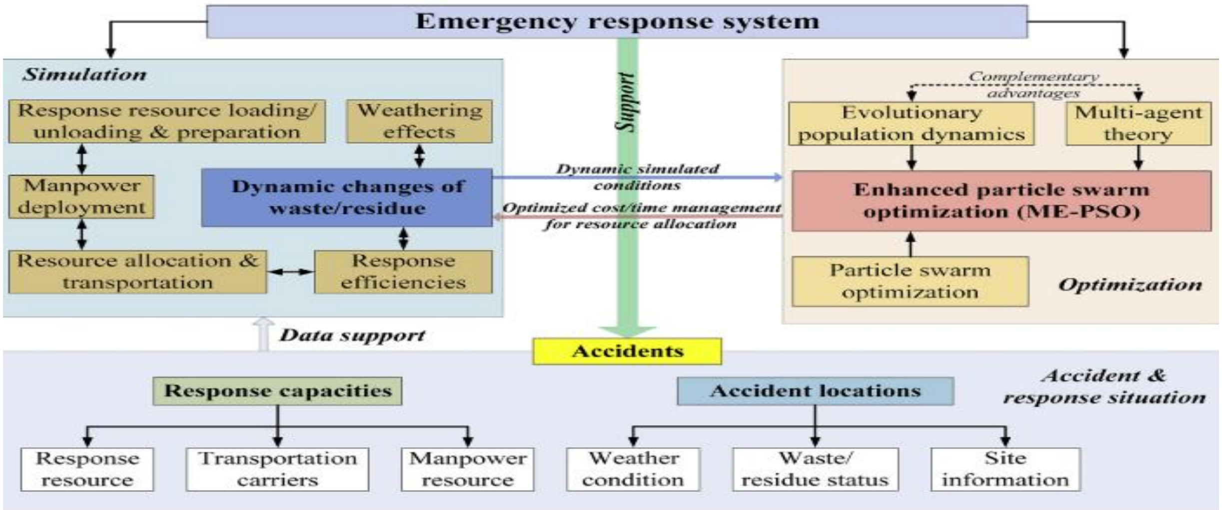

Figure 2: Framework of a simulation-optimization emergency response system (Ye *et al.,* 2021)

Details of Study Area

Bonga oil field is situated in the deep waters of the Gulf of Guinea (Lat:4.5532° N, Long:4.6163° E), some 120 km away from the Niger Delta, at depths of more than 1000 m and operated as Oil Mining Lease (OML) 118, as shown in Figure 3. Its production capacity is more than 200 thousand barrels of oil per day. SNEPCO operates the field for NNPC and its partners (SNEPCO, 2023; Offshore Technology, 2024). It leaked more than 40,000 barrels of oil into the Atlantic Ocean during a cargo transfer from the FPSO on December 20, 2011. The spill is believed to be one of the biggest in Nigerian history (NOSDRA, 2012). The countries which may be at risk of impact are Nigeria, Cameroon, Equatorial Guinea and São Tomé and Príncipe. Satellite observations indicate distances: Nigeria ~121 km, Cameroon ~489.75 km, Equatorial Guinea ~451.74 km, Príncipe ~425.62 km, São Tomé ~483.91 km (Copernicus, 2025).

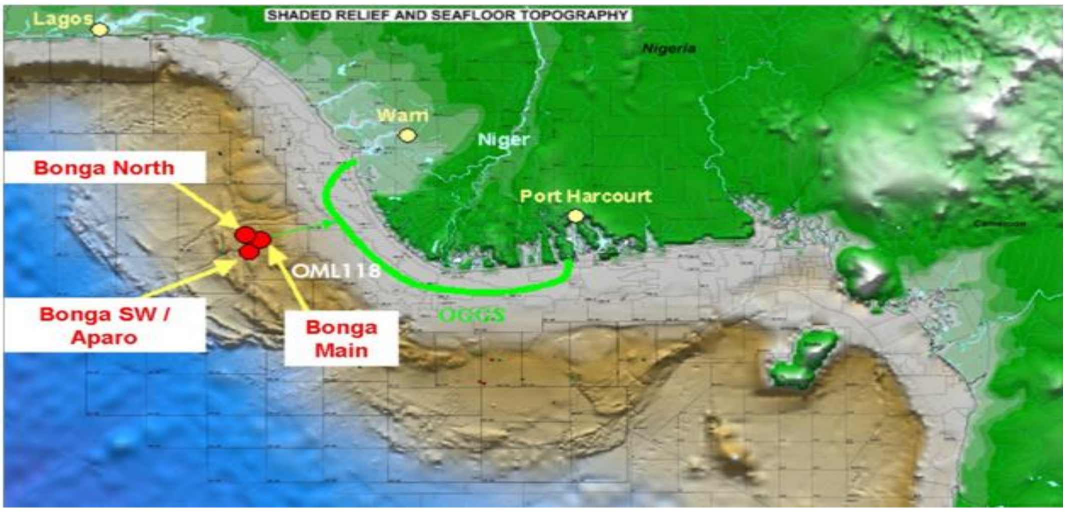

Figure 3: Location of Block OML118 and Bonga Field area offshore Nigeria (Xiao *et al.*, 2016).

MATERIALS AND METHODS

Simulation Tools and Software

Blowout and Spill Occurrence Model (BLOSOM) is a tool developed by the U.S. Department of Energy (NETL) for simulating the fate and transport of oil under variable environmental conditions. It is a stand-alone package for deep-water blowout scenarios from source to final fate. BLOSOM incorporates six modules: Jet/Plume, Transport, Weathering, Crude Oil, Gas/Hydrates, and Hydrodynamic Handler (Sim *et al.*, 2015; NETL, 2017); the Interaction diagram of BLOSOM's simulated processing modules is shown in Figure 4, while the user interface of BLOSOM, which shows the input parameters, is presented in Figures 5a to 5e.

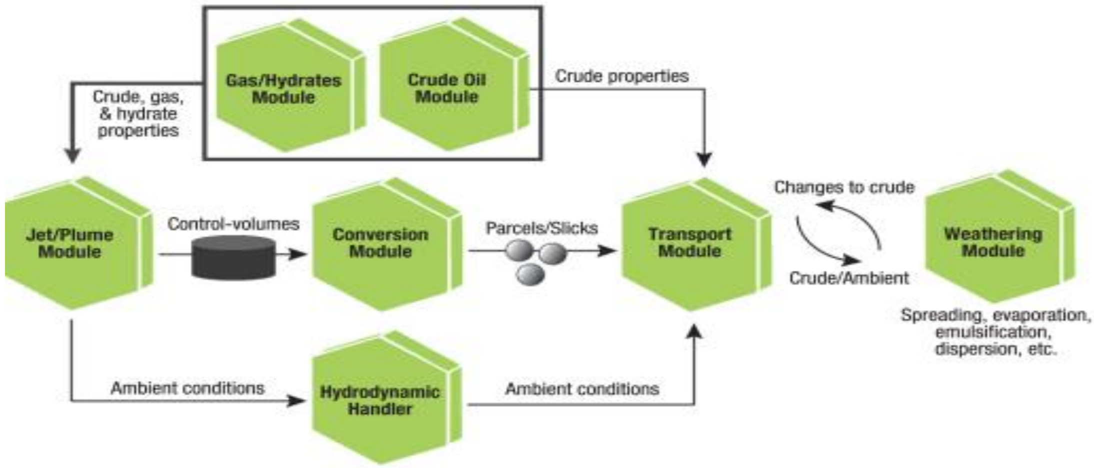

Figure 4: Interaction diagram of BLOSOM's simulated processing modules (NETL, 2017).

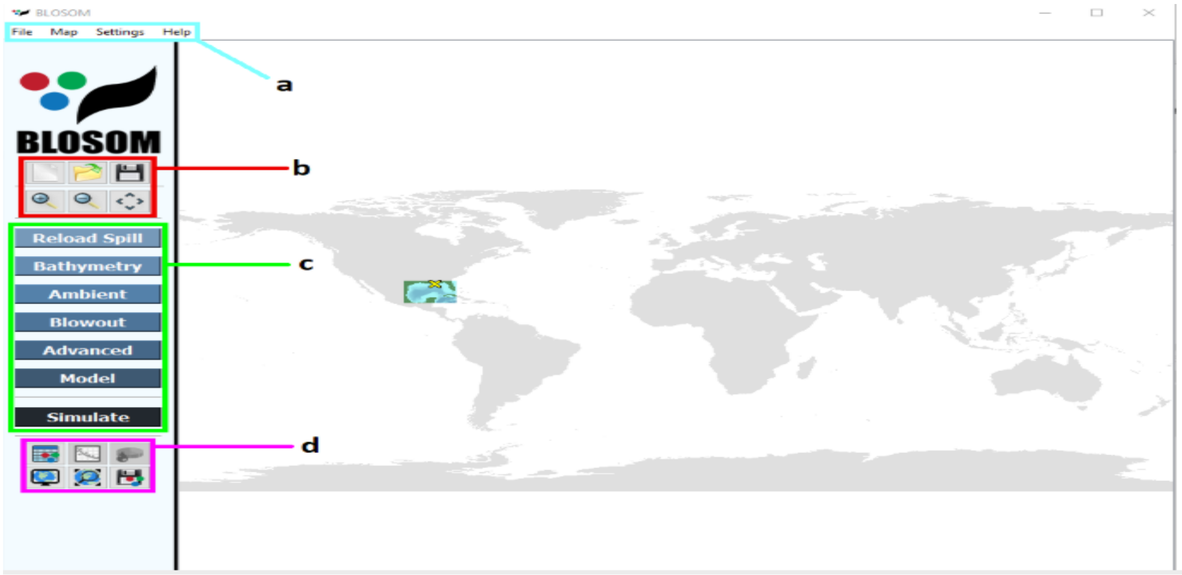

Figure 5a: BLOSOM user interface (NETL, 2021)

Oil Spill Cleanup Operations Model (OSCOM) is a spatial optimization tool for modeling response operations, using mathematical programming to minimize total time and cost in dispatching cleanup equipment (Grubesic *et al*., 2017). The output from BLOSOM is the input files to OSCOM for processing. Minitab is a statistical analysis tool for validating predictive models, performing regression and correlation analysis, and creating visualizations.

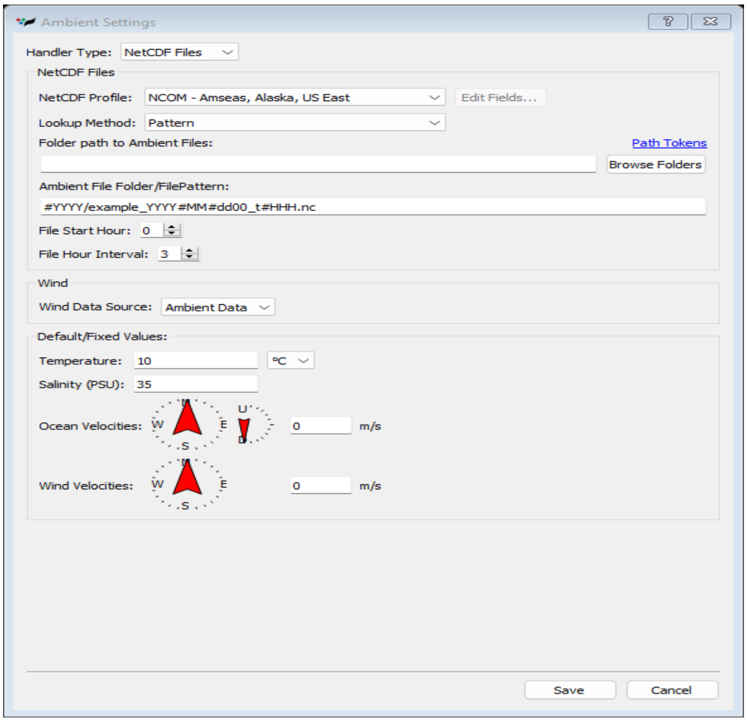

Figure 5c: Ambient Settings of BLOSOM

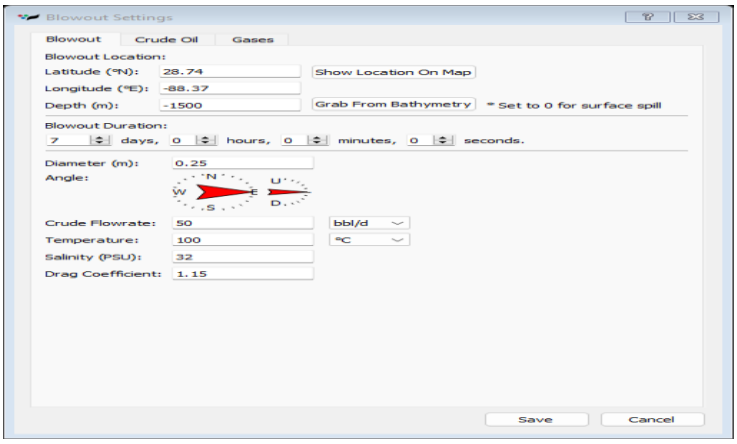

Figure 5d: Blowout Settings of BLOSOM

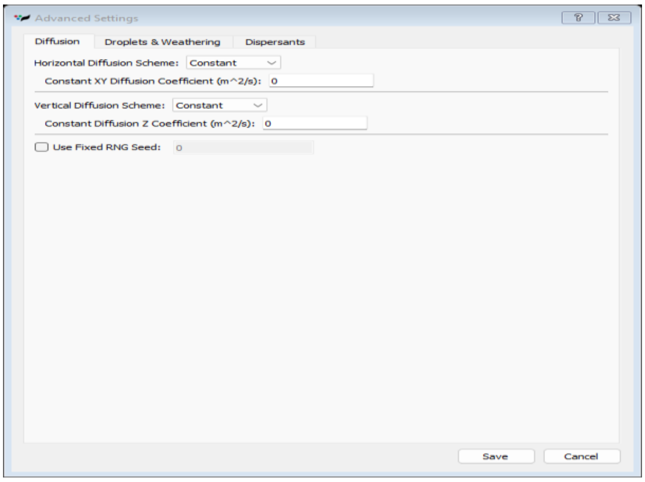

Figure 5e: Advanced Settings of BLOSOM

Oil Spill Cleanup Operations Model (OSCOM) is a spatial optimization tool for modeling response operations, using mathematical programming to minimize total time and cost in dispatching cleanup equipment (Grubesic *et al*., 2017). The output from BLOSOM is the input files to OSCOM for processing. Minitab is a statistical analysis tool for validating predictive models, performing regression and correlation analysis, and creating visualizations.

Data Collection and Sources

Table 1 summarises the data types, specific parameters and sources of data acquisition.

Table 1: Data types and sources

Data Type	Specific Parameters	Source
Environmental Parameters and Geospatial data	Ambient Ocean Data (ocean currents, wind, temperature, salinity),	NiMet, NIMASA, NHA and HYCOM
	Bathymetry raster ocean data	GEBCO
	Vector shoreline	Natural Earth Data
Oil Properties	Specific gravity, viscosity, composition	SNEPCO reports
Response Resources	Equipment inventory and locations	CNA, OSRL, NOSDRA
Historical Spill Data	Release rate, duration, location	NOSDRA, SNEPCO

Oil Spill Simulation and Trajectory Modeling

BLOSOM was deployed to model the Bonga spill under four environmental conditions: Environmental data (wind, current, temperature), determine oil properties and release rate, model the surface transport and subsurface dispersion, and output projected fate (evaporation, dispersion, emulsification, biodegradation). Simulations were performed with daily step intervals that covered the spread within the EEZ of Nigeria and the possible transboundary movement.

Response logistics optimisation

OSCOM modelled how best to allocate equipment in response centers. The equipment availability, limited budget, time-to-site, and environmental sensitivity rankings are considered constraints. The dispatch schedules are optimized by a Mixed-Integer Linear Programming (MILP) model with the goals of minimizing response time, maximizing the oil recovered, and minimizing the environmental damage.

DSS integration architecture

The DSS unites all of its elements through the modular architecture outlined below and represented in Figure 6:

- Input Layer: Real-time and past data.
- Modeling Layer: BLOSOM and OSCOM engines.
- Analytical Layer: Statistical analysis (Minitab) to detect outliers.

• Decision Layer: Optimization models and decision rules.

• Visualization Layer: GIS to map-based analytics.

• Output Layer: Strategy recommendations and reports in real-time.

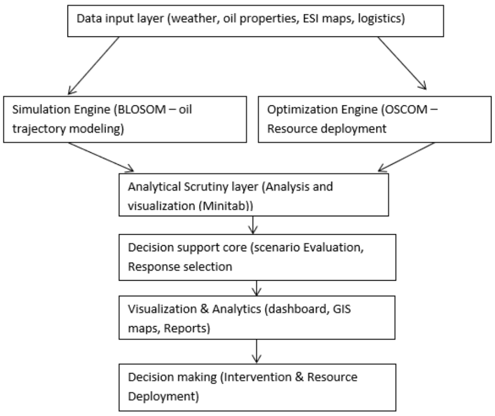

Figure 6: Flowchart of the Decision Support System (DSS) for Oil Spill Response.

RESULTS

Simulation Results from BLOSOM

a) The BLOSOM model was set up using the reported conditions from the Bonga spill incident. Input parameters included an estimated release of about 40,000 barrels over a 48hour period, a water depth of roughly 1,200 metres, and typical December conditions for the Gulf of Guinea, with wind speeds ranging between 5 and 15 knots, current velocities of about 0.2 to 0.5 metres per second, and sea temperatures around 26 to 28 degrees Celsius. The simulation outputs showed that the oil slick moved in a west-southwesterly direction, which is consistent with the influence of the Guinea Current and the seasonal Harmattan winds. The leading edge of the slick was projected to reach the Nigerian coastline, specifically the Bayelsa and Rivers State areas, within 72 to 96 hours after the discharge began.

b) Under more extreme wind conditions of about 15 knots, the model indicated that the slick could extend beyond Nigerian waters. In such a scenario, the oil could enter Cameroon's Exclusive Economic Zone within roughly five to six days, reach Equatorial Guinea in about seven to eight days, and approach São Tomé and Príncipe within eight to ten days. These findings underscore the trans boundary risks that were earlier discussed in the paper and highlight the importance of regional cooperation in spill management.

c) The weathering analysis from the simulation suggested that after ten days, approximately 35 to 40 percent of the spilled crude would have evaporated, while about 15 to 20 percent would have undergone natural dispersion. Another 10 to 15 percent was estimated to have formed emulsions, and the remaining 25 to 30 percent would still be present as surface slick or sheen. These Figures are broadly in line with published weathering patterns for light crude oils in tropical marine environments.

d) The model also helped identify shorelines that were most at risk. The Niger Delta mangroves, the Qua Iboe estuary, and the Cross River delta emerged as the most ecologically sensitive areas, with estimated oil arrival times of three to five days from the time of the spill. This kind of information is useful for planning pre-emptive protective measures.

Optimisation Results from OSCOM

a) The OSCOM model was applied to optimise the deployment of response equipment from five existing depots located at Onne, Port Harcourt, Calabar, Lagos, and Escravos. The optimisation considered several practical constraints, including budget limits, travel distances to the spill site, equipment availability, and the environmental sensitivity of different coastal areas.

b) The results showed a notable improvement over the current ad hoc approach. The optimised dispatch plan reduced the average time for equipment to reach the spill site from about 8.2 hours to roughly 4.7 hours, representing a reduction of about 43 percent. This suggests that better coordination and pre-planning could make a real difference in the critical early hours of a spill response.

c) In terms of recovery performance, the OSCOM outputs indicated that an optimised response could achieve a recovery rate of between 62 and 68 percent within the first 72 hours. This compares favourably with the estimated 45 to 50 percent recovery typically achieved under uncoordinated response efforts, based on historical data from similar incidents.

d) The model also generated cost estimates. The optimised approach pointed to a total response cost of approximately $14.6 million, which is about 22 percent lower than what might be expected from conventional deployment strategies. This cost saving is largely attributable to better resource utilisation and reduced travel times.

e) The optimisation further recommended that dispersants be applied ahead of the slick's leading edge and in an upwind direction to maximise their effectiveness. This strategy was projected to reduce shoreline oiling by around 30 to 35 percent, which is a significant environmental benefit.

f) Equipment utilisation rates also improved under the optimised plan. The model suggested that usage rates could increase from about 52 percent under current practices to roughly 81 percent, meaning fewer assets would sit idle while others are overstretched.

g) Finally, a sensitivity analysis carried out using Minitab revealed that wind speed and distance to shore were the two most influential factors affecting response time, with both showing statistical significance at the p-value less than 0.05 level. Current velocity and oil viscosity had a moderate but less pronounced effect. This kind of insight is valuable for prioritising data collection and planning efforts in future spill events.

DSS Prototype

A working theoretical model (as outlined in Section 3.5) was created, ready to be tested and implemented in reality.

CONCLUSION

This paper has developed a theoretical framework for developing a Nigeria-specific Decision Support System to respond to offshore oil spills. It is a framework that combined oil fate and transport modeling in BLOSOM with logistics optimisation (OSCOM) and statistical analytics (Minitab). This DSS, when implemented, would show significant improvement in the time and environmental impact mitigation associated with decision-making with respect to the 2011 Bonga oil spill data. The ability to model oil trajectory aids in predicting movement of the slick and arrival time at the shoreline, which can be used to exercise proactive deployment to prevent the arrival of oil in ecologically sensitive regions and cross-border zones. The distances between Bonga Field and regional shorelines indicate that response windows of 2-5 days are critical depending on the wind and current conditions.

RECOMMENDATIONS

1. Adoption: This DSS framework should be adopted by regulatory agencies (NOSDRA, NIMASA) and operators to strengthen the capacity of the national response to oil spills.
2. Real-time Integration: Integrate satellite and drone data feeds to provide real-time monitoring of oil spill events.
3. Training: The stakeholders should be trained on how to use the DSS interface to prepare for an emergency.
4. Policy Update: National contingency plans should be updated to include DSS-enabled decision-making processes.

5. Implementation: The simulation and validation follow the steps presented in this theoretical framework.
6. Cross-Border Collaboration: There should be regional agreements to share access to the outputs of DSS and coordinate response protocols

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